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Pulse synchronisation in passively *Q*-switched lasers emitting at 1.053 and 1.064 μm

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***Abstract*. Pulse synchronisation with an accuracy of no worse than ±5 ns is demonstrated in passively *Q*-switched neodymium phosphate glass and Nd : YAG lasers. Two operating regimes are realised: the 'sub-threshold' regime (when the slave Nd : YAG laser does not generate a giant pulse if its passive *Q* switch is not irradiated by the master Nd : glass laser) and the 'above-threshold' regime (when the pulse irradiating the passive *Q* switch of the slave laser advances its generation).**

Keywords: *solid-state lasers, passive Q-switching, laser radiation synchronisation.*

1. Introduction

Many laser pump – probe pulse experiments require the time synchronisation of radiation of at least two beams incident on a medium at different instants, which can also differ, depending on the type of measurements, either by the pulse wavelength or duration. In some experiments, a single laser can be used which emits the fundamental frequency beam and the second beam of radiation obtained by the nonlinear conversion of its fundamental radiation (generation of harmonics, stimulated Raman scattering [1] or parametric generation [2]). The radiations of both beams should often satisfy certain requirements to the mode composition and the minimal width of the spectrum. This is rather simply provided using passive *Q*-switching due to a long development of lasing [3].

However, the long lasing development time in passively *Q*-switched lasers, which considerably facilitates the achievement of the single-frequency regime, also has a disadvantage. Thus, upon pulse flashlamp pumping of the active medium of a laser, a considerable scatter in the time of appearance of a giant pulse with respect to the onset of a discharge through the flashlamp is observed, which in the case of cw diode pumping leads to changes in the repetition period of the giant pulse, thereby complicating considerably the synchronisation of radiation from passively *Q*-switched lasers.

The synchronisation of giant pulses in passively *Q*-switched lasers without using seed radiation was described in a number of old and recent papers [4 – 10]. While the authors of first papers [4 – 6], who studied, as a rule, ruby lasers, pursued the obvious goal of increasing the total emitted energy (power), the aim of the recent papers was to obtain simultaneous lasing at different wavelengths in neodymium-doped media: 1064 and 1342 nm in [8, 9] and 946 and 1064 nm in [10]. In this sense, the unique is paper [7] in which the synchronisation of pulses from ruby and neodymium lasers was demonstrated by using various modifications of phthalocyanine dyes. Note that [4 – 7] and recent [8 – 10] papers differ in the methods of synchronisation of giant laser pulses.

The first experiments were the logical continuation of the active *Q*-switching method in which the Kerr or Pockels *Q* switch was replaced by a passive *Q* switch, while the control electric signal was replaced by the laser pulse [4, 6, 7]. Correspondingly, an additional laser was used to control the bleaching of a saturable dye of passive *Q* switches of other lasers.

The pulse synchronisation principle used in paper [8] is substantially different. The authors employed a V : YAG passive *Q* switch, which had two inhomogeneously broadened absorption bands at 1064 and 1342 nm, and two independent diode-pumped active Nd : YVO_4 elements located in a compound resonator. However, synchronisation was lost even when the pump level of active elements was changed only by a few tens of milliwatts [8]. Later, the parameters of simultaneous lasing at these wavelengths were somewhat improved [10]. This was achieved, in particular, by using a passive Cr : YAG *Q* switch in addition to the V : YAG crystal. A similar method was used to synchronise radiation pulses at 946 and 1064 nm by employing a Cr, Nd : YAG crystal for passive *Q*-switching [9].

A scheme with two ruby lasers, one of which is completely independent (master) and is used to bleach a saturable filter of another (slave) laser, is described in [5]. It was pointed out, however that the synchronisation of radiation pulses from these lasers was not complete because pulses from the slave laser were delayed approximately by 50 ns with respect to pulses from the master laser. In this paper, we present the results of investigation of the scheme used in [5] applied to Nd : phosphate glass and Nd : YAG lasers.

