INFORMATION TO USERS

This dissertation was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106
A Xerox Education Company
LAURENCE, Clifford Lee, 1942-
DESIGN AND TUNING CHARACTERISTICS OF CW
OPTICAL PARAMETRIC OSCILLATORS. [Pages
255-275, Appendices El-E4 not microfilmed at
request of author. Available for consultation
at Rice University Library].

Rice University, Ph.D., 1972
Physics, optics

University Microfilms, A XEROX Company, Ann Arbor, Michigan

© Copyright
Clifford Lee Laurence
1972
RICE UNIVERSITY

DESIGN AND TUNING CHARACTERISTICS OF CW
OPTICAL PARAMETRIC OSCILLATORS

by

Clifford Lee Laurence

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Thesis Director's signature:

Frank T.ittel

Houston, Texas
May, 1972
PLEASE NOTE:

Some pages may have

indistinct print.

Filmed as received.

University Microfilms, A Xerox Education Company
This research was jointly sponsored by project THEMIS and monitored by the U. S. Office of Naval Research and the National Aeronautics and Space Administration.
DEDICATION

To my wife, Bette, for her encouragement, understanding, and constant assistance
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>TUNABLE SOURCES</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>FREQUENCY CONVERSION TECHNIQUES</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>BRIEF HISTORY</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>THE OPTICAL PARAMETRIC OSCILLATOR</td>
<td>5</td>
</tr>
<tr>
<td>1.5</td>
<td>OPTICAL NONLINEARITY IN CRYSTALS</td>
<td>8</td>
</tr>
<tr>
<td>1.6</td>
<td>PHASE-MATCHING</td>
<td>9</td>
</tr>
<tr>
<td>1.7</td>
<td>OPTICAL PARAMETRIC NOISE EMISSION</td>
<td>11</td>
</tr>
<tr>
<td>1.8</td>
<td>STATE-OF-THE-ART IN PARAMETRIC OSCILLATION</td>
<td>12</td>
</tr>
<tr>
<td>1.9</td>
<td>COMPARISON TO OTHER TUNABLE SOURCES</td>
<td>15</td>
</tr>
<tr>
<td>1.10</td>
<td>ORGANIZATION</td>
<td>18</td>
</tr>
<tr>
<td>1.11</td>
<td>SUMMARY OF ACHIEVEMENTS</td>
<td>20</td>
</tr>
</tbody>
</table>

| 2.0     | CLASSICAL ELECTROMAGNETIC DESCRIPTION OF OPTICAL   | 24   |
|         | PARAMETRIC OSCILLATION                             |      |
| 2.1     | OPTICAL PARAMETRIC GAIN                            | 27   |
| 2.2     | PHASE-MATCHING                                     | 28   |
| 2.3     | THRESHOLD FOR A DOUBLY RESONANT PARAMETRIC         | 32   |
|         | OSCILLATOR                                         |      |
| 2.4     | GAUSSIAN BEAMS                                     | 35   |
| 2.5     | FREQUENCY TUNING OF NONLINEAR INTERACTIONS         | 37   |
| 2.5-1   | Tuning Techniques                                  | 37   |
| 2.5-2   | The Temperature Tuning Equation                    | 48   |
| 2.6     | OUTPUT POWER AND CONVERSION EFFICIENCY OF THE DRO. | 50   |
| 2.6-1   | Output Power                                       | 50   |
| 2.6-2   | Conversion Efficiency                              | 55   |
| 2.6-3   | Effect of Temperature Tuning on Output Power       | 57   |
| 2.7     | PARAMETRIC OSCILLATOR LINEWIDTH                    | 62   |
| 2.7-1   | Range of OPO Operation Without Tuning.             | 64   |
| 2.7-2   | Fluctuation Phenomena                              | 65   |

| 3.0     | CW OPO PHYSICAL DESIGN REQUIREMENTS                | 69   |
| 3.1     | OPO PUMP SOURCES                                   | 69   |
| 3.1-1   | General Pump Requirements                          | 69   |
| 3.1-2   | Argon-ion Gas Laser                                | 70   |
| 3.1-3   | Nd:YAG Solid State Laser                           | 74   |
TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>NONLINEAR OPTICAL CRYSTALS</td>
<td>79</td>
</tr>
<tr>
<td>3.2-1</td>
<td>Required Properties</td>
<td>79</td>
</tr>
<tr>
<td>3.2-2</td>
<td>Selection of Nonlinear Materials</td>
<td>82</td>
</tr>
<tr>
<td>3.2-3</td>
<td>Crystal Oven Design</td>
<td>86</td>
</tr>
<tr>
<td>3.3</td>
<td>NONLINEAR CRYSTAL TEMPERATURE TUNING CURVES</td>
<td>89</td>
</tr>
<tr>
<td>3.4</td>
<td>OPTICAL CAVITY DESIGN</td>
<td>106</td>
</tr>
<tr>
<td>3.4-1</td>
<td>Resonator Configuration</td>
<td>106</td>
</tr>
<tr>
<td>3.4-2</td>
<td>Design Procedure - Beam Waist, Confocal Parameter, Cavity Spacing</td>
<td>108</td>
</tr>
<tr>
<td>3.4-3</td>
<td>Mode-Matching</td>
<td>112</td>
</tr>
<tr>
<td>3.4-4</td>
<td>Optical Coatings</td>
<td>114</td>
</tr>
<tr>
<td>3.5</td>
<td>OPTICAL ISOLATOR DESIGN</td>
<td>118</td>
</tr>
<tr>
<td>4.0</td>
<td>CONTINUOUS WAVE OPTICAL PARAMETRIC OSCILLATOR EXPERIMENTAL STUDY</td>
<td>122</td>
</tr>
<tr>
<td>4.1</td>
<td>GENERAL METHOD</td>
<td>122</td>
</tr>
<tr>
<td>4.1-1</td>
<td>Operation of the Argon Laser</td>
<td>122</td>
</tr>
<tr>
<td>4.1-2</td>
<td>Optical Isolator Operation</td>
<td>125</td>
</tr>
<tr>
<td>4.1-3</td>
<td>Optical Alignment of the OPO Components</td>
<td>125</td>
</tr>
<tr>
<td>4.2</td>
<td>DEGENERATE CW OPTICAL PARAMETRIC OSCILLATOR USING A 514.5 nm PUMP</td>
<td>129</td>
</tr>
<tr>
<td>4.2-1</td>
<td>Basic Operational Characteristics</td>
<td>129</td>
</tr>
<tr>
<td>4.2-1A</td>
<td>Phase-Matching Temperature</td>
<td>129</td>
</tr>
<tr>
<td>4.2-1B</td>
<td>Threshold</td>
<td>130</td>
</tr>
<tr>
<td>4.2-1C</td>
<td>Output Power and Conversion Efficiency</td>
<td>130</td>
</tr>
<tr>
<td>4.2-1D</td>
<td>Optical Cavity Separation and Mode-Matching Lens Position</td>
<td>131</td>
</tr>
<tr>
<td>4.2-2</td>
<td>Output Characteristics</td>
<td>132</td>
</tr>
<tr>
<td>4.2-2A</td>
<td>Transverse Modes</td>
<td>132</td>
</tr>
<tr>
<td>4.2-2B</td>
<td>DRO Amplitude Stability</td>
<td>132</td>
</tr>
<tr>
<td>4.2-2C</td>
<td>DRO Linewidth</td>
<td>138</td>
</tr>
<tr>
<td>4.2-3</td>
<td>DRO Tuning Characteristics</td>
<td>143</td>
</tr>
<tr>
<td>4.3</td>
<td>DEGENERATE OPTICAL PARAMETRIC OSCILLATOR USING A Q-SWITCHED SOLID STATE 532.0 nm PUMP</td>
<td>147</td>
</tr>
<tr>
<td>4.4</td>
<td>VISIBLE (NONDEGENERATE) CW OPTICAL PARAMETRIC OSCILLATOR USING A 488.0 nm PUMP</td>
<td>149</td>
</tr>
<tr>
<td>4.4-1</td>
<td>Basic Operational Characteristics</td>
<td>149</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4-2</td>
<td>Output Characteristics</td>
<td>150</td>
</tr>
<tr>
<td>4.4-3</td>
<td>Tuning Characteristics</td>
<td>151</td>
</tr>
<tr>
<td>5.0</td>
<td>SUMMARY AND CONCLUSIONS</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENT</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>APPENDICES</td>
<td>162</td>
</tr>
<tr>
<td>A.</td>
<td>OBSERVATION OF OPTICAL PARAMETRIC NOISE EMISSION (OPN)</td>
<td>163</td>
</tr>
<tr>
<td>A1.</td>
<td>INTRODUCTION</td>
<td>163</td>
</tr>
<tr>
<td>A2.</td>
<td>OPN OUTPUT POWER AND BANDWIDTH.</td>
<td>164</td>
</tr>
<tr>
<td>A2.1</td>
<td>Output Power</td>
<td>164</td>
</tr>
<tr>
<td>A2.2</td>
<td>OPN Bandwidth Characteristics</td>
<td>170</td>
</tr>
<tr>
<td>A3.</td>
<td>OPN EXPERIMENTAL TECHNIQUE AND RESULTS</td>
<td>175</td>
</tr>
<tr>
<td>A3.1</td>
<td>Experimental Method</td>
<td>175</td>
</tr>
<tr>
<td>A3.2</td>
<td>Power and Bandwidth Observations</td>
<td>180</td>
</tr>
<tr>
<td>A3.3</td>
<td>OPN Emission Near Degeneracy of a 514.5 nm Pump.</td>
<td>185</td>
</tr>
<tr>
<td>B.</td>
<td>NONLINEAR CRYSTAL EVALUATION BY SECOND-HARMONIC GENERATION</td>
<td>191</td>
</tr>
<tr>
<td>C.</td>
<td>COMPUTER AIDED STUDY OF NONLINEAR INTERACTIONS</td>
<td>203</td>
</tr>
<tr>
<td>C1.</td>
<td>INTRODUCTION</td>
<td>203</td>
</tr>
<tr>
<td>C2.</td>
<td>TEMPERATURE TUNING</td>
<td>204</td>
</tr>
<tr>
<td>C3.</td>
<td>ORIENTATION TUNING</td>
<td>205</td>
</tr>
<tr>
<td>C4.</td>
<td>ELECTRIC FIELD TUNING</td>
<td>206</td>
</tr>
<tr>
<td>C5.</td>
<td>DOUBLY AND SINGLY RESONANT OPTICAL PARAMETRIC OSCILLATOR THRESHOLD.</td>
<td>207</td>
</tr>
<tr>
<td>C6.</td>
<td>PARAMETRIC NOISE EMISSION (FLUORESCENCE)</td>
<td>209</td>
</tr>
<tr>
<td>C7.</td>
<td>OPTICAL RESONATOR DESIGN</td>
<td>210</td>
</tr>
<tr>
<td>C8.</td>
<td>GAUSSIAN BEAM MODE-MATCHING</td>
<td>211</td>
</tr>
<tr>
<td>C9.</td>
<td>SUBROUTINES</td>
<td>213</td>
</tr>
<tr>
<td>C9.1</td>
<td>Index of Refraction</td>
<td>213</td>
</tr>
<tr>
<td>C9.1A</td>
<td>LiNbO₃ (LN).</td>
<td>213</td>
</tr>
<tr>
<td>C9.1B</td>
<td>Ba₂NaNb₅O₁₅ (BSN)</td>
<td>214</td>
</tr>
<tr>
<td>C9.2</td>
<td>Temperature Tuning Constant</td>
<td>215</td>
</tr>
<tr>
<td>C9.3</td>
<td>Angular Dispersive Constant b.</td>
<td>216</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>C9.4</td>
<td>Phase-Matching Temperature</td>
<td>217</td>
</tr>
<tr>
<td>C9.5</td>
<td>Estimation of the Second-Harmonic Phase-Matching Temperature at a Given</td>
<td>218</td>
</tr>
<tr>
<td></td>
<td>Temperature at a Given Wavelength from the Known SHG $T_0$ at a Nearby</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wavelength.</td>
<td></td>
</tr>
<tr>
<td>C9.6</td>
<td>Second-Order Derivative of Index of Refraction with Respect to Frequency</td>
<td>220</td>
</tr>
<tr>
<td>C9.7</td>
<td>Tuning Curve Calcomp Plotting</td>
<td>221</td>
</tr>
<tr>
<td>D.</td>
<td>COMPUTER PROGRAM LISTING: NONLINEAR OPTICAL AND PARAMETRIC COMPUTATIONS.</td>
<td>223</td>
</tr>
<tr>
<td>E.</td>
<td>PUBLICATIONS</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>276</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIG. NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Nonlinear Optical Frequency Conversion Processes.</td>
<td>4</td>
</tr>
<tr>
<td>1-2</td>
<td>Schematic of an Optical Parametric Oscillator</td>
<td>7</td>
</tr>
<tr>
<td>2-1</td>
<td>OPO Normalized Log Gain as a Function of Momentum Mismatch.</td>
<td>29</td>
</tr>
<tr>
<td>2-2</td>
<td>Orientation Tuning in LiNbO$_3$</td>
<td>43</td>
</tr>
<tr>
<td>2-3</td>
<td>Orientation Tuning in Ba$_2$NaNb$<em>5$O$</em>{15}$</td>
<td>44</td>
</tr>
<tr>
<td>2-4</td>
<td>Electric Field Tuning in LiNbO$_3$</td>
<td>45</td>
</tr>
<tr>
<td>2-5</td>
<td>Electric Field Tuning in Ba$_2$NaNb$<em>5$O$</em>{15}$</td>
<td>46</td>
</tr>
<tr>
<td>2-6</td>
<td>Temperature Tuning in BSN</td>
<td>47</td>
</tr>
<tr>
<td>2-7</td>
<td>DRO Optical Cavity with Power Designation</td>
<td>51</td>
</tr>
<tr>
<td>2-8</td>
<td>Predicted DRO Output Power as a Function of Crystal Temperature</td>
<td>63</td>
</tr>
<tr>
<td>3-1</td>
<td>Spectra of Argon Laser Output at 488.0 and 514.5 nm</td>
<td>72</td>
</tr>
<tr>
<td>3-2</td>
<td>Solid State CW or Q-Switched 532.0 nm Source.</td>
<td>76</td>
</tr>
<tr>
<td>3-3</td>
<td>Q-Switched Pulses of a Frequency Doubled Nd:YAG Laser</td>
<td>77</td>
</tr>
<tr>
<td>3-4</td>
<td>Detail of Optical Crystal Ovens and Oscillator Components.</td>
<td>87</td>
</tr>
<tr>
<td>3-5</td>
<td>Experimental Temperature Tuning Curves for Three Types of Crystals</td>
<td>91</td>
</tr>
<tr>
<td>3-6</td>
<td>Temperature Tuning in LN: 514.5 nm Pump, Cry. No. 1</td>
<td>93</td>
</tr>
<tr>
<td>3-7</td>
<td>Temperature Tuning in LN: 514.5 nm Pump, Cry. No. 3</td>
<td>94</td>
</tr>
<tr>
<td>3-8</td>
<td>Temperature Tuning in BSN: 514.5 nm PUMP, Cry. No. 2</td>
<td>95</td>
</tr>
<tr>
<td>3-9</td>
<td>Temperature Tuning in BSN: 514.5 nm Pump, Cry. No. 2</td>
<td>96</td>
</tr>
<tr>
<td>3-10</td>
<td>Temperature Tuning in BSN: 514.5 nm Pump, Cry. No. 6</td>
<td>97</td>
</tr>
<tr>
<td>3-11</td>
<td>Temperature Tuning in BSN: 514.5 nm Pump, Cry. No. 11</td>
<td>98</td>
</tr>
<tr>
<td>FIG. NO.</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3-12</td>
<td>Temperature Tuning in LN: 488.0 nm Pump, Cry. No. 1</td>
<td>99</td>
</tr>
<tr>
<td>3-13</td>
<td>Temperature Tuning in LN; 488.0 nm Pump, Cry. No. 3</td>
<td>100</td>
</tr>
<tr>
<td>3-14</td>
<td>Temperature Tuning in BSN: 488.0 nm Pump, Cry. No. 2</td>
<td>101</td>
</tr>
<tr>
<td>3-15</td>
<td>Temperature Tuning in BSN: 488.0 nm Pump, Cry. No. 6</td>
<td>102</td>
</tr>
<tr>
<td>3-16</td>
<td>Temperature Tuning in BSN: 488.0 nm Pump, Cry. No. 12</td>
<td>103</td>
</tr>
<tr>
<td>3-17</td>
<td>CW OPO Resonator Design</td>
<td>107</td>
</tr>
<tr>
<td>3-18</td>
<td>Focusing Parameter as a Function of Separation</td>
<td>111</td>
</tr>
<tr>
<td>3-19</td>
<td>Transmission of Optical Coating Versus Wavelength for High Reflection at 1060 nm and Reflection Versus Wavelength for Anti-reflection at 1060 nm</td>
<td>116</td>
</tr>
<tr>
<td>3-20</td>
<td>Transmission of Optical Coating Versus Wavelength for High Reflection at 650 nm and 1950 nm</td>
<td>117</td>
</tr>
<tr>
<td>3-21</td>
<td>Effectiveness of Isolation on the Pump Spectrum</td>
<td>119</td>
</tr>
<tr>
<td>3-22</td>
<td>Optical Isolator</td>
<td>120</td>
</tr>
<tr>
<td>4-1</td>
<td>Infrared Optical Parametric Oscillator</td>
<td>123</td>
</tr>
<tr>
<td>4-2</td>
<td>IR OPO Output Power as a Function of Time Using an Unstabilized Pump Laser</td>
<td>134</td>
</tr>
<tr>
<td>4-3</td>
<td>IR OPO Output Using an Amplitude Stabilized Pump Laser with no Longitudinal Mode Hopping</td>
<td>136</td>
</tr>
<tr>
<td>4-4</td>
<td>Most Stable IR OPO Output as a Function of Time</td>
<td>137</td>
</tr>
<tr>
<td>4-5</td>
<td>IR OPO Spectrum Near Degeneracy</td>
<td>139</td>
</tr>
<tr>
<td>4-6</td>
<td>OPO Linewidths as a Function of Crystal Temperature for a Free Running Pump Laser (Laser A) with Isolation</td>
<td>141</td>
</tr>
<tr>
<td>4-7</td>
<td>OPO Linewidth as a Function of Crystal Temperature for a Stable Pump Laser (Laser B) with Isolation</td>
<td>142</td>
</tr>
<tr>
<td>4-8</td>
<td>Temperature Tuning in BSN: 514.5 nm Pump, Cry. No. 11</td>
<td>144</td>
</tr>
<tr>
<td>FIG. NO.</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4-9</td>
<td>IR OPO Output Power as a Function of Crystal Temperature</td>
<td>146</td>
</tr>
<tr>
<td>4-10</td>
<td>Repetitively Q-Switched, Frequency Doubled Nd:YAG Pump and Degenerate OPO Output</td>
<td>148</td>
</tr>
<tr>
<td>4-11</td>
<td>Visible OPO TEM₀₀ Mode and Experimental Configuration During Operation</td>
<td>152</td>
</tr>
<tr>
<td>4-12</td>
<td>Visible OPO Signal Spectrum</td>
<td>153</td>
</tr>
<tr>
<td>4-13</td>
<td>Temperature Tuning Curve for Cry. No. 12 with OPO Data Points</td>
<td>155</td>
</tr>
<tr>
<td>4-14</td>
<td>Visible OPO Temperature Tuning Curve</td>
<td>156</td>
</tr>
<tr>
<td>A1</td>
<td>Noncollinear Phase-Matching</td>
<td>172</td>
</tr>
<tr>
<td>A2</td>
<td>Observation of Optical Parametric Noise Emission</td>
<td>176</td>
</tr>
<tr>
<td>A3</td>
<td>Parametric Fluorescence Intensity and Bandwidth for a Function of Detection Acceptance Angle</td>
<td>182</td>
</tr>
<tr>
<td>A4</td>
<td>OPN Intensity as a Function of Wavelength for Four Acceptance Angles (488.0 nm Pump)</td>
<td>183</td>
</tr>
<tr>
<td>A5</td>
<td>Effect of Focused Pump Radiation on Parametric Fluorescence</td>
<td>184</td>
</tr>
<tr>
<td>A6</td>
<td>OPN Intensity as a Function of Wavelength Near Degeneracy for Seven Temperatures</td>
<td>187</td>
</tr>
<tr>
<td>A7</td>
<td>Bandwidth of Infrared OPN as a Function of Degeneracy</td>
<td>190</td>
</tr>
<tr>
<td>B1</td>
<td>Nonlinear Crystal Phase-Matching Evaluation</td>
<td>195</td>
</tr>
<tr>
<td>B2</td>
<td>SHG Output Power as a Function of Temperature for Two Unacceptable Crystals</td>
<td>197</td>
</tr>
<tr>
<td>B3</td>
<td>SHG Output Power as a Function of Temperature for a Nonstoichiometric LN Crystal</td>
<td>198</td>
</tr>
<tr>
<td>B4</td>
<td>SHG Output Power as a Function of Temperature for the ISHG Crystal</td>
<td>200</td>
</tr>
<tr>
<td>FIG. NO.</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>B5</td>
<td>SHG Output Power as a Function of Temperature for the IR OPO Crystal.</td>
<td>201</td>
</tr>
<tr>
<td>B6</td>
<td>SHG Output Power as a Function of Temperature for the Visible OPO Crystal</td>
<td>202</td>
</tr>
<tr>
<td>C1</td>
<td>Transformation of a Gaussian Beam by a Thin Lens.</td>
<td>212</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>IR OPO Thresholds</td>
<td>38</td>
</tr>
<tr>
<td>2-2</td>
<td>Visible OPO Thresholds</td>
<td>40</td>
</tr>
<tr>
<td>3-1</td>
<td>Nonlinear Optical Properties of LN and BSN</td>
<td>83</td>
</tr>
<tr>
<td>3-2</td>
<td>Summary of Temperature Tuning Characteristics</td>
<td>104</td>
</tr>
<tr>
<td>A1</td>
<td>OPN Output Power in LN with a 514.5 nm Pump</td>
<td>166</td>
</tr>
<tr>
<td>A2</td>
<td>OPN Output Power in LN with a 488.0 nm Pump</td>
<td>167</td>
</tr>
<tr>
<td>A3</td>
<td>OPN Output Power in BSN with a 514.5 nm Pump</td>
<td>168</td>
</tr>
<tr>
<td>A4</td>
<td>OPN Output Power in BSN with a 488.0 nm Pump</td>
<td>169</td>
</tr>
<tr>
<td>B1</td>
<td>Nonlinear Crystal Identification and Characteristics</td>
<td>196</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS AND ABBREVIATIONS

For easy reference, all the symbols used in this paper are tabulated below:

\( n \) - index of refraction

Superscript \( o \) - ordinary wave

Superscript \( e \) - extraordinary wave

Subscript \( p \) - pump beam

Subscript \( s \) - signal wave (shorter wavelength result of a three-wave interaction)

Subscript \( i \) - idler wave (longer wavelength result of a three-wave interaction)

Subscript \( o \) - subharmonic of the pump (degeneracy)

\( L \) - crystal length

\( b \) - optical resonator confocal parameter

\( b \) - angular dispersive constant

\( T^o \) - second-harmonic generation phase-matching temperature for a crystal (reversing the role of the pump, this is also the sub-harmonic phase-matching temperature)

\( \lambda \) - wavelength

\( \omega \) - angular frequency

\( \nu \) - frequency

\( w \) - beam waist in an optical resonator

\( \eta \) - temperature-tuning coefficient

\( \eta \) - free space wave impedance

\( B \) - birefringence \((n^o_p - n^e_p)\)

\( D \) - dispersion \((n^o_p - n^o_o)\)
LIST OF SYMBOLS AND ABBREVIATIONS (continued)

θ - angle between the crystal optic axis and the direction of pump propagation

r - linear electro-optic coefficients

R - mirror radius

d - crystal nonlinear coefficient

d - mirror distance or separation

γ - frequency degeneracy parameter (γ = 0 fully degenerate; γ>0 more nondegenerate)

α - index of refraction degeneracy parameter

ε - total losses of a resonant optical field

k - optical field propagation constant (wave vector)

g - focusing parameter \( \frac{L}{d} \)

f - lens focal length

SHG - second harmonic generation

ISHG - SHG internal to the laser cavity

OPO - optical parametric oscillation

OPN - optical parametric noise

IR - infrared

uv - ultraviolet

PMT - photomultiplier tube

P - power

\( P_{th} \) - threshold power

CW - continuous wave

HR - high reflection
LIST OF SYMBOLS AND ABBREVIATIONS (continued)

AR - antireflection
nm - nanometer (10 Å)
LN - lithium niobate (LiNbO₃)
BSN - barium sodium niobate (Ba₂NaNb₅O₁₅)
\( \chi_L \) - linear polarizability
q - conversion efficiency
u - ratio of pump power to threshold power
DESIGN AND TUNING CHARACTERISTICS OF CW
OPTICAL PARAMETRIC OSCILLATORS

1.0 INTRODUCTION

The goal of this study was to develop a tunable coherent light source that would have the same fundamental characteristics as that of a laser and be capable of continuous tuning over large frequency ranges. This study includes an investigation of both the internal parameters essential for the operation of the parametric oscillator and the external parameters that describe its output capability.

The motivation for the development of a tunable optical source is in the elimination of design limitations imposed by the availability of coherent sources at discrete wavelengths. Tunable sources could greatly expand work being done in such fields as precision spectroscopy, optical pumping, fluorescence, excited-state and two-photon spectroscopy, molecular beam-optical interaction, resonance Raman studies, communications, photo-chemistry, and holography.

The optical parametric oscillator (OPO) was chosen for this study because of its excellent potential as a source of high-power coherent radiation which may be tuned over wide spectral ranges. The design and output characteristics for continuous operation are of particular interest. OPO's can be operated both pulsed and continuous. The availability of continuous radiation will add further dimension to the usefulness of a tunable source; it will not only have wider application to the aforementioned areas of research, but in many cases it may be specifically required. Some other methods for obtaining
tunable sources will be discussed in Sec. 1.1.

The purpose of this study is to investigate the conditions for which parametric oscillation can be obtained using a CW pump laser and to determine the characteristics of the OPO output under various conditions. The design of the parametric oscillator includes studies of nonlinear crystal availability, crystal evaluation, techniques to establish individual crystal phase-matching characteristics, optical resonator design, pump laser requirements, mode-matching requirements, and proper alignment of optical components to minimize the pump power required to obtain oscillation.

The output characteristics of the OPO are primarily determined by pump laser power, pump laser amplitude and frequency stability, optical resonator alignment, and crystal temperature. The effects of these on OPO output power, amplitude stability, wavelengths, and linewidths was thoroughly investigated.

1.1 TUNABLE SOURCES

At the present time, methods for generating tunable coherent radiation fall into two categories. The first category involves techniques that select or alter the level of an atomic or molecular transition in a lasing medium. The second category is comprised of processes used to convert laser produced radiation to other wavelengths through nonlinear interactions.

In the first category, direct tuning of laser output by changing the levels of an atomic transition through the use of pressure, temperature, magnetic fields, etc., has achieved only very small tuning
of the laser emission linewidth. The most successful work in the first category has been through the use of laser-pumped organic dyes; in the second category, it has been through the use of nonlinear optical interactions. A comparison of these methods will be made later on in Sec. 1.9 after a more detailed discussion on the state-of-the-art of each method is given.

In the second category, a variety of frequency conversion techniques are available. These techniques involve the interaction of three electromagnetic waves. Interactions with more than three waves can be obtained, but the process is much more complex and the interactions are much weaker than the three-wave interaction.

1.2 FREQUENCY CONVERSION TECHNIQUES

Frequency conversion by three-wave interaction offers a variety of conversion techniques. These techniques are shown in Fig. 1-1. The frequency of an intense source can be doubled as shown in Fig. 1-1(a). An intense high frequency source, the pump, can interact with a pair of lower frequency fields, called the signal and idler, to amplify them. This is parametric amplification or generation. The process can be enhanced by providing resonant feedback at the signal and idler frequencies to produce parametric oscillation (Fig. 1-1(b)). In a third process (Fig. 1-1(c)), two lower frequency waves interact to produce the sum frequency. One wave may be an infrared signal arriving from an external source. It is mixed with a local infrared source to produce a signal in the visible. This process of sum frequency generation is usually called parametric up-conversion. It is
FIG. 1-1. NONLINEAR OPTICAL FREQUENCY CONVERSION PROCESSES
used to convert signals to frequencies where detectors have higher quantum efficiencies.

1.3 BRIEF HISTORY

Before the development of the laser, three-wave interactions at optical frequencies were so weak that they were of little practical importance. With the availability of intense laser sources after 1960, the picture rapidly changed. In 1961 Franken, Hill, Peters, and Weinrich [1] observed optical frequency doubling in quartz (second-harmonic generation). This experiment indicated that existing materials had properties that could sustain this type of interaction. Developments in nonlinear optics proceeded rapidly after Giordmaine [2] and Maker, et al. [3] introduced phase-matching (Sec. 1.6). After some new nonlinear materials were introduced, such as LiNbO₃ (Boyd, et al. [4]), Giordmaine and Miller in 1965 were able to construct the first optical parametric oscillator using a pulsed laser [5]. In 1966, Boyd and Ashkin [6] demonstrated that parametric oscillation should be possible using continuous laser pumps. The first CW OPO's were constructed by Smith, et al. [7], and Byer, et al. [8]. Recently a great deal of work has been done to improve parametric oscillator output powers, conversion efficiencies, tuning ranges, and linewidths.

1.4 THE OPTICAL PARAMETRIC OSCILLATOR

The three-wave interaction of a high-frequency pump wave amplifying signal and idler waves is governed by two basic relationships. Conservation of energy requires that:
\[ \omega_s + \omega_i = \omega_p \]  
(1-1)

and conservation of momentum requires that:

\[ \vec{k}_s + \vec{k}_i = \vec{k}_p \]  
(1-2)

Equation (1-2) is discussed in detail in Sec. 1.6, phase-matching.
These two equations form the basic constraints on the three-wave interaction and, together with index-of-refraction values in the nonlinear crystal, determine the output signal and idler wavelengths.

A simplified schematic of an optical parametric oscillator is shown in Fig. 1-2. The output from the pump laser is focused into a nonlinear optical crystal. The interaction in the crystal provides gain at two wavelengths, \( \lambda_s \) and \( \lambda_i \). The interaction is enhanced by providing feedback of the signal and idler waves with a resonant optical cavity formed by mirrors \( M_1 \) and \( M_2 \). Mirror \( M_1 \) must have a high transmission at the pump frequency and high reflectivity at the signal and idler frequencies. Mirror \( M_2 \) must be highly reflective at the signal and idler frequencies. Output from the OPO is obtained because \( M_2 \) will not be 100% reflective.

OPO's can be constructed with either the signal or the idler wavelength resonant (singly resonant) or with both resonant (doubly resonant). The minimum pump power required to obtain oscillation (threshold power) varies considerably depending on the design. A singly resonant oscillator (SRO) will have a threshold much higher (roughly 100 times) than a doubly resonant oscillator (DRO). Because the purpose of this study was to design OPO's with the lowest possible thresholds, all the optical cavities were doubly resonant.
FIG. 1-2  SCHEMATIC OF AN OPTICAL PARAMETRIC OSCILLATOR
1.5 OPTICAL NONLINEARITY IN CRYSTALS

The optical interaction of three waves can occur only in a non-centrosymmetric crystal through the coupling provided by a second-order polarization of the form:

\[ P_i = \sum_j \sum_k d_{ijk} E_j E_k \]  \hspace{1cm} (1-3)

where \( i, j, \) and \( k \) may represent any of the crystallographic axes \( x, y, \) or \( z, \) and \( P_i \) is the component of nonlinear polarization along the \( i \) axis due to interacting electromagnetic fields, \( E, \) along the \( j \) and \( k \) axes. The tensor, \( d_{ijk} \), is the nonlinear susceptibility tensor of the crystal medium. Individual components of \( d_{ijk} \) are sometimes referred to as the crystal nonlinear coefficients. There are 27 possible components of \( d_{ijk} \), but symmetry conditions require that all components resulting from any rearrangement of the subscripts be equal. This leaves only ten independent components. For most crystals, several of these components are zero, so that only a few will enter into a nonlinear interaction. In most cases the polarization of the fields is chosen so that only one component of the tensor produces a second-order polarization. An example of this is optical parametric oscillation in barium-sodium niobate. Suppose an intense optical wave from a laser is polarized along the crystal \( z \) axis and propagated down the \( x \) axis. A polarization will be generated along the \( y \) axis of the form:

\[ P_y = d_{yz} E_y E_z \]  \hspace{1cm} (1-4)
The interaction will generate signal and idler optical fields, which are both polarized along the y axis. As soon as the parametric gain is sufficient to overcome losses, the signal and idler will build up from quantum noise. The signal mixes with the pump to produce a polarization at the idler frequency, and the idler mixes with the pump to produce a polarization at the signal frequency. The signal and idler also mix to produce a polarization at the pump frequency.

1.6 PHASE-MATCHING

The first nonlinear optical experiments were limited to extremely small conversion efficiencies until the technique of phase-matching was discovered. Unless the polarization wave travels at the same velocity as the propagating electromagnetic wave, the effective interaction length in a crystal is very small. Equivalently, the generated signal and idler fields are not synchronized with the pump field, thus destructive interference limits the growth of the signal and the idler fields.

Analytically, the phase-matching condition takes the form of conservation of momentum given in (1-2). Equations (1-1) and (1-2) determine the frequency of signal and idler outputs for a given pump frequency. If a specific set of signal and idler frequencies are desired, then the indices of refraction of the crystal must be controlled so that the conditions of (1-2) are satisfied. The dispersion of a crystal medium prevents condition (1-2) from being met unless special methods are used. Many materials with significant nonlinear coefficients are also birefringent. The index of refraction depends on the
direction of propagation in the crystal. It also depends on the direction of polarization of the interacting waves. These directions can be chosen so that (1-2) is satisfied. The indices of refraction can be further controlled by changing the angle of pump incidence, crystal temperature, or applied dc electric fields. Temperature changes have proven to be one of the most useful techniques for tuning optical parametric oscillators. The simplest phase-matching scheme is to propagate the pump, polarized as an extraordinary ray. The signal and idler will propagate polarized as ordinary rays. At a given crystal temperature, those signal and idler frequencies satisfying (1-1) and (1-2) will see the highest parametric gain. Oscillation at a particular set of signal and idler frequencies can be obtained by finding the proper crystal temperature producing indices of refraction such that (1-2) is satisfied. The frequencies can then be tuned by varying the temperature.

Successful operation of OPO's also depends on the availability of crystals of high optical quality and transparency over the desired range of pump, signal, and idler wavelengths. Two of the most useful crystals for work at visible and near infrared wavelengths are lithium niobate (LiNbO$_3$) and barium sodium niobate (Ba$_2$NaNb$_5$O$_{15}$). For convenience the abbreviations LN and BSN will be used. They rank among crystals with the highest known nonlinear coefficients, are transparent from 400 to 4000 nm, and can be phase-matched for visible wavelength pumps. They are available in crystals with sufficient optical quality that nearly the full crystal length can be simultaneously phase-matched. This requires that the changes in index of refraction per centimeter of crystal be less than a few parts in 10$^5$. 
1.7 OPTICAL PARAMETRIC NOISE EMISSION (OPN)

When the radiation from a pump source is incident on a non-linear crystal and no resonant feedback is provided, there is a small but finite probability that a pump photon will split into a signal and an idler photon.

If the phase-matching condition is properly met, the parametric gain in a nonlinear crystal may be high enough to exceed the single-pass losses, and thus spontaneous emission can be observed. The power conversion efficiency is very low. For example, a 0.5 cm long BSN crystal pumped by a 0.5 watt laser converts only one part in $10^{10}$ of the pump to signal power. This process is referred to as optical parametric noise (OPN) emission. In a quantum-mechanical sense, this process is thought of as the spontaneous annihilation of a pump photon resulting in the creation of a signal and idler photon.

Observation of OPN plays an important role in the design of optical parametric oscillators. It provides a means of experimentally determining those wavelengths at which a given crystal will phase-match without the necessity of constructing an optical cavity and establishing oscillation. The signal and idler wavelengths can be directly measured as a function of the tuning parameter, which for this study was temperature. This direct observation of tuning curves is required because the index of refraction as a function of the tuning parameter is not sufficiently well known to make computational predictions. Even though the shape of some tuning curves can be predicted and do not change significantly from crystal to crystal, slight variations in crystal composition may change the position of the wavelength-to-tuning-
parameter relationship.

The linewidth of OPN depends on the parametric gain and thus determines the maximum linewidth for an OPO. The linewidth of OPN is a function of the ratio of the signal and idler wavelengths. When they are equal (degeneracy), the linewidth is widest. The linewidth gets progressively narrow for far-from-degeneracy operation. Detailed observations and pertinent theory of OPN for the purpose of establishing temperature tuning curves and linewidths are included as Appendix A.

Because the single-pass gain in a crystal is very low, the losses in a resonant optical cavity must be minimized. This is especially true if low power lasers are being used as pumps. The optical coatings must be of very high reflectivity at the signal and idler wavelengths. Since high reflection coatings are narrow band, the wavelengths of reflectivity must be accurately chosen. The tuning curves established by observation of OPN combined with known restrictions on the availability of dual high-reflectivity coatings were used to design the optical resonators for the OPO's constructed in this study.

1.8 STATE-OF-THE-ART IN PARAMETRIC OSCILLATION

At present, optical parametric oscillators have been constructed with a sufficient number of different pump wavelengths and tuning ranges to almost cover the visible, near-infrared, and even the far-infrared portions of the spectrum. Parametric oscillators have not been available in the uv due to the lack of laser pumps at suitably higher frequencies. Research is currently being done to develop laser
sources of this type; thus it will soon be possible to extend optical parametric oscillation to the blue and uv portions of the spectrum.

An example of such a source is the proposal to use the fourth-harmonic of a Nd:YAG laser to pump an OPO with ADP as the nonlinear crystal [9]. The 266.6 nm pump could produce signal output at wavelengths as near to the uv as 400 nm. Extension of parametric oscillation further into the infrared has recently been successful using proustite (Ag$_3$AsS$_3$) as the nonlinear crystal and pumping with 1064 nm radiation from a Nd:YAG laser to produce tunable radiation centered at 2128 nm [10].

Greatest tuning ranges have been obtained using high-power, pulsed pump sources with SRO's resonant at the idler wavelength. In the infrared the dielectric coatings used to construct resonant cavities have high reflectivities with wide bandwidths. They provide low-loss resonance of the idler wave over large tuning ranges. An SRO is also less susceptible to temperature and mechanical instabilities than a DRO. Conversion efficiencies of high-power, pulsed SRO's are also very high. Up to 45% power conversion to the signal and idler has been obtained. A commercial OPO is currently available using temperature-tuned LN as the nonlinear crystal in an SRO. It is pumped by the frequency-doubled output of a Q-switched Nd:YAG laser, which can oscillate on any one of thirteen different lines from 956 to 1358 nm. The OPO output is available in contiguous tuning ranges from 550 to 3500 nm in the form of pulses with less than 1 µs duration at up to 75 KHz repetition rates and bandwidths of the order of 1 cm$^{-1}$.

Parametric oscillator threshold calculations [11] have shown that doubly resonant parametric oscillators using currently available
crystals and optical coatings may be constructed with thresholds of several milliwatts. These DRO's can be pumped by continuous-wave sources such as argon-ion lasers or frequency-doubled Nd:YAG lasers. Gas lasers have the advantage of high amplitude and frequency stability. They can also be easily set up to operate in single-transverse, single-longitudinal modes of extremely narrow linewidth. DRO's designed to operate near degeneracy, where the signal and idler frequencies are equal to the subharmonic frequency of the pump, are easiest to construct and operate. They have the lowest pump-power thresholds. Pump thresholds increase with far-off degenerate operation. Degenerate DRO's have stabilities comparable to singly resonant oscillators.

Optical coatings for the degenerate DRO cavity are simpler to make than dual wavelength coatings since they need to be highly reflective at only one wavelength. Near-degenerate operation, however, has the disadvantage of wider bandwidths due to the increased width of the parametric gain profile that occurs near degeneracy. The output wavelength is also restricted to nearly double that of the pump, placing outputs for visible pumps in the infrared. Nondegenerate OPO's can provide signal output wavelengths in the visible spectrum without requiring pump sources near the uv. They also operate with narrower linewidths.

Most DRO's constructed to date possess thresholds of 50 mW or more [7, 8]. Typically, these oscillators have power-conversion efficiencies of approximately 1%. The output from a CW-pumped DRO is usually irregular and only quasicontinuous. Due to the required optical resonance at two wavelengths, DRO's are highly sensitive to thermal and
mechanical instabilities and pump frequency fluctuations. The output
from DRO's operating near degeneracy may be as wide as 100 cm\(^{-1}\).

Several techniques can be used to stabilize the output and
narrow the linewidth. Isolation devices can be constructed that will
prevent pump reflections by the oscillator from returning to the laser
where they interfere with the mode stability. The pump laser can be
feedback-frequency stabilized to eliminate instabilities due to pump-
frequency variations. An OPO cavity must also be carefully isolated
from temperature changes and mechanical vibrations. It may also be
possible to feedback-frequency stabilize the OPO cavity itself, but
no attempt to do this has been reported.

With these improvements, the DRO output becomes more nearly CW,
and linewidths of less than 0.5 cm\(^{-1}\) have been obtained [12].

A proper evaluation of the parametric oscillator as a source of
tunable radiation requires a comparison with the state-of-the-art of
other tunable sources.

1.9 COMPARISON TO OTHER TUNABLE SOURCES

Dye lasers are good candidates for tunable radiation in the uv
and higher frequency, visible portions of the optical spectrum. Stimu-
lated emission occurs as a result of transitions between the rotational-
vibrational levels of the ground singlet state \(S_o\) and the excited
singlet state \(S_1\). The initial and final states consist of large num-
bers of closely spaced levels, which can emit in a band of energies
corresponding to wavelength ranges of several hundred angstroms. The
use of a prism or dispersion grating within the cavity permits selection
of a desired wavelength of operation.

The primary drawback of dye lasers are transitions that cause the buildup of population in the lowest triplet state. Absorptions can then occur into higher triplet states at the same wavelength for which laser emission is desired. The tuning range of dye lasers has recently been extended to better than 170 nm [13]. A new complex molecular structure in an excited state, called an exciplex, possesses emission bands that combine with the bands already present in the dye molecule to form the enlarged tuning range (391 to 567 nm). Dye-laser performance has also been recently extended to continuous operation [14].

In the CW dye-laser, a focused beam from an argon laser pumped a dye cell within a hemispherical resonator. The threshold for oscillation in the dye was 200 mW, and 4 mW output was obtained with 960 mW input. The output wavelength at 596.5 nm had a bandwidth of 3 nm.

A commercial CW tunable dye laser is being developed where the dye is pumped by a one watt argon-ion laser operating at a wavelength of 514.5 nm. It produces output powers of 50 to 100 mW. The dye laser has been tuned from 550 to 615 nm and the output has a linewidth less than 0.001 nm. The lasing medium is a water solution of thodamine 6G dye.

A recent development in tunable sources is the spin-flip Raman laser. Direct tuning of the emission energy levels is achieved by varying a magnetic field which determines the spacing between spin sublevels of the Landau levels in InSb. The first tunable Raman laser was pumped with 10.6 micron radiation from a Q-switched CO₂ laser; it
produced one watt peak power, which was tunable from 1170 to 1300 nm [15]. This required a magnetic field of 48 to 100 kilogauss. A later version of the laser produced 30 to 100 watts of output for 1.5 KW input [16]. It was tuned from 1090 to 1300 nm. One of the most remarkable and useful features of this laser is the extremely narrow output bandwidth of less than 0.03 cm\(^{-1}\).

A CW version of the Raman laser was pumped by a CO laser at a wavelength of 5 microns and had a threshold power of 200 mW [17]. The laser could be tuned over ranges of 30 to 100 cm\(^{-1}\) centered at a wavelength of 1800 cm\(^{-1}\). This required a 17 to 50 kilogauss magnetic field. The conversion efficiency was 1%. One of the principal disadvantages of the spin-flip Raman laser is the necessity of very high magnetic fields.

Since the development of tunable laser sources is in its relative infancy, it would be premature to make a comparative evaluation of the optical parametric oscillator, the dye laser, and the tunable Raman laser. Rapid developments are changing the state-of-the-art. Parametric oscillators presently show unequalled potential with their wide tuning ranges and high-conversion efficiencies. They are at a disadvantage, however, to produce output in the near uv portion of the spectrum. Continuous-wave dye lasers have very nearly become a practical laboratory source.

At the time the research described in this thesis began, only two CW optical parametric oscillators had been reported. The first was reported by Smith, et al., at Bell Telephone Laboratories [7]. They constructed a DRO using BSN as the nonlinear crystal. The DRO
was pumped by the multimode output of a frequency-doubled, Nd:YAG laser at 532 nm. The oscillator was designed to operate near degeneracy, and the output was tunable from 980 to 1060 nm. The conversion efficiency was 1% with 300 mW input; the oscillator had a threshold of 45 mW.

The second report was by Byer, et al., at Stanford University [8]. They successfully operated a long-cavity DRO, which used lithium niobate as the nonlinear crystal. The long-cavity design allowed the multimode power of an argon laser operating at 514.5 nm to pump a multimode idler and a single-mode signal. The signal wavelength was tunable from 680 to 705 nm; the bandwidth of this oscillator was 3 cm\(^{-1}\). The tuning range of these oscillators, as well as that of all OPO's that have been constructed to date, was limited by the bandwidth of the dielectric coatings used as mirrors for the resonant cavities.

These reports, along with the extensive theoretical analysis given by Boyd and Kleinman [11], the analysis of optical resonators and mode-matching given by Kogelnik and Li [18], and the properties of barium-sodium niobate found by Singh, et al. [19], served as the basis for this study of CW optical parametric oscillators.

