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Pulsed-diode-pumped, all-solid-state, electro-optically controlled picosecond Nd : YAG lasers

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Abstract. **The results of the development of repetitively pulsed, diode-pumped, electro-optically controlled picosecond Nd : YAG lasers of two designs are presented. The first design uses the active–passive mode locking with electro-optical lasing control and semiconductor saturable absorber mirrors (SESAM). This design allows the generation of 15–50-ps pulses with an energy up to 0.5 mJ and a maximum pulse repetition rate of 100 Hz. The laser of the second design generates 30-ps pulses due to combination of positive and negative electro-optical feedback and the control of the electro-optical modulator by the photocurrent of high-speed semiconductor structures.**

Keywords: *picosecond pulses, diode pumping, electro-optical modulators.*

1. Introduction

The need to develop all-solid-state, diode-pumped, repetitively pulsed picosecond lasers stems from a wide range of research and technological problems for which the use of high-power picosecond light pulses has become quite conventional [1–3]. New fields for the application of picosecond pulses are also emerging. The possibility of using X-rays generated upon scattering of high-power picosecond laser pulses by relativistic electrons for medical diagnostics has been explored actively in recent years [4, 5].

Modern picosecond lasers must replace flashlamp-pumped lasers in which solutions of polymethylene dyes are used as saturable absorbers. The use of diode pumping of solid-state lasers makes it possible to discard low-efficient flashlamp pumping in favour of systems based on laser diodes and diode arrays providing the lasing efficient of tens per cent. Moreover, diode-pumped lasers produce a high-quality beam, which is required for laser processing of materials, lithography, pump of parametric oscillators and amplifiers, etc.

At present, diode pumping is used mainly in cw lasers producing ultrashort pulses. This is due, on the one hand, to a relatively simple realisation of cw lasers using semiconductor saturable absorbers mirrors (SESAM) [6], and, on the other hand, to an endeavour to obtain the highest average power at the lowest cost. The record-high energy of pulses from such lasers is hundreds of nanojoules [7]. It is important that a regenerative amplifier must be used in addition to the cw laser in order to generate millijoule pulses. Consequently, such systems turn out to be quite expensive and cumbersome.

In the 1980s, a technique was developed for mode locking radiation from flashlamp-pumped solid-state lasers by using dye solutions as saturable absorbers. This technique is based on the use of an active or passive negative feedback (NFB) [8–13] and is currently employed for generating picosecond pulses. The best possibilities for a flexible control of lasing is provided by an active electro-optical NFB, based on the use of an intracavity electro-optical modulator (EOM). This allