Investigation into the Polarization of the Beams of a Nd$^{3+}$ Barium Crown Glass Laser Operated at Liquid Nitrogen Temperature

by

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ABSTRACT

By designing a greatly improved high time-resolution polarimeter, measurements and calculations, at various pumping levels, of the time variation of polarization of the beams of a Nd$^{3+}$-barium crown glass laser have been made at liquid nitrogen temperature. It was found that, as far as the time-variation behavior of polarization is concerned, operation of the laser at 77°K or room temperature makes no qualitative difference. Under normal pumping conditions, the majority of spikes have degrees of polarization greater than 50%. The average degree of polarization per spike over one flash generally tends to go down with increasing pumping energy. Unfortunately the variation of polarization with time is so complicated that no preferred relation between polarization and time can be concluded. The sources of polarization have been discussed in detail, and the experimental results interpreted. The polarization properties of the polarized part of each spike—e.g. the direction of rotation and orientation and ellipticity of the polarization ellipse—have also been investigated.

In addition, the existences of the multimode emission and the coherence between $E_x$ and $E_y$ of the light waves of this laser were justified by this experiment.
I. Introduction

I-1. Polarization of Radiation:

When it was established that there is a connection between the polarization characteristics of radiation from and the properties of a microscopic system, new ways were opened up for studying such systems. Two possible methods for further studies became immediately clear. First, polarization studies could be used to obtain information on the structure of a radiating system in an isolated state. Second, study of its interaction with the surrounding medium could be used as a method for investigating the behavior of the radiating system in the ambient system. Polarization measurements play an important role in all branches of spectroscopy. Nevertheless, there has been no systematic account of the results obtained in these studies and of the principles which may be used in their interpretation.

Polarization of radiation consists in the anisotropy of the distribution of electromagnetic vibrations in the plane perpendicular to the direction of the ray. Natural (unpolarized) radiation of ordinary light sources may become partially or completely polarized during its interaction with matter which always accompanies reflection, refraction and absorptions. The effect of an external magnetic field (Zeeman effect), of an electric field externally applied (Stark effect), and of built-in electric and magnetic fields produced by the environment of radiative agents (e.g. crystal fields) plays an essential part in the theory of the polarization of the radiation emitted by atoms, ions and diatomic molecules. Classically, the polarization results from the anisotropy of radiation emitted by elemental radiators: electric dipole oscillator, magnetic dipole oscillator, electric rotor, etc. The quantum theory of polarization of radiation is based on
an analysis of transition matrix elements which determine the probabilities of electron transitions; these transitions are accompanied by the emission or absorption of light. The spatial anisotropy of the matrix elements of a transition determines the anisotropy of the radiation field, and consequently, the polarization of the emitted light.

The quantum mechanical methods used to study the anisotropy of elementary acts of resonance absorption and resonance emission of light in the case of atomic systems under the action of central field of forces have been worked out beautifully \(^{(2-b)}\). In the case of diatomic molecules, complex molecules and optically anisotropic crystals, theoretical investigations have also been done pretty well by approximation \(^{(2-c)}\). The method consists in analyzing the matrix elements for dipole, quadrupole, etc., transitions. Exact expressions for the corresponding moments and wave functions can not be, as a rule, written down. It is therefore necessary to use approximations based, in the first place, on the symmetry properties of the system, which in a number of cases can lead to an almost complete solution. Experimental confirmation of this type of work has been done in some particular cases \(^{(2-c)}\).

To the contrary, no theoretical efforts seem to have been made to study the polarization of laser beams. The additional difficulties involve radiation processes other than resonance process, e.g. forced electric dipole transition, and non-radiative transition, and a special function of discrete selection of the continuous spectrum of fluorescence through the presence of an optical resonator in a laser. For this reason, we have to turn to experimental investigations first.

1-2. The laser material: Nd\(^{3+}\) ions doped in a barium crown glass base:

There are some reasons for having chosen a laser of such a type for
this thesis experiment:

1. The trivalent ions of many rare earth elements, e.g. Nd, Yb, Ho, Gd, have been reported to demonstrate stimulated emission in glasses. Nd\(^{3+}\) is the only ion capable of stimulated emission at room temperature; all others show this property at liquid nitrogen temperature only.

2. Glass has obvious advantages over other host materials, e.g. crystals, since it has a lower cost of manufacture, has virtually unlimited sizes and shapes, has broader light absorption bands (increasing pumping efficiency), and may have a tailored composition to fit certain physical requirements.

3. Barium crown glass has been found to have a longer decay lifetime of fluorescence (greater than 0.75 msec with favorable Nd concentration) than other experimental glasses\(^{11-b;13;19;20}\). Longer decay time implies higher quantum efficiency.

As a consequence, the chosen material for laser action has a best prospect in developing high energy lasers for basic or applied research.  

I-3. Development of measuring polarization of pulsed beams:

The conventional method of measuring the polarization of a continuous steady light beam with a linear polarizer, a quarter wave plate and a photodetector—the measurements of quantities: \(I(\psi_0^0), I(\psi_2^0), I(\psi_3^0), I(\psi_4^0)\) are made at different instants—can not apply to the measurement of the

* These four quantities will be explained later.
polarization of a laser light beam such as the stimulated emission from a neodymium glass laser. The reason lies in the fact that polarization of the latter varies from flash to flash (or firing) even operating at same pumping level and changes rapidly, less than $1 \times 10^{-6}$ sec, with time even in the same flash. The method of Brunton(29) and Pavliscak(30) using a Courtney-Pratt biprism, a microdesitometer, and high speed photographic techniques of high speed framing camera has been recently reported to operate at a speed as fast as 800,000 frames per second, being equivalent to a time resolution of a little larger than $1 \times 10^{-6}$ sec, has a little insufficient time resolution and a poor accuracy in a quantitative sense. Not applicable is also the concept of measuring laser beam polarization by means of observing the coincidence of two spectrographs of laser beams with and without having passed through linear or circular polarizers. It limits itself to determine whether or not the polarization of a steady beam is completely linearly or circularly polarized.

To the polarimeter designed for this experiment, the basic principle of Lu and Rabson's: high time resolution polarimeter(39) has been applied, but two essential improvements have been made out of it.

I-4. Comments on this thesis subject:

In addition to the fact that polarization of radiation of a macroscopic system provides information on the structure of the system, it has been known that the fraction of light emitted in a given direction will depend not only on the total energy emitted by the substance, but also on the state of polarization of the radiation(2-d). Therefore, polarization modulation should be related to intensity modulation. For comparison, let us also look at the following: Control of the general intensity of a beam
of light can be achieved advantageously by using a pair of linear polarizers. The pair of polarizers make it possible to vary the attenuation smoothly and throughout a great range of performance. Furthermore, the attenuation obeys a fixed and well-known law of Malus:

\[ I = I_0 T_0 \cos^2 \theta \]

where \( I_0 \) is the intensity before the pair of polarizers is inserted, \( T_0 \) is the transmittance of the parallel pair and \( \theta \) is the angle between these two transmission axes. It is interesting to obtain more information on this practical possible ways of light intensity modulation through the effect of polarization on the luminescence energy yield.

Before the polarization of a laser beam can be conveniently by desired time varying signals or others which are introduced to change the polarization state of radiation, more theoretical and experimental work should be done. The main goal of doing this experiment was to investigate the time varying behavior of polarization of the beams of a Nd\(^{3+}\) - glass laser operating at 77°K. Thus, a comparison of experimental results obtained at this temperature and room temperature can be made. A published note "Seek Beam Modulation By Electric Polarization"\(^{(27)}\) has encouraged this worker to keep on investigating this subject.

* Another interesting way of modifying the polarization state of radiation from a given macroscopic radiating system is, by means of proper filters, to change the spectral composition by filtering out some spectral components or narrowing down its spectral spread.
II. Brief Description of the Origins of Polarization of Radiation From a Radiating System

Elementary radiation or monochromatic light—due to classical dipole-oscillators, rotors; or a quantum mechanical transition from a high-energy level to a lower energy level of electrons—is always polarized. However, in order that the polarization should appear in the radiation from a macroscopic system, it is necessary that the mutual orientation of the elemental radiating radiators or systems should not be random. Obviously a random aggregate of the elemental radiators gives a completely unpolarized radiation. A regular orientation of the separate elements of a macroscopic system may be due to the system itself, and this is the case, for example, in anisotropic crystals, or it may be due to outside induction by electric and magnetic fields, by mechanical action, or, finally, by light incident from outside the system, since a light ray is, by its very nature, always anisotropic. The last case, where the anisotropy in the distribution of the radiating elements of a macroscopic system is due to the anisotropic action of a light ray, is particularly important in the case of the phenomenon of polarized luminescence.

II-1. Polarized Radiation As a Consequence of the Natural Anisotropy of a Macroscopic System:

If the absorbing or emitting body is a crystal then the separate emitting centers lie in a regular field determined by the surrounding molecules and ions forming the crystal lattice. The symmetry character of this field determines the character of the orientation of the centers. In the case of optically anisotropic crystals, the meaning of the orientation which arises in this way is obvious. However, orientation can sometimes
appear in optically isotropic crystals having a crystal lattice with a high
degree of structural symmetry. Although, in principle, the natural anisotropy
of a system may be reduced to the orientation of radiators in external
fields, the complexity of real crystal systems is such that this could be
done only in isolated cases.

The analogous phenomena can also occur in media whose anisotropy
is not due to structural regularity but a high statistical probability for
a given orientation of the component elements.

In the case of regular crystals, the orientation of the emitting centers
may be complete, and the emitted light may be practically totally polarized
--- if all centers are oriented parallel to each other. In statistically
anisotropic media of the cellophane type, one may speak of a degree of
polarization of the emitted light, which is determined by the degree of
orientation of the emitting centers. The same concept may be used in the
discussion of crystals with a number of possible directions of orientation.
The degree of polarization of the radiation due to anisotropy of the system
may be defined as

$$P = \frac{I_z - I_x}{I_z + I_x}$$

where $I_z$ and $I_x$ are intensity along and perpendicular to orientation axis
respectively.

II-2. Polarized Radiation As a Consequence of the Effect of Electric and
Magentic Fields :

One must distinguish two cases giving rise to polarized radiation
during the interaction of a radiating system with external magnetic and
electric fields:

1. external field acts directly on the radiation agents
2. this action is transmitted to the radiation agents through the
which
system with these agents are bound.
Since the splitting of lines in practically reliable fields is small, and
the intensities of the $\Pi$- and $\Sigma$-components (resonance radiation due to electric
dipole transition) emitted in a given direction is the same, polarized
radiation of isotropically excited media can only be observed after spectral
resolution. It is clear that this effect can only be detected in sufficiently
narrow spectral lines emitted by atoms or ions or relatively simple molecules.
In the two cases considered above, the polarization of radiation is due
to the anisotropy of the medium in which the radiators are imbeded. In these
cases the polarization will occur independently of whether the agent which
excites the radiation is anisotropic or not.
II-3. Polarized Radiation Excited by Light:

In this case, the anisotropy of the emitted light is due to the effect
of exciting light on an isotropic medium. Because the light vibrations
are transverse, even the natural, unpolarized light is always anisotropic,
since there are no vibrations in the direction of propagation. The elementary
absorbing and emitting systems are also always anisotropic, and hence a
light ray incident on the medium will interact preferentially with those of
them which have a certain definite spatial orientation relative to the
exciting light vibrations. As a result, radiators with a definite spatial
orientation will play a predominant part in the various phenomena, and
if one is concerned with the emission by these radiators, then it will
be turn out to partially or completely polarized.

