propagate down the guide. This distributed-demultiplex capability would be useful in distributing individualized programs to users spaced along the guide. Detailed device design and questions about system reliability and cost require further investigation.

ACKNOWLEDGMENT

The author wishes to thank Dr. J. R. Hauser for valuable encouragement and discussions.

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Investigation of the Characteristics of a Mode-Locked Nd:Glass Laser with the Aid of a Picosecond Streak Camera

MARTIN C. RICHARDSON

***Abstract*—An infrared-sensitive streak camera, capable of resolving optical pulses of durations of ~3 ps, has been used to analyze the temporal development of the individual picosecond pulses in a mode-locked pulse train. A progressive increase in the duration of the individual pulses throughout the pulse train is observed, the rate of increase in the pulse duration being an approximate quadratic function of the optical field.**

In addition, temporal analysis of the laser output signal, dispersively delayed with the aid of a grating pair, confirms the existence of phase-modulation effects during the development of the mode-locked pulse train.

INTRODUCTION

UNTIL RECENTLY, the measurement of the duration of picosecond pulses emitted by mode-locked lasers involved the use of one of a variety of nonlinear autocorrelative techniques utilizing such phenomena as two- and three-photon fluorescence, second- and third-harmonic generation, and other intensity-dependent processes. However, with the development of ultrafast streak cameras with picosecond resolution, it is now possible to make direct unambiguous measurement of the individual mode-locked pulses. Initial measurements were first made of the output of mode-locked Nd:glass lasers. Bradley *et al.* resolved the ~ 4-ps 5300-Å second harmonic of the laser output [1], while Schelev *et al.*, using an infrared-sensitive camera, observed the fundamental signal [2]. Subsequently, both the pulse-duration and background energy content of picosecond dye laser pulses were also measured [3], [4].

The capability of making direct measurements of the individual pulses themselves should lead to a better understanding of the development of the pulses during the evolution of the pulse train, and also of the mechanism which gives rise to a spectral bandwidth much larger than the transform limit defined by the pulse duration. This is particularly desirable for the case of mode-locked Nd:glass lasers, in which evidence for subpicosecond structure [5]–[7], frequency chirping [8]–[12], and self-phase modulation and self-focusing [11], [13], [14] have been obtained. In addition, using a technique based on transient stimulated Raman scattering, von der Linde *et al.* have deduced that the pulse shape is weakly asymmetric, with an exponential decay slower than the Gaussian rise time [15], [16], although, at present, this has not been detected by direct measurement.

Manuscript received January 12, 1973. Part of this paper was presented at the Annual Meeting of the Optical Society of America, Ottawa, Ont., Canada, November 1971.

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This paper reports an extension of the previous study [2] of the output of a mode-locked Nd:glass laser with the aid of a streak camera having a resolution (instrumental function) of ~5 ps and an Ag–O–Cs (S1) photocathode, sensitive at the laser wavelength. This has made possible the measurement of pulses of ~3 ps in duration. Through a study of the history of the pulse within the laser resonator, direct observation has been made of a progressive increase in the duration of the individual pulses of the resulting pulse train, heretofore only deduced from autocorrelation measurements of the second harmonic [17]. In addition, picosecond temporal analysis of the laser output, dispersively delayed with the aid of a grating pair, gives further evidence for the occurrence of phase-modulation effects during the generation of the pulse train.

Experimental Details

The laser, which has been described in detail elsewhere [18], produced a single smoothly varying pulse train, of ~900 ns in length, having an envelope which did not alter significantly from shot to shot (typically < 10-percent variation in amplitude over 10 shots). The probability of producing a single train was > 95 percent. The individual pulses were separated by 6.7 ns and had a maximum energy of ~3 mJ. Although other workers have reported the observation of secondary satellite pulses associated with the dye cell–mirror distance [11], [19], no such pulses were observed above a level of ~1 percent of the peak pulse amplitude. The train of pulses from the laser was transmitted through a pulse delay device [2], [18], consisting of a number of parallel glass plates, 6.0 mm thick and spaced 28.5 mm apart. The reflected beams from the latter were directed onto a 20-μ slit, which was imaged by means of an 86-mm focal-length lens onto the photocathode of the image converter camera. Thus for each individual pulse of the mode-locked pulse train, the slit was illuminated by a series of pulses spaced alternately by 60 and 240 ps. A small fraction of the laser beam, reflected from a glass slide, was used to switch a laser-triggered spark gap (LTSG) [20]. The latter was incorporated into a 50-Ω transmission-line pulse generator, which produced a rectangular 10-kV 20-ns duration pulse having a rise time of ~120 ps.

