A RAPID-SCANNING AUTOCORRELATION SCHEME FOR CONTINUOUS MONITORING OF PICOSECOND LASER PULSES

Zafer A. YASA and Nabil M. AMER

Applied Physics and Laser Spectroscopy Group, Lawrence Berkely Laboratory, University of California, Berkeley, CA 94720, USA

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We describe a scheme for rapidly introducing a periodic linear time delay to a train of picosecond laser pulses. By incorporating this scheme in one arm of the Michelson interferometer of a conventional autocorrelator, the second order intensity autocorrelation function of a cw train of picosecond pulses is continuously displayed on an oscilloscope.

1. Introduction

With the advent of synchronous pumping, mode-locked cw dye lasers have become an important tool for performing time-resolved spectroscopy. The standard method for measuring the width of the pulses produced by these laser systems is the well known second harmonic (SHG) autocorrelation technique [1–3]; however, useful autocorrelation traces require minutes to obtain. Hence, it is desirable to devise methods which enable the continuous monitoring of the temporal characteristics of these pulses in "real' time". One approach involves the rapid introduction of a periodically varying time delay in one arm of the Michelson interferometer (MI) used in conventional second harmonic generation autocorrelators. Previously reported methods for implementing this approach employ nonlinear [4,5] or stepwise linear [6] variable time delays. However, they have a limited scanning range [4–6] and are not dispersion-free [6].

In this communication we describe a simple, yet precise, method for the introduction of a periodic time delay to a train of picosecond laser pulses. It enables the high resolution display of the autocorrelation function of picosecond pulses continuously on an oscilloscope. It is highly linear over a wide scanning range ($\geqslant$ 150 ps), and is dispersion-free.

2. The rapid-scan autocorrelation scheme

The rapid introduction of a *linear* periodic time delay is achieved by incorporating in one arm of the Michelson interferometer a pair of parallel mirrors mounted on the two ends of a shaft rotating at a constant angular frequency f (see fig. 1). Thus, after being equally split by the beam splitter, one half of the incoming train of picosecond pulses is incident on mirror M_1 and is reflected to mirror M_2 from which it is transmitted in a direction parallel to that of the original direction. Following a rotation of the shaft by an angle θ, this beam will traverse a different path (i.e., is delayed) and is transmitted with a certain displacement while remaining parallel to the direction of incidence. The transmitted beam is normally incident on a stationary mirror M_3, from which it is retroreflected, retracing the incident beam in the opposite direction.

In the other arm of the MI, a stationary mirror M_4 (mounted on a translation stage) retroreflects the other half of the incoming train of pulses, and the two reflected beams (from mirrors M_3 and M_4) are then recombined collinearly at the beam splitter. The combined beam is focused onto an angle-phase-matched nonlinear crystal and the generated second harmonic is detected by a photomultiplier as in conventional autocorrelators. In our scheme, however, the photomultiplier output is the input to a high impedance oscilloscope. The time-base of the oscilloscope is triggered by the output of the

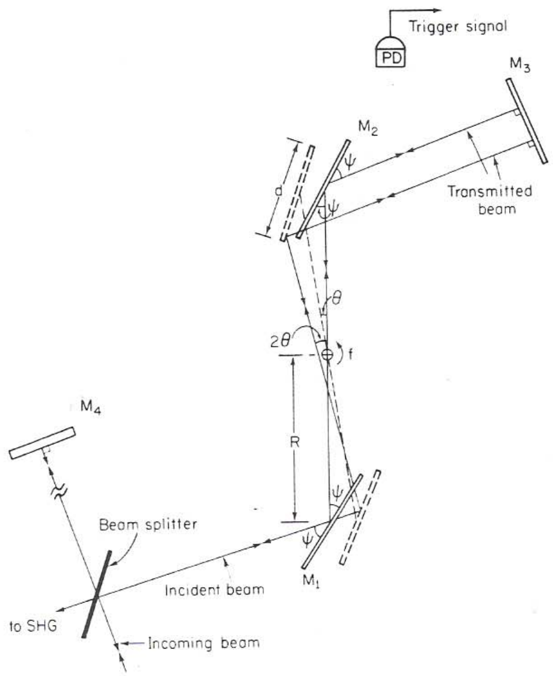

Fig. 1. The rapid-scanning Michelson interferometer part of the SHG autocorrelator. R is the radius of the rotating shaft, d is the mirror diameter, and ψ is the angle of mirror orientation with respect to the incident beam. Dashed lines represent the shaft and mirrors after a rotation by an angle θ. PD is the photodiode used to trigger the oscilloscope.

photodiode PD which is placed between M_2 and M_3 such that it intercepts a portion of the beam before it is incident on M_2. As shall be seen in the next section, the rotation of the parallel pair of mirrors M_1 and M_2 results in a linear variation of delay with time. Hence, the oscilloscope directly displays the second order intensity autocorrelation (with background) of the incoming train of pulses. To properly position the autocorrelation trace, one translates mirror M_4 such that the peak occurs at the center of the scan range on the oscilloscope screen. The calibration of the oscilloscope in terms of delay is done by measuring the displacement of the autocorrelation peak on the screen for a given translation of M_4.

We note that in order to obtain a background-free SHG, one simply replaces M_4 with a corner cube. Furthermore, by keeping M_1 and M_2 fixed (no rotation) and translating M_4 with a stepping motor, a conventional slow autocorrelation scan can be obtained.