In the case of isotropic excitation of an aggregate of atoms, e.g.
in a gas discharge, the intensities of the $\Pi$- and $\Sigma$- components turn to be
the same and the radiation is unpolarized. In the case of excitation by
light only certain definite transitions will take place in atoms; in particular, if the light is linearly polarized, one will have transitions in which the magnetic quantum number remains the same ($\Delta M = 0$, $\Pi$-component). As a result, the intensities of the $\Pi$- and $\sigma$-components will be, in general, unequal, i.e. the radiation will be polarized. Let us suppose that the transition $^3\Sigma \rightarrow ^1P_1$ takes place on absorption of light. If the absorbed light is linearly polarized, then the transition will take place to a magnetic sublevel of the excited state $^1P_1$ with $\Delta M = 0$. The opposite transition $^1P_1 \rightarrow ^1S_0$ can also occur with $\Delta M = 0$, i.e. they will be accompanied by the emission of linearly polarized light.
III. The Theory of Partial Polarization of a Quasi-monochromatic Light

A strictly monochromatic light is always polarized; a natural light is unpolarized. In general, the variation of the electric vectors of a quasi-monochromatic light is neither completely regular as the former, nor completely irregularly as the latter. And we may say that the light is partially polarized.

Laser beams may be described as quasi-monochromatic light waves. The wavelength spread of the stimulated emission of a laser is much narrower than the wavelength of the spontaneous emission due to the transition between those two levels (or bands) which are involved in laser action. In solid state lasers, multi-mode oscillations and multi-level transitions are almost inevitably involved in the laser action if no particular measure is taken to eliminate them. The output light of a solid state laser is composed of a great number of sharp spectral lines. For example, the stimulated emission of a Nd\(^{3+}\) doped glass laser centered at 1.06 micron covers a wavelength range of the order of 100 Å—really depending on the preparation of the laser material and the pumping levels. That is, the ratio of wavelength spread to the center wavelength is less than 0.01. Therefore, such a laser light may be considered as a quasi-monochromatic one, and this ratio shows how well this light may be approximated. This means the total wave amplitude of a laser beam does not change much within the coherence time \(1/\Delta f\), where \(\Delta f\) is the frequency spread.

III-1. The Coherency Matrix of a Quasi-monochromatic Plane Wave:

Consider a quasi-monochromatic light of mean frequency \(\bar{f}\) propagating in z-direction. The x- and y- components of its electric field vector at time \(t\) and space point \(\mathbf{r}\), are
\[ E_x(\mathbf{r}, t) = A_x(\mathbf{r}, t) \exp\left(i\phi_x(\mathbf{r}, t) - \frac{\omega}{2} t^2\right) \]
\[ E_y(\mathbf{r}, t) = A_y(\mathbf{r}, t) \exp\left(i\phi_y(\mathbf{r}, t) - \frac{\omega}{2} t^2\right) \]

where \( \phi_x, \phi_y \) are phase angles.

The coherency matrix is then defined as

\[
J(z, T) = \begin{pmatrix}
J_{xx}(z, T) & J_{xy}(z, T) \\
J_{yx}(z, T) & J_{yy}(z, T)
\end{pmatrix} = \begin{pmatrix}
\langle E_x(\mathbf{r}, t) E_x^*(\mathbf{r}, t) \rangle & \langle E_x(\mathbf{r}, t) E_y^*(\mathbf{r}, t) \rangle \\
\langle E_y(\mathbf{r}, t) E_x^*(\mathbf{r}, t) \rangle & \langle E_y(\mathbf{r}, t) E_y^*(\mathbf{r}, t) \rangle
\end{pmatrix}
\]

where \( \langle \cdots \rangle \) represents the instrumental average, i.e. a temporal average over the resolution time of the photodetectors employed and a spatial average over their active surfaces. More specifically, in this experimental setup, the spatial average is carried out over the intersection in \( xy \)-plane of the narrow laser beams and the front surfaces of the photocathodes of photomultipliers, and the time average may be over either the resolution time \( T \) of photomultipliers of the setup or the whole period \( T \) of laser action if integrators have been inserted in the output circuits of PM's (photomultipliers). In the reported experiment, integrators of photocurrents have not been used; \( T \) should be referred to the former. Since an average has been taken over \( xy \)-plane, \( \mathbf{r} \)-dependence becomes \( z \)-dependence. The existence of \( z \)-dependence is due to the fact that the laser beams have been attenuated through optical devices they have passed and, furthermore, the amplitudes of their total waves vary during propagation.

Next, let us look at the properties of these matrix elements.

1. \( J_{xx} \geq 0 \)
2. \( J_{yy} \geq 0 \)
3. \( J_{xy} = J_{yx}^* \)
4. \( \text{Det.} (J) = J_{xx} J_{yy} - J_{xy} J_{yx} \geq 0 \)
5. \( \text{Det.} (J) \) and Trace \( J \) are invariant under rotation of coordinates systems.
In fact, \( J_{xx} \) or \( J_{yy} \) is just the intensity of the light after the original light has passed through an ideal linear polarizer with its transmission axis in the \( x \)- or \( y \)-direction. And their sum is the total intensity of the original light. When there is no correlation between \( E_x \) and \( E_y \), then 
\[
J_{xy} = J_{yx} = 0.
\]
Totally, the whole matrix characterizes a monochromatic or quasi-monochromatic light.

The coherency matrix becomes simpler in some special cases. For a natural light, which is obtained from a body being made to glow by raising its temperature, can be represented by
\[
J = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]
where \( I \) is its total intensity.

For a completely polarized (linearly, circularly or elliptically) light the ratio of the amplitude of \( E_x \) to that of \( E_y \) and their phase difference are time-independent, i.e., \( A_x(F,t) \neq A_y(F,t) \) (depends on only \( F \)) and \( \phi_x(F,t) = \phi_y(F,t) = \phi(F) \) = \( \phi(F) \), \( \det J = 0 \). The coherency matrix of an elliptically polarized light is
\[
J = \begin{pmatrix} \langle A_1^2 \rangle & \langle A_1 A_2 e^{+i\phi} \rangle \\ \langle A_1 A_2 e^{-i\phi} \rangle & \langle A_2^2 \rangle \end{pmatrix}
\]
For a circularly polarized light
\[
J = \frac{1}{2} \begin{pmatrix} 1 & \pm i \\ -i & 1 \end{pmatrix}
\]
\( I = 2 \langle A_1^2 \rangle = 2 \langle A_2^2 \rangle \)

For a linearly polarized light
\[
J = \begin{pmatrix} \langle A_1^2 \rangle & \langle (-1)^m A_1 A_2 \rangle \\ \langle (-1)^m A_1 A_2 \rangle & \langle A_2^2 \rangle \end{pmatrix}
\]
m = integers

III-2. Realization of Measuring Coherency Matrix Elements:

Suppose that the \( y \)-component of the electrical field vector is subject
to a retardation $\mathcal{E}$ with respect to the $x$- component (this can be done by
passing the light through a compensator with a retardance $\mathcal{E}$ and its fast axis
along $x$- axis) and consider the light intensity of the light vibrations in
the direction which makes an angle $\theta$ with positive $x$ - axis —— this
intensity $I(\theta, \mathcal{E})$ would be observed by sending the light through a polarizer
with its transmission axis at an angle $\theta$ with respect to the reference
OX in the horizontal. Since the fast-axis and slow-axis lie in $x$- and $y$-
direction respectively, after passing through the compensator $E_x$ will lead
$E_y$ by an angle $\mathcal{E}$. The component of the electric vector in the $\theta$ - direction,
after the retardation has been introduced, is

$$E(\vec{r}, t; \theta, \mathcal{E}) = E_x(\vec{r}, t) \cos \theta + E_y(\vec{r}, t) \sin \theta e^{-i\mathcal{E}}$$

so that

$$I(\theta, \mathcal{E}) = \langle E(\vec{r}, t; \theta, \mathcal{E}) E^*(\vec{r}, t; 0, \mathcal{E}) \rangle$$

$$= J_{xx} \cos \theta + J_{yy} \sin \theta + \cos \theta \sin \theta \left( J_{xy} e^{-i\mathcal{E}} + J_{yx} e^{i\mathcal{E}} \right)$$

it follows that $I(0^\circ, 0^\circ) = J_{xx}$

$$I(90^\circ, 0^\circ) = J_{yy}$$

$$I(45^\circ, 0^\circ) = \frac{1}{2} (J_{xx} + J_{yy}) + \frac{1}{2} (J_{xy} + J_{yx})$$

$$= \frac{1}{2} (J_{xx} + J_{yy}) + \text{Re} J_{xy}$$

$$I(45^\circ, 90^\circ) = \frac{1}{2} (J_{xx} + J_{yy}) - \frac{1}{2} (J_{xy} - J_{yx})$$

$$= \frac{1}{2} (J_{xx} + J_{yy}) + \text{Im} J_{xy}$$

Carrying out the solution, we obtain

$$J_{xx} = I(0^\circ, 0^\circ)$$

$$J_{yy} = I(90^\circ, 0^\circ)$$

$$\text{Re} J_{xy} = 2 I(45^\circ, 0^\circ) - I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ)$$

$$\text{Im} J_{xy} = 2 I(45^\circ, 90^\circ) - I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ)$$

where $J_{xy} = \text{Re} J_{xy} + i \text{Im} J_{xy}$
These four quantities $I(0^\circ,0^\circ)$, $I(90^\circ,0^\circ)$, $I(45^\circ,0^\circ)$ and $I(45^\circ,90^\circ)$ can be measured in an experimental arrangement; hence the coherency matrix characterizing a laser beam can be obtained experimentally.

Note that the intensity defined above is just the magnitude of the average Poynting vector except a constant factor characterizing the medium.

III-3. Degree of Polarization:

It is easily shown that any quasi-monochromatic light wave may be regarded as the sum of a wave of natural light and a wave of monochromatic (and hence polarized) light independent of the former, and that this representation is unique. That means, if we separate the coherency matrix in the following way:

\[
J = \begin{bmatrix}
J_{xx} & J_{xy} \\
J_{yx} & J_{yy}
\end{bmatrix} = \begin{bmatrix}
A & 0 \\
0 & A
\end{bmatrix} \begin{bmatrix}
B & D \\
D^* & C
\end{bmatrix}
\]

with $A \geq 0$, $B \geq 0$, $C \geq 0$, and $BC - DD^* = 0$

then we have

\[
A = \frac{1}{2} (J_{xx} + J_{yy}) - \frac{1}{2} \sqrt{(J_{xx} + J_{yy})^2 - 4 \det J}
\]

\[
B = \frac{1}{2} (J_{xx} - J_{yy}) \frac{1}{2} \sqrt{(J_{xx} + J_{yy})^2 - 4 \det J}
\]

\[
C = \frac{1}{2} (J_{xx} - J_{yy}) + \frac{1}{2} \sqrt{(J_{xx} + J_{yy})^2 - 4 \det J}
\]

\[
D = J_{xy}, \quad D^* = J_{yx}
\]

The ratio of the intensity of the polarized portion to the total intensity is called the degree of polarization $P$ of the wave; hence

\[
P = \frac{B + C}{\text{Trace } J} = \frac{1 - \frac{4}{4} \det J}{(J_{xx} + J_{yy})^2} = \frac{\text{Imax}(\theta, \xi) - \text{Imin}(\theta, \xi)}{\text{Imax}(\theta, \xi) + \text{Imin}(\theta, \xi)}
\]
III-4. Stokes's Parameters of a Quasi-monochromatic Plane Wave:

We see that in order to characterize a quasi-monochromatic plane wave, four real quantities are in general necessary. Now let us introduce another 4-parameter representation which is closely related to the coherency matrix. These four Stokes' parameters are $S_0$, $S_1$, $S_2$, $S_3$ which are, in terms of the elements of coherency matrix,

$$
S_0 = J_{xx} + J_{yy}
$$

$$
S_1 = J_{xx} - J_{yy}
$$

$$
S_2 = J_{xy} + J_{yx} = 2 \text{Re} J_{xy}
$$

$$
S_3 = i (J_{yx} - J_{xy}) = 2 \text{Im} J_{xy}
$$

$S_0$ represents the total intensity of the light. $S_1$ is the excess of intensity in $x$-direction over that in $y$-direction, indicating a preference of linear polarization in $x$-direction. The physical significance of the others will be explained in the following. Since

$$
\begin{pmatrix}
B & D \\
D^* & C
\end{pmatrix}
$$

contains four real quantities, mathematically it can be expanded into four coherency matrices:

$$
\begin{pmatrix}
B & D \\
D^* & C
\end{pmatrix} = I_1 \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \text{(linear polarization in } x \text{-direction)}
$$

$$
+ I_2 \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} + I_3 \begin{pmatrix} 1 & \pm 1 \\ \pm 1 & 1 \end{pmatrix} + I_4 \begin{pmatrix} 1 & \pm i \\ \pm i & 1 \end{pmatrix}
$$

$$
\quad \text{(linear polarization } \pm 45^\circ \text{ or } \pm 135^\circ \text{ linear polarization relative to } x \text{-direc.)}
$$

$$
\quad \text{circular polarization)}
$$

Solving these four equations, we obtain
\[ I_3 = \pm 2 \Re J_{xy} \quad I_4 = \pm 2 \Im J_{xy} \]
\[ I_1 = \frac{1}{2} (J_{xx} - J_{yy}) + \frac{1}{2} \sqrt{(J_{xx} + J_{yy})^2 - 4 \text{Det} J} - \Re J_{xy} - \Im J_{xy} \]
\[ I_2 = \Re J_{xy} + \Im J_{xy} \]

For physical reasons we can possibly make the choice of sign in such a way that \( I_3 \geq 0 \), \( I_4 \geq 0 \). Therefore, \( S_2 \) is closely related to the intensity of the portion of \( 45^\circ \) or \( 135^\circ \) depending on the sign of \( S_2 \). \( S_3 \) has a similar relation to the intensity of the portion of the circular polarization either right- or left-handed.

