INTERFEROMETRIC STUDIES OF MODE LOCKED
 Nd^{3+} :GLASS LASERS

by

Rajiv R. Shah, T.A. Rabson, and D.M. Kim

March 1975

TECHNICAL REPORT #7505

INTERFEROMETRIC STUDIES OF MODE LOCKED Nd^{3+} :GLASS LASERS*

Rajiv R. Shah (Member), T.A. Rabson (Member), and D.M. Kim
Department of Electrical Engineering
Rice University
Houston, Texas

ABSTRACT

A general technique for measuring the electric field vector of the ultra-short pulses from mode locked laser systems is described. The technique is applied to perhaps the most difficult laser to analyze, the dye mode locked, Nd^{3+} :glass laser whose pulses change rapidly in bandwidth and amplitude, are chirped, and can occur in quite short pulse trains. The results of these measurements indicate a rather rapid change in the phases between modes and a plot of the phase change as a function of mode frequency has been obtained.

* This work supported in part by the National Science Foundation.

INTERFEROMETRIC STUDIES OF MODE LOCKED Nd^{3+} :GLASS LASERS

Rajiv R. Shah, T.A. Rabson, and D.M. Kim

1. INTRODUCTION

Numerous techniques have been developed for analysis of the output of mode locked lasers [1]. The technique to be reported here is unusual in its inherent simplicity and the fact that its basic concepts are rooted in classical optics modified to take into account the transient nature of the output of mode locked Nd^{3+} :glass lasers. The methods used so far are two- and three-photon fluorescence [2,3,4], second and third harmonic generation [5,6,7], time resolved spectroscopy [8,9], and photographing with ultrafast streak cameras with picosecond time resolution [10,11]. The information obtained from all but the time resolved spectroscopy method is limited mainly to the spectral or temporal intensity profiles of the picosecond pulses. However, the phase of the mode locked field is equally important since the typical mode locked output from pulsed lasers does not usually reach a steady state and such phenomena as chirping, partial mode locking, and substantial change of pulse characteristics from pulse to pulse even within a single firing of the laser are known to exist in mode-locked Nd:glass lasers. Cross correlation measurements between two different lasers have been used to measure the time duration of one of the mode locked HeNe lasers and it was suggested that the technique be applied to mode locked Nd^{3+} :glass lasers [12]. The necessity of having one unchirped laser was also mentioned in [12], whereas our technique only requires the cross correlation of two pulses in the pulse train of a single laser in

order to obtain relative phase information.

One can measure the amplitude and frequency of the cavity modes which are present in the output pulse of a mode locked laser by various well-known spectroscopic methods including the use of a Michelson interferometer which essentially gives the autocorrelation of the pulse. However, to determine completely the nature of the pulse, one must also determine the relative phase of the different modes in the pulse. These phases do not change appreciably throughout the duration of the pulse (usually less than 10 picoseconds). It is shown in this paper how one can obtain by numerical techniques the relative phase change from one pulse to another from the experimentally determined cross correlation of the two pulses. If the form of one of the pulses in the train is known, then by forming the cross correlation of it with other pulses, the form of the other pulses can be determined. In addition to the cross correlation, the bandwidth and mode amplitude of the unknown pulses must be measured. The theory and experimental results of techniques involving time-resolved linear interferometry is presented herein. Specifically it is pointed out that the measurements of fringe visibilities of auto- and cross-correlations of Nd^{3+} :glass lasers can lead to information regarding: (i) the pulse bandwidth as well as the fraction and nature of the noise present, (ii) the change of bandwidth between two successive pulses, and, finally, (iii) the evolution of the relative phase of modes in any region of the pulse train. An interferometric technique of this kind, performed in different regions of the pulse train, combined with the fact that the pulses in the rising edge of the train are usually bandwidth limited [2,9], can ultimately lead to the calculation

of the time-dependent phase dispersion which occurs throughout the pulse train.

In section II, we present an outline of the theory of auto- and cross-correlation of short pulses. The experimental procedures for measuring these functions are described in section III. The numerical analysis of the experimental data and the final results are presented in section IV.

II. THEORY

The fringe visibility (F.V.) as measured by the Michelson Interferometer (sketched in Fig. 1) is given by

$$F.V. = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (1)$$

where the total registered intensity

$$I = \int_{-\infty}^{\infty} dt \langle |E_i(t) + E_j(t+\tau)|^2 \rangle \quad (2)$$

consists of the linear superposition of the time-delayed electric field of the same ($i = j$) or different pulses ($i \neq j$).