3. Geometrical considerations

From the geometry given in fig. 1, it can be shown that the optical path difference ($\Delta l(\theta)$) of the back reflected beam as a function of the rotation angle θ is given by

$$\Delta l(\theta) = 4R\,[\sin 2\psi \sin\theta - (1-\cos 2\psi)(1-\cos\theta)]\,, \tag{1}$$

where R is the shaft radius and ψ is orientation angle of the mirror. For $\theta \ll \pi/2$

$$\Delta l(\theta) \simeq 4R\theta\,[\sin 2\psi - \tfrac{1}{2}\theta(1-\cos 2\psi)]\,. \tag{2a}$$

Since the second term within the square bracket in eq. (2a) is small, then

$$\Delta l(\theta) \simeq 4R\theta \sin 2\psi\,. \tag{2b}$$

From eq. (2b) it is seen that, for small values of θ, $\Delta l(\theta)$ is a linear function of the rotation angle θ. This implies that, at a fixed rotation frequency f, the delay introduced to a train of ultrashort pulses will vary linearly with time.

When $d \ll R$ (where d is the diameter of mirrors M_1 or M_2), mirror M_2 intercepts the beam over a small range of rotation angles $0 \leqslant \theta \leqslant \theta_{max}$, where θ_{max} is given by

$$\theta_{max} \simeq \frac{d}{R}\frac{\sin\psi}{(2-\cos 2\psi)}\,. \tag{3}$$

Substituting eq. (3) into eq. (2b), we obtain the range optical path differences

$$\Delta l \simeq \frac{4d \sin 2\psi \sin\psi}{(2-\cos 2\psi)}\,, \tag{4}$$

which is maximized when $\psi = \pi/4$. At this angle

$$\Delta l \simeq \sqrt{2}d\,. \tag{5}$$

The non-linearity (NL) over the total scan range can be determined by comparing the second term in the square bracket in eq. (2a) with the first. For θ_{max}, this yields

$$\mathrm{NL} \simeq \frac{d}{4R}\tan\psi\,\frac{(1-\cos 2\psi)}{(2-\cos 2\psi)}\,, \tag{6}$$

which, for $\psi = \pi/4$, is

$$\mathrm{NL} \simeq d/8R\ . \qquad (7)$$

As a numerical example, for $d = 2.5$ cm, $R = 7.5$ cm, and $\psi = \pi/4$ the scan range $\tau = \Delta l/c = \sqrt{2}d/c = 117$ ps, where c is the speed of light. The nonlinearity is 4% over that entire range. Increasing R improves the linearity of the scan.

4. Experimental results and discussion

In fig. 2 we show the intensity autocorrelation trace (with background) for a cw train of incompletely mode-locked R6G dye laser pulses as displayed on an oscilloscope using the above described method. As can be seen from the figure, the coherence spike and the contrast ratio of 3 : 2 : 1 are clearly observed. The input average power to the autocorrelator was only ~ 4 mW. With the 0.1 mm KDP crystal we used, the filtered SH background level was ~ 100 mV.

Given eq. (2b) and since $\theta = 2\pi ft$, where t is time, a delay of $\Delta\tau$ is related to a time increment Δt as follows:

$$\Delta\tau/\Delta t = 8\pi Rf/c\ . \qquad (8)$$

In our experimental setup: $R = 12.25$ cm, $d = 3.5$ cm, and $f = 5$ Hz. The experimentally determined calibration factor $\Delta\tau/\Delta t$ is 50 ps/ms, which is in excellent agreement with eq. (9). From fig. 2 we determine the total scan range τ (= $[\Delta\tau/\Delta t] \times 3.3$ ms) to be 165 ps, which agrees very well with the prediction of eq. (5).

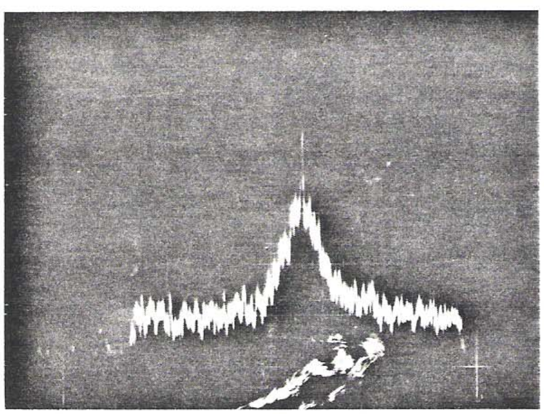

Fig. 2. Rapidly-scanned second order intensity autocorrelation trace of a cw train of ultrashort dye laser pulses. Horizontal scale is 500 μs/division. Vertical scale is 50 mV/division.

Given the experimental calibration factor of 50 ps/ms and assuming a sech^2 shape, the width of the pulse shown in fig. 2 is 15 ps.

In principle, the time resolution of this autocorrelator is set by the second harmonic generation process itself. This is true as long as the rise time of the detection and display parts of the autocorrelator are sufficiently fast such that $\Delta t_r = \Delta\tau_r c/8\pi Rf$, where Δt_r is the width of the autocorrelation trace on the oscilloscope corresponding to the fastest resolvable pulsewidth $\Delta\tau_r$. Assuming $\Delta\tau_r \simeq 0.1$ ps, it follows that typical values of Δt_r are on the order of one microsecond which is easily reached in practice. We estimate our experimental resolution to be 0.1 ps.

We should like to point out that the parallel mirrors configuration is insensitive to vibration; in addition, the alignment process is straightforward. We also note that the small feedback to the laser cavity did not have any observable effect on the picosecond pulse operation of the dye laser.

5. Conclusions

We have presented a simple fast-scanning autocorrelation scheme for "real-time" display of ultrashort pulses. This scheme has wide scanning range, high resolution, and is dispersion-free. This autocorrelator should prove useful for optimizing the performance of cw mode-locked dye lasers. It enables one to monitor pulse duration and characteristics while concurrently performing the experiment of interest.

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