The polarized portion has the following Stokes parameters:

\[
\begin{align*}
S_0^p &= B + C = \frac{S_1 + S_2 + S_3}{2} \\
S_1^p &= B - C = S_1 \\
S_2^p &= D + D^* = S_2 \\
S_3^p &= i(D^* + D) = S_3
\end{align*}
\]

The unpolarized portion has the following:

\[
\begin{align*}
S_0^u &= 2\pi = \text{Tr} \cdot J - B - C \\
S_1^u &= S_2^u = S_3^u = 0
\end{align*}
\]

Obviously, \( S_j = S_j^p + S_j^u \) \( j = 0, 1, 2, 3 \)

The degree of polarization of the original wave may be written as

\[ P = \frac{S_0^p}{S_0} / \sqrt{S_1^2 + S_2^2 + S_3^2} / S_0 \]

To describe the ellipse traced by the tip of the electric field vector of the polarized portion (elliptical polarization in general), there are the following expressions for the ellipticity \( e \) and the orientation of angle \( \theta \) relative to x-axis:

\[ e = \tan \chi = \pm \frac{b}{a}, \quad -\frac{\pi}{4} \leq \chi \leq \frac{\pi}{4} \text{, where } \sin 2\chi = S_2 / \sqrt{S_1^2 + S_2^2 + S_3^2} \]
\[ a^2 + b^2 = S_0 \quad \text{and } \tan 2\theta = S_2 / S_1 \quad 0 \leq \theta \leq \pi \text{ where } a, b \text{ are semi-major and semi-minor axes respectively.} \]
IV. Properties of Nd$^{3+}$ active Ions in a Barium Crown Glass Base

IV-1. Energy Levels and Spectral Properties:

A typical energy diagram of levels for trivalent ions of neodymium doped in barium crown glass is shown in Fig.-1. Absorption at any of the excited levels above the $^4F_{3/2}$ state leads to fluorescence from the upper $^4F_{3/2}$ state. Approximately one third of the pumping is provided by the three levels shown in the near infrared. Another one third of the pumping is done by the strongest absorptions in the yellow at about 17,000 cm$^{-1}$. The near ultraviolet absorptions at 28,000 cm$^{-1}$ gives about 20% of the pumping. The other levels contribute the remaining pumping. The fluorescence emission is in the form of three bands with their peaks at 0.83, 1.06, and 1.35 micron. These correspond to the emission from the $^4F_{3/2}$ state to the states $^4I_{13/2}$, $^4I_{11/2}$, and $^4I_{9/2}$. In Fig.-2 is shown the spectral distribution of the detailed absorption bands or levels of a 2% by weight doping of Nd$^{3+}$ in a typical glass base. The absorption bands and levels are almost coincident with those above $^4F_{3/2}$ of Fig.-1, though the glass compositions of these two figures were not identical. To meet the distribution of the above absorption bands or levels, FEK XE-1-3 xenon flashlamps were chosen for the pumping sources in this experiment. Their spectral-energy output characteristics at any pumping levels are not available. However, it is known that it should be similar to that of xenon short-arc lamps, whose typical spectral energy distribution at a low power density is as shown in Fig.-3. High power density will enhance in the blue and ultraviolet wavelength preferentially$^{(15)}$. The characteristics of XE-1-3 flashlamps are expected to vary with peak power loadings in a similar fashion.
Fig. 2
Typical absorption spectrum of 2% doping neodymium glass. The upper levels of the transitions from the ground state are indicated at the appropriate absorption bands. (13)

Fig. 1
Energy level diagram for 2% Nd³⁺ doped in a barium crown glass base. (11-b)

Fig. 3
Representative spectral energy distribution of a low power density lamp (Xenon short-arc lamps, types X-75/76). (14)
Fig. 4. Fluorescence spectrum of Nd\textsuperscript{3+} 2 wt. % doped in a barium crown glass at 77 K (11–b).

Fig. 5. Emission spectrum of 2 wt.% Nd\textsuperscript{3+} doping neodymium glass at room temperature (13).
The fluorescence spectrum of a weight % doping of Nd$_2$O$_3$ in a barium crown glass base at 77°K is shown in Fig.-4. At room temperature the doublet structure is still evident but is not as well resolved. For comparison, the same sample used in Fig.-2 is shown in Fig.-5. From the absorption spectrum (11-b), it is clear that the $^{4}F_{3/2}$ state is split into two Kramers doublets with an energy separation of about 120cm$^{-1}$. This separation is sufficient for only the lower state of the $^{4}F_{3/2}$ to be occupied during fluorescence at 77°K. The upper state is partially occupied at 300°K. The doublet structure shown in Fig.-4 indicates the splitting of the ground state $^{4}I_{9/2}$ into two states. In alkali-alkaline earth silicates, the ground state splitting ranges from 350 cm$^{-1}$ up to 450 cm$^{-1}$, depending on the actual glass composition. In high lead silica glasses and in lanthanum borate glasses, there is no obvious splitting but rather a single broad line at 0.88 micron. The terminal level $^{4}I_{11/2}$ also has a splitting of the order 250 cm$^{-1}$ (26). The splitting of the $^{4}I_{9/2}$ ground state has an important bearing on the pumping of the neodymium laser. All of the strong absorptions have additional absorption bands on the long wavelength side due to the split ground state, (11-b) and hence the pumping efficiency is affected.

* Kramers Theorem: In the absence of an external magnetic field, the stationary states of an atomic system are always "degenerate" when the system contains an odd number of electrons. Nd atom has the following electronic configuration: Xe structure and 6S$^2$, 4f$^4$, 5d$^0$. In a Nd$^{3+}$ ion, 3 electrons of 4f$^4$ have been removed; 57 electrons, an odd number, remain—the degree of degeneracy being an even number. If the number of electrons is even and the stationary states is non-degenerate, the energy level will not be influenced in the first approximation by a magnetic field.
The laser action is accomplished in the following processes (see Fig. 1):

\[ \text{Level 1 (Pumping)} \rightarrow \text{Level 2 (transition)} \rightarrow \text{Level 3 (emissions)} \]

- Level 4 ---- 4-level-transition laser at 0.88 micron
- Level 3 ---- 3-level-transition laser at 1.06 micron
- Level 2 ---- 2-level-transition laser at 1.35 micron

Approximately about 80% of the fluorescence emission is emitted at 1.06 micron. For a 1.06 micron Nd³⁺-glass laser, the laser resonator is designed to favor this radiation --- purposely lowering the threshold of 1.06 micron radiation instead of the other two.

The laser output beam consists of a great number of sharp line spectra (9) (multiple axial-mode and transverse-mode oscillations in the resonator cavity). The spectral width depends on the type of glass base and the pumping levels. The Nd³⁺-glass laser (barium crown glass base) tested in this experiment is around 100 Å (11-b) centered at 1.06 micron, the width increasing with pumping energy level. Except for small details, the spectrum is reproducible in a given sample (17). It has been demonstrated that (23,24) the number of spectral lines and their wavelengths produced during a flash of an Nd³⁺-glass laser vary with time. This time-variation behavior also depends on the pumping --- the number of multiple lines emitted simultaneously increases as the pumping energy increases. The stimulated emission of such a laser shows the familiar random behavior of spikes in solid state lasers, each spike lasting about $10^{-6}$ seconds --- by a spike we mean a relaxation pulse of radiation, which builds up and dies away, in a highly irregular manner, leaving the sample essentially quiescent until the next spike begins.

For an ion in a crystal or other solid, both permitted and forbidden
Transitions are possible. It is well-known that the electric dipole transition occurs only between levels with opposite parity, and magnetic dipole and electric quadrupole transitions are possible only between levels with the same parity. For free rare earth atoms or ions, the intra-\( \mathcal{I}_N \) electric dipole transitions are forbidden because all levels of the same electronic configuration have the same parity. This is not true when the atom or ion is a part of the crystal or solid. Electric dipole transitions among levels of the 4f shell not only can be observed but also form a major part of the spectra of rare earth ions in crystals or other solids. This type of transition is called "forced electric dipole transition" (25). The intensity of the spectra due to this forced dipole transition is much weaker than the normal electric dipole transition, but stronger than the normal magnetic dipole and electric quadrupole transitions.

IV-2. Miscellaneous Properties:

The laser material of \( \text{Nd}^{3+} \) ions in a barium crown glass base has the following typical composition (17) (concentration by weight): 0.10% to 2.0% \( \text{Nd}_{2}O_{3} \) for active ions, and 5% \( \text{SiO}_{2} \), 25% \( \text{BaO} \), 15% \( \text{K}_{2}O \), 1% \( \text{Sb}_{2}O_{3} \) for barium crown glass. The glass has a specific weight of approximate 3 and a nominal index of refraction of 1.54. The decay lifetime of the fluorescence from \( 4F_{3/2} \) state has been found to be the longest compared with some other experimental glasses giving values in the range 0.56 msec (17) to 0.75 msec (11-b). However, when the barium crown glass contains 5% or 10% of \( \text{Nd}_{2}O_{3} \), the decay time decreases to 0.5 msec (11-b) or less than 0.15 msec (17) respectively. In general, the power input for laser threshold varies inversely as the product of active ion concentration and fluorescent decay lifetime (22). The conversion efficiency, i.e. the ratio of the laser output energy to the electric
energy input to the pumping sources, increases as Nd₂O₃ concentration is increased from 0.13% to 2.0%. Concentration quenching (the decay time begins to drop down as the ion concentration increases to a certain value) of the decay lifetime occurs above 2% and the efficiency decreases slowly as the concentration is increased to 6% (16), the composition of which the power threshold is a minimum. At 10% the efficiency is equivalent to that of 1% concentration.

A Nd³⁺-potassium silicate glass laser has been found comparable in decay lifetime with a Nd³⁺-barium crown glass laser. The decay time was reported to be around 0.81 msec. Studies on the lasers with neodymium ions in other types of glasses were numerous (16, 19, 21).

As a result of the so-called lanthanide contraction, the 4f electrons are well shielded by the 5s², 5p⁶ closed shell (outer shell of Xe electronic configuration). The interactions between these 4f electrons of Nd³⁺ ions and their environment through the electric field produced by the glass base are relatively weak; the spin-orbit coupling is much more important. However, the fluorescence characteristics of Nd³⁺ ions, and in particular, the decay time, is affected significantly as a result of this small perturbation of environmental field. Note that the internal electric field produced by the glass base apparently have random directions and magnitudes due to the amorphous nature of glass.
V. Experimental Set-up

V-1. Experimental Arrangements Excluding Power Supply and Display System:

The whole setup (see Fig. 6), includes 1. a polarimeter or an optical system to measure polarization of a light beam (see Fig. 7), 2. a cryogenic cooling dewar, model 125, Optics Technology, Inc., and a laser rod (see Fig. 8), 3. a FEK XE-1-3 and a pumping cavity (see Fig. 9).