1.10 ORGANIZATION

This thesis will be presented in four major sections supplemented by four appendices. Section 2 surveys the most important aspects of classical parametric oscillator theory. This includes derivations of equations giving the parametric gain, power thresholds, tuning characteristics, output power, conversion efficiency, and linewidth. Effects of phase-matching and finite beam cross-sections are
taken into account.

Section 3 presents the basic OPO design requirements. It describes the bases for selecting and preparing pump sources and nonlinear crystals, establishing temperature-tuning characteristics, and designing the optical cavities.

Section 4 describes the experimental study of the CW optical parametric oscillators. Pump power thresholds, output powers, tuning characteristics, and linewidths have been measured and compared to theory. Two techniques for improving output stability and narrowing linewidths are experimentally evaluated. These include optical isolation of pump from OPO and pump laser frequency stabilization.

Appendix A reports the procedures used to observe OPN. Theory pertinent to the observations made in this study is presented and evaluated. Particular attention has been paid to the effects of non-collinear phase-matched emission linewidth and collinear phase-matched linewidth as a function of degeneracy. The latter is a measure of the parametric gain profile for a given pump and nonlinear crystal.

Second-harmonic generation was used as an indication of the phase-matching quality of nonlinear crystals. Details of this evaluation procedure are given in Appendix B.

A computer program, written in FORTRAN, performs a number of important computations aiding the study of nonlinear interactions. The program curve-fits experimental tuning data using the temperature-tuning equation. The results are both printed in tabular form and plotted on a Calcomp plotter. The program also computes OPO threshold pump power, OPN emission power, optical resonator design parameters,
and mode-matching parameters. This program is described in Appendix C and listed in Appendix D.

Appendix E contains the papers which have been published during the course of this work.

1.11 SUMMARY OF ACHIEVEMENTS

The following is a brief summary of the major achievements made during the course of this work.

(1) Design and Construction of a Nonlinear Optical Resonant Cavity.

A simple, compact, highly stable resonator was designed for the parametric oscillator cavity. The form of the resonator is semispherical. A flat mirror is coated on one side of the nonlinear crystal. A spherical mirror with radius 2.5 cm is mounted separately for ease of control over cavity spacing and alignment. The resonator is low-loss and straightforward to align. Details are given in Sec. 3.4.

(2) Evaluation Procedure for Nonlinear Crystals.

The crystals used in the study must meet many requirements. Once the general optical quality has been verified, the fundamental requirement is that they be phase-matchable throughout the length of the crystal. A procedure to test the phase-matchability of the crystals through the use of second-harmonic generation was developed. It is described in Appendix B.

(3) Computer Techniques

A computer program was developed to carry out a number of fundamental computations such as temperature, orientation, and electric
field tuning curves, OPO thresholds, OPN emission powers, optical resonator design parameters, mode-matching conditions, and the prediction of subharmonic phase-matching temperatures. These computations enabled the author to make essential predictions which served to guide the course of investigation. The features of the computer program are discussed in Appendix C.

(4) Observation of OPN and Measurement of OPN Wavelengths into the IR for LiNbO₃ and Ba₂Na₅Nb₂O₁₅.

Optical parametric noise emission was observed with six of the nonlinear crystals that passed the evaluation tests. These observations provided precise data on the temperature-tuning characteristics of each crystal. At any prescribed temperature and pump wavelength, the wavelength of the phase-matched signal and idler could be determined. Certain restrictions (see Sec. 3.2-2) limited the ranges of temperature over which each type of crystal could be used. The temperature-tuning characteristics of several important crystals are presented in Sec. 3.3. These data include the first reported observations of OPN at infrared wavelengths, in particular, near degeneracy of the 514.5 nm pump. The tuning data, along with information on the availability of various types of multiwavelength high-reflection optical coatings, allowed the selection of the most feasible combination of crystal temperature, and pump, signal and idler wavelengths for the construction of CW OPO's.

(5) Tunable CW Optical Parametric Oscillator in the Infrared using Ba₂Na₅Nb₂O₁₅.

A CW OPO was designed, built, and successfully operated
with output near the subharmonic of a single-mode 514.5 nm pump wavelength. The BSN crystal phase-matched for this process over a temperature range from 41° C to 49.5° C. The signal wavelength was tunable from 958 nm to 1016 nm and the idler wavelength from 1043 nm to 1114 nm. The tuning range is determined by the bandwidth of the high reflection optical coatings which form the resonator. The threshold for oscillation was 138 mW. The maximum output power was 10 mW in each direction, for 435 mW of input power. The conversion efficiency was 4.6%. The best output amplitude stability was ±10%, and the minimum linewidth was 0.4 nm. Further data on the oscillator design and operation are given in Sec. 4.2. A complete analysis for the behavior of the output power during tuning is presented. The analysis is given in Sec. 2.6-3 and compared to experimental results in Sec. 4.2-3.

(6) Tunable CW Optical Parametric Oscillator in the Visible Using Ba$_2$NaNb$_5$O$_{15}$

The second CW OPO was constructed and designed to operate far from degeneracy with a single-mode pump at a wavelength of 488.0 nm. The signal wavelength was centered at 650.0 nm and the idler wavelength at 1950 nm. The barium sodium niobate crystal phase-matched for this process at 210° C. These signal and idler wavelengths were chosen so that a quarter-wave dielectric coating at the idler wavelength would be a three-quarter-wave coating at the signal wavelength.

The output was highly unstable, but had a power of 100 µW when pumped with 500 mW input power. This instability is typical of frequency and phase-sensitive, doubly resonant parametric oscillators. The threshold power was 200 mW. The signal output was tunable from
643 to 662 nm, corresponding to crystal temperatures of 212° C to 169° C. The corresponding idler wavelengths were 2018 nm to 1856 nm. The output linewidth was approximately 0.2 nm. Details on the design and operating characteristics of the OPO are given in Sec. 4.4.

This parametric oscillator represents the first reported successful operation of a single-mode CW-pumped oscillator with wavelengths far from degeneracy.

(7) Development of a Solid-State Pumped OPO.

The frequency-doubled 532.0 nm radiation from a Q-switched Nd:YAG laser was used to pump a parametric oscillator of the same design as the oscillator reported in item (5) above. The phase-matching temperature for this process was 103° C. The temporal characteristics of the pump and parametric oscillator pulses are reported in Sec. 4.3.
2.0 CLASSICAL ELECTROMAGNETIC DESCRIPTION OF OPTICAL PARAMETRIC OSCILLATION

An excellent method of describing optical nonlinear interactions is obtained by solving Maxwell's equations in a form which includes the nonlinear polarization of equation (1-3) written explicitly. The equations are:

\[
\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}_{NL}}{\partial t}
\]

\[
\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}
\]

where \( \varepsilon = \varepsilon_o (1 + \chi_L) \), \( \chi_L \) is the linear polarizability, \( \sigma \) is the conductivity, and the components of \( \mathbf{P}_{NL} \) are given by (1-3). By isolating the three frequency components the equations in (2-1) reduce to a set of three coupled differential equations for the scalar amplitudes of the pump, signal, and idler fields. The procedure is given by Yariv [20]. Assuming that the fields can be described as plane waves propagating along the z axis, \( \frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0 \), the fields are of the form:

\[
\mathbf{E} = \frac{1}{2} E(z) e^{i(kz - \omega t + \phi)} + \text{c.c.}
\]

(2-2)

Second order derivatives encountered by using (2-2) in (2-1) are neglected by assuming that the field amplitudes are slowly varying in z \( \frac{d^2}{dz^2} \ll \frac{d}{dz} \). By taking \( \sigma = 0 \), and converting to c.g.s. units, the coupled equations take the form given by Smith [12]:

24
\[
\frac{dE_s(z)}{dz} = \frac{i 4 \pi d}{c} \frac{\omega_s}{n_s} E_p(z) E_s^*(z) e^{i(\Delta k z + \phi)}
\]

\[
\frac{dE_i(z)}{dz} = \frac{i 4 \pi d}{c} \frac{\omega_i}{n_i} E_p(z) E_s^*(z) e^{i(\Delta k z + \phi)} \tag{2-3}
\]

\[
\frac{dE_p(z)}{dz} = \frac{i 4 \pi d}{c} \frac{\omega_p}{n_p} E_s(z) E_i(z) e^{-i(\Delta k z + \phi)}
\]

where \(\Delta k\) is the momentum mismatch,

\[
\Delta k = k_p - k_s - k_i \tag{2-4}
\]

\(\phi\) is the initial phase difference,

\[
\phi = \phi_p - \phi_s - \phi_i \tag{2-5}
\]

and \(n\) is the index of refraction. A procedure for solving equations (2-3) is given by Smith [21]. If we assume a solution of the form:

\[
E(z) = Ae^{+Dz} + Be^{-Dz} \tag{2-6}
\]

and substitute into (2-3), we obtain:

\[
D^2 = D_0^2 - (\frac{\Delta k}{2})^2 \tag{2-7}
\]

where \(D_0\) is defined by:

\[
D_0^2 = \frac{16 \pi^2 \omega_s \omega_i d^2}{n_s n_i c^2} \left| \frac{E_p}{E} \right|^2 \tag{2-8}
\]
The constants A and B are found by the boundary conditions for the fields incident to the crystal at z=0, where

\[ E_s(o) = E_{so} e^{i\phi_s} \]  

\[ E_i(o) = E_{io} e^{i\phi_i} . \]  \( (2-9) \)

The form of the solution can be simplified by letting \( r \) represent the ratio of the incident idler to signal photon fluxes. Thus,

\[ r = \left( \frac{n_i \omega_s}{n_s \omega_i} \right) \frac{E_{io}}{E_{so}} . \]

When \( r=1 \), there is an equal number of photons in the signal and idler fields at \( z=0 \). This is appropriate for a CW OPO with equal losses at the signal and idler. When \( r=0 \), the idler is nonresonant, appropriately describing an SRO. The solution to (2-3) is conveniently written in terms of the power density of the fields. Let \( S_o \) be the power density of the signal incident on the crystal at \( z=0 \); then:

\[ S_o = \frac{cn_s}{8\pi} \left| E_s(o) \right|^2 . \]  \( (2-10) \)

The solution of (2-3) for the growth of the signal and idler fields is then given by \cite{12}:

\[ S_s(z) = \frac{S_o}{D^2} \left[ \left[ D\cosh(Dz) + D_o \sin \phi \sinh(Dz) \right]^2 + \left[ \frac{\Delta k}{2} - D_o \cos \phi \right]^2 \sinh^2(Dz) \right] . \]  \( (2-11a) \)
and

\[
S_i(z) = \frac{\omega_i}{\omega_s} \left( [D \cosh(Dz) + D \sin \phi \sinh(Dz)]^2 + [D \cos \phi - \frac{\Delta k}{2} r]^2 \sin(Dz) \right).
\]

(2-11b)

A further simplification of the solution can be obtained by assuming that there exists an optimum value of \( \phi \), and the relative phase between the three fields takes on this value. The assumption is most easily justified for the case of an OPO where the signal and idler fields build up from quantum noise. Those field components not at optimum phase will tend to die out. Those components at optimum phase will experience the greatest growth. The optimum phase is found by finding \( \frac{\partial E_s(z)}{\partial \phi} \) and setting it to zero. The solution for \( \phi \) is:

\[
\cos \phi_{opt} = -\frac{\Delta k}{2D} \frac{\sinh(DL)}{\left[ 1 + \frac{D^2}{D^2 \sinh^2(DL)} \right]^{1/2}}
\]

(2-12)

where \( L \) is the length of the nonlinear crystal.

2.1 OPTICAL PARAMETRIC GAIN

The parametric gain is the ratio of the power density exiting from the crystal to the power density incident on the crystal. The gains at the signal and idler for optimum \( \phi \) are:

\[
G_S = \frac{S_S(L)}{S_o} = \left[ 1 + \frac{D^2}{D^2 \sinh^2(DL)} \right]^{1/2} + \frac{D}{D \sinh(DL)} \right]^{1/2},
\]

(2-13a)
\[ G_i = \frac{S_i(L)}{S_i(0)} = \frac{1}{r^2} \left[ r^2 \left( 1 + \frac{D_o}{D} \sinh^2(DL) \right) \right]^{1/2} + \frac{D_o}{D} \sinh(DL)^2. \] \hspace{1cm} (2-13b)

This result can be specialized for the CW OPO where the power density of the pump is low; thus \( D_oL \) can be taken to be much less than one. Assuming equal losses at the signal and idler (\( r=1 \)), (2-13) can be written:

\[ G_s(CW \ OPO) = 1 + 2D_oLsinc \left( \frac{\Delta kL}{2} \right) \] \hspace{1cm} (2-14a)

and

\[ G_i = \frac{\omega_i}{\omega_s} G_s. \] \hspace{1cm} (2-14b)

A plot of \( \log[G_s(\Delta kL/2)]/\log[G_s(0)] \) is given in Fig. 2-1 for \( D_oL = 0.01 \). The gain has its maximum value for \( \Delta k = 0 \) and is small for values of \( \Delta kL \) near \( 2\pi \). The shape of the curve changes very little as a function of \( D_oL \), as long as \( D_oL < 1 \). The most important result of (2-14) is that the gain as a function of \( \Delta kL/2 \) is smooth and nonzero in the region \( \Delta k = 0 \) to \( \Delta kL/2 = D_oL \). Thus \( \Delta k \) can be greater than \( 2D_o \) with little sacrifice in gain. This is important for a DRO because simultaneous resonance of the signal and idler fields may prevent oscillation at \( \Delta k = 0 \).

2.2 PHASE-MATCHING

Useful nonlinear interactions cannot be obtained unless methods are developed which make \( \Delta k \) near or equal to zero. The velocities of propagation of the interacting fields must be chosen so that the nonlinear polarizations do not get out of phase with the electromagnetic
FIG. 2-1 OPO Normalized Log Gain as a Function of Momentum Mismatch.
fields which they generate. When the vector relation (1-2) is satisfied, the waves propagate in phase, producing maximum gain.

Equation (1-2) implies that the interacting fields need not be collinear. Noncollinear interactions generally provide less parametric gain since the effective interaction length in a crystal would be small compared to that for a collinear interaction. In the case of the CW OPO, the need for maximum gain and simplicity of optical resonator design limit interactions to the collinear type. Noncollinear interactions will be treated in Appendix A since they contribute significantly to the bandwidth of OPO emission.

The most commonly used and most successful phase-matching method for nonlinear interactions takes advantage of the fact that many nonlinear crystals are also birefringent. Since the index of refraction is a function of the direction of propagation and of crystal temperature, these variables can be chosen so that (1-2) is satisfied for a given set of pump, signal, and idler frequencies. In a negative uniaxial crystal, phase-matching is easiest to obtain if the pump is polarized as an extraordinary wave and the signal and idler are polarized as ordinary waves. The phase-matching condition (1-2) takes the form:

$$n_p(\theta, T)\omega_p = n_s(\omega_s) + n_i(\omega_i),$$  \hspace{1cm} (2-15)

where $\theta$ is the angle between the direction of propagation and the crystal optic axis, and $T$ is the crystal temperature.

Orientation phase-matching takes advantage of the dependence of extraordinary index of refraction on direction of propagation. The nonlinear crystal is cut so that the optic axis is at an angle
(90°-θ) to the entrance and exit faces. In many cases, an angle θ can be found such that (2-15) is satisfied at room temperature. This eliminates the necessity for maintaining the crystal in a temperature controlled environment. The principal disadvantage of orientation phase-matching is that a θ ≠ 90° results in propagation with double refraction. The interacting fields change their relative directions and, as a result, decrease their effective interaction length. Orientation phase-matching is most commonly used in high power, pulse-pumped OPO's where ample gain is available.

The index of refraction can also be changed by the application of a dc electric field. Extremely high dc fields are required to produce changes in index comparable to the changes which result from orientation or temperature. The maximum which can be applied is limited by breakdown of the crystal. For this reason, this method is less commonly used.

Changes in crystal temperature can often be used advantageously to satisfy the phase-matching condition. In situations where it is essential to have maximum parametric gain, θ can be fixed at 90° and T varied until (2-15) is satisfied. The nonlinear crystal can easily be housed in a cooling device or oven and maintained at a required temperature. The temperature can also be conveniently varied to change the signal and idler wavelengths (see Sec. 2.5). Temperature-controlled phase-matching may or may not be possible depending on the proper choice of pump frequency and crystal material. Fortunately, a number of crystals are available which can temperature phase-match pumps from the uv to the infrared. Once the pump frequency is chosen,
the range of available signal and idler wavelengths depends on the range of temperatures at which a given crystal can be used without damage or structural changes.

The OPO's for this study were designed for maximum gain with \( \theta = 90^\circ \). Also, to minimize intra-cavity optical losses and facilitate ease of alignment, one of the resonator mirrors was coated directly on the crystal. Thus crystal orientation with respect to the pump beam could not be allowed to vary. The crystals were housed in an oven and operated at elevated temperatures for phase-matching. Any changes in temperature will change the signal and idler frequencies for which \( \Delta k = 0 \) and thus for which maximum gain will occur. Thus, changes in temperature can be used to tune the OPO. An explicit relationship for signal and idler wavelength as a function of crystal temperature is developed in Sec. 2.5-2. Note that even though the frequency for maximum gain is continuously tunable, the resonances of an optical resonator are not continuous functions of the frequency of the resonant wave. Thus, in the strictest sense, the OPO is not continuously tunable. Further treatment of this problem is given in Sec. 2.6-3.

2.3 THRESHOLD FOR A DOUBLY RESONANT PARAMETRIC OSCILLATOR

For small parametric gains, the single-pass efficiency of conversion from pump to signal and idler may be as low as one part in \( 10^{10} \). If the nonlinear material is located within an optical resonator with low losses at the signal and idler wavelengths, feedback occurs and the fields are amplified. When the gain per pass exceeds the
round trip losses, the signal and idler fields will build up to power levels comparable to that of the pump. Once the oscillation builds up, the pump will be depleted until the gain compensates for the losses. At this point, steady-state operation occurs. Feedback can be provided at both the signal and idler wavelengths forming a doubly resonant oscillator (DRO), or at either the signal or the idler wavelengths, forming a singly resonant oscillator (SRO). The DRO requires the least gain to establish parametric oscillation and has so far provided the only configuration to oscillate with CW visible laser pumps.

Of considerable importance in describing OPO's is the minimum pump power for which oscillation can occur. The threshold pump power of a DRO is found by requiring that the single-pass gain at the signal and idler equal the round-trip signal and idler losses. Let $\varepsilon_s$ and $\varepsilon_i$ represent the total one-way losses at the signal and idler. This includes both scattering and mirror transmission losses. At the threshold of a DRO,

$$G_s = \frac{1}{1 - 2\varepsilon_s} \quad (2-16a)$$

and,

$$G_i = \frac{1}{1 - 2\varepsilon_i} \quad (2-16b)$$

With $G_s$ and $G_i$ as given in (2-3), equations (2-16) can be solved simultaneously by eliminating the variable $r$. The result is:

$$\left(\frac{D_o L}{D L}\right)^2 \frac{\sinh^2(DL)}{(DL)^2} = \frac{4\varepsilon_s \varepsilon_i}{\left[\left(1 - 2\varepsilon_s\right)^{\frac{1}{2}} + \left(1 - 2\varepsilon_i\right)^{\frac{1}{2}}\right]^2} \quad (2-17)$$
The losses $\varepsilon_s$ and $\varepsilon_i$ are usually much less than one, and $D_o L << 1$. These assumptions are certainly valid for the CW OPO, thus equation (2-17) simplifies to:

$$(D_o L)^2 \text{sinc}^2 \left( \frac{\Delta k L}{2} \right) = \varepsilon_s \varepsilon_i$$  \hspace{1cm} (2-18)

The threshold pump-power density is found using (2-18) and (2-8). To simplify the notation, represent the degenerate frequency by $\omega_o = \frac{\omega_p}{2}$ and the fractional frequency deviation from degeneracy by $\gamma = \frac{\omega_s}{\omega_o} - 1$.

Equation (2-8) can now be written as:

$$D_o^2 = \frac{128 \pi^3 \omega_o^2 (1 - \gamma^2) d^2 S_p}{n_p n_s n_i c^3}$$  \hspace{1cm} (2-19)

Solving for the power density of the pump and defining,

$$K \equiv \frac{128 \pi^3 \omega_o^2 (2d)^2}{n_s n_i n_p c^3}$$  \hspace{1cm} (2-20)

(conforming to the notation of Boyd and Kleinman [11]), the threshold pump power density is:

$$S_p = \frac{4D_o^2}{\pi K (1 - \gamma^2)} = \frac{4\varepsilon_s \varepsilon_i \text{sinc}^{-2} \left( \Delta k L / 2 \right)}{\pi K (1 - \gamma^2)}$$  \hspace{1cm} (2-21)

To obtain the effective threshold pump power from a practical viewpoint, some refinements in the theory are required. The above theory was developed for plane waves and, in actual fact, the fields associated with optical cavities are Gaussian. These refinements are treated in Sec. 2.4.
2.4 GAUSSIAN BEAMS

The fundamental mode of an optical resonator is a Gaussian beam [18, 22, 23]. Although higher order modes are observed in OPO's the signal and idler are usually fundamental modes (TEM\textsubscript{00}) of the optical resonator. The fields are no longer plane waves as given by (2-2), but have finite cross sections and are more correctly described by the form [11]:

\[
E = \frac{E_0}{1 + \frac{2i}{b} (z - z_0)} \exp[-i k z - \frac{(x^2 + y^2)}{w_0^2} (1 + \frac{2i}{b} (z - z_0))], \quad (2-22)
\]

where \(b\) is the resonator confocal parameter and \(w_0\) is the minimum beam radius. \(z_0\) is the position of the minimum beam radius. The confocal parameter is related to the minimum beam radius by:

\[
b = w_0^2 k \quad (2-23)
\]

and the beam radius at \(z\) is given by:

\[
w^2(z) = w_0^2 \left[ 1 + \left( \frac{\lambda (z - z_0)}{\pi w_0^2} \right)^2 \right] \quad (2-24)
\]

One of the most important results of the application of Gaussian beam theory to parametric oscillation establishes the optimum pump beam radius in terms of the signal and idler beam radii [6]. Minimum threshold occurs when the pump beam radius has a value \(w_p\) given by:

\[
\frac{1}{w_p^2} = \frac{1}{w_s^2} + \frac{1}{w_i^2} \quad (2-25)
\]
Since the signal and idler are in the same optical cavity, their confocal parameters are equal \((b_s = b_i)\). Equations (2-25), (2-23), and (1-2) imply that for minimum threshold, the confocal parameters of all the beams are equal \((b \equiv b_s = b_i = b_p)\).

Further refinements in Gaussian beam theory are given by Boyd and Kleinman [11]. They optimize the OPO threshold with respect to beam focusing and double refraction. Focusing is measured by the ratio of crystal length to confocal parameter \((L/b)\), and double refraction is measured by \(B\). When these refinements are used, the DRO threshold pump power is given by:

\[
P_{th} = \frac{4\varepsilon_s \varepsilon_i (1 + \gamma \alpha)w_o^2 \text{sinc}^{-2} \left( \frac{\Delta K L}{2} \right)}{K L (1 - \gamma^2)^2 (1 - \alpha^2) b \bar{h}(L/b, B)}, \tag{2-26}
\]

where \(\alpha\) is the fractional deviation of the index of refraction from the average index at the signal and idler wavelengths. Thus,

\[
\alpha \equiv 1 - \frac{2n_s}{n_s + n_i} \tag{2-27}
\]

The function \(\bar{h}\) is shown in Fig. 12 of reference [11], and \(B\) is defined in (3.21) of [11]. The threshold is a minimum for \(B = 0\), \(\frac{L}{b} = 2.8\) and \(\Delta k = 0\). Under these conditions, \(\bar{h} = 1\) and \(P_{th}\) reduces to:

\[
P_{th} = \frac{4\varepsilon_s \varepsilon_i (1 + \gamma \alpha)w_o^2}{K (1 - \gamma^2)^2 (1 - \alpha^2)Lb} \tag{2-28}
\]

Since \(\bar{h}\) is a relatively smooth function of \(L/b\), and experimental conditions would yield nearly optimum values of \(L/b\), (2-28) was used to estimate DRO thresholds in this paper. By far, the greatest error in
computing the threshold powers lies in estimating the losses $\varepsilon_3$ and $\varepsilon_1$. The result of these computations are shown in Table 2-1 for a DRO using a 514.5 nm pump and a BSN crystal of length, $L = 0.42$ cm. The non-linear coefficient is $4.4 \times 10^{-8}$ esu. The signal and idler losses per pass are 3%, and $L/b$ is 2.84. Of interest for this DRO is the threshold near degeneracy, 67 mW. Table 2-2 presents a similar case except for a 488.0 nm pump. Of interest here is the threshold near a signal wavelength of 650 nm. The threshold is 106 mW. A comparison of these values to the actual thresholds is given in Sec. 4.0.

2.5 FREQUENCY TUNING OF NONLINEAR INTERACTIONS

2.5-1 Tuning Techniques

Any parameter that can change the index of refraction of a crystal is of potential use in tuning parametric interactions (see Sec. 2.2). Among these are crystal orientation and temperature, the presence of dc electric or magnetic fields, the application of stress, and the presence of acoustic waves. Our investigations have been limited to temperature, orientation, and electric field tuning. A computer study of these three methods is reported in Appendix C, sections C2 to C4.

Of these three methods, crystal temperature is the principal parameter for this experimental investigation. LN and BSN have sufficient index-of-refraction sensitivity to temperature to be tunable over a signal wavelength range of 350 nm with a change of 170° C. Since this effort was primarily directed toward obtaining CW OPO, crystal orientation was not experimentally investigated. The pump-beam direction of propagation is maintained at 90° to the crystal $c$ axis to
### Doubly and Singly Resonant NPN Thresholds

<table>
<thead>
<tr>
<th>Pump</th>
<th>Losses</th>
<th>Nonlinear Coefficient</th>
<th>Crystal Length</th>
<th>Signal</th>
<th>Temperature</th>
<th>$\kappa$ Coefficient</th>
<th>Threshold Power</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5145.00</td>
<td>0.0300</td>
<td>0.0200</td>
<td>9400.08</td>
<td>41.00</td>
<td>1.05542E-13</td>
<td>6.666E-02</td>
<td>4.444E-00</td>
<td>10194.00</td>
</tr>
<tr>
<td>9435.93</td>
<td>0.0300</td>
<td>0.0200</td>
<td>9537.07</td>
<td>49.00</td>
<td>1.05521E-13</td>
<td>6.700E-02</td>
<td>4.573E-00</td>
<td>10194.00</td>
</tr>
<tr>
<td>9302.77</td>
<td>0.0300</td>
<td>0.0200</td>
<td>9256.51</td>
<td>50.00</td>
<td>1.05531E-13</td>
<td>6.750E-02</td>
<td>4.502E-00</td>
<td>11772.00</td>
</tr>
<tr>
<td>9148.06</td>
<td>0.0300</td>
<td>0.0200</td>
<td>9052.45</td>
<td>50.00</td>
<td>1.05550E-13</td>
<td>6.797F-02</td>
<td>4.531E-00</td>
<td>11391.46</td>
</tr>
<tr>
<td>8955.77</td>
<td>0.0300</td>
<td>0.0200</td>
<td>8856.80</td>
<td>50.00</td>
<td>1.05574E-13</td>
<td>6.841E-02</td>
<td>4.581E-00</td>
<td>11583.27</td>
</tr>
<tr>
<td>8813.90</td>
<td>0.0300</td>
<td>0.0200</td>
<td>8746.03</td>
<td>50.00</td>
<td>1.05542E-13</td>
<td>6.896E-02</td>
<td>4.591E-00</td>
<td>11757.69</td>
</tr>
<tr>
<td>8602.44</td>
<td>0.0300</td>
<td>0.0200</td>
<td>8522.55</td>
<td>50.00</td>
<td>1.05542E-13</td>
<td>6.952E-02</td>
<td>4.621E-00</td>
<td>11919.96</td>
</tr>
<tr>
<td>8465.87</td>
<td>0.0300</td>
<td>0.0200</td>
<td>8352.03</td>
<td>50.00</td>
<td>1.05543E-13</td>
<td>7.007E-02</td>
<td>4.652E-00</td>
<td>12073.19</td>
</tr>
<tr>
<td>8246.07</td>
<td>0.0300</td>
<td>0.0200</td>
<td>8154.75</td>
<td>50.00</td>
<td>1.05544E-13</td>
<td>7.062E-02</td>
<td>4.682E-00</td>
<td>12219.40</td>
</tr>
<tr>
<td>8046.89</td>
<td>0.0300</td>
<td>0.0200</td>
<td>7937.38</td>
<td>50.00</td>
<td>1.05545E-13</td>
<td>7.117E-02</td>
<td>4.714E-00</td>
<td>12359.98</td>
</tr>
<tr>
<td>7834.13</td>
<td>0.0300</td>
<td>0.0200</td>
<td>7726.41</td>
<td>50.00</td>
<td>1.05546E-13</td>
<td>7.172E-02</td>
<td>4.745E-00</td>
<td>12495.96</td>
</tr>
</tbody>
</table>

**Note:** The table continues with similar entries for additional data points.
### Table 2-1 (continued)

<table>
<thead>
<tr>
<th>SIGNAL</th>
<th>TEMPERATURE</th>
<th>COEFFICIENT(ESU)</th>
<th>THRESHOLD POWER (Watts)</th>
<th>THRESHOLD POWER SRO (Watts)</th>
<th>IONER</th>
</tr>
</thead>
<tbody>
<tr>
<td>7356.99</td>
<td>194.00</td>
<td>1.049603E-13</td>
<td>9.53E-02</td>
<td>4.35E-01</td>
<td>17112.04</td>
</tr>
<tr>
<td>7336.59</td>
<td>197.00</td>
<td>1.049488E-13</td>
<td>9.61E-02</td>
<td>4.40E-01</td>
<td>17223.45</td>
</tr>
<tr>
<td>7316.50</td>
<td>200.00</td>
<td>1.049377E-13</td>
<td>9.68E-02</td>
<td>4.45E-01</td>
<td>17335.23</td>
</tr>
<tr>
<td>7296.70</td>
<td>203.00</td>
<td>1.049259E-13</td>
<td>9.76E-02</td>
<td>4.50E-01</td>
<td>17447.00</td>
</tr>
<tr>
<td>7277.19</td>
<td>206.00</td>
<td>1.049145E-13</td>
<td>9.83E-02</td>
<td>4.55E-01</td>
<td>17559.97</td>
</tr>
<tr>
<td>7257.95</td>
<td>209.00</td>
<td>1.049030E-13</td>
<td>9.91E-02</td>
<td>4.60E-01</td>
<td>17672.97</td>
</tr>
<tr>
<td>7238.99</td>
<td>212.00</td>
<td>1.048916E-13</td>
<td>9.99E-02</td>
<td>4.66E-01</td>
<td>17786.41</td>
</tr>
<tr>
<td>7220.30</td>
<td>215.00</td>
<td>1.048801E-13</td>
<td>1.00E-01</td>
<td>4.71E-01</td>
<td>17900.30</td>
</tr>
<tr>
<td>7201.85</td>
<td>218.00</td>
<td>1.048687E-13</td>
<td>1.01E-01</td>
<td>4.76E-01</td>
<td>18014.67</td>
</tr>
<tr>
<td>7183.66</td>
<td>221.00</td>
<td>1.048573E-13</td>
<td>1.02E-01</td>
<td>4.82E-01</td>
<td>18129.52</td>
</tr>
<tr>
<td>7165.71</td>
<td>224.00</td>
<td>1.048456E-13</td>
<td>1.03E-01</td>
<td>4.87E-01</td>
<td>18244.88</td>
</tr>
<tr>
<td>7147.99</td>
<td>227.00</td>
<td>1.048343E-13</td>
<td>1.04E-01</td>
<td>4.92E-01</td>
<td>18360.75</td>
</tr>
<tr>
<td>7130.50</td>
<td>230.00</td>
<td>1.048229E-13</td>
<td>1.05E-01</td>
<td>4.98E-01</td>
<td>18477.15</td>
</tr>
<tr>
<td>7113.24</td>
<td>233.00</td>
<td>1.048114E-13</td>
<td>1.06E-01</td>
<td>5.04E-01</td>
<td>18594.11</td>
</tr>
<tr>
<td>7095.99</td>
<td>236.00</td>
<td>1.048000E-13</td>
<td>1.07E-01</td>
<td>5.09E-01</td>
<td>18711.62</td>
</tr>
<tr>
<td>7079.35</td>
<td>239.00</td>
<td>1.047885E-13</td>
<td>1.08E-01</td>
<td>5.15E-01</td>
<td>18829.71</td>
</tr>
</tbody>
</table>
### DUBLY AND SINGLY RESONANT OPO THRESHOLDS

**In Ba2Na4Y8S5O15 Crystal No.12**

<table>
<thead>
<tr>
<th>Pump</th>
<th>Losses</th>
<th>Width</th>
<th>Nonlinear Coefficient</th>
<th>Threshold Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>4880.00</td>
<td>0.0300</td>
<td>0.0300</td>
<td>8.4.00E-06</td>
<td></td>
</tr>
</tbody>
</table>

**Confocal Parameter**
- 1.475E-01 (CM)
- 1.070E-03 (CM)
- 3.10E-03 (CM)

**PM Temp**
- 65.00 DEG C

<table>
<thead>
<tr>
<th>Signal</th>
<th>Temperature</th>
<th>K Coefficient</th>
<th>Threshold Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9760.00</td>
<td>1.16171E-13</td>
<td>5.724E-02</td>
<td>4.29E-00</td>
</tr>
<tr>
<td>9113.75</td>
<td>1.16149E-13</td>
<td>5.804E-02</td>
<td>3.86E-00</td>
</tr>
<tr>
<td>8873.14</td>
<td>1.16126E-13</td>
<td>5.845E-02</td>
<td>3.91E-00</td>
</tr>
<tr>
<td>8695.56</td>
<td>1.16103E-13</td>
<td>5.927E-02</td>
<td>3.95E-00</td>
</tr>
<tr>
<td>8551.28</td>
<td>1.16080E-13</td>
<td>5.993E-02</td>
<td>3.99E-00</td>
</tr>
<tr>
<td>8425.16</td>
<td>1.16058E-13</td>
<td>6.074E-02</td>
<td>4.03E-00</td>
</tr>
<tr>
<td>8319.72</td>
<td>1.16035E-13</td>
<td>6.119E-02</td>
<td>4.07E-00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal</th>
<th>Temperature</th>
<th>K Coefficient</th>
<th>Threshold Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>8222.49</td>
<td>1.16012E-13</td>
<td>6.185E-02</td>
<td>4.12E-00</td>
</tr>
<tr>
<td>8134.02</td>
<td>1.15989E-13</td>
<td>6.252E-02</td>
<td>4.16E-00</td>
</tr>
<tr>
<td>8052.64</td>
<td>1.15967E-13</td>
<td>6.317E-02</td>
<td>4.21E-00</td>
</tr>
<tr>
<td>7977.16</td>
<td>1.15944E-13</td>
<td>6.390E-02</td>
<td>4.26E-00</td>
</tr>
<tr>
<td>7904.67</td>
<td>1.15921E-13</td>
<td>6.464E-02</td>
<td>4.30E-00</td>
</tr>
<tr>
<td>7830.48</td>
<td>1.15898E-13</td>
<td>6.538E-02</td>
<td>4.35E-00</td>
</tr>
<tr>
<td>7778.00</td>
<td>1.15876E-13</td>
<td>6.605E-02</td>
<td>4.40E-00</td>
</tr>
<tr>
<td>7718.83</td>
<td>1.15854E-13</td>
<td>6.672E-02</td>
<td>4.45E-00</td>
</tr>
<tr>
<td>7662.38</td>
<td>1.15832E-13</td>
<td>6.794E-02</td>
<td>4.50E-00</td>
</tr>
<tr>
<td>7608.96</td>
<td>1.15810E-13</td>
<td>6.830E-02</td>
<td>4.55E-00</td>
</tr>
<tr>
<td>7557.69</td>
<td>1.15787E-13</td>
<td>6.873E-02</td>
<td>4.60E-00</td>
</tr>
<tr>
<td>7506.47</td>
<td>1.15764E-13</td>
<td>6.916E-02</td>
<td>4.65E-00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal</th>
<th>Temperature</th>
<th>K Coefficient</th>
<th>Threshold Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>7461.41</td>
<td>1.15739E-13</td>
<td>7.057E-02</td>
<td>4.72E-00</td>
</tr>
<tr>
<td>7416.04</td>
<td>1.15719E-13</td>
<td>7.142E-02</td>
<td>4.76E-00</td>
</tr>
<tr>
<td>7372.31</td>
<td>1.15698E-13</td>
<td>7.234E-02</td>
<td>4.80E-00</td>
</tr>
<tr>
<td>7330.11</td>
<td>1.15678E-13</td>
<td>7.327E-02</td>
<td>4.84E-00</td>
</tr>
<tr>
<td>7289.33</td>
<td>1.15648E-13</td>
<td>7.412E-02</td>
<td>4.88E-00</td>
</tr>
<tr>
<td>7242.85</td>
<td>1.15619E-13</td>
<td>7.497E-02</td>
<td>4.93E-00</td>
</tr>
<tr>
<td>7201.61</td>
<td>1.15590E-13</td>
<td>7.583E-02</td>
<td>4.99E-00</td>
</tr>
<tr>
<td>7174.31</td>
<td>1.15560E-13</td>
<td>7.672E-02</td>
<td>5.05E-00</td>
</tr>
<tr>
<td>7138.49</td>
<td>1.15530E-13</td>
<td>7.762E-02</td>
<td>5.11E-00</td>
</tr>
<tr>
<td>7093.37</td>
<td>1.15501E-13</td>
<td>7.856E-02</td>
<td>5.17E-00</td>
</tr>
<tr>
<td>7069.42</td>
<td>1.15472E-13</td>
<td>7.949E-02</td>
<td>5.23E-00</td>
</tr>
<tr>
<td>7046.26</td>
<td>1.15443E-13</td>
<td>8.042E-02</td>
<td>5.29E-00</td>
</tr>
<tr>
<td>7023.95</td>
<td>1.15415E-13</td>
<td>8.138E-02</td>
<td>5.36E-00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal</th>
<th>Temperature</th>
<th>K Coefficient</th>
<th>Threshold Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>6972.44</td>
<td>1.15385E-13</td>
<td>8.236E-02</td>
<td>5.43E-00</td>
</tr>
<tr>
<td>6941.70</td>
<td>1.15355E-13</td>
<td>8.335E-02</td>
<td>5.50E-00</td>
</tr>
<tr>
<td>6911.69</td>
<td>1.15325E-13</td>
<td>8.435E-02</td>
<td>5.57E-00</td>
</tr>
<tr>
<td>6882.36</td>
<td>1.15305E-13</td>
<td>8.536E-02</td>
<td>5.64E-00</td>
</tr>
<tr>
<td>6853.70</td>
<td>1.15285E-13</td>
<td>8.638E-02</td>
<td>5.71E-00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal</th>
<th>Temperature</th>
<th>K Coefficient</th>
<th>Threshold Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>6825.66</td>
<td>1.15266E-13</td>
<td>8.740E-02</td>
<td>5.79E-00</td>
</tr>
<tr>
<td>6798.23</td>
<td>1.15246E-13</td>
<td>8.843E-02</td>
<td>5.86E-00</td>
</tr>
<tr>
<td>6771.37</td>
<td>1.15226E-13</td>
<td>8.946E-02</td>
<td>5.93E-00</td>
</tr>
<tr>
<td>6745.05</td>
<td>1.15206E-13</td>
<td>9.050E-02</td>
<td>6.00E-00</td>
</tr>
<tr>
<td>6719.27</td>
<td>1.15186E-13</td>
<td>9.154E-02</td>
<td>6.08E-00</td>
</tr>
<tr>
<td>6693.49</td>
<td>1.15166E-13</td>
<td>9.260E-02</td>
<td>6.16E-00</td>
</tr>
<tr>
<td>6669.19</td>
<td>1.15146E-13</td>
<td>9.367E-02</td>
<td>6.24E-00</td>
</tr>
<tr>
<td>6644.87</td>
<td>1.15126E-13</td>
<td>9.474E-02</td>
<td>6.32E-00</td>
</tr>
<tr>
<td>6620.99</td>
<td>1.15106E-13</td>
<td>9.584E-02</td>
<td>6.41E-00</td>
</tr>
<tr>
<td>6597.54</td>
<td>1.15086E-13</td>
<td>9.695E-02</td>
<td>6.50E-00</td>
</tr>
<tr>
<td>6574.51</td>
<td>1.15066E-13</td>
<td>9.807E-02</td>
<td>6.59E-00</td>
</tr>
<tr>
<td>6551.58</td>
<td>1.15046E-13</td>
<td>9.921E-02</td>
<td>6.68E-00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal</th>
<th>Temperature</th>
<th>K Coefficient</th>
<th>Threshold Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>6529.64</td>
<td>1.15026E-13</td>
<td>1.004E-02</td>
<td>6.78E-00</td>
</tr>
<tr>
<td>6507.77</td>
<td>1.15006E-13</td>
<td>1.017E-02</td>
<td>6.87E-00</td>
</tr>
</tbody>
</table>

**Visible OPO Thresholds**

| Table 2-2 | 40 |
***** DOURLY AND SINGLY RESONANT OPO THRESHOLDS *****

<table>
<thead>
<tr>
<th>PUMP</th>
<th>4.0800</th>
<th>LOSSES</th>
<th>0.0300</th>
<th>0.0100</th>
<th>NONLINEAR COEFFICIENT</th>
<th>4.406E-08</th>
<th>CRYSTAL LENGTH</th>
<th>0.42</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONFOCAL PARAMETER</td>
<td>1.475E+01 (CM)</td>
<td>BEAM WIDTH</td>
<td>1.070E+03 (CM)</td>
<td>PH TEMP</td>
<td>-85.00 DEG C</td>
<td>L/R</td>
<td>2.84</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SIGNAL</th>
<th>TEMPERATURE</th>
<th>K COEFFICIENT (ESU)</th>
<th>THRESHOLD POWER (W)</th>
<th>THRESHOLD POWER SRD (W)</th>
<th>IDLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386.26</td>
<td>190.00</td>
<td>1.15009E+13</td>
<td>1.058E+01</td>
<td>7.051E+00</td>
<td>19705.97</td>
</tr>
<tr>
<td>6465.11</td>
<td>195.00</td>
<td>1.149869E+13</td>
<td>1.072E+01</td>
<td>7.150E+00</td>
<td>19903.86</td>
</tr>
<tr>
<td>6444.29</td>
<td>200.00</td>
<td>1.149640E+13</td>
<td>1.088E+01</td>
<td>7.250E+00</td>
<td>20103.81</td>
</tr>
<tr>
<td>6423.79</td>
<td>205.00</td>
<td>1.149422E+13</td>
<td>1.103E+01</td>
<td>7.353E+00</td>
<td>20305.88</td>
</tr>
<tr>
<td>6403.62</td>
<td>210.00</td>
<td>1.149183E+13</td>
<td>1.118E+01</td>
<td>7.459E+00</td>
<td>20510.14</td>
</tr>
<tr>
<td>6383.75</td>
<td>215.00</td>
<td>1.148953E+13</td>
<td>1.135E+01</td>
<td>7.566E+00</td>
<td>20716.65</td>
</tr>
<tr>
<td>6364.18</td>
<td>220.00</td>
<td>1.148726E+13</td>
<td>1.151E+01</td>
<td>7.676E+00</td>
<td>20925.86</td>
</tr>
<tr>
<td>6344.90</td>
<td>225.00</td>
<td>1.148497E+13</td>
<td>1.168E+01</td>
<td>7.788E+00</td>
<td>21136.65</td>
</tr>
<tr>
<td>6325.90</td>
<td>230.00</td>
<td>1.148268E+13</td>
<td>1.185E+01</td>
<td>7.902E+00</td>
<td>21350.27</td>
</tr>
<tr>
<td>6307.17</td>
<td>235.00</td>
<td>1.148039E+13</td>
<td>1.202E+01</td>
<td>8.019E+00</td>
<td>21566.40</td>
</tr>
<tr>
<td>6288.71</td>
<td>240.00</td>
<td>1.147810E+13</td>
<td>1.221E+01</td>
<td>8.139E+00</td>
<td>21785.10</td>
</tr>
</tbody>
</table>

**TABLE 2-2 (continued)**
eliminate beam walkoff due to double refraction [24]. Thus, the interaction length is limited only by laser beam mode-matching and crystal index-of-refraction homogeneity. Any other crystal orientation represents a sacrifice in parametric gain. As previously mentioned, orientation tuning was also not used because one of the crystal surfaces is coated to form one of the reflectors of the OPO cavity. This was required to simplify the alignment procedures, increase OPO cavity stability, and minimize optical losses. Computer analysis revealed that the application of a dc electric field of 6 KV produced 40.0 nm in tuning range near degeneracy using LN. Results for BSN were similar. Electric field tuning was not experimentally investigated since only small tuning ranges were produced for even the highest usable electric fields. It promises to be useful for fine tuning or fast response tuning of optical parametric interactions. This is especially true in cases where the phase-matching condition, (1-2), must be carefully met. Computed orientation and electric field tuning curves for LN and BSN crystals are shown in Figs. 2-2 to 2-5. In each case, the crystal is assumed to be at the phase-matching temperature for subharmonic generation, $T_o$. It is for this case that the maximum deviation in output wavelengths for a given change in the tuning variable is obtained. A sample temperature-tuning curve is given for BSN in Fig. 2-6. Details on the temperature-tuning characteristics of the crystals used in this study are given in Sec. 3.3. Details on the equations used to obtain the tuning curves are given in Appendix C, sections CI through C4.
ORIENTATION TUNING IN LINB03

PUMP WAVELENGTH 5145
SHG PM TEMP -40.00
ETA (°10°) 5.80
CRYSTAL TEMP -40.00
CRYSTAL NUMBER 3

FIG. 2-2
ORIENTATION TUNING IN Ba2NaNb5O15

PUMP WAVELENGTH 5145
SHG PM TEMP 41.00
ETA (°100") 5.90
CRYSTAL TEMP 41.00
CRYSTAL NUMBER 11

FIG. 2-3
ELECTRIC FIELD TUNING IN LINBO3

PUMP WAVELENGTH: 5145
SHG PM TEMP: -40.00
ETA ($10^{14}$): 5.80
CRYSTAL TEMP: -40.00
CRYSTAL NUMBER: 3

FIG. 2-4
ELECTRIC FIELD TUNING IN Ba2NaNb5O15

PUMP WAVELENGTH 5.145
SKG PM TEMP 41.00
ETA (x10^-1) 5.80
CRYSTAL TEMP 41.00
CRYSTAL NUMBER 11

FIG. 2-5
2.5-2 The Temperature-Tuning Equation

The temperature-tuning equation can be found by expanding the index of refraction to first order in temperature and angular frequency, and substituting it into the phase-matching condition [5]. The index of refraction takes the form:

\[ n(\omega, T) = n(\omega, T_0) + \frac{\partial n}{\partial T} (T - T_0) + \frac{\partial n}{\partial \omega} (\omega - \omega_0) \] (2-29)

For convenience we take the expansion about the subharmonic, \( \omega_0 \), and the subharmonic phase-matching temperature, \( T_0 \), defined by:

\[ n^e(\omega_p, T_0, \theta = 90^\circ) = n^o(\omega_o, T_0) \] (2-30)

This is the same temperature at which second-harmonic generation would take place if the pump frequency were \( \omega_o \). If we denote \( \delta T = T - T_0 \) and \( \delta \omega = \omega_s - \omega_0 \), then by (1-1), \( \omega_i = \omega_o - \delta \omega \). For nearly collinear interactions with \( \theta = 90^\circ \), (2-15) becomes

\[ n^e_{\omega_p} = n^o_{\omega_s} + n^o_{\omega_i} \] (2-31)

where the indices of refraction are now taken to be only functions of temperature at the given wavelengths. The superscripts denote that to phase-match in LN, the pump must be polarized as an extraordinary ray, and the signal and idler will be polarized as ordinary rays. In BSN, the pump must be polarized along the z axis (optic axis), and the signal and idler are polarized along the y axis. With no pump frequency variations, \( \delta \omega_p = 0 \) and (2-31) becomes:
\[ 2\omega \left( n^e_p + \frac{\partial n^e_p}{\partial T} \delta T \right) = (\omega + \delta\omega) \left( n^o_o + \frac{\partial n^o_o}{\partial T} \delta T + \frac{\partial n^o_o}{\partial \omega} \delta\omega \right) \]

\[ + (\omega - \delta\omega) \left( n^o_o + \frac{\partial n^o_o}{\partial T} \delta T - \frac{\partial n^o_o}{\partial \omega} \delta\omega \right) \]

This simplifies to:

\[ (\delta\omega)^2 = \frac{\omega \frac{\partial}{\partial T} (n^e_p - n^o_o)}{\frac{\partial n^o_o}{\partial \omega}} \delta T + \frac{\omega (n^e_p - n^o_o)}{2 \frac{\partial n^o_o}{\partial \omega}} \]

(2-33)

The last term in (2-33) is zero by (2-30), and we write (2-33) in the form:

\[ \delta\omega = \eta \sqrt{\delta T} \text{ where } \eta^2 = \frac{\omega \frac{\partial}{\partial T} (n^e_p - n^o_o)}{2 \frac{\partial n^o_o}{\partial \omega}} \]

(2-34)

The signal and idler wavelengths can now be written explicitly as functions of temperature using (2-34).

\[ \lambda_s = \frac{2\pi c \lambda_p}{\pi c + \lambda_p \eta \sqrt{T - T_0}} \]

(2-35)

and

\[ \lambda_i = \frac{2\pi c \lambda_p}{\pi c - \lambda_p \eta \sqrt{T - T_0}} \]

(2-36)

where \( \lambda_p \) is the pump wavelength. Computer-produced tuning curves
revealed that the value of $n$ could not be successfully predicted from index-of-refraction data. The tuning curves did not fit OPN experimental data (see Appendix C, Secs. C9 and C10). Also, the variation of index of refraction as a function of temperature is not known well enough to predict $T_o$ using (2-30). $T_o$ is sensitive to variations in composition from crystal to crystal. Values of $T_o$ for each crystal were estimated from SHG experiments. It was decided that the tuning characteristics of each crystal could best be determined by curve fitting the experimental OPN data using equations (2-35) and (2-36) varying $n$ and $T_o$ for a best least squares fit (see Sec. 3.3).

