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Microprocessor-based system for measurement of the characteristics of ultra-short laser pulses

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Abstract. A low-cost, microprocessor-based system is described for measuring, computing and displaying the parameters of ultra-short laser pulses immediately after a shot. The apparatus presented is particularly useful whenever the intensity or the duration of the pulse plays an essential role in the investigation.

1. Introduction

The appearance of high-intensity picosecond light pulses, produced by passively mode-locked solid state lasers, has offered an excellent possibility of investigating multiphoton interactions and making the direct time-resolved measurement of various transient processes feasible. The characteristics of the picosecond pulses depend on several parameters of the laser system. The fluctuations of these parameters can be reduced but not eliminated (Bechtel and Smith 1975, Wilbrandt and Weber 1975, Lü *et al* 1985). Therefore the scattering of the data in an experiment using these picosecond pulses can be further reduced only in the case that the characteristics of every pulse used are measured separately.

The aim of this work was to develop a low-cost instrument capable of measuring the autocorrelation function, the duration (FWHM), the energy and the peak power of the pulse of a passively mode-locked Nd:glass laser system in a few seconds after every shot. In the design we considered the following to be important: economy, high sensitivity and fast data processing. While commercially-available computerised optical multichannel analysers are rather expensive, the components of the described home-made apparatus are available in most laser laboratories.

Our set-up is based on the non-collinear second-harmonic generation (NSHG) proposed by Janszky *et al* (1977), and first realised by Gyuzalian *et al* (1979) and Kolmeder *et al* (1979). We detected the second harmonic (SH) beam by a photodiode array. A high scanning rate for serial readout is required in order to make the influence of the dark leakage current and background noise on the output signal negligible (Logoni *et al* 1984). Because of this requirement, real-time processing by the computer has been given up. Accordingly, the scanning rate is limited only by the analogue-to-digital conversion rate and by the detector itself (typical clock frequencies may reach 2–3 MHz). The video signal of the array as well as the result of the energy measurement are sent into a 4k RAM after high-speed A/D conversion. The data in this memory are read out and processed by the computer after the measurements. The program written in machine code ensures fast data processing.

2. Investigation of the time behaviour of light pulses by the NSHG method

There are two widely used methods for measuring the time behaviour of individual, non-reproducible ultra-short light pulses: the streak camera and the two-photon fluorescence (TPF) method. The first is very expensive, while the cheap second method requires a careful photometric analysis of the photographed track because of the small contrast ratio.

Contrary to the two methods already mentioned, the NSHG method is cheap, background-free and its resolution is better than that of the streak camera. The principle of the NSHG method is shown for square pulses in figure 1. Two pulses with wavevectors $\boldsymbol{k}_{\omega 1}, \boldsymbol{k}_{\omega 2}$ (created by the preceding beam splitter) cross each other in a non-linear crystal at an angle φ and produce a second-harmonic wave with wavevector $\boldsymbol{k}_{2\omega}$, if the phase matching condition $\boldsymbol{k}_{\omega 1} + \boldsymbol{k}_{\omega 2} = \boldsymbol{k}_{2\omega}$ is satisfied. Figure 1 shows schematically that the length of the pulses is 'projected' in the z direction. The spatial distribution of the SH signal allows determination of the autocorrelation function, i.e. the duration of a single ultra-short laser pulse. It is very important for the NSHG method that the diameter d of the incoming beams should be larger compared with the length, $c\tau$, of the pulse. The intensity distribution of the second-harmonic beam gives directly the autocorrelation function of the investigated pulse. Furthermore the spatial width of the SH beam, w (FWHM), and the pulse duration, τ (FWHM) are related as follows:

$$w = u(\omega)\tau/\beta \sin(\tfrac{1}{2}\varphi) \qquad (1)$$

where $u(\omega)$ is the group velocity of the incident pulses and β is the shape factor. For gaussian pulses $\beta = \sqrt{2}$ (Kolmeder *et al* 1979). By changing the crossing angle φ the temporal resolution is adjusted. The best choice is when the walk-off angle between the wavevector and the Poynting vector of the SH beam is zero.