V-2. Comments on Components of the Whole Set-up:

1. The cryogenic cooling dewar—-

The laser rod was screwed inside an inner protection tubing at the bottom of the output tube, which would be immersed in the liquid nitrogen when liquid N\textsubscript{2} was introduced into the flask of the dewar. The condensing chamber was to condense the water vapor possibly contained in the air in the output tube, so that no water drop would condense on the periphery of the laser rod. A transparent glass plate was attached to the upper end of the output tube by high vacuum grease. The air inside the output tube was evacuated through the evacuation tube, and then a small amount of gas N\textsubscript{2} was introduced down into the protection tubing as a medium of thermal convention. This amount was so small that, even if gas N\textsubscript{2} might liquidify at the bottom of the protection tubing, the liquidified nitrogen would not reach the lower end of the rod.

![Refraction Index Diagram](diagram.png)
Fig. 6
The whole setup of the experiment (excluding power supply and display system)
Right side view
Fig. 7
The polarimeter
Model of beam splitters
in two layers
Fig. 9
An optical pumping cavity with a flash tube and a laser rod placed at its foot (inside view).

Fig. 8
A cryogenic cooling dewar with a laser rod and its protection tube mounted.
Shown on the diagram on p.24 of the cross-section of the lower part of
the dewar, two typical incident light rays—one hitting on and the other
missing from the laser rod—are obviously observed to reflect some
incident light energy off the dewar. Also materials in between the rod
and the dewar wall, and bubbling of liquid nitrogen absorb a significant
fraction of pumping light. It is easily seen that this configuration of exposing
the rod to a pumping source has lower efficiency than that by directly exposing it
to the same source. Therefore, the measured threshold of the same \( \text{Na}^{3+} \) glass-
laser rod placed in this pumping configuration was 145 joules, which almost
doubled that (65 joules) by exposing the same rod directly to pumping light.

2. Pumping Cavity:

The cavity is of elliptical cylindrical geometry which has the
following dimensions:

\[
\text{major axis } = 2a = 4_{1/4}^\text{in}, \quad \text{minor axis } = 2b = 2_{1/4}^\text{in}, \quad \text{ellipticity } = e = 0.223
\]
of the cross-sectional ellipse, and the height of the cylinder is 3\in.

Now let us estimate the efficiency in the following (12):

\[
c/d = \text{diameter of sample}/ \text{diameter of flash lamp} = 0.25^\text{in}/0.26^\text{in} = 0.93
\]
\[
\sin \Theta_1 = d/(4ae), \quad \cos \Theta_3 = \left(1 - \frac{1 - e^2}{2}(1+c/d)\right)^{1/2}
\]
\[
\sin \Theta_0 = d \sin \Theta_3 / c
\]
The percentage efficiency \( E = \frac{100}{\pi} \left(\Theta_3 + c(\Theta_0 - \Theta_1)/d\right) \approx 79\%
\]
The inner surface of the aluminum cavity was machined and buffed and
was estimated to have a reflectivity 85\%. Taking into account the cooling
configuration mentioned previously, 50\% more reduction was necessary. Thus,
the actual optical efficiency of the cavity was approximately equal to

\[
79\% \times 85\% \times 50\% = 34\%
\]
The rod inside the dewar and the flashtube were mounted exactly at
the foci of the elliptical cylinder (see Fig. 9) whose two ends were
made of high reflective material.

3. Beam Splitters:
Ten 45°-silvered mirrors (beam splitters) were properly arranged so that they divided a vertical laser beam into four equal, horizontal, parallel components without changing its polarization state. Each component beam has passed four splitters, undergoing two reflections and two transmissions, before arriving at a PM. Of those four planes of incidence, two are horizontal, and the other two vertical.

The features of this ten-splitter arrangement are:

(1) The detailed optical path of a light ray passing through each beam splitter is shown to the right.

According to the law of refraction:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 = n_3 \sin \theta_3 = n_4 \sin \theta_4 \]

By means of the law of reflection,

\[ \theta_1 = C_4 \text{, refraction index} \]

That means the beam arrives at any beam splitter at 45° and leaves at 45° (both reflected and refracted beams).

(2) Let \( E_\perp (E_\parallel) \) be the component of the original electric field vector \( E \) (//) to the plane of incidence of the first splitter; \( r_\perp \) and \( t_\perp \) (\( r_\parallel \) and \( t_\parallel \)) the reflection and transmission coefficients of the component of the electric field perpendicular (parallel) to any plane of incidence; \( E'_\perp (E'_\parallel) \) the actual value of \( E_\perp (E_\parallel) \) after the component beam has passed through four proper beam splitters. Assume that all of the beam splitters were made identical so that \( r_\perp \), \( r_\parallel \), \( t_\perp \), \( t_\parallel \) with respect to any beam splitters are the same. It can be shown that \( E_\perp \) and \( E_\parallel \) are subject to the following reduction (reduction factors are arranged in the order in which beam components pass each set of four splitters):
The prime and unprime electric fields are simply related by a unity 2 x 2 Jones matrix multiplied by a factor. Hence, the polarization of the four component beams is preserved through the ten splitters.

It is doubtful that Dr. Sun Lu's arrangement of beam splitters (12) has satisfied the condition that those six component beams have the same polarization as the original one. Obviously in his arrangement, components beams pass through 2, 4, 6, 8, 8 splitters respectively (in the order from the beam to PM-1 to that to PM-6). It seems that, the component beams to PM-1, PM-2, PM-5 do not fulfill the requirement, but beams to PM-3, PM-4 and PM-6 do not. The most important reason is that any two of the four quantities $r_{\perp}$, $r_{\parallel}$, $t_{\perp}$, $t_{\parallel}$, are not equal even the beams enter and leave the mirrors at 45°.

(3) Since all component beams are subject to an identical reduction (at least in principle) through sets of four splitters, they have equal intensities.

$$\text{J}$$ All of the four distances from the first beam splitter to the four
polarizers were made equal. Its significance will be explained in V-3-2.

4. The Ideal Isotropic, Absorbing Plate:

Suppose its transmittance is \( T^2 \). Then its effect can be expressed by a diagonal Jones matrix \( (5-a) \), which relates the electric field \( E_x^1, E_y^1 \) after passing through linear, and \( E_x, E_y \) before entering the optical device

\[
\begin{pmatrix}
E_x^1 \\
E_y^1
\end{pmatrix} = \begin{pmatrix}
T & 0 \\
0 & T
\end{pmatrix} \begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

The attenuation or absorbing effect of devices such as beam splitters particularly arranged in the way shown in Fig.-7, compensators, polarizers, can be accounted for in this manner. They do not change the original polarization.

5. Ideal Homogeneous Linear Polarizers:

With its transmission axis at \( \theta \) with respect to horizontal axis, they have an effect expressed in the following Jones matrix \( (5-a) \)

\[
\begin{pmatrix}
E_x^1 \\
E_y^1
\end{pmatrix} = \begin{pmatrix}
\cos^2 \theta & \sin \theta \cos \theta \\
\sin \theta \cos \theta & \sin^2 \theta
\end{pmatrix} \begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

Obviously, the plastic, laminated, Polaroid type HR polarisers, used in this experiment, for radiation in the range 0.3—2.7 micron do change the light polarization to achieve the measurements of \( I(\theta, \varepsilon) \).

6. The Ideal Homogeneous Linear Compensator:

With a retardance \( \varepsilon \) and its fast axis at \( \phi = 0^\circ \) (in \( \phi X \) direction), it has an effect expressed by the following Jones matrix \( (5-a) \)

\[
\begin{pmatrix}
E_x^1 \\
E_y^1
\end{pmatrix} = \begin{pmatrix}
\cos^2 \phi \, e^{i\varepsilon/2} + \sin^2 \phi \, e^{-i\varepsilon/2} & 2i \cos \phi \sin \phi \sin \varepsilon/2 \\
2i \sin \phi \cos \phi \sin \varepsilon/2 & \cos^2 \phi \, e^{-i\varepsilon/2} + \sin^2 \phi \, e^{i\varepsilon/2}
\end{pmatrix} \begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

\[
\begin{pmatrix}
E_x^1 \\
E_y^1
\end{pmatrix} = \begin{pmatrix}
e^{i\varepsilon/2} & 0 \\
0 & e^{-i\varepsilon/2}
\end{pmatrix} \begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]
A practical compensator with transmittance $T_c^2$ has a Jones matrix
\[
\begin{pmatrix}
e^{i\frac{\pi}{2}} & 0 \\
0 & e^{i\frac{\pi}{2}}
\end{pmatrix}
\begin{pmatrix}
T_c & 0 \\
0 & T_c
\end{pmatrix}
\]
Consequently it does not change the polarization.

7. Flash tubes:

PEK 1E-1-3 flash tubes have been used as pumping light source with allowed maximum energy input 400 Joules. The spectral distribution of the output of these xenon discharge lamps is such that it emits intense light in the region of strong absorption bands of Nd glass material. Thus in the laser material can absorb a large fraction of the light energy emitted by the flash tubes.

8. Silicon Sheets As Light Intensity Attenuators:

The transmission region of Si-sheets of 2 mm thickness is in the range of 1.2—15 micron with 10% maximum transmittance at both ends of the spectral region (A.I.P. Handbook). The actual thickness used was 1—1.5 mm. The sensitivity of the photocathodes of RCA-7102 and the transmittance of Si-sheets are combined together so that, at 1.06 micron, the sensitivity is about 12% of the maximum sensitivity of RCA-7102 photomultipliers, and the transmittance is less than 5% of the maximum transmittance of silicon sheets. Therefore, silicon sheets are good attenuators of a beam centered at 1.06 micron.

Now it might be interesting to pay attention to Dr. Winogradoff's description on the attenuators. In using the elemental silicon attenuators, the beam measured is allowed to fall on one face of the polished silicon wafer; the radiation is completely absorbed in the first 10^-4 cm depth. This produces a large number of free electrons and holes in the silicon. These
excess carriers recombine by radiative and non-radiative processes, the
former producing radiation at wavelength longer than that in the beam being
measured. Since the absorption coefficient of silicon for its own recombina-
tion is low, some of this radiation will emerge from the back surface of
the silicon attenuator. The low efficiency of conversion from the incident
to the emerging beam provides the function of attenuation. Since the silicon
sheets might change the polarization state of the beam, they should be put
behind polarizers in the polarimeter. This recombination techniques permits
measurements showing the fine detail in intensity variation within a laser
flash with a resolution better than $2 \times 10^{-8}$ sec.

9. Photomultipliers(PM's):

RCA-7102 PM's fitted in "mumetal" magnetic shield were used as square-
law current detectors of low level, visible to near infrared light. The
rise time of the anode pulse is typically $2.4 \times 10^{-9}$ sec. They respond faster
than the PM output circuits. The use of an average anode current well below
the maximum rated current of 10 micro-amp is recommended. Best signal-to-
noise ratio is obtained with an anode voltage in the range of 1000–1250 v.
for pulse excitation. It has been shown in Forrester's work(8) that (at least
for quasi-monochromatic light) the current emitted in the photoelectric
effect is proportional to the square of the total wave amplitude, the
instantaneous intensity, of the electric field of the radiation being
detected and not the square of the individual Fourier components before
addition. Therefore, the instantaneous photocurrent is time varying even
though the amplitudes of the spectral components themselves may be constant.
It can be said that the magnitude of the integrating time interval in the
process of squaring, integrating and averaging the classical electric
field wave to obtain the instantaneous intensity of the photodetector, is significantly smaller than 0.1 nanosecond (cf. the resolution time of RCA-7102). In the present investigation, it is assumed (9-a) that the photovoltaic effect is sufficiently fast to follow fluctuations in the intensity of the laser signal. In considering the quasi-monochromacity of laser light the assumption seems very reasonable.

10. Finally, E.G.&G. TR-35 pulse transformer with a thyratron tube were used in the trigger circuit (References for power supply and trigger circuit, 10; 11-a).