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2. Experiment

We used in experiments a master Nd : GLS-23 glass laser (L1) and a slave Nd : YAG laser (L2) (Fig. 1). The first laser, with the active element of diameter 5 mm and length 100 mm, had a resonator of length 80 cm formed by a highly reflecting spherical mirror with the radius of curvature 3 m and an output longitudinal-mode selector [11] with the reflection coefficient ~ 45 % at the maximum. Passive Q-switching was performed by means of a Cr^{4+} : YAG crystal with the initial transmission $T_{01} = 75\,\%$. The active element of the second laser had a diameter of 6 mm and length of 80 mm. The plane-spherical resonator of this laser of length 45 cm was formed by a spherical mirror with the radius of curvature 2 m and an output longitudinal-mode selector, which was similar to that used in the Nd : glass laser. Passive Q-switching was performed with a Q switch based on the BDN (No. 1055) dye in a polymer matrix with the transmission $T_{02} = 18\,\%$, which was mounted directly in front of an aperture of diameter 1.5 mm. The radiation of both lasers had the transverse intensity distribution close to the TEM_{00} mode and the output energy of 6 – 8 mJ for the giant-pulse duration ~ 50 ns for L1 and 4 – 6 mJ for the giant-pulse duration ~ 8 ns for L2. The typical beam radius (at the e^{-2} intensity level) at the output of the Nd : glass laser was $w \approx 0.65$ mm. Taking a distance into account, this provided the maximum power density up to 3 MW cm^{-2} ($w \approx 1.7$ mm) on the passive Q switch of the Nd : YAG laser.

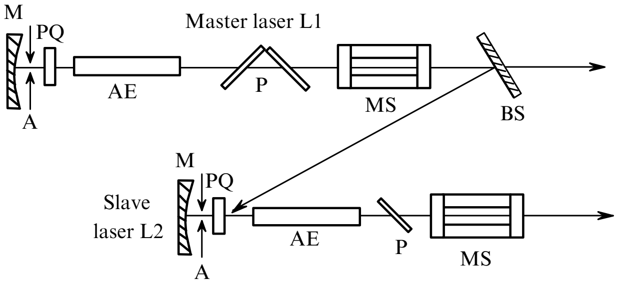

Figure 1. Scheme of laser pulse synchronisation experiments: (M) highly reflecting mirror; (A) aperture; (PQ) passive Q switch; (AE) active element; (P) polariser; (MS) longitudinal mode selector; (BS) beamsplitter.

Before proceeding to pulse synchronisation experiments, we measured for both lasers the delay time of the giant pulse maximum t_{g} with respect to the ignition pulse of the flashlamp as a function of the lasing threshold excess $E_{\mathrm{p}}/E_{\mathrm{th}\,i}$ ($i = 1, 2$) (up to the pump energy corresponding to the appearance of the second giant pulse) (Fig. 2). The measurements were performed by using LFD-2 photodiodes and a Tektronix TDS5104B oscilloscope, which averaged measurements and calculated the corresponding dispersion for a series of 50 – 100 pulses for each pump power. Our measurements showed that the scatter of t_{g} for L1 [curve (*1*)] near the lasing threshold was 2.6 %, decreasing down to 0.16 % when the lasing threshold was exceeded by 35 %. The corresponding values for L2 [curve (*2*)] were 1.8 % and 0.4 %. Thus, the minimal scatter in the appearance time of giant pulses for independently operating lasers in the range of the lasing threshold excess used in the experiments was ±1 μs in the better case. Note that in this pump range, both lasers emitted at a single longitudinal mode, the output energy stability being ±5 %.

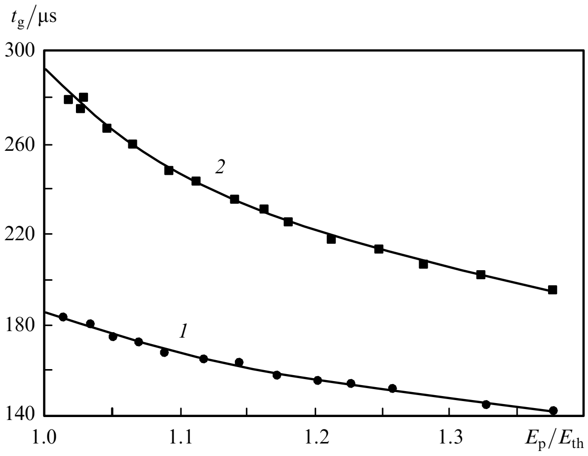

Figure 2. Dependences of the giant-pulse delay with respect to the flashlamp ignition pulse on the excess over the generation threshold for the neodymium glass laser (*1*) and the Nd : YAG laser (*2*).