A. Autocorrelation

For the case of autocorrelation, for which $i = j$, the net registered intensity can be expressed in terms of the power spectrum of the electric field as

$$I(\tau) = 2\text{Re} \int d\omega [\langle |E(\omega)\rangle|^2 + \langle |\epsilon(\omega)|^2 \rangle] [1 + e^{-i\omega\tau}] \quad (3)$$

Here we have partitioned the field power spectrum into the mode-locked signal, $\langle |E(\omega)\rangle|^2$, and random noise, $\langle |\epsilon(\omega)|^2 \rangle$, to include the effect of noise on fringe visibility since the output pulse is generally accompanied by noise

due to imperfect mode-locking. Upon inserting (3) into (1), we obtain

$$F.V. = \frac{\int d\omega [|\langle \mathcal{E}(\omega) \rangle|^2 + \langle |\epsilon(\omega)|^2 \rangle] e^{-i(\omega - \omega_0)\tau}}{\int d\omega [|\langle \mathcal{E}(\omega) \rangle|^2 + \langle |\epsilon(\omega)|^2 \rangle]} \quad (4)$$

where ω_0 is the central frequency of the emission.

From (4) note that by measuring the F.V. of the field autocorrelation one can distinguish the nature of noise present in the mode-locked pulses. For instance, for the case of white noise, the F.V. will go to zero for large delay time τ . The same is true if the bandwidth of the noise is of the same order of magnitude as that of the mode-locked signal within the broad gain profile. If, on the other hand, the bandwidth of the noise is much less than that of the signal, the F.V. will not go to zero even for large T . Additionally, one can also obtain the fraction of power present in the noise and the ratio of bandwidths of two successive pulses. These points will be pursued further in the following sections.

B. Cross-Correlation

For the case of cross correlation between two pulses in the same pulse train, the F.V. can be analyzed in the same way as in the autocorrelation. In this case, however, there exist two important differences: (a) the two pulses can have different power spectra, i.e., bandwidths, which can be measured separately by autocorrelation techniques (see section IV); (b) more importantly, the relative phase difference existing between the modes of the two pulses under consideration can significantly modify the F.V. profile. Because the F.V. curves for cross-correlation are quite sensitive to relative

mode phase, they can be used to measure these phases.

Thus we may write in this case

$$F.V. = \frac{|S(\tau) + \int \{ \langle |\epsilon(\omega)|^2 \rangle \}_{av} e^{-i(\omega-\omega_0)\tau} d\omega|}{\int d\omega [\{ \langle \epsilon(\omega) \rangle \}^2 + \{ \langle |\epsilon(\omega)|^2 \rangle \}]} \quad (5)$$

Here, $\{ \langle \epsilon(\omega) \rangle \}_{av}^2$, $\{ \langle |\epsilon(\omega)|^2 \rangle \}_{av}$ represent respectively the powers in the mode-locked signal and noise averaged over the two interfering pulses, and the signal portion of F.V.,

$$S(\tau) \equiv \int | \langle \epsilon_1(\omega) \rangle | | \langle \epsilon_2(\omega) \rangle | e^{i\Delta\chi(\omega)} e^{-i(\omega-\omega_0)\tau} d\omega \quad (6)$$

contains explicitly the relative phase between the two pulses

$$\Delta\chi(\omega) = \chi_1(\omega) - \chi_2(\omega) \quad (7)$$

III. AUTO- AND CROSS-CORRELATION MEASUREMENTS

A. Experimental Setup

The experimental systems for generation and measurement of picosecond pulses are depicted schematically in Fig. 2. The setup consists of 1) a mode-locked Nd^{3+} :glass laser; 2) a triangular two-photon-fluorescence (TPF) monitoring arrangement; 3) a diffraction spectrometer; and 4) a photodiode-oscilloscope detection system. In addition, the arrangement necessary for time-resolved interferometry includes: 1) a Michelson interferometer (MI); 2) an image converter camera (ICC); 3) a laser-triggered spark gap (LTSG); and 4) a 17-meter optical delay path.

The laser cavity consists of two plane-wedge mirrors with 99 and 65 percent reflectivities. The active medium is an Owens Illinois type ED2 Nd:glass

rod 20.5 cms long, 1 cm in diameter and cut at Brewster angles at both ends. The rod was pumped by an ILC helical Xenon flashlamp. The cavity was made to oscillate in the TEM_{00} mode by inserting a 3-5 mm spatial filter into the cavity. Mode-locking was achieved using Eastman Kodak dyes A-9860 in 1,2-dichloroethane or A-9740 in chlorobenzene.