V-3. The Polarimeter:

1. Comments:

Since three real quantities are necessary to characterize the polarization state of a light beam, four PM’s are required to measure any four so that total intensity is also measured values of \( I(\theta, \phi) \) simultaneously. This can be accomplished by dividing the original beam being measured into four components by means of ten beam splitters mentioned in V-2-3. One component beam is directed through a quarter wave plate at 10,829 Å, which is approximated as the quarter wave plate at 10,600 Å here; and then through a linear polarizer, an attenuator, to a photomultiplier. Each of the other three components passes through a polarizer and an attenuator only before falling on a photocathod. In the experiment, the quarter wave plate was so placed that its flat axis was horizontal, and the quantities \( I(90^\circ, 0^\circ) \) by PM-1, \( I(90^\circ, 0^\circ) \) by PM-3, \( I(45^\circ, 90^\circ) \) by PM-2, \( I(45^\circ, 0^\circ) \) by PM-5, were simultaneously measured. The output photocurrents of PM’s and hence the vertical voltage displays on oscilloscopes are proportional to \( I(\theta, \phi) \) and hence to the original beam intensity. The proportional constant is contributed by the absorptions by mirrors, attenuators,
compensator, polarizers, and the sensitivity of PM's, the gains of PM output circuits and display oscilloscopes, and the division of the original beam into components.

2. Features:

All the distances between the center of the first beam splitter and the positions of polarizers were designed to be equal to 9°. In cluding the distances between the first splitter and the output end of the laser rod, and the distances between photocathods of PM's and polarizers, the total distances between the photocathods and the output end of the laser rod are slightly adjustable around 22°. These four distances were made equal as exactly as possible while making measurements. Since the instantaneous intensity or the total wave amplitude of the electric field of the laser signal is rapidly varying in time, the total distances travelled by the four component beams from the light source to the individual photocathods should be equal; otherwise, even if measurements of I(θ,2) by the four PM's are made equal simultaneously, they are not physical properties of the original beam emitted from the laser rod at a certain same instant. Without knowing exactly how the laser beam amplitude varies with time, it is impossible to have the equal distance design.

Note that for a quasi-monochromatic light, \( \lambda_x(F,t) \), \( \lambda_y(F,t) \), \( \phi_x(F,t) \) and \( \phi_y(F,t) \) are time dependent, but they change only by small relative amounts in any time interval small compared to the coherence time, the reciprocal of the effective spectral width \( \Delta \) of the light. Suppose the laser radiation is in the frequency range 3 x 10^14 to 1 x 10^15/1.055 cps with 100 k0 width, the coherence time \( 1/\Delta = 2.74 \times 10^{-11} \) sec. However, if there is a difference of 1.5 cm path in travelled by component beams,
then the difference in travelling time will be $5 \times 10^{-11}$ sec which is a little larger than the above coherence time; hence there is no guarantee that the total wave amplitude of the component beams do not undergo considerable change during travelling that small distance, even the laser beam is very reasonably considered as "quasi-monochromatic light. This is the first feature which has been neglected in Sun Lu's polarimeter.

The second feature, which is more important, is that each of the four component beams pass through four properly placed beam splitters so that no change in polarization due to the presence of those beam splitters is guaranteed. (See V-2-3).

Nevertheless, the photocurrent of RCA-7102 follows the fluctuations in the instantaneous intensity of the laser signal as fast as $2.4 \times 10^{-9}$ sec only. Note also that the resolution in intensity variations of silicon sheets has been reported to be better than $2 \times 10^{-8}$ sec. Let us assume both of them can respond to signal variation as fast as one nanosecond. The effect of the inequality in total distances on the observed photocurrents will not be significant as long as the difference in distance is not greater than $3 \times 10^{10}$ cm/sec $\times 1 \times 10^{-9}$ sec $= 30$ cm. No matter what the real resolution of optical devices are, the concept is significant.
VI. Procedures of Taking Data

1. Although the sample protection tube and the output tube of the dewar assembly were immersed in liquid nitrogen when oscillographs were taken, the temperature around the sample was surely subject to temporary change due to the thermal shock of pumping light pulse. In order to estimate this temperature change, a chromel-alumel thermocouple was inserted into the protection tube through the output tube in the absence of the laser rod.

The results are summarized in Table-1:

<table>
<thead>
<tr>
<th>Flashtube Input</th>
<th>Voltage across the storage capacitor of 120 f</th>
<th>Pumping energy in joules</th>
<th>Temperature Before Pumping</th>
<th>Maximum Temperature After Pumping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100 v.</td>
<td>72.6</td>
<td>76°C k</td>
<td>89°C k</td>
<td></td>
</tr>
<tr>
<td>1500 v.</td>
<td>135</td>
<td>76°C k</td>
<td>92°C k</td>
<td></td>
</tr>
<tr>
<td>2000 v.</td>
<td>240</td>
<td>78°C k</td>
<td>103°C k</td>
<td></td>
</tr>
<tr>
<td>2500 v.</td>
<td>375</td>
<td>78°C k</td>
<td>117°C k</td>
<td></td>
</tr>
</tbody>
</table>

Table-1

The temperature rise temporarily due to the pumping was completely removed in less than 30 sec, depending on how hard the pumping was. Meanwhile, the temperature rise was not high above liquid nitrogen temperature. Consequently, the following data were taken at a time interval of 1 — 2 minutes between two successive flashes. And oscillographs in G-series were started to take one hour after F-series were finished.

2. The block diagram of the whole experimental setup including power supply and display system is shown in Fig.-10. The following procedures were carried out in obtaining data. First, set the flashtube input voltage to a desired
Fig. 10 Block diagram of the whole experimental arrangement
value to go with energy storage capacitor of 240/μf in obtaining desired
pumping energy level, place all polarizers at θ = 0, and then fired in a
flash and took the four oscillographs corresponding to four I(0°,0°) simul-
taneously at the four positions of PM's. It was followed by setting the
polarizer in front of PM-5 at 45° = 0, the one in front of PM-3 at θ = 90°,
the one in front of PM-2 at θ = 45° and a quarter wave plate was mounted,
but the one in front of PM-1 remained in-rotated. Under these settings,
second flash was fired and the four measurements were obtained of I(45°,0°),
I(90°,0°), I(45°,90°) and I(0°,0°). The data in the first flash provided
the information for calibration; the second one the information on calculating
the polarization states of individual spikes of the laser beam. At other pump-
ing levels, the same procedures were followed. Both F-series and G-series
oscillographs were taken in this way. However, 20μsec/cm time base was used
for the former and no compensator was introduced when measuring those four
I(0°,0°)'s; 10μsec/cm time base was set for the latter and the compensator
was introduced when measuring those four I(0°,0°)'s at each pumping level—
so that the attenuation through the quarter wave plate was taken into account.
Note that each oscillograph in F-series covered all spikes in that flash,
while each oscillograph in G-series did only those spikes in the later half
of that flash.
VII. Experimental Results

The laser rod tested was a type of solid state laser with active ions Nd$^{3+}$ in a host material of barium crown glass. It was prepared by Isomet Corp. and is 2" in length, ⅛" in diameter, and its high efficiency optical resonator has both flat ends with multi-layer dielectric coatings, one end transmitting 85%, the other less than 1%. When it was tested, it was already three years old.

VII-1. Some Test Conditions:

The flash tube input ranged from 1100 v.d.c. (or 145 joules, the threshold value) to 1300 v.d.c. (or 363 joules) from a storage capacitor bank of 240 μF. The anode voltage of all PM's was set at 1100 v. during the whole period of taking oscillographs of the laser beams. A pulse generator provided the function of horizontal delay for display oscilloscopes. Oscillographs were recorded by Polaroid high speed land films. For other conditions, see part VI.

VII-2. The method of analyzing the data:

A different method of calibration from Dr. Sun Lu's has been applied here. He used a TEK-type-Z difference amplifier, plug-in unit with TEK-585 oscilloscope to compare the outputs simultaneously from any two PM's. By adjusting the anode voltage of PM's and attenuations of silicon attenuators, he was supposed to be able to get a zero-line display on oscilloscope (complete cancellation) of the values of I(0°,0°) from those two PM's. In practice, perfect cancellation of two I(0°,0°) signals rarely occurred on display.

One defect of the coupling circuits from PM's to terminal cables set a limit on this calibration—— due to a slight difference of rise times and non-coincidence of gain responses of coupling circuits, a few corresponding
spikes in a firing from the two PM's would not appear exactly at the same instant and in the same shapes of spikes. In addition, human eyes introduced a considerable error in the judgment of cancellation in a very short period of less than 0.25 msec during which all spikes appeared one by one, each lasting less than $1 \times 10^{-6}$ sec. The new type of calibration in this experiment was to take the oscillographs of $I(0^\circ,0^\circ)$ signals in a calibration flash simultaneously from the four PM's. Then the height of corresponding individual spikes in the four pictures were carefully identified and read, and hence relative calibration factors were obtained from spike to spike. Finally, the relative calibration factors of the four PM's at their own positions were determined by the average over the individual calibration factors of spikes in that flash.

It was found that, when the four PM's were used to measure $I(0^\circ,0^\circ)$'s at a certain pumping level, most of the corresponding spikes fluctuated in the same manner relatively, but a few of them did increase or decrease in an opposite direction. These exceptional spikes were excluded from the averaging process of calibration factors. This unfavorable phenomenon might result from the inequality of the distances travelled by the four component beams before falling on photocathodes. Therefore, on falling on the different photocathodes, the total wave amplitudes of those corresponding spikes might be varying in opposite direction. This seems to justify clearly that the amplitude of the laser light wave is rapidly time-varying. To take into account the possible non-linear response which PM's may run into, the relative calibration factors were obtained respectively at various pumping levels.

The detailed procedures of obtaining the relative calibration factors and the proper values of $I(0^\circ,0^\circ)$, $I(90^\circ,0^\circ)$, $I(45^\circ,0^\circ)$, $I(45^\circ,90^\circ)$ for
calculation of degree of polarization, chirality matrix elements, and Stokes parameters, whose expressions have been discussed in part III, will be made available below. At a certain pumping level, two functional flashes were fired, one was a calibration flash, the other a datum flash. Suppose the readings directly obtained from spikes in the oscillographs of a calibration flash are \( I_1(0^\circ, 0^\circ), I_2(0^\circ, 0^\circ), I_3(0^\circ, 0^\circ), I_4(0^\circ, 0^\circ) \), or \( I_1^n(0^\circ, 0^\circ), I_2^n(0^\circ, 0^\circ), I_3^n(0^\circ, 0^\circ), I_4^n(0^\circ, 0^\circ) \). Let \( I_1(0^\circ, 0^\circ) = I_1^n(0^\circ, 0^\circ) \), where \( n \) is the number of spikes of interest.

From the datum flash, let \( I^d(0^\circ, 0^\circ), I^d(90^\circ, 0^\circ), I^d(45^\circ, 0^\circ), I^d(45^\circ, 90^\circ) \) be the direct readings of any four corresponding in the oscillographs, spikes of the datum flash from PM-1, PM-3, PM-2, PM-5 respectively, and \( I(0^\circ, 0^\circ) = I^d(0^\circ, 0^\circ)/I_1(0^\circ, 0^\circ), \quad I(90^\circ, 0^\circ) = I^d(90^\circ, 0^\circ)/I_3(0^\circ, 0^\circ) \)

\( I(45^\circ, 90^\circ) = I^d(45^\circ, 90^\circ)/1.0, \quad I(45^\circ, 0^\circ) = I^d(45^\circ, 0^\circ)/I_5(0^\circ, 0^\circ) \)

Substitution of these four quantities \( I(0^\circ, 0^\circ), I(90^\circ, 0^\circ), I(45^\circ, 90^\circ), I(45^\circ, 0^\circ) \) into proper expressions for physical quantities in part III yields Table-2 and Table-3.

VII-3. Typical Pumping Light:

Pumping light was detected by placing a RCA-7102 PM at a proper distance from the flash tube, using an anode voltage 900 v. for the PM and a capacitor bank of 240µF in the laser power supply. In Fig.-11 is shown the real shape of pumping pulses at various pumping levels, the vertical heights in different oscillographs do not show the relative magnitudes of pumping energy because the light was not detected at the same distance from...
Flashtube input
1200 V.DC.

