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Synchronisation of a femtosecond laser and a *Q*-switched laser to within 50 ps

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***Abstract*. A Nd : YLF laser emitting 2-ns pulses synchronised with a femtosecond Cr : forsterite laser is built. The pulse duration and synchronisation are ensured by two Pockels cells, in which voltage pulses are synchronised with the femtosecond laser by fast emitter-coupled logic elements. One of the Pockels cells ensures *Q*-switching, while the other cuts a short pulse from a 15-ns *Q*-switched pulse. The experimental results show that the two-step scheme proposed for synchronisation of a *Q*-switched laser and a passively mode-locked laser provides quite simple and reliable synchronisation of these lasers with a jitter of a few tens of picoseconds.**

Keywords: *synchronisation of lasers, jitter, Pockels cell, pulse shaping.*

1. Introduction

Precise synchronisation of pulses from two independent lasers is required in some applications, e.g., in a parametric amplifier of chirped pulses [1 – 5]. The necessary condition for an efficient parametric interaction is that the error in the overlap of a pump pulse and a pulse being amplified in a nonlinear crystal does not exceed 10 % of duration of the pulses. The pulse being amplified is a stretched pulse from a femtosecond laser with a characteristic duration of 1 ns. Thus, the time jitter of two lasers (a random uncontrollable displacement of the pulse of one laser relative to that of the other laser) should not exceed 100 ps.

The synchronisation of two lasers operating in the mode locking regime does not involve considerable difficulties at present (see, for example, Ref. [6] and references therein). However, to pump parametric amplifiers of chirped pulses, the duration of the pump pulse should be 1.5 – 2 times longer than that of a pulse being amplified [3], i.e., the pump pulse duration should be a few nanoseconds. In addition, the oscillator generating such pulses should operate in a pulsed (*Q*-switched) rather than in a continuous-wave regime because the low pulse energy in the latter case makes it quite difficult to realise high-power pumping. It is extremely difficult to achieve a stable active mode locking for *Q*-switched nanosecond pulses because the number of modes participating in lasing is small (less than 10).

At the same time, high-power pulses of such a duration can easily be formed in the *Q*-switched regime with longitudinal mode selection [7, 8]. Such pulses can be formed either directly in a very short cavity, or with the help of electro-optical gates cutting a short pulse from a *Q*-switched pulse of duration 10 – 30 ns. Thus, the problem of synchronisation (with a jitter less than 100 ps) of a mode-locked laser with a *Q*-switched laser is quite important. The main problem is that it is difficult to make the jitter between a *Q*-switching electric pulse and a *Q*-switched light pulse much smaller than the round-trip transit time in the cavity.

In this paper, we propose and implement experimentally the method for synchronising a *Q*-switched laser and a passively mode-locked femtosecond laser within 50 ps.

2. Principle of synchronising two lasers

Consider first in detail all the reasons for the emergence of a jitter upon synchronising a passive mode-locked laser and a *Q*-switched laser (Fig. 1). A fast photodiode can be used to form a sequence of electric pulses with a duration of fractions of a nanosecond and with a jitter J_0 much smaller than 100 ps from a sequence of mode-locked laser pulses. We shall disregard this jitter in the following analysis. It is necessary to form from the sequence of electric pulses, a single pulse with an amplitude and duration providing the control of the Pockels cell in the cavity to produce *Q*-switching. Generally speaking, a considerable jitter, which will be denoted by J_1, may appear in the course of

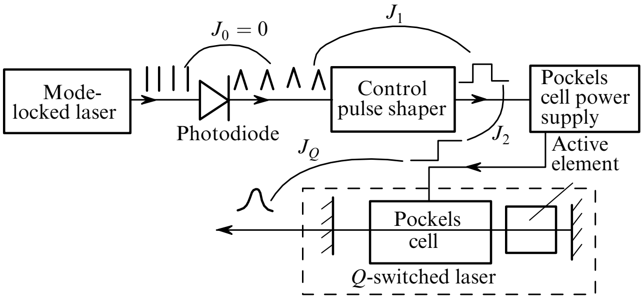

Figure 1. General scheme for synchronising a *Q*-switched laser and a mode-locked laser.

