Optical and Quantum Electronics 14 *(1982) 391–394*

A simple technique for real time pulsewidth measurements of single ultrashort laser pulses

S. M. SALTIEL, S. D. SAVOV, I. V. TOMOV
Faculty of Physics, Sofia University, BG-1126 Sofia, Bulgaria

Received 4 January 1982

A simple technique is described employing noncollinear second harmonic generation, for real time measurement of the pulse duration of individual pulses in the 1 ps to 1 ns range. The pulsewidth is derived from the recorded two points of the second-order autocorrelation function. The system may be used as a permanent on-line monitor of the pulsewidth.

1. Introduction

Ultrashort pulses have a broad field of application in physics, chemistry and biology. In these investigations pulses with well-known parameters are needed. However, picosecond pulses generated by passively mode-locked solid-state lasers have substantial fluctuations of the pulse duration [1, 2]. In order to obtain reliable information in experiments with such pulses, the pulse duration in every shot must be measured. The repetition rate of the above mentioned laser systems is usually of the order of 10 Hz or more, and therefore simple and rapid monitoring of the pulse duration is required.

Modern fast oscilloscopes can be used to observe the pulseform, but it is a very difficult task to obtain directly the pulse duration in digital or analog form for further rapid processing. Most of the methods for measuring the pulse duration of single pulses such as streak cameras, two photon fluorescence, and methods based on noncollinear second harmonic generation [3, 4] usually include photographic processing and time consuming photodensitometric analysis and cannot be used for real time measurements. Clearly each of these methods can be used together with an optical multichannel analyser [5, 6] and this would be the best way to determine the value of the pulsewidth. However, the cost of such a system may be prohibitive.

In this paper a simple technique for single pulse duration measurement using noncollinear second harmonic generation is described theoretically and realized experimentally. The system allows real time pulsewidth measurement in the 1 ps to 1 ns range. The pulse duration is derived from two recorded points on the autocorrelation function. One point at zero delay (for normalization) and the other at a delay of the order of the pulsewidth.

2. Two-point second-order autocorrelation technique

In analysis of autocorrelation methods for pulsewidth measurements some assumptions about the pulse waveforms are made. We will consider the most commonly used analytic expressions for the pulse shape and corresponding second-order autocorrelation functions, $G^{(2)}(\tau)$, in order to evaluate the capability of the proposed technique. The ability of the harmonic generation autocorrelation to measure picosecond duration accurately has been discussed in the literature [7, 8]. In the pulsewidth measurement when the second-order autocorrelation is used, one must assume a specific temporal shape in order to extract the pulse duration τ_p from the recorded autocorrelation width τ_G [8]. However, once we have assumed a pulse shape we need only two points to derive the pulsewidth. It should be noted that in all expressions for the autocorrelation function, $G^{(2)}(\tau)$, the delay time, τ, is normalized by the pulsewidth, τ_p, and we may write $G^{(2)}(\tau/\tau_p)$. At a fixed delay, $\tau = \tau_d$, the value of the normalized

TABLE I Pulse shape models and corresponding second-order autocorrelation functions

Number	Pulseshape, $\Phi(u)$ ($u = t/\tau_p$)	Normalized autocorrelation function $G^{(2)}(v)/G^{(2)}(0)$ ($v = \tau_d/\tau_p$)	τ_p/τ_G	$\tau_p = f(\tau_d, g)$
1	$\exp(-4u^2 \ln 2)$	$\exp(-2v^2 \ln 2)$	$1/2^{1/2}$	$\tau_d\left(\frac{2\ln 2}{\lvert\ln g\rvert}\right)^{1/2}$
2	$\begin{cases}\exp(-\lvert u\rvert \ln 2) & t \geqslant 0\\ 0 & t<0\end{cases}$	$\exp(-\lvert v\rvert \ln 2)$	0.5	$\tau_d \frac{\ln 2}{\lvert\ln g\rvert}$
3	$\frac{1}{1+4u^2}$	$\frac{1}{1+v^2}$	0.5	$\tau_d\left(\frac{g}{1-g}\right)^{1/2}$
4	$\operatorname{sech}^2(1.7627u)$	$3\,\frac{1.7627v \coth(1.7627v) - 1}{\sinh^2(1.7627v)}$	0.6482	–
5	$\exp(-2\lvert u\rvert \ln 2)$	$(1 + 2\lvert v\rvert \ln 2)\exp(-2\lvert v\rvert \ln 2)$	0.4130	–