The picosecond camera incorporates an RCA 73435 image-converter tube and an EMI 9694 four-stage magnetically focused image intensifier. Its principal characteristics and its mode of operation have already been described in detail [2], [18]. However, an alternative method of generating the required grid and deflection electrode voltage pulses was used. By feeding the 10-kV rectangular-pulse output of the LTSG into a matched series-parallel 50-Ω transmission-line pulse divider, 4 equal-amplitude 5-kV pulses of negative and positive polarity were obtained. With sufficient biasing of the deflection electrodes, the linear regions of the rise of a negative and a positive pulse were used for deflection of

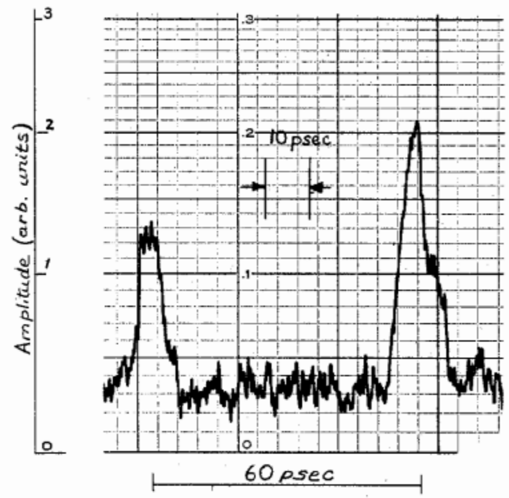

Fig. 1. Densitometer trace of streak photograph of mode-locked laser pulse produced at the beginning of the pulse train. Two pulses, separated by 60 ps, derived from successive reflections from surfaces of the pulse delay device are shown.

the shutter-tube image, providing a streak velocity of ~1.6 10^{10} cm · s^{-1}. The remaining two rectangular voltage pulses were used, with appropriate division, 1) for producing a positive accelerating field of ~3600 V · cm^{-1} at the photocathode surface to limit the electron transit time spread [2], [18], and 2) for providing a negative monitor signal. When the latter was added to the signal of the laser output, obtained with the aid of a fast photodiode, a record was obtained of the time during the mode-locked pulse train when the camera had been activated. By adjustment of the operating conditions of the LTSG, the camera could be operated at any particular time during the pulse train with an accuracy of ~50 ns.

Temporal Variation of Individual Pulses in the Pulse Train

The minimum pulse duration measured was that of pulses occurring in the initial buildup of the mode-locked pulse train. This is illustrated in Fig. 1, which shows the densitometer trace of two pulses separated by 60 ps. These were derived from a single pulse of the pulse train with the aid of the pulse delay device, the camera being activated at the onset of the laser output, when the individual pulse energy was less than one tenth of the peak pulse energy, that is, $\lesssim 0.3\ 10^{-3}$ J. It can be seen that the recorded signal duration is ~6.0 ps. Taking into account the streak-limited resolution of ~3.5 ps (for a streak velocity of ~1.6 10^{10} cm/s and a recorded dynamic spatial resolution of ~2 lp/mm) and the calculated resolution limit set by the transit time spread of the photoelectrons emanating from the photocathode, in this case ~3.6 ps [18], it is concluded that the recorded pulse duration is ~3.0 ps.

Typical streak photographs of the pulse taken at different times during the pulse train are shown in Fig. 2. It can be seen that the shortest pulses are recorded at the beginning of the train, and that, with successive passes

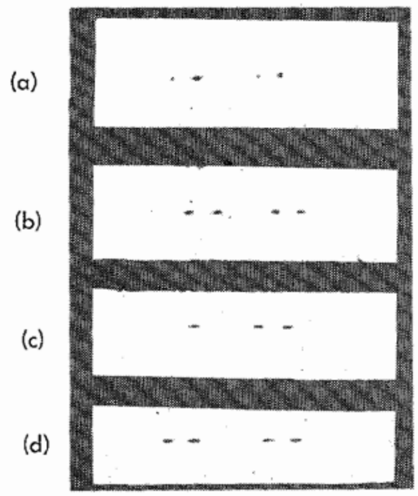

Fig. 2. Streak photographs of the laser pulse taken at (a) 0, (b) 100, (c) 200, and (d) 900 ns during the pulse train. Each doublet of pulses results from the two reflections from one of the 6-mm thick parallel glass plates of the pulse delay device. Each doublet is separated by 240 ps.

