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MEASUREMENT OF MODE-LOCKED ULTRASHORT LASER PULSES BY DIFFERENT ORDER PHOTOELECTRIC EFFECTS

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ABSTRACT

A simple experimental method consisting of simultaneous oscilloscopic observation of current signals induced by linear and nonlinear photoelectric effects is given for the determination of the duration and intensity of ultrashort pulses.

РЕЗЮМЕ

Описывается простой метод экспериментального определения длительности и интенсивности ультракоротких лазерных импульсов. Метод основан на одновременном осциллоскопическом наблюдении сигналов, исходящих от нелинейных фотоэмиссионных процессов различных порядков, вызванных лазерными импульсами.

KIVONAT

Ultrarövid laserimpulzusok időtartamának és intenzitásának meghatározására szolgáló, egyszerü kisérleti módszert ismertetünk. A módszer lényegét különböző, lineáris illetve nemlineáris fotoeffektusból származó elektromos impulzusok megfigyelése képezi.

INTRODUCTION

The widespread application of mode-locked lasers in quantum electronic research requires the measurement of the time duration and intensity of the pulses in the train. The duration of these pulses varies between the natural bandwidth limited 10^{-13}-10^{-12} sec [1,2] and 10^{-9} sec corresponding to an artificially narrowed spectral width |3| . The time duration can be measured by

1./ direct electronic methods /photocell [3,4] and streak camera [2,5]/ or by

2./ indirect nonlinear methods /two-photon fluorescence [6], harmonic generation [7,8], auto Kerr effect [9]/.

With the help of the direct electronic methods ~70 psec resolution was achieved by using photocells and about 5 psec resolution by streak cameras. The latter is nearly sufficient for the observation of pulses in the picosecond range, but the camera is rather complicated and expensive. The photocell is very convenient but can be used only above 100 psec pulse duration. Two-photon fluorescence /TPF/ is the most general indirect method but it gives only an average value for the whole train without any information about the duration of the individual pulses, which varies from pulse to pulse. Other nonlinear methods [7, 8, 9] combine effects of different order nonlinearity to avoid the inadequacy of the TPF method.

The method described here is a technically very simple indirect nonlinear method in which the problem is solved by the simultaneous oscilloscopic registration of current signals induced by linear and nonlinear photoelectric effects which are detected using a linear and a nonlinear photocell and two oscilloscopes /or, if necessary, only one/.

PRINCIPLE OF THE MEASUREMENT

It is well known that in the case of an n^{th} order photoelectric effect the dependence of the photocurrent j on the light intensity I is

$$j \sim I^n$$

In log-log coordinates this expression gives a straight line with a slope $n = \left[\frac{\text{work function}}{\text{photon energy}} + 1\right]_{int}$, as confirmed by experiments [10, 11].

It was noted in our paper on the nonlinear photoelectric effect /NLP/ experiment, however, that a marked asymmetry was observed in the ascendent and descendent halves of the laser pulse train: linear signals V_L of the same magnitude but from different halves of the train corresponded to nonlinear signals V_{NL} of very different magnitudes /see Fig. 1/. This anomaly was explained by the lengthening of successive pulses of the train, which is indicated by both theory and experiment [7, 11, 12].

The experimental arrangement shown in Fig. 2. is similar to that used for the NLP and field emission measurements [11, 12]. The time integrals of signals V_L and V_{NL} registered on oscilloscopes+ O_1 and O_2 are proportional to the numbers of electrons N and M emerging from the linear and nonlinear photodetectors, respectively; these numbers are at the same time proportional to the first and the n^{th} power of the intensity $I(t)$. The numbers of electrons induced by the i^{th} pulse of the mode-locked laser train are:

$$N_i = \frac{a}{R_1} \int_{-\infty}^{\infty} V_{iL}(t)dt = \alpha \int_{-\infty}^{\infty} I_i(t)dt \qquad /1/$$

$$M_i = \frac{a}{R_2} \int_{-\infty}^{\infty} V_{iNL}(t)dt = \beta_n \int_{-\infty}^{\infty} I_i^n(t)dt \qquad /2/$$

where α and β_n are the yield constants of the linear and nonlinear photoelectric effect, $a^{-1} = (1{,}6\cdot 10^{-19})$ [coulomb], R_1 and R_2 are the photocell resistances. The real intervals for integration do not reach the neighbouring pulses and, in general, the whole calculation is valid only for pure mode-locked pulses without any satellites.