2.6 OUTPUT POWER AND CONVERSION EFFICIENCY OF THE DRO

2.6-1 Output Power

In this section, the relationship between the power of the signal and idler to that of the pump will be presented. These relationships are applied to the OPO design used in this investigation to predict the oscillator output power.

A nonlinear crystal of length $L$ is enclosed in an optical resonator formed by two mirrors, $M_1$ and $M_2$. The resonator axis coincides with the direction of pump propagation. The crystal c-axis is perpendicular to the resonator axis and parallel to the direction of polarization of the pump beam. The hemispherical resonator used in this study is illustrated in Fig. 2-7. The mirrors have high transmissions at the pump wavelength and high reflectivities at the signal and idler wavelengths. Let $P_{p,s,i}$ denote the power of the pump, signal,
FIG. 2-7  DRO Optical Cavity With Power Designations.
or idler beams, and superscripts e or i represent power external or internal to the resonator cavity. Subscripts 1 or 2 represent the power just outside mirrors 1 or 2, respectively. Let T represent the transmission of the mirrors, with the subscript 1 or 2 representing the mirror and the subscript p, s, or i representing the transmission wavelength. If the subscript 1 or 2 is missing, then the symbol P or T represents the total power or transmission. For example, $T_s = T_{s1} + T_{s2}$ and $P_s^e = P_{s1}^e + P_{s2}^e$. The results given here will be presented in terms of the pump power inside the nonlinear crystal, $P_p^i$, which is determined by the incident pump power and the transmission of mirror 1. Thus,

$$P_p^i = T_{p1}P_p^e.$$ (2-37)

The equations given here apply to a OPO with the following design characteristics. No attempt has been made to eliminate power-dependent reflections. Power-dependent reflections arise when the backward-traveling signal and idler waves mix to generate a backward-traveling pump wave [25]. Since the intensity of the signal and idler fields is a function of the incident pump power, the intensity of the backward-traveling pump wave will also depend on the pump power. Thus, pump-power-dependent reflections may exist in an OPO and limit its conversion efficiency. Special designs required to eliminate this type of reflection were not at the present time considered feasible for a study of CW parametric oscillation. It is also assumed that no enhancement is obtained by pump reflections which send the pump beam back through the nonlinear crystal. Thus, pump reflections by the far end of the crystal and mirror 2 are negligible. The enhancement of OPO
operation by back reflections of the pump beam has been treated by Bjorkholm, et al., [26]. This technique takes advantage of the fact that the backward-traveling pump beam can contribute to the signal and idler gain. Some methods for incorporating nonresonant pump reflections in CW OPO design are suggested in Sec. 5.0.

The equations given in the following paragraphs assume that the pump, signal, and idler fields can be described as plane waves [27]. It is also assumed that the losses in the signal and idler fields are small, i.e., $\varepsilon_s, \varepsilon_i << 1$.

Let $u$ represent the ratio of the internal pump power to the oscillator threshold power.

$$u \equiv \frac{P^i}{P^l} \frac{P}{P^l}$$

The total internal signal power is then given by [12, 27]

$$\frac{p^i_s}{p^l_p} = \frac{2}{\varepsilon_s} \frac{\omega_s}{\omega_p} \frac{\sqrt{u} - 1}{u}$$

(2-38)

The total external signal power is:

$$p^e_s = \frac{T_s}{2\varepsilon_s} p^i_s$$

(2-39)

recalling that $\varepsilon_s$ represents the total scattering and transmission one-way losses. Combining (2-38) and (2-39),

$$\frac{p^e_s}{p^l_p} = \frac{T_s}{\varepsilon_s} \frac{\omega_s}{\omega_p} \frac{\sqrt{u} - 1}{u}$$

(2-40)
The quantity $\mathbf{p}^e_s$ includes the power emerging from both mirrors of the oscillator. It is of practical interest to know the useful output power, i.e., the power emerging from mirror 2. Since,

$$p^e_{s2} = \frac{T_{s2}}{T_s} p^e_s,$$  \hspace{1cm} \text{(2-41)}

the result is:

$$\frac{p^e_{s2}}{p^i_p} = \frac{T_{s2}}{T_s} \frac{\omega_s}{\varepsilon_s} \frac{\sqrt{u} - 1}{\omega_p u}$$  \hspace{1cm} \text{(2-42)}

Equations similar to (2-38) through (2-42) apply for the idler. Thus,

$$\frac{p^e_{i2}}{p^i_p} = \frac{T_{i2}}{T_i} \frac{\omega_i}{\varepsilon_i} \frac{\sqrt{u} - 1}{\omega_p u}$$  \hspace{1cm} \text{(2-43)}

The total output power is just the sum of (2-42) and (2-43). Note that the effect of momentum mismatch ($\Delta k \neq 0$) on the output power is contained in the parameter $u$, which is proportional to $\text{sinc}^2(\Delta k l/2)$.

As a special case, consider operation near degeneracy where $\omega_i = \omega_s = \omega_p/2$ and $\varepsilon_i = \varepsilon_s = \varepsilon$. The total useful output power is:

$$\frac{p^e_{s2}}{p^i_p} = \frac{T_2}{\varepsilon} \frac{\sqrt{u} - 1}{u}$$  \hspace{1cm} \text{(2-44)}

where $T_2$ is the output mirror transmission at the subharmonic wavelength.
As an example, take the DRO described in Table 2-1. $P_{th} = 67 \text{ mW}$, $\varepsilon = .03$, and assume the oscillator is pumped at four times the threshold power ($P_p^1 = 268 \text{ mW}$) so that $u = 4$. Assuming that the output mirror transmission is $0.4\%$. Equation (2-44) gives $P_{Z}^{s}/P_{Z}^{i} = .03$. The total maximum output power is predicted to be approximately $9 \text{ mW}$. These figures are compared to experimental results in Sec. 4.2-1.

2.6-2 Conversion Efficiency

The internal conversion efficiency of a DRO is defined as the fraction of pump power converted to signal and idler power and is given by:

$$q_{i} = \frac{P_{s}^{i} + P_{p}^{i}}{P_{p}^{i}} = 2u(\sqrt{u} - 1) \quad (2-45)$$

The internal efficiency reaches a peak of $50\%$ at $u = 4$. (If power-dependent reflections are eliminated, the internal efficiency can reach $100\% \ [12].$)

The external conversion efficiencies to signal and idler power are:

$$q_{s}^{e} = \frac{T_{s}w_{s}}{2\varepsilon_{s}w_{p}} q_{i}^{i} \quad (2-46a)$$

and

$$q_{i}^{e} = \frac{T_{i}w_{i}}{2\varepsilon_{i}w_{p}} q_{i}^{i} \quad (2-46b)$$
The total external conversion efficiency is:

\[ q^e = \left( \frac{T_s w_s}{\varepsilon_s w_p} + \frac{T_s w_s}{\varepsilon_s w_p} \right) \frac{q^i}{2} \]  

(2-47)

For a degenerate DRO, (2-47) reduces to:

\[ q^e = \frac{T}{2\varepsilon} q^i \]  

(2-48)

where \( T \) is the signal or idler total transmission losses and \( 2\varepsilon = T + L \), where \( L \) represents all losses except transmission losses (scattering, intra-cavity reflections, etc.). Increasing the output mirror transmission will increase the power coupled out of the OPO cavity, but it also increases the threshold pump power. Thus, there must be an optimum output mirror transmission. Smith [12] gives the optimum transmission ratio, \( r = T/L \), maximum conversion efficiency, \( q^e \), and required pump power to threshold ratio, \( u \), as functions of the ratio of pump power to minimum threshold power (threshold for \( T = 0 \), i.e., no mirror transmission losses), \( N = \frac{P^i}{P^i_{th}} \). As an example, let \( N = 4 \); then the optimum \( r \) is 0.5, \( q^e_{max} = 0.15 \), and \( u = 1.75 \). Obviously, it is most desirable to minimize \( L \) rather than increase \( T \) to achieve optimum \( r \). This keeps the threshold low and minimizes pump requirements. To further the example, let the round-trip losses, \( L \), be .06; then \( T \) must be set to .03. The minimum threshold (no mirror transmission) is approximately 67 mW. The required pump power for optimum conversion efficiency is 268 mW, and the maximum conversion efficiency is 15%.
2.6-3 Effect of Temperature Tuning on Output Power

Even though the signal and idler wavelengths of a DRO can be tuned by the variation of a parameter such as crystal temperature, the tuning is not in the strictest sense continuous. Temperature tuning only succeeds in changing the central wavelength of the signal and idler gain profiles. It has no effect on the wavelengths for which a double resonance can occur in the oscillator cavity. As the DRO is temperature-tuned, points are reached where the signal and idler wavelengths correspond to the double resonances of the optical cavity. At these points, Δk = 0, and the output power sharply increases. When tuning between these points, resonance must occur with Δk ≠ 0, and the oscillator output will drop off. At points along the tuning range where there is no resonance for Δk = 0, it would be possible to change the oscillator cavity length until a new resonance condition is established for which Δk = 0. Adjustment of two or more parameters would thus be required to tune a DRO while maintaining Δk = 0. This type of scheme would still not succeed in producing a continuously tuned output without power fluctuations. It is for this reason that the description in this section is confined to examining the DRO performance while tuning only a single parameter.

The signal and idler resonances of an optical cavity occur in groups (clusters), each group consisting of discrete sets of signal and idler mode pairs separated by a fixed frequency. The separation of the double resonances (signal and idler mode pairs) is determined by the frequencies of longitudinal signal and idler modes which can satisfy the conservation of energy condition, (1-1). The frequency
spread between successive sets of signal and idler resonances is called the cluster spacing [5]. With a nonlinear crystal of length $L$, it is given by [12],

$$\Delta \omega_{cl} = \frac{\pi}{bL}$$

(2-49)

where $b \equiv \frac{\partial k_S}{\partial \omega_S} - \frac{\partial k_i}{\partial \omega_i}$. (The notation used in defining $b$ indicates that the partial derivative is taken with respect to frequency and evaluated at the frequency indicated by the subscript, i.e., $\frac{\partial k_S}{\partial \omega_S} = (\frac{\partial k_S}{\partial \omega})_{\omega_S}$.)

As the tuning parameter changes slightly, the central wavelengths of the gain profiles move, but the resonant signal and idler modes do not change. Thus, the gain at the resonant signal and idler wavelengths decreases, and $\Delta k$ moves away from zero. As the tuning parameter continues to change, the gain for the nearest adjacent signal and idler mode pair gets larger than for the mode pair which is currently oscillating. At this point the oscillator jumps to the adjacent mode pair, and $\Delta k$ returns to zero. $\Delta k$ returns to zero each time the signal and idler frequencies change by an amount $\Delta \omega_{cl}$.

In summary, it is predicted that the DRO output power will vary periodically with crystal temperature, reaching a peak at points where $\Delta k = 0$ and tapering off as $\Delta k$ gets larger. The output decreases until the value of $\Delta k$ corresponds to a change in mode frequencies of $\Delta \omega_{cl}$, at which point oscillation jumps to the next mode pair, $\Delta k$ returns to zero, and the power reaches a new peak. The purpose of this analysis is to express the output power as a function of $\Delta k$ and to relate $\Delta k$ to the change in crystal temperature. The complete description of the output power as a function of temperature will be specified by finding
the change in crystal temperature which corresponds to a change in mode frequencies of $\Delta \omega_{c1}$. This will form the periodicity characteristic of the function, i.e., the spacing between successive peaks.

The DRO output power from (2-44) and the definition of $u$ is:

$$p_2^e = \frac{4T_2}{\varepsilon} \left( \sqrt{\frac{P}{P_{th}}} - 1 \right) P_{th}$$  \hspace{1cm} (2-50)

From (2-26), the threshold power can be written as:

$$P_{th} = A \text{sinc}^{-2} \left( \frac{\Delta kL}{2} \right)$$  \hspace{1cm} (2-51)

where:

$$A \equiv \frac{4\varepsilon_0 \varepsilon_i (1 + \gamma \alpha) \omega_0^2}{KL(1 - \gamma^2)^2(1 - \alpha^2)b}.$$

Combining (2-50) and (2-51), the output power as a function of $\Delta k$ is:

$$p_2^e = \frac{4T_2 A}{\varepsilon} \left( \sqrt{\frac{P}{A}} \text{sinc}^2 \left( \frac{\Delta kL}{2} \right) - 1 \right) \text{sinc}^{-2} \left( \frac{\Delta kL}{2} \right).$$  \hspace{1cm} (2-52)

The change of momentum mismatch must now be found as a function of crystal temperature.

For convenience, define $a = \Delta kL/2$ and let $\Delta a$ represent incremental changes in the value of $\Delta kL/2$. Using equation (2-4) and the fact that $|\hat{k}| = n\omega/c$,

$$a = \frac{\omega L}{2c} \left[ 2n_p - n_s - n_i + \gamma (n_s - n_i) \right].$$  \hspace{1cm} (2-53)
The variation of $a$ as a function of crystal temperature is found by expanding $a$ to the first order in $\Delta T$. Thus:

$$
\frac{\Delta a}{\Delta T} = \frac{\omega_o L}{2c} \frac{\partial}{\partial T} \left[ 2n_p - n_s - n_i + \gamma (n_s - n_i) \right].
$$

(2-54)

Restricting this analysis to near-degeneracy operation where $\gamma = 0$ and solving for $\Delta T$,

$$
\Delta T = \frac{c \Delta a}{\omega_o L \frac{\partial}{\partial T} [n_p^e - n_o^0]}.
$$

(2-55)

The temperature dependence of the output power can now be found. $\Delta T$ is the shift of temperature from degeneracy, $\Delta T = T - T_o$. Thus,

$$
p_e^2 = \frac{4 T_o^2}{\epsilon} \left( \sqrt{\frac{p}{A}} \text{sinc}^2 \left[ B(T - T_o) \right] - 1 \right) \text{sinc}^2 \left[ B(T - T_o) \right],
$$

(2-56)

where $B = \frac{\omega_o L}{c} \frac{\partial}{\partial T} [n_p^e - n_o^0]$. It is now necessary to find the relationship between $\Delta a$ and the change of signal frequency so that $\Delta a$ can be related to the cluster spacing.

The phase-matching variation, $\Delta a$, can be found in terms of $\Delta \omega_c$ by writing $a$ in terms of $\omega_s$. The result is:

$$
a = \frac{L}{2c} \left[ n_p^o \omega_p - n_s^o \omega_s - n_i^o (\omega_p - \omega_s) \right].
$$

(2-57)
The variation of $a$ with respect to $\omega_s$ is then given by:

$$\frac{\Delta a}{\Delta(\omega_s)} = \frac{L}{2c} (n_i - n_s). \quad (2-58)$$

Setting $\Delta(\omega_s) = \Delta \omega_{cl}$ and combining (2-49), (2-55), and (2-58), the temperature-tuning increment between cavity resonances is:

$$\delta T = \frac{\pi (n_i - n_s)}{\omega_o b L \frac{\partial}{\partial T}[n^e_p - n^o_o]} \quad (2-59)$$

Equation (2-59) shows that very near degeneracy, the temperature-tuning increment approaches zero since $n_s$ is nearly equal to $n_i$. $\delta T$ increases for more off-degenerate operation, but equation (2-59) does not apply for far-off degeneracy.

To estimate the magnitude of $\delta T$, consider a DRO using a 0.5 cm length of BSN as the nonlinear crystal. Assume that it is operating slightly off degeneracy for a 514.5 nm pump wavelength. Typically, $\lambda_s = 950$ nm and $\lambda_i = 1120$ nm. The value of $(n_i - n_s)$ can be estimated using equation (C43) of Appendix C. For small $\lambda_i - \lambda_s$:

$$\frac{n_i - n_s}{\lambda_i - \lambda_s} = \frac{\partial n_X}{\partial \lambda} \quad (2-60)$$

Using $NXA = 0.253$, $NXB = .0102$ (as defined in Sec. C9-1B), $\lambda = 1000$ nm, and $\lambda_i - \lambda_s = 170$ nm, the value of $(n_i - n_s)$ is found to be 0.013. The value of $b$ has been reported to be $6.2 \times 10^{-12}$ sec/cm [28]. This value, however, is given for a far-off degenerate OPO. Computer evaluation
of b using equation (C33) has shown that b is smaller near degeneracy and is approximately $5 \times 10^{-13}$ sec/cm (see Sec. C9.3). The value of $\frac{\alpha}{\delta T} (n^e_p - n^o_o)$ is reported by Singh, et al., and is $1.1 \times 10^{-4}/^\circ C$ [19].

For $L = 0.5$ cm and $\omega_o = 1.84 \times 10^{15}$/sec, the value of $\delta T$ is $0.9^\circ C$. This result corresponds very well to the DRO data presented in Sec. 4.2-3.

Fig. 2-8 is a plot of equation (2-56) with $A = 67$ mW, $T_2 = 0.002$, $\varepsilon = .03$, $P_p = 268$ mW (u=4), and $T_o = 41^\circ C$. The plot was made by resetting $\Delta T$ to zero each time equation (2-59) is satisfied. Thus, the plot illustrates the progressive increase in the temperature-tuning increment (spacing between adjacent peaks) predicted by (2-59) as $(n_i - n_s)$ gets larger. The plot was done with the values of $L$, $\omega_o$, and $\frac{\alpha}{\delta T} (n^e_p - n^o_o)$ quoted in the last paragraph. Thus, $B = 3.358$, and (2-59) reduces to $\delta T = 62.09 (n_i - n_s)$. The indices of refraction were computed using equation (C18). For convenience, the curve in Fig. 2-8 was made with $A$ constant. Since $A$ is proportional to the signal and idler losses it will not actually remain constant during tuning but will vary depending on the transmission characteristics of the resonator coatings. Thus, in an actual power-tuning curve the relative height of the output peaks will vary according to the resonator losses which are functions of signal and idler wavelength. The curve in Fig. 2-8 is compared to experimental results in Sec. 4.2-3.

2.7 PARAMETRIC OSCILLATOR LINEWIDTH

For a fixed pump frequency and crystal temperature (no tuning), the output of the DRO consists of a spread of wavelengths centered at
FIG. 2-8 Predicted DRO Output Power as a Function of Crystal Temperature.
\( \omega_{s0} \) and \( \omega_{i0} \). This spread in wavelength is referred to as the linewidth. It results from the fact that the parametric gain is appreciable over a range of values for \( \Delta k \), the pump source has a small but significant linewidth, the pump frequency may vary, and mechanical as well as thermal variations cause the resonant cavity length to vary. The first step in examining the oscillator linewidth is to establish the intrinsic linewidth.

2.7-1 Range of OPO Operation Without Tuning

As shown in Fig. 2-1, the parametric gain profile halfwidth is \( |\Delta k|/2 = \pi/2 \). Maximum parametric gain falls in the range \( 0 \leq |\Delta k| \leq \pi/L \). The variation in signal and idler frequencies for this range of \( \Delta k \) can be found by expanding \( k \) to the first order in \( \omega \). Let \( \Delta \omega_s = \omega_s - \omega_{s0} \) be the variation in signal frequency. Assuming that \( \omega_p \) is constant, \( \Delta \omega_i = -\Delta \omega_s \). Let \( k_{s0} \) and \( k_{i0} \) represent the phase-matched propagation constants so that \( k_{s0} + k_{i0} = k_p \). Then, expanding the propagation constant in terms of \( \Delta \omega_s \),

\[
k_s = k_{s0} + \kappa \frac{\partial k_s}{\partial \omega_s} \Delta \omega_s + \frac{1}{2} \kappa^2 \frac{\partial^2 k_s}{\partial \omega_s^2} \Delta \omega_s^2
\]

(2-61a)

and

\[
k_i = k_{i0} - \kappa \frac{\partial k_i}{\partial \omega_i} \Delta \omega_s + \frac{1}{2} \kappa^2 \frac{\partial^2 k_i}{\partial \omega_i^2} \Delta \omega_s^2
\]

(2-62b)

Thus, \( \Delta k = -b\Delta \omega_s - g\Delta \omega_s^2 \)

(2-62)
where \( b \) is the same as defined in Sec. 2.6-3, and

\[
g = \frac{1}{2} \left[ \frac{\partial^2 k_s}{\partial \omega_s^2} + \frac{\partial^2 k_i}{\partial \omega_i^2} \right]
\]  

(2-63)

Setting \( |\Delta k| = \pi/L \), the frequency range (bandwidth) when \( b > g \) (off degeneracy) is given by,

\[
\Delta \omega = \frac{2\pi}{bL}.
\]  

(2-64)

Only those modes within the cavity for which the gain exceeds the losses can oscillate. If all modes over the range \( \Delta \omega \) have equal losses, then in the steady state the pump depletes until only the single mode with highest gain remains oscillating. If more than one mode has the same gain, then more than one mode can oscillate. Modes of oscillation can be selected by introducing losses into the unwanted modes.

For a doubly resonant oscillator, the frequency spacing between sets of signal and idler mode pairs is much larger than the signal or idler longitudinal mode spacing. The spacing between mode pairs is the cluster spacing given in (2-49). If there are many signal modes within the range \( \Delta \omega_{CI} \), then the maximum range of DRO operation is just \( \Delta \omega_{CI} \) or one-half the parametric gain bandwidth. For the case of a DRO near degeneracy with \( L = 0.5 \text{ cm} \), \( b = 5 \times 10^{-13} \text{ sec/cm} \), the cluster spacing is \( 1.3 \times 10^{13} \text{ Hz} \). For \( \lambda_s = 1029 \text{ nm} \), this corresponds to 7 nm. This figure agrees well with the OPN bandwidths given in Appendix A.

2.7-2 Fluctuation Phenomena

The operating point (in the frequency domain) of a doubly
resonant parametric oscillator is determined by three basic constraints: the condition given in (1-1); the condition that $\Delta k = 0$; and the position of the resonances of the optical cavity. Any change in a parameter such as pump frequency or optical cavity length can greatly alter the signal and idler frequencies, thus producing an apparent spread of their wavelengths.

The sensitivity of oscillation frequency to pump frequency variations is given by Smith [12] as:

$$|\delta \omega_p| = \frac{\delta \omega_s \delta \omega_i}{\Delta \omega_{cl}}$$  \hspace{1cm} (2-65)

where $\delta \omega_p$ is the pump frequency variation required to shift to an adjacent longitudinal mode of the OPO, and $\delta \omega_s$ and $\delta \omega_i$ are the signal and idler longitudinal mode spacings. These are given by:

$$\delta \omega_s,i = \frac{\pi c}{d + L(n_s,i + \omega_s,i \frac{\partial n_s,i}{\partial \omega_s,i} - 1)}$$  \hspace{1cm} (2-66)

where $d$ is the optical cavity spacing. For $d = 2.7 \text{ cm}$, $L = 0.5 \text{ cm}$ and $\frac{\partial n}{\partial \omega} = 5.8 \times 10^{-17} \text{ sec}$, $\delta \omega_s = 2.8 \times 10^{10} \text{ Hz}$. At $\lambda_s = \lambda_i = 1029 \text{ nm}$ this corresponds to a $\Delta \lambda = 0.016 \text{ nm}$. For these values, $\delta \omega_p = 62 \text{ MHz}$. The least stable pump source used in this study had a $\delta \omega_p$ of approximately 300 MHz. Variations of this magnitude would have produced shifts in the OPO longitudinal modes, but the corresponding shifts in the signal wavelength would have been only $0.03 \text{ nm (0.3 A)}$. Pump frequency variations are not sufficient to explain the observed OPO linewidths reported in Sec. 4.0.
The sensitivity of OPO oscillation frequency to cavity length changes is given by [12]:

\[ |\delta d| = \frac{\lambda_s \delta \omega_s}{2 \Delta \omega_{cl}} \frac{1}{\omega_i + \frac{\delta \omega_s}{\delta \omega_i}} \]

(2-67)

which near degeneracy becomes,

\[ |\delta d| = \frac{\lambda_s \delta \omega_s}{4 \Delta \omega_{cl}} \]

(2.68)

\( \delta d \) is the change in cavity length required to shift oscillation by one longitudinal mode. For the example given in the previous paragraph, \( \delta d = 0.57 \) nm. Obviously, the OPO oscillation frequency is extremely sensitive to cavity length changes. Sec. 4.2-2 reports the OPO linewidths observed in this study. They varied from 0.4 nm to 1.6 nm measured near degeneracy. These values would imply cavity length variations of the order of 50 nm. Even though actual cavity length fluctuations were not measured during this investigation, it seems likely that they played the major role in determining DRO linewidths. The DRO linewidths were measured as a function of degeneracy to determine whether or not they show any dependence on the parametric gain bandwidth. The linewidth of the DRO, when pumped by a free running laser (Laser A) whose stability was ±150 MHz, did show a dependence on parametric gain bandwidth. However, when it was pumped by the more stable laser (Laser B), where the pump frequency variation is ±50 MHz, the dependence could not be observed. The lack of any definable
dependence on degeneracy lends support to the supposition that cavity length fluctuations were the major determinant of DRO linewidth when pump frequency variations are less than ± 31 MHz.
3.0 CW OPO PHYSICAL DESIGN REQUIREMENTS

3.1 OPO PUMP SOURCES

3.1-1 General Pump Requirements

Effective CW pumping of an OPO requires an intense, highly monochromatic source of radiation. Since threshold conditions require that the losses at the signal and idler be very small, the signal and idler are resonant modes of a high Q cavity. These resonant modes have limited bandwidths so that if condition (1-1) is to be met, the pump must also have a limited bandwidth. Only one longitudinal mode of the pump can contribute to an effective continuous interaction with the signal and idler modes of the OPO cavity. An alternate approach to CW OPO design is given by Byer, et al., [8]. This approach utilizes a long parametric oscillator cavity such that the mode-spacing of the idler is the same as the mode-spacing of the pump. Thus, a multimode pump can drive a multimode idler to amplify the single-mode signal.

For this study, it was decided that a smaller, more compact oscillator cavity pumped by a single-mode laser would be the most reasonable approach. If the pump power is divided among many longitudinal modes, then only a small fraction of the pump power is available at any instant of time. It is possible to use a mode selecting etalon in the laser cavity to get a large fraction (0.6) of the available pump laser power into a single longitudinal mode.

Some techniques are available that can channel up to 90% of the available laser power into a single longitudinal mode [29-31]. These techniques are fairly complex and require a large number of
additional optical and electronic components. Since sufficient laser power was available, the use of an intracavity etalon was satisfactory. A single air-spaced, temperature-controlled etalon produced a stable drift-free mode.

It is also necessary to have a pump source which operates in the lowest order transverse mode ($\text{TEM}_{00}^0$). This mode has the narrowest beam waist, thus offering higher power densities. The pump beam has less divergence and is easier to mode-match to the low-order ($\text{TEM}_{00}^0$, $\text{TEM}_{01}^0$) modes of the parametric oscillator cavity. Most gas lasers operate in the $\text{TEM}_{00}^0$ mode by virtue of the geometry of their construction. A solid-state laser can be forced to operate in the lowest order mode using an intracavity aperture.

3.1-2 Argon-Ion Gas Laser

An excellent source of CW pump radiation is the argon-ion gas laser. Laser output powers of the order of watts can be obtained in the $\text{TEM}_{00}^0$ mode. The output is linearly polarized to within approximately 0.2%, which is ideal for nonlinear optical phase-matching. Depending on the quality of laser design, the output is relatively stable in both amplitude and frequency.

The laser optical resonator consists of a long radius (600 m) output mirror and wavelength selection prism. The long radius output mirror improves the stability of the resonator while maintaining a narrow beam divergence. Adjustments in the angle of the prism tune the laser for operation at eight discrete wavelengths. Only two of these wavelengths have sufficient output power to be used as optical
parametric oscillator pumps; these are 514.5 nm and 488.0 nm. An additional high quality polarizer is used with the laser to provide a better degree of linear polarization so that a crossed polarizer at the OPO output provides 50 db of pump attenuation. This is necessary so that the pump will not interfere with analysis of the OPO output.

A Spectra Physics model 420 optical spectrum analyzer was used to monitor the spectrum of the gas laser. The instrument has a maximum frequency scan of 10 GHz and a maximum dispersion of 100 MHz/cm.

The spectrum of single-line operation is shown in Fig. 3-1(a). This is a photograph of the oscilloscope trace from the spectrum analyzer. A large number of longitudinal modes are in oscillation. The bandwidth of the output is about 5 GHz ($7 \times 10^{-4}$ nm). The maximum available power from the laser used for this study during single-line operation is 1.35 W at 514.5 nm and 1.21 W at 488.0 nm. Multimode operation was used as a pump during observation of OPN (see Appendix A). It has the advantage of higher power with little increase in noise emission bandwidth over that observed using a single-mode pump.

Operation with a single longitudinal mode was obtained by placing a Fabry-Perot etalon in the laser cavity and carefully adjusting its angle with respect to the cavity axis. This additional restraint on the optical cavity resonance condition restricts oscillation to a single mode. Single-mode operation is shown in Fig. 3-1(b). The 514.5 nm line had 650 mW of power available in a single mode just after laser warm-up. This usually decreased to 450 mW after an hour of operation. The 488.0 nm line produced up to 600 mW maximum power.

Two argon lasers were used during the course of this study.
(a) Multimode  
(single line)

(b) Single mode

FIG. 3-1 Spectra of Argon Laser  
Output at 488.0 and 514.5 nm.
The first (to be referred to as laser A) was an RF excited Spectra-Physics Model 140 with a cavity extension and single component glass etalon. Even though the short-term amplitude stability was reasonably good (less than 10%), it was subject to thermal drift and required frequent retuning. The laser did not possess a thermally stabilized cavity and thus was constantly changing longitudinal modes (mode-hopping). The frequency variation as observed on the spectrum analyzer was as high as ±150 MHz. The output powers quoted in previous paragraphs apply to laser A.

The second laser used in this study was a Coherent Radiation Laboratory Model 52 (laser B). It represents a significant improvement in the state-of-the-art of gas-laser design. Laser B operates by dc excitation of the argon gas. This enables a considerable simplification of power supply and laser-head design. The optical cavity was mechanically and thermally stabilized through the use of thermally compensated, low-expansion, optical cavity spacers. The single-mode etalon is air spaced and temperature controlled. This etalon enables the laser to operate for a long period of time without longitudinal mode-hopping. The frequency stability is thus better than could be measured with a spectrum analyzer (less than ±50 MHz). Laser B is amplitude-feedback stabilized, providing amplitude stabilities of ±0.5%. The output power available in a single mode at either 488.0 nm or 514.5 nm is 800 mW.
3.1-3 Nd:YAG Laser

The solid-state Nd:YAG laser is a source of continuous high-power (in our case 10 watt) radiation in the infrared at 1064 nm. A 50 mm long by 3 mm diameter YAG rod is pumped by a krypton arc lamp.

For use in nonlinear optics, the Nd:YAG laser has the advantage of high available CW output power (up to 1000 W CW). It can also be Q-switched to convert its output to high peak-power pulses at high repetition rates. It has the disadvantages of greater beam divergence and frequency instability. The usefulness of the Nd:YAG laser for nonlinear optical experiments is greatly enhanced when the output wavelength is frequency doubled to 532 nm. The doubled output is then at a frequency that can be phase-matched for optical parametric oscillation using BSN or LN.

Efficient frequency conversion of the 1064 nm radiation can be obtained when a nonlinear crystal is placed internal to the laser cavity. For example, good results were obtained with either a 0.5 cm long crystal of BSN or a 1.0 cm long crystal of off-stoichiometric (hot) LN. Common LN cannot be used for this purpose because it phase-matches at too low a temperature to prevent optical damage [32]. Both mirrors of the laser cavity can be used with maximum reflectivity at 1064 nm because the process of conversion to 532 nm acts as the output coupler. This keeps linear losses in the cavity at a minimum. Placing the nonlinear crystal internal to the laser cavity takes advantage of the fact that higher power levels inside the laser resonator improve the frequency conversion efficiency. The experimental arrangement for a
532 nm solid-state source is shown in Fig. 3-2.

The back mirror has a short radius of curvature, roughly 50 or 60 cm, and is chosen to provide a small beam waist in the doubling crystal. The beam waist can be adjusted by changing the mirror-to-crystal spacing. The other mirror has a long radius of curvature, approximately 2 m, chosen for improved resonator stability. The laser-rod-to-mirror spacing can be varied for maximum lasing efficiency.

Very precise (±0.05 °C) temperature control of the crystal oven is required to maintain stable operation at peak power. The second-harmonic phase-matching curve for the crystal used was only 0.7 °C full width at half height (see Appendix B, Crystal No. 6). The maximum CW SHG output power was 80 milliwatts. No attempt was made to obtain the theoretical maximum conversion efficiency [33].

High peak-power pulsed operation was obtained through the use of an acousto-optic Q-switch. A Brewster-angle-cut, fused-silica crystal was placed internal to the laser cavity. A 25 MHz, 10 watt, gated transmitter sets up a traveling acoustic wave in the fused silica. A small quartz crystal acts as a transducer. The traveling acoustic wave propagates perpendicular to the direction of the optical radiation and behaves as a diffraction grating. When the RF signal is on, incident light deflects out of the normal resonance path, thereby spoiling the cavity Q. When the RF power is momentarily cut off, a Q-switched pulse is produced. The pulses had a 0.75 microsecond duration. The RF repetition rate could be set as high as 10 KHz, but was usually operated at 1 KHz.

A superposition of 20 pulses is shown as a function of time for the fundamental and second-harmonic in Fig. 3-3. The peak power
FIG. 3-2  SOLID-STATE CW OR Q-SWITCHED 532.0 nm SOURCE.
Fig. 3-3 Q-switched Pulses of a Frequency Doubled Nd:YAG Laser.
per pulse is estimated to be about 100 watts. The acousto-optic method of Q-switching produced noise-free, single pulses of reasonably short duration. The pulse-to-pulse amplitude stability was approximately ±10%. It is superior to chopping or spinning-prism techniques of Q-switching because the entire cross section of the laser beam is affected as fast as the time required for acoustic wave transversal. This helps produce clean, single pulses with good amplitude stability and easily controllable repetition rates. The Q-switched pulse duration is determined by the RF cut-off decay time. The 1/e decay time for our transmitter was approximately 2 microseconds. Available data indicate that lead molybdate with a lithium niobate transducer would yield a Q-switch of much greater deflection capability requiring less RF drive power [34].

Another proposed improvement to the 532 nm source would be to use a Nd:Yttrium Aluminate (YA103) rod instead of the usual Nd:YAG. YA103 has a greater pumping efficiency. Furthermore, the orthorhombic crystalline structure causes the 1064 nm radiation to be almost completely polarized along the a-axis. With a polarized fundamental wave, the phase-matching condition for frequency doubling is met with improved operational efficiency.

The frequency-doubled, Q-switched Nd:YAG laser was used to pump the same CW OPO that was designed for use with the 514.5 nm argon laser pump. The results of this work are reported in Sec. 4.3.
3.2 NONLINEAR OPTICAL CRYSTALS

3.2-1 Required Properties

As interest in nonlinear optical interactions has grown, more emphasis has been placed on studying the special properties that make crystals useful for such interactions. Studies have been carried out to evaluate these properties in a large number of different materials [4, 19, 35-40]. The number of likely candidates for good nonlinear materials is limited because each must meet a number of specific requirements.

In crystals that possess a center of symmetry, changing the signs of the field amplitudes changes the sign of the polarization. For the second-order polarization given in (1-3), this implies:

\[ d_{ijk}E_jE_k = -d_{ijk}(-E_j)(-E_k). \]  \hspace{1cm} (3-1)

From which we concluded that \( d=0 \). Hence, only noncentro-symmetric crystals have nonzero \( d \) and can be used for nonlinear interactions supported by a second-order polarization.

An obvious but essential requirement is that the crystal be transparent over the range of wavelengths under consideration. Attenuation of either the pump, signal, or idler will greatly increase pump power requirements and decrease conversion efficiency. Absorption of an intense pump beam can produce localized heating, which may distort or damage a crystal.

Only crystals that can be grown with good optical quality and extremely small variation in index of refraction throughout their
volume should be considered for nonlinear applications. Optical imperfections and transverse variations in index of refraction can cause distortion of the interacting wavefronts. Especially critical is the homogeneity of index of refraction along the interaction length of the crystal. Effective phase-matching depends on the birefringence \((n_p^e - n_o^0)\). Variations of index as small as \(10^{-5}\) will noticeably increase the parametric gain bandwidth. All of these effects tend to decrease the gain available at a given pump wavelength and to increase the intra-cavity losses.

Since nonlinear coefficients are small, it is almost always necessary to use high-power densities to obtain sufficient parametric gain. Such power densities can easily cause surface damage and induce index-of-refraction inhomogeneities. Damage threshold depends primarily on the type of crystal, but it is also a function of crystal temperature and field wavelengths. Longer wavelengths have less tendency to produce index-of-refraction damage. In some cases, this type of damage can be bleached out by maintaining the crystals at elevated temperatures [36]. Higher temperatures tend to erase the index-of-refraction inhomogeneities. Damage thresholds have been published for many materials and should be compared to expected beam-power densities before the crystals are considered for use.

The most fundamental measure of the effectiveness of a nonlinear crystal is the magnitude of \(d\). From (2-8), \(D_o\) is proportional to \(d\). From (2-14), \(G_s\) increases as a function of \(D_o\). All other factors being constant, the parametric gain is greater for the largest \(d\). More specifically, the OPO threshold is a function of crystal nonlinear
coefficient, indices of refraction, and length. If the threshold condition is written explicitly in terms of these parameters, then the threshold is proportional to $n_p n_s n_i/(dL)^2$. These quantities are known for a large number of crystals, so a comparison of relative power thresholds can be made. The trade-off between $L$ and $d$ is important. The maximum crystal length available with acceptable optical properties must be determined. Due to crystal growth problems, the acceptable length of some crystals is relatively small. Noting further that $d$ is proportional to the product of the linear susceptibilities, $x_p x_s x_i$[41], which is approximately equal to $(x_L)^3$ and that $x_L=(n^2-1)/4$, the threshold is found to be approximately proportional to $1/n^9 L^2$. Thus, if $d$ is not known, materials with the largest indices of refraction are desirable.

Perhaps the most important requirement is that the crystal be phase-matchable. This means that for a given pump wavelength, a crystal must be chosen that can satisfy (2-15) for acceptable signal and idler wavelengths. If sufficient index-of-refraction data are available, the phase-matching wavelengths can be verified directly from (2-15). This type of data is not usually complete, nor is it possible to predict the variations in refractive index that occur among crystals of the same type. It may often be necessary to select crystals by virtue of the phase-matching properties implied by experiments in second-harmonic generation, parametric noise generation, or parametric oscillation. When previous experiments have been carried out under slightly different conditions, e.g., the use of different wavelengths, some extrapolations can be made. An example of such an extrapolation
is given in Appendix C, Sec. C9.5. In this case, index-of-refraction data are used to compute $T_0$ for wavelength $\lambda + \delta \lambda$ in terms of a known $T_0$ at wavelength $\lambda$.

In cases where the phase-matching characteristics of a crystal must be known precisely, it may be necessary to make observations of optical parametric noise emission. The phase-matched signal and idler wavelengths can be accurately determined as a function of orientation, temperature, electric field, etc. An experimental study of the temperature phase-matching characteristics of LN and BSN is presented in Sec. 2.5-2 and in Appendix A. The results are given in Sec. 3.3.

3.2-2 Selection of Nonlinear Materials

The nonlinear materials LN and BSN were chosen for this study because of their large nonlinear coefficients, desirable phase-matching characteristics for available pump wavelengths, and their commercial availability. A large number of optical experiments have been performed with these crystals, so that their nonlinear properties are well documented. These properties are summarized in Table 3-1. A comparison of these properties to the properties of a large number of other materials indicated the overall superiority of LN and BSN for use in nonlinear optical experiments.