through the amplifying medium, the pulse progressively increases in duration to values of ~25 ps at the end of the train.[1] This variation of the pulse duration as a function of time during the pulse train is plotted in Fig. 3(a), which shows that the maximum increase in the pulse duration occurs during the first ~300 ns of the pulse train. This can be compared with the change in the amplitude of the individual pulses of the train Fig. 3(b), as recorded with a fast photodiode–oscilloscope combination, which, since it has a time constant many times greater than the pulse duration, effectively records the energy of the individual pulses. From Fig. 3(a), (b) it is possible to deduce the mean power of each pulse, and the variation of this as a function of time during the pulse train is shown in Fig. 3(c). By comparison of Fig. 3(a), (c) it can be seen that the maximum increase in the pulse duration occurs when the mean power of the pulse is greatest.

In addition, an analysis of the effect the high field existing within the laser resonator has on the pulse duration shows, from Fig. 4, an approximate quadratic dependence of the increase in pulse duration of consecutive output pulses on the field within the resonator. From this it can be deduced that for each double transit of the optical resonator, a picosecond pulse increases in duration, approximately according to the rule

$$\Delta t = 1.1 \; 10^{-34} \, E^4 \text{ ps}$$

where $E(\mathrm{V \cdot cm^{-1}})$ is the mean field value existing within each pulse inside the laser resonator.

[1] *Note Added in Proof:* Recently, R. J. Dewhurst et al. (*Opt. Commun.*, vol. 6, p. 356, Dec. 1972) have reported direct measurement of pulse broadening in the second harmonic of a mode-locked Nd:glass laser. Pulsewidths varying from 3.8 ps at the beginning of the pulse train to greater than 15 ps at the end were recorded.

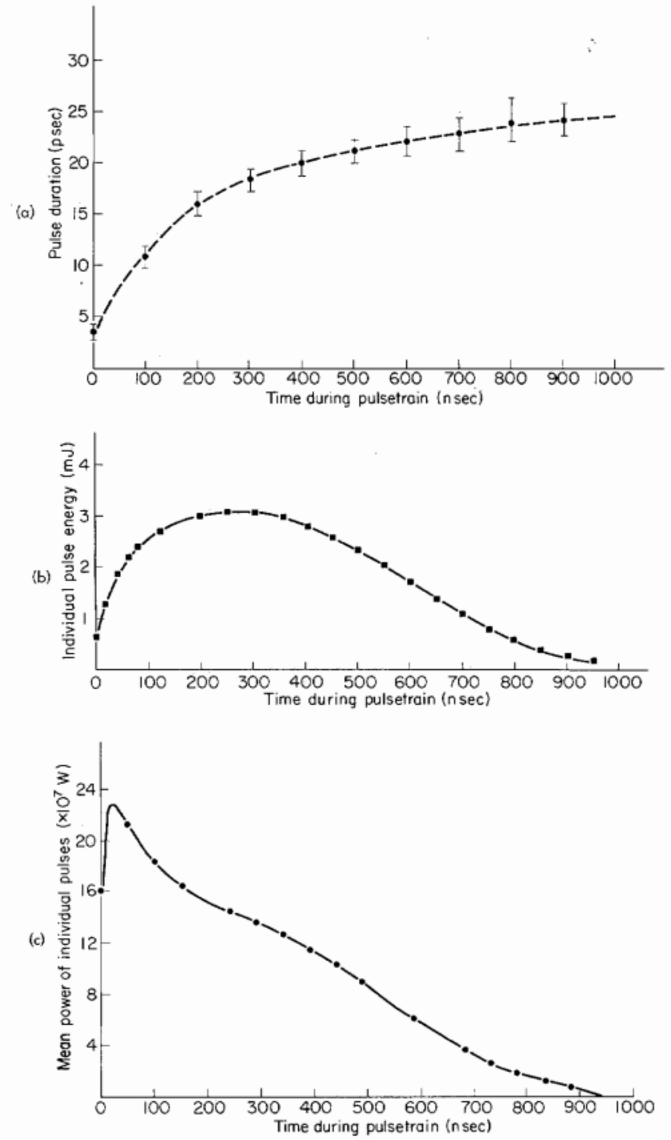

Fig. 3. Variation of (a) the pulse duration, (b) the pulse energy, and (c) the mean pulse power of individual pulses in the mode-locked output of the Nd:glass laser. Each point in (a) represents an average value of the pulse duration, obtained from 10 to 20 laser shots, for pulses observed within a 100-ns interval in the pulse train.