Assuming that the time dependences of $I(t)$ and $V(t)$ are of the form $\exp\left[-(t/\tau)^2\right]$ and $\exp\left[-\frac{t}{T}\right]$ respectively:

$$N_i = \frac{a}{R_1} V_{iL}(o)\, T_{O_1} = \sqrt{\pi}\cdot \alpha\, I_i(o)\, \tau_i \qquad /3/$$

$$M_i = \frac{a}{R_2} V_{iNL}(o)\, T_{O_2} = \sqrt{\pi}\cdot \beta_n\, I_i^n(o)\, \frac{\tau_i}{\sqrt{n}} \qquad /4/$$

+ V_L and V_{NL} can be observed on the same oscilloscope by delaying one of the signals with respect to the other by a portion of the pulse separation 2L/c in the mode-locking train.

where T_{O_1} and T_{O_2} are the oscilloscopic resolutions and τ_i is the half width of the i^{th} light pulse.

From the two equations

$$\tau_i = \frac{1}{\sqrt{\pi}} \left[\frac{N_i^n}{M_i} \frac{1}{\sqrt{n}} \frac{\beta_n}{\alpha^n} \right]^{\frac{1}{n-1}} \qquad /5a/$$

$$I_i = \left[\frac{M_i}{N_i} \sqrt{n} \frac{\alpha}{\beta_n} \right]^{\frac{1}{n-1}} \qquad /5b/$$

while the relative values are

$$\frac{I_j}{I_i} = \left[\frac{M_j \; N_i}{M_i \; N_j} \right]^{\frac{1}{n-1}} = \left[\frac{V_{jNL}(o) \; V_{iL}(o)}{V_{iNL}(o) \; V_{jL}(o)} \right]^{\frac{1}{n-1}} \qquad /6a/$$

$$\frac{\tau_j}{\tau_i} = \left[\frac{N_j^n \; M_i}{M_j \; N_i^n} \right]^{\frac{1}{n-1}} = \left[\frac{(V_{jL})^n \; V_{iNL}}{V_{jNL}(o) \left(V_{iL}(o)\right)^n} \right]^{\frac{1}{n-1}} \qquad /6b/$$

Thus, by measuring M_i and N_i, α and β_n being known [10, 11, 12], the absolute values of τ_i and I_i can be obtained from equ. 5, or alternatively, without knowing α and β_n relative values for I_j/I_i and τ_j/τ_i can be simply calculated from equ. /6/.

From the ratio $\Theta_i = \tau_{i+1}/\tau_i$ and the difference $\Delta\tau_i = \tau_{i+1} - \tau_i$ the pulse duration is

$$\tau_i = \frac{\Delta \tau_i}{\Theta_i - 1} \qquad /7/$$

The value of the pulse lengthening $\Delta\tau_i$ can be easily estimated with the help of the following simplified model. Let us assume that one ultrashort pulse is of the minimum duration τ_o permitted by the bandwidth $\Delta\Omega$ of a mode--locked Nd glass laser. Taking into account that for two frequencies separated by $\Delta\Omega$ the transit times on a distance X in a refractive medium are different, the lengthening of the pulse will be

$$\Delta\tau = \frac{x}{c} \left[\frac{\partial\eta}{\partial\Omega} \Delta\Omega + \frac{1}{2} \frac{\partial^2\eta}{\partial\Omega^2} (\Delta\Omega)^2 \right] = \frac{x\Delta\Omega}{c} \left[\frac{\partial\eta}{\partial\Omega} + \frac{\Delta\Omega}{2} \frac{\partial^2\eta}{\partial\Omega^2} \right] \qquad /8/$$

where η is the index of refraction and c is the velocity of light in vacuum. For pulses of the same bandwidth the dispersion lengthening will be the same, regardless of their original time durations. (If the lifetime of the dye is comparable to or shorter than the pulse duration, the dispersion lengthening will be limited by the dye, as was shown recently by the experiments of Babenko et al. [13].)