The synchronisation of the master Nd : glass laser and the slave Nd : YAG laser with the Q switch bleached by radiation from the master laser could be achieved in two regimes.

In the first 'sub-threshold' regime, the pump level of the slave L2 was maintained below the giant-pulse generation threshold, while the excess over the generation threshold for L1 was maintained equal to 1.25. In this case, the delay of the flashlamp ignition for L2 with respect to the ignition of the flashlamp for L1 was varied in the range $T_{\mathrm{d}} = 75 - 325$ μs, and the delay of the second giant pulse (GP2) with respect to the first giant pulse (GP1), the GP2 amplitude and duration were measured. The measured delays t_{d} between the maxima of giant pulses of the two lasers, which were averaged, as above, over a few tens of pulses, are presented in Fig. 3a for three pump energies of L2. The minimal delay of GP2 for all the curved in Fig. 3a is $T_{\mathrm{d}} \approx 186$ μs, which, taking into account the instant of appearance of GP1 with respect to the flashlamp ignition ($t_{\mathrm{g}} \approx 150$ μs), corresponds approximately to the maximum of the inverse population of the active medium of L2. In this case, the scatter of t_{d} values was ±2 ns in the middle of the range of variations of T_{d} and increased up to ±7 ns at its boundaries. Variations in the amplitude and duration of GP2 corresponding to the pump level of L2 below the threshold by 1.6 %, normalised to their values during the operation of L2 in the independent regime, are presented in Fig. 3b, while typical oscillograms are shown in Fig. 3c. Note that approximately 10 % of pulses of the slave laser were emitted at several longitudinal modes. The dependences t/t_0 and U/U_0 corresponding to the pump levels of L2 below the threshold by 9.3 % and 16.4 % are not presented here; they also have the extremum at $T_{\mathrm{d}} \approx 185$ μs, which is, however, less pronounced.

In the second ('above-threshold' regime), the pump level of the slave L2 was maintained sufficient for generating a giant pulse. In this case, laser pulses could be synchronised only if during the operation of both lasers in the independent regime, GP1 was ahead of GP2 by the time $t_{\mathrm{d}0}$ exceeding 2 – 5 μs. The delay $t_{\mathrm{d}0}$ could be varied by changing the time