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formation of such a single pulse. This is the first reason for a poor synchronisation of the lasers.

The single pulse separated this way controls the Pockels cell. It is fed to the power supply of the cell, which in turn imparts a high voltage drop to an electro-optical crystal. The jitter between the controlling pulse and the high-voltage pulse is the second reason for a poor synchronisation of lasers; we denote this jitter as J_2. Owing to the low inertia of the Pockels effect, the jitter between the high-voltage pulse and the instant of optical loss switching in the cavity can be neglected. The total jitter $J_1 + J_2$ introduced by the controlling pulse shaper and the power supply of the Pockels cell can be reduced to 100 ps using modern radioelectronics methods (see Section 3).

The most serious difficulty is associated with the third reason for poor synchronisation of lasers, namely, the jitter between the instant of Q-switching of the cavity and the laser pulse; we denote this jitter as J_Q. If the generation threshold is not exceeded at the instant of Q-switching, lasing starts from spontaneous noise. This leads to a jitter, which cannot be eliminated in principle and which is several times larger than the round-trip transit time in the cavity. If the generation threshold is exceeded prior to Q-switching and free running pulse occurs in the cavity at the instant of Q-switching, then the jitter J_Q will be an order of magnitude smaller than the cavity round trip time. Thus, to ensure a jitter of 100 ps, the optical length of the round trip in the cavity must be of the order of 10 cm; i.e., the distance between the mirrors should not exceed 3 – 4 cm. It is difficult to design such a laser and even impossible in principle upon flashlamp pump.

The method for synchronisation of lasers we propose is based on a two-step scheme of formation of a short laser pulse. The cavity round-trip transit time in a Q-switched laser is chosen equal to 3 – 4 ns, which ensures the generation of a 10 – 15-ns Q-switched pulse with a jitter $J_Q \sim 1$ ns. A pulse of the required duration (1 – 3 ns) is then separated by an external Pockels cell. This cell is controlled by the same pulse as the intracavity Pockels cell, but this pulse is delayed by the required time. It will be shown below that the jitter of the separated laser pulse relative to the controlling pulse can be made much smaller than J_Q.

In our opinion, the most efficient method of separating a short pulse is to use an external Pockels cell controlled by a half-wave voltage in the quarter-wave geometry (Fig. 2). Before arrival of the controlling pulse, the voltage across the crystal is equal to zero. The crystal is an isotropic medium with zero transmittance T from the input to the output. After the stabilisation of the half-wave voltage, the crystal becomes a $\lambda/2$ plate and, hence, its transmittance T is also equal to zero. During the period when the voltage drops from zero to the half-wave voltage, the transmittance first increases to unity (at the instant when the voltage is equal to the quarter-wave voltage) and then decreases to zero again. This makes it possible to form an optical pulse with the FWHM duration approximately equal to $0.5\tau_\text{v}$ using a single voltage drop of duration τ_v.

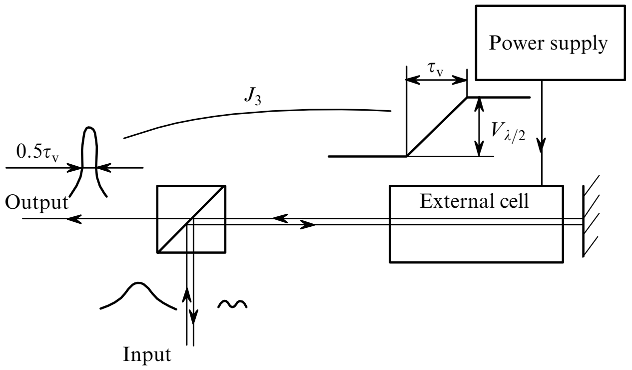

Figure 2. Scheme for separating a short pulse with the help of an external Pockels cell.