From /7/ and /8/ we can get

$$\tau_i = \frac{x\Delta\Omega}{c} \frac{1}{\Theta_i - 1} \left[\frac{\partial\eta}{\partial\Omega} + \frac{\partial^2\eta}{\partial\Omega^2} \frac{\Delta\Omega}{2} \right] \qquad /9/$$

The intensity dependence of the refractive index $\eta = \eta_o + \eta_2 E^2$ may also cause modifications in the shape of the pulse, though these are negligible compared with the dispersion lengthening at the power values used. It should be noted, however, that the $\eta(E^2)$ dependence may alter the time substructure of a given single picosecond pulse by self-phase modulation [1, 14, 15, 16]. Furthermore, the second term in η could modify the diameter of the beam [15] /which was assumed to be constant/, the power density being above the self-focusing threshold [17]. Considering, however, that in our laser TEM_{OO} mode distribution was achieved and filaments were never observed, we may safely assume that the change of the beam cross section is small, all the more because the variation of the beam diameter would be of opposite sign in the ascendant and descendant halves of the mode-locking train, whereas the experiment shows a continuous increase in duration from pulse to pulse /Fig.4/.

RESULT

From our former measurements [11, 12] with a Nd glass laser and Au target, where the order of the NLP was n=4 , for β_4 we obtained the value $\sim 4\cdot 10^{-97}$ [electron/cm2] / [(photon/cm2 sec)^4 sec] while the efficiency α /including the transmission of the filters/ was about 10^{-8} electron/photon Typical values for N and M were $\sim 10^{10}$ and $4\cdot 10^{8}$ electrons, respectively. Thus using /5a/

$$\tau \sim 8\cdot 10^{-12} \text{ sec}$$

It should be emphasized that β_4 was determined by TPF method, so that our τ determination is an indirect, calibrated time duration measurement only.

In Fig. 1 the $V_L - V_{NL}$ pulse pairs of a mode-locking train are plotted in log-log coordinates. Note that at the beginning and end of the train the different V_{NL} signals correspond to V_L signals of the same magnitude. The asymmetry is due to the fact that the envelope of the V_L monitor signal train differs from the calculated /equ. /6a/ / real intensity envelope. An average of normalized monitor trains and the corresponding calculated intensity variation can be seen in Fig. 3.

Fig. 4 shows the relative changes of pulse duration calculated from linear-quadratic /Cs_3Sb cathode, $n = 2$ / and linear-fourth order /Au-cathode, $n=4$ / photoelectric effect measurements. The greater errors of the second order measurements are due to the non - TEM_{oo} mode of operation and poorer reproducibility. From Fig. 4 :

$$\Theta_1 = \frac{\tau_2}{\tau_1} \approx 1,1 \quad .$$

In our experiment $x \sim 2(\ell+d) \sim 50cm$, where ℓ and d are the lengths of the rod and the dye cell, respectively, $\Delta\Omega \sim 2\cdot 10^{13}$Hz and $\left[\frac{\partial\eta}{\partial\Omega} + \frac{\partial^2\eta}{\partial\Omega}\frac{\Delta\Omega}{2}\right] \sim 10^{-17}$sec [12, 18], so for τ with the use of /9/ we obtain

$$\tau_1 = [3 \div 4] \cdot 10^{-12} \text{ sec}$$

while

$$\tau_{10} = [6 \div 8] \cdot 10^{-12} \text{ sec}$$

This value is in agreement with the value of ~ 8 psec obtained from /5a/ and with the $[5\div 10]\cdot 10^{-12}$ sec duration obtained with TPF method [11,12]. This agreement shows that our assumptions are valid.

The absolute intensity from /5b/ is

$$I \sim 10^{29} \frac{\text{photon}}{\text{cm}^2 \text{ sec}} \sim 20 \text{ GW/cm}^2$$

CONCLUSION

The described method anables us

a./ to determine the variation of the real peak intensity and pulse duration in a mode-locked train*

b./ to estimate the absolute peak intensity and pulse duration from the linear and nonliear photoelectric signals/ α and β_n being known/

c./ to calculate the pulse duration/without α and β_n / from the bandwidth, dispersion and relative lengthening.

As the value of τ may change in a wide range for different trains, $\Theta = \tau_{i+1}/\tau_i$

varies from 1,03 to 1,30 explaining the observed change in the degree of asymmetry /see Fig. 2/. For a relatively greater initial pulse duration $\tau \sim 10^{-11}$ sec the asymmetry vanishes, or at least becomes less than the experimental error.**

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* Recently the variation of pulsewidth in a mode-locking train was also observed by direct electronic method [ФЭР] , and gave similar results [19].

** In our experiments on the NLP [10, 11, 12] only these measurements of small asymmetry were taken into account, and the pulse - lengthening problem was avoided by automatic selection of trains containing $\tau \sim 10^{-11}$ sec pulses only.

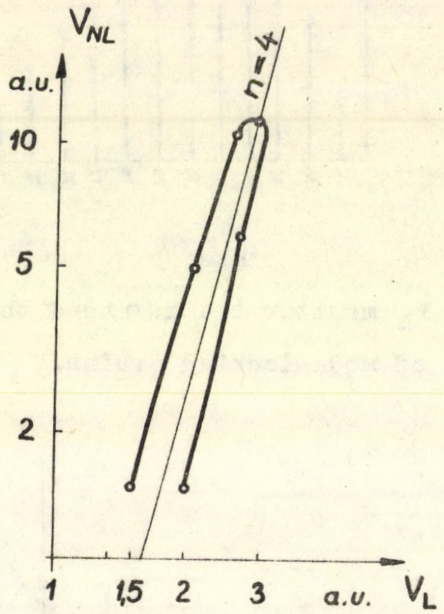

Fig. 1

The asymmetry in the variation of the V_{NL} nonlinear signal as a function of the signal V_L.