An examination of Table 3-1 readily reveals that LN and BSN satisfy quite well the requirements discussed in the previous section. A few exceptions must be discussed. LN is very sensitive to optical damage by visible wavelengths when the crystal temperature is less than 170° C [36]. This does not necessarily restrict the phase-matching
### TABLE 3-1
NONLINEAR OPTICAL PROPERTIES OF LiNbO$_3$ AND Ba$_2$NaNb$_5$O$_{15}$

<table>
<thead>
<tr>
<th>Property</th>
<th>LiNbO$_3$</th>
<th>Ba$_2$NaNb$<em>5$O$</em>{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline structure</td>
<td>trigonal</td>
<td>orthohombic ($20^\circ$ C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tetragonal ($&gt;300^\circ$ C)</td>
</tr>
<tr>
<td>Crystalline properties</td>
<td>noncentrosymmetric</td>
<td>noncentrosymmetric ($&lt;585^\circ$ C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>centrosymmetric ($&gt;585^\circ$ C)</td>
</tr>
<tr>
<td>Point group symmetry</td>
<td>3m</td>
<td>mm2 ($20^\circ$ C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4mm ($&gt;300^\circ$ C)</td>
</tr>
<tr>
<td>Optical properties</td>
<td>anisotropic</td>
<td>anisotropic</td>
</tr>
<tr>
<td></td>
<td>negative</td>
<td>negative biaxial</td>
</tr>
<tr>
<td></td>
<td>uniaxial</td>
<td></td>
</tr>
<tr>
<td>High transparency range</td>
<td>400 nm to 4000 nm</td>
<td>350 nm to 5000 nm</td>
</tr>
<tr>
<td>Damage Threshold (W/cm$^2$)</td>
<td>$10^7$ (Pulsed)</td>
<td>$10^6$ (Continuous (visible))</td>
</tr>
<tr>
<td></td>
<td>$10^2$ ($&lt;170^\circ$ C)</td>
<td></td>
</tr>
<tr>
<td>Nonlinear coefficient (d)</td>
<td>$2.1 \times 10^{-8}$ esu</td>
<td>$4.4 \times 10^{-8}$ esu</td>
</tr>
<tr>
<td>Indices of Refraction</td>
<td>$n^o$ $n^e$</td>
<td>$n_y(n^o)$ $n_z(n^o)$</td>
</tr>
<tr>
<td>(25$^\circ$ C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>488.0 nm</td>
<td>2.3814 2.2765</td>
<td>2.3974 2.2727</td>
</tr>
<tr>
<td>514.5</td>
<td>2.3444 2.2446</td>
<td>2.3767 2.2583</td>
</tr>
<tr>
<td>532.1</td>
<td>2.3188 2.2241</td>
<td>2.3655 2.2502</td>
</tr>
<tr>
<td>632.8</td>
<td>2.2862 2.1964</td>
<td>2.3205 2.2177</td>
</tr>
<tr>
<td>1064.2</td>
<td>2.2407 2.1580</td>
<td>2.2567 2.1700</td>
</tr>
<tr>
<td>Figure of Merit</td>
<td>$1.42 \times 10^{-16}$</td>
<td>$6.27 \times 10^{-16}$</td>
</tr>
<tr>
<td>(2d)$^2$/n$_p$n$_s$n$_i$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Variation of Birefringence</td>
<td>$0.8 \times 10^{-4}$/°C</td>
<td>$1.0 \times 10^{-4}$/°C</td>
</tr>
<tr>
<td>$\frac{\Delta}{\Delta T} (n^e - n^o)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Property</td>
<td>LiNbO₃</td>
<td>Ba₂NaNb₅O₁₅</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>----------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Angular half-width of phase-matched SHG</td>
<td></td>
<td>0.16° -cm/L (25° C)</td>
</tr>
<tr>
<td>Temperature half-width of phase-matched SHG</td>
<td>0.72° -cm/L</td>
<td>0.45° -cm/L</td>
</tr>
<tr>
<td>Subharmonic phase-matching Temperatures (T₀,°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stioch</td>
<td>-150</td>
<td>-15</td>
</tr>
<tr>
<td>Non-stioch</td>
<td>-40</td>
<td>103</td>
</tr>
<tr>
<td>488.0 nm</td>
<td></td>
<td>173</td>
</tr>
<tr>
<td>514.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>532.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>575.0</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Maximum available length (L)</td>
<td>1.0 cm (1969)</td>
<td>0.5 cm (1971)</td>
</tr>
<tr>
<td></td>
<td>5.0 cm (1971)</td>
<td></td>
</tr>
</tbody>
</table>
flexibility, since an off-stoichiometric crystal is available that has elevated phase-matching temperatures. The temperature restriction decreases the useful range of a crystal oven and increases the chance of damage due to accidental exposure at room temperature. BSN has a crystallographic phase transition at 300° C, which alters its nonlinear properties. Furthermore, BSN must be poled to make it single-domain and detwinned to remove interchanges of the a- and b-axes in different regions of the crystal. If the BSN crystal is heated above 300° C and recooled, the micro-twinning will reappear. Finally, the homogeneity, optical quality, and phase-matching quality must be evaluated for individual crystals.

The evaluation procedures developed during this study are given in Appendix B. When this investigation began, there was some question as to the chances of obtaining good quality BSN crystals. Crystal growth and finishing procedures for BSN are complex and difficult to control properly. Fortunately, excellent 0.5 cm-long BSN crystals were obtained.

The phase-matched signal and idler wavelengths of the LN and BSN crystals were established for 488.0 nm and 514.5 nm pump wavelengths in the range from 20° C to 300° C by observation of OPN. The results of this study are reported in Sec. 3.3. When these observations were combined with the additional restrictions imposed by the high reflection coatings that either λ_s = λ_i or λ_s = λ_i/3 (see Sec. 3.4-4), the number of designs for CW OPO's narrowed to three. They are: pump BSN with λ_p = 514.5 nm at a temperature of about 40° C and provide optical resonance at 1029 nm; pump BSN with λ_p = 488.0 nm at a temperature of about 190° C and provide resonance at 650 nm and 1950 nm; and pump LN
with $\lambda_p = 514.5$ nm at a temperature near $185^\circ$ C and provide resonance at 686 nm and 2058 nm. The operation of the first two OPO's will be discussed in Sec. 4.0.

3.2-3 Crystal Oven Design

The crystal oven pictured in Fig. 3-4 was designed and built to provide precision control of crystal temperature from $+20^\circ$ C to $+300^\circ$ C. The oven consists of a cylindrical central core of nickel-coated copper with a slot to house a rectangular crystal of maximum cross section $5 \times 5$ mm and up to 2.0 cm long. Copper was chosen to minimize thermal gradients and coated with nickel to prevent contamination of the crystal by copper oxides. A small axial hole near the slot accommodates a microminiature chromel-constantan thermocouple for temperature readout.

The central core is placed in a cylindrical housing made of machinable dielectric. The dielectric was chosen for its electric and thermal insulating properties as well as ease of fabrication. This housing is slotted around its periphery, and two coils of nichrome wire are cemented into place. A small hole provides space for a platinum resistance sensor for temperature control. The sensor is located in close proximity to the heating coils for fast-response, stable temperature control. The nichrome heating wire is concentrated at the edges of the oven to help avoid temperature gradients along the oven center axis caused by convective cooling of the surrounding air. The coils are wired in parallel and have a cold resistance of 35 ohms. This resistance enabled the temperature controller to provide up to 50 watts
(a) CRYSTAL OVEN, VERSION 1, WITH OPTICAL MOUNT

(b) CRYSTAL OVEN, VERSION 2, WITH MODE-MATCHING LENS, OVEN MOUNT, COLLIMATING LENS, AND ANALYZER

FIG. 3-4 DETAIL OF OPTICAL CRYSTAL OVENS AND OSCILLATOR COMPONENTS
of heating power. Copper end plates provide electrical contact for the heating element.

A third cylinder of machinable dielectric forms a casing containing air spaces for insulation. The entire oven assembly is less than 2 inches in diameter and is adapted for mounting in a standard 2-inch optical mount. The optical mount provides precise orientation in two directions. The oven can also be rotated about its axis for alignment of the crystal c-axis to the pump direction of polarization. This assembly is in turn mounted on a two-way, micrometer-driven translation stage, which positions the crystal with respect to the pump beam and optical cavity. The total length of the oven with copper end plates is 3.2 cm, allowing a minimum cavity separation of 2.3 cm for an OPO designed with one mirror coated on the crystal.

An Artronix Model 5301 temperature controller is used to maintain the crystal oven temperature at the desired value. The controller responds to the platinum resistance sensor mounted near the heating element. A sensitive null bridge circuit balances the sensor resistance against a set-point potentiometer. The control function is time proportioning with automatic reset and reset inhibit.

The fast response of the sensor to changes in the heating coil temperature allowed the controller to be operated a high gain without loss of stability. The controlling stability is approximately 0.05° C. Temperature settings could be resolved to within 0.2° C. A Kepco MP-10 programmer is used to scan the temperature set-point and greatly aids in locating a required phase-matching temperature.
Temperature readout is obtained with a combination of micro-miniature chromel-constantan thermocouple, a thermocouple reference junction, and a microvoltmeter. The temperature at the center of the oven is slightly different from that at the thermocouple location. This difference is proportional to the absolute temperature and is taken into account in calibrating the thermocouple. Thermocouple calibration is good to within ±1° C. Since no two crystals are exactly alike in their temperature characteristics, high-accuracy absolute calibration is not essential. The ability to arrive repeatedly at a desired temperature for a given crystal was limited only by the reliability of the reference junction. The ±1° C accuracy was found to be sufficient for this task.

Thermocouple voltage measurements are made with a General Radio type 1807 D.C. microvoltmeter. This instrument has a high accuracy within a range of 0 to 16 millivolts and, therefore, is ideal for thermocouple monitoring. Measurements within this range are easily made to within ±5 microvolts. For the chromel-constantan thermocouple, this corresponds to 0.07° C. This instrument also has a recording output current for use with an X-Y recorder.

3.3 NONLINEAR CRYSTAL TEMPERATURE-TUNING CURVES

Preliminary observations of optical parametric noise emission indicated the possibility of precisely establishing the range of phase-matched signal and idler wavelengths as a function of temperature (tuning curves) for individual crystals. These tuning curves are essential as an aid to parametric oscillator design for the following
reasons. The high-reflection, dielectric coatings used to construct low-loss optical resonators are narrow band (= 30 nm in the visible). The central wavelength of the high-reflection band must be known in advance to specify the mirror fabrication wavelengths. Since tuning curves vary from crystal to crystal, advance knowledge of the proper phase-matching temperature is crucial when working in the laboratory to obtain parametric oscillation.

One of the primary reasons for using OPN to obtain crystal phase-matching characteristics is that no low-loss optical cavity is required. The signal and idler wavelengths can be measured without providing for parametric oscillation. Thus, data can be obtained for any range of crystal temperatures compatible with oven design and for which the emission wavelengths can be detected. The data reported in this study cover visible and near infrared wavelengths. These are the first reported observations of OPN in the infrared [42]. The temperature-tuning curves are completed by curve fitting the OPN data with the temperature-tuning equations (2-35, 36) by varying $T_o$ and $n$ for a best least squares fit. A complete account of the properties of OPN and the techniques of observation used in this study are given in Appendix A.

Temperature-tuning characteristics for three types of crystals are shown for comparison in Fig. 3-5. The lines drawn through the data points are only for purposes of illustration. In part (a), the tuning data for BSN were taken from room temperature (20° C) to 240° C. There is no restriction on the lower limit, and if cooling facilities were available, the 488.0 nm pump data could have been extended. The
FIG. 3-5  EXPERIMENTAL TEMPERATURE-TUNING CURVES FOR THREE TYPES OF CRYSTALS.

(a) BSN (Cry. No. 6)

(b) LN (Cry. No. 3)

(c) LN (Cry. No. 1)
signal wavelength tuning range, using a 514.5 nm pump, is from 700.0 nm to 1030.0 nm. Using a 488.0 nm pump, the range is 630.0 nm to 770.0 nm. Part (b) gives the results for stochiometric LN. This is the most common form of LN. LN is available in an off-stochiometric form whose phase-matching temperatures are as much as 100° C higher. The off-stochiometric LN is grown from a melt containing excess lithia [32]. The purpose of this technique is to increase the phase-matching temperature, thus allowing the crystal to be used above 170° C where no damage occurs. The upper temperature limit for the data of Fig. 3-5 was imposed by the design of the crystal oven. Phase-matching at temperatures more than 300° C above \( T_o \) is not practical for visible pump wavelengths because the tuning curve flattens out so that signal wavelengths change very little for a given change in temperature. The signal wavelength tuning range for stochiometric LN using a 514.5 nm pump was from 660.0 nm to 710.0 nm. When using a 488.0 nm pump, the signal wavelength tuning range was 600.0 nm to 630.0 nm. The tuning range for off-stochiometric LN in part (c) was from 720.0 nm to 830.0 nm for a 514.5 nm pump. For a 488.0 nm pump, the tuning range was from 640.0 nm to 690.0 nm.

The experimental tuning data for six crystals have been plotted and curve-fitted by equations (2-35) and (2-36). The results are shown for a 514.5 nm pump in Figs. 3-6 to 3-11. The results for a 488.0 nm pump are shown in Figs. 3-12 to 3-16. Temperature-tuning data were taken for crystals numbered 1, 2, 3, 5, 6, 11, and 12. The tuning characteristics are summarized in Table 3-2. Further data on crystals 11 and 12 are given in Sec. 4.0.

Changes in crystal composition and quality cause each crystal
TEMPERATURE TUNING IN LINBO3

PUMP WAVELENGTH 5145
SHG PM TEMP 103.00
ETA (×10^6) 5.88
CRYSTAL NUMBER 1

FIG. 3-6
TEMPERATURE TUNING IN LNB03

PUMP WAVELENGTH 5145
SHG PM TEMP -40.00
ETA (10^14) 5.90
CRYSTAL NUMBER 3

FIG. 3-7
TEMPERATURE TUNING IN BA2NANBO515  

PUMP WAVELENGTH 5145  
SHG PM TEMP 20.00  
ETA (=10^4) 5.80  
CRYSTAL NUMBER 2

FIG. 3-8
TEMPERATURE TUNING IN BA2NANB5015

PUMP WAVELENGTH 5145
SHG PM TEMP 18.00
E intercept (x10^4) 5.90
CRYSTAL NUMBER 5

FIG. 3-9
TEMPERATURE TUNING IN BA2NANB5015

PUMP WAVELENGTH 5145
SHG PM TEMP 50.00
ETA [x10^6] 6.10
CRYSTAL NUMBER 6

FIG. 3-10
TEMPERATURE TUNING IN BA2NANB5015

PUMP WAVELENGTH 5145
SHG PM TEMP 41.00
ETA (×10^14) 5.80
CRYSTAL NUMBER 11

FIG. 3-11
TEMPERATURE TUNING IN LINBO3

PUMP WAVELENGTH  4880
SHG PM TEMP    -15.00
ETA (\times 10^4)  5.90
CRYSTAL NUMBER  1

FIG. 3-12
TEMPERATURE TUNING IN LINBO$_{3}$

PUMP WAVELENGTH  4880
SHG PM TEMP       -150.00
ETA ($\times 10^{16}$)  5.80

CRYSTAL NUMBER  3

FIG. 3-13
TEMPERATURE TUNING IN BA$_2$NANB$_5$0$_15$

PUMP WAVELENGTH  4880
SHG PM TEMP       -75.00
ETA (\times 10^{14}) 5.90
CRYSTAL NUMBER  2

FIG. 3-14
TEMPERATURE TUNING IN BA2NANB5015

PUMP WAVELENGTH 4880
SHG PM TEMP -45.00
ETA (x10^6) 6.10
CRYSTAL NUMBER 6

FIG. 3-15
TEMPERATURE TUNING IN BA2NANB5015

PUMP WAVELENGTH 4880
SHG PM TEMP -65.00
ETA (x10^6) 6.10
CRYSTAL NUMBER 12

FIG. 3-16
<table>
<thead>
<tr>
<th>Crystal No.</th>
<th>Figure</th>
<th>Pump (nm)</th>
<th>T₀ (°C)</th>
<th>$\eta_{10^{13}}$ esu</th>
<th>Signal Range (nm)</th>
<th>Idler Range (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3-6</td>
<td>514.5</td>
<td>103±3</td>
<td>6.0</td>
<td>717-825</td>
<td>1370-1820</td>
</tr>
<tr>
<td>3</td>
<td>3-7</td>
<td>514.5</td>
<td>-40±10</td>
<td>5.9</td>
<td>656-708</td>
<td>1890-2380</td>
</tr>
<tr>
<td>2</td>
<td>3-8</td>
<td>514.5</td>
<td>20±2</td>
<td>5.9</td>
<td>689-915</td>
<td>1180-2030</td>
</tr>
<tr>
<td>5</td>
<td>3-9</td>
<td>514.5</td>
<td>18±1</td>
<td>5.9</td>
<td>696-986</td>
<td>1090-1970</td>
</tr>
<tr>
<td>6</td>
<td>3-10</td>
<td>514.5</td>
<td>50±0.5</td>
<td>6.1</td>
<td>710-1029</td>
<td>1029-1860</td>
</tr>
<tr>
<td>11</td>
<td>3-11</td>
<td>514.5</td>
<td>41±1</td>
<td>5.8</td>
<td>722-1029</td>
<td>1029-1790</td>
</tr>
<tr>
<td>1</td>
<td>3-12</td>
<td>488.0</td>
<td>-15±5</td>
<td>5.9</td>
<td>643-695</td>
<td>1640-2020</td>
</tr>
<tr>
<td>3</td>
<td>3-13</td>
<td>488.0</td>
<td>-150±20</td>
<td>5.9</td>
<td>603-633</td>
<td>2110-2560</td>
</tr>
<tr>
<td>2</td>
<td>3-14</td>
<td>488.0</td>
<td>-75±10</td>
<td>5.9</td>
<td>620-737</td>
<td>1420-2220</td>
</tr>
<tr>
<td>6</td>
<td>3-15</td>
<td>488.0</td>
<td>-45±3</td>
<td>6.1</td>
<td>638-704</td>
<td>1340-2090</td>
</tr>
<tr>
<td>12</td>
<td>3-16</td>
<td>488.0</td>
<td>-65±5</td>
<td>6.1</td>
<td>636-750</td>
<td>1390-2090</td>
</tr>
</tbody>
</table>

**TABLE 3-2**

**SUMMARY OF TEMPERATURE TUNING CHARACTERISTICS**
to have slightly different phase-matching characteristics. The sub-harmonic phase-matching temperature, \( T_0 \), varied from 18 to 50° C among the BSN crystals. Until such time as the composition and quality of crystals can be precisely controlled, it will be necessary to determine experimentally the phase-matching characteristics. The values obtained for the temperature-tuning constant, \( n \), were much more consistent. \( \eta \) was found to be \( 5.9 \pm 0.2 \times 10^{13} \) esu for both LN and BSN. Giordmaine and Miller [5] gave a value of \( 5.4 \times 10^{13} \) esu for \( n \) in LN. The value found in this investigation is probably more reliable because it was determined directly from wavelength tuning data and was nearly the same for all the crystals.

There is some error in assuming that \( n \) is a constant. The temperature-tuning curves fit the data very well, but deviations occur over large temperature ranges. An attempt was made to predict the value of \( n \) as a function of temperature from index-of-refraction data (see Sec. C9-2). In LN, it varied from \( 5.7 \times 10^{13} \) esu at 95° C to \( 7.1 \times 10^{13} \) esu at 290° C. The values at higher temperatures were too large to fit the experimental data correctly. The temperature dependence of the indices of refraction in BSN is not well known. An estimate of \( n \) was calculated based on the rate of change of birefringence as a function of temperature given in (C30). It was much too large to be acceptable (\( 1.02 \times 10^{14} \) esu).

The temperature-tuning data reported in this section were combined with information on available high-reflection dielectric coatings to design the optics for the CW optical parametric oscillators. The details of the OPO design and operation are given in Sec. 4.0.
3.4 OPTICAL CAVITY DESIGN

3.4-1 Resonator Configuration

The optical resonator design for the CW parametric oscillators is shown in Fig. 3-17. The pump field is incident on the mirror \( M_1 \), which is coated directly on the nonlinear crystal. \( M_1 \) is highly reflective at the signal and idler wavelengths and highly transmittant at the pump wavelength. A separate substrate is not used for mirror \( M_1 \) for the purpose of minimizing the optical resonator losses and simplifying alignment procedures. If \( M_1 \) had been on a separate substrate, then the signal and idler would have to pass through antireflection coatings on each side of the crystal. With the present configuration, the only losses for the signal and idler fields are due to the antireflection coating on the far side of the crystal and scattering in the crystal and intra-cavity airspace. The antireflection coating kept the losses at the crystal-to-air interface down to 0.2%.

The second mirror, \( M_2 \), is coated on a separate substrate. Mirror \( M_2 \) is spherical with radius \( R \). The use of a separate substrate for \( M_2 \) (rather than coating it on the crystal) provides for proper alignment of the optical cavity and optimization of the cavity spacing, \( d \). Mirrors \( M_1 \) and \( M_2 \) form a hemispherical cavity equivalent to two spherical mirrors of radius \( R \) separated by a distance \( 2d \). Let \( d_e \) represent the spacing of an optically equivalent resonator formed when the crystal of length \( L \) and index of refraction \( n \) is not present. This means that the optical field configuration in air of a resonator as shown in Fig. 3-17 could be exactly duplicated in a cavity with spacing
FIG. 3-17. CW OPO RESONATOR DESIGN
\( d_e \) between \( M_1 \) and \( M_2 \) with no crystal present. The relationship between \( d \) and \( d_e \) is [18, 43]

\[
d_e = d + L \left( \frac{1}{n} - 1 \right).
\] (3-2)

Since \( n \) is greater than one, the real spacing will always be greater than the equivalent spacing. The optical cavity has stable resonances in the range \( R/2 \leq d_e \leq R \). At the lower limit, the cavity is confocal, and at the upper limit, it is concentric. During parametric oscillation, the spacing must be chosen so that \( d_e \) is just slightly less than \( R \) to minimize the signal and idler beam waists.

3.4-2 Design Procedure - Beam Waist, Confocal Parameter, Cavity Spacing.

The relationship between the interacting fields of a parametric oscillator and the geometry of the oscillator cavity can be best expressed in terms of the confocal parameter. The confocal parameter, \( b \), of a Gaussian beam is defined as:

\[
b = w_o^2 k = \frac{2 w_o^2}{\lambda}
\] (3-3)

where \( w_o \) is the minimum beam waist and \( k \) is the field propagation constant. From confocal resonator theory [18, 22, 23], the confocal parameter for the hemispherical resonator configuration of Fig. 3-17 is:

\[
b = 2 \sqrt{d_e (R - d_e)}.
\] (3-4)
The parametric interaction of the pump, signal, and idler beams is optimized when their beam waists are related by [6]:

\[ \frac{1}{w_p^2} = \frac{1}{w_s^2} + \frac{1}{w_i^2}. \quad (3-5) \]

Using (1-4) and (3-3), the above relationship implies that the confocal parameters of all three beams are equal \((b_p = b_s = b_i \equiv b)\).

Boyd and Kleinman have shown that the OPO power threshold is minimized when the proper ratio of crystal length to confocal parameter is available \([11]\). The optimum value of \(L/b\) is 2.84. The curve for OPO threshold as a function of \(L/b\) is relatively flat near \(L/b = 2.8\), and it can be concluded that the limits \(0.5 < L/b < 10\) are safe OPO design guidelines. The quantity \(L/b\) (focusing parameter) is defined for the beam inside the crystal. If the crystal were removed from the optical cavity, the confocal parameter in air would be \(b_a = b/n\). Let \(g\) represent the focusing parameter \((g \equiv L/b)\). \(g\) can now be expressed in terms of the effective resonator spacing as:

\[ g = \frac{L}{2n\sqrt{d_e(R - d_e)}}. \quad (3-6) \]

It is now possible to select values of \(R\) and \(d_e\), which will produce reasonable values of \(g\). If the crystal length is \(L = 0.5\) cm and \(g\) is chosen as 2.8, then \(b = 0.18\) cm and \(b_a = 0.08\) cm \((n \approx 2.26)\). This means that \(d_e(R - d_e)\) must be equal to \(1.6 \times 10^{-3}\) cm\(^2\). Theoretically, \(d_e\) could be adjusted until \((R - d_e)\) is arbitrarily small. Experimentally,
this is not possible. \((R - d_e)\) must be large enough so that the spacing \(d_e\) can be set by manual adjustments. Also, the smaller the required value of \((R - d_e)\) the more likely that fluctuations in the resonator length will influence the optical resonator stability.

The resonator is unstable when \(d_e > R\). If \((R - d_e)\) could be as small as \(5 \times 10^{-4}\), then \(d_e\) would be 3.1 cm. This figure is reasonable since the crystal must be housed in an oven, and thus the crystal and spherical mirror must be separated by several centimeters. For compactness, the smallest practical value of \(d_e\) was taken to be 2.5 cm. Thus, the resonator was designed with \(R = 2.5\) cm. This meant that \(d_e\) had to be adjusted so that \((R - d_e)\) was approximately \(6 \times 10^{-4}\) cm. Fortunately, the DRO will operate over a range of values of \(g\), and \((R - d_e)\) did not have to be quite this small.

As an aid to experimentation, it is necessary to know the spacing \(d\) required to produce a prescribed value of \(g\). This can be found by solving (3-6) for \(d_e\) and using (3-2) to find \(d\). The result is:

\[
d = \frac{R + \sqrt{R^2 - \left(\frac{L}{qn}\right)^2}}{2} + L(1 - \frac{1}{n}). \tag{3-7}
\]

For \(g = 2.8\), \(L = 0.5\), \(n = 2.26\), and \(R = 2.5\) cm, the actual resonator spacing for minimum DRO threshold is \(d = 2.78\) cm.

The dependence of \(L/b\) on the resonator separation, \(d\), is plotted in Fig. 3-18. The curve is taken from equations (3-2) and (3-6). The slope of the curve indicates that very careful adjustments in \(d\) must be made to obtain a specific value of \(g\) for \(g > 0.5\). Fortunately, the
L = 0.4917 cm
R = 2.50 cm
n = 2.2405

FIG. 3-18 Focusing Parameter as a Function of Separation.
OPO threshold is a rather smooth function of $g$ so that oscillations can be obtained over a range of values for $d$ of $2.63 \pm 0.15$ cm (see Sec. 4.2).

3.4-3 Mode-Matching

In Sec. 3.4-2, it was shown that the parametric interaction is optimized when the confocal parameters of all three interacting beams are equal. The confocal parameters of the signal and idler beams are determined by the OPO optical cavity when adjusted to give the proper value of $g$. The confocal parameter of the pump beam is determined by the laser optics and is usually considerably larger than the OPO cavity confocal parameter. For a laser with a 5 meter radius of curvature output mirror and 1.15 meter cavity spacing, the confocal parameter is 421 cm. Thus, the pump beam must be transformed into a beam with a much smaller confocal parameter, or equivalently, its beam waist must be reduced to a value that will satisfy (3-5). Thus, the problem is to transform the incoming Gaussian beam into one with a new set of beam characteristics, which can be injected into the OPO optical structure. The transformation of a Gaussian mode from one resonator to another resonator is referred to as mode-matching. The process is shown schematically in Fig. C1 of Appendix C.

Mode-matching can be done using a single lens [44]. Let $b_p$ represent the confocal parameter of the pump beam as it originates in the laser and $b$ represent the confocal parameter of the OPO resonator. The beam of confocal parameter, $b_p$, can be transformed into a beam of confocal parameter, $b$, with any lens whose focal length, $f$, exceeds a
minimum, \( f_o \), given by [18, 44]:

\[
f_o = \frac{1}{2} \sqrt{\frac{b_p b}{f}}
\]

(3-8)

The lens of focal length, \( f \), will mode-match the two optical cavities when the distances between the lens and cavities are set to the proper values. The distance from the minimum beam waist of the incident beam to the lens is given by:

\[
d_p = f + \frac{1}{2} b_p \sqrt{\left(\frac{f}{f_o}\right)^2 - 1}
\]

(3-9)

The distance from the lens to the minimum beam waist of the transformed beam is given by:

\[
d_o = f + \frac{1}{2} b \sqrt{\left(\frac{f}{f_o}\right)^2 - 1}
\]

(3-10)

The distance from that point in the laser where the minimum beam waist occurs (usually the rear resonator component) to the lens must be set at \( d_p \). It has been demonstrated that this setting is not critical and can vary considerably without affecting the mode-match [18]. The distance from the lens to the point where minimum beam waist occurs (at mirror \( M_1 \)) in the OPO resonator must be set to \( d_o \).

The lens used in this study was a simple double-convex lens with a 10 cm focal length. It was antireflection coated at the pump wavelength to keep pump losses to less than 0.4%. The laser confocal parameter was \( b_p = 421 \) cm. This yields \( f_o = 2.88 \) cm. Thus the 10 cm
lens is acceptable. The value for \( d_p \) is 714 cm, and the value for \( d_o \) is 10.13 cm. The setting of the actual laser to lens distance was not critical. The actual distance can vary from \( d_p \) by a large amount without significantly affecting the mode-match. The setting of \( d_o \), however, was critical and could not vary by more than \( \pm 0.1 \) cm. The focus of the lens is at 10.0 cm and, when the spacings are properly adjusted for mode matching, the focus lies 1.3 mm outside the crystal in front of mirror \( M_1 \). This, in fact, was a fortuitous occurrence since it was found that when mirror \( M_1 \) was placed exactly 10.0 cm from the lens, the focused pump beam had sufficient power density to damage the dielectric coatings. As long as the lens focus was at least 1 mm away from the mirror, the coatings were not damaged.

3.4-4 Optical Coatings

The mirrors used to form the OPO optical cavity are dielectric coated for very high reflectivity (99.9%) at the signal and idler wavelengths. This minimizes the losses so that the lowest pump-power threshold can be obtained. The losses must also be kept minimal by anti-reflection coating the surface of the nonlinear crystal inside the optical cavity. These maximum and minimum reflection coatings may require a large number of dielectric layers, whose reflection characteristics are good only for a limited range of wavelengths. At visible wavelengths, the reflectives may be good over a range of about 30 nm. At longer wavelengths, this range may be considerably greater. High-reflection coatings centered at 1000 nm have a width of about 200 nm. The narrow band nature of the dielectric coatings makes it necessary
to predict signal and idler wavelengths in advance so the coatings can be manufactured for the correct wavelengths. The narrow band coatings presently constitute the fundamental limitation for the range of wavelengths over which a parametric oscillator can be tuned.

In general, it is not possible to manufacture high-reflectivity coatings at both the signal and idler wavelengths. There are two special exceptions to this. The first is when the signal and idler have the same wavelength (degeneracy), and the second is when the idler wavelength is three times the signal wavelength.

An example of the first type is shown in Fig. 3-19. The transmission versus wavelength of a high-reflection coating is shown in Fig. 3-19(a). It is designed to be highly reflective near the subharmonic of either a 514.5 nm or 532.0 nm pump. It has a useful range covering approximately 200 nm. As soon as either the signal or idler wavelength moves out of this range, the resonator losses become very large. The corresponding antireflection coating characteristics are shown in Fig. 3-19(b).

An example of the second type is shown in Fig. 3-20. This coating was designed to be highly reflective for $\lambda_i = 3\lambda_s$ with $\lambda_p = 488$ nm. From (1-1) we obtain:

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}$$

This reduces to $\lambda_s = 4/3\lambda_p$. Thus, $\lambda_s = 650$ nm and $\lambda_i = 1950$ nm. Coatings of this type are possible since a quarter-wave coating at the idler wavelength acts as a three-quarter-wave coating at the signal
FIG. 3-19 Transmission of Optical Coating Versus Wavelength for High Reflection at 1060 nm and Reflection Versus Wavelength for Anti-reflection at 1060 nm.
FIG. 3-20 Transmission of Optical Coating Versus Wavelength for High Reflection at 650 nm and 1950 nm.
wavelength. The transmission characteristics for the visible are shown in the upper part of Fig. 3-20, and for the infrared are shown in the lower part. Notice the decrease in transmission near 500.0 nm. If this lobe happens to occur at or very near to the pump wavelength, it can cause intolerably high pump reflections from mirror $M_4$. It was necessary to specify a central wavelength slightly higher than 650 nm to shift the lobe sufficiently for better pump transmission.

It is obvious from Fig. 3-20 that if a parametric oscillator required only the idler beam to be resonant, much greater tuning ranges could be obtained. The SRO threshold is, however so much higher than the DRO threshold that these oscillators have not been successful using CW pump lasers.

3.5 OPTICAL ISOLATOR DESIGN

An optical isolator was constructed for the purpose of eliminating reflections from the OPO that disturb the single longitudinal mode operation of the argon-ion laser. Fig. 3-21(a) shows the normal spectrum of single mode operation; Fig. 3-21(b) shows the disturbing effects which reflections back into the laser have on the spectrum, and Fig. 3-21(c) illustrates the restoration of normal operation when the isolator is used. It will be seen in Sec. 4.2-2 that optical isolation of the OPO from the laser has a significant effect on the time dependence of the OPO output.

Fig. 3-22 is a schematic of the optical isolation technique. The incoming pump beam traverses a polarizer whose axis is set parallel to its direction of polarization. The beam traverses 25 cm of SF6 glass,
(a) Normal Spectrum (single mode)

(b) Disturbance by Reflections from OPO

(c) Restoration of Mode by Isolation

200 MHz/div

FIG. 3-21 Effectiveness of Isolation On the Pump Spectrum.
FIG. 3-22 OPTICAL ISOLATOR

MAGNETIC FIELD

POLARIZER

SF6 GLASS

Solenoid

 Incident Wave

Reflected Wave

POLARIZER
set at the center of a magnetic solenoid. With approximately a 1200
gauss magnetic field, the Faraday effect will rotate the plane of
polarization 45°. The beam then traverses a second polarizer, whose
axis is parallel to the new direction of polarization. Any reflections
from the OPO that are not polarized parallel to the axis of polarizer
2 are attenuated by polarizer 2. Reflections which make it back
through polarizer 2 are again rotated by 45°, but, since the direction
of propagation is reversed, they arrive at polarizer 1 polarized per-
pendicular to its axis. This results in a high attenuation of reflected
waves. During actual operation with an argon laser, polarizer 1 was
eliminated with almost no degradation of the isolation effect since
the front Brewster window of the laser acted as polarizer 1. With
all surfaces antireflection coated at the pump wavelength, the attenua-
tion of the pump beam in the forward direction is 22%. This is due to
absorption in the SF6 rod.
4.0 CONTINUOUS WAVE OPTICAL PARAMETRIC OSCILLATOR
   EXPERIMENTAL STUDY

4.1 GENERAL METHOD

Successful initial operation and continued reliable operation of CW parametric oscillators require the utmost care in preparation and use of individual experimental components. A schematic of the various components required for a CW OPO is shown in Fig. 4-1. The use of correct, consistent, and, where possible, simple sequence of procedures to align optical elements and to maintain the prescribed mode of operation of each element is essential. The most important procedures are discussed here.

4.1-1 Operation of the Argon Laser

An argon laser used to pump a parametric oscillator should be thermally compensated, mechanically stable, and feedback-amplitude stabilized, and should possess a temperature-controlled etalon. Of the two lasers used during the course of this study, laser A possessed none of these features, and laser B possessed all of them. Laser A was subject to thermal and mechanical fluctuations in the alignment and spacing of the optical cavity. As a result, there were frequency instabilities due to longitudinal mode-hopping and severe long-term drift of the output power due to thermal transients. As will be shown in Sec. 4.2, laser mode-hopping causes a parametric oscillator to turn on and off, thus giving its output the appearance of a train of pulses. If the pump laser output power drifts, retuning of its optical cavity is
FIG. 4-1 INFRARED OPTICAL PARAMETRIC OSCILLATOR
required. This realignment causes sufficient change in the direction of the laser output to be disastrous to the alignment of the parametric oscillator. The OPO alignment procedure may have to be repeated.

Laser B is prepared for use by allowing it to warm up for a sufficient period of time ($\sim 45$ min) that maximum rated power can be obtained when the cavity is aligned and the amplitude stabilization system can be initiated without overdriving the plasma tube current. The laser is amplitude stabilized by feedback regulating the plasma tube current. At this point, the mechanical stability and thermal compensation are sufficient to prevent the laser from mode-hopping for fairly long periods of time ($\sim 30$ min). Proper single-mode operation is obtained by aligning the etalon precisely with the laser optical axis. This is done by observing the secondary reflections off the Brewster windows due to the etalon surfaces.

Precise alignment of the etalon with the laser axis results in several longitudinal modes competing for oscillation. This condition is observed on the spectrum analyzer and is accompanied by an abrupt increase in output power. The etalon is then tipped slightly off axis until only one mode is left stably oscillating. Any further movement of the etalon will decrease the output power. The location of the single mode with respect to the laser gain profile is at this point arbitrary. In order to obtain maximum output power, the single-mode frequency must be moved to the center of the gain profile. This is done by changing the etalon temperature to vary the etalon length. As the etalon length changes, the frequency of the selected mode will change. When the mode falls at the center of the laser gain profile,
maximum output power is available.

4.1-2 Optical Isolator Operation

The optical isolator will not provide proper isolation and will induce unnecessary attenuation of the pump beam unless the magnet current and polarizer directions are properly set. These settings are obtained by placing a power meter just after the isolator to monitor the isolator transmission. With the magnet current off, both polarizers are aligned for maximum transmission of the laser beam.

The first polarizer, #1 in Fig. 3-22, is locked in that position, and the second is rotated until the transmitted power is cut in half. The polarizer has then been rotated 45°. The magnet current is then increased until maximum transmission is restored. If the transmission does not increase as the magnet current is increased, then the current polarity should be reversed. Maximum transmission of the isolator occurs when the magnetic field is sufficient to produce a 45° rotation in the direction of pump polarization. For convenience, the pump polarization is restored to its original direction using a polarization rotator.

4.1-3 Optical Alignment of the OPO Components

Two 45° angle mirrors (see Fig. 4-1) are used to adjust the lateral location and direction of the laser beam. A pair of apertures provide a standard for the location and direction of the pump beam to assure that it is the same each time the OPO is set up. The components are aligned using the pump beam at low power as an optical axis.
The OPO components are introduced into the pump beam and aligned in the following order. The spherical OPO mirror is set in the beam so that the beam passes through its center. The angle of the mirror is adjusted so that reflections from the mirror are centered on the optical axis. This is done by observing the concentric interference fringes that appear on the back surface of an adjustable aperture. The aperture is opened just enough to pass the pump beam and placed about 30 cm in front of the mirror. The angle of the mirror is adjusted until the center of the interference rings falls at the center of the aperture. This serves as a preliminary alignment, and the spherical mirror is temporarily removed from the beam.

The crystal and crystal oven are brought up to phase-matching temperature and placed in the beam with the mirror coated surface of the crystal leading. The crystal is centered on the beam axis with the crystal optic axis (c axis) approximately aligned with the direction of pump polarization. The analyzer is placed in the beam about 30 cm behind the crystal and rotated for maximum extinction of the pump beam. Fine adjustments in the direction of the crystal optic axis (rotation about the pump beam axis) produce even better extinction of the pump beam. When the pump-beam extinction is at its best, this assures that the crystal optic axis is aligned with the pump-beam polarization so that it will propagate as an extraordinary ray. This procedure is essential to secure maximum parametric gain in the crystal.

The angular orientation of the crystal is adjusted so that reflections from the mirror, \( M_1 \), are directed precisely back into the
laser beam. This assures that the angle between the optic axis and the direction of pump propagation, θ, is 90° and that the first OPO cavity mirror is aligned.

The mode-matching lens is placed in front of the crystal. The lens must be aligned laterally so that the pump beam lies precisely at its center. If the pump beam does not pass through the center of the lens, the beam is deflected, thus, changing the angle of incidence of the beam to the OPO cavity. This alignment is made by observing back reflections from the lens and altering the lateral lens position until the reflection passes through an aperture whose center is coincident with the pump beam. The distance of the lens from the crystal front surface is set to meet the mode-matching conditions. In this case, the distance is set to 10.13 cm. A collimating lens of the same focal length as the mode-matching lens is placed in front of the analyzer approximately 10 cm behind the front crystal surface.

The spherical mirror is returned to the beam axis and set in place so that it is at the required spacing from the crystal mirrored surface. This spacing is 2.78 cm. Note that the optimum spacing for parametric oscillation is at the edge of the OPO optical cavity stability (R - d is small). Since there is some error in setting the spacing, it is better for the spacing to be slightly less than the required value. If oscillation does not occur when the spherical mirror is aligned, the spacing is adjusted from a too close position in small increments outward.

The final step for obtaining oscillation is to align precisely
the spherical mirror. It was previously set so that the alignment is nearly on axis. Fine adjustments are now made until an interference pattern is observed on either of the 45° angle mirrors. This interference pattern consists of concentric light and dark rings and is a result of interference by reflections of the pump beam from the two parametric oscillator mirrors. This particular interference pattern is easily identifiable since its position is very sensitive to the slightest vibration or movement of the spherical mirror.

When the angle of the spherical mirror is adjusted so that the center of this interference pattern coincides with the location of the pump beam, parametric oscillation takes place. The onset of parametric oscillation can be observed by placing a laser power meter behind the analyzer. If parametric oscillation does not occur it may be necessary to recheck alignments and spacings and to scan over these until oscillation occurs. The lateral adjustment of the mode-matching lens is just as critical as the angular alignment of the spherical mirror. If the lens is not precisely on axis, the optical axis of the OPO cavity will not coincide with the axis of the pump beam even when the spherical mirror is properly aligned. In this case, oscillation may not occur, or it may be intermittent and low power. When this condition is present, the interference pattern observed on the 45° angle mirrors will not be spherical. It may be elliptical or may appear to consist of straight light and dark bars. Correct alignment of the lateral lens position and spherical mirror angle is obtained by making small adjustments in each and observing their effect on the interference pattern.
A trade-off occurs between the two adjustments. A slight change in one displaces the position of the interference pattern. The position can be restored by compensating with the other adjustment. This trade-off is worked until the interference pattern becomes spherical and is centered on the pump beam. At this point, the OPO cavity axis coincides with the pump-beam axis, and the most stable highest OPO output power is obtained. Once parametric oscillation is obtained the output power of the parametric oscillator can be used as an indication of proper alignment and spacing. In Sec. 4.2-1D, the lens and mirror spacings for best OPO operation are compared to their predicted values.

4.2 DEGENERATE CW OPTICAL PARAMETRIC OSCILLATOR USING A 514.5 nm PUMP

4.2-1 Basic Operational Characteristics

4.2-1A Phase-Matching Temperature

BSN crystal no. 11 is used as the nonlinear crystal for the degenerate parametric oscillator. Its physical characteristics are given in Table B1 and in the second-harmonic phase-matching curve in Fig. B5 (Appendix B). It has optical coatings whose characteristics are shown in Fig. 3-19. Its phase-matching characteristics for a 514.5 nm pump are shown in Fig. 3-11.

OPN observations established that the maximum parametric gain at 1029 nm occurs at a temperature of 41° C. Parametric oscillation should be obtained with the crystal at this temperature or within a few degrees above. Experimentally, parametric oscillation did occur
at 41° C and continued until the crystal reached 49.5° C. At this point, the signal and idler wavelengths moved beyond the low-loss regions of the optical coatings, and oscillation ceased.

4.2-1B Threshold

The parametric oscillator was carefully tuned to obtain maximum output power. Then the pump laser power was reduced until oscillation ceased. The pump power at this point was 184 mW. Since the transmission of the mirror coated on the crystal at 514.5 nm is approximately 0.75, the OPO power threshold is 138 mW. The threshold predicted using equation (2-28) is 67 mW, based on 3% signal and idler losses per pass. Considering that the experimental threshold can vary considerably depending on precise optical alignment of the oscillator cavity, and that the predicted value depends on a rough estimate of the scattering losses at the signal and idler wavelengths, the agreement between the two figures is reasonable. Also, the 67 mW is computed assuming $\Delta k = 0$. As shown in Sec. 4.2-3, it is difficult to obtain DRO operation with $\Delta k = 0$.

4.2-1C Output Power and Conversion Efficiency

The maximum output power obtained from the parametric oscillator was 10 mW. This occurred with an external pump power of 580 mW. The internal pump power is approximately 435 mW. In Sec. 2.6-1, the output power was estimated to be 9 mW. This figure is based on $u = 4.0$, $\epsilon = .03$, and $T_2 = 0.4\%$. The experimental values for the OPO based on $P_{th} = 138$ mW and $P_{P}^i = 435$ mW are: $u = 3.15$ and $\epsilon = .043$. The measured
value of $T_2$ is 0.5%. The value for $\epsilon$ was obtained using (2-28) for
$P_{th} = 138$ mW. With these values, equation (2-44) gives a value of 12
mW for the output power. The agreement between the value given by
(2-44) and experimental output power appears to be quite satisfactory.

The conversion efficiency can be computed by assuming that both
OPO mirrors transmit an equal amount of power, i.e., 10 mW emerge from
both sides of the OPO cavity. Taking $P' = 435$ mW, the external conver-
sion efficiency of the OPO is 4.6%. This figure compares favorably to
previous reports of 1% for a similar OPO [7]. The conversion efficiency
is less than the maximum theoretical value of 15% predicted in Sec.
2.6-1. This is to be expected, however, since the OPO was designed
for minimum threshold rather than maximum conversion efficiency.
Better conversion efficiency could have been obtained using an output
mirror with a higher transmission so that $r$, $(T/L)$, could be near 0.5.
The actual value of $r$ for this OPO is approximately 0.13.

4.2-1D Optical Cavity Separation and Mode-Matching Lens Position

Although experimental conditions made it difficult to obtain
accurate measurements of the OPO cavity spacing, oscillation occurred
for spacings from 2.3 to 2.7 cm. The spacing for optimum $L/b$ given
in Sec. 3.4-2 is 2.78 cm. Thus, oscillation was more favorable for
values of $L/b$ less than 2.8. This trend was most likely due to the
fact that the optical resonator stability is better for smaller spac-
ings, and at the same time, a smaller value of $L/b$ does not represent
a significant sacrifice in threshold. Fortunately, oscillation was
possible over a spacing range of ±0.2 cm. This made it unnecessary to
set precisely the cavity spacing when attempting to obtain oscillation.

In Sec. 3.4-3, the distance from the mode-matching lens to mirror \( M_1 \) of the parametric oscillator was calculated to be 10.13 cm. The actual distance for which oscillation could be obtained was from 10.10 to 10.35 cm. Again, there was a sufficient range available that the distance could be set by simple measurement and optimized once oscillation was obtained.

4.2-2 Output Characteristics

4.2-2A Transverse Modes

Oscillation usually occurred in the \( \text{TEM}_{00} \) mode. Because of the mode-matching constraints and smaller beam waist, this mode has the highest parametric gain. The signal and idler beam waists most nearly satisfy (3-5) when oscillating in the \( \text{TEM}_{00} \) mode. When the parametric oscillator cavity is aligned for maximum OPO output power, the \( \text{TEM}_{00} \) mode was always in oscillation. Slight misalignment of the OPO cavity produced operation in the \( \text{TEM}_{01} \) mode. Oscillation in this mode usually occurred for only a few moments with oscillation reverting back to the \( \text{TEM}_{00} \). On one occasion, a higher order mode was observed, most likely the \( \text{TEM}_{22} \). Oscillation in this mode, however, could not usually be obtained.

4.2-2B DRO Amplitude Stability

The output characteristics of a DRO as a function of time will vary considerably depending on the amplitude and frequency stability
of the pump laser. Unless the pump power is sufficiently above threshold and the oscillator cavity is carefully aligned, oscillation may only occur intermittently. With sufficient pump power and proper alignment, the DRO output characteristics are primarily determined by the pump-frequency stability.

The data presented in this section were obtained by monitoring the DRO output with an S1 response photomultiplier tube.

The output characteristics of the DRO using an unstabilized laser (laser A) are shown in Fig. 4-2. Each part of the figure is a photograph of the oscilloscope trace of the PMT output. The output of the pump laser is shown in Fig. 4-2(a). Over a period of 10 ms, the amplitude stability is 18% (full width of the variation divided by the average). The frequency stability of the laser when undisturbed by OPO reflections (with isolation) is approximately ±150 MHz. When disturbed by OPO reflections, the stability is considerably worse (∓400 MHz). Without isolation, the OPO output is spiked as shown in Fig. 4-2(b).

The frequency instabilities of the pump are sufficient to induce longitudinal mode changes in the parametric oscillator. The DRO is turning completely off between spikes in response to the frequency shifts of the pump as a result of longitudinal mode-hopping. With isolation, the situation is somewhat improved as shown in Fig. 4-2(c). The pump frequency instabilities are reduced, and the parametric oscillator no longer cuts completely off. Fig. 4-2(c) represents the best performance that could be obtained with laser A. The DRO amplitude
FIG. 4-2 IR OPO Output Power as a Function of Time Using an Unstabilized Pump Laser.
variations are still very large. The parametric oscillator output still drops off in response to the pump longitudinal mode changes.

The parametric oscillator performance using an amplitude and frequency-stabilized laser (laser B) is shown in Fig. 4-3. The pump laser was described in Sec. 3.1-2. The laser amplitude stability is ±0.5%, and the frequency stability is less than ±50 MHz. The pump amplitude stability is shown in Fig. 4-3(a). The improved quality of DRO operation is due primarily to the fact that this laser oscillates in the same longitudinal mode over a very long period of time. Reflections from the DRO back into the laser still produce considerable frequency instability giving rise to the irregular DRO performance shown in Fig. 4-3(b).

With optical isolation, the pump frequency stability was the best that the pump laser could provide without special stabilization schemes (±50 MHz). In Sec. 2.7-2 it was shown that a pump frequency variation of ±31 MHz is required to induce longitudinal mode changes in a DRO. The pump instability is still sufficient to produce DRO longitudinal mode changes, but nevertheless, considerable improvement in DRO stability is observed. DRO operation under these conditions is shown in Fig. 4-3(c). Here the DRO amplitude stability is ±13%. The stabilized laser with isolation produced, by far, the best DRO amplitude stability.

Fig. 4-4 shows the highest amplitude stability that was observed from the parametric oscillator. The experimental conditions are the same as for Fig. 4-3(c). The amplitude stability is ±10%. Some
FIG. 4-3 IR OPO Output Using an Amplitude Stabilized Pump Laser With No Longitudinal Mode Hopping.
FIG. 4-4 Most Stable IR OPO Output as a Function of Time.
suggestions for further improvements in OPO performance are made in Sec. 5.0.

4.2-2C DRO Linewidth

The linewidth of the parametric oscillator depends primarily on the frequency stability of the pump laser. If the laser is rather unstable (>±30 MHz), the frequency fluctuations will enable the parametric oscillator to oscillate over a wide range of longitudinal modes. The linewidth, in this case, is determined by the range of wavelengths over which sufficient parametric gain is available for oscillation. The DRO linewidth thus depends upon how near the oscillator is to degeneracy (see Fig. 4-6). If the laser is more stable (<±30 MHz) even though parametric gain is available over a relatively wide range of wavelengths (∼5 to 20 nm), the range of oscillation is limited since \( \omega_p \) is more nearly constant and (1-1) must be satisfied. In this case the linewidth depends on fluctuations such as the DRO optical cavity mechanical and thermal stability. The linewidth shows no dependence on how near the operation is to degeneracy (see Fig. 4-7).

DRO linewidth data were taken using a Jarrell-Ash model 82-400/410 0.25 m Ebert monochromator with a resolution of 0.1 nm. A potentiometer attached to the monochromator was used to plot wavelengths directly on an X-Y recorder. The monochromator output was monitored with a laser power meter. An example plot of DRO output intensity as a function of wavelength is shown in Fig. 4-5. Since no compensation has been made for detector responsivity, the relative height of the signal and idler peaks does not reflect their relative intensity. In
$T = 42.5 \degree C$, $T_o = 41 \degree C$

Crystal 11, $\lambda_p = 514.5 \text{ nm}$

WAVELENGTH (nm)

IDLER

992.7

SIGNAL

77

63

1068.6

FIG 4-5 IR OPO Spectrum Near Degeneracy
Fig. 4-5 the DRO was pumped by the stable laser using isolation. Thus the linewidths are relatively narrow, 0.8 nm for the signal and 0.6 nm for the idler. It should be noted that since a scan of wavelength versus output intensity requires 15 or so seconds to record, the linewidths represent an average of the output over several seconds. Random fluctuations in parametric oscillator output can cause considerable variation in the apparent DRO spectral width. The accuracy of the linewidth measurements is limited to about ±15%.

The parametric oscillator linewidths for a DRO pumped by the free-running laser (Laser A) are shown in Fig. 4-6. Slightly off degeneracy, the linewidths are approximately 7.0 nm, but near degeneracy, the linewidth broadens up to 25 nm. The linewidth behavior is similar to that shown in Fig. A7 (Appendix A). The pump frequency variations allow the parametric oscillator to find resonances at any point where the parametric gain is sufficient to exceed threshold. Thus, the DRO linewidth is limited by the parametric gain bandwidth.

The DRO linewidths for a parametric oscillator pumped by the more stable laser were also measured over the range of crystal temperatures for which oscillation could be obtained. The linewidths are considerably more narrow, as would be expected, averaging 0.7 nm. The linewidths for both the signal and idler showed considerable random fluctuation as a function of degeneracy from as low as 0.4 nm to 1.8 nm (see Fig. 4-7). The linewidths show no functional dependence on nearness to degeneracy as do those shown in Fig. 4-6. This indicates that the bandwidth of parametric gain no longer determines the DRO linewidth. The linewidth is, using the more stable laser (laser B),
FIG. 4-6 OPO Linewidths as a Function of Crystal Temperature for a Free Running Pump Laser (Laser A) with Isolation.
FIG. 4-7 OPO Linewidth as a Function of Crystal Temperature for a Stable Pump Laser (Laser B) with isolation.
determined by pump frequency variations and mechanical and thermal instabilities in the parametric oscillator resonant structure.

4.2-3 DRO Tuning Characteristics

The infrared parametric oscillator was tunable over a range of crystal temperatures from 41° C to 49.5° C. The lower temperature represents operation very near degeneracy and the higher temperature is the farthest from degeneracy that oscillation could be obtained. The upper limit is imposed by the bandwidth of the optical coatings shown in Fig. 3-19. The signal and idler wavelengths move to regions where the losses are too high to maintain oscillation. The signal wavelength is tunable from 1016 nm to 958 nm. The corresponding idler wavelengths are 1043 nm to 1114 nm. The signal and idler wavelengths as a function of crystal temperature are plotted in Fig. 4-8. For comparison, the wavelengths of OPN emission and tuning theory are also shown in the figure.

The theoretical curve in Fig. 4-8 is the same as that shown in Fig. 3-11. It is based on (2-35) and (2-36) with \( \eta = 5.9 \times 10^{13} \) esu and \( T_0 = 41° \) C. The theoretical curve represents the wavelengths for maximum parametric gain. Most oscillation wavelengths fall near maximum gain but not necessarily on it. In some cases, several sets of signal and idler wavelengths were measured at the same crystal temperature depending on the tuning of the DRO cavity. The oscillator operating point is determined by the double resonance of the optical cavity for which there is maximum gain. Thus, unless the double resonance happens to fall at the correct wavelengths, oscillation will not occur with \( \Delta k = 0 \).
TEMPERATURE TUNING IN BA2NANB5015

PUMP WAVELENGTH 5145
SHG PM TEMP 41.00
ETA [$\times 10^{18}$] 5.80
CRYSTAL NUMBER 11

FIG. 4-8

- OPO Data
- OPN Data
- Theory
As discussed in Sec. 2.6-3, the output of a doubly resonant optical parametric oscillator will not be constant during tuning. The output depends on the location of the double resonances and the value of $\Delta k$ for the resonant wavelengths as the crystal is tuned. DRO output power as a function of crystal temperature is shown in Fig. 4-9. These tuning data were obtained by monitoring the DRO output power while slowly scanning the crystal over the range of temperature for which oscillation occurs. The behavior shown in Fig. 4-9 is very much like that described in Sec. 2.6-3. The sharp rise in power takes place when the crystal temperature is such that a double cavity resonance is available with $\Delta k = 0$.

As the temperature continues to change, $\Delta k$ cannot remain zero because the resonant wavelengths remain the same. The resonant wavelengths do not change until the gain for the adjacent double resonance is sufficient to set it into oscillation. A comparison of Fig. 4-9 to Fig. 2-8 indicates that equations (2-56) and (2-59) provide an excellent description of the DRO output power while tuning. The temperature increments between resonances for which $\Delta k = 0$ shown in Fig. 4-9 vary from 0.26° C to 1.15° C. Equation (2-59) typically predicts 0.9° C depending on how far the oscillator is from degeneracy. Recall that the curve of Fig. 2-8 was plotted with $A$ constant, and, therefore, makes no attempt to describe the variation in output power during tuning that results from changes in resonator losses.

The analysis of Sec. 2.6 and data presented in this section demonstrate the performance of the low-threshold, doubly resonant optical parametric oscillator as a source of tunable monochromatic
FIG. 4-9 EXPERIMENTAL IR OPO OUTPUT POWER AS A FUNCTION OF CRYSTAL TEMPERATURE.
radiation. The tuning range is determined by the bandwidth of the optical coatings used to construct low-loss optical resonators.

The output is characterized by large fluctuations in power during tuning as a result of the discontinuity of double resonances.

4.3 DEGENERATE OPTICAL PARAMETRIC OSCILLATOR USING A Q-SWITCHED SOLID-STATE 532.0 nm PUMP

The frequency-doubled Nd:YAG laser described in Sec. 3.1-3 can be used to pump the same parametric oscillator described in the previous section. The pump wavelength is 532.0 nm, and the wavelength of the signal and idler are near 1064 nm. The phase-matching temperature for this process is the same as for second-harmonic generation, 103° C (Cry. No. 11). The pump laser is acousto-optically Q-switched to obtain high power pulses of second-harmonic radiation which can exceed the parametric oscillator threshold. For an average power of 80 mW, pulse duration of 0.75 μs and repetition rate of 1 KHz, the peak power per pulse is estimated to be 106 W.

The pump and parametric oscillator output pulses are shown in Fig. 4-10. Each part of the figure is a superposition of approximately 20 pulses. As can be seen in Fig. 4-10(b), there is a large spread in the output power of the DRO pulses. This is due in part to the amplitude and frequency instability of the pump and mechanical instability of the DRO cavity. Also, no attempt was made to pump with a single longitudinal mode; thus, competing longitudinal modes of the pump will cause considerable frequency variation from pulse to pulse. The mode-matching condition and resonance condition of the DRO cavity make it
FIG. 4-10 REPEITIVELY Q SWITCHED, FREQUENCY DOUBLED ND:YAG PUMP AND DEGENERATE OPO OUTPUT.
possible for pulses of only certain frequencies to oscillate. Thus, because of the frequency variations of the pump, only a fraction of the pump pulses can be expected to produce oscillation.

4.4 VISIBLE (NONDEGENERATE) CW OPTICAL PARAMETRIC OSCILLATOR USING A 488.0 nm PUMP

4.4-1 Basic Operational Characteristics

A nondegenerate CW DRO was constructed using BSN crystal no. 12 as the nonlinear crystal. Its physical characteristics are given in Table B1 and in the second-harmonic phase-matching curve given in Fig. B6. The crystal's phase-matching characteristics for a 488.0 nm pump wavelength are shown in Fig. 3-16. Of particular interest is the fact that near 200° C the crystal phase-matches for a visible signal wavelength which is one third the idler wavelength. As explained earlier, this is a suitable condition for designing dual-wavelength, high-reflection coatings.

One side of the crystal and one spherical mirror were coated for high reflection at 650 nm and 1950 nm. The transmission characteristics of the coatings are shown in Fig. 3-20. The opposite side of the crystal is antireflection coated for the same wavelengths. The crystal high-reflection coating (mirror M1) transmitted approximately 80% of the incident pump power. Great care was required to prevent damage to the optical coatings by the focused pump radiation. When the focus of the lens was placed directly on the crystal surface, absorption of pump radiation by surface impurities caused severe damage to the coating. As long as the lens focus was kept at least
1 mm outside of the surface of the coating, no damage occurred.

The output of the visible DRO came in irregular bursts or chains of pulses. Once the DRO was aligned, oscillation would occur as soon as the pump was admitted to the oscillator cavity, but the oscillation ceased within fractions of a second. As an aid to taking data on the output signal wavelengths, a low-frequency chopper was used to maintain oscillation on a periodic basis. Apparently, thermal effects in the crystal due to absorption of the optical fields result in nonuniform phase-matching over the crystal cross section [45]. The minimum pump power for which oscillation could be obtained was approximately 200 mW. The threshold computations given in Table 2-2 predict the threshold to be 100 mW based on signal and idler losses of 3%. The maximum output power of the oscillator was estimated to be 100 μW with 500 mW of input pump power. The optimum resonator spacing was 2.62 cm. This again indicated that best results are with L/b less than 2.8. For a spacing of 2.62 cm, L/b is equal to 0.4. Because of the high slope of the L/b versus cavity spacing for L/b>0.5, it is likely that optical resonator stability is playing a more important role in determining the oscillation threshold than the parametric gain optimization indicated by the value of 2.8 for L/b. The lens position for best mode-matching was 10.18 cm. Oscillation was obtained for a range of 10.15 cm to 10.45 cm. This corresponds quite well to the expected value of 10.13 cm.

4.4-2 Output Characteristics

Visible oscillation was obtained in the two lowest order
transverse modes, TEM\textsubscript{00} and TEM\textsubscript{01}. The TEM\textsubscript{00} mode predominated, but oscillation in the TEM\textsubscript{01} mode occurred frequently. A photograph of the TEM\textsubscript{00} mode is shown in Fig. 4-11(a). The fine structure is due to some optical imperfection in the nonlinear crystal and several optical components used to attenuate the pump beam. Fig. 4-11(b) is a photograph of the visible parametric oscillator during operation. The components in the photo are from left to right: mode-matching lens with micro-positioner, crystal oven, output mirror mount (M\textsubscript{2}), collimating lens with polarization analyzer, filter holder, and screen for projection of the DRO output.

The spectrum of the signal output from the visible DRO is given in Fig. 4-12. The linewidth of the signal is 0.18 nm. The spectrum was taken using the stable pump laser and isolation. The narrower linewidth is expected because of the shorter wavelength of the signal and the fact that the parametric gain bandwidth is much more narrow far from degeneracy. It should be noted that the apparent narrow linewidth of this DRO may be because it is oscillating near threshold, and the oscillations could not be maintained long enough to get a good spectral scan by the monochromator. Thus, oscillations over the full linewidth may not have been detected.

4.4-3 Tuning Characteristics

The visible parametric oscillator was temperature tunable over a range of crystal temperatures from 169° C to 212° C. This tunes the signal wavelength from 662.1 nm to 643.7 nm. The corresponding idler wavelengths are 1856 nm to 2018 nm. From Fig. 3-20 it can be concluded
FIG. 4-11 VISIBLE OPO TEM$_{00}$ MODE AND EXPERIMENTAL CONFIGURATION DURING OPERATION.
FIG. 4-12 Visible OPO Signal Spectrum.
that the tuning range was limited by the bandwidth of the visible portion of the high-reflection coating.

The signal wavelengths of the parametric oscillator as a function of crystal temperature are plotted in Fig. 4-13. The entire tuning curve is shown so that a direct comparison can be made with the OPN data of Fig. 3-16. The theoretical curve is again from equations (2-35) and (2-36) with \( T_0 = -65^\circ \text{C} \) and \( \eta = 6.1 \times 10^{13} \) esu. To within the resolution of the wavelength measurements, the parametric oscillator signal wavelengths correspond to the wavelengths of maximum parametric gain. The tuning curve for the visible parametric oscillator is shown in detail in Fig. 4-14. The theoretical curve is the same as in Fig. 4-13, and a larger number of experimental DRO data points are included. No significant deviation from the predicted tuning characteristics could be observed.
TEMPERATURE TUNING IN BA2NANB5015

Plot 3

PUMP WAVELENGTH 4880
SHG PM TEMP -65.00
ETA (x1014) 6.10
CRYSTAL NUMBER 12

FIG. 4-13
FIG. 4.14 Visible OPO Temperature Tuning Curve

CRYSTAL 12

\[ \lambda_p = 488.0 \text{ nm} \]

TEMPERATURE (°C)

640 650 660 670

645 655 665

SIGNAL WAVELENGTH (nm)

Experimental

Theoretical
5.0 SUMMARY AND CONCLUSIONS

This investigation of CW optical parametric oscillation was carried out by constructing oscillators in two forms. The degenerate oscillator had signal and idler output wavelengths at or near the sub-harmonic of the pump wavelength (γ = 0). The other oscillator (non-degenerate) had signal and idler output wavelengths far from the sub-harmonic of the pump (γ = 0.6). The degenerate oscillator output had an amplitude stability of ±10% and a linewidth of 0.4 nm. This quality of operation required that the pump laser be stable to within ±50 MHz and that it be isolated from reflections off the OPO cavity. The signal wavelength of the degenerate oscillator was tunable from 958 nm to 1016 nm. OPN data indicate that, without the limitations imposed by the bandwidth of the high-reflection coatings, this parametric oscillator has a potential tuning range of signal wavelength from 700 nm to 1029 nm with corresponding idler wavelengths from 1882 nm to 1029 nm.

An analysis was made to explain the behavior of the DRO output power as the oscillator is tuned. The analysis indicated that the variations in output power are due to periodic suppression of the phase-matching condition due to the lack of continuity in the double resonances of the oscillator cavity.

The successful operation of the nondegenerate oscillator represented the first report of a CW DRO pumped by a single-mode visible laser with signal and idler wavelengths far from degeneracy. The output of the oscillator was irregular, occurring in bursts, and could only be maintained on a periodic basis by chopping the pump beam. Its
linewidth was 0.18 nm. The output signal wavelength was tunable from 644 nm to 662 nm. The OPN data on this crystal when pumped with 488 nm radiation indicate that, without limitations imposed by the bandwidth of the high-reflection coatings and providing that the crystal could be cooled as low as -65° C, the potential tuning range of the signal wavelength is from 630 nm to 976 nm with corresponding idler wavelengths from 2179 nm to 976 nm. The output behavior of this oscillator is characteristic of the instabilities associated with doubly resonant oscillators whose signal and idler wavelengths are widely separated. When the constraints that govern the interaction, equations (1-1) and (1-2), are combined with the required double resonance of the optical cavity, the system is over-determined. A certain amount of leeway is available since $\omega_p$ is not precisely constant and parametric gain is still available when (1-2) is not precisely satisfied. The behavior of the nondegenerate oscillator implies that, when oscillation occurs, thermal effects may be present that destroy the phase-matching condition.

Experience with the two parametric oscillators indicates considerable advantage in simplicity of design and quality of operation if the oscillator operates near degeneracy. The tuning curves also indicate a greater change in signal and idler wavelengths for a given change in temperature near degeneracy. Since, at present, most pump sources are visible or infrared, these facts point to the excellent potential of parametric oscillators as sources of tunable coherent radiation in the infrared region of the spectrum. In view of the recent developments on dye laser sources, they must be considered at
the present time superior to the parametric oscillator as sources of tunable radiation at visible wavelengths.

There are a number of ways that the output power, conversion efficiency, amplitude stability, and linewidth of CW OPO's may be further improved. Some of these techniques, which are outlined here, constitute interesting areas for further investigation.

A narrower output linewidth could be obtained by using a feedback-frequency-stabilized pump laser and, by designing an OPO resonator spaced by low expansion, thermally compensated materials. These changes should help to better define the role of pump frequency variations and resonator stability in determining the OPO linewidth. Tittel, et al., [46] have recently developed a technique for feedback-frequency stabilizing an argon-ion laser to within ±3 MHz.

The backward traveling signal and idler waves in a DRO mix to produce a backward traveling pump wave. The intensity of the backward traveling pump wave is proportional to the pump power [25]. Thus, a conventional DRO has power-dependent reflections that limit its ultimate maximum internal conversion efficiency to 50% [12]. Special configurations, such as a ring cavity, could be used to eliminate these reflections. When power-dependent reflections are eliminated, the conversion efficiencies are doubled.

Another possible method for improving the operation of a parametric oscillator is to use a nonresonant reflection of the pump beam. This concept would be straightforward to incorporate into an already existing oscillator design. Bjorkholm [26] has shown that a reflected pump beam traveling back through the OPO cavity can continue to amplify
the signal and idler fields. Taking advantage of the reflected pump wave may be as simple as making mirror $M_2$ of the oscillator cavity highly reflective at the pump wavelength as well as the signal and idler wavelengths. Depending on the reflection coefficient for the pump and on the relative phases of the pump, signal, and idler upon reflection at $M_2$, it may be possible to lower the threshold by a factor of four and to double the conversion efficiencies [12].
ACKNOWLEDGEMENT

The author gratefully acknowledges the inspiration and assistance of the many people who made this research possible. My deepest appreciation to Dr. Frank Tittel who introduced me to the interesting field of nonlinear optics and who expertly assisted with the research effort. My thanks also go to Mr. John Klebba and Mr. Ronald Kelly for their work in setting up the photomultiplier tubes and to Jim Chappell for fabrication of crystal ovens and optical components. Thanks to Patty Butterworth, James Harriss, and Bette Laurence for technical writing assistance.
APPENDIX A: OBSERVATION OF OPTICAL PARAMETRIC NOISE EMISSION (OPN)

A1. INTRODUCTION

Detailed observations of OPN in lithium niobate and barium sodium niobate were made as an aid to the design of CW optical parametric oscillators. These observations provided precise experimental determination of the signal and idler wavelengths emitted for a given pump wavelength in a specific crystal as a function of crystal temperature. Tuning characteristics vary considerably for different crystals and may even vary among crystals of the same type. Since an optical cavity is not required for OPN observations, the range over which data can be taken is limited only by crystal properties and the ability to detect weak signals at longer wavelengths. The data can be extended by curve-fitting the experimental observations to the temperature-tuning equation (see Sec. 2.5-2). This procedure is especially helpful in predicting idler emission wavelengths where low output powers make detection difficult for wavelengths longer than 1100 nm.

Several investigators have given theoretical descriptions and reported observations of OPN [28, 47, 48]. Detailed quantum mechanical treatment of the subject has also been done [49, 50]. If the light from a pump laser traverses a birefringent crystal of high optical nonlinearity, there exists a small probability that incident photon will split into signal and idler photons.

The most successful theoretical treatment has been made by assuming that the parametric emission process results from the mixing of zero point fluxes at both the signal and idler wavelength with the
pump field [50]. This produces a polarization which attempts to radiate at all frequencies and all directions. Its ability to radiate effec-
tively is determined by the extent to which the phase-matching condi-
tion given in (1-2) is satisfied. Thus equations (1-1) and (1-2) deter-
mine the wavelengths of the observed emission. These equations are used to derive the temperature-tuning equations in Sec. 2.5-2.

The temperature-tuning curves for the crystals used in this study are given in Sec. 3.3. In each figure, the X's mark experimental OPN data. At each crystal temperature, the central wavelength of the OPN intensity distribution was recorded. Each point thus represents the wavelength of maximum parametric gain at the given crystal tempera-
ture. In all cases, the orientation of the crystal optic axis (c axis) was kept at an angle of 90° to the direction of pump wave propagation to eliminate the angular dependence of the extraordinary index of refrac-
tion and to maintain the same conditions necessary during operation of the crystal in a parametric oscillator.

Once OPN curves are available, accurate specifications for optical coatings can be made during the design of an OPO cavity. Once the full range of phase-matched wavelengths for a given crystal is known, a particular central point of OPO operation can be chosen in accordance with the type of high-reflection coatings that are available.

A2. OPN OUTPUT POWER AND BANDWIDTH

A2.1 Output Power

An estimate of the output power at the signal wavelength of OPN was made to establish the feasibility of observing the emission
with available laboratory equipment. The experimental method is discussed in Sec. A3.1. The output power computations were based on the work of Byer and Harris [28]. They derive the output power by assuming that the signal output is a result of a mixing process between a plane-collimated pump wave and a zero-point idler flux of one photon per black-body mode of quantizing volume. The OPN output power is given in equation (C9). This equation has been evaluated as a function of signal wavelength with the aid of a FORTRAN computer program. Details of the evaluation are given in Sec. C6.

Results from the computer program are given in Table A1 for LN with a 514.5 nm pump, in Table A2 for LN with a 488.0 nm pump, in Table A3 for BSN with a 514.5 nm pump, and in Table A4 for BSN with a 488.0 nm pump. The results were obtained for a pump power of 420 mW and an acceptance angle of 1.65 degrees. This acceptance angle provides maximum OPN output power at minimum bandwidth. The power and bandwidth data given in Sec. A3.2 were used to determine this angle. The predicted OPN power at exit from the crystal is approximately $10^{-8}$ watts, increasing to $10^{-7}$ watts near degeneracy. Since the increase as a function of wavelength is slight compared to the decrease in photo-cathode efficiency, the latter will be the major limiting factor of detectability. In the presence of a collimating lens, polarizer and high-pass filters, the OPN power reaching the monochromator input slit is expected to be considerably less. The detectability threshold of the experimental equipment (see Sec. A3.1) was measured at 632.8 nm with a He-Ne laser and a set of calibrated filters. The minimum detectable power at the input to the monochromator was estimated to be $10^{-12}$ watts. These
**PARAMETRIC NOISE EMISSION**

**CRYSTAL NO. 3**

**PUMP WAVELENGTH = 514.500 A**
**PUMP POWER = 4.500E+00 WATTS**
**ACCEPTANCE ANGLE = 1.65 DEG**

**CRYSTAL LENGTH = 1.50 CM**
**D COEFFICIENT = 2.2000E+08 ESU**
**CORRECTED PHASE MATCHING TEMP = -40.00 DEG C**
**EXTERNAL SECOND HARMONIC POWER FOCUSED AND PHASE MATCHED AT 90 DEG = 3.500E+03 (WATTS)**

<table>
<thead>
<tr>
<th>SIGNAL WAVELENGTH (A)</th>
<th>FLUOR OUTPUT PWR (WATT)</th>
<th>IDLER WAVELENGTH (A)</th>
<th>PH TEMPERATURE (DEG C)</th>
<th>BETA COEFFICIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>6500.00</td>
<td>1.593E+08</td>
<td>24680.81</td>
<td>267.28</td>
<td>5.2778E+17</td>
</tr>
<tr>
<td>6600.00</td>
<td>1.633E+08</td>
<td>23338.14</td>
<td>260.91</td>
<td>5.2406E+17</td>
</tr>
<tr>
<td>6700.00</td>
<td>1.673E+08</td>
<td>22168.17</td>
<td>236.38</td>
<td>5.1854E+17</td>
</tr>
<tr>
<td>6800.00</td>
<td>1.712E+08</td>
<td>21139.58</td>
<td>213.57</td>
<td>5.1163E+17</td>
</tr>
<tr>
<td>6900.00</td>
<td>1.752E+08</td>
<td>20228.21</td>
<td>192.36</td>
<td>5.0359E+17</td>
</tr>
<tr>
<td>7000.00</td>
<td>1.793E+08</td>
<td>19415.93</td>
<td>172.65</td>
<td>4.8065E+17</td>
</tr>
<tr>
<td>7100.00</td>
<td>1.833E+08</td>
<td>16865.17</td>
<td>154.33</td>
<td>4.5849E+17</td>
</tr>
<tr>
<td>7200.00</td>
<td>1.875E+08</td>
<td>16026.28</td>
<td>137.30</td>
<td>4.4749E+17</td>
</tr>
<tr>
<td>7300.00</td>
<td>1.917E+08</td>
<td>15487.53</td>
<td>121.50</td>
<td>4.4148E+17</td>
</tr>
<tr>
<td>7400.00</td>
<td>1.960E+08</td>
<td>14968.31</td>
<td>106.82</td>
<td>4.3537E+17</td>
</tr>
<tr>
<td>7500.00</td>
<td>2.005E+08</td>
<td>16385.36</td>
<td>93.21</td>
<td>4.4218E+17</td>
</tr>
<tr>
<td>7600.00</td>
<td>2.052E+08</td>
<td>15927.49</td>
<td>80.60</td>
<td>4.3098E+17</td>
</tr>
<tr>
<td>7700.00</td>
<td>2.101E+08</td>
<td>15505.48</td>
<td>68.91</td>
<td>4.1974E+17</td>
</tr>
<tr>
<td>7800.00</td>
<td>2.154E+08</td>
<td>15115.25</td>
<td>58.10</td>
<td>4.0853E+17</td>
</tr>
<tr>
<td>7900.00</td>
<td>2.202E+08</td>
<td>14753.36</td>
<td>48.11</td>
<td>4.0175E+17</td>
</tr>
<tr>
<td>8000.00</td>
<td>2.257E+08</td>
<td>14416.81</td>
<td>38.88</td>
<td>3.9738E+17</td>
</tr>
<tr>
<td>8100.00</td>
<td>2.313E+08</td>
<td>14103.05</td>
<td>30.37</td>
<td>3.9363E+17</td>
</tr>
<tr>
<td>8200.00</td>
<td>2.370E+08</td>
<td>13809.82</td>
<td>22.54</td>
<td>3.7556E+17</td>
</tr>
<tr>
<td>8300.00</td>
<td>2.433E+08</td>
<td>13535.08</td>
<td>15.38</td>
<td>3.6077E+17</td>
</tr>
<tr>
<td>8400.00</td>
<td>2.506E+08</td>
<td>13277.42</td>
<td>8.73</td>
<td>3.5426E+17</td>
</tr>
<tr>
<td>8500.00</td>
<td>2.584E+08</td>
<td>13035.20</td>
<td>8.60</td>
<td>3.4397E+17</td>
</tr>
<tr>
<td>8600.00</td>
<td>2.664E+08</td>
<td>12804.66</td>
<td>2.83</td>
<td>3.3903E+17</td>
</tr>
<tr>
<td>8700.00</td>
<td>2.749E+08</td>
<td>12591.14</td>
<td>7.85</td>
<td>3.2003E+17</td>
</tr>
<tr>
<td>8800.00</td>
<td>3.027E+08</td>
<td>12387.41</td>
<td>12.80</td>
<td>3.1013E+17</td>
</tr>
<tr>
<td>8900.00</td>
<td>3.384E+08</td>
<td>12149.54</td>
<td>16.52</td>
<td>2.9604E+17</td>
</tr>
<tr>
<td>9000.00</td>
<td>3.386E+08</td>
<td>12011.67</td>
<td>20.22</td>
<td>2.9720E+17</td>
</tr>
<tr>
<td>9100.00</td>
<td>3.578E+08</td>
<td>11836.05</td>
<td>23.54</td>
<td>2.8826E+17</td>
</tr>
<tr>
<td>9200.00</td>
<td>3.831E+08</td>
<td>11627.38</td>
<td>27.49</td>
<td>2.7028E+17</td>
</tr>
<tr>
<td>9300.00</td>
<td>4.137E+08</td>
<td>11519.88</td>
<td>29.09</td>
<td>2.6219E+17</td>
</tr>
<tr>
<td>9400.00</td>
<td>4.512E+08</td>
<td>11366.16</td>
<td>31.37</td>
<td>2.5435E+17</td>
</tr>
<tr>
<td>9500.00</td>
<td>4.908E+08</td>
<td>11223.31</td>
<td>33.34</td>
<td>2.4675E+17</td>
</tr>
<tr>
<td>9600.00</td>
<td>5.594E+08</td>
<td>11086.87</td>
<td>35.03</td>
<td>2.3935E+17</td>
</tr>
<tr>
<td>9700.00</td>
<td>6.413E+08</td>
<td>10956.42</td>
<td>36.44</td>
<td>2.3224E+17</td>
</tr>
<tr>
<td>9800.00</td>
<td>7.569E+08</td>
<td>10831.58</td>
<td>37.59</td>
<td>2.2533E+17</td>
</tr>
<tr>
<td>9900.00</td>
<td>9.322E+08</td>
<td>10711.99</td>
<td>38.51</td>
<td>2.1845E+17</td>
</tr>
<tr>
<td>10000.00</td>
<td>1.129E+09</td>
<td>10597.32</td>
<td>39.19</td>
<td>2.1217E+17</td>
</tr>
<tr>
<td>10100.00</td>
<td>1.638E+09</td>
<td>10487.29</td>
<td>39.66</td>
<td>2.0591E+17</td>
</tr>
<tr>
<td>10200.00</td>
<td>3.604E+09</td>
<td>10381.60</td>
<td>39.93</td>
<td>1.9985E+17</td>
</tr>
</tbody>
</table>
TABLE A2

OPA OUTPUT POWER IN LN WITH A 488.0 nm PUMP

<table>
<thead>
<tr>
<th>PUMP WAVELENGTH (nm)</th>
<th>CRYSTAL NO.</th>
<th>90° DEG POSITION</th>
<th>90° DEG MATCHED</th>
<th>90° DEG CORRECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>427.5</td>
<td>1</td>
<td>4.605E-01</td>
<td>4.005E-01</td>
<td>4.005E-01</td>
</tr>
<tr>
<td>458</td>
<td>2</td>
<td>5.51E-01</td>
<td>5.26E-01</td>
<td>5.26E-01</td>
</tr>
<tr>
<td>488</td>
<td>3</td>
<td>6.46E-01</td>
<td>6.15E-01</td>
<td>6.15E-01</td>
</tr>
<tr>
<td>519</td>
<td>4</td>
<td>7.43E-01</td>
<td>7.14E-01</td>
<td>7.14E-01</td>
</tr>
<tr>
<td>530</td>
<td>5</td>
<td>8.39E-01</td>
<td>8.03E-01</td>
<td>8.03E-01</td>
</tr>
<tr>
<td>583</td>
<td>6</td>
<td>9.40E-01</td>
<td>9.05E-01</td>
<td>9.05E-01</td>
</tr>
<tr>
<td>600</td>
<td>7</td>
<td>1.045E-00</td>
<td>1.005E-00</td>
<td>1.005E-00</td>
</tr>
<tr>
<td>628</td>
<td>8</td>
<td>1.15E-00</td>
<td>1.109E-00</td>
<td>1.109E-00</td>
</tr>
<tr>
<td>630</td>
<td>9</td>
<td>1.25E-00</td>
<td>1.203E-00</td>
<td>1.203E-00</td>
</tr>
<tr>
<td>650</td>
<td>10</td>
<td>1.35E-00</td>
<td>1.306E-00</td>
<td>1.306E-00</td>
</tr>
<tr>
<td>669</td>
<td>11</td>
<td>1.45E-00</td>
<td>1.408E-00</td>
<td>1.408E-00</td>
</tr>
</tbody>
</table>

注：

- 上表数据根据波长和晶体编号确定输出功率
- 输出功率在90°位置、90°匹配和90°校正情况下
- 数据单位为E-01

**Parameter Noise Emission Table**

<table>
<thead>
<tr>
<th>PUMP WAVELENGTH (nm)</th>
<th>CRYSTAL NO.</th>
<th>90° DEG POSITION</th>
<th>90° DEG MATCHED</th>
</tr>
</thead>
<tbody>
<tr>
<td>427.5</td>
<td>1</td>
<td>4.605E-01</td>
<td>4.005E-01</td>
</tr>
<tr>
<td>458</td>
<td>2</td>
<td>5.51E-01</td>
<td>5.26E-01</td>
</tr>
<tr>
<td>488</td>
<td>3</td>
<td>6.46E-01</td>
<td>6.15E-01</td>
</tr>
<tr>
<td>519</td>
<td>4</td>
<td>7.43E-01</td>
<td>7.14E-01</td>
</tr>
<tr>
<td>530</td>
<td>5</td>
<td>8.39E-01</td>
<td>8.03E-01</td>
</tr>
<tr>
<td>583</td>
<td>6</td>
<td>9.40E-01</td>
<td>9.05E-01</td>
</tr>
<tr>
<td>600</td>
<td>7</td>
<td>1.045E-00</td>
<td>1.005E-00</td>
</tr>
<tr>
<td>628</td>
<td>8</td>
<td>1.15E-00</td>
<td>1.109E-00</td>
</tr>
<tr>
<td>630</td>
<td>9</td>
<td>1.25E-00</td>
<td>1.203E-00</td>
</tr>
<tr>
<td>650</td>
<td>10</td>
<td>1.35E-00</td>
<td>1.306E-00</td>
</tr>
<tr>
<td>669</td>
<td>11</td>
<td>1.45E-00</td>
<td>1.408E-00</td>
</tr>
<tr>
<td>Signal Wavelength (A)</td>
<td>Fluor Output Power (Watts)</td>
<td>Idler Wavelength (A)</td>
<td>PM Temperature (Deg C)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------------------------</td>
<td>----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>650.00</td>
<td>1.35E-08</td>
<td>2.68E+01</td>
<td>3.68E+02</td>
</tr>
<tr>
<td>660.00</td>
<td>1.41E-08</td>
<td>2.33E+01</td>
<td>3.17E+02</td>
</tr>
<tr>
<td>670.00</td>
<td>1.46E-08</td>
<td>2.16E+01</td>
<td>2.94E+02</td>
</tr>
<tr>
<td>680.00</td>
<td>1.50E-08</td>
<td>2.03E+01</td>
<td>2.72E+02</td>
</tr>
<tr>
<td>690.00</td>
<td>1.55E-08</td>
<td>1.91E+01</td>
<td>2.53E+02</td>
</tr>
<tr>
<td>700.00</td>
<td>1.60E-08</td>
<td>1.86E+01</td>
<td>2.35E+02</td>
</tr>
<tr>
<td>710.00</td>
<td>1.64E-08</td>
<td>1.82E+01</td>
<td>2.18E+02</td>
</tr>
<tr>
<td>720.00</td>
<td>1.69E-08</td>
<td>1.78E+01</td>
<td>2.02E+02</td>
</tr>
<tr>
<td>730.00</td>
<td>1.73E-08</td>
<td>1.75E+01</td>
<td>1.87E+02</td>
</tr>
<tr>
<td>740.00</td>
<td>1.78E-08</td>
<td>1.71E+01</td>
<td>1.74E+02</td>
</tr>
<tr>
<td>750.00</td>
<td>1.82E-08</td>
<td>1.68E+01</td>
<td>1.61E+02</td>
</tr>
<tr>
<td>760.00</td>
<td>1.87E-08</td>
<td>1.65E+01</td>
<td>1.49E+02</td>
</tr>
<tr>
<td>770.00</td>
<td>1.92E-08</td>
<td>1.63E+01</td>
<td>1.39E+02</td>
</tr>
<tr>
<td>780.00</td>
<td>1.97E-08</td>
<td>1.61E+01</td>
<td>1.30E+02</td>
</tr>
<tr>
<td>790.00</td>
<td>2.02E-08</td>
<td>1.58E+01</td>
<td>1.19E+02</td>
</tr>
<tr>
<td>800.00</td>
<td>2.08E-08</td>
<td>1.56E+01</td>
<td>1.11E+02</td>
</tr>
<tr>
<td>810.00</td>
<td>2.14E-08</td>
<td>1.54E+01</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>820.00</td>
<td>2.20E-08</td>
<td>1.52E+01</td>
<td>9.64E+01</td>
</tr>
<tr>
<td>830.00</td>
<td>2.26E-08</td>
<td>1.50E+01</td>
<td>9.08E+01</td>
</tr>
<tr>
<td>840.00</td>
<td>2.32E-08</td>
<td>1.48E+01</td>
<td>8.61E+01</td>
</tr>
<tr>
<td>850.00</td>
<td>2.38E-08</td>
<td>1.46E+01</td>
<td>8.17E+01</td>
</tr>
<tr>
<td>860.00</td>
<td>2.44E-08</td>
<td>1.44E+01</td>
<td>7.80E+01</td>
</tr>
<tr>
<td>870.00</td>
<td>2.50E-08</td>
<td>1.42E+01</td>
<td>7.52E+01</td>
</tr>
<tr>
<td>880.00</td>
<td>2.56E-08</td>
<td>1.40E+01</td>
<td>7.26E+01</td>
</tr>
<tr>
<td>890.00</td>
<td>2.62E-08</td>
<td>1.38E+01</td>
<td>7.04E+01</td>
</tr>
<tr>
<td>900.00</td>
<td>2.68E-08</td>
<td>1.36E+01</td>
<td>6.84E+01</td>
</tr>
<tr>
<td>910.00</td>
<td>2.74E-08</td>
<td>1.34E+01</td>
<td>6.66E+01</td>
</tr>
<tr>
<td>920.00</td>
<td>2.80E-08</td>
<td>1.32E+01</td>
<td>6.50E+01</td>
</tr>
<tr>
<td>930.00</td>
<td>2.86E-08</td>
<td>1.30E+01</td>
<td>6.35E+01</td>
</tr>
<tr>
<td>940.00</td>
<td>2.92E-08</td>
<td>1.28E+01</td>
<td>6.22E+01</td>
</tr>
<tr>
<td>950.00</td>
<td>2.98E-08</td>
<td>1.26E+01</td>
<td>6.10E+01</td>
</tr>
<tr>
<td>960.00</td>
<td>3.04E-08</td>
<td>1.24E+01</td>
<td>6.00E+01</td>
</tr>
<tr>
<td>970.00</td>
<td>3.10E-08</td>
<td>1.22E+01</td>
<td>5.91E+01</td>
</tr>
<tr>
<td>980.00</td>
<td>3.16E-08</td>
<td>1.20E+01</td>
<td>5.83E+01</td>
</tr>
<tr>
<td>990.00</td>
<td>3.22E-08</td>
<td>1.18E+01</td>
<td>5.75E+01</td>
</tr>
<tr>
<td>1000</td>
<td>3.28E-08</td>
<td>1.16E+01</td>
<td>5.68E+01</td>
</tr>
<tr>
<td>1010</td>
<td>3.34E-08</td>
<td>1.14E+01</td>
<td>5.61E+01</td>
</tr>
<tr>
<td>10200</td>
<td>3.52E-07</td>
<td>1.10E+01</td>
<td>5.24E+01</td>
</tr>
<tr>
<td>Signal Wavelength (A)</td>
<td>Fluor Output Pwr (Watts)</td>
<td>Idler Wavelength (A)</td>
<td>PM Temperature (Deg C)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>6000.00</td>
<td>1.445E-08</td>
<td>26142.86</td>
<td>320.11</td>
</tr>
<tr>
<td>6100.00</td>
<td>1.517E-08</td>
<td>24400.00</td>
<td>295.37</td>
</tr>
<tr>
<td>6200.00</td>
<td>1.585E-08</td>
<td>22921.21</td>
<td>265.73</td>
</tr>
<tr>
<td>6300.00</td>
<td>1.648E-08</td>
<td>21650.70</td>
<td>236.03</td>
</tr>
<tr>
<td>6400.00</td>
<td>1.709E-08</td>
<td>20547.37</td>
<td>210.61</td>
</tr>
<tr>
<td>6500.00</td>
<td>1.767E-08</td>
<td>19580.25</td>
<td>186.40</td>
</tr>
<tr>
<td>6600.00</td>
<td>1.823E-08</td>
<td>18725.58</td>
<td>164.67</td>
</tr>
<tr>
<td>6700.00</td>
<td>1.877E-08</td>
<td>17964.88</td>
<td>143.80</td>
</tr>
<tr>
<td>6800.00</td>
<td>1.932E-08</td>
<td>17283.33</td>
<td>124.67</td>
</tr>
<tr>
<td>6900.00</td>
<td>1.985E-08</td>
<td>16669.31</td>
<td>106.98</td>
</tr>
<tr>
<td>7000.00</td>
<td>2.040E-08</td>
<td>16113.21</td>
<td>90.62</td>
</tr>
<tr>
<td>7100.00</td>
<td>2.095E-08</td>
<td>15607.62</td>
<td>75.50</td>
</tr>
<tr>
<td>7200.00</td>
<td>2.152E-08</td>
<td>15148.83</td>
<td>61.45</td>
</tr>
<tr>
<td>7300.00</td>
<td>2.212E-08</td>
<td>14720.66</td>
<td>48.48</td>
</tr>
<tr>
<td>7400.00</td>
<td>2.274E-08</td>
<td>14330.16</td>
<td>36.81</td>
</tr>
<tr>
<td>7500.00</td>
<td>2.340E-08</td>
<td>13949.87</td>
<td>25.89</td>
</tr>
<tr>
<td>7600.00</td>
<td>2.411E-08</td>
<td>13635.29</td>
<td>15.86</td>
</tr>
<tr>
<td>7700.00</td>
<td>2.487E-08</td>
<td>13324.62</td>
<td>6.45</td>
</tr>
<tr>
<td>7800.00</td>
<td>2.571E-08</td>
<td>13035.62</td>
<td>-1.79</td>
</tr>
<tr>
<td>7900.00</td>
<td>2.662E-08</td>
<td>12765.56</td>
<td>-53.51</td>
</tr>
<tr>
<td>8000.00</td>
<td>2.763E-08</td>
<td>12512.89</td>
<td>-16.45</td>
</tr>
<tr>
<td>8100.00</td>
<td>2.876E-08</td>
<td>12275.78</td>
<td>-22.06</td>
</tr>
<tr>
<td>8200.00</td>
<td>3.004E-08</td>
<td>12053.01</td>
<td>-28.77</td>
</tr>
<tr>
<td>8300.00</td>
<td>3.149E-08</td>
<td>11843.27</td>
<td>-34.03</td>
</tr>
<tr>
<td>8400.00</td>
<td>3.315E-08</td>
<td>11643.85</td>
<td>-39.76</td>
</tr>
<tr>
<td>8500.00</td>
<td>3.508E-08</td>
<td>11458.56</td>
<td>-43.00</td>
</tr>
<tr>
<td>8600.00</td>
<td>3.735E-08</td>
<td>11281.57</td>
<td>-46.79</td>
</tr>
<tr>
<td>8700.00</td>
<td>4.006E-08</td>
<td>11114.14</td>
<td>-50.14</td>
</tr>
<tr>
<td>8800.00</td>
<td>4.338E-08</td>
<td>10965.16</td>
<td>-53.09</td>
</tr>
<tr>
<td>8900.00</td>
<td>4.739E-08</td>
<td>10803.98</td>
<td>-55.65</td>
</tr>
<tr>
<td>9000.00</td>
<td>5.253E-08</td>
<td>10660.19</td>
<td>-57.46</td>
</tr>
<tr>
<td>9100.00</td>
<td>5.924E-08</td>
<td>10523.22</td>
<td>-59.73</td>
</tr>
<tr>
<td>9200.00</td>
<td>6.637E-08</td>
<td>10392.59</td>
<td>-61.99</td>
</tr>
<tr>
<td>9300.00</td>
<td>8.151E-08</td>
<td>10267.67</td>
<td>-64.55</td>
</tr>
<tr>
<td>9400.00</td>
<td>1.020E-07</td>
<td>10148.67</td>
<td>-63.53</td>
</tr>
<tr>
<td>9500.00</td>
<td>1.382E-07</td>
<td>10034.63</td>
<td>-64.25</td>
</tr>
<tr>
<td>9600.00</td>
<td>1.999E-07</td>
<td>9925.42</td>
<td>-64.72</td>
</tr>
<tr>
<td>9700.00</td>
<td>5.742E-07</td>
<td>9820.75</td>
<td>-64.96</td>
</tr>
</tbody>
</table>
results indicate that OPN should be observable over a range of wavelengths where the responsivity of the photomultiplier tube is not down by much more than $10^{-3}$ compared to that at 632.8 nm.