Let us estimate the effect of the Q-switched pulse jitter J_Q on the jitter J_3 of the separated pulse relative to the high voltage drop across the external Pockels cell. Let us suppose that the voltage drops from zero to the half-wave voltage during the time from $-\tau_\text{v}/2$ to $+\tau_\text{v}/2$, and the Q-switched pulse of duration τ_0 has the Gaussian shape, the maximum peak being displaced from instant $t = 0$ by J_Q. Then the intensity of the separated pulse is determined by the formula

$$I_\text{out} = I_\text{input} T$$

$$= \begin{cases} I_0 \exp\left[-\dfrac{(t - J_Q)^2}{\tau_0^2}\right] \cos^2\left(\dfrac{\pi t}{\tau_\text{v}}\right), & |t| < \dfrac{\tau_\text{v}}{2}, \\ 0, & |t| \geqslant \dfrac{\tau_\text{v}}{2}. \end{cases}$$

Because $J_Q \neq 0$, the time instant t^* at which the separated (output) pulse $I_\text{out}(t)$ has a maximum also differs from zero. We assume that the jitter of the separated pulse is $J_3 = |t^*|$. Differentiating I_out with respect to time and equating the derivative to zero, we obtain the following equation for J_3:

$$\tan\frac{\pi J_3}{\tau_\text{v}} = (J_Q - J_3)\frac{\tau_\text{v}}{\pi^2\tau_0^2}.$$

Considering that $J_3 \ll \tau_\text{v}/\pi \ll \tau_0$, we obtain

$$J_3 = \frac{\tau_\text{v}^2}{\pi^2\tau_0^2} J_Q. \tag{1}$$

One can see from this formula that $J_3 \ll J_Q$; i.e., the jitter J_3 between the output laser pulse and the voltage drop across the external Pockels cell is considerably smaller than the jitter J_Q between the Q-switched pulse and the voltage drop across the intracavity Pockels cell. Since $J_Q \approx 1$ ns and $\tau_\text{v} \ll \pi\tau_0$, the necessary condition $J_3 \leqslant 100$ ps is satisfied.

Thus, the total jitter J between the lasers in the proposed scheme of synchronisation of pulses from two lasers can be estimated from the expression

$$J = J_1 + J_2 + J_3$$

and can be easily made smaller than 100 ps, as was done in our experiment.

3. Experimental results

The general scheme of the experiment is shown in Fig. 3. The time diagrams of optical and electrical pulses and their jitters relative to the pulses from a cw mode-locked laser are shown in Fig. 4.

The mode-locked laser was a cw Cr : forsterite laser (Avesta). Mode locking was carried out using a Kerr lense.

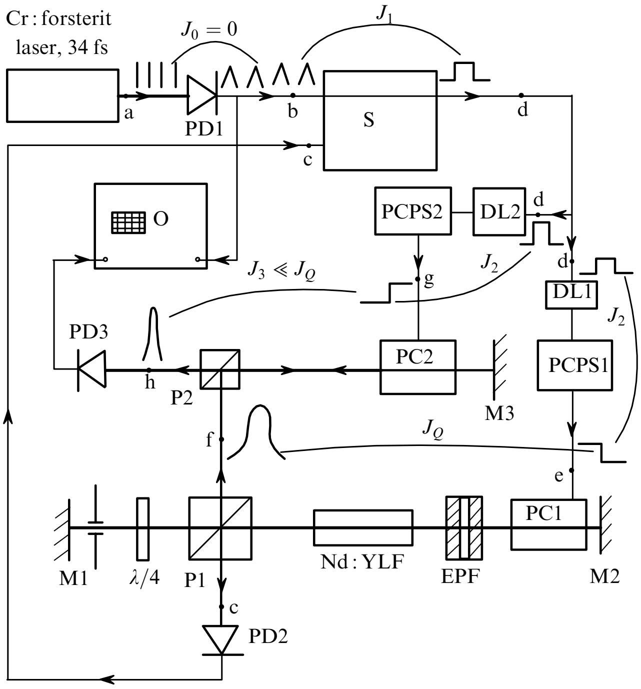

Figure 3. Scheme of the experiment (bold lines show the laser beam and fine lines show the electrical connections; letters a – h correspond to the time diagrams shown in Fig. 4: (PD) photodiode; (S) synchroniser; (PCPS) Pockels cell power supply; (PC) Pockels cell; (M) mirror; (P) polariser; (FPE) Fabry – Perrot etalon; (DL) delay line.