autocorrelation function is

$$\frac{G^{(2)}(\tau_d/\tau_p)}{G^{(2)}(0)} = g. \tag{1}$$

The pulse duration τ_p is found by solving this equation. Thus the measured value of g may be used to calculate the pulsewidth. The case of $g = 0.5$ has been treated in detail by Sala *et al.* [8], for ten assumed pulse shapes. We will consider five of those pulses as given in Table I. For three of them, Equation 1 has been solved analytically to find τ_p. Fig. 1 presents the ratio τ_p/τ_d as a function of g. We note that only for a known pulse shape may the pulsewidth τ_p be derived from a single measured value of g. However, from Fig. 1 one can see that deviations of the ratio τ_p/τ_d for different pulse shapes at fixed g from one another, are not large. If the pulse shape is not known an approximation:

$$\tau_p = \tau_d(4.87g^2 - 2.78g + 1.27) \tag{2}$$

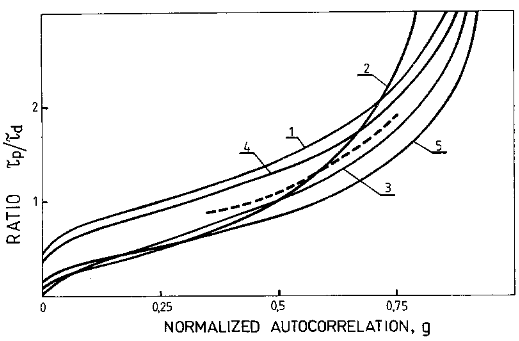

Figure 1 Ratio τ_p/τ_d versus normalized autocorrelation function g. The solid curve number corresponds to the pulse shape from Table I. The dotted curve represents Equation 2.

may be used. For g in the range 0.35–0.75 the error in the pulsewidth obtained from Equation 2 is less than 30%.

3. Experimental arrangement

From the above analysis it is clear that the pulsewidth may be derived if the value of $G^{(2)}(\tau/\tau_p)$ at a fixed delay, $\tau = \tau_d$ and $G^{(2)}(0)$ (for normalization), is known. This allows a simple arrangement for pulsewidth monitoring to be developed. The experimental set-up is shown in Fig. 2. The incident beam diameter, $D = 4p$, is determined by an aperture A_1, introduced to simplify the analysis. After passing through a Fresnel biprism, FB, two beams crossing in the nonlinear crystal at an angle 2α are formed. The crystal is oriented for noncollinear second harmoinc generation phase matching and is situated at a distance from the Fresnel biprism where the two crossing beams overlap. The pulsewidth measurement range is determined by a delay τ_d introduced in half of one of the interacting beams as shown in Fig. 2. A

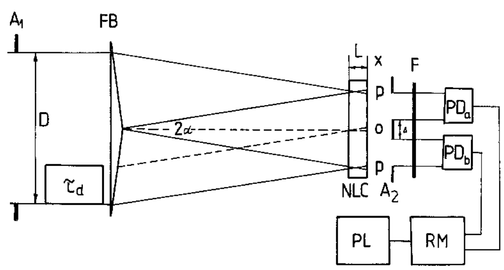

Figure 2 Experimental arrangement for pulsewidth measurement. A_1, A_2, apertures; τ_d, optical delay; FB, Fresnel biprism; NLC, nonlinear crystal; F, second harmonic filter; PD_a and PD_b, photodiodes; RM, ratiometer; PL, plotter.

screen A_2, with two slits in it blocks the light coming from the crystal. The slits are situated symmetrically relative to the point $x = 0$. The light passing through the slits is recorded by two photodiodes.