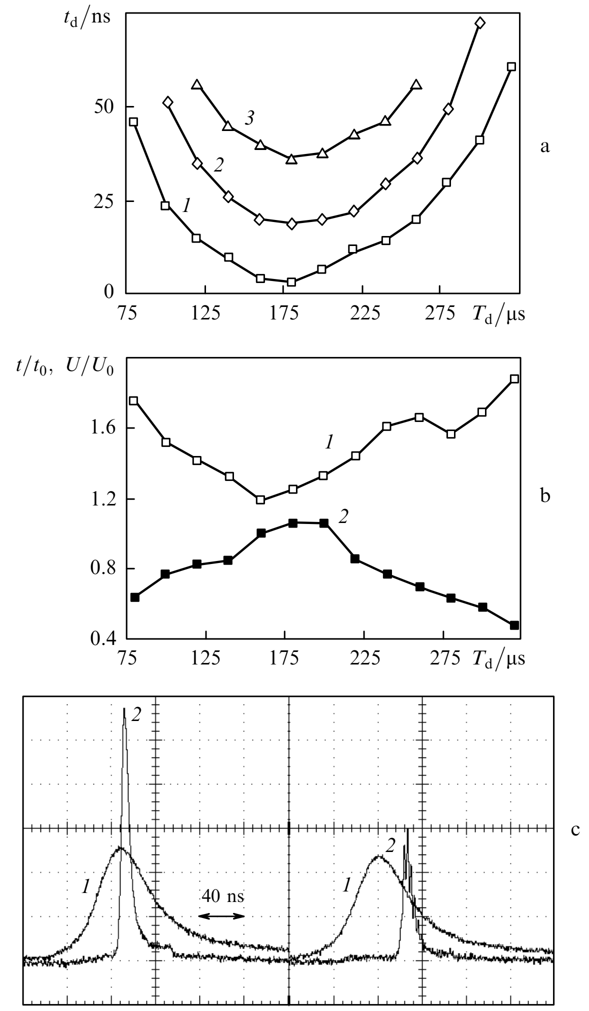

Figure 3. Delays of the giant pulse of the slave Nd : YAG laser with respect to the giant pulse of the master Nd : glass laser for different pump levels of L2: 1.6 % (*1*), 9.3 % (*2*), and 16.4 % (*3*) below the generation threshold (a); relative changes in the GP2 duration (*1*) and amplitude (*2*) for the pump level of L2 1.6 % below the generation threshold (b) (t_0 and U_0 are the GP2 duration and amplitude, respectively, for independently operating L2); typical oscillograms of GP1 (*1*) and GP2 (*2*) (c).

interval T_d between the instants of ignition of flashlamps of the lasers at the fixed pump level of L2 or by changing the pump level at the fixed T_d. The dependence of t_d on t_{d0} measured for the pump level of L2 $E_p/E_{th2} = 1.25$ is presented in Fig. 4a. Note that, for the selected parameters, the dependence in Fig. 4a is close to the linear dependence $t_d \approx 10^{-3} t_{d0}$. While for $t_{d0} = 50$ μs, the pulse duration of the slave laser is ~ 11 ns and its amplitude is ~ 1.4 times smaller than the corresponding value of the independently operating Nd : YAG laser, for $t_{d0} = 2$ μs, they almost completely coincide.

Curve (*1*) in Fig. 4b, unlike Fig. 4a, was obtained for the fixed value $T_d = 40$ μs and the same irradiation level of the passive Q switch of L2 (~ 3 MW cm^{-2}), while curve (*2*) was obtained for the irradiation level 2.25 times higher (an additional neodymium glass amplifier was used). Due to the increase in the maximum power density on the passive Q switch up to ~ 7 MW cm^{-2}, GP2 was ahead of GP1 by ~ 20 ns.

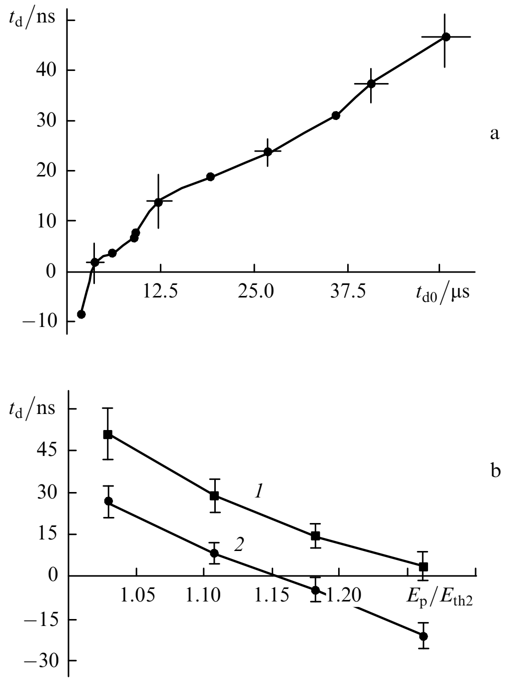

Figure 4. Dependences of the GP2 delay with respect to GP1 on the giant-pulse appearance delay for lasers operating independently (a) and on the L2 pump energy for radiation power densities incident on the passive Q switch equal to ~ 3 (*1*) and ~ 7 MW cm^{-2} (*2*) (b).

3. Discussion of the results

To understand why the system of two lasers, of which one is used to bleach the passive Q switch of another, can not only simultaneously generate two giant pulses but the GP emitted by the slave laser can be ahead of the GP emitted by the master laser, one should consider the properties of the polymer Q switch used in the Nd : YAG laser. The absorption cross section σ for most of such Q switches is approximately 10^{-16} cm^2 [12] and higher [13]. In this case, a considerable change in the Q-switch transmission is achieved at comparatively low power densities. The calculated changes in the transmission of the Q switch (with the initial transmission $T_0 = 18$ %) caused by a laser pulse (Fig. 5a) with parameters similar to those used in the experiment described above ($E = 5$ mJ, $\tau = 50$ ns) are shown in Fig. 5b for several values of σ. It was assumed in calculations that the effective upper-level lifetime of the Q-switch material considerably exceeds the laser pulse duration. In this case, as follows from Fig. 5b, the Q-switch transmission is doubled at the leading edge of the pulse even for the pessimistic value $\sigma = 10^{-17}$ cm^2. For $\sigma = 10^{-16}$ cm^2, such a change occurs approximately 60 ns before the pulse maximum at the total irradiation dose ~ 100 μJ (taking the aperture diameter of 1.5 mm into account). A considerable decrease in the Q-switch absorption long before the maximum of the giant pulse of the master laser is also confirmed by the appearance of beats of the slave laser radiation, which demonstrates the reduction in the development time of the slave laser generation, which proves to be insufficient for selection of longitudinal modes.