A more refined theoretical treatment of OPN has been given by Kleinman [50]. Using a quantum mechanical perturbation, he assumes a zero-point energy of $\frac{1}{2} \hbar \omega$ in each interaction mode. After forming the interaction energy, the transition rate for the process of a pump photon decaying into a signal and idler photon can be found. The interaction energy is proportional to the nonlinear susceptibility of the crystal. Kleinman has also greatly expanded the analysis of processes that depend on phase-matching. Evaluation of the results of Ref. [28] proved adequate, however, as an aid to experimentation. The observed data could be well understood in terms of the more simplified analysis in reference [28].

A2.2 OPN Bandwidth Characteristics

There are two contributions to OPN bandwidth. The first is the limiting or minimum bandwidth of the collinear interaction described by (1-1) and (2-15). It arises from the quantum mechanical uncertainty of the signal momentum within the crystal given by $\Delta k L \approx 2 \pi$. In the formulation of Ref. [28], this can be written in Hz as,

$$B = \frac{2\pi}{bl} ,$$

(A1)

where $b$ is defined in Sec. 2.6-3.

The second contribution to bandwidth is due to the presence of off-axis or noncollinear phase-matched emission. Since (1-2) is the
most general form of the phase-matching condition, it can be satisfied as shown in Fig. A1.

The noncollinear interaction is then described by (1-1) and (1-2). Equation (1-2) can be rewritten in terms of index of refraction as (see Fig. A1):

\[
(\omega p s)^2 = (\omega p p)^2 + (\omega p s)^2 - 2\omega p p \omega p s \cos \theta. \quad (A2)
\]

The bandwidth of the signal emission is determined by the signal emission frequency occurring at the maximum angle, \( \theta \), which the detector can receive. The larger the acceptance angle, \( \theta \), the greater the expected spread in received noncollinear signal frequencies. The noncollinear emission does not contribute symmetrically to the OPN bandwidth. It produces a spectrum weighted toward the high-frequency side. The greater the acceptance angle, the more asymmetric the spectrum appears. This effect is illustrated from experimental data in Fig. A4. The fact that the asymmetry is weighted toward high frequencies can be understood by using (1-1) in (A2) to eliminate \( \omega p \) and solve for \( \omega s \) in terms of \( \theta \). In this case, \( \omega p \) is a constant. The result is:

\[
- \frac{\omega p (n^2 s - n^2 i)}{2\omega p n s} - \frac{\omega s (n^2 s - n^2 i)}{2\omega p n s} + \frac{n^2 i}{n p s} = \cos \theta \quad (A3)
\]

Solving (A3) for the signal frequency:

\[
\omega s = \frac{\cos \theta - C + \sqrt{C^2 - 2C\cos \theta - 4DA}}{2D} \quad (A4)
\]
FIG. A1  NONCOLLINEAR PHASE-MATCHING
where for brevity, we define:

\[ A = -\frac{n_p^2(n_i^2 - n_s^2)}{2n_p n_i n_s}, \quad D = -\left(\frac{n_i^2 - n_s^2}{2\omega n_p n_i n_s}\right), \quad \text{and} \quad C = \frac{n_i^2}{n_p n_s}. \]

The plus sign was chosen in (A4) assuming that the physically correct solution to (A3) is the root of the quadratic equation that represents the higher frequency. The behavior of \( \omega_s \) can be found by forming \( \frac{d\omega_s}{d\theta} \) and assuming \( \theta \) is small (\( \theta \) is usually less than 0.01 rad). Differentiating (A4) with respect to \( \theta \):

\[
\frac{d\omega_s}{d\theta} = \frac{1}{2D} \left[ \frac{C + C \cos \theta}{\sqrt{C^2 - 2 \cos \theta + \cos^2 \theta - 4DA}} - 1 \right] \sin \theta
\]

\[ \approx \frac{1}{2D} \left[ \frac{C + 1}{\sqrt{C^2 - 2C + 1 - 4DA}} - 1 \right] \theta \quad \text{(A5)} \]

It remains to show that the coefficient of \( \theta \) in (A5) is positive. For LN and \( \lambda_p = 488.0 \text{ nm}, \lambda_s = 633.0 \text{ nm}, \lambda_i = 2130 \text{ nm}, \) the indices of refraction are: \( n_p = 2.24, n_s = 2.29, \) and \( n_i = 2.19. \) This yields \( C = 0.793 \text{ and } 4DA = 0.0414, \) and the quantity in brackets is +39. Since \( D > 0 \text{ and } \theta > 0, \) then \( \frac{d\omega_s}{d\theta} \) is positive. This confirms that the non-collinear signal emission will weight the distribution toward higher frequencies (lower wavelengths).

For all crystals and pump wavelengths used in this investigation, the asymmetry was toward the higher wavelengths. Since the indices of refraction are complex functions of wavelength for various crystals, it is difficult to presume that all signal OPN would be
asymmetric toward higher frequencies. This condition occurs in (A5) when \( C \geq DA \), where \( C \) and \( DA \) are only functions of the indices of refraction. For \( C < DA \), the asymmetry would be weighted toward lower frequencies.

Of special interest for experimental purposes is the limiting bandwidth of (A1) near degeneracy, \( \omega_s \approx \omega_i \). To simplify notation, let the degeneracy parameter, \( \gamma \), be defined by:

\[
\omega_s = \omega_o (1 + \gamma) \\
\omega_i = \omega_o (1 - \gamma) \\
\omega_p = 2\omega_o
\]  
(A6)

The indices parameter \( \alpha \) is defined by:

\[
n_s = n_o (1 + \alpha) \\
n_i = n_o (1 - \alpha)
\]  
(A7)

where \( n_o \) is defined as \( n_o = (n_s + n_i)/2 \). Using \( b \) in the form given by (C11), equation (A1) becomes:

\[
B = \frac{C}{L} \frac{1}{(n_s - n_i) + \omega_s \frac{\partial n_s}{\partial \omega_s} - \omega_i \frac{\partial n_i}{\partial \omega_i}}
\]

which with (A6) and (A7) is:

\[
B = \frac{C}{L} \frac{1}{2n_o \alpha + \omega_o [n'_s(1 + \gamma) - n'_i(1 - \gamma)]}
\]  
(A8)
where the prime denotes differentiation with respect to angular frequency, $\omega$. Near degeneracy, it can be assumed that $\omega_s = \omega_i$ and that $n_s' = n_i' = n'$. Thus (AB) can be written in terms of degeneracy, $\gamma$, as:

$$B = \frac{1}{\frac{\ln \alpha}{2c} + \frac{\ln n'}{2c} \gamma}.$$  \hspace{1cm} (A9)

This equation was used to curve-fit the bandwidth data that are presented in Sec. A3.3. The equation proves to be an excellent description of the limiting bandwidth near degeneracy.

A3. OPN EXPERIMENTAL TECHNIQUE AND RESULTS

A3.1 Experimental Method

A schematic of the experimental apparatus used to take OPN wavelength and bandwidth data is shown in Fig. A2. The pump radiation is provided by an argon-ion laser. The laser is described in detail in Sec. 3.1-2. The laser was operated multimode at either the 488.0 nm or 514.5 nm lines. Operation in a single longitudinal mode was not required for OPN observations. It was verified that the mode of operation had no noticeable effect on the OPN data, and the use of multimode operation provided more pump power when it was required. Up to 1.2 watts CW pump power was available, but most of the data were taken with 0.5 watts.

The output of the laser is chopped at 200 Hz by a mechanical chopper to provide a reference frequency for amplification of the output of the photomultiplier tube detectors by a phase-sensitive amplifier.
FIG. A2 OBSERVATION OF OPTICAL PARAMETRIC NOISE EMISSION
A Princeton Applied Research Model HR-8 is used for this purpose. The amplifier is essential for observation of low signal-to-noise ratio signals, and provides a noise-free dc voltage proportional to the signal intensity that can be used to drive an X-Y recorder.

A bandpass filter is used to eliminate unwanted laser-plasma fluorescence, which can interfere with the OPN signals. The narrow-band fluorescence lines were present over a wide range of wavelengths in the visible and near infrared. The filter has 87% transmission from 400 nm to 600 nm and high attenuation for a long range of wavelengths on either side of the pass band.

Focusing and collimating lenses of 10 cm focal length are used to make it possible to observe OPN with greater acceptance angles than would be possible if the pump beam were simply passed directly through the crystal. Even though the total power of OPN emission is not increased by increasing the pump power density, focusing made it possible to collect and focus a greater amount of OPN power through the monochromator.

An air-spaced Glan-Thompson polarizer is used to obtain pump linear polarization to within .01%. Since the pump is already linearly polarized, the purpose of the polarizer is not to help meet the phase-matching condition (the pump must propagate as an extraordinary ray), but to obtain a high degree of pump attenuation when a second polarizer is used as an analyzer. The two polarizers provided a pump-power extinction coefficient of $10^{-5}$. High-pass standard optical filters provide additional strong attenuation of the pump beam after cross-polarization. These filters attenuate the power of radiation
at wavelengths below the cutoff wavelength by a factor of $10^{-5}$. Their transmittance above the cutoff wavelength is 89%. One or two such filters are necessary to isolate OPN from the pump for observation. The combination of crossed polarizers and high-pass filters provide 140 db of pump attenuation.

A short focal length lens is used to focus the OPN signal onto the slit of a Jarrell-Ash model 82-410 0.25 m Ebert monochromator. The monochromator is used to obtain the wavelength and bandwidth data on the OPN. It has a resolution of ±0.1 nm and wavelength calibration accuracy of ±0.3 nm. Calibration was done by linearly interpolating among the wavelengths of several known laser emissions. A small circular aperture was used instead of the usual entrance slit to the monochromator so that noncollinear phase-matched OPN would be symmetrically selected from the emission. A potentiometer connected to the readout of the monochromator provided for direct plotting of wavelength on an X-Y recorder.

The combination of set-point programmer and precision temperature controller is used to locate and scan over crystal temperature. This is particularly useful in locating OPN emission for selected signal wavelengths.

The output from the monochromator is monitored by RCA C31000F and C31000J photomultiplier tubes. The C31000 series photomultiplier tubes have high-gain, gallium-phosphide coatings on the first dynode. This provides an order of magnitude increase in secondary emission ratio over previously used materials, decreasing noise-induced current while improving the overall current gain. The current gain is typically
$10^7$. The C31000F tube has an extended response S20 surface with a quantum efficiency peak of 10% near 550 nm. It has a useful range from 400 nm to 960 nm.

This particular C31000F tube had a surprisingly low dark current of 2.1 nanoamperes when operated at room temperature (22° C) and 2000 volts. The C31000J tube had an S1 surface with a quantum efficiency peak of 0.43% near 780 nm. It has a useful range from 450 nm to 1150 nm. The high current-gain of this tube combined with the inherent low noise level of the S1 surface made it impossible to operate this tube at room temperature. Vapor from the boil-off of liquid nitrogen provides cooling down to -60° C. The dark current for the C31000J at -42° C is 135 nanoamperes when operated at 2000 volts.

Since the signal powers are very low, proper alignment of optical components was critical for these observations. Most components could be aligned by observing reflections of the pump beam on properly placed apertures. The crystal and focusing lens were carefully aligned to provide pump incidence normal to the crystal face. Observation of a small portion of pump power, transmitted by removal of the filters, was used to align the focusing lens on the monochromator slit.

To obtain maximum OPN output, the pump must propagate with its polarization parallel to the crystal optic axis. To align the crystal with pump polarization, advantage was taken of the fact that misalignment would destroy the linear polarization of the incoming beam. With the crystal removed, the polarizer is set parallel to the incoming pump polarization. The analyzer is set cross-polarized for maximum extinction. The crystal is then put in place with its c-axis approxi-
mately parallel to the pump polarization. Its orientation can then be fine-adjusted by rotation about an axis parallel to the pump beam until maximum extinction is re-established.

A3.2 Power and Bandwidth Observations

The following OPN power and bandwidth observations were made using LN as the nonlinear crystal. This was done so that comparisons could be made to previously published data. Little published data are available on OPN emission from BSN. There is no reason to suspect that, except for phase-matching temperature and differing values of b, there are any basic differences in the description of OPN emission characteristics from the two crystals.

The OPN signal power emission was measured by comparison to an attenuated He-Ne laser. A LN crystal was pumped with 440 mW of 488.0 nm radiation and temperature-tuned until the central wavelength was at 633.0 nm. The temperature at which this occurred was 166° C. The He-Ne laser was attenuated until the deflection on the phase-sensitive amplifier was the same as for the OPN emission. The OPN power with a 1.65° acceptance angle (see Fig. A3) was found to be approximately $7.8 \times 10^{-11}$ watts at the input to the monochromator.

In Sec. A2.1 it was predicted that the power would be something less than $10^{-8}$ watts. If the losses in OPN power between the crystal and monochromator are a factor of five, then the prediction is still a factor of fifty over the observed value. The prediction still appears to be reasonable, since there are a number of optical components whose alignment and attenuation could have affected the measured value.
Reflections by the focusing lens and crystal-face cut the effective pump power to about 350 mW. It is also questionable to try to compare the power of OPN emission, which has considerable spectral bandwidth and large angular divergence, to that of a well-collimated, narrow-band laser emission.

Measurements of the intensity and bandwidth of OPN in LN with a 488.0 nm pump and a signal wavelength of 633.0 nm are shown in Fig. A3. This work confirms the results of Byer and Harris shown in Fig. 5 of Ref. [28]. These measurements made it possible to determine an optimum acceptance angle, $\theta = 1.65^\circ$, at which temperature tuning data should be taken. Use of this angle assures that the data have minimum bandwidth (no contribution from noncollinear phase-matching) without making a sacrifice in received power.

The intensity as a function of wavelength for several acceptance angles is shown in Fig. A4. This illustrates the effects of the non-collinear phase-matching contribution to the OPN bandwidth. For acceptance angles greater than .03 rad, the distribution is heavily weighted toward higher frequencies. When the acceptance angle is sufficiently small, the distribution is symmetrical. This represents the limiting bandwidth. Even in the presence of some noncollinear emission, the distributions are still sharply peaked at the center of the limited bandwidth portion of the curve. This made it possible to take OPN wavelength measurements accurate to within the resolution of the monochromator.

Fig. A5 compares the intensity distribution as a function of wavelength for nonfocused OPN. In Fig. A5(a), the focusing and
FIG. A3  PARAMETRIC FLUORESCENCE INTENSITY AND BANDWIDTH
FOR A FUNCTION OF DETECTION ACCEPTANCE ANGLE
FIG. A4  OPN INTENSITY AS A FUNCTION OF WAVELENGTH FOR FOUR ACCEPTANCE ANGLES (488.0 nm PUMP).
FIG. A5 EFFECT OF FOCUSED PUMP RADIATION ON PARAMETRIC FLUORESCENCE

PUMP: 4880 Å (460 mV)
MTL: COLD LiNbO₃
P.M. TEMP: 195°C

(a) NON-FOCUSED

(b) FOCUSED
collimating lenses were eliminated. Fig. A5(b) is the same observation with focusing. The overall OPN intensity was much less in (a) than in (b). The bandwidth is also narrower in (a). Since Kleinman [50] has shown that OPN output power is not enhanced by focusing, the differences between (a) and (b) can be explained by the geometrical effects of focusing. When focused, the pump beam is confined to a small point near the center of the crystal and diverges on leaving the crystal. Thus the effective acceptance angle is larger when the pump is focused than when it is not.

A3.3 OPN Emission Near Degeneracy of a 514.5 nm Pump

Detailed data on OPN emission near degeneracy are presented here for comparison to equation (A9). Previous to this time, no data have been published on OPN emission at infrared wavelengths or near degeneracy. These data are important because they most dramatically illustrate the dependence of parametric gain bandwidth on nearness to degeneracy. The data indicate that, unless a very stable pump source is available, a parametric oscillator near degeneracy may have a relatively wide range of wavelengths for which there will be sufficient gain for oscillation.

Observations of OPN in the near infrared were made possible by the use of the C31000J photomultiplier tube described in Sec. 2.2. At 800 nm, the response of the S20 surface in the C31000F tube had dropped to the point where the S1 surface was required. Observations were made up to 1140 nm, a limit imposed by the range of the monochromator. At this wavelength, the signal-to-noise ratio had dropped to a
point where observations at much longer wavelengths would have been impossible.

The wavelength at degeneracy for the signal and idler is the subharmonic of 514.5 nm, 1029 nm. In BSN, the subharmonic phase-matching temperature, $T_o$, could therefore be accurately determined with data in this wavelength region. $T_o$ was typically 40° C. Even though the subharmonic of 488.0 nm, 976 nm, is a readily detectable wavelength, $T_o$ could not be directly determined since the phase-matching temperature is at approximately -50° C and no provisions were available for operating at this temperature. This value was estimated by curve-fitting the OPN data in the nondegenerate region.

The intensity distribution as a function of wavelength is shown for seven temperatures near degeneracy in Fig. A6. In (a) at 50° C, the bandwidth is very wide and the signal and idler are indistinguishable. As the temperature rises to 52.5° C, the signal and idler have split as shown in part (c). The idler emission could not be observed beyond a temperature of 53° C because of monochromator limitations. Parts (d) through (g) show the signal emission at higher temperatures. The acceptance aperture was kept at 1.65° so that the data indicate limiting bandwidth. The data of Fig. A6 represent the first reported direct observations of OPN emission near degeneracy from both the signal and idler waves. It can be seen from the temperature-tuning curve shown in Fig. 2-6 that the change in signal and idler wavelengths for a given change in temperature is large near degeneracy and becomes quite small away from degeneracy. Thus the crystal temperature had to be within 3° of degeneracy in order to observe the idler emission with
FIG. A6  OPN INTENSITY AS A FUNCTION OF WAVELENGTH NEAR DEGENERACY FOR SEVEN TEMPERATURES.
Fig. A6 (continued)
a wavelength less than 1140 nm.

The bandwidth data of Fig. A6 are plotted as a function of degeneracy, \( \gamma \), in Fig. A7. \( \gamma \) is defined in (A6). The experimental data points were least-squares curve-fitted using equation (A9). The equation successfully describes the behavior of OPN bandwidth near degeneracy. The parameters used to make the curve-fit in Fig. A7 can be used to estimate the values of \( \alpha \) and \( n' \) in (A9). The curve-fit is of the form,

\[
B'(A) = \frac{1}{-0.00117 + 0.0937\gamma}
\]

This yields:

\[
\frac{\pi L \omega \alpha}{\lambda^2} = 1.17 \times 10^5 \text{ cm}^{-1}
\]

and

\[
\frac{\pi L \omega n'}{\lambda^2} = 9.37 \times 10^6 \text{ cm}^{-1}
\]

where conversion of bandwidth from angstroms to Hz units was made. With \( \lambda = 1.03\mu \) and \( n_o = 2.26 \), the value of \( \alpha \) is \( 3.5 \times 10^{-4} \) and \( n' \) is \( 3.5 \times 10^{-17} \) seconds. These agree with results from index of refraction data. Computer evaluation of equation (C31) gives a value of \( 2 \times 10^{-17} \) seconds for \( n' \).
FIG. A7 Bandwidth of infrared OPN as a function of degeneracy
APPENDIX B: NONLINEAR CRYSTAL EVALUATION BY SECOND-HARMONIC GENERATION

The first nonlinear optical phenomena were observed in quartz (SiO$_2$) [1]. Crystals of higher optical nonlinear coefficients, $d$, were soon discovered, and potassium dihydrogen phosphate (KDP) came into common use. At the present time, a very large number of substances have been evaluated for nonlinear optics [39]. The most common substances now in use are lithium niobate (LiNbO$_3$) and barium sodium metaniobate ($\text{Ba}_2\text{NaNb}_5\text{O}_{15}$). They have nonlinear coefficients 12 and 26 times that of quartz, respectively. Since the square of the nonlinear coefficient enters into the conversion efficiency equations for nonlinear interactions, this increase represents a tremendous improvement.

LiNbO$_3$ (LN) is a negative uniaxial birefringent crystal of point-group symmetry $3m$. It is grown by pulling from a melt, and therefore does not possess the hygroscopic problem of solution-grown crystals. Since it can be operated at temperatures from 170° to 1100° C, it has wide-range flexibility for temperature controlled phase-matching. The lower temperature limit is set to avoid optically induced index-of-refraction inhomogeneities [36]. The upper limit is imposed by the crystal's approach to the melting point. LN should be operated in an $O_2$-enriched atmosphere to avoid loss of oxygen from the crystalline structure. This results in significant transparency degradation. The crystal is now available in high optical quality, single crystals up to 5 cm in length. Sufficient index of refraction data are available to predict orientation, electric field, and tempera-
ture-tuning characteristics of this crystal. LN is grown in either stoichiometric, "cold," or off-stoichiometric, "hot" forms. The latter form is obtained by using excess lithia in the melt. This increases the phase-matching temperature of the crystal so that it can be phase-matched above 170° C for a larger number of useful wavelengths, for example, second-harmonic generation of 1064 nm radiation.

$\text{Ba}_2\text{NaNb}_5\text{O}_{15}$ (BSN) is an optically negative biaxial crystal. Below 300° C, it is orthorhombic and of point-group mm2. It is also grown by pulling from a melt. It has the highest known nonlinear optical coefficient, $4.4 \times 10^{-8}$ esu. Because of difficulty in growing the crystals, it is available in lengths of only 0.5 cm. It has the significant advantage over LN of less susceptibility to optically induced index-of-refraction inhomogeneities and can, therefore, be used from room temperature or below up to 240° C. The upper limit is imposed because of the change in crystalline structure at 300° C. At this temperature, it becomes tetragonal. Since the crystal must be poled and detwinned to obtain an optically homogeneous single-domain crystal, the twinning can reappear if crystal structure transitions are allowed to take place. Excellent data are now available to predict the electro-optic, acousto-optic, and parametric-tuning characteristics of this crystal. See Sec. 3.2 and reference [19] for details.

There are a large number of characteristics that a nonlinear optical crystal must possess before it can be considered for use in the design of a low-threshold OPO. Details on these characteristics and their evaluation procedures are given in Sec. 3.2. The purpose of this appendix is to outline the technique for evaluating the phase-
matching quality of individual crystals by second-harmonic generation and to give the results of this evaluation for the crystals used in this study. The full width at half height of the second-harmonic generation intensity versus crystal-temperature curve is taken as the fundamental test of crystal phase-matching quality. The width of the curve will be excessive if the birefringence (difference between the index of refraction of the ordinary and extraordinary rays) is not constant along the length of the crystal. If the birefringence is not constant, the phase-matching condition, (1-2), cannot be met throughout the length of the crystal and the parametric gain will be reduced. If the curve consists of multiple or irregular peaks, then a lack of singularity of crystal domain is indicated.

Obviously, the longer the crystal, the more difficult they are to grow to meet these specifications. At the present time, the longest length of BSN with good phase-matching characteristics is 0.5 cm. Should BSN become available in lengths of several centimeters, it would greatly improve the CW oscillation thresholds. It has been shown that, for an optically homogeneous crystal of BSN, the minimum full width at half height is $\Delta T = 0.45^\circ C \text{ cm/L} [19]$, where $L$ is the crystal length. We can estimate the corresponding value for LN when frequently doubling 1150 nm radiation by evaluating equation (24) of reference [19] with $\lambda = 1.15 \times 10^{-4}$ cm and $\frac{\partial}{\partial T}(n^2 - n^\omega) = 5.9 \times 10^{-5}^\circ C$ [51]. The result is $\Delta T = 0.86^\circ C \text{ cm/L}$. This compares well to a value of 0.72 given by Nash, et al. [52]. These values are used as guidelines for acceptance of crystals on the basis of the phase-matching curve width.
The experimental technique for obtaining second-harmonic phase-matching curves is shown in Fig. B1. A Nd:YAG laser provides 1.0 watt of 1064 nm radiation that is linearly polarized to traverse the BSN crystal as an ordinary ray. Stiochiometric LN was evaluated using the second-harmonic of a He-Ne laser operating at a wavelength of 1150 nm. The focusing lens enhances the production of SHG by increasing the energy density of the pump. An analyzer and lowpass filter stop the pump from reaching the detector. A programmer scans the set point of a precision temperature controller to gradually pass the crystal through the phase-matching temperature.

Table B1 is a list identifying and giving characteristics of the crystals tested during our work. Most crystals were rejected because of obvious optical inhomogeneities or unacceptably wide phase-matching curves. Some were not used because, at the time, our ovens were not of sufficient length to prevent phase-matching problems due to oven temperature gradients.

The phase-matching curves for two unacceptable crystals are shown in Fig. B2. Crystal No. 8 (LN) had a double peak, indicating two areas in the crystal, phase-matching at slightly different temperatures. Crystal No. 7 (BSN) had a full width at half height of 1.3° C. This indicates a slightly larger width than acceptable, but the crystal may still be good for a variety of nonlinear applications. It was deemed not acceptable for CW OPO work because it was felt that no sacrifice in parametric gain for the 0.5 cm crystal could be tolerated. The SHG curve in Fig. B3 is for off-stiochiometric LN (Crystal No. 1), which has a slightly split peak and fairly wide full width at half
FIG. B1  NONLINEAR CRYSTAL PHASE-MATCHING EVALUATION.
<table>
<thead>
<tr>
<th>NO.</th>
<th>MATERIAL</th>
<th>SIZE (mm)</th>
<th>$T_o$ (°C) at $\lambda$ (nm)</th>
<th>SHG $\Delta T$ (°C)</th>
<th>DESCRIPTIONS AND USES</th>
<th>COMPANY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LN</td>
<td>5x5x10</td>
<td>172.5 @ 1064</td>
<td>2.07</td>
<td>ISHG of Nd:YAG (off-stoichiometric)</td>
<td>Cry. Tech</td>
</tr>
<tr>
<td>2</td>
<td>BSN</td>
<td>4x4x6</td>
<td>87.5 @ 1064</td>
<td>0.82</td>
<td>double domain not accepted</td>
<td>Cry. Tech</td>
</tr>
<tr>
<td>3</td>
<td>LN</td>
<td>4x4x15</td>
<td>168.0 @ 1150</td>
<td>0.50</td>
<td>not accepted</td>
<td>Chromatix</td>
</tr>
<tr>
<td>4</td>
<td>LN</td>
<td>5x5x30</td>
<td>173.0 @ 1150</td>
<td>0.83</td>
<td>too long for oven</td>
<td>Cry. Tech</td>
</tr>
<tr>
<td>5</td>
<td>BSN</td>
<td>5x5x5</td>
<td>83.5 @ 1064</td>
<td>0.55</td>
<td>optical striations not accepted</td>
<td>Cry. Tech</td>
</tr>
<tr>
<td>6</td>
<td>BSN</td>
<td>4x4x4.5</td>
<td>101.0 @ 1064</td>
<td>0.72</td>
<td>ISHG of Nd:YAG</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>7</td>
<td>BSN</td>
<td>5x5x5</td>
<td>104.5 @ 1064</td>
<td>1.30</td>
<td>$\Delta T$ too large</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>8</td>
<td>LN</td>
<td>5x5x10</td>
<td>159.5 @ 1064</td>
<td>----</td>
<td>not accepted</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>9</td>
<td>BSN</td>
<td></td>
<td></td>
<td></td>
<td>not accepted</td>
<td>Cry. Tech</td>
</tr>
<tr>
<td>10</td>
<td>LN</td>
<td>5x5x20</td>
<td>179.0 @ 1150</td>
<td>0.79</td>
<td>Visible OPO at 690nm &amp; 2100nm using 514.5 nm pump</td>
<td>Chromatix</td>
</tr>
<tr>
<td>11</td>
<td>BSN</td>
<td>5x5x5</td>
<td>103 @ 1064</td>
<td>0.94</td>
<td>IR OPO at 1029nm using 514.5nm pump</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>12</td>
<td>BSN</td>
<td>5x5x5</td>
<td>84.0 @ 1064</td>
<td>0.87</td>
<td>Visible OPO at 650 nm &amp; 1950nm using 488.0nm pump</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>13</td>
<td>BSN</td>
<td>5x5x5</td>
<td></td>
<td></td>
<td>IR OPO at 1029nm using 514.5nm pump</td>
<td>Union Carbide</td>
</tr>
</tbody>
</table>
FIG. B2  SHG OUTPUT POWER AS A FUNCTION OF TEMPERATURE FOR TWO UNACCEPTABLE CRYSTALS.
FIG. B3  SHG OUTPUT POWER AS A FUNCTION OF TEMPERATURE FOR A NONSTOICHIOMETRIC LN CRYSTAL.
height. It was accepted and functioned quite well as an internal second-harmonic generator for the Nd:YAG laser, but was not considered acceptable for use in an OPO. The best of the SHG curves is shown in Fig. B4 for Crystal No. 6. It has a full width of only 0.72° C. This crystal was used for ISHG and could have been used for OPO if properly coated.

Crystal No. 11 was used for the infrared OPO, and its SHG curve is shown in Fig. B5. Crystal No. 12 was used for the visible OPO, and its SHG curve is shown in Fig. B6. Detailed description of the use of these crystals are given in Sec. 4.0.
FIG. B4  SHG OUTPUT POWER AS A FUNCTION OF TEMPERATURE FOR THE ISHG CRYSTAL.
FIG. B5 SHG OUTPUT POWER AS A FUNCTION OF TEMPERATURE FOR THE IR OPO CRYSTAL.
FIG. B6  SHG OUTPUT POWER AS A FUNCTION OF TEMPERATURE FOR THE VISIBLE OPO CRYSTAL.
APPENDIX C: COMPUTER AIDED STUDY OF NONLINEAR INTERACTIONS

C1. INTRODUCTION

A computer program was developed in FORTRAN to aid in experimentation and to verify several important nonlinear optical parameters. The program consists of seven major sections, whose functions are supported by seven subroutines. The major sections are:

1. Temperature-Tuning Equation
2. Orientation-Tuning Equation
3. Electric-Field-Tuning Equation
4. Doubly and Singly Resonant OPO Thresholds
5. Optical Parametric Noise-Emission Power
6. Optical Resonator Design
7. Gaussian Beam Mode-Matching

The following subroutines perform computations required by the above program functions and can be used independently if required.

1. Index of Refraction (Sellmeier Equations) for LN and BSN
2. Temperature-Tuning Constant ($\eta$)
3. Angular Dispersive Constant ($b$)
4. Phase-Matching Temperature
6. Second-Order Derivative of Index of Refraction with Respect to Frequency
7. Automatic Plotting of Tuning Curves

In the following sections, the equations used for the computations are
given along with required input parameters and the resulting output quantities.

The variation of signal and idler frequency is described in terms of deviations from degeneracy where \( \omega_0 = \frac{\omega_0}{2} \), thus \( \omega_s = \omega_0 + \delta \omega \), \( \omega_i = \omega_0 - \delta \omega \). \( T_0 \) is taken as the subharmonic phase-matching temperature at degeneracy, thus \( n^e_p(T_0) = n^o_o(T_0) \) and it is also the second-harmonic phase-matching temperature if the role of pump and subharmonic are interchanged. The program calculates \( \delta \omega \) as a function of \( \delta T = T - T_0 \), \( \delta E = E, \delta \phi = 90^\circ - \theta \) subject to the selection rules of three-wave collinear parametric interactions for negative uniaxial crystals.

\[
\omega_p = \omega_s + \omega_i \tag{C1}
\]

\[
\frac{n^e_p}{p} = \frac{n^o_s}{s} + \frac{n^o_i}{i} \tag{C2}
\]

The variations in temperature, electric field, and angle of propagation change the index of refraction appearing in (C2) and thereby determine the value of the signal and idler frequencies that satisfy (C1) and (C2).

C2. TEMPERATURE TUNING

The variation of frequency for a given change in temperature is given by [5]:

\[
\delta \omega = n \sqrt{\delta T} \tag{C3}
\]
where, \[ \eta^2 = \frac{\omega}{\rho a T} \left( n_p^e - n_o^e \right) \cdot \frac{\partial n_o^e}{\partial \omega} \].

The derivation of (C3) is given in Sec. 2.5-2. \( T_o \) is an unknown function of crystal properties and varies from crystal to crystal. It must therefore, be experimentally determined and used as a fixed input parameter to the program. If \( T_o \) is not known at the required wavelength but is known at a nearby wavelength, the program can estimate the value of \( T_o \) at the required wavelength with an accuracy of 1.0° C. See Sec. C9.5, subroutine TPMT.

The program accepts the pump wavelength, \( \lambda_p \), and \( T_o \) as input parameters. It calculates the value of \( \lambda_s \) and \( \lambda_i \) at various requested temperature increments above \( T_o \). The program can calculate \( \eta \) on the basis of index-of-refraction data or can accept it as an input constant. See Sec. C9.2, subroutine ETA (\( \eta \)).

Experimental tuning data can also be input to the program. In this case, the program can generate a tuning curve which best fits the experimental data. This is done by varying \( \eta \) over a range of possible values which have been input to the program. An example of a tuning curve with experimental data is given in Fig. 2-6.

C3. ORIENTATION TUNING

The index of refraction is a function of the angle between the pump beam and the optic axis. It is usually desirable that the pump beam propagate at 90° to the optic axis. At this angle the effects of
double refraction and beam walk-off are minimized. In some cases, however, temperature restrictions are such that orientation tuning is required. Therefore, the program also calculates values of \( \lambda_s \) and \( \lambda_i \) for various increments \( \delta \Phi = 90^\circ - \theta \), where \( \theta \) is the angle between pump beam and optic axis. It assumes that the crystal is at temperature \( T_o \). In this case, \( \delta \omega \) is found to be [53],

\[
\delta \omega^2 = \frac{-\omega_o \sin^2 \delta \Phi}{[\left( \frac{3n_o^0}{\partial \omega} \right) \omega_o + \frac{1}{2} \omega_o \left( \frac{3n_o^0}{\partial \omega} \right)^2]} 
\]

\[\text{(C4)}\]

where, \( A = \frac{Bn^0_o(0)}{2n^0_o} (2 + \frac{B}{n^0_p}) \). \( B \) is the birefringence = \( n^o_p - n^e_p \) and \( \omega_o = \frac{\omega}{2} \). See Sec. C9.2 and C9.6 on subroutines ETA and DNOD2W for the calculation of \( \frac{3n^0_o}{\partial \omega} \) and \( \frac{3n^0_o}{\partial \omega^2} \). An orientation-tuning curve is given in Fig. 2-2.

**C4. ELECTRIC FIELD TUNING**

Electro-optic modulation of the indices of refraction in a crystal offers a method of fast tuning and also a method of fine tuning. \( \delta \omega \) is much smaller in this case than for temperature and orientation tuning. The size of the field that can be applied is limited by breakdown within the nonlinear crystal. The frequency variation is given by [6, 54],

\[
\delta \omega^2 = \frac{\omega_o n^o_o (r_{13} - r_{33}) E_z}{2 \left( \frac{3n^0_o}{\partial \omega} \right) \omega_o} 
\]

\[\text{(C5)}\]
where \( r_{13} \) and \( r_{33} \) are the linear electro-optic coefficients of the crystal, and \( E_z \) is the electric field along the optic axis. It is assumed that no other dc field is present in the crystal. Values of \( \lambda_s \) and \( \lambda_i \) are calculated for requested increments of \( E_z \) assuming the crystal is at temperature \( T_0 \). An electric field-tuning curve is given in Fig. 2-4.

**C5. DOUBLY AND SINGLE RESONANT OPTICAL PARAMETRIC OSCILLATOR THRESHOLD**

Perhaps the most important parameter describing an optical parametric oscillator is the minimum pump power required for the onset of oscillations. This is found by equating the round-trip loss in the signal and idler to the one-way power gain in the nonlinear medium. Writing \( n_o, \omega_o, \gamma \) and \( \alpha \) in terms of:

\[
\begin{align*}
2\omega_o &= \omega_s + \omega_i \\
2n_o &= n_s + n_i \\
\omega_s &= \omega_o (1 - \gamma) \\
n_s &= n_o (1 - \alpha) \\
\omega_i &= \omega_o (1 + \gamma) \\
n_i &= n_o (1 + \alpha)
\end{align*}
\]

We may use the threshold power expression derived by Boyd and Kleinman [11] for a doubly resonant OPO:

\[
P_{th} = \frac{4\varepsilon_e \varepsilon_i (1 + \gamma \alpha)}{K(1 - \gamma^2)^2(1 - \alpha^2)bL} \quad (C7)
\]

where \( K = 128 \pi^2 \omega_o^2 (2d)^2/(n_p n_s n_i c^3) \). \( d \) is the nonlinear coefficient of the crystal. \( L \) is the crystal length, and \( b \) is the cavity confocal parameter. \( \omega_o \) is the beam waist of the subharmonic beam and is
calculated from the confocal parameter, \( w_0^2 = \frac{b\lambda_0}{2\pi} \). \( \varepsilon_s \) and \( \varepsilon_i \) are the cavity losses of the signal and idler beams respectively. The focusing parameter \( L/b \) is required as input by the program. From this, \( b \) and \( w_0 \) are obtained. Optimum \( L/b \) has been established to be 2.84 [11]. Equation (C7) has been written to the nearest approximation for optimum \( L/b \) and is obtained from Boyd and Kleinman's equation (3.30) by taking

\[ \tilde{h}(\sigma, \beta, \xi) = (\pi^2/\xi)|\tilde{h}(\sigma, \beta, \xi)|^2 = 1. \]

This holds for \( B \) near zero and \( 1 < L/b < 10 \) as shown in Fig. 12 of reference [11]. Equation (C7) applies for the case of \( \theta = 90^\circ \) and \( \Delta k = 0 \). Thus, it neglects effects of double refraction and momentum mis-match. Further details on (C7) are given in Sec. 2.3. Tables 2-1 and 2-2 give the power thresholds predicted by (C7) for the parametric oscillators discussed in Sec. 4.0.

The threshold condition for the singly resonant optical parametric oscillator is given by:

\[ P_{th} = \frac{8\varepsilon(1 + \gamma a)w_0^2}{K(1 - \gamma^2)^2(1 - a^2)bL} \] \hspace{1cm} (C8)

where \( \varepsilon \) represents the losses for the wave that is resonant.

The computer program requires as input the pump wavelength, losses at the signal, losses at the idler, the effective nonlinear coefficient of the crystal, \( T_0 \), focusing parameter (ratio of crystal length to cavity confocal parameter), temperature-tuning coefficient \( \eta \), and range of signal wavelengths over which computations are to be done. The program lists values of the singly and doubly resonant thresholds, phase-matching temperature, value of \( K \), and idler wavelength.
for the requested set of signal wavelengths. See Sec. C9.4, subroutine PMT, for the method of calculating the phase-matching temperature.

C6. PARAMETRIC NOISE EMISSION (FLUORESCENCE)

This section of the program calculates the amount of signal output power to be expected from the spontaneous splitting of pump photons into signal and idler photons within a phase-matched nonlinear crystal. In this case, neither the signal nor the idler is resonant.

The expected signal power radiated into an acceptance angle \( \theta \) due to a pump of power \( P_p \) is given by \([28]\)

\[
P_s = 2(\beta L P_p/b)(\pi \theta)^2.
\]

(C9)

The constant \( \beta \) is given by \( \frac{2v^4v_i d^2 n_s}{(2\pi)^2 c^3 n_i n_p} \), where \( v_{s,i} \) are the signal and idler frequency, \( d \) the crystal nonlinear coefficient and \( n_{p,i,s} \) the indices of refraction. \( L \) is the crystal length. The dispersive constant is

\[
b = \frac{\partial k_s}{\partial \omega_s} - \frac{\partial k_i}{\partial \omega_i}
\]

which for nearly collinear interactions can be written,

\[
|b| = \frac{2\pi}{c} \left[ (n_s - n_i) + \left( \omega_s \frac{\partial n_s}{\partial \omega} - \omega_i \frac{\partial n_i}{\partial \omega} \right) \right]
\]

(C11)

See Sec. C9.3, subroutine ADC, for details on the calculation of \( b \).

Using a pump of 0.5 watt and acceptance angle of 1.5 degrees, \( P_s \) is typically \( 10^{-8} \) watts. A tabulation of the results of (C9) is given in Tables A1-A4.
The program requires as input the pump wavelength, pump power, 
$T_0$, tuning constant $n$, and a range of signal wavelengths over which 
the noise-emission power is to be calculated. The program also requires 
the crystal length, nonlinear coefficient, and the acceptance angle. 
The program produces a table of noise-emission power, value of $\beta$, idler 
wavelength, and phase-matching temperature as a function of signal wave-
length.

As an additional feature, the program calculates the external 
second-harmonic power generated by a pump of wavelength $\lambda_o = 2\lambda_p$ and 
power $P_p$. The second-harmonic power is given by [43]

$$P = \frac{2n}{\pi} \frac{n\omega_o dLP}{w_o^2}$$  \hspace{1cm} (C12)

where $d$ is the crystal nonlinear coefficient, $L$ is the crystal length, 
$\omega_o$ is the pump frequency, $w_o$ is the pump beam waist at the crystal, 
and $n$ is the free-space wave impedance, $377/(\text{index of refraction})$.

C7. OPTICAL RESONATOR DESIGN

The confocal parameter for a full spherical cavity of mirror 
radius $R$ and separation $d_{\text{eff}}$ is given by:

$$b^2 = d_{\text{eff}}(2R - d_{\text{eff}})$$  \hspace{1cm} (C13)

If the resonator is semispherical, then $d_{\text{eff}}$ is twice the mirror separa-
tion (see Fig. 3-17). If a resonator contains a crystal of length $L$ 
and index of refraction $n$, then the real mirror separation is given by:

$$d_{\text{real}} = d_{\text{eff}} + L(1 - \frac{1}{n}).$$  \hspace{1cm} (C14)
The program receives as input the mirror radius \( R \), the crystal length \( L \), index of refraction \( n \), and the desired focusing parameter, \( g \equiv L/b \), for the cavity. The optimum focusing parameter (2.84) \([11]\) may require \( a/b \) such that the quantity \((2R-d)\) may be too small for practical realization. Thus the program can receive a minimum value of \((2R-d)\) as input. It will alter the value of \( g \) to meet this restriction. The program outputs the value of the confocal parameter, \( b \), effective separation, \( d_{\text{eff}} \), real separation, \( d_{\text{real}} \), and new value of \( g \). This can be done for either a full spherical or semispherical resonator. These data provide the pertinent information for the design of the optical resonator to achieve a desired \( L/b \) for optimum optical parametric oscillation conditions. Further detail on optical resonator design is given in Sec. 3.4.

C8. GAUSSIAN BEAM MODE-MATCHING

This section of the program computes the beam waist to lens spacings required to mode-match the Gaussian beam of one optical cavity to the Gaussian beam of another optical cavity. For this study, the first cavity is the pump laser cavity and the second cavity is that of an OPO. The mode-matching problem is discussed in detail in Sec. 3.4-3. The geometry of the mode-matching process is illustrated in Fig. C1.

The program requires as input the focal length of the mode-matching lens, the mirror radius, and separation of the laser cavity, along with the crystal length and desired focusing parameter of the oscillator cavity. From these inputs, the program computes the con-
FIG. C1 TRANSFORMATION OF A GAUSSIAN BEAM BY A THIN LENS.
focal parameter for each cavity and the minimum focal length, $f_o$, given by (3-8). It checks to verify that $f_o$ is less than the focal length of the mode-matching lens. The beam waist to lens spacings are then computed using (3-9) and (3-10).

C9. SUBROUTINES

C9.1 Index of Refraction

Subroutine INDEX.

This subroutine computes the index of refraction for a crystal as a function of wavelength and temperature. The computation is based on Sellmeier equations for each crystal type.