Small fractions of the laser output were sampled to monitor: a) the two-photon-fluorescence (TPF) in $10^{-2}M$ solution of Rhodamine-6 G in ethanol using a triangular arrangement; b) the spectra of the pulse trains on Kodak 1Z plates at the output of a Jarrel Ash Series 70-000 3.4 meter Ebert grating spectrograph with a first-order reciprocal linear dispersion of $5.0 \text{ \AA/mm}$; and c) the intensity profiles of pulse trains using an ITT F-4000 biplanar vacuum photodiode detector displayed on a Tektronix 7904 oscilloscope.

The rest of the beam was allowed to reach the Michelson Interferometer (MI) after traveling a distance of 17 meters in air (effective delay $\approx 55\text{ns}$). The movable arm of the interferometer could be moved through a distance $L = L_0 + 2\ell$, where ℓ is the optical length of the cavity and L_0 is the distance of the fixed mirror from the beamsplitter. The movable mirror was mounted on a translation stage provided with a micrometer gauge to allow small, accurately measured displacements. The output of the MI was viewed through a TRW Instruments STL Model 1D Image Converter Camera (ICC) with an S-1 spectral response tube and fitted with a Model 7B High Speed Streak Unit. Fast and efficient triggering of the ICC was achieved by using a laser-triggered spark gap (LSTG). A small fraction of the beam focused with a short focal length lens was used to trigger the spark gap. The LSTG delays were typically less than 40 ns.

The experimental setup described above allowed simultaneous recording of the TPF, the spectrum, the intensity profile and streaked interference fringes of the mode-locked laser output.

B. Techniques

Reproducible regular pulse-trains were obtained under carefully controlled conditions. High peak power, short pulse trains were generated using a concentrated mode-locking dye solution and pumping voltages approximately 20 percent above threshold. The optical length of the cavity as determined by adjacent pulse crosscorrelation TPF was 74.8 cms. Pulse trains generated under these conditions were typically of 100 to 150 nanoseconds duration. Spectral widths were determined from the microdensitometer records of the processed photographic plates. Photographs of the TPF taken with an $f = 5.6$ cms, 1:1.3 camera were similarly analyzed with a microdensitometer.

Since the interference patterns were obtained for pulses with durations $\sim 10^{-12}$ secs, the arms of the interferometer had to be equal to within a fraction of a mm. The ICC was triggered by a high voltage pulse (~ 600 V) obtained from the LTSG. For pulse trains of 100 to 150 ns duration and a triggering accuracy ≤ 40 ns of the spark gap, exposures could be obtained only on some shots of the laser for a 2 meter delay path. This indicated that the region of observation was close to the tail of the pulse train. Introducing a 17-meter delay path shifted the region of observation further up in the pulse train. The ICC was operated without the objective lens and with a slit in front of the photocathode. The streaking rate of the ICC was 50mm/20ns and the direction of sweeping was parallel to that of the fringes.

Time resolved interference patterns were recorded on Kodak Royal X-Pan film. The film was developed using Acufine developer. Under conditions of operation and processing identical to that in the actual experiment, the characteristic curve for the film was plotted using density steps from the Kodak photographic step tablet. From the microdensitometer traces of the interference fringes and the characteristic curve of the film, the values of intensity maxima, minima and hence of F.V. were obtained. For each setting of the interferometer arm (zero, one or two cavity transit time delays) values of F.V. were obtained for various values of the differential delay τ , between the interferometer arms. Simultaneously, the TPF, the spectrum, and the intensity profile were recorded for each value of τ .

C. Results

The pulse trains were of 100 to 150 nanoseconds duration, consisting of 20-30 pulses. Typical widths for the time-integrated spectra ranged between 9 and 15 cm^{-1} and the time integrated TPF widths were between 2 and 5 ps. In each interference pattern from the image converter camera, four sets of interference fringes were obtained corresponding to four consecutive pulses in the same pulse train as in [12]. From these pictures one can obtain the difference in sharpness of the sets of fringes for different delay times.

In Figure 3 the measured autocorrelation fringe visibility as a function of differential delay time, τ , in the arms of the interferometer is plotted. The pulses in a streaked picture are any four consecutive pulses in the region of the pulse train being probed limited by the accuracy of the triggering system. Note in particular that the F.V. does not fall off to zero for large delay time. From

this curve one can determine the bandwidth of the mode-locked signal and can also infer the nature as well as the power fraction of noise, as will be explicitly presented in the next section. In addition, by comparing the F.V. for any two successive sets of fringes in a streaked interference pattern one can obtain the change of bandwidth between two successive pulses.