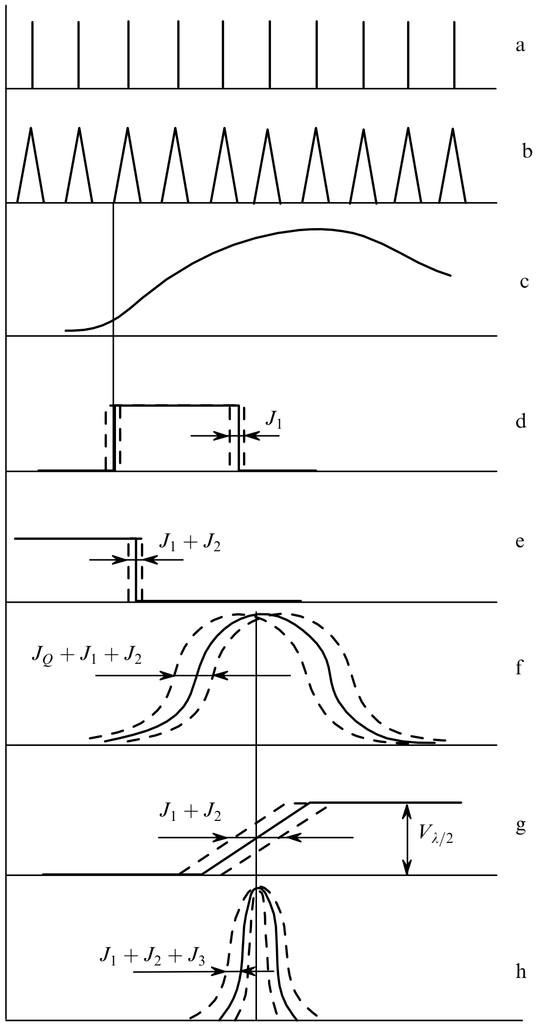

Figure 4. Time diagrams of pulses at points a – h in Fig. 3.

The laser was pumped by a 8-W Yb-doped cw fibre laser ('IRE-Polyus' Research and Production Association). The pulse duration was 34 fs, the spectral width of the pulse was 50 nm, the pulse repetition rate was 76 MHz, and the average power was 270 mW. An insignificant part of laser radiation (Fig. 4a) was directed to photodiode FD1, which formed a sequence of voltage pulses of duration 1 ns (Fig. 4b).

The Q-switched laser was a based Nd : YLF crystal of diameter 5 mm with an illuminated part of length 75 mm. The crystal was cut at an angle of 5° to the optical axis. This ensured efficient lasing at a wavelength of 1053 nm, the preferred enhancement of one polarisation [9], and a strong birefringence required for the suppression of thermally induced birefringence and the depolarisation caused by it [10]. Pumping was carried out by two lamps with an electric energy of 60 J for a pulse duration of 200 μs and a pulse repetition rate of 2 Hz. We used a linear cavity of length 0.5 m with reflectivity 99.6 % of mirrors M1 and M2. Polariser P1 and a $\lambda/4$ plate ensured the polarisation extraction of radiation. The transverse modes were selected by a diaphragm of diameter 1.7 mm.

A Fabry – Perrot etalon of thickness 15 mm with a reflectance of 70 % for each mirror was used for selecting longitudinal modes. The etalon was mounted at an angle to the cavity axis to exclude spurious lasing between mirror M1 and etalon mirrors. The appearance of a pulse with two longitudinal modes was detected by a special sensor (not shown in Fig. 3) analysing the presence of intermode beats in the giant pulse. The probability of the appearance of a two-mode pulse did not exceed 0.1 %.

The intracavity Pockels cell PC1 based on a DKDP crystal had a length of 20 mm. A constant voltage applied to the crystal (Fig. 4e) ensured a decrease in the Q-factor such that the lasing threshold was achieved at the instant of maximum inversion. As a result, a free-running laser pulse of duration 200 ns was emitted (Fig. 4c). This pulse was incident on the photodiode PD2, the signal from which was directed to the synchroniser S forming a control pulse (Fig. 4e). The control pulse was directed via delay lines DL1 and DL2 to trigger the Pockels cell power suppliers PCPS1 and PCPS2. The jitter introduced by the delay lines was negligibly small. The voltage applied to the intracavity Pockels cell PC1 was reduced to zero (Fig. 4e), which led to the generation of a Q-switched pulse (Fig. 4f) with the FWHM duration of 15 ns ($t_0 = 9$ ns) and an energy of 8 mJ. The Q-switched pulse jitter J_Q relative to the high voltage drop was less than 1 ns for an observation time of 15 min. Note that for such a Q-switching, the (longitudinal and transverse) mode selection occurs during the formation of a free-running laser pulse. This considerably improves the mode selection owing to a large number of round-trip transits in the cavity (see also Ref. [8]).