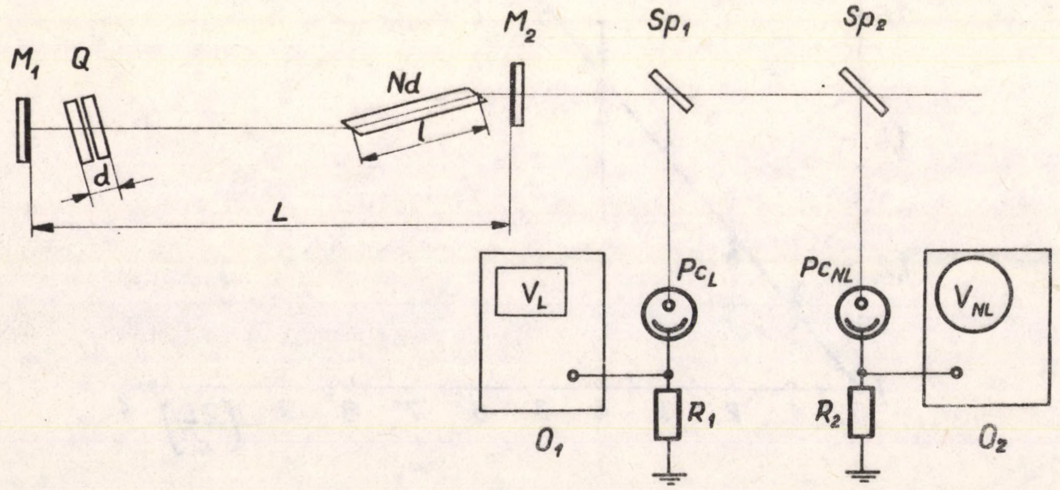

Fig. 2

The experimental arrangement: M_1 and M_2 mirrors; Q-bleachable dye /N° 3955/; Nd-Brewster-ended Nd glass; Sp_1, Sp_2 -splitters; Pc_L and Pc_{NL} -linear and nonlinear photocells; R_1, R_2-resistances; O_1 and O_2 -oscilloscopes with V_L, V_{NL} signals, respectively.

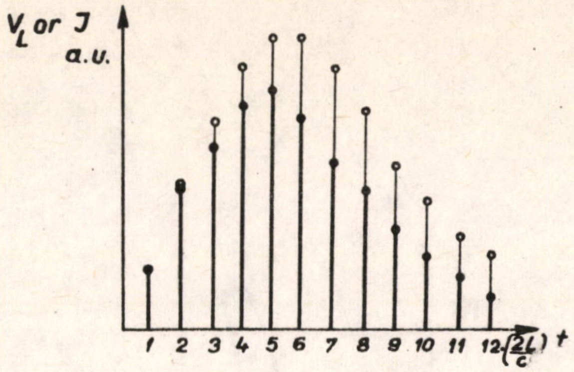

Fig. 3

Variation of the V_L monitor train:(o) and the calculated real intensity I:(•) of mode-locking trains.

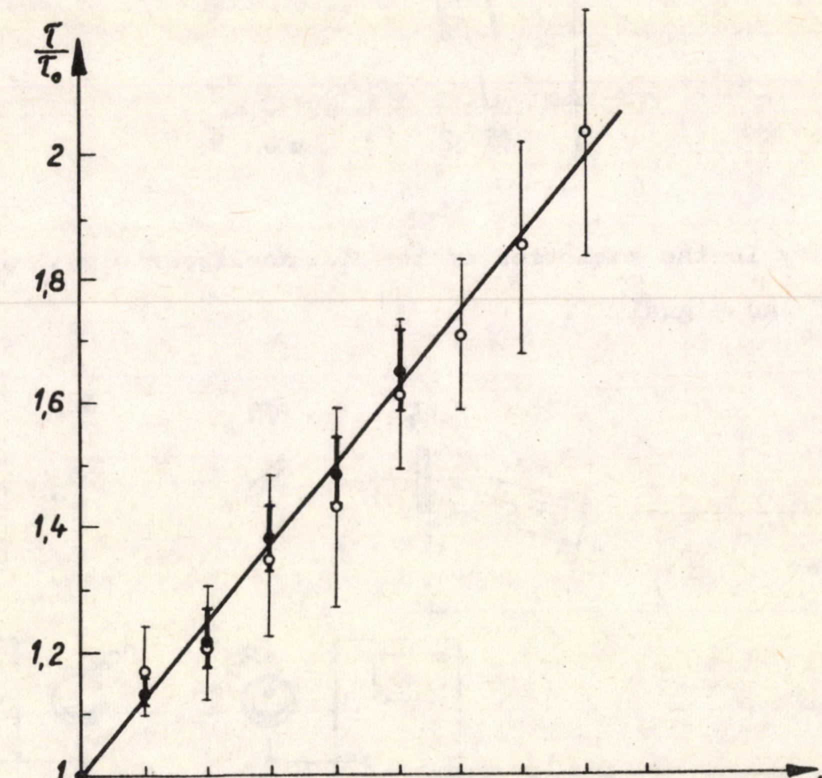

Fig. 4

The change of relative pulse duration from pulse to pulse in the linear-quadratic:(o) and the linear-fourth order:(•) photoelectric effect.

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