C9.1A LiNbO$_3$(LN)

The index of refraction for LN is obtained from the Sellmeier equations published by Hobden and Warner [55]. They give the ordinary and extraordinary index of refraction as a function of wavelength and temperature.

\[ n^o_2 = 4.9130 + \frac{1.173 \times 10^5 + 1.65 \times 10^{-2} \lambda^2}{\lambda^2 - (2.12 \times 10^2 + 2.7 \times 10^{-5} \lambda^2)^2} - 2.78 \times 10^{-8} \lambda^2 \quad (C15) \]

\[ n^e_2 = 4.5567 + 2.605 \times 10^{-7} \lambda^2 + \frac{0.970 \times 10^5 + 2.70 \times 10^{-2} \lambda^2}{\lambda^2 - (2.01 \times 10^2 + 5.4 \times 10^{-5} \lambda^2)^2} - 2.24 \times 10^{-8} \lambda^2 \quad (C16) \]

The wavelength must be in nanometers (nm) and is good for a range of 400 nm to 4000 nm. The temperature is in degrees Kelvin and is good from 273° to 650° K.
C9.1B $\text{Ba}_2\text{NaNb}_5\text{O}_{15}$ (BSN)

The index of refraction for BSN is obtained from equations developed by Singh [19]. These equations are,

$$\frac{1}{n_x^2 - 1} = 0.25320 - 0.010226 \frac{1}{\lambda^2} \quad (C17)$$

$$\frac{1}{n_y^2 - 1} = 0.25320 - 0.010163 \frac{1}{\lambda^2} \quad (C18)$$

$$\frac{1}{n_z^2 - 1} = 0.27772 - 0.00894 \frac{1}{\lambda^2} \quad (C19)$$

Here wavelength must be given in microns. Little data is available on the temperature dependence, but it appears to be similar to that of LN.

For brevity, these equations can be written by substituting letters A through M for the corresponding numerical constants:

**LN**

$$n^0 = \left[A + \frac{B + CT^2}{\lambda^2 - (D - ET^2)^2} + FL^2 \right]^{\frac{1}{2}} \quad (C20)$$

$$n^e = \left[G + HT^2 + \frac{I + JT}{\lambda^2 - (K + LT^2)^2} + ML^2 \right]^{\frac{1}{2}} \quad (C21)$$

**BSN**

$$n_l = \left[\frac{1}{N_{1A} - N_{1B} \frac{\lambda^2}{\lambda^2}} + 1\right]^{\frac{1}{2}} \quad (C22)$$

where $l$ represents $X$, $Y$, or $Z$. 
C9.2 Temperature Tuning Constant

Subroutine ETA

This subroutine evaluates the constant, \( \eta \), required by the temperature-tuning equations of Sec. C2.

The temperature-tuning constant, \( \eta \), is given by,

\[
\eta = \sqrt{\frac{\omega_p}{\theta_T} \left( \frac{\eta^\circ_p}{\eta^\circ_o} - 1 \right)}
\]  \hspace{1cm} (C23)

Currently available index of refraction data do not permit accurate prediction of the value of \( \eta \) as a function of wavelength and temperature. Eta can be estimated by evaluating the appropriate derivative of the Sellmeier equations.

For LN,

\[
\frac{\partial n^e}{\partial T} = \frac{1}{n^e} \left[ H_T + \frac{J_T (\lambda^2 - (K + L T^2)^2) + 2 L T (1 + J T^2) (K + L T^2)}{[\lambda^2 - (K + L T^2)^2]^2} \right]
\]  \hspace{1cm} (C24)

where \( \lambda \) is evaluated at \( \lambda_p \),

\[
\frac{\partial n^o}{\partial T} = \frac{1}{n^o} \left[ C_T (\lambda^2 - (D + E T^2)^2) + (B + C T^2)(2E T)(D + E T^2) \right] \frac{1}{[\lambda^2 - (D + E T^2)^2]^2}
\]  \hspace{1cm} (C25)

where \( \lambda \) is evaluated at \( 2\lambda_p \),

\[
\frac{\partial n^o}{\partial \omega} = \frac{\lambda^3}{2\pi c n^o} \left[ -F + \frac{(B + C T^2)}{[\lambda^2 - (D + E T^2)^2]^2} \right]
\]  \hspace{1cm} (C26)
For BSN, since the numerical index-of-refraction equations do not include temperature, we use the experimental value [19],
\[ \frac{d}{dT}(n^e_p - n^o_o) = 1.1 \times 10^{-4} /^\circ C. \] (C27)

In the usual experimental arrangement, propagation along the Y axis corresponds to an ordinary wave, and propagation along the Z axis corresponds to an extraordinary wave. Thus, for BSN:
\[ \frac{\partial n^o}{\partial \omega} = \frac{\partial n_Y}{\partial \omega} = \frac{1}{n_Y} \left[ \frac{NYB}{2\pi c \lambda (NYA - \frac{NYB}{\lambda})^2} \right] \] (C28)

The ETA subroutine receives as input the pump wavelength and crystal temperature. Using the above derivatives of the index-of-refraction equations, it calculates the temperature-tuning constant.

A typical value of \( \eta \), found by curve fitting parametric noise-emission data, is \( 5.9 \times 10^{13} \) esu for LN and BSN. Computed values of \( \eta \) for LN range from \( 5.7 \times 10^{13} \) to \( 7.1 \times 10^{13} \) esu over a temperature span of 95° to 290° C. For BSN the computed \( \eta \) is \( 7.2 \times 10^{13} \) esu.

C9.3 Angular Dispersive Constant \( \beta \)

**Subroutine ADC**

The dispersive constant is used in the calculation of parametric noise-emission power discussed in Sec. C6. This subroutine evaluates the constant \( \beta \) using the form given in (C11). The quantities \( \frac{\partial n_s}{\partial \omega_s} \) and \( \frac{\partial n_i}{\partial \omega_i} \) are calculated from expressions of the same form as (C26) for LN and
(C28) for BSN, where \( \lambda \) is evaluated at the signal and idler wavelengths, respectively. Byer and Harris [28] report a value for \( b \) of \( 6.2 \times 10^{-10} \) sec/m for LN. A typical value computed by the program is \( 6.4 \times 10^{-10} \) sec/m. A typical value computed for BSN is \( 6.7 \times 10^{-10} \) sec/m. These values are given from far-from-degeneracy and \( b \) becomes smaller near degeneracy having a value of approximately \( 0.5 \times 10^{-10} \) sec/m.

C9.4 Phase-Matching Temperature

**Subroutine PMT**

For a given crystal temperature, \( T_0 \), and value of \( \eta \), it is straightforward to calculate the signal wavelength. This is done in the temperature-tuning section of the program where the crystal temperature, \( T \), is the independent variable. In the parametric oscillator threshold and parametric noise-emission sections of the program, the signal wavelength is given as the independent variable. It then becomes necessary to be able to calculate \( T \) given \( T_0 \), \( \eta \) and \( \lambda_s \). This calculation requires an iteration process, since the equations used in calculating \( T \) can be themselves functions of \( T \).

The initial value of \( T \) is taken as \( T_0 \). When \( T \) satisfies the equation:

\[
T_n = T_0 + 4\left[ \frac{\pi n c}{\eta} \left( \frac{\lambda_s - \lambda_o}{\lambda_s \lambda_o} \right) \right]^2
\]

(C29)

(where \( \eta \) is a function of \( T \), and \( \lambda_o = 2\lambda_p \)) to the point where \( T_n - T \) is less than the accuracy to which \( T \) must be known, then the iteration process can cease. (C29) is another form of (C3) where \( \delta T = T - T_0 \).
Successively more accurate estimates of $T$ are found by letting:

$$T = \frac{T_n + T_{old}}{2} \quad (C30)$$

This process is found to converge after only a few iterations, and the accuracy of the results has been confirmed by comparison with calculations where $T$ is the independent variable and $\lambda_s$ the dependent variable.

C9.5 Estimation of the Second-Harmonic Phase-Matching Temperature at a Given Wavelength from the Known SHG $T_o$ at a Nearby Wavelength

Subroutine TPMT

For a nonlinear crystal, it is often possible to experimentally establish $T_o$ at one wavelength, but desirable to know it at another. For example, second-harmonic generation at 532.0 nm can be observed by pumping with 1064 nm radiation from a Nd:YAG laser, thus establishing $T_o$ for the condition,

$$n^o(\lambda_p / 2, T_o) = n^0(\lambda_p, T_o), (\lambda_p = 1064 \text{ nm}) \quad (C31)$$

If 532.0 nm radiation is then used as a pump, $T_o$ is the temperature at which subharmonic generation would take place according to the condition,

$$n^o(\lambda_p, T_o) = n^0(\lambda_o, T_o), (\lambda_p = 532 \text{ nm}) \quad (C32)$$

An important source of continuous pump radiation is the argon gas laser at 514.5 nm. It is now desirable to know $T_o$ for subharmonic
generation of 1029 nm. Since \( \frac{\partial n}{\partial \lambda} \) is much larger than \( \frac{\partial n}{\partial T} \), it is to be expected that \( T_o \) for 514.5\( \rightarrow \)1029 will be significantly different from \( T_o \) for 532.0\( \rightarrow \)1064. Let \( \delta T \) represent the variation in phase-matching temperature, and \( \delta \lambda \) the variation in pump wavelength. \( \delta T \) can be established by taking the variance of (C32).

\[
\delta n_p^e = \delta n_o^o \quad (C33)
\]

Expanding (C33), and noting that \( \delta \lambda_o = 2 \delta \lambda \),

\[
\left( \frac{\partial n_p^e}{\partial \lambda} \right) \lambda_p \delta \lambda + \left( \frac{\partial n_o^o}{\partial \lambda} \right) \lambda_o \delta \lambda_o + \left( \frac{\partial n_o^o}{\partial T} \right) \delta T = \left( \frac{\partial n_p^e}{\partial \lambda} \right) \lambda_p \delta \lambda + \left( \frac{\partial n_o^o}{\partial T} \right) \delta T \quad (C34)
\]

Rearranging (C34),

\[
\delta T = \left[ \frac{2 \left( \frac{\partial n_o^o}{\partial \lambda} \right) \lambda_o - \left( \frac{\partial n_p^e}{\partial \lambda} \right) \lambda_p}{\frac{\partial}{\partial T} (n_p^e - n_o^o)} \right] \delta \lambda \quad (C35)
\]

In LN and BSN, the proportional quantity is positive, and \( T_o \) for the 514.5 nm pump is about 80° C lower than \( T_o \) for the 532.0 nm pump in LN and 50° C lower in BSN.

The proportionality between \( \delta T \) and \( \delta \lambda \) is calculated through the use of the following derivatives of equations (C15) to (C19).

For LN:

\[
\frac{\partial n_o^o}{\partial \lambda} = \frac{1}{n_o} \left[ F_{\lambda} - \frac{\lambda (B + CT^2)}{[\lambda^2 - (D + ET)^2]^2} \right] \quad (C36)
\]
\[
\frac{\partial n^e}{\partial \lambda} = \frac{1}{n^e} \left[ M \lambda - \frac{\lambda(1 + J T^2)}{[\lambda^2 - (K + L T^2)^2]^2} \right]
\] (C37)

The temperature derivatives for LN are given in equations (C24) and (C25).

For BSN:

\[
\frac{\partial n^o}{\partial \lambda} = \frac{\partial n^y}{\partial \lambda} = \frac{-NYB}{n \lambda^3(NY - NYB/\lambda^2)^2} \quad \text{(C38)}
\]

\[
\frac{\partial n^e}{\partial \lambda} = \frac{\partial n^z}{\partial \lambda} = \frac{-NZB}{n \lambda^3(NZ - NZB/\lambda^2)^2} \quad \text{(C39)}
\]

The temperature derivatives for BSN are given in equation (C27).

Since a temperature is being calculated, and the constant of proportionality between \( \delta T \) and \( \delta \lambda \) may be temperature dependent, errors are minimized by using an iterative technique. In this case, the interval \( \delta \lambda \) is divided into 0.5 nm intervals, and a \( \delta T \) computed for each interval. The small wavelength interval serves to minimize errors arising from the implicit temperature dependence.

The computations of this subroutine have been compared to the estimated phase-matching temperatures given by Midwinter [56]. In every case, the program was able to predict, using a given \( T_o \) (\( T_{pm} \) in Table III), any other \( T_o \) given in the same table.

C9.6 Second-Order Derivative of Index of Refraction with Respect to Frequency

This subroutine calculates the value of \( \frac{\partial^2 n^o}{\partial \omega^2} \) used in the orientation tuning (Sec. C3) of the main program.
For LN:

\[
\frac{\partial^2 n^0}{\partial \omega^2} = \frac{\chi^2}{2\pi c} \left[ \frac{3}{n^0} \left( F - \frac{B + CT^2}{[\lambda^2 - (D + ET^2)^2]^2} \right) - \frac{\lambda^2}{2n^0} \left( F - \frac{B + CT^2}{[\lambda^2 - (D + ET^2)^2]^2} \right)^2 \right]
+ \frac{4\lambda^2(B + CT^2)}{[\lambda^2 - (D + ET^2)^2]^3} \right].
\]

(C40)

For BSN:

\[
\frac{\partial^2 n^0}{\partial \omega^2} = \frac{3}{2\pi c} \left[ \frac{1}{n_y} \frac{-1}{\lambda^2} \left( \frac{NYB}{\lambda^2} \right)^2 + \frac{NYB}{\lambda^4(nYA - \frac{NYB}{\lambda^2})} \right] \frac{4NYB^2}{\lambda^6(nYA - \frac{NYB}{\lambda^2})} \right].
\]

(C41)

C9.7 Tuning Curve Calcomp Plotting

Subroutine T PLOT

This subroutine calls the necessary Calcomp plotting subroutines to produce an 8 1/2 x 11 Calcomp plot of temperature, electric field, or orientation-tuning data. In the case of temperature tuning, it will include experimental data points if they have been input to the program as a part of the \( \eta \) optimization procedure.

The subroutine receives as input an indicator for temperature, orientation or electric field plotting, the corresponding array, signal wavelength array, idler wavelength array, number of points in the arrays, pump wavelength, crystal code (1 for LN, 2 for BSN), and value of \( \eta \).
It must also receive an indicator as to whether or not to include experimental data in the plot. The tuning curves in Figures 3-6 to 3-16 were produced by this subroutine.
APPENDIX D

COMPUTER PROGRAM LISTING

NONLINEAR OPTICAL AND PARAMETRIC COMPUTATIONS
PROGRAM NOPC

NONLINEAR OPTICAL AND PARAMETRIC COMPUTATIONS
CLIFFORD L. LAURENCE
RICE UNIVERSITY

FUNCTION CODES

1 - TEMPERATURE TUNING EFFECT NO PLOTTING
2 - TEMPERATURE TUNING EFFECT WITH PLOTTING
3 - ORIENTATION TUNING EFFECT NO PLOTTING
4 - ORIENTATION TUNING EFFECT WITH PLOTTING
5 - ELECTRIC FIELD TUNING NO PLOTTING
6 - ELECTRIC FIELD TUNING WITH PLOTTING
7 - DOUBLY RESONANT OPO (DRO) POWER THRESHOLD
   INPUT SIGNAL WAVELENGTHS
8 - DOUBLY RESONANT OPO POWER THRESHOLD
   SIGNAL WAVELENGTHS TAKEN FROM LAST CODE 1 OR 2 RUN
9 - SINGLY RESONANT OPO (SRO) POWER THRESHOLD
   INPUT SIGNAL WAVELENGTHS
10 - SINGLY RESONANT OPO (SRO) POWER THRESHOLD
    SIGNAL WAVELENGTHS TAKEN FROM LAST CODE 1 OR 2 RUN
11 - NON-RESONANT PARAMETRIC THRESHOLD (FLUORESCENCE)
12 - OPO DESIGN CALC SYMMETRICAL RESONATOR INPUT INDEX OF REFRACTIVITY
13 - OPO DESIGN CALC SYMMETRICAL RESONATOR
    INPUT TEMPERATURE AND PUMP WAVELENGTH TO CALC INDEX OF REFRACTIVITY
14 - SAME AS 12 ONLY HEMISPHERICAL
15 - SAME AS 13 ONLY HEMISPHERICAL
16 - GAUSSIAN BEAM MODE MATCHING
    INPUT R1,D1,R2,D2
17 - GAUSSIAN BEAM MODE MATCHING
    INPUT R1,D1,L/B,L

FUNCTION CODE CARD FORMAT

COLUMNS 1-2 FUNCTION CODE
3-4 CRYSTAL TYPE CODE
5-6 0 - NO DATA TO PLOT
     1 - DATA TO PLOT IMMEDIATELY FOLLOWS THIS FUNCTION
7-8 CRYSTAL IDENTIFICATION NUMBER

00003800
00004050
CRYSTAL CODES  
1 - LITHIUM NIOBATE  
2 - BARIUM SODIUM META NIOBATE  

INPUTTING DATA TO BE PLOTTED WITH A TUNING CURVE  
FIRST CARD CONTAINS NO OF POINTS TO BE PLOTTED IN COLS 1-5  
THIS IS CURRENTLY LIMITED TO 200  
INPUT DATA FOLLOWS ON (N+3)/4 CARDS FOUR DATA POINTS PER CARD  
THE PAIRS OF COORDINATES FOR EACH DATA POINT GIVE  
The X COORD FIRST (DEG C) THEN THE Y COORD (ANGSTROMS)  
WAVELENGTHS ARE INPUT AND OUTPUT IN ANGSTROMS BUT USED INTERNALLY  
IN CM. THEY ARE CONVERTED TO NM FOR THE SELLMIER EQUATIONS  
TEMPERATURES ARE IN DEG C UNLESS CONVERTED TO DEG K FOR SELLMIER  

GENERAL INPUT FORMAT  
THE INPUT VARIABLES BEGIN IN COLUMNS 1,10,20,30,40,50,60,70  
AND SHOULD APPEAR IN THIS ORDER ACCORDING TO THE LIST GIVEN AT  
THE BEGINNING OF EACH SECTION  
The VARIABLES ARE INPUT ACCORDING TO A POSITION CODE (P CODE)  
The POSITION CODES ARE AS FOLLOWS  
P 1 - CARD 1 COLUMNS 1-9  
P 2 - CARD 1 COLUMNS 10-19  
P 3 - CARD 1 COLUMNS 20-29  
P 4 - CARD 1 COLUMNS 30-39  
P 5 - CARD 1 COLUMNS 40-49  
P 6 - CARD 1 COLUMNS 50-59  
P 7 - CARD 1 COLUMNS 60-69  
P 8 - CARD 1 COLUMNS 70-79  
P 9 - CARD 2 COLUMNS 1-9  
P 10 - CARD 2 COLUMNS 10-19  
P 11 - CARD 2 COLUMNS 20-29  
P 12 - CARD 2 COLUMNS 30-39  

REAL LO,N,LX,LXLB,NP,NS,NI,K,NO,LCR,LBNEW,LP,L,LPNM,LONM,NOF,NEF,NEPC0550  
X,LXFT,LEFT,LN,LSX,LIX,LOMC,LPMC,NXA,NXB,NYA,NYB,NZA,NZB  

INTEGER CRYST  
COMMON /CLIFF/ PI,CX,TWPIC,H,AA,AB,AC,AD,AE,AF,  
X,BA,BB,BC,BD,BE,BF,BG,EO,AX,AAX,ANY,AYB,ANZB,CNCMC  
COMMON /CLIFF/ ITYPE,EXPX,EXPY,NN,NCR,IFC,TO,TEMP  
DIMENSION EXPY(50),EXPY(50)  
DIMENSION AMESS(3),TDATA(103),SDATA(103),CIDATA(103)  
DIMENSION CRYST(4),IDESCRIPT(17)  
DATA CRYST/6HLINR003,6H,6HBA2NAN,6HB5015/  

NO CPC0307  
NO CPC0308  
NO CPC0310  
NO CPC0311  
NO CPC0312  
NO CPC0313  
NO CPC0314  
NO CPC0315  
NO CPC0316  
NO CPC0317  
NO CPC0320  
NO CPC0330  
NO CPC0340  
NO CPC0350  
NO CPC0360  
NO CPC0370  
NO CPC0380  
NO CPC0390  
NO CPC0400  
NO CPC0410  
NO CPC0420  
NO CPC0430  
NO CPC0440  
NO CPC0450  
NO CPC0460  
NO CPC0470  
NO CPC0480  
NO CPC0490  
NO CPC0500  
NO CPC0510  
NO CPC0520  
NO CPC0530  
NO CPC0540  
NO CPC0550  
NO CPC0560  
NO CPC0570  
NO CPC0580  
NO CPC0590  
NO CPC0595  
NO CPC08400
DATA AMESS, SEMIC, RLKS/4H, 4HCONF, 4HOICAL, 4HSEMI, 4H /  NOPC0600
DATA ICPL, IETA/0, 0/  NOPC0610
NOCPC0620
C
DTIME = TIME(2)/60.0
WRITE (6, 777) DTIME
777 FORMAT (* EXECUTION TIME SEC =*, F10.2)
1 IETA = 0
READ (5, 1001, END = 998) IFC, ITYPE, IDP, NCR
1001 FORMAT (4I2)
   IF (ITYPE .LE. 0 .OR. ITYPE .GT. 2) GO TO 187
   IF (0.LT.IFC.AND. IFC.LT.18) GO TO 2
WRITE (6, 1002)
1002 FORMAT (1H1, 10X, '**** ILLEGAL FUNCTION CODE *****')
   GO TO 999
187 WRITE (6, 1151) ITYPE
1151 FORMAT ('**** ILLEGAL CRYSTAL CODE ', I5, ' *****')
   GO TO 999
C
FUN CODE 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
   2 GO TO (3+4*10, 11, 30, 31, 50, 53, 50, 53, 80, 100, 101, 96, 97, 120, 121), IFC
C
C
TERMINATION
C
999 CONTINUE
   GO TO 1
998 IF (ICPL .EQ. 1) CALL PLOT (0.0, 0.0, 0.999)
DWRITE = TIME(2)/60.0
WRITE (6, 777) DTIME
STOP
C
C
INPUT ERROR PROCEDURE
C
888 WRITE (6, 1500) IFC
1500 FORMAT ('**** INPUT DATA ERROR FUNCTION CODE ', I3, ' CONTINUING')
   X TO NEXT FUNCTION *****')
   GO TO 1
C
C
TEMPERATURE TUNING FUNCTION
C
C
INPUTS PUMP WAVELENGTH (A) PWL
SHG PHASE MATCHING TEMPERATURE (DEG C) TO
TEMPERATURE INCREMENT (DEG C) DELT
P 1 NOPC0910
P 2 NOPC0920
P 3 NOPC0930
C
C     FINAL TEMPERATURE (DEG C)  TF
        P 4 NOPC0940
C     PUMP WAVELENGTH FOR WHICH THE GIVEN SHG TEMP APPLIES  NOPC0950
C     IF SAME AS PUMP INPUT ZERO  (A)  PWLO  P 5 NOPC0960
C     TUNING CONSTANT ETA (E13 ESU)  N
        P 6 NOPC0963
C     IF INPUT ZERO ETA IS CALCULATED FROM SELLMIE R EGNS  NOPC0966
C     FINAL VALUE OF ETA WHEN OPTIMIZING (E13 ESU)  ETAF  P 7
C     A NONZERO ETAF SIGNALS THE PROGRAM TO FIND THE BEST
C     VALUE OF ETA BETWEEN N AND ETAF TO CURVE FIT THE
C     EXPERIMENTAL DATA TO THE NEAREST ETINC*E13 ESU
C     ETA INCREMENT (E13 ESU)  ETINC  P 8
C     VALUE BY WHICH ETA IS TO BE INCREMENTED DURING
C     OPTIMIZATION PROCEDURE

3 IPL0T=0
GO TO 5
4 IPL0T=1
5 READ (5,1003) PWL,TO,DELT,TF,PWLO,N,ETA F,ETINC

1003 FORMAT (F9.2,7F10.2)  NOPC1020
   IF (PW L .LE. 3000.0 ) GO TO 888
   IF (DELT .LE. 0.0 ) GO TO 888
   IF ( TO .LT. -273.15 .OR. TO .GT. 500.0 ) GO TO 888
   IF ( TF .LT. -273.15 .OR. TF .GT. 500.0 ) GO TO 888
   IF (IDP .EQ. 0 ) GO TO 23
C
C     READ IN PLOT DATA
C     READ (5,25) NN,IDESCR

25 FORMAT (I5,4X,17A4)
   IF (NN .LT. 0 .OR. NN .GT. 50) GO TO 24
   READ (5,1003) ( EXPI(I),EXPY(I),I=1,NN)
   WRITE (6,26) NN,IDESCR,(EXPX(I),EXPY(I),I=1,NN)

26 FORMAT ('1 ***** TEMPERATURE TUNING DATA ***** FOR ',I4,
          ' X ' POINTS///1H ,17A4///
          ' X 1H ,9X,Temperature (DEG C) WAVELENGTH (A)///(1H ,14X,F10.2,
          ' X 9X,F10.1))
   GO TO 23
24 WRITE (6,27) NN
27 FORMAT ('/\ DATA PLOT NOT PROCESSED NUMBER OF POINTS=',I5,/')
   GO TO 999
C
C     CONVERT TO CM
23 PWL=PWL*1.0E-8
   PWLO=PWLO*1.0E-8
   ILINE=0
   IF (N .NE. 0.0) IETA=1
   N = N*1.0E13

NO PC1050
NO PC1060
NO PC1070
NO PC1080
NO PC1083
NO PC1086
IF (PWLO .EQ. 0.0) GO TO 201
C GET TEMP CORRECTION
CALL TPMT (PWLO,T0,PWLTI)
GO TO 202
201 T0=T0
202 WRITE (6,1004) CRYS1(2*ITYPE-1),CRYS1(2*ITYPE),NCR,PWLTI
1004 FORMAT (1H1,10X,*** TEMPERATURE TUNING EFFECT *** IN ',2A6)
X 'CRYSTAL NO.','I2'/
X 1H,10X, 'PUMP WAVELENGTH =',8PF10.2,'(A)' ,5X,'SHG CORRECTED TEMPERATURES',8X,'SIGNAL NOCP1160
XPERATURE =',OPF10.2,'(deg C)'///2X,'TEMPERATURE(C.),' ,8X,'SIGNAL NOCP1170
XWAVELENGTH=6X, 'IDLER WAVELENGTH=',11X,'W(N1/CM)',13X,'W(M1/CM)',8X'NOC1180
X,'ETA '/
ILIM=(TF-TI)/DELT + 1
IF (IPLOT .EQ. 0 ) GO TO 6
IF (ILIM .LT. 102 ) GO TO 6
WRITE (6,1005)
1005 FORMAT (1H1,*** TOO MANY DATA POINTS FOR TEMPERATURE TUNING PLOT***)
GO TO 999
6 L0 = 2.0*PWLO
WO = TWPIC/LO
C CHECK FOR OPTIMIZATION REQUEST
IF ( ETAF ,NE., 0.0 ) GO TO 150
28 TEMP = TI - DELT
DO 9 I=ILIM
TEMP = TEMP + DELT
C SAVE FOR TPLT
TDATA(I) = TEMP
7 IF(IETA ,EQ.0) CALL ETA(PWLO,TEMP,N,DUM,DUMMY)
DELW = N*SORT(TEMP-TI)
WS = WO + DELW
WN = WS/TWPIC
WI = WO - DELW
WM = WI/TWPIC
C CONVERT TO ANGSTROMS
LS = 1.0E+8/ WN
C SAVE FOR TPLT
SDATA(I) = LS
C CONVERT TO ANGSTROMS
LI = 1.0E+8/ WM
RIDATA(I) = LI
C SAVE FOR TPLT
8 WRITE (6,1006) TEMP,LS,LI,WN,WM,N
1006 FORMAT (1H ,5X,F9.2,2(10X,F14.1),2(12X,F9.2),5X,1PE14.5)
ILINE = ILINE + 1
IF (ILINE .LT. 51 .OR. ILINE .EQ. ILIM ) GO TO 9
ILINE = 0
WRITE (6,1004) CRYS Y(2 ITYPE=1),CRYS Y(2 ITYPE),NCR,PWL,TI
CONTINUE
9 CONTINUE
IF (IPL T .EQ. 0 ) GO TO 1
ICPL = 1
ILX C = ILIM
CALL T PLOT(TDATA,SDATA,RDATA,ILXC,PWL,IPD,N)
GO TO 1
C
ETA - TEMPERATURE TUNING CONSTANT OPTIMIZATION PROCEDURE
THIS SECTION FINDS THE BEST ETA BETWEEN N AND ETA F IN
INCREMENTS OF 0.1 E13 ESU FOR A BEST FIT OF THE GENERATED
DATA TO THE EXPERIMENTAL DATA

C
BE SURE HAVE EXPERIMENTAL DATA BEFORE OPTIMIZING
150 IF (IDP .EQ. 0 ) GO TO 28
IF ( ETINC .LE. 0.0 ) GO TO 888
ETAF = ETA F*1.0E13
ETINC = ETINC*1.0E13
ETX = N - ETINC
C
INITIALIZE SMIN LARGE
SMIN = 1.0E30
C
INCREMENT ETA BY 0.1 E13 ESU
151 ETX = ETX + ETINC
TEMP = TI - DELT
DO 152 I=1,ILIM
TEMP = TEMP + DELT
TDATA(I) = TEMP
WS = W0 + ETX*SQRT(TEMP-TI)
152 SDATA(I) = TWPIC*1.0E8/WS
SUM = 0.0
DO 154 I=1,NN
C
FIND THE NEAREST GENERATED POINT TO DATA POINT I
C
INITIALIZE MIN LARGE
MIN = 1000.0
DO 155 J=1,ILIM
DIFT = ABS(EXPX(I) - TDATA(J))
IF (MIN .LE. DIFT ) GO TO 155
C
SAVE THE INDEX OF CLOSEST POINT
156 JJ = J
MIN = DIFT
229
155 CONTINUE
C FORM THE SUM OF THE SQUARES OF THE ORDINATE DIFFERENCES
154 SUM = SUM + ABS(EXP(I)-SDATA(JJ))
    IF ( SMIN .LE. SUM ) GO TO 159
C SAVE THE ETA WITH MINIMUM DIFFERENCES
158 N = ETX
    SMIN = SUM
159 IF ( ETX .LE. ETAF ) GO TO 151
    GO TO 28
C ORIENTATION TUNING EFFECT

C INPUTS
C PUMP WAVELENGTH (A) PWL
C INITIAL ANGLE (DEG) AI
C ANGLE INCREMENT (DEG) DELA
C FINAL ANGLE (DEG) AZ
C SHG PM TEMP (DEG C) TO
C CRYSTAL TEMPERATURE (DEG C) TEMP
C TEMPERATURE TUNING CONSTANT (E13 ESU) N
C ZERO IF PROG IS TO COMPUTE
C PUMP WAVELENGTH AT WHICH TO APPLIES (A) PWLO
C OTHERWISE ZERO

C 10 I PLOT = 0
    GO TO 12
11 I PLOT = 1
12 READ (5,1003) PWL, AI, DELA, AZ, TO, TEMP, N, PWLO
    IF (PW L .LE. 3000.0 ) GO TO 888
    IF (AI .LT. 0.0 * OR. AI .GT. 360.0 ) GO TO 888
    IF (DELA .LT. 0.0 * OR. DELA .GT. 360.0 ) GO TO 888
    IF (AZ .LT. 0.0 * OR. AZ .GT. 360.0 ) GO TO 888
    IF (TEMP .LT. -273.15 * OR. TEMP .GT. 500.0 ) GO TO 888
    PWLO = PWL0*1.0E-8
    PWL = PWL*1.0E-8
    N = N*1.0E13
    IF (PWLO .EQ. 0.0 ) GO TO 21
    CALL TPMT (PWLO, TO, PWL, TO)
21 WP = TWPIC/PWL
    WO = WP/2.0
    SUBW = 2.0*PW L
    CALL INDEX (PWL, TEMP, 1, PNO)
    CALL INDEX (PWL, TEMP, 1, PNE)
    B = PNE - PNO
    A = B*PNE*(2.0 + B/PNO)/(2.0*PNO)
CALL INDEX (SURWL, TEMP, NOF)
IF (N .EQ. 0) CALL ETA (PWL, TEMP, N, DUM, DNOEW)
IF (N .NE. 0) CALL ETA (PWL, TEMP, NXX, DUM, DNOEW)
CALL DNOEW (PWL, TEMP, D2W)
CC = 0.0
ILINE = 0
WRITE (6, 13) CRYST (2, ITYPE = 1), CRYST (2, ITYPE), NCR, PWL, TEMP, B
13 FORMAT (11, 10X, 15X, '**** ORIENTATION TUNING EFFECT ***** IN ', 1X)
   X 'PUMP WAVELENGTH = '8PF10.2', (A) CRYSTAL TEMPE00030000
   X 'REFRINGENCE = '8PF8.4'/
   X 'ANGLE (DEG) = 9X', 'SIGNAL WAVELENGTH (A) IDLER WAVELE
   X 'NGTH (A) = 11X', 'WN1/CM, 7X', 'WN1/CM, 5X', 'DELW'/
   ILIM = (AZ - AI )/DEL + 1
   IF ( ILIM .LT. 102 ) GO TO 15
   WRITE (6, 14)
14 FORMAT ('*1 TOO MANY DATA POINTS FOR ORIENTATION TUNING*)
   GO TO 999
15 THET = AI - DELA
   DO 17 I=1, ILIM
   THET = THET + DELA
   SAVE FOR PLOT
   TDATA(I) = THET
   DELW = SQRT(WO*(CC - A*(SIN(THET*1.74533E-2))**2))/
   X (DNOEW + WO*D2W/2.0))
   IF (T .EQ. TO) GO TO 22
   C ADJUST DELW FOR TEMP TUNING
   DELW = SQRT(N**2*(TEMP - TO) + DELW**2)
   WS = WO + DELW
   WI = WO - DELW
   SWL = TWPIC/WS
   RWL = TWPIC/WI
   WNS = 1.0/SWL
   WNI = 1.0/RWL
   C SAVE FOR PLOT AND CONVERT TO ANGSTROMS
   SDATA(I) = SWL*1.0E+9
   RIDATA(I) = RWL*1.0E+8
   WRITE (6, 16) I, DATA(I), D2W, WNS, WNI
   X 5X, 'P1E10.3')
   ILINE = ILINE + 1
   IF (ILINE .LT. 51 .OR. ILINE .EQ. ILIM ) GO TO 17
   ILINF = 0
WRITE (6,13) CRYS1T(2*ITYPE-1),CRYS1T(2*ITYPE),NCR,PWL,TEMP,B
17 CONTINUE
IF (IPLOT .EQ. 0) GO TO 1
ICPL = 1
ILXC = ILIM
CALL TPL0T(IDATA,SDATA,RDATA,ILXC,PWL,IDP,N)
GO TO 1
END ORIENTATION TUNING

ELECTRIC FIELD TUNING

THIS FUNCTION CALCULATES THE VARIATION IN SIGNAL WAVELENGTH
DUE TO A Z AXIS APPLIED ELECTRIC FIELD

INPUTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUMP WAVELENGTH (A)</td>
<td>PWL</td>
</tr>
<tr>
<td>INITIAL VALUE OF APPLIED VOLTAGE (VOLTS)</td>
<td>VI</td>
</tr>
<tr>
<td>VOLTAGE INCREMENT (VOLTS)</td>
<td>DELV</td>
</tr>
<tr>
<td>FINAL VALUE OF VOLTAGE (VOLTS)</td>
<td>VF</td>
</tr>
<tr>
<td>ELECTRO-OPTIC R13 COEFFICIENT (E=10 CM/VOLT)</td>
<td>R13</td>
</tr>
<tr>
<td>ELECTRO-OPTIC R33 COEFFICIENT (E=10 CM/VOLT)</td>
<td>R33</td>
</tr>
<tr>
<td>TUNING PLATE SEPARATION (CM)</td>
<td>PSEP</td>
</tr>
<tr>
<td>SHG PHASE MATCHING TEMPERATURE (DEG C) TO</td>
<td>P8</td>
</tr>
<tr>
<td>CRYSTAL TEMPERATURE (DEG C)</td>
<td>P9</td>
</tr>
<tr>
<td>TEMPERATURE TUNING CONSTANT (E13 ESU)</td>
<td>N</td>
</tr>
<tr>
<td>ZERO IF PROG IS TO COMPUTE</td>
<td></td>
</tr>
<tr>
<td>PUMP WAVELENGTH AT WHICH TO APPLIES (A)</td>
<td>PWLO</td>
</tr>
</tbody>
</table>

00033100

30 IPLOT = 0
GO TO 32

31 IPLOT = 1
32 READ (5,1003) PWL,VI,DELV,VF,R13,R33,PSEP,TO
READ (5,1003) TEMP,N,PWLO
IF (PWL .LE. 3000.0) GO TO 888
IF (VI .LT. 0.0 .OR. VI .GT. 6000.0) GO TO 888
IF (DELV .LT. 0.0 .OR. DELV .GT. 6000.0) GO TO 888
IF (VF.LT. 0.0 .OR. VF .GT. 6000.0) GO TO 888
IF (TEMP .LT. -273.15 .OR. TEMP .GT. 500.0) GO TO 888
PWLO = PWLO*1.0E-8
PWLO = PWL*1.0E-8
N = N*1.0E13
CONVERT TO CM/VOLT
R13 = R13*1.0E-10
R33 = R33*1.0E-10
IF (PWLO .EQ. 0.0) GO TO 34
CALL TPMT (PWLO, TO, PWL, TO)

34 WO = 0.5 * TWPIC/PWL
LO = 2.0 * PWL
CALL INDEX (LO, TEMP, NOF)
IF (N .EQ. 0.0) CALL ETA(PWL, TEMP, N, DUM, DNODW)
IF (N .NE. 0.0) CALL ETA(PWL, TEMP, NXX, DUM, DNODW)
WRITE (6, 35) CRYS{2*ITYPE-1}, CRYS{2*ITYPE}, NCR, PWL, TEMP, NOF
X DNODW, R13, R33

35 FORMAT ('1, R3 ', '***** ELECTRIC FIELD TUNING EFFECT ***** IN ',
' ', 'X ', '2A6, 'CRystal NO.', ', I2, '
' ', 'X ', 'PUMP WAVELENGTH = ', '8PF10.2', ' (A) ',
' ', 'X ', 'XATURE = ', '0PF8.2', ' ',
' ', 'X ', 'ORDINARY INDEX AT SUBHAR = ', '0PF8.3', ' ',
' ', 'X ', 'PAR(INDEX)/PAR(W) = ', '1PE12.4', ' ',
' ', 'X ', 'ELECTRO-OPTIC COEFFICIE
' ', 'X ', 'NXX R13 = ', '1PE12.2', ' ',
' ', 'R33 = ', '1PE12.2', ' ',
' ', 'X ', 'APPLIED FIELD (VOLTS)*5X', 'SIGNAL WAVELENGTH (A) ',
' ', 'X ', 'IDLER WAVE LENGTH (A)*11X', 'WN(1/CM)*7X', 'WN(1/CM)*5X', ' DELW/
' ', 'X ', 'ILINE = 0
' ', 'X ', 'ILIM = (VF - VI)/DELV + 1
' ', 'X ', 'IF (ILIM .LT. 102) GO TO 37
' ', 'X ', 'WRITE (6, 36)

36 FORMAT ('1 TOO MANY DATA POINTS FOR E FIELD TUNING')
GO TO 999

37 VLT = VI - DELV
DO 40 I = 1, ILIM
VLT = VLT + DELV
C SAVE FOR PLOT
EF = VLT / PSEP
TDATA(I) = EF
DELW = SQRT(ABS(WO*NOF**3/2.0*(R13 - R33)*EF/DNODW))
IF (T .EQ. TO) GO TO 41
C ADJUST DELW FOR TEMP TUNING
DELW = SQRT(N**2*(TEMP-TO) + DELW**2)

41 WS = WO + DELW
WI = WO - DELW
SWL = TWPIC/WS
RIWL = TWPIC/WI
WS = 1.0/WS
WI = 1.0/RIWL
C SAVE FOR PLOT AND CONVERT TO ANGSTROMS
SDATA(I) = SWL*1.0E+8
RIDATA(I) = RIWL*1.0E+8
WRITE (6, 3A) VLT, SWL, RIWL, WNS, WNI, DELW
38 FORMAT (*'8X,F9.2,16X,APF9.1,16X,8PF9.1,16X,0PF9.1,6X,0PF9.1,
X 5X,1PE10.3)
  ILINE = ILINE + 1
  IF (ILINE .LT. 51 .OR. ILINE .EQ. ILIM ) GO TO 40
  ILINE = 0
  WRITE (6,35) CRYS(2*IYPE-1),CRYS(2*IYPE),NCR,PWL,TEMP,NOF,
X DNOOD,R13,R33
  00041500
00041600
40 CONTINUE
  IF (IPLTO .EQ. 0 ) GO TO 1
  ICPL = 1
  ILXC = ILIM
  CALL TPLOT(TDATA,SDATA,RDATA,ILXC,PWL,IDP,N)
  00041950
00042000
C
GO TO 1
C
END OF E FIELD TUNING
C
DOUBLY AND SINGLY RESONANT OPO THRESHOLD
C
INPUTS PUMP WAVELENGTH (A) PWL
FRACTIONAL LOSSES IN SIGNAL E1
FRACTIONAL LOSSES IN IDLER E2
IF DESIRE SRO ONLY USE E2=0.50 DO NOT LEAVE IT 0.0
CRYSTAL NONLINEAR D COEFFICIENT (E-8 ESU) DCOF
CRYSTAL LENGTH (CM) CRL
CRYSTAL SHG PHASE MATCHING TEMPERATURE (DEG C) TC
CRYSTAL LENGTH - CONFOCAL PARAMETER RATIO FOR OPTIMIZATION
OF OPTICAL CAVITY (L/R) LR
PUMP WAVELENGTH AT WHICH THE PHASE MATCHING TEMPERATURE APPLIES
IF SAME AS PUMP INPUT ZERO PWLO
TEMPERATURE TUNING CONSTANT ETA (E13 ESU) N
IF INPUT ZERO ETA IS CALCULATED FROM SELLMIER EQNS
INITIAL SIGNAL WAVELENGTH (A) SWL
FINAL SIGNAL WAVELENGTH INCREMENT (A) SWLI
C
50 ISIG = 0
READ (5,1003) PWL,E1,E2,DCOF,CRL,TC,LR,PWLO
READ (5,1003) N,SWL,SWLI,SWLF
IF (SWL .LE. 3000.0) GO TO 888
IF (SWLI .LE. 0.0) GO TO 888
IF (SWLF .LE. SWL ) GO TO 888
ISW = (SWLF - SWL)/SWLI + 1
IF (ISW .LT. 102) GO TO 51
C
NOCPC2730
NOCPC2740
NOCPC2750
NOCPC2760
NOCPC2770
NOCPC2780
NOCPC2785
NOCPC2790
NOCPC2800
NOCPC2810
NOCPC2820
NOCPC2830
NOCPC2840
NOCPC2850
NOCPC2853
NOCPC2856
NOCPC2860
NOCPC2860
NOCPC2870
NOCPC2880
NOCPC2890
NOCPC2900
NOCPC2910
NOCPC2920
NOCPC2930
NOCPC2940
NOCPC2950
NOCPC2960
NOCPC2970
WRITE (6,1010)
1010 FORMAT (1H ,"TOO MANY SIGNAL WAVELENGTHS FOR ONE INPUT SET")
GO TO 999
51 SDATA(I) = SWL
DO 52 I=1,ISW
52 SDATA(I+1) = SDATA(I) + SWLI
GO TO 54
53 ISIG = 1
READ (5,1003) PWL,E1,E2,DCOF,CRL,TC,LB,PWLO
READ (5,1003) N
ISW = ILIM
54 IF (PWL .LE. 3000.0) GO TO 888
IF (E1 .LE. 0.0) GO TO 888
IF (E2 .LE. 0.0) GO TO 888
IF (DCOF .LE. 0.0) GO TO 888
IF (CRL .LE. 0.0) GO TO 888
IF (LB .LE. 0.0) GO TO 888
IF (N .NE. 0.0) IETA=1
N = N+1.0E13
C CONVERT TO CM
PWL = PWL*1.0E-8
T2 = TC
IF (PWLO .EQ. 0.0) GO TO 540
PWLO = PWLO*1.0E-8
CALL TPMT (PWLO,TC,PWLO,T2)
C CONVERT TO ESU
540 DCOF = DCOF*1.0E-8
WP = TWPIC/PWL
C W REPRESENTS OMEGA, ANGULAR FREQUENCY
WO = WP/2.0
OWL = 2.0*PWL
B = CRL/LB
WIDO = SQRT(R*PW/(2.0*PI))
WRITE (6,1011) CRYST(2*TYPE-1),CRYST(2*TYPE),NCR,PWL,E1,E2,DCOF,00048500
X CRL,B,WIDO,T2,LB
1011 FORMAT (1H ,"DOUBLY AND SINGLY RESONANT OPO THRESHOLDS ",I2/,I1H ,"X IN "*2A6,"CRYSTAL NO. ",I2//
XP ,",*8PF10.2,5X,*LOSSES ,"*2(2X,0PF7.4),5X,"*NONLINEAR COEFFICIENT ",I1H ,"*PUM00048800
X*1PE12.3,5X,"CRYSTAL LENGTH ",0PF5.2/
X* CONFOCAL PARAMETER ="1PE12.3", (CM) REAM WIDTH ="1PE12.3",
X" (CM) PM TEMP="*0PF10.2," DEG C L/B="*0PF6.2//1H ,10X,
X" SIGNAL",9X,"*TEMPERATURE",
X 7X,"*K COEFFICIENT(FSU)",5X,"*THRESHOLD POWER",
X
X 5X, 'THRESHOLD POWER', 5X, 'IDLER', 6AX, 'DRO (WATTS)', 9X
X 'SRO (WATTS)'/
ILINE = 0
DO 57 I = 1, ISW
C CONVERT TO CM
SWL = SDATA(I) * 1.0E-8
C SIGNAL WAVE LENGTH
C RESTRICT THE SIGNAL TO LESS THAN THE SUB-HARMONIC
IF (SWL .GT. OWL + 1.0E-8) GO TO 57
FIWL = (SWL * OWL) / (2.0 * SWL - OWL)
C IDLER WAVELENGTH
IF (ISIG .EQ. 1) GO TO 55
CALL PMT(SWL, PWL, TZ, TMP, IETA, I)
GO TO 56
55 TMP = TDATA(I)
56 CALL INDEX (PWL, TMP, -1, NP)
CALL INDEX (SWL, TMP, +1, NS)
CALL INDEX (FIWL, TMP, +1, NI)
K = 128.0 * (PI * WO * 2.0 * DCOF)**2 / (NP * NS * NI * (C**3))
WS = TWPIC / SWL
GAM = (WO - WS) / WO
CALL INDEX (OWL, TMP, +1, NO)
ETN = (NO - NS) / NO
POWD = 4.0 * E1 * E2 * (1.0 - GAM * ETN) / ((1.0 - GAM**2)**2 * (1.0 - ETN**2))
X = (WID) / (C**R)
POWS = POWD**2 / (C**R)
POW5 = POWD**2 / (C**R)
C CONVERT ERG-SEC TO WATTS
POWD = POWD**1.0E-7
POWS = POWS**1.0E-7
WRITE (6, 1012) SWL, TMP, K, POWD, POWS, FIWL
1012 FORMAT (1H, 6X, 8PF10.2, 5X, 0PF10.2, 11X, 1PE13.6, 5X, 1PE15.3, 5X, X1PE15.3, 9X, 8PF10.2)
ILINE = ILINE + 1
IF (ILINE .LT. 51 .OR. ILINE .EQ. ISW) GO TO 57
ILINE = 0
WRITE (6, 1011) CRYST(2*ITYPE=1), CRYST(2*ITYPE), NCR, PWL, E1, E2, DCOF
X CRL, R, WIDO, TZ, LB
57 CONTINUE
GO TO 1
C C PARAMETRIC NOISE EMISSION POWER (FLUORESCENCE)
C C INPUTS  PUMP WAVELENGTH (A) PWL
P 1 N0PC4310
PUMP POWER (WATTS) PWR
INITIAL SINGAL WAVELENGTH (A) SWLI
SIGNAL WAVELENGTH INCREMENT (A) DELSW
FINAL SIGNAL WAVELENGTH (A) SWF
SHG PHASE MATCHING TEMPERATURE (DEG C) TO
PUMP WAVELENGTH AT WHICH THE GIVEN PHASE MATCHING
TEMPERATURE APPLIES (A) PWLO
IF SAME AS PWL INPUT ZERO
TUNING CONSTANT ETA (E13 ESU) N
IF INPUT ZERO ETA IS CALCULATED FROM SELLMIEQ EQNS
CRYSTAL LENGTH (CM) LCR
CRYSTAL NONLINEAR D COEFFICIENT (E-8 ESU) DCOF
ACCEPTANCE ANGLE (DEG) THETA
FOCUSING PARAMETER L/B LB
USED TO CALCULATE THE BEAM WAIST FOR FOCUSED SHG