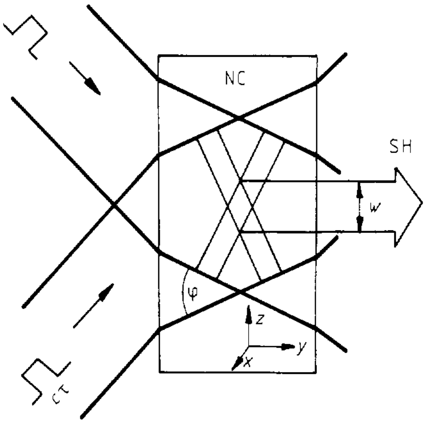

Figure 1. The principle of the non-collinear second-harmonic generation method (NSHG). NC, the non-linear crystal; $c\tau$, the length of the pulse; SH, the second-harmonic beam; φ, the crossing angle; w, the SH beam diameter. (The figure is in the yz plane.)

We used uniaxial $\mathrm{LiIO_3}$ crystal in which NSHG of oo-e type is realised (the incoming pulses have ordinary and the SH pulse has extraordinary polarisation). In a uniaxial crystal the walk-off angle is zero when 90° phase matching is realised. ($k_{2\omega}$ is perpendicular to the optical axis. The non-linear crystal is oriented with its optical axis along the z axis of the Cartesian coordinate system shown in figure 1.) The dispersion in $\mathrm{LiIO_3}$ allows 90° phase matching for the crossing angle $\varphi = 39.6°$.

In order to make the diameter of the incoming beams sufficiently large compared with the length of the pulses, the beams have to be expanded. The authors of previous works mentioned above have carried out the expansion with spherical

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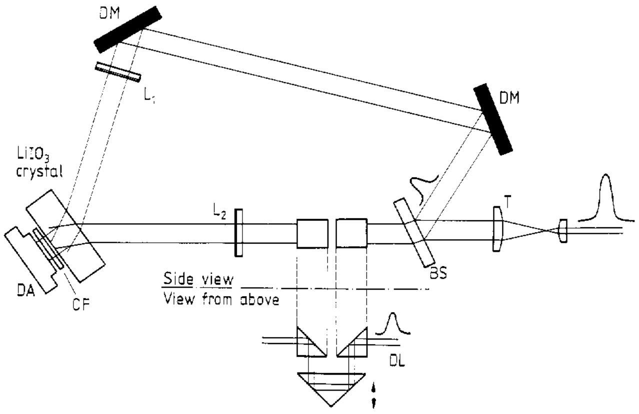


Figure 2. Experimental set up for the measurement of the autocorrelation function of the pulse by non-collinear second-harmonic generation. T, telescope consisting of cylindrical lenses; BS, beam splitter; DM, dielectric mirrors; DL, delay line; L_1, L_2, cylindrical lenses; OF, optical filter; DA, detector array.

lenses. But expansion in the x direction (figure 1) is unnecessary because the SH intensity distribution in this direction contains no information on the time behaviour of the pulse. Therefore, contrary to the works mentioned above, we expand the incoming beams only in the direction perpendicular to the x axis and focus them in the x direction into the non-linear crystal with cylindrical lenses. This simple modification of the method involves two important consequences. On one hand the total generated SH beam reaches the linear detector array, on the other hand, the higher intensity of the incoming beams results in SH pulse of greater energy. As a result of these modifications pulses with energy of two orders of magnitude smaller than earlier can be investigated using the same detector array.

The arrangement for the measurement of the time behaviour of the pulse is shown in figure 2. The beam is expanded by the telescope (T) consisting of two cylindrical lenses to form a 15 mm long stripe. In this case, (1) holds for pulses shorter than 20 ps with good accuracy. The beam splitter (BS) splits the pulse into two identical pulses, which are then focused perpendicularly to the direction of the expansion by the cylindrical lenses L_1 and L_2 into the 3 mm thick $LiIO_3$ crystal. The delay line (DL) is used to make the optical pathlengths identical. The narrow second-harmonic beam is detected by the detector array (DA) consisting of 256 photodiodes (RL256EC, EG&G Reticon). The optical filter (OF) prevents the fundamental pulses from entering the detector. Time resolution of the measurement is determined by the degree of beam expansion and by the number of the photodiodes per unit length (20 photodiodes/mm in our case).