Fig. 11 Shapes of pumping light pulses (intensity vs time).
Oscilloscope settings: 0.5 m-sec, 0.5 x 10 V/cm.
Capacitor bank: 240 μf.
the flash tube. From this figure we see the pumping light is not a good rectangular pulse. It also shows that the curve of pumping intensity vs. time changes a little from pumping level to pumping level. Pumping duration is about 0.25 msec.

VII-4. Typical Pictures Showing Spiking Behaviors of the Laser Beams:

In Fig.-12 is shown a typical spiking behavior of the instantaneous variation of intensities of the laser beams from four flashes at a pumping level 40% above the threshold. F-1-5 and F-1-5-a from two calibration flashes fired at different instants show the variation of the $I(0^\circ,0^\circ)$ signal detected by PM-5. F-2-5 and F-2-5-a from two datum flashes fired at different time instants show the variation behavior of $I(45^\circ,0^\circ)$ detected by PM-5. In Fig.-13 is shown the varying behavior of the $I(0^\circ,0^\circ)$'s in a calibration flash at a pumping level of 112% above the threshold, F-7-1 detected by PM-1, F-7-3 by PM-3, F-7-5 by PM-5 and F-7-2 by PM-2. In Fig.-14 is shown the time behavior of the instantaneous intensities $I(0^\circ,0^\circ)$, $I(0^\circ,0^\circ)$, $I(45^\circ,0^\circ)$ and $I(45^\circ,90^\circ)$ in a datum flash at 112% pumping level above the threshold. The picture F-8-1 was detected by PM-1, F-8-3 by PM-3, F-8-5 by PM-5 and F-8-2 by PM-2.

Though the spiking behavior is random, we observed the regularity that individual spikes last around $1 \times 10^{-6}$ sec, and that the correspondence among spikes from the four pictures of any flash, calibration one or datum one, at any pumping energies. Also the behavior is reproducible to such an extent that it is not difficult to identify a large fraction of corresponding spikes from different firings at same pumping level (e.g. see Fig.-12). Meanwhile, the behavior is irreproducible to such a degree that the time variation of polarization (of spikes) from firing to firing at same pumping.
Fig. 12 Two calibration flashes (upper two pictures) and two datum flashes (lower two pictures) of the neodymium glass laser at a pumping level of 140% of threshold.
Fig. 13 A calibration flash at a pumping level of 212% of the threshold of the Nd⁺⁺⁺ glass laser.
Fig. 14 A datum flash at a pumping level of 212% of the threshold of the Nd$^{3+}$-glass laser.
level can not be obviously distinguished from that of of polarization from firing to firing at different pumping levels (see below VII-6).

VII-5. Experimental Results:

From the experimental data taken in picture form, the coherency matrix elements and Stokes parameters of the laser beams and their polarized and unpolarized parts, and the degrees of polarization of the original laser beams can be easily calculated by means of the proper expressions in part III. The so calculated results are listed below in Table-2 and Table-3. The typical and obvious spikes of a flash fired at a certain pumping level are tabulated in chronological order. Note that

$S_0$ represents the total intensity of the original laser light.

$S_1$ represents the preference for horizontal (if positive) or vertical (if negative) polarization.

$S_2$ represents the preference for $+45^\circ$ (if positive) or $+135^\circ$ (if negative) polarization.

$S_3$ represents the preference for right- (if positive) or left- (if negative) circular polarization.

When $e$ is positive (or negative), that means the the elliptical polarization of the polarized part is right- (or left-) handed.

Other representations of symbols used are referred to part III. Since elements of coherency matrix and its corresponding Stokes parameters have same physical significance, the former are omitted in the tables. In the tables below, relative intensities of spikes in $S_0$ column are observed at a pumping level, but those at different pumping levels are not comparative in exact sense.
Table-2  (F-series )

<table>
<thead>
<tr>
<th>Pumping energies (joules)</th>
<th>Chronological spikes</th>
<th>Original light waves</th>
<th>Unpolarized parts</th>
<th>Polarized parts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$S_0$</td>
<td>$S_1$</td>
<td>$S_2$</td>
</tr>
<tr>
<td>173 or 19% above threshold</td>
<td>2</td>
<td>0.092</td>
<td>-0.035</td>
<td>-0.025</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.104</td>
<td>-0.046</td>
<td>-0.035</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.101</td>
<td>-0.040</td>
<td>-0.023</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.036</td>
<td>+0.019</td>
<td>-0.052</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.115</td>
<td>-0.102</td>
<td>10.011</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.150</td>
<td>-0.0112</td>
<td>+0.021</td>
</tr>
<tr>
<td>203 or 4.9% above threshold</td>
<td>1</td>
<td>0.271</td>
<td>-0.025</td>
<td>-0.142</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.184</td>
<td>-0.012</td>
<td>-0.036</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.183</td>
<td>-0.126</td>
<td>-0.035</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.254</td>
<td>-0.240</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.310</td>
<td>-0.220</td>
<td>+0.051</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.324</td>
<td>-0.286</td>
<td>-0.129</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.222</td>
<td>+0.017</td>
<td>-0.051</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.345</td>
<td>+0.190</td>
<td>+0.210</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.237</td>
<td>-0.017</td>
<td>-0.056</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.274</td>
<td>-0.220</td>
<td>+0.014</td>
</tr>
<tr>
<td></td>
<td>203 or</td>
<td>235 or</td>
<td>25% above</td>
<td>62.5% above</td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
<td>--------</td>
<td>-------------</td>
<td>--------------</td>
</tr>
<tr>
<td></td>
<td>4% above threshold</td>
<td>(F-1-&amp;\ F-2-&amp;)</td>
<td>6% above threshold</td>
<td>(F-3 &amp; F-4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.309</td>
<td>0.325</td>
<td>0.009</td>
<td>0.017</td>
</tr>
<tr>
<td>3</td>
<td>0.271</td>
<td>0.264</td>
<td>0.021</td>
<td>0.013</td>
</tr>
<tr>
<td>6</td>
<td>0.287</td>
<td>0.288</td>
<td>0.087</td>
<td>0.022</td>
</tr>
<tr>
<td>8</td>
<td>0.323</td>
<td>0.321</td>
<td>0.023</td>
<td>0.013</td>
</tr>
<tr>
<td>9</td>
<td>0.362</td>
<td>0.310</td>
<td>0.012</td>
<td>0.016</td>
</tr>
<tr>
<td>10</td>
<td>0.244</td>
<td>0.319</td>
<td>0.020</td>
<td>0.017</td>
</tr>
<tr>
<td>11</td>
<td>0.591</td>
<td>0.576</td>
<td>-0.111</td>
<td>-0.126</td>
</tr>
<tr>
<td>12</td>
<td>0.283</td>
<td>0.283</td>
<td>-0.017</td>
<td>-0.172</td>
</tr>
</tbody>
</table>

The table continues with similar entries for higher thresholds and percentages.
| 235 or 62\% above threshold | 1 | 0.381 | 0.029 | +0.027 | -0.323 | 85.2 | 0.056 | 0.325 | -0.905 | 219°15' |
| 2 | 0.377 | 0.070 | -0.324 | -0.168 | 83.6 | 0.072 | 0.372 | -0.238 | 116°05' |
| 3 | 0.359 | 0.051 | +0.233 | -0.239 | 93.7 | 0.0215 | 0.338 | -0.415 | 38°41' |
| 4 | 0.359 | 0.051 | +0.316 | -0.159 | 100 | 0 | 0.359 | -0.234 | 103°25' |
| 5 | 0.446 | 0.094 | +0.660 | -0.332 | 79.3 | 0.096 | 0.350 | -0.719 | 16°18' |
| 6 | 0.459 | 0.107 | -0.250 | -0.358 | 97.9 | 0.010 | 0.449 | -0.199 | 16°35' |
| 8 | 0.424 | 0.116 | -0.220 | -0.123 | 65.9 | 0.145 | 0.279 | -0.213 | 148°50' |
| 9 | 0.526 | -0.114 | -0.429 | -0.249 | 100 | 0 | 0.524 | -0.302 | 127°35' |
| 10 | 0.646 | 0.074 | -0.340 | -0.252 | 66.4 | 0.216 | 0.429 | -0.325 | 11°07' |
| 11 | 1.036 | -0.240 | -0.252 | -0.392 | 50.3 | 0.512 | 0.524 | -0.150 | 113°15' |
| 12 | 0.396 | -0.088 | -0.124 | -0.192 | 62.0 | 0.151 | 0.245 | -0.431 | 117°20' |
| 13 | 0.405 | 0.291 | +0.270 | -0.330 | 75.2 | 0.1602 | 0.516 | -0.363 | 21°25' |
| 14 | 0.418 | -0.110 | -0.296 | -0.196 | 62.0 | 0.046 | 0.372 | -0.238 | 34°50' |
| 15 | 0.450 | 0.142 | +0.312 | -0.220 | 90.6 | 0.043 | 0.407 | -0.293 | 32°50' |
| 16 | 0.286 | 0.022 | -0.132 | -0.092 | 57.0 | 0.1236 | 0.162 | -0.307 | 14°20' |
| 17 | 0.393 | 0.090 | +0.244 | -0.196 | 81.8 | 0.072 | 0.326 | -0.335 | 34°53' |
| 18 | 0.326 | 0.084 | -0.047 | -0.053 | 33.2 | 0.2165 | 0.110 | -0.257 | 165°27' |
| 19 | 0.675 | 0.147 | -0.328 | -0.390 | 85.6 | 0.098 | 0.577 | -0.390 | 14.5° |
| 20 | 0.495 | -0.033 | +0.050 | -0.110 | 25.5 | 0.370 | 0.125 | -0.501 | 61°31' |
| 21 | 0.244 | 0.024 | +0.048 | -0.083 | 42.5 | 0.141 | 0.103 | -0.564 | 116°15' |
| 22 | 0.286 | 0.002 | +0.116 | -0.062 | 47.6 | 0.139 | 0.127 | -0.241 | 44°30' |
| 23 | 0.244 | 0.024 | +0.165 | -0.063 | 76.8 | 0.051 | 0.193 | -0.124 | 136°40' |
| 24 | 0.33 | 0.013 | +0.005 | -0.055 | 13.1 | 0.295 | 0.048 | -0.737 | 12°23' |
| 25 | 0.444 | -0.036 | +0.317 | -0.135 | 77.5 | 0.1005 | 0.317 | -0.202 | 48°15' |