We will consider a pulse incident on the aperture A_1 with Gaussian spatial distribution along the x-axis

$$A_1(x,t) = A_0 \exp\left(-\frac{x^2}{w^2}\right)\phi(t) \qquad (3)$$

here $\phi(t)$ is the temporal profile of the pulse and w is the $1/e$ field radius of the beam. The second harmonic in the upper half of the nonlinear crystal, $x > 0$, is generated by interaction of the fundamental beams with amplitudes

$$A'_{1a}(x,t) = A_0 \exp\left[-\frac{(x-p)^2}{w^2}\right]\phi(t-\gamma x) \qquad (4a)$$

$$A''_{1a}(x,t) = A_0 \exp\left[-\frac{(x+p)^2}{w^2}\right]\phi(t+\gamma x) \qquad (4b)$$

where $\gamma = c^{-1}\sin\alpha$ and c is velocity of light. The second harmonic in the lower half of the crystal, $x < 0$, is generated by the beams

$$A'_{1b}(x,t) = A_0 \exp\left[-\frac{(x-p)^2}{w^2}\right]\phi(t-\gamma x-\tau_d) \qquad (5a)$$

$$A''_{1b}(x,t) = A_0 \exp\left[-\frac{(x+p)^2}{w^2}\right]\phi(t+\gamma x). \qquad (5b)$$

The second harmonic intensity distribution after the crystal is

$$I_{2a}(x) = B\exp\left(-\frac{4x^2}{w^2}\right)G^{(2)}\left(\frac{2\gamma x}{\tau_p}\right), \quad x > 0 \qquad (6a)$$

$$I_{2b}(x) = B\exp\left(-\frac{4x^2}{w^2}\right)G^{(2)}\left(\frac{2\gamma x+\tau_d}{\tau_p}\right), \quad x < 0. \qquad (6b)$$

The quantity B is a collection of constants, for a given experiment, involving second-order nonlinear susceptibility, crystal length, etc.

The case when $\tau_d = 0$, $w \gg p$ and $\tau_p \ll 2\gamma p$ was treated by Janszly *et al.* [3] and experimentally verified by Gyuzalian *et al.* [4], Kolmoder *et al.* [6] and Saltiel *et al.* [9]. That is the situation when the whole autocorrelation function is recorded. We will consider the case when $\tau_p \gg 2\gamma p$ and $\tau_d \gg 2\gamma p$. Then the autocorrelation function is almost constant over the slit. For example, if the pulsewidth $\tau_p = 10$ ps, $\alpha = 10$ mrad and $p = 2$ mm the variation of $G^{(2)}(2\gamma x/\tau_p)$ over the slit is less than 1% for all pulse shapes considered. Thus from Equation 6 we find that the second harmonic energy recorded by the photodiode 'a' is proportional to $G^{(2)}(0)$ and the energy recorded by the photodiode 'b' is proportional to $G^{(2)}(\tau_d/\tau_p)$. The ratio of the signals recorded by the photodiodes is equal to the normalized autocorrelation g.

The blocked area around $x = 0$ confined by both slits, should be chosen to have $\Delta > 2\beta L$ and $\Delta > 2\alpha L/n_1$. Here β is the birefringence angle, n_1 is the index of refraction for the pumping wave and L is the crystal length. The lower limit for α is determined by the requirement that the phase matching acceptance for collinear and noncollinear phase matching are not overlapping. Group velocity dispersion which may limit the crystal length is also neglected.

In the arrangement shown in Fig. 2, a 4 cm long KDP crystal cut for type I second harmonic generation with collinear phase matching was used. The crossing angle was 11 mrad. Pulses with a Gaussian shape were produced from an actively mode-locked Nd:YAG laser [9, 10]. The pulse duration was varied in the range 160 ps–1 ns and plane parallel glass rods 9, 12 and 24 cm long were used to create the necessary optical delay. In the proposed scheme the condition $w \gg p$ is not required and therefore a smaller extension of the beam is needed. Thus the energy necessary for pulsewidth mesurement is much less than in the schemes where the whole autocorrelation function is recorded [4, 6]. To measure pulses of 160 ps (FWHM) duration about 10 μJ of fundamental radiation energy was needed as determined by photodiode sensitivity. For shorter pulses the required energy will decrease.