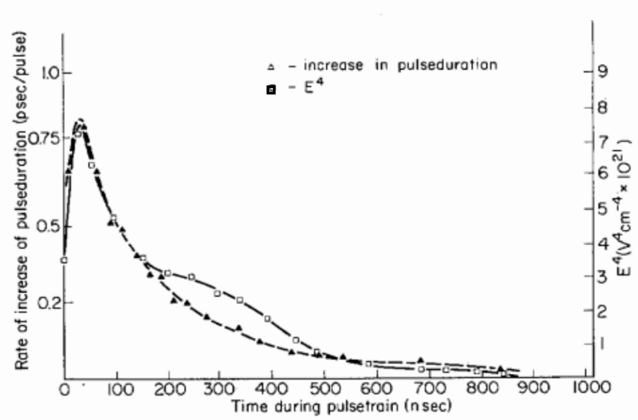

Fig. 4. Comparison of the change in pulse duration for consecutive laser pulses and the field intensity within the optical resonator as a function of time during the pulse train.

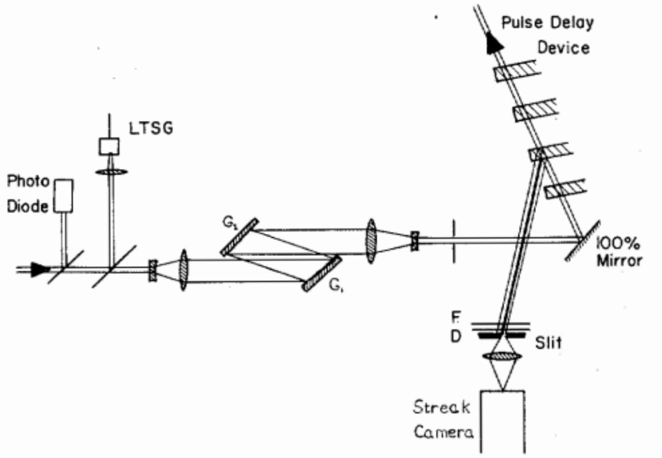

Fig. 5. Schematic of experimental arrangement for the streak photography of the dispersively delayed pulses from the mode-locked laser. Legend: G_1, G_2—diffraction gratings; LTSG—laser-triggered spark gap; D—diffuser; F—infrared filter. The beam diameter was expanded by a factor ~3–~20 mm, for passage through the grating pair, to prevent the latter from being damaged.

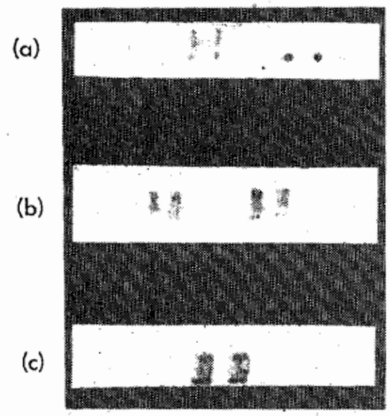

Fig. 6. Typical time-resolved signals obtained from the dispersive delay of mode-locked pulses (a) at the beginning of the pulse train, (b) 100, and (c) 400 ns after the onset of the pulse train. Each doublet of pulses separated by 60 ps results from glass plates in the pulse delay device, in the same manner as the results shown in Fig. 2.

Examination of Dispersively Delayed Mode-Locked Pulses

In order to investigate the character of possible FM structure on the individual pulses, the train of picosecond pulses from the mode-locked laser was passed through a dispersive delay [21], as shown in Fig. 5. The dispersive delay consisted of a pair of parallel gratings ruled with 1200 lines/mm, separated by 10 cm, and oriented at an angle of incidence to the beam of 60°. Hence, the device had a dispersive delay of 5.8 ps/100 Å for 1.06-μ radiation. The resulting optical signal was then directed through the pulse delay device and displayed on the photocathode of the streak camera in the same manner as previously described [18]. Streak photographs of the output from the dispersive delay were obtained for pulses in different parts of the pulse train, and it was evident that the character of the dispersively delayed signal changed during the development of the train of mode-locked pulses. This is clearly illustrated in Fig. 6, which shows three typical streak photographs of the dispersively delayed signal obtained at the beginning of the pulse train and at 100 and 400 ns later.