In Fig. 4 we present the F.V. curves for cross-correlation between two consecutive pulses. The substantial difference in the general shape of this curve as compared to that of autocorrelation clearly demonstrates the relative phase dispersion existing between two consecutive pulses. This will be elaborated upon in section IV. Experimentally measured values of F.V. for the correlation of pulses separated by two cavity transit times are given in Fig. 5. For this case, due to the rapid variation of the F.V. values within the delay time intervals used (which are the same as in Figs. 3 and 4) one should take the curve with data points connected qualitatively. However, the significance of this curve will be explained later.

IV. ANALYSIS AND CONCLUSIONS

In interpreting the auto-correlation fringe visibility, we approximate the actual power spectrum of the mode-locked signal and noise with, in general, different bandwidths. In as much as the main information contained in this F.V. is the bandwidth, our Gaussian approximation with the corresponding bandwidth determined to fit the data optimally is a reasonable assumption. Needless to say, this approximation is not essential. However, any improvement in actual data fitting does not lead to substantial change in the information to be obtained. Hence (4) can now be written as

$$F.V. = [e^{-\beta \tau_p^2} + f][1 + f]^{-1} \quad (8)$$

where the dimensionless time parameter, τ_p , is scaled with respect to picosecond unit ($\tau_p = \Delta\Omega t$, $\Delta\Omega = 10^{12}$) and β is the correspondingly scaled bandwidth of the signal. In view of the fact that the auto-correlation curve, Fig. 3, does not fall off to zero but reaches a constant value for a large delay time, it is clear that the bandwidth of the noise is much less than that of the signal. Thus we may, to a good approximation, take the time dependence of noise to be essentially constant, f , in τ_p scale in which case f represents the power fraction of noise with respect to signal power.

By optimally fitting equation (8) to our auto-correlation data we find that $f = 0.25$ and $\beta = 1.125$. This means that about 75 percent of the laser output power goes into the mode-locked optical pulses whose spectral bandwidth is approximately 10 cm^{-1} . These values for f and β fit the data to within 3 percent error [Fig. 6].

We next consider the cross-correlation, first between two pulses separated by one cavity transit time. In so doing we take the total power and fraction of noise in these two pulses to be the same. This is a good approximation considering the fact that the pulses are two consecutive pulses in a single pulse train. We point out, however, that the bandwidths of these two pulses are substantially different from each other. Their ratio is to be estimated by measuring the auto-correlation F.V. for two consecutive sets of fringes for a given delay time in a single streaked autocorrelation interference pattern. Bandwidth modulation of this kind has also been previously observed by Duguay, et al. with a different technique [2].

As mentioned earlier, the relative phase dispersion existing between these two pulses can affect significantly the F.V. curve for cross-correlation. In order to obtain this phase dispersion, we first represent the relative phase as

$$\Delta\chi(\omega) = a \sin K\left(\frac{\omega - \omega_0}{\Delta\Omega}\right) + b \cos K\left(\frac{\omega - \omega_0}{\Delta\Omega}\right) \quad (9)$$

Here, the parameters a , b and K (scaled with respect to picosecond units) will be determined in such a way that the ensuing theoretical expression fits optimally the experimental data. The fit to data will undoubtedly improve if we increase the number of available parameters by adding more terms in (9) such as the harmonic terms. But as will become clear later, (9) is adequate for the analysis of our data.

Upon inserting (9) into (5) and (6), with the identity

$$e^{iz \sin \theta} = \sum_{n=-\infty}^{\infty} J_n(z) e^{in\theta}$$

with J_n representing n^{th} order Bessel Function, we find, as in the case of autocorrelation,

$$\text{F.V.} = \left(\frac{2r}{1+r^2}\right)^{\frac{1}{2}} [1+f]^{-1} [f + |S(\tau_p)|] \quad (10)$$

with

$$\begin{aligned} S(\tau_p) = \sum_{\pm} \{ & [A_0 e^{-\gamma\tau_p^2} + A_{\pm 1} e^{-\gamma(\tau_p \pm K)^2} + A_{\pm 2} e^{-\gamma(\tau_p \pm 2K)^2}] \\ & + i[B_{\pm 1} e^{-\gamma(\tau_p \pm K)^2} + B_{\pm 2} e^{-\gamma(\tau_p \pm 2K)^2}] \} \end{aligned} \quad (11)$$

$$\gamma = 2r^2\beta/[1+r^2] \quad (12)$$

and

$$\begin{aligned}
A_0 &= J_0(a)J_0(b) \\
A_{\pm 1} &= \pm J_0(b)J_1(a) \\
A_{\pm 2} &= J_0(b)J_2(a) - J_0(a)J_2(b) \\
B_{\pm 1} &= J_0(a)J_1(b) \\
B_{\pm 2} &= \pm J_1(a)J_1(b)
\end{aligned} \tag{13}$$

Here r denotes the ratio of bandwidth of these pulses.