We used this real-time measuring technique for matching the Nd:YAG cavity length to the modulation frequency. The cavity length was adjusted by translating the cavity mirrors. The speed of the motor-driven mirror was 2 mm min^{-1}. The signals I_{2a} and I_{2b} from two photodiodes were fed into a ratiometer (RM) whose output gives $\ln(I_{2b}/I_{2a})$.

Fig. 3 shows the dependence of the ratiometer output and corresponding pulsewidth versus the change of the laser cavity length.

The scheme described above allows pulse duration measurements as short as 1 ps. However,

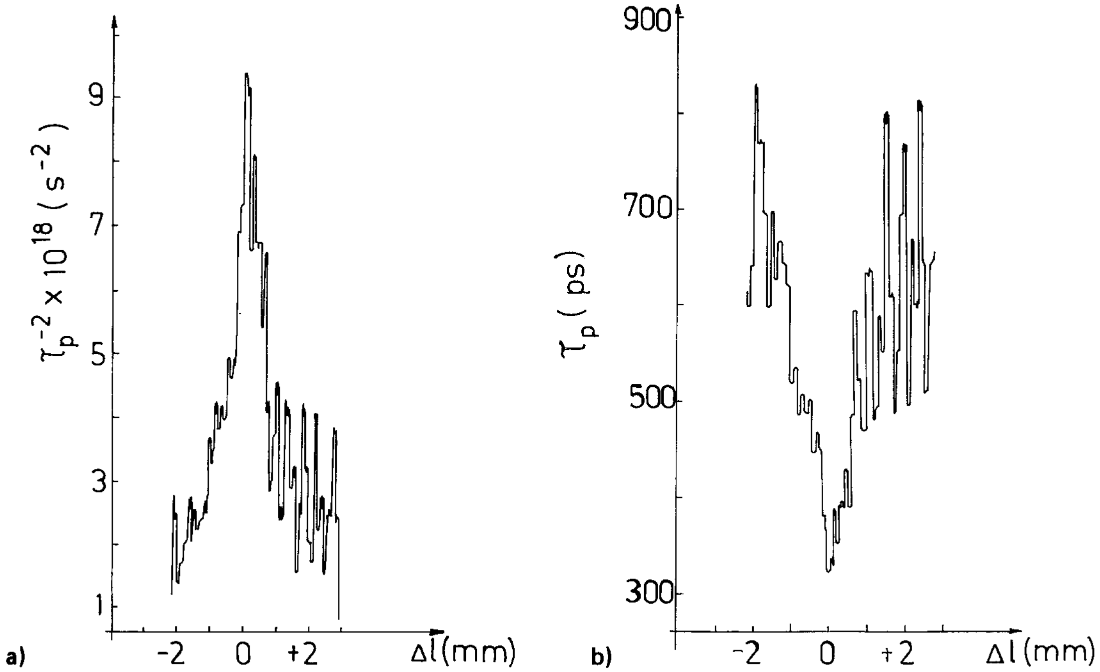

Figure 3 (a) Ratiometer output and (b) pulsewidth, versus change of laser cavity length.

for the range 1–10 ps a simplification of the scheme is possible. Instead of plane parallel glass plate, a 90° cut calcite crystal is used to introduce a delay between waves with ordinary and extraordinary polarization for one half of the beam ($D/2$). The biprism in Fig. 2 is removed. Both parts of the laser beam are directed onto a nonlinear crystal oriented for type II second harmonic generation with collinear phase matching. Thus, half of the beam generated a signal proportional to $G^{(2)}$ received by one of the photodiodes. The other half of the beam, which passes through the delay, generates a signal proportional to $G^{(2)}(\tau_d'/\tau_p)$ which is received by the other photodiode. The delay introduced by the calcite crystal is $\tau_d' = c^{-1}l(n_o - n_e)$, where n_o and n_e are indices of refraction for ordinary and extraordinary waves and l is the calcite crystal length.

The advantages of the proposed technique are obvious; 1. there is higher sensitivity since less beam extension is required and longer crystals may be used; 2. conventional crystals cut for collinear SHG may be used; 3. rapidity of data acquisition and analysis. This scheme may be employed as a permanent on-line monitor and thus real time data processing which requires a numerical value of the pulsewidth may be carried out.

Acknowledgement

The authors acknowledge useful discussion with Professor M. Bass.

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