3. The experimental set up

The laser-connected part of the optical set up can be seen in figure 3. One pulse is switched out of the train of a passively mode-locked Nd:glass laser by using a light-triggered spark gap (LTS). This pulse is amplified in the amplifying rod in three stages. A small portion (4%) of the energy of the amplified pulse is split off by a glass wedge for NSHG correlation measurement. Similarly another small part of the beam is used for energy measurement. The train without the switched-out pulse can be seen using a photodiode and a storage oscilloscope (see figure 3), which is not necessary but may prove useful in some cases.

A schematic diagram of the electronic part of the measuring set up and the timing diagram of the corresponding electrical pulses are given in figure 4(*a*) and (*b*) respectively. The flash sparking circuit starts the whole apparatus. A sequence of electrical pulses produced by the second pulse generator scans the detector array at a rate of 1 MHz. The first scanning is carried out immediately before the appearance of the laser pulse to erase the contents of each pixel, i.e. to decrease the background noise and the influence of the dark leakage current.

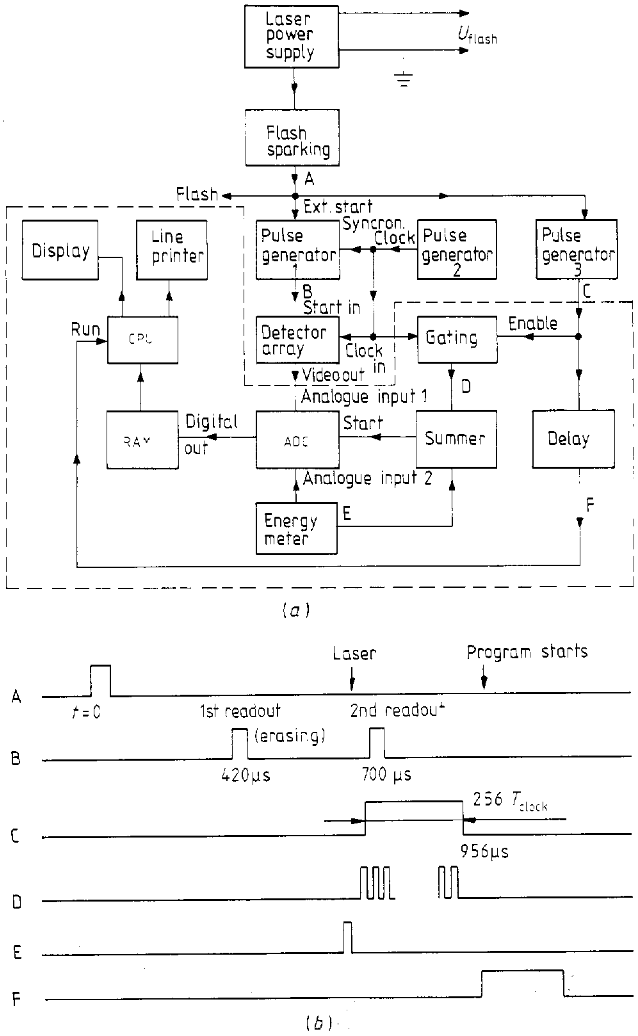


Figure 4. (*a*) Block diagram of the instrument. (*b*) Timing diagram for the apparatus.

The laser pulse arrives 5–10 μs after the end of the erase. At this moment the energy meter (NGL 200, made in the Central Research Institute of Physics, Hungary) starts the conversion of