As can be seen from Fig. 6(a), pulses at the beginning of the pulse train, which have durations of $<$ 10 ps, pass through the dispersive delay without apparent change. Although the duration of this signal approaches the resolution limit of the camera, other studies of the spectrum of pulses from this region of the pulse train [11], [13], [16] have indicated that the pulse is transform limited, and hence would not be modified by passage through the grating pair. However, the streak photographs of dispersively delayed pulses from later times in the pulse train are distinctly different from those which did not pass through the grating pair. As can be seen from Fig. 6(b), pulses observed in the first 100 ns or so of the pulse train, where, from Fig. 3(c), the mean power of the pulses reaches its peak value, possessed a definite structure in the dispersively delayed signal. On many occasions this took the form of two definite components separated by as much as 15 ps, such as is visible in Fig. 6(b). In general, the separation of the two components increased for later pulses observed in this region of the pulse train. At still later times in the pulse train, from 200 ns to the end, the dispersively delayed signal has a more complicated structure, as is shown in Fig. 6(c). However, as can be seen by comparing this result with that of Fig. 3(c), the total duration of the signal remained similar to that of the pulses which did not pass through the grating pair.

The observation of this structure in the dispersively delayed signals from individual picosecond pulses in the mode-locked laser pulse train confirms the existence of frequency chirping within pulses occurring after the initial buildup of the pulse train. However, the interpretation of this structure is still ambiguous. Although it is possible that such a signal could result from a smoothly varying pulse, having a linear or S-shaped chirp, a similar result might also be obtained from a pulse made up of several frequency modulated subpicosecond components. Nevertheless, it is clear from the results presented here that a more comprehensive understanding of the nature and development of Nd:glass mode-locked laser pulses will best be obtained with the use of diagnostic techniques which analyze directly the features of the individual pulses of the pulse train. Further improvements in the resolution of high-speed streak cameras, to the region of a picosecond or less [22], [23], will be of considerable value to such investigations.

Acknowledgment

The author wishes to thank Dr. A. J. Alcock for many useful discussions during the course of these studies. He also wishes to thank K. Leopold, P. Burtyn, W. J. Orr, and K. Sala for their technical assistance.

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Mode Selection in GaAs Injection Lasers Resulting from Fresnel Reflection

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Abstract—**In several recent papers, attention has been given to the Fresnel reflectivity associated with cleaved facets of the laser. The small dimensions of the heterostructure waveguide give rise to a considerable angular spread in the energy incident on the facet. As a result, the mode reflectivity is not given simply by the Fresnel equation, which is only valid for an infinite plane wave. Rather, it is a properly weighted average over the plane-wave distribution of the mode. The differences in mode reflectivity with respect to TE and TM modes, as well as the variations with mode number, have been offered as a possible explanation for the predominant appearance of TE modes and preference for higher order modes in the large optical-cavity (LOC) geometry. However, the considerations to date have ignored the finite extent of the field in the junction plane. This situation is rectified in this paper. It is shown that the splitting in the mode reflectivity values between TE (electric field in the junction plane) and TM (electric field perpendicular to the junction plane) modes is reduced, and under certain conditions TM modes can be favored. In particular, it is shown that if a TE mode is oscillating, then there is a preference for a lowest order mode in the plane of the junction and a highest order mode in the transverse plane. Conversely, if for some reason a TM mode is oscillating, then the preference is for highest order modes in the plane of the junction and lowest order modes in the transverse plane.**

Manuscript received January 17, 1973; revised March 7, 1973.
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Introduction

DURING the past two years, it has become apparent that the Fresnel reflectivity of the cleaved end mirrors can play a significant mode-selecting role in the GaAs double-heterostructure laser [1]–[4]. Although the considerations have been mostly theoretical in nature, there has been experimental confirmation in the work of Reinhart, who changed the index of refraction of the region outside the mirrors to observe changes in the laser