The main element of the entire system is the synchroniser. It generates the control pulse (Fig. 4d) synchronised with one of the pulses with a repetition rate of 76 MHz (Fig. 4b) when a pulse from the photodiode PD2 initiated by the free-running laser radiation is supplied to the second input (Fig. 4c). The main element of the synchroniser is a two-step D trigger employing fast emitter-coupled elements capable of operation at frequencies up to 450 MHz with a rapid (a few nanoseconds) time response. The jitter J_1 between the pulses shown in Figs 4b and 4d was mainly determined by the internal jitter of the emitter-coupled logic and did not exceed 30 ps. A detailed description of the circuit diagram and of the synchroniser operation is given in Ref. [11].

A 20-mm long DKDP crystal was also used in the external Pockels cell PC2 (see Fig. 3). This cell was mounted in the quarter-wave geometry described above and, hence, a half-wave voltage drop (Fig. 4g) of duration $\tau_v \approx 4$ ns ensured the FWHM duration of 2.3 ns of the separated pulse. The delay line DL1 was used to synchronise the instant of maximum transmission of the cell (corresponding to the quarter-wave voltage) with the Q-switched pulse maximum (see Figs 4f–h). The energy of the separated pulse was about 1 mJ.

Fig. 5 shows the oscillograms of a Q-switched pulse, a separated pulse, and an idler pulse (reflected towards the cavity by polariser P2). One can see from Fig. 5b that the external Pockels cell PC2 contains voltage over-oscillations that lead to the emergence of a second (satellite) peak in the intensity of the separated pulse. The amplitude of this satellite depends considerably on the duration τ_v of the high-voltage drop: the quicker the drop, the larger the amplitude of the satellite. However, an increase in τ_v leads to a proportional increase in the duration of the separated pulse. The delay of the high-voltage pulse by a certain time t_d relative to its optimal position also leads to a decrease in the satellite amplitude. Note that this does not increase the jitter J_3. It can easily be shown that expression (1) remains valid for all values of time t_d. It is also important to note that upon a subsequent amplification of the separated pulse in laser amplifiers operating in the saturation mode, the amplitude of the satellite will be amplified to a much smaller extent than the amplitude of the main pulse (Fig. 5d).

In our experiments, we measured the jitter between two lasers using an Infiniium digital oscilloscope (1.5 GHz) (Agilent Technology). Pulses from photodiodes PD1 and PD3 were fed to the two inputs of the oscilloscope. The oscilloscope automatically determined the time interval τ between the leading fronts of these pulses averaged over 1 min and the standard deviation, i.e., the total jitter J.

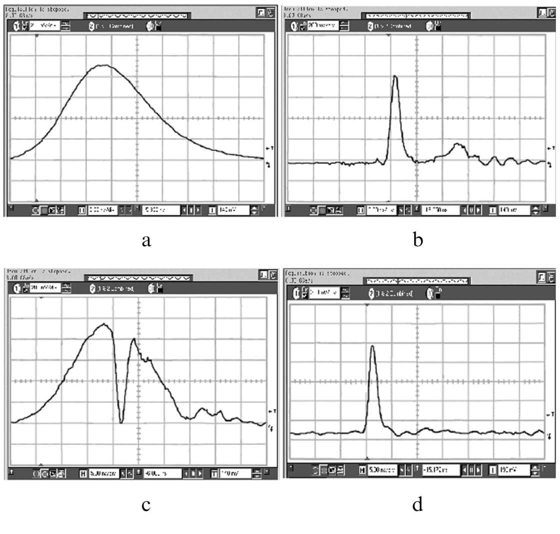

Figure 5. Oscillograms of a Q-switched pulse (a), a separated pulse (b), an idler pulse (reflected towards the cavity by polariser P2) (c), and a separated pulse after its amplification to 1.2 J in Nd : YLF amplifiers (d). Horizontal sweep is 5 ns/division.