<p>| 270 or 86% above threshold | 4 | 1.107 | -0.323 | -0.556 | -0.614 | 82.2 | 0.199 | 0.908 | -0.389 | 120°35' |
| 5 | 0.940 | 0.058 | -0.440 | -0.072 | 58.4 | 0.307 | 0.453 | -0.102 | 138°20' |
| 6 | 1.096 | 0.134 | +0.132 | -0.672 | 62.9 | 0.398 | 0.697 | -0.763 | 22°33' |
| 7 | 0.955 | -0.117 | -0.066 | -0.150 | 21.9 | 0.754 | 0.201 | -0.437 | 10°15' |
| 9 | 0.345 | -0.011 | -0.170 | -0.100 | 49.5 | 0.117 | 0.193 | -0.271 | 133°10' |
| 11 | 0.696 | 0.250 | -0.156 | -0.272 | 94.7 | 0.295 | 0.401 | -0.391 | 16°40' |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>12</td>
<td>0.429</td>
<td>0.073</td>
<td>-0.230</td>
<td>-0.178</td>
<td>70.9</td>
<td>0.031</td>
<td>0.343</td>
<td>-0.276</td>
<td>142°03'</td>
</tr>
<tr>
<td>13</td>
<td>0.511</td>
<td>0.155</td>
<td>-0.240</td>
<td>-0.100</td>
<td>77.0</td>
<td>0.106</td>
<td>0.404</td>
<td>-0.126</td>
<td>146°33'</td>
</tr>
<tr>
<td>14</td>
<td>0.703</td>
<td>0.078</td>
<td>-0.416</td>
<td>-0.403</td>
<td>62.9</td>
<td>0.116</td>
<td>0.938</td>
<td>-0.100</td>
<td>17.1°18'</td>
</tr>
<tr>
<td>15</td>
<td>0.502</td>
<td>0.056</td>
<td>-0.836</td>
<td>-0.204</td>
<td>96.5</td>
<td>0.017</td>
<td>0.158</td>
<td>-0.222</td>
<td>136°40'</td>
</tr>
<tr>
<td>16</td>
<td>0.950</td>
<td>0.056</td>
<td>-0.903</td>
<td>-0.145</td>
<td>95.7</td>
<td>0.0295</td>
<td>0.921</td>
<td>-0.067</td>
<td>136°05'</td>
</tr>
<tr>
<td>17</td>
<td>1.168</td>
<td>0.452</td>
<td>-0.033</td>
<td>-1.056</td>
<td>98.2</td>
<td>0.058</td>
<td>1.164</td>
<td>-0.760</td>
<td>175°15'</td>
</tr>
<tr>
<td>18</td>
<td>0.928</td>
<td>0.302</td>
<td>-0.180</td>
<td>-0.054</td>
<td>36.6</td>
<td>0.571</td>
<td>0.357</td>
<td>-0.090</td>
<td>161°35'</td>
</tr>
<tr>
<td>19</td>
<td>0.704</td>
<td>0.078</td>
<td>-0.498</td>
<td>-0.032</td>
<td>70.5</td>
<td>0.209</td>
<td>0.166</td>
<td>-0.032</td>
<td>135°32'</td>
</tr>
<tr>
<td>20</td>
<td>0.922</td>
<td>0.028</td>
<td>-0.563</td>
<td>-0.164</td>
<td>61.4</td>
<td>0.581</td>
<td>0.592</td>
<td>-0.121</td>
<td>136°25'</td>
</tr>
<tr>
<td>21</td>
<td>1.011</td>
<td>0.395</td>
<td>-0.674</td>
<td>-0.342</td>
<td>85.7</td>
<td>0.036</td>
<td>0.917</td>
<td>-0.315</td>
<td>30°10'</td>
</tr>
<tr>
<td>22</td>
<td>0.886</td>
<td>0.128</td>
<td>-0.092</td>
<td>-0.032</td>
<td>31.0</td>
<td>0.320</td>
<td>0.166</td>
<td>-0.151</td>
<td>162°05'</td>
</tr>
<tr>
<td>23</td>
<td>0.570</td>
<td>0.212</td>
<td>-0.252</td>
<td>-0.050</td>
<td>53.6</td>
<td>0.235</td>
<td>0.335</td>
<td>-0.051</td>
<td>155°50'</td>
</tr>
<tr>
<td>24</td>
<td>0.720</td>
<td>0.005</td>
<td>-0.552</td>
<td>-0.320</td>
<td>63.7</td>
<td>0.082</td>
<td>0.633</td>
<td>-0.262</td>
<td>138°18'</td>
</tr>
<tr>
<td>25</td>
<td>0.201</td>
<td>0.023</td>
<td>-0.115</td>
<td>-0.032</td>
<td>59.0</td>
<td>0.0313</td>
<td>0.120</td>
<td>-0.037</td>
<td>140°25'</td>
</tr>
<tr>
<td>26</td>
<td>0.335</td>
<td>0.090</td>
<td>-0.003</td>
<td>-0.116</td>
<td>26.5</td>
<td>0.211</td>
<td>0.117</td>
<td>-0.459</td>
<td>177°25'</td>
</tr>
<tr>
<td>27</td>
<td>0.263</td>
<td>-0.044</td>
<td>-0.182</td>
<td>-0.135</td>
<td>86.5</td>
<td>0.0376</td>
<td>0.230</td>
<td>-0.326</td>
<td>128°13'</td>
</tr>
<tr>
<td>28</td>
<td>0.274</td>
<td>-0.156</td>
<td>-0.120</td>
<td>-0.163</td>
<td>65.6</td>
<td>0.437</td>
<td>0.837</td>
<td>-0.551</td>
<td>121°09'</td>
</tr>
<tr>
<td>29</td>
<td>1.150</td>
<td>0.750</td>
<td>-0.396</td>
<td>-0.050</td>
<td>73.6</td>
<td>0.300</td>
<td>0.850</td>
<td>-0.035</td>
<td>13°50'</td>
</tr>
</tbody>
</table>

| 307 or 112% above threshold (E-7 & F-8) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.524 | -0.390 | -0.810 | -0.323 | 64.4 | 0.5414 | 0.983 | -0.172 | 122°03' |
| 2 | 1.648 | 0.052 | 0.924 | -0.574 | 65.9 | 0.506 | 1.142 | -0.271 | 145°50' |
| 3 | 0.943 | -0.093 | -0.326 | -0.166 | 39.7 | 0.555 | 0.335 | -0.051 | 155°50' |
| 4 | 0.919 | -0.117 | -0.278 | -0.023 | 33.1 | 0.623 | 0.633 | -0.262 | 138°18' |
| 5 | 1.479 | 0.361 | -0.605 | -0.793 | 60.5 | 0.289 | 0.256 | -0.110 | 123°08' |
| 6 | 0.919 | 0.121 | -0.321 | -0.438 | 55.7 | 0.404 | 0.515 | -0.560 | 31°50' |
| 7 | 0.978 | -0.222 | -0.261 | -0.116 | 35.1 | 0.611 | 0.367 | -0.163 | 115°15' |
| 8 | 0.730 | -0.058 | -0.228 | -0.340 | 57.0 | 0.315 | 0.415 | -0.522 | 126°41' |
| 9 | 0.925 | -0.075 | -0.070 | -0.070 | 92.6 | 0.019 | 0.876 | -0.081 | 132°33' |
| 10 | 1.121 | -0.319 | -0.616 | -0.202 | 61.4 | 0.397 | 0.724 | -0.122 | 121°25' |
| 11 | 1.120 | -0.050 | -0.552 | -0.280 | 53.9 | 0.513 | 0.607 | -0.206 | 130°50' |
| 12 | 0.667 | -0.053 | -0.554 | -0.054 | 63.8 | 0.108 | 0.559 | -0.088 | 132°15' |
| 13 | 1.356 | 0.156 | -0.928 | -0.072 | 77.6 | 0.303 | 1.053 | -0.236 | 40°15' |
| 14 | 0.631 | 0.031 | -0.354 | -0.142 | 60.5 | 0.248 | 0.383 | -0.193 | 137°30' |
| 15 | 0.985 | -0.135 | -0.282 | -0.050 | 32.4 | 0.663 | 0.317 | -0.030 | 122°15' |
| 16 | 1.326 | -0.194 | 0.188 | +0.204 | 27.3 | 0.938 | 0.338 | +0.336 | 67.3³3¹ |
| 17 | 1.035 | 0.195 | -0.510 | -0.390 | 64.5 | 0.364 | 0.691 | -0.320 | 45.2⁵¹ |
| 19 | 1.018 | -0.262 | -0.216 | -0.196 | 39.4 | 0.626 | 0.392 | -0.261 | 109.⁶⁵¹ |
| 20 | 1.603 | -0.147 | -0.880 | +0.130 | 63.1 | 0.596 | 1.101 | -0.070 | 120.⁵⁵¹ |
| 21 | 1.96 | 0.120 | 0.76 | -0.960 | 62.0 | 0.730 | 1.23 | -0.481 | 109.³⁰¹ |
| 22 | 1.845 | 0.240 | 1.64 | -0.56 | 95.1 | 0.9 | 1.75 | -0.164 | 40.⁵⁰¹ |
| 23 | 0.564 | 0.034 | -0.220 | -0.168 | 49.0 | 0.287 | 0.376 | -0.339 | 135.⁵⁰¹ |
| 24 | 0.436 | 0.016 | 0.226 | -0.232 | 86.7 | 0.0596 | 0.1044 | +0.131 | 146.⁰⁵¹ |
| 25 | 0.444 | 0.124 | -0.304 | -0.083 | 76.5 | 0.602 | 0.468 | -0.364 | 205⁵⁰¹ |
| 26 | 1.15 | 0.27 | 0.256 | -0.30 | 10.3 | 0.294 | 0.316 | -0.163 | 172.⁴⁰¹ |
| 28 | 0.61 | 0.29 | -0.076 | -0.10 | 23.3 | 0.931 | 2.15 | -0.281 | 135.³⁷¹ |

<table>
<thead>
<tr>
<th>346.5 cr</th>
<th>139% above threshold (F-9 &amp; F-10)</th>
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<tr>
<td>1</td>
<td>2.46</td>
</tr>
<tr>
<td>2</td>
<td>1.49</td>
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<td>3</td>
<td>1.754</td>
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<tr>
<td>4</td>
<td>1.666</td>
</tr>
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<td>5</td>
<td>1.486</td>
</tr>
<tr>
<td>6</td>
<td>2.455</td>
</tr>
<tr>
<td>7</td>
<td>1.371</td>
</tr>
<tr>
<td>8</td>
<td>0.960</td>
</tr>
<tr>
<td>9</td>
<td>1.034</td>
</tr>
<tr>
<td>10</td>
<td>2.92</td>
</tr>
<tr>
<td>11</td>
<td>0.960</td>
</tr>
<tr>
<td>12</td>
<td>2.51</td>
</tr>
<tr>
<td>13</td>
<td>1.758</td>
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<td>14</td>
<td>0.992</td>
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<tr>
<td>15</td>
<td>0.983</td>
</tr>
<tr>
<td>16</td>
<td>2.45</td>
</tr>
<tr>
<td>17</td>
<td>1.802</td>
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<td>1.312</td>
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<td>1.185</td>
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<tr>
<td>22</td>
<td>2.12</td>
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...
### Table-3 (G-series)

<table>
<thead>
<tr>
<th>Keeping energies (joules)</th>
<th>Chronological spikes</th>
<th>Original Light waves (% or P)</th>
<th>Unpolarised parts</th>
<th>Polarised parts</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( s_0 )</td>
<td>( s_1(p) )</td>
<td>( s_2(p) )</td>
</tr>
<tr>
<td>203 or 403 above threshold</td>
<td>1</td>
<td>0.059</td>
<td>0.001</td>
<td>-0.054</td>
</tr>
<tr>
<td>(G-1 &amp; G-2)</td>
<td>2</td>
<td>0.153</td>
<td>0.022</td>
<td>+0.046</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.146</td>
<td>0.019</td>
<td>-0.116</td>
</tr>
<tr>
<td>235 or 625 above threshold</td>
<td>1</td>
<td>0.151</td>
<td>0.041</td>
<td>-0.031</td>
</tr>
<tr>
<td>(G-3 &amp; G-4)</td>
<td>2</td>
<td>0.248</td>
<td>0.141</td>
<td>-0.191</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.176</td>
<td>0.043</td>
<td>-0.036</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.164</td>
<td>0.003</td>
<td>-0.044</td>
</tr>
<tr>
<td>270 or 825 above threshold</td>
<td>2</td>
<td>0.206</td>
<td>0.020</td>
<td>-0.111</td>
</tr>
<tr>
<td>(G-5 &amp; G-6)</td>
<td>3</td>
<td>0.252</td>
<td>-0.026</td>
<td>-0.154</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.382</td>
<td>-0.012</td>
<td>-0.014</td>
</tr>
<tr>
<td></td>
<td>307° or</td>
<td>112° above</td>
<td>(G-7 &amp; G-8)</td>
<td>366.5 or</td>
</tr>
<tr>
<td>---------------</td>
<td>----------</td>
<td>-------------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
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<td></td>
<td>0.431</td>
<td>0.101</td>
<td>0.042</td>
<td>0.092</td>
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<tr>
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<td>0.191</td>
<td>0.071</td>
<td>0.007</td>
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<td>0.388</td>
<td>0.007</td>
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<td>0.007</td>
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<tr>
<td></td>
<td>0.339</td>
<td>-0.041</td>
<td>-0.054</td>
<td>-0.078</td>
</tr>
<tr>
<td></td>
<td>0.525</td>
<td>0.033</td>
<td>-0.423</td>
<td>-0.250</td>
</tr>
<tr>
<td></td>
<td>0.691</td>
<td>0.382</td>
<td>0.016</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td>0.297</td>
<td>0.134</td>
<td>0.162</td>
<td>0.173</td>
</tr>
<tr>
<td></td>
<td>0.437</td>
<td>-0.012</td>
<td>0.106</td>
<td>0.063</td>
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<tr>
<td></td>
<td>0.203</td>
<td>0.052</td>
<td>0.492</td>
<td>0.203</td>
</tr>
<tr>
<td></td>
<td>0.087</td>
<td>0.056</td>
<td>0.492</td>
<td>0.203</td>
</tr>
<tr>
<td></td>
<td>0.281</td>
<td>0.309</td>
<td>0.492</td>
<td>0.203</td>
</tr>
<tr>
<td></td>
<td>0.131</td>
<td>-0.282</td>
<td>36°10°</td>
<td>0.096</td>
</tr>
</tbody>
</table>

- **Note:** All measurements are given in degrees.
VII-6. Time Variation of Polarisation:

From the data in Table-2 and Table-3, the time behavior of polarisation of chronological spikes is plotted in Fig.-15 and Fig.-16 (only those points at intersections of line segments are data points).