We take the values $f = 0.25$, $r = 1.74$ appearing in (10) as obtained from autocorrelation data to fit the theoretical expression to the cross-correlation curve. Numerical analysis of one cavity delay cross-correlation was performed by varying the parameters a , b and K . The best fit is obtained for $a = -0.23$, $b = 0.77$, and $K = 1.555$, in which case the error is 2.5% [see Fig. 7]. In Fig. 8, we show the relative phase dispersion corresponding to this best fit. The shape of this phase curve shows explicitly that there exists both positive and negative frequency chirping as well as a substantial degree of non-linear phase dispersion occurring within the bandwidth of the mode-locked signal. This rapid change in phase and bandwidth is understandable considering the fact that the pulses investigated here lie near the peak amplitude region of short high power pulse trains.

We also applied our analysis to previously reported data obtained under different conditions [13]. The auto and one cavity delay crosscorrelation F.V.'s reported therein were measured for the case of (i) long pulse trains of durations 400-500 ns, and (ii) the region of investigation long after the start of the pulse train. The results of the analysis are shown in

Figures 9,10 ,11 . The bandwidth of the pulse is 23 cm^{-1} , the fraction of noise power $f = 28\%$ and the ratio of bandwidths of two successive pulses, $r = 1.2$. The main difference lies in the cross-correlation and, hence, the phase dispersion curve. Note that in this case there is essentially no relative phase dispersion, which tends to indicate that the pulses in the latter part of the train of such quasi-continuous pulse trains are almost identical in phase.

Since, as pointed out earlier, the experimental curve for cross-correlation between pulses that are two cavity transit times apart should be taken only qualitatively [see Section III] we did not carry out explicit numerical analysis. Instead we have assumed that in the region of the pulse train investigated, the phase dispersion and bandwidth modulation between any two successive pulses remains the same. Hence we extrapolated our analysis for one cavity delay correlation by taking the relative phase dispersion to be $2\Delta\chi$ and the net ratio between bandwidths to be r^2 . The resulting F.V. is plotted in Fig.12 together with the data points. The agreement between these two curves lends some degree of confidence to the techniques of analysis.

The train of pulses produced by a mode-locked Nd:glass laser have been difficult to measure and analyze because of the short duration of the pulse train, the rapid variation from pulse to pulse, and the fact that they possessed subpicosecond substructure and internal frequency chirping. It is shown in this paper that the auto- and cross-correlation data obtained by time resolved linear interferometry can make it possible to determine accurately the changes in mode phase and amplitude taking place from pulse to pulse. If the initial pulses are measured to be minimum bandwidth pulses as they are in most

systems, then the succeeding pulses are consequently known. As a result, the method of measurement and analysis presented here is especially valuable for determining the form of the output pulses from a Nd^{3+} :glass mode-locked laser system.