Fig. 6 shows the time dependence of J from the instant of switching of the synchroniser. One can see that the average jitter between two lasers was about 50 ps. The time τ varied very slowly during continuous operation of both lasers: τ increased only by 50 ps over a period of 30 min. Such a slow pulse spread was easily compensated by using delay lines.

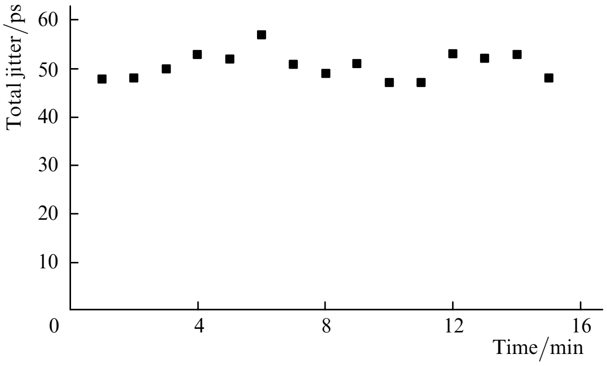

Figure 6. Time dependence of the total jitter J between two lasers.

4. Conclusions

The experimental results presented above show that the two-stage scheme proposed by us for synchronisation of a Q-switched laser with a passively mode-locked cw laser makes it possible to synchronise these lasers quite easily and reliably to within 50 ps. A further decrease in the jitter requires thermal stabilisation of the electronic circuits, a decrease in the spread of the parameters of the avalanche transistors used in the power supply of the external Pockels cell, and stabilisation of the Q-switched laser pumping (for example, by using diodes instead of flashlamps).

The synchronisation system was used for parametric amplification of chirped pulses from a Cr-forsterite laser. The Nd : YLF laser radiation was amplified in two stages to an energy of 2 J, converted into second harmonic, and used to pump the parametric amplifier. The results of these experiments are being prepared for publication.

References

1. Dubietis A., Jonusauskas G., Piskarskas A. *Opt. Commun.*, **88**, 437 (1992).
2. Ross I.N., Matousek P., Towrie M., Langley A.J., Collier J.L. *Opt. Commun.*, **144**, 125 (1997).
3. Matousek P., Rus B., Ross I.N. *IEEE J. Quantum Electron.*, **36**, 158 (2000).
4. Jovanovic I., Ebbers C.A., Stuart B.C., Hermann M.R., Morse E.C., in *Conference on Lasers and Electro-Optics (CLEO). OSA Trends in Optics and Photonics* (Washington, DC.: OSA, 2002) p. 387.
5. Freidman G., Andreev N., Ginzburg V., Katin E., Khazanov E., Lozhkarev V., Palashov O., Sergeev A., Yakovlev I., in *Conference on Lasers and Electro-Optics (CLEO). OSA Trends in Optics and Photonics* (Washington, DC.: OSA, 2002) p. CPDA9-1.

6. Zaporozhchenko A.V., Tylets N.A. *Kvantovaya Elektron.*, **23**, 527 (1996) [*Quantum Electron.*, **26**, 512 (1996)].
7. Koechner W. *Solid-State Laser Engineering* (Berlin, Geidelberg, New York, Barselona, Hong Kong, London, Milan, Paris, Singapore: Springer, 1999).
8. Andreev N., Khazanov E., Palashov O. *Proc. SPIE Int. Soc. Opt. Eng.*, **3267**, 264 (1998).
9. D'yakova A.F., Kornev A.F., Reiterov V.M., Soms L.N., Stupnikov V.K., Tkachuk A.M., Ushakova O.A. *Izv. Akad. Nauk SSSR. Ser. Fizich.*, **55**, 294 (1991).
10. Mezenov A.V., Soms L.N., Stepanov A.I. *Termooptika tverdotel'nykh lazerov* (Thermooptics of Solid-State Lasers) (Leningrad: Mashinostroenie, 1986).
11. Khazanov E., Anastasiev A., Katin E., Palashov O. *Proc. SPIE Int. Soc. Opt. Eng.*, **4629**, 144 (2002).