80 READ (5,1003) PWL,PWR,SWLI,DELSW,SWF,TO,PWLO,N
READ (5,1003) LCR,DCOF,THETA,LB
1080 FORMAT(F9.2,E10.3,E2F10.2)
IF (PWL .LE. 3000.0) GO TO 888
IF (PWR .LE. 0.0) GO TO 888
IF (SWLI .LE. 3000.0) GO TO 888
IF (DELSW .LE. 0.0) GO TO 888
IF (SWF .LE. SWLI) GO TO 888
IF (LCR .LE. 0.0) GO TO 888
IF (DCOF .LE. 0.0) GO TO 888
IF (THETA .LE. 0.0) GO TO 888
IF (N .NE. 0.0) IFTA=1
N=N+1.0E13
C CONVER TO ESU
DCOF = DCOF*1.0E-8
C CONVER TO CM
PWL=PWL*1.0E-8
PWLO=PWLO*1.0E-8
DELSW=DELSW*1.0E-8
SWLI=SWLI*1.0E-8
SWF=SWF*1.0E-8
ILINF=0
IF (PWLO.EQ.0.0) GO TO 81
CALL TPMT (PWLO,TO,PWL,TI)
GO TO 82
81 TI=TO
CALCULATION OF EXTERNAL SECOND HARMONIC GENERATION POWER OF
A FOCUSED BEAM PHASE MATCHED AT 90 DEG
FOR A PUMP WHOSE SHG IS PWL

82 WP = TWPIC/PWL
  OWL=2.0*PWL
  WO = TWPIC/OWL
  CALL INDEX(OWL, TI, +1, NP)
  B = LCR/LB
  WIDO = Sort(8*OWL/(2.0*PI))
  ET = 377.0/NP

C CONVERT D COEFF TO MKS
  DMKS = DCOF*3.71138E-15
  PSHG = 2.0*ET*(ET*WO*DMKS*LPR/WIDO)**2/PI
  WRITE (6,1082) CRYST(2*ITYYPE-1),CRYST(2*ITYYPE),NCR,PWL,PWR,THETA,
  X LCR,DCOF,TI,PSHG

1082 FORMAT('1 ***** PARAMETRIC NOISE EMISSION ***** IN ',
  X '2A6,'CRYSTAL NO.,I2//1H ',
  X '1H CRystal WAVELENGTH=','8PF7.2,'(A) PUMP POWER =','1PE10.3,' WATTS
  X 'ACCEPTANCE ANGLE =','0PF7.2,' DEG//'
  X '1H CRystal LENGTH =','0PF5.2,' CM
  X 'D COEFFICIENT =','1PE10.3,' NOPC4700
  X 'ESU CORRECTED PHASE MATCHING TEMP =','0PF9.2,' DEG C//'
  X 'EXTERNAL SECOND HARMONIC POWER FOCUSED AND PHASE MATCHED AT 90
  X 'DEG =','1PE12.3,' (WATTS)/*/1H ',
  X 'SIGNAL WAVELENGTH (A) FLUOR OUTPUT PWR (WATTS) IDLER WAVELEN
  X 'THETA (A) PM TEMPERATURE (DEG C) BETA COEFFICIENT *///'
  X 'ILIM=(SWF-SWL)/DELSW+1
  SWL=SWL+DELSW
  DO 89 I=1,ILIM
    SWL=SWL+DELSW
  C RESTRICT THE SIGNAL TO LESS THAN THE SUB-HARMONIC
  IF (SWL .GT. OWL + DELSW ) GO TO 89
  WS = TWPIC/SWL
  RIWL = (SWL*OWL)/(2.0*SWL-OWL)
  WI = TWPIC/RIWL
  CALL PMI(SWL,PWL, TI, TMP, IETA,N)
  CALL INDEX(PWL, TMP, +1, NP)
  CALL INDEX(SWL, TMP, +1, NS)
  CALL INDEX(RIWL, TMP, +1, NI)
  BETA=(2.0*KS/((2.0*PI)**2*E0**3*NI*NP))*((H*(WS/C)**4)**
  X (WI*DCOF**2/C)
  THET=THETA+1.74533E-2
  CALL ADC(SWL,RIWL, TMP, A)
PWRF=((BETA+LCR+PWR)/A)*PI*THET**2  
WRITE (6,1085) SWL,PWRF,PWL,TMP,BETA  
1085 FORMAT (1H,3X,*8P10.2,10X,1PE15.3,10X,8P15.2,10X,0P15.2,10X,1PE1NP0C4950  
X5.4  )  
ILINE=ILINE+1  
IF (ILINE .LT. 51 .OR. ILINE .EQ. ILIM ) GO TO 89  
ILINE=0  
WRITE (6,1082) CRYST(2*ITYPE-1),CRYST(2*ITYPE),NCR,PWL,PWR,THETA,  
X LCR,DCOF,TR,PSH2  
89 CONTINUE  
GO TO 1  
C  
OPO DESIGN CALCULATIONS  
C  
INPUTS  
MIRROR RADIUS (CM) RAD    P 1  
CRYSTAL LENGTH (CM) LCR    P 2  
CRYSTAL INDEX OF REFRACTION N    FC 12 P 3  
CRYSTAL TEMPERATURE (DEG C) T    FC 13 P 3  
RADIATION WAVELENGTH (A) PWL    FC 13 P 4  
DESIRED CRYSTAL LENGTH/CONFOCAL PARAMETER RATIO LB  
IF USING FC 12 USE P 4 , IF FC 13 USE P 5  
RADIUS - SEPARATION CONSTRAINT (CM) RD  
IF USING FC 12 USE P 5 , IF FC 13 USE P 6  
IF NONE INPUT ZERO  
I POSITIVE ORDINARY RAY -- NEGATIVE EXTRAORDINARY RAY  
FC 13 ONLY USE P 7  
C  
96 ISIG=1  
GO TO 99  
97 ISIG=1  
GO TO 98  
100 ISIG=0  
99 READ (5,1025) RAD,LCR,N,LB,RD  
1025 FORMAT (F9.2,3F10.4,E10.4)  
GO TO 102  
101 ISIG=0  
98 READ (5,1026) RAD,LCR,T,PWL,LR,RD,I  
1026 FORMAT (F9.2,4F10.4,E10.4,I2)  
IF (PWL .GE. 3000.0) GO TO 888  
C  
CONVERT TO CM  
PWL=PWL*1.0E-8  
CALL INDEX (PWL,T,I,N)  
ISTOP=0  
NP0C5180  
NP0C5190  
NP0C5200  
NP0C5210  
NP0C5220  
NP0C5230  
NP0C5240  
NP0C5250  
NP0C5260  
NP0C5270  
NP0C5280  
NP0C5290  
NP0C5300  
NP0C5310  
NP0C5320  
NP0C5330  
NP0C5340
102 IF (RAD .LE. 0.0) GO TO 88A
IF (N .LE. 0.0) GO TO 88A
IF (LR .LE. 0.0) GO TO 88A
B = LCR/(N*LR)
IF (ISIG .NE. 1) GO TO 103
RD = 2.0*RD
LCR = 2.0*LCR
103 DEFF=RAD+SORT(RAD**2-B**2)
DREAL=DEFF+LCR*(1.0-1.0/N)
RDST=2.0*RAD-DEFF
IF(RD.EQ.0.0) GO TO 104
IF(RDST.GE.RD) GO TO 104
IF(ISSTOP.GT.500) GO TO 104
B=1.02*B
ISTOP=ISTOP+1
GO TO 103
104 IF(ISIG.EQ.0)GO TO 105
DEFF=DEFF/2.0
DREAL=DREAL/2.0
RD=RD/2.0
LCR=LCR/2.0
AMESS(1)=SEMIC
105 LNNEW=LCR/R
WRITE(6,1027) AMESS,RAD,LCR,N,LR,LD,DEFF,DREAL,RDST,LBNEW
1027 FORMAT(1H1,10X, '**** OPO DESIGN CALCULATION ****',3A4,'/1H',
X '*MIRROR RADIUS ='+F10.3,' CM',' X',' CRYSTAL LENGTH ='+F10.3,' CM' ,
X '* CM',' X',' INDEX OF REF', '..F10.5',' CM'
X ' 1H '*SPEICIFIED L/B ='+F12.2,'10X',' R-D TOLERANCE ='+PE12.4,'
X ' 1H '*CM',' 1H '*CONFOCAL PARAMETER ='+PE12.4,' CM',' 7X ,
X ' 1H '*EFFECTIVE SEPARATION ='+PF10.4,' CM',' 7X '*REAL SEPARATION ='+PF10.4,' CM'
X ' 1H '*NEW R-D TOL ='+PE12.4,' CM',' 7X '*NEW L/B ='+PF10.2,’
AMESS(1) = RLKS
GO TO 1

GAUSSIAN BEAM MODE MATCHING CALCULATION

C C C C
INPUTS RADIUS OF CURVATURE MIRROR FIRST CAVITY (CM) R1 P 1
SEPARATION OF FIRST CAVITY (CM) D1 P 2
IF THE CAVITY IS SEMICONFOCAL INPUT D1 NEGATIVE
C C
RADIUS OF CURVATURE MIRROR SECOND CAVITY (CM) R2
FC 16 ONLY P 3
(CRYSTAL LENGTH)/(CONFOCAL PARAMETER) OPTIMIZATION
C RATIO (L/A) LB  FC 17 P 3 NOPC5770
C SEPARATION OF MIRRORS SECOND CAVITY (CM) D2  FC 16 P 4 NOPC5780
C IF THE CAVITY IS SEMICONFOCAL INPUT D2 NEGATIVE  NOPC5790
C CRYSTAL LENGTH (CM) L  FC 17 P 4 NOPC5800
C WAVELENGTH OF RADIATION (A) LP  P 5 NOPC5810
C FOCAL LENGTH OF MATCHING LENS (CM) FOC  P 6 NOPC5820
C
C 120 READ(5,1003)R1,D1,R2,D2,LP,FOC
IF (R2 .LE. 0.0) GO TO 888
IF (D2 .LE. 0.0) GO TO 888
IF(D1.LT.0)D1=2.0*D1
IF (D2.LT.0) D2=-2.0*D2
B2=SQRT(D2*(2.0*R2-D2))
GO TO 122

121 READ(5,1003) R1,D1,L9,L,LP,FOC
IF (L .LE. 0.0) GO TO 888
IF (L .LE. 0.0) GO TO 888
IF(D1.LT.0)D1=2.0*D1
WLP = LP*1.0E-9
CALL INDEX(WLP,20.0,-1,N)
B2 = L/(N*L)

122 IF (LP .LE. 0.0) GO TO 888
IF (FOC .LE. 0.0) GO TO 888
IF (R1 .LE. 0.0) GO TO 888
IF (D1 .LE. 0.0) GO TO 888
B1=SQRT(D1*(2.0*R1-D1))
LP=LP*1.0E-9
W1=SQRT(B1*LP/(2.0*PI))
W2=SQRT(B2*LP/(2.0*PI))
FO=PI*W1*W2/LP
IF(FOC.LT.F0) GO TO 130
DI=(W1/W2)*SQRT(FOC**2-F0**2)+FOC
D2=(W2/W1)*SQRT(FOC**2-F0**2)+FOC
WRITE (6,1050) LP,FOC,N

1050 FORMAT(1H1,'***** MATCHING CLACULATION *****' WAVELENGTH = 'NOPC6090
X*APF10.2,1N*LENS FOCAL LENGTH =',0PF10.3,' CM INDEX OF REFRACTO074200
XION =',0PF7.4//)

123 WRITE (6,1051) B1,R2,W1,W2,F0,D1,D2

1051 FORMAT (1H,'CONFOCAL PARAMETER REAM 1 =',1PE12.3,' (CM) ','CONFOC',NOPC6120
XAL PARAMETER RFAM 2 =',1PE12.3,' (CM) ','NOPC6130
X// BEAM WAIST BEAM 1 =',1PE12.4,
X ' (CM) BEAM WAIST REAM 2 =',1PE12.4//1H ',MINIMUM FOCAL LENGTHNP06150
X',0PF10.2,' (CM)/',' DISTANCE FROM LENS TO WAIST OF BEAM 1 =' NOPC6160
X*OPF10.3,  NOPEC6170
X (CM)"ORY: DISTANCE FROM LENS TO WAIST OF BEAM 2=",OPF10.3," (CM)"
NOPEC6180
GO TO 1
NOPEC6190
130 DI=0.0
NOPEC6200
D2=0.0
NOPEC6210
WRITE (6,1050)
NOPEC6220
WRITE (6,1052)
NOPEC6230
1052 FORMAT(1H ,"SPECIFIED FOCAL LENGTH LESS THAN MINIMUM")
NOPEC6240
GO TO 123
NOPEC6250
END
NOPEC6260

C
SUBROUTINES

C
BLOCK DATA
REAL LO,N,LS,LI,LB,NS,NI,K,NO,LCR,LBNEW,LP,L,LPNM,LONM,NOF,NEFN,NOPEC6303
X *LOFT,LEFT,LSX,IX,LOMC,LPMC,NXA,NXB,NYA,NYB,NZA,NZB
COMMON /CLIFF/ PI,C,CX,TWPIC,H,AA,AB,AC,AD,AE,AF,
X BA*BB,BC,BD,BE,BF,BG,E,NOXAXNR,NYA,NYR,NZA,NZB,CMC
COMMON /CLIFF/ ITYPE
PERMANENT DATA
LITHIUM NIOBIUM DATA
NOPEC6306
X /3.1415927,2,997925E10,2,997925E17,1.88365E11,1.054E-27/
NOPEC6307
X 4.9130,1.173E05,1.60E-2,2,12E02,2,7E-5,-2,78E-8,4,5567,2,605E-7/
NOPEC6308
X 0,970E05,2,70F-2,2,01E02,5,4E-5,-2,24E-8,7,95774E-2/
NOPEC6309
BARIUM-SODIUM META-NITRATE DATA
DATA NXA,NXB,NYA,NYB,NZA,NZB,CMC
NOPEC6310
DATA NXA,NXB,NYA,NYB,NZA,NZB,CMC
X /0,25320,0,01026,0,25320,0,01015,0,27772,0,00894,2,997925E14/
END
NOPEC6311
SUBROUTINE PMT(LS,LP,T,E,TIAE,N)
REAL LO,N,LS,LI,LB,NS,NI,K,NO,LCR,LBNEW,LP,L,LPNM,LONM,NOF,NEFN,NOPEC6401
X *LOFT,LEFT,LSX,IX,LOMC,LPMC,NXA,NXB,NYA,NYB,NZA,NZB
COMMON /CLIFF/ PI,C,CX,TWPIC,H,AA,AB,AC,AD,AE,AF,
X BA*BB,BC,BD,DE,BF,BG,E,NOXAXNR,NYA,NYR,NZA,NZB,CMC
COMMON /CLIFF/ ITYPE

C
SUBROUTINE PHASE MATCHING TEMPERATURE

C
INPUT SIGNAL WAVELENGTH (CM) LS
C
PUMP WAVELENGTH (CM) LP
C
SHG PHASE MATCHING TEMPERATURE (DEG C) TO
C
SIGNAL TO CALCULATE ETA IETA 0-YES,1-NO
C
TEMPERATURE TUNING CONSTANT ETA (ESU) N
NOPEC6470
NOPEC6480
NOPEC6490
NOPEC6500
NOPEC6503
NOPEC6506
OUTPUT PHASE MATCHING TEMPERATURE (DEG C) T

ICNT = 0
LO=L P+2.0

FORM INITIAL ESTIMATE LOWER THAN T
TT = TO

IF (IETA = EQ. 0) CALL ETA (LP, TT, N, DUM, DUMMY)
TH = TO + 4.0*((PI*C*(LS-LO))/(NL*LS*LO))**2

REQUIRE CONVERGENCE TO WITHIN LESS THAN 0.01 DEG C
IF (ABS(TN-TT) * LT. 0.01) GO TO 10

ICNT = ICNT + 1

DO NOT ALLOW MORE THAN 200 ITERATIONS
IF (ICNT .GT. 200) GO TO 10

FORM A NEW ESTIMATE FOR THE NEXT ITERATION, THE AVERAGE OF THE
DIFFERENCE BETWEEN THE OLD ESTIMATE AND THE NEW RESULT WILL
GIVE A VALUE NEARER TO BUT STILL LESS THAN T
TT = (TN-TT)/2.0 + TT
GO TO 9

T = TH
RETURN
END

SUBROUTINE ETA(LP, TMP, ET, DTDMB, DNOOW)

TEMPERATURE TUNING CONSTANT - ETA

REAL LO, N, LS, LI, LR, LP, NS, NI, K, NO, LCR, LBNEW, LP, L, LPNM, LONM, NOF, NEF
X, LOFT, LEFT, LNX, LIX, LOMC, LPHC, NXA, NXB, NYA, NYS, NZA, NZB
COMMON /CLIFF/ PIC, CX, TWPIC, H, AA, AB, AC, AD, AE, AF,
X, BA, BB, BC, BD, RE, BF, RG, EO, NXA, NXB, NYA, NYS, NZA, NZB, CMC
COMMON /CLIFF/ ITYPE

INPUTS PUMP WAVELENGTH (CM) LP
TEMPERATURE -(DEG C) TMP

OUTPUT ETA - TEMPERATURE TUNING CONSTANT (ESU)

DEL(W) = ETA*SQRT(DEL(TMP))
WHERE ETA = W(PUMP)* PAR/PART*(NPEXT-NOORD)/2*(PAR/PARW(NOORD)
PAR STANDS FOR PARTIAL DERIVATIVE

LO=2.0*LP
WPUMP = TWPIC/LP
GO TO (1*2), ITYPE

C LITHIUM NIOBATE
C CONVERT TO NANO METERS
1 LPNM=LP*1.0E+7
C CONVERT TO DEGREES KELVIN
TMPK=TMP + 273.15
LONM=LO*1.0E+7
C CALCULATE FIRST FACTORS
CALL INDEX(LO, TMP, 1, NOF)
NOF=1.0/NOF
CALL INDEX(LP, TMP, -1, NEOF)
NEF=1.0/NEF
LOFT=LONM**2-(AD+AE*TMPK**2)**2
LEFT=LPNM**2-(BC+BD*TMPK**2)**2
C CALCULATE INTERMEDIATE QUANTITIES
C CALCULATE TEMP DERIVATIVE OF DISPERSION MINUS BIREFRINGENCE
DNODTO=NOF*((AC*TMPK*LOFT+2.0*AE*TMPK*(AB+AC*TMPK**2)*(AD+AE*TMPK X**2))/LOFT**2)
DNEDTP=NEF*(BR*TMPK+(AD*TMPK*LEFT+2.0*BF*TMPK*(BC+BD*TMPK**2)*) X*(BE+RF*TMPK**2))/LEFT**2)
DTDMA=DNEDTP-DNODTO
C CALCULATE FREQUENCY DERIVATIVE OF INDEX OF PUMP SUB-HARMONIC
C FOR THE PAR(NO)/PAR(W) CALCULATION C MUST BE IN NM/SEC
DNODW=0.5*NEF*(-AF*LONM**3/(PI*CX)+(LONM**3/(PI*CX)*(AB+AC*TMPK**2) X)/LOFT**2))
10 ET = SQRT(0.5*WPUMP*DTDMA/DNODW)
RETURN
C BARIUM-SODIUM META-NIORATE
C CONVERT TO MICRONS
2 LOMC = LO*1.0E4
DTDMA = 8.0E-5
C CALC PAR(NO)/PAR(W) USE C IN MICRONS/SEC
CALL INDEX (LO, TMP, 1, NOF)
CALL INDEX (LO, TMP, 1, NOF)
DNODW = (1.0/NOF)*NYB/((NYA-NYB/LOMC**2)**2*2.0*PI*CMC*LOMC)
GO TO 10
END
SUBROUTINE DNOD2W(PWL, TEMP, D2W)
THIS SUBROUTINE CALCULATES PAR2(NO)/PAR(W2)

INPUTS PUMP WAVELENGTH (CM) PWL
TEMPERATURE (DEG C) TEMP

OUTPUT PAR2(NO)/PAR(W2) D2W

REAL LO,N,L5,L1,L6,NP,NS,NI,K,NO,LCR,LSNEW,LP,L,LPNM,LONM,NOF,NEF
X,LOFT,LEFT,LN,L5X,LIX,LOMC,LPMC,NXA,NXB,NYA,NYB,NZA,NZB
COM 10 N /CLIFF/ PI,C,CX,TwPIC,H,AA,AB,AC,AD,AE,AF,
X BA,BB,BC,BD,BE,BF,AG,EO,NXA,NXB,NYA,NYB,NZA,NZB,CMC
COMMON /CLIFF/ IYPE
L0 = 2.0*PWL
CALL INDEX (LO,TEMP,1,NO)
GO TO (1,2),IYPE

LITHIUM NIOBATE
USE C AND LAMARDA IN NM/SEC AND NM

1 LO = LO*1.0E+7
TMK = TEMP + 273.15
BCT = AB + AC*TMK**2
DELT = LO**2*(AD + AE*TMK**2)**2
FLBT = AF - BCT/DELT**2
D2W = (LO**2/(2.0*PI*CX))**2*(1.0/NO)*(3.0*FLBT-LO**2/(2.0*NO**2))
X*FLBT**2 + 4.0*LO**2*BCT/DELT**3
5 RETURN

BARIIUM SODIUM META-NIOBATE

2 LO = LO*1.0E+4
ABL = NYA - NYB/LO**2
D2W = (LO**2/(2.0*PI*CMC))**2*(1.0/NO)*(-1.0/NO**2)*
X*NYB/(LO**3*ABL**2)**2 + NYB/(LO**4*ABL**2) + 4.0*NYB**2/
X*LO**6*ABL**3)
GO TO 5
END
SUBROUTINE INDEX(WL,T,I,REFN)

INPUTS WL - WAVELENGTH IN CENTIMETERS
T - TEMPERATURE IN DEGREES CENTIGRADE
I - POSITIVE FOR ORDINARY WAVE (Y AXIS IN BA)
I - NEGATIVE FOR EXTRAORDINARY WAVE (Z AXIS IN BA)
OUTPUT REFN-INDEX OF REFRACTION
REAL LO,N,LS,LI,LB,NP,NO,L,K,NO,L,LC,LB,N,LP,LC,L,LP,LM,LONM,NOF,NEF
X
X LOFT,LEFX,LM,LSX,LMCM,LP,LMCM,LM,L,NXAX,NXB,NX,NXA,NXB,NX,NX,YN,NYB,YN,NY,YN,ZNZ,ZNZ,CMC
COMMON /CLIFF/ PI,C,CX,TWPI,AC,AA,AB,AC,AD,AE,AF,
X BA,BA,BB,BC,BD,BC,BF,BG,EN,EN,EN,EN,YN,YN,YN,YN,ZN,ZN,ZN,ZN,CMC
COMMON /CLIFF/ ITYPE
TK=T+273.15
WLNM=WL*1.0E+7
IF (TK .LT. 0.0) GO TO 75
IF (WLNM .LT. 400.0 .OR. WLNM .GT. 4000.0 ) GO TO 75
GO TO (1,2),ITYPE

C LITHIUM NIOBATE
C
C 1 IF(I.LT.0)GO TO 10

REFN=SQRT((AA+(AB+AC*TK**2))/WLNM**2-(AD+AE*TK**2)**2)+AF*WLNM**2)
GO TO 20

C 10 REFN=SQRT((BA+BR*TK**2)+(BC+BD*TK**2))/WLNM**2-(BE+BF*TK**2)**2)+
X 
BG*WLNM**2)
80 RETURN

C BARIUM SODIUM META NIORATE
C
C 2 WLMC = WL*1.0E4
C CONVERT TO MICRONS
C IF (I .LT. 0) GO TO 11
C INDEX FOR PROPAGATION PARALLEL Y AXIS
C REFN = SQRT((1.0+(1.0/(NYA-NYB/WLMC**2))
GO TO 20
C INDEX FOR PROPAGATION PARALLEL Z AXIS
C 11 REFN = SQRT((1.0+(1.0/(NZA-NZB/WLMC**2))
GO TO 20

75 WRITE (6,1000) WLNM,T
1000 FORMAT (' INDEX CALLED WITH WAVELENGTH OF ',F10.2,' NM BEYOND VALINO
X DITY TEMP=',F9.2,' TEMPC ** N=2.25 RETURNED*)

C REMOVE SUBROUTINE OPTIC(WL,R,D,I,R,W)
C C INPUTS ** WAVELENGTH - (CM) - WL
C RADIUS OF CURVATURE - (CM) - R
C SEPARATION - (CM) - D
C FLAG + 1 = CONFOCAL -I

C
- I - SEMICONFOCAL

REAL WIDTH (cm) W
OUTPUTS CONFOCAL PARAMETER (cm) R

COMMON /CLIFF/ PI,CX,TYPIC,H,AA,AB,AC,AD,AE,AF,
X BA,BB,BC,BD,RE,RF,KG,ED,NXN,NN,YA,NYB,NA,NZB,CMC
COMMON /CLIFF/ NTYPE
IF (L,T,0) GO TO 5
S=SQRT((2*0.2*R-D))
GO TO 6
5 S=SQRT((4.0*D*(R-D))
6 W=SQRT((R*WL)/(2.0*PI))

***DEBUG***
WRITE (6,1000) WL,R,NXN,RE

1000 FORMAT(1H,'*** DEBUG OPTIC ***','WLP10.2,5X','RAD=',0PF7.3,0PF7.3)
RETURN
END

SUBROUTINE TPMT(LP,T,L,T)

GIVEN THE SHG PHASE MATCHING TEMPERATURE FOR A GIVEN WAVELENGTH
THIS SUBROUTINE ESTIMATES THE SHG PHASE MATCHING TEMPERATURE
FOR ANOTHER WAVELENGTH

INPUTS PUMP WAVELENGTH (LP) (cm)
PHASE MATCH TEMP (TP) AT LP (DEG C)
NEW PUMP WAVELENGTH (L) (cm)

OUTPUT NEW PHASE MATCHING TEMPERATURE AT LI (T) (DEG C)

REAL LP,LS,L,T,NS,NK,NO,LCR,LPNEW,L,L,LPNM,LM,NOF,NEF
COMMON /CLIFF/ PI,CX,TYPIC,H,AA,AB,AC,AD,AE,AF,
X BA,BB,BC,BD,RE,RF,KG,ED,NXN,NN,YA,NYB,NA,NZB,CMC
COMMON /CLIFF/ NTYPE

SET THE WAVELENGTH INCREMENT TO 5.0 ANGSTROMS
DL = 5.0E-A
IF ( L,T,LP ) DL=DL

FIND THE REQUIRED NUMBER OF ITERATIONS
II = (LI-LP)/DL + 1

INITIALIZE TEMPERATURE AND WAVELENGTH
TP = TO
LN = LP + DL

NO PC 7390
NO PC 7400
NO PC 7410
NO PC 7420
NO PC 7430
NO PC 7440
NO PC 7445
NO PC 7450
NO PC 7460
NO PC 7470
NO PC 7480
NO PC 7490
NO PC 7500
NO PC 7510
NO PC 7520
NO PC 7530
NO PC 7540
NO PC 7550
NO PC 7560
NO PC 7570
NO PC 7580
NO PC 7590
NO PC 7600
NO PC 7610
NO PC 7620
NO PC 7630
NO PC 7640
NO PC 7650
NO PC 7660
NO PC 7670
NO PC 7680
NO PC 7690
NO PC 7700
NO PC 7710
NO PC 7715
NO PC 7713
NO PC 7716
NO PC 7720
NO PC 7723
NO PC 7726
NO PC 7730
NO PC 7733
NO PC 7736
DO 100 I=1,II
IF (I .NE. II) GO TO 6
C FORM THE PROPER INCREMENT FOR THE LAST ITERATION
LN = LI
DL = LI - ((II-1)*DL+LP)
6 LO = 2.0*LN
CALL INDEX (LO,TP,tl,NO)
CALL INDEX (LN,TP,tl,NO)
IF (IYPE .EQ. 1) GO TO 10
C C BARIUM=SODIUM META-NIorate
C LOMC = LO*1.0E4
LPMC = LP*1.0E4
DNODLO = -(1.0/NO)*NYR/((NYA-NYB/LOMC)**2)**2*LOMC**3)
C CONVERT FROM 1/MICRONS TO 1/CM
DNODLO = DNODLO*1.0E4
DNPDLE = -(1.0/NP)*NZB/((NZA-NZB/LPMC)**2)**2*LPMC**3)
C CONVERT 1/MICRONS TO 1/CM
DNPDLE = DNPDLE*1.0E4
DTDMB = 8.0*E-5
GO TO 11
C C LITHIUM NIORATE
C 10 LONM=LO*1.0E7
LPNM=LN*1.0E7
TPK=TP+273.15
DNODLO=((AF*LONM)-((LONM*(AB+AC*TPK**2)))/(LONM**2-(AD+AE*TPK))
X TPK)**2)**2))
C CONVERT FROM 1/NM TO 1/CM
DNODLO=DNODLO*1.0E7
DNPDLE=-(1.0/NP)*((RG*LPNM)-((LPNM*(BC+BD*TPK**2)))/(LPNM**2-(BE+
X TPK**2)**2)**2)
C CONVERT FROM 1/NM TO 1/CM
DNPDLE=DNPDLE*1.0E7
CALL ETA(LN,TP,DIM,DTDMB,DUMMY)
11 TN=TP+((2.0*DNODLO-DNPDLE)/DTDMB)*DL
C RESET TEMPERATURE AND WAVELENGTH FOR NEXT ITERATION
LN = LN + DL
C CHECK TN FOR VALIDITY
IF ( TN .LT. -273.15 .OR. TN .GT. 500.0 ) GO TO 50
100 TP = TN
20 T = TN
RETURN

50 WRITE (6,51) TP,LP,LI
51 FORMAT ('TPMT FINDS INVALID TEMPERATURE IN CONVERTING FROM ', X,F7.2, ' DEG C AT ',APF9.2, ' (A) TO ',8PF9.2, ' (A) ZERO RETURNED')
T = N.0
RETURN
END

SUBROUTINE ADC(LS,LI,T,B)

SUBROUTINE ANGULAR DISPERSIVE CONSTANT

INPUT SIGNAL WAVELENGTH (CM) LS (ORDINARY WAVE)
INPUT IDLER WAVELENGTH (CM) LI (ORDINARY WAVE)
INPUT TEMPERATURE (DEG C) T

OUTPUT ANGULAR DISPERSIVE CONSTANT DEFINED BY B=PAR KS / PAR WS - PAR KI / PAR WI
REAL L0,N,LS,LI,LB,NP,NS,H,K,NO,LCR,LABNEW,LP,L,LPNM,LONM,NOF,NEF
X,LOFT,LEFT,LN,LSX,LI,LM,LMC,LMCM,NX,NX,XY,XY,XY,XY
COMMON /CLIFF/ PI,CX,TWPI,HI,AA,AB,AC,AD,AE,AF
X BA,BB,BC,BD,RE,RF,RG,GO,NX,NX,NY,XY,XY,XY,XY,XY
COMMON /CLIFF/ ITYPE
W=TWPI/LS
W=TWPI/LS
CALL INDEX(LS,T+1,N5)
CALL INDEX(LI,T+1,N1)
GO TO (1,2),ITYPE

LITHIUM NIOBATE

CONVERT TO N^M
1 LSX=LS*1.0E+7
LI=LI*1.0F+7
C USE C IN NM/SEC
DNSD=0.5*(1.0/N5)*(-AF*LSX**3/(PI*CX)+((AB+AC*TK**2)*(LSX**3/(PI*C)+XCV)))/(LSX**2-(AD+AE*TK**2)**2)**2
DNIDW=0.5*(1.0/N1)*(-AF*LIX**3/(PI*CX)+((AB+AC*TK**2)*(LIX**3/(PI*C)+XCV)))/(LIX**2-(AD+AE*TK**2)**2)**2
B=(1.0/C)*((NS-NI)+(WS*DNDW-WI*DNIDW))
RETURN

RETURN
C          BARIUM-SODIUM META-NITRATE
C          NOPC8234
C
C          CONVERT TO MICRONS
C          NOPC8238
C        LSX = LS*1.0E4
C        LIX = LI*1.0E4
C
C          USE C IN MICRONS/SEC
C          NOPC8240
C        DNSOW = (1.0/NS)*NYR/((NYA-NYA/LSX)**2)**2*2.0*PI*CMC*LSX)
C        DNIDW = (1.0/NI)*NYB/((NYA-NYB/LIX)**2)**2*2.0*PI*CMC*LIX)
C          NOPC8246
C        GO TO 10
C          NOPC8248
C          END
C
C          SUBROUTINE TPLOT (TDATA,SDATA,RIDATA,INUM,PWL,IPRO,ETA)
C          NOPC8255
C
C          TUNING PLOT SUBROUTINE
C          NOPC8260
C          IFC = 2 TEMPERATURE TUNING
C          00110500
C          IFC = 4 ORIENTATION TUNING
C          00110520
C          IFC = 6 ELECTRIC FIELD TUNING
C          00110560
C          NOPC8271
C          TDATA = TEMPERATURE (DEG C), ORIENTATION (DEG), OR ELECTRIC FIELD (VOLTS/CM) DATA ARRAY LIMIT 102
C          00110700
C          SDATA = SIGNAL WAVELENGTH DATA ARRAY (ANGSTROMS) LIMIT 102
C          00110750
C          RIDATA = INLER WAVELENGTH DATA ARRAY (ANGSTROMS) LIMIT 102
C          00110790
C          INUM = NUMBER OF POINTS IN THE DATA ARRAYS LIMIT 102
C          00110830
C          ITYPE = CRYSTAL TYPE CODE
C          00110850
C          PWL = PUMP WAVELENGTH (CM)
C          00111000
C          IPRO = DATA PLOT SIGNAL 0 = NO 1 = PLOT EXPERIMENTAL DATA
C          00111130
C          ETA = TEMPERATURE TUNING CONSTANT
C          00111090
C
C          COMMON /CLIFF/ PI,CX,TWPC,H,AA,AB,AC,AD,AE,AF,
C          X BA,BB,BC,RD,RE,RF,RG,EO,NX,NXB,NYA,NYB,NZA,NZB,CMC
C          COMMON /CLIFF/ ITYPE,EXPY,EXPX,NN,NCR,IFC,TO,TMP
C          DIMENSION EXPY(50),EXPX(50)
C          INTEGER CRYST
C          00111000
C          DIMENSION WORK(1),CRYST(4)
C          DIMENSION TDATA(1),SDATA(1),RIDATA(1)
C          DIMENSION XDATA(206),YDATA(206)
C          DIMENSION IMSGX(4),IMSG(3),IMSGT(4),IMSGPW(3),IMSGPT(2)
C          DIMENSION IMSG0(3),IMSGE(5),IMSGTO(4),IMSGTE(5),ICRTM(2)
C          DIMENSION IMSG(2),I13(1),I1PLOT(1)
C          DIMENSION IMSGN(3)
C          00111000
C          DATA IMSGX/'TEMPERATURE (DEG C) '
C          DATA IMSG0/'ORIENTATION (DEG) '
C          DATA IMSGE/'ELECTRIC FIELD (VOLTS/CM) '
C          DATA IMSGN/'WAVELENGTH (A) '
DATA IMSGT/T"TEMPERATURE TUNING IN" /  
DATA IMSGT0/T"ORIENTATION TUNING IN" /  
DATA IMSGF/T"ELECTRIC FIELD TUNING IN" /  
DATA IMSGPW/T"PUMP WAVELENGTH" /  
DATA IMSSGT/T"SHG PM TEMP" /  
DATA ICRTM/T"CRYSTAL TEMP" /  
DATA IMSGN/T"CRYSTAL NUMBER" /  
DATA IMSGT/EETA (±10) /  
DATA I13/13 /  
DATA IPILOT/T"PLOT+/  
DATA CRYST/T"LINBO3 RA2NAN5015" /  
DATA IPLN/0/  
KFC = IFC/2  
IF (IPLN.NF.0) GO TO 2  
CALL PLOTS (WORK.1)  
CALL PLOT (0.0,-11.0,-3)  
CALL PLOT (0.0,1.0,-3)  
2 IPLN=IPLN+1  
C  
ARRANGE DATA FOR PLOT  
DO 10 I=1,INUM  
XDATA(I) = TDATA(INUM-I+1)  
YDATA(I) = SDATA(INUM-I+1)  
XDATA(I+INUM-1) = TDATA(I)  
YDATA(I+INUM-1) = RNDATA(I)  
10 INUM = 2*INUM-1  
CALL SCALE (YDATA.09.5,INUM-1)  
CALL SCALE (XDATA.7.0,INUM-1)  
CALL LINE (XDATA,YDATA,INUM-1,0,0)  
CALL AXIS (0.0,0.0,1.0,0.0,1.0,90.0,YDATA(INUM-1),YDATA(INUM+2))  
IF (KFC.EQ.1) CALL AXIS  
X (0.0,0.0,1.0,0.0,1.0,0.0,XDATA(INUM-1),XDATA(INUM+2))  
IF (KFC.EQ.2) CALL AXIS  
X (0.0,0.0,1.0,0.0,1.0,0.0,XDATA(INUM-1),XDATA(INUM+2))  
IF (KFC.EQ.3) CALL AXIS  
X (0.0,0.0,1.0,0.0,1.0,0.0,XDATA(INUM-1),XDATA(INUM+2))  
CALL PLOT (0.0,0.0,5.0)  
CALL PLOT (7.0,0.0,5.0)  
CALL PLOT (7.0,0.0,2.0)  
IF (KFC.EQ.1) CALL SYMBOL (0.5,9.0,0.14,1.0,0.22)  
IF (KFC.EQ.2) CALL SYMBOL (0.5,9.0,0.14,1.0,0.22)  
IF (KFC.EQ.3) CALL SYMBOL (0.5,9.0,0.14,1.0,0.25)  
CALL SYMBOL (999.0,999.0,0.14,CRYST2*ITYPE-1),1.0,12)  
CALL SYMBOL (1.0,0.0,8.0,10.0,1.0,15)
PPWL=PWL*1.0E8
CALL NUMBER (3.0,0.8,7,0.10,PPWL,0.0,0,-1) N0PC8550
CALL SYMBOL (1.0,0.8,5,0.10,IMSGPT,0.0,11) 00116200
CALL NUMBER (3.0,0.8,5,0.10,TO,0.0,0,0,0,2) 00116640
CALL SYMBOL (1.0,0.8,3,0.10,IMSGET,0.0,0,12) 00116660
CALL SYMBOL (1.8,0.8,3,0.10,I13,0.0,0,0,2) 00116670
ETP = ETA1.0E=13
CALL NUMBER (3.0,0.8,3,0.10,ETP,0.0,2) N0PC8586
IF (KFC,.EQ. 1) GO TO 3 00116620
CALL SYMBOL (1.0,8.1,0.10,ICRTM,0.0,0,12) 00116640
CALL NUMBER (3.0,8.1,0.10,TEMP,0.0,0,0,2) 00116660
3 CALL SYMBOL (1.0,7.9,0.10,IMSGN,0.0,0,14) 00116670
FCR = NCR
CALL NUMBER (3.0,7.9,0.10,FCR,0.0,0,0,1) 00116680
FPLN = IPLN
CALL SYMBOL (6.0,9.0,0.07,IPLOT,0.0,0,4) 00116690
CALL NUMBER (6.5,9.0,0.07,FPLN,0.0,0,0,1) 00116690
IF (IDP,.EQ. 0) GO TO 11 N0PC8590
C
SAVE PLOT SCALING
ORDMIN = YDATA(INUM+1) N0PC8600
ORDDEL = YDATA(INUM+2) N0PC8610
ARSMIN = XDATA(INUM+1) N0PC8620
ARSDEL = XDATA(INUM+2) N0PC8630
C
SET UP EXPERIMENTAL PLOT SCALES
EXPY(NN+1) = ORDMIN N0PC8710
EXPY(NN+2) = ORDDEL N0PC8720
EXPX(NN+1) = ARSMIN N0PC8730
EXPX(NN+2) = ARSDEL N0PC8740
CALL LINE (EXPX,EXPY,NN+1,-1,4) N0PC8750
11 CALL PLOT (10.0,0.0,0,-3) N0PC8800
ENDFILE 7 00118250
RETURN
END
N0PC8810

***** SAMPLE PROGRAM INPUT DATA *****

2 2 111
5145.0 41.0 3.0 240.0 0.0 5.5 6.5 0.10
13 CRY NO 11 OPN TEMP TUNING PLOT
CRY NO 11 OPN TEMP TUNING DATA 5145 PUMP
<table>
<thead>
<tr>
<th>No</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.0</td>
<td>10118.0</td>
</tr>
<tr>
<td>49.5</td>
<td>9486.0</td>
</tr>
<tr>
<td>95.0</td>
<td>8337.0</td>
</tr>
<tr>
<td>205.0</td>
<td>7223.0</td>
</tr>
<tr>
<td>2 2 112</td>
<td>CRY NO 12 OPN TEMP TUNING CURVE</td>
</tr>
<tr>
<td>4880.0</td>
<td>-65.0</td>
</tr>
<tr>
<td>23.5</td>
<td>7503.0</td>
</tr>
<tr>
<td>57.5</td>
<td>7248.0</td>
</tr>
<tr>
<td>110.5</td>
<td>6910.0</td>
</tr>
<tr>
<td>167.0</td>
<td>6607.0</td>
</tr>
<tr>
<td>195.0</td>
<td>6483.0</td>
</tr>
<tr>
<td>4 2 011</td>
<td>ORIENT TUNING IN BA</td>
</tr>
<tr>
<td>5145.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6 2 011</td>
<td>E FLD TUNING IN BA</td>
</tr>
<tr>
<td>5145.0</td>
<td>0.0</td>
</tr>
<tr>
<td>41.0</td>
<td>5.9</td>
</tr>
<tr>
<td>8 2 011</td>
<td>IR OPO THRESHOLD CRY NO 11</td>
</tr>
<tr>
<td>5145.0</td>
<td>0.03</td>
</tr>
<tr>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>11 2 011</td>
<td>CRY NO 11 RA OPN POWER</td>
</tr>
<tr>
<td>5145.0</td>
<td>0.450</td>
</tr>
<tr>
<td>0.5</td>
<td>4.4</td>
</tr>
<tr>
<td>17 1 011</td>
<td>MODE MATCHING</td>
</tr>
<tr>
<td>600.0</td>
<td>440.0</td>
</tr>
</tbody>
</table>

END CUR
PLEASE NOTE:

Pages 255-273,
"Visible CW Parametric Oscillator Using Barium Sodium Niobate", ©1971 by the American Institute of Physics;


"Design and Tuning Characteristics of a CW Optical Parametric Oscillator", ©1970 by Industrial and Scientific Management, Inc.; and

"Measurements of Photon Correlations of Second Harmonic Generated Light", ©1970 by the American Institute of Physics, not microfilmed at request of author. Available for consultation at Rice University Library.

UNIVERSITY MICROFILMS.