VII-7. Variation of Polarisation With Pumping:

The average degree of polarisation over considered spikes at a pumping level is different from that at another pumping level. This variation of polarisation with pumping is plotted in Fig.-17, based on the data of Tables-2 and -3.
Fig. - 15 Time variation of polarization of the laser spiking beams (F-series)
Fig. 16  
Time Variation of polarization of the Nd-glass laser beams (G-series) 

Laser action starting about 100 \mu \text{s} before this time 

Time increasing, \( \mu \text{sec} \) 
110 120 130 140 150 160 170 180 190 

Fig. 17  
Variation of average polarization with pumping energies of the Nd-glass laser
VIII. General Conclusions and Interpretations.

VIII-1. Some general conclusions drawn from the experimental results:

1. The polarization of individual spikes of the Na$^{+}$-glass laser beams varies from spike to spike no matter what the said spikes belong to same flash or different flashes, to same pumping level or different pumping levels. Most of the spikes have more than 50% polarization. Few spikes have degrees of polarization below 50%, and a few do achieve 100%, indicating the polarized parts of the majority of the considered spikes are larger than their corresponding unpolarized parts. The first spike of each firing is expected to be a single mode emission and hence completely polarized, but it is difficult to display it on an oscilloscope.

2. The polarized parts of spikes are elliptically polarized except very few having circular polarization (marked "c" beside those "e = ±1.0" in tables-2 and -3 )---- very few of the spikes having elliptical polarization parts tend to be linearly polarized in the polarized parts ( e is close to zero ). A large fraction of considered spikes (about four fifths) have left-handed elliptically polarized parts ( see e and $S_2$ columns ), and a large portion of then ( about seven tenths ) tend to orient their major axes of polarization ellipses around 135° direction rather than 45° direction ( see $\phi$ and $S_2$ columns ). Also about seven tenths of the spikes prefer horizontal ( positive $S_1$ ) to vertical ( negative $S_1$ ) polarization. All of these major phenomena, especially the direction of rotation and orientation of the polarization ellipse, probably imply something fundamental: e.g. particular spectral components of spikes and structure of the laser material.

3. The time-variation behavior of polarization is as unpredictable as that of time-resolved spectroscopy; no preferred relation between degree of pol-
arization and time can be concluded.

4. The average degree of polarization per spike tend to decrease with the increase of pumping energy; however this tendency is not pure, i.e. there are small rises on the way of decrease with increasing pumping.

5. $E_x$ and $E_y$ of each spike are mutually coherent since $J_{xy} \neq 0$ (see Tables-2 and -3).

6. The amplitude of the laser light wave varies very rapidly with time, at least as fast as $10^{-8}$ sec.

7. The fact that few spikes show complete polarization implies that most of the spikes are composed of multiple spectral sharp lines.

VIII-2. Interpretations:

1. The few completely polarized spikes can be easily seen since their radiations are monochromatic. However, most of the spikes consist of simultaneous emission, or successive emission within the lasing period of a spike, of multiple spectral lines. Their degrees of polarization at a particular time, or averages over a spike duration, should depend upon the actual spectral compositions, the relative intensities of various spectral components, and the direction of emission and the type of polarization of each monochromatic component at a particular instant or time interval. Though the glass base of the interested laser is amorphous and seems to result in unpolarized laser beams. In fact, this is not true. There are several sources which can account for the partial polarization phenomenon of the beams in the experimental results:

4. Anisotropy of the macroscopic radiating system

Even if the laser material has been manufactured in ideally isotropic manner, pumping induced imperfections are inevitable. By means of optical metallography, transmission electron microscopy, and electron diffraction
techniques, Towse (41) has investigated a barium crown glass:Nd$^{3+}$ laser rod which developed permanent internal imperfections during laser pumping. The imperfections were found to be microcracks resulting from differential thermal expansion between crystallites (resulting from devitrification) and the surrounding noncrystalline medium. By a Wyman–Green interferometer, Towse (42) has been able to measure changes in optical length of ruby and neodymium glass laser rods both during and after excitation by the pump flash. His results show that all rods expand linearly with time during the time the pump is on and that all rods develop a distortion which depends on the radial energy density distribution within the rods. After the pump goes off, the rods relax to the unexcited state. The relaxation is interrupted when hot air propagated from the flashtube to the rods causing the rods to reheat and causing an extremely concave appearance. In the pumping configuration, the pumping light is anisotropically distributed. Certainly these investigations on the effect of pumping thermal shock show considerable anisotropic imperfections and distortions after and during pumping flash in this experiment.

An analogous phenomenon to structural anisotropy may occur in the Nd-glass laser material whose anisotropy is due to a high statistical probability for a given orientation or a number of possible directions of orientation of the emitting centers of the neodymium active ions.

(See also part II-1).

B. Pumping energy

Due to the amorphous structure of glass and its random local field, it is obvious that there are no definite modes of oscillation which have such lower thresholds as compared with other modes that they predominate over any other modes of oscillation and become the only possible modes that can
be observed at normal pumping (see the evidence of the time variation of the spectral components from time resolution spectroscopy). We expect that the glass laser can oscillate at a great number of different modes under normal pumping condition, i.e. these different modes have comparable thresholds to oscillate. At low pumping energy near threshold only the mode or modes with lowest threshold can oscillate, and each spike consists essentially of one mode or few modes of oscillation, and possesses a definite or more definite polarization. This is why the polarization is higher at lower pumping.

The laser pumping energy determines how many and which spectral lines have reached above their thresholds (wavelength-dependent) and the relative intensities of the stimulated radiations of the emitted lines. Consequently the beam polarization depends on the pumping level. The higher the pumping level, the greater the chance of multimode radiation and hence the larger the tendency of the multiple radiation becoming optically isotropic. This illustrates the general tendency that the average degree of polarization per spike goes down with increasing pumping.

C. The shape of pumping light pulses

The shape of pumping pulses represents the instantaneous pumping energy, which accounts for the temporal effect of pumping on the variation of polarization of the laser beam.

D. Temperature effect

The ambient temperature of active ions affects the occupation distribution of their energy states. This natural occupation is dominated by the pumping occupation. Lowering temperature usually lowers thresholds for laser action. The temperature also affects, to a considerable degree, the spectral composition, and the relative intensities of various spectral components of the laser beams. The general conclusions of VIII-1 on the results at liquid N\textsubscript{2} temperature was found qualitatively to apply to the experimental results at room temperature (Sun Lu's dissertation), especially comparing
spikes at pumping levels of 173 J., 307 J. of the experiment with those at
80 J., 140 J. of his report. The threshold in his pumping configuration was found
to be 65 J.; here it was 145 J. Thus comparison of both results at same pumping levels above thresholds. This shows the temperature has small effect on polarization. Note that the measurements of the polarization of the laser radiation from gallium arsenide diodes at 77°k and 4.2°k also showed that there was no qualitative difference in the polarization of the radiation at these two temperatures.

E. Anisotropy of the pumping light

Because the light vibrations are transverse, even the unpolarized light such as the gas discharge glow of the light output of the xenon flash tube used is always anisotropic. Though the pumping light rays incident on the laser rod come from all directions, the total incident light energy does not distribute itself isotropically on the surface and inside the active rod because of the obviously non-uniform pumping geometry arranged. In addition, the spectral composition and the intensity-spectrum distribution of the flash tube output can influence the absorption of the pumping light, which in turn plays a role in the properties (polarization, frequencies and intensities) of the laser output beams.

Due to the actual difficulty of isolation of one effect from the other, it is not accurate to weight relative importance of the above effects. However, it can be said that factors A., B., and E. are surely more important.

2. The time variation behavior of polarization is so complicated or random that it can only be said that it should be closely related to the time resolved spectroscopy with high resolution details of the laser beam, and to the particular direction of emission and type of polarization of each mono-
chromatic component of the multimodes at any instant, and to their relative intensities of radiation.

3. The difference between F-series and G-series in Fig.-17 can be interpreted satisfactorily as follows. In F-series, no attenuation due to the compensator has been taken into account in measurement of \( I(0^\circ,0^\circ) \) of PM-2 in calibration flashes. Therefore, on obtaining the calibration factor \( I_2(0^\circ,0^\circ) \) of PM-2, \( I_2(0^\circ,0^\circ) \) should be a little larger than that considered in G-series in which the attenuation has been considered. This means, \( I(45^\circ,90^\circ) = I'(45^\circ,90^\circ)/I_2(0^\circ,0^\circ) \) should be a little larger in G-series. Hence in F-series, \( |\text{Im } J_{xy}| = |2 I(45^\circ,90^\circ) - I(0^\circ,0^\circ) - I(90^\circ,0^\circ)| \) will be a little smaller (or larger) and hence

\[
\text{Det. } J = J_{xx} J_{yy} - |\text{Re } J_{xy}|^2 - |\text{Im } J_{xy}|^2 \text{ will be a little larger (or smaller)}
\]

if \( \text{Im } J_{xy} \) is positive (or if \( \text{Im } J_{xy} \) is negative). Finally looking at

\[
P = \sqrt{1 - 4 \text{Det. } J/(J_{xx} + J_{yy})^2}
\]

we observe that \( P \) will be a little smaller (or larger) if \( \text{Im } J_{xy} \) is positive (or if \( \text{Im } J_{xy} \) is negative). As stated in VII-1-2, the majority of spikes have negative \( S_3 \) or negative \( \text{Im } J_{xy} \). Thus their degrees of polarization will be larger than those in series in which the attenuation has been taken into account. In addition, Fig.-15 shows that spikes occurred in the earlier half seem to have, in general, a little higher degree of polarization than those in the later half of the lasing period. As a consequence, average degrees of polarization per spike in F-series at most of the pumping levels done appear a little larger than those in G-series.
IX. Closure

The variation of polarization from spike to spike in one flash at a pumping level have been demonstrated experimentally and discussed above. How about that variation of a typical spike from different firing at same pumping level? The difficulty to answer this lies in the fact that the spiking behavior of the laser beams is not completely reproducible—— the partial irreproducibility might be due to the permanent pumping imperfections or due to the temperatures of the laser rod during the period of taking pictures of the beam intensity behavior in time being different from firing to firing even at same pumping energy.

To investigate the details of each spike, the best way is to make the laser beam as reproducible as possible and then to get a light shutter or the like which can be operated on-off at intervals of about the duration of a spike so that the isolation of individual spikes in one flash is possible. Then if the spectral sharp lines of the laser beam and the properties of each line are investigated, the properties of each multi-mode spike, the structural properties of the laser material, and the processes of absorptions by, radiations from and terminations at, certain energy levels or bands, can be understood much better. It follows that the ways of how to best control the beam polarization would be probably shown up.

In this experiment, the degrees of polarization of spikes vary in a great range. But the polarization has been shown to be artificially controllable to a great extent. It has been, for example, experimentally established that the introduction into a resonator of a glass plate inclined at a small angle to the axis of the laser resonator may ensure almost complete polarization of stimulated radiation of glass rods activated by neodymium.
The importance of polarization studies and measurements in investigating the properties of the radiating systems and their surrounding media have been pointed out in part I-1.
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