REFERENCES

1. D.J. Bradley and G.H.C. New, "Ultrashort pulse measurements," Proc. of the IEEE, vol. 62, no. 3, 313-345, March 1974.
2. M.A. Duguay, J.W. Hansen, and S.L. Shapiro, "Study of the Nd:Glass laser radiation," IEEE J. Quantum Electron., vol. QE-6, no. 11, 725-743, Nov. 1970.
3. R.J. Harrach, "Determination of ultrashort pulse widths by two-photon fluorescence patterns," Appl. Phys. Lett., vol. 14, 148-151, Mar. 1969.
4. P.M. Rentzepis, C.J. Mitschelle, and A.C. Sanman, "Measurement of ultrashort pulses by three photon fluorescence," Appl. Phys. Lett., vol. 17, 122-125, Aug. 1970.
5. H.P. Weber, "Method for pulsewidth measurement of ultrashort light pulses generated by phase-locked lasers using nonlinear optics," J. Appl. Phys., vol. 38, no. 5, 2231-2235, April 1967.
6. P.B. Bey, J.F. Giuliani, and H. Rabin, "Phase-matched optical harmonic generation in liquid media employing anomolous dispersion," IEEE J. Quantum Electron., vol. QE-4, no. 11, 932-939, Nov. 1968.
7. R.C. Eckardt and C.H. Lee, "Optical third harmonic measurements of sub-picosecond light pulses," Appl. Phys. Lett., vol. 15, no. 12, 425-427, Dec. 1969.
8. A.J. Demaria, D.A. Stetser, and W.H. Glenn, Jr., "Ultrashort light pulses," Science, vol. 156, 1557-1568, June 1967.
9. A.J. Demaria, W.H. Glenn, Jr., M.J. Brienza, and M.E. Mack, "Picosecond laser pulses," Proc. of the IEEE, vol. 57, no. 1, 2-25, Jan. 1969.
10. D.J. Bradley, B. Liddy, W. Sibbett, and W.E. Sleat, "Picosecond electron-optical chronography," Appl. Phys. Lett., vol. 20, no. 6, 219-221, March 1972.
11. M. Ya. Schelev, M.C. Richardson, and A.J. Alcock, "Image-converter streak camera with picosecond resolution," Appl. Phys. Lett. vol. 18, no. 8, 354-357, April 1971.
12. R.W. Uhlhorn and D.F. Holshouser, "Cross-correlation detection of subnanosecond optical pulses," IEEE J. Quantum. Electron., QE-6, 775-782, Dec. 1970.
13. H.J. Ruiz, J.J. Turner, and T.A. Rabson, "Interpulse coherence of picosecond pulses," Optics Communications, vol. 6, no. 4, 435-437, Dec. 1972.

FIGURE CAPTIONS

- FIG. 1 Schematic representation of the Michelson Interferometer as used for measuring auto and cross correlations. L_0 is the distance of the fixed mirror from the beamsplitter and l is the optical length of the laser cavity. E_1, E_2, E_3 are any three consecutive pulses in the pulse train. τ is the differential displacement of the movable mirror.
- FIG. 2 Experimental arrangement for generation and measurement of picosecond pulses. In addition to the Michelson Interferometer and Image Converter Camera necessary for measuring time-resolved correlations, the experimental setup includes a TPF monitor and a 3.4meter spectrograph.
- FIG. 3 Measured Fringe Visibility as a function of delay time, τ , for auto-correlation.
- FIG. 4 Measured Fringe Visibility as a function of differential delay time, τ , for 1 cavity-delay cross correlation.
- FIG. 5 Measured values of Fringe Visibility as a function of differential delay time, τ , for 2 cavity-delay cross correlation. The dotted curve represents the experimental values connected only qualitatively, due to rapid variation of F.V. within the delay time intervals used.
- FIG. 6 Comparison of experimental and theoretical plots of autocorrelation F.V. as a function of differential delay time, τ . Fit to data within 3.2%.
- FIG. 7 Comparison of experimental and theoretical plots of 1 cavity delay cross correlation F.V. as a function of differential delay time, τ . Fit to data within 2.6%.

FIG. 8 Relative phase dispersion plotted in frequency units of power spectrum bandwidth. The shape of the curves demonstrates the existence of positive and negative frequency chirping as well as substantial degree of nonlinear phase dispersion in the peak amplitude region of short, high power, pulse trains. The region of the curve near $\Delta\omega = 0$ is most important because the amplitude of the modes is largest there.

FIG. 9 Comparison of experimental and theoretical plots of autocorrelation F.V. as a function of differential delay time, τ , for the data reported in [13]. Fit to data within 2.5%.

FIG. 10 Comparison of experimental and theoretical plots of 1 cavity delay cross correlation F.V. as a function of differential delay time, τ , for the data reported in [13]. Fit to data within 6.2%.

FIG. 11 Relative phase dispersion in frequency units of power spectrum bandwidth for the data reported in [13]. Essentially there is no phase dispersion. Phase change is constant, for pulses in the tail region of long quasicontinuous pulse trains.

FIG. 12 Theoretical and experimental fringe visibilities for 2 cavity delay cross correlation. The experimental points of Fig. 8 have been included for comparison. The theoretical curve was obtained by extrapolation of the analysis for 1 cavity delay cross correlation with the parameter values calculated for Fig. 10.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FREQUENCY IN UNITS OF POWER SPECTRUM WIDTH

FIGURE 8

FIGURE 9

FIGURE 10

FREQUENCY IN UNITS OF POWER SPECTRUM WIDTH

FIGURE 11

FIGURE 12