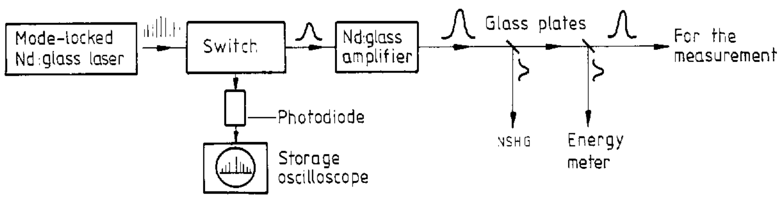


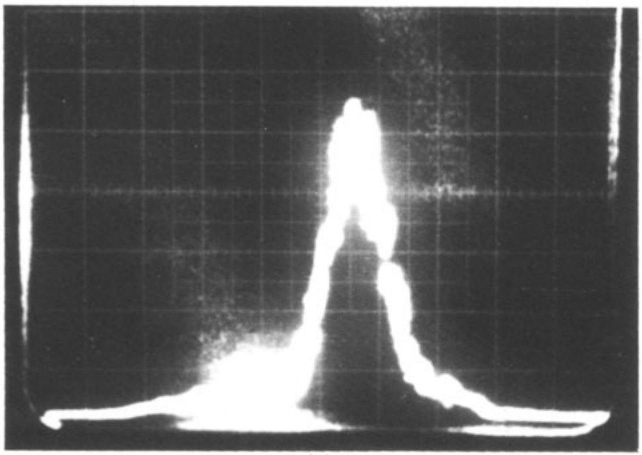
Figure 3. Schematic diagram of the system for generation of ultra-short light pulses.

its own data through the summing circuit. A few microseconds later the electrical pulses (B, C) induce the readout and conversion of the detector array's data. The two analogue inputs are summed in the ADC. The laser pulse appears from 685 to 695 μs after the sparking of the flash. Thus the time interval of about 20 μs has safely been chosen between the first erasing and second readouts. The 5 μs just before the second readout of the array is utilised to digitise the result of the energy measurement. A preliminary study has shown that the dark current and the background do not give rise to any considerable error. The delayed pulse of the third pulse generator initiates the program, which computes the duration (FWHM) and the peak power of the laser pulse (supposing gaussian pulse shape), prints these values together with the energy of the pulse, and displays the autocorrelation function. After carrying out these tasks, the program sets the address register to zero and the instrument awaits the next shot, which occurs every 20 s.

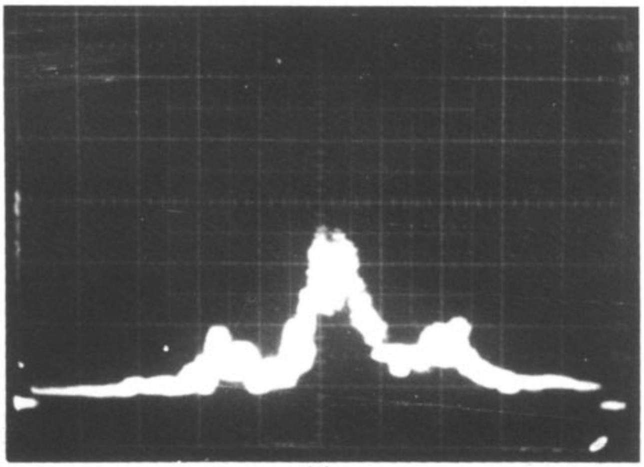
For only the analogue visualisation of the autocorrelation function of the pulse can a storage oscilloscope be simply used in place of the microprocessor and the enjoining blocks (the part of the arrangement enclosed by broken line in figure 4(*a*)). The electrical pulse (C) triggers the oscilloscope and the video output of the detector array is the input signal for the oscilloscope.

4. Experimental results

First, the time behaviour of the pulses has been investigated by the oscilloscope-based instrument. Oscilloscope photographs of two autocorrelation functions are shown in figure 5. The pulse in 5(*a*), which has been switched out from the first part of the train, is regular, nearly bandwidth limited, while the pulse in 5(*b*), switched out from the second part of the train, is strongly split. The autocorrelation function and the printed parameters of a pulse, which have been measured and computed by the microprocessor-based system, are given in figure 6. The data of the detector cells are pair-wise averaged and thus temporal resolution of about 0.4 ps is achieved. 20–40 μJ of pulse energy is sufficient for the NSHG, i.e. the sensitivity of the instrument enables us to measure the characteristics of pulses whose energy is less than 1 mJ. In this case the signal-to-noise ratio is about 10:1. Pulses of energy of about 10 mJ result in saturation of the detector cells.