Both in the 'sub-threshold' and 'above-threshold' regimes, for each irradiation level of the Q switch (the master laser radiation energy) there exists the optimal

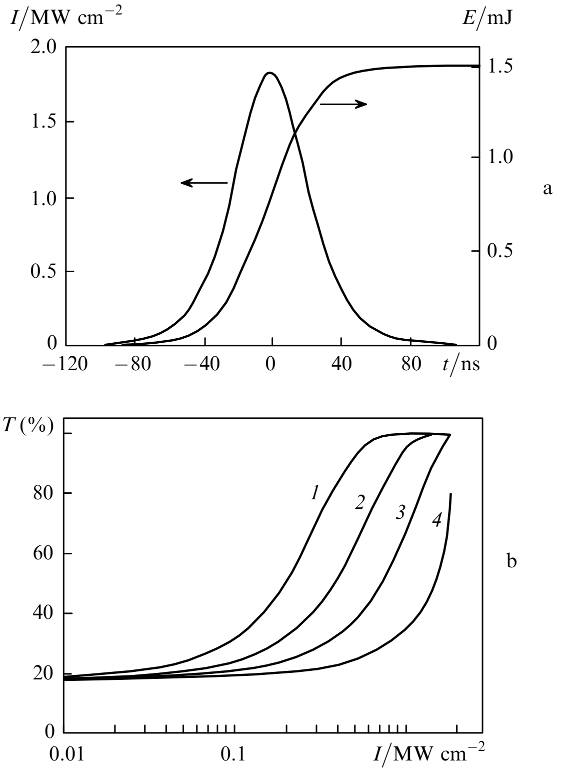

Figure 5. Time dependences of the intensity I and the total irradiation dose of the Q switch of the slave Nd : YAG laser (a) and dependences of the Q-switch transmission on I for absorption cross sections 10^{-16} (*1*), 5×10^{-17} (*2*), 2.5×10^{-17} (*3*), and 10^{-17} (*4*) (b).

irradiation of the Q switch of the slave laser at which the delay of its pulse is minimal, while radiation parameters prove to be almost the same as during the independent operation. As follows from experiments, these parameters are achieved at the maximal inverse population: in the 'subthreshold' regime, near the threshold of generation of the first giant pulse by the slave laser (Figs. 3a, b), and in the 'above-threshold' regime, near the generation threshold of the second giant pulse (Fig. 4b).

The practical application of the method of synchronisation of radiation from two lasers will undoubtedly require the optimisation of the optical scheme in Fig. 1. The transmission of the beamsplitter used in our experiments was ~ 20 %, which was sufficient to control the parameters of GP1. Real experiments can require either the laser beam focusing on the Q switch of the slave laser (to match the beam diameters of the master and slave lasers in the Q-switch plane) or using an additional amplifier.

4. Conclusions

We have shown that the pulses of passively Q-switched neodymium lasers can be synchronised without seed radiation with an accuracy of ±5 ns. This is valid at least for neodymium phosphate glass and Nd : YAG lasers emitting ~ 50-ns and ~ 8-ns pulses, respectively, and for a passive Q switch with $\sigma \sim 10^{-16}$ cm^2 in the slave laser. It is hoped that such synchronisation can be also achieved when the master (or slave) laser is passively mode-locked. Usually, even the synchronisation of such a laser with an electrooptically Q-switched laser is quite complicated and is achieved electronically [14] or by using passive Q-switching with seed radiation [15].

The high peak power of synchronised lasers, the width of their spectrum and the frequency difference achieving ~ 100 cm^{-1} make them promising for generating monochromatic radiation at the frequency ~ 2.7 THz.

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