(*a*)



(*b*)

Figure 5. Autocorrelation functions of pulses switched out from the first and second part of the train (3.5 ps div^{-1}).

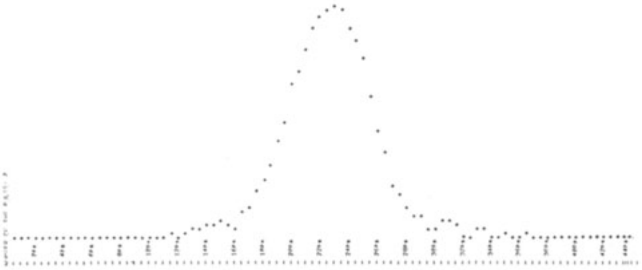


Figure 6. The autocorrelation function of a picosecond pulse which has been switched out from the middle part of the train and it is measured by the microprocessor-based data acquisition system. Energy = 8.3 mJ, FWHM = 5.8 ps, peak power = 1.3 GW.

5. Summary

In conclusion it has been shown that a versatile apparatus can be built for the measurement of the autocorrelation function of picosecond pulses employing low-cost devices available in most laboratories.

This autocorrelation measuring set up is especially helpful in experiments in which the intensity dependence of various nonlinear processes is investigated. In many time-resolved measurements of relaxations – for instance in the measurement of excitation lifetimes – only the convolution of the time history of the investigated process and the pulse shape can be measured. Thus, whenever the relaxation takes place in the picosecond time domain comparable with the duration of the picosecond pulse used for the investigation, knowledge of the accurate pulse shape, i.e. the autocorrelation function, is required to determine the lifetime of the excitation.

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Four-channel TEA nitrogen laser for interferometric measurements on the plasma focus

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Abstract. A four-channel TEA nitrogen laser for interferrometric measurements on the plasma focus has been realised. Four high-power pulses having a delay of about 20 ns with respect to each other and a jitter smaller than 2.5 ns are generated. At a charging voltage of 16 kV the characteristics of each emitted pulse are 780 μJ with 1% output reproducibility and $\leqslant 2.5$ ns pulse duration. The electrical conversion efficiency is found to be ~ 0.072.

1. Introduction

Laser interferometry is the main non-disturbing optical method of estimating the charged particle density in plasmas. Particularly in plasma focus investigations, using an appropriate light source of nanosecond duration, interferometric measurements can provide valuable information on the concentration and time–space evolution of the electronic density.

Due to the nanosecond time scale of the dynamic processes in the plasma focus, in the single-frame as well as in multi-frame interferometric technique, the nitrogen laser remains the best light source from the point of view of the pulse duration, intensity and wavelength. Thus, using a nitrogen laser, one can probe the electronic density in the plasma up to the critical value of about $n_e \simeq 10^{28}$ m^{-3} ($n_e = 1.115 \times 10^5/\lambda^2$ m^{-3}, where $\lambda = 337.1$ nm).

Some results concerning space evolution of the electronic density in the plasma focus, generated in a 20 kJ (20 kV) device, obtained with a single-frame interferometer system and using an improved numerical method for interferogram processing and computation of the electronic density have been reported in a previous paper (Baltog *et al* 1985). To investigate both the space and the time evolution of the electronic density in the plasma focus several subsequent interferograms are needed for a single plasma focus discharge. Therefore, the multi-frame interferometric technique requires a train of high quality light pulses of equal intensity, delayed in time in a controlled relation to each other and precisely synchronised with some events from the plasma focus device.

Such a train of light pulses could be obtained either by dividing the light pulse from a single laser by means of optical delay lines or using a corresponding number of coupled lasers.

Although the first method ensures the generation of a train of closely-spaced laser pulses with no time jitter, in the case of multi-frame interferometric measurements on the plasma focus it presents some disadvantages. So, the several hundred nanosecond duration of the plasma focus discharge requires for such investigations a train of pulses which is spread over a time interval that is too long to be easily obtained from a single laser plus optical delay lines. Such a system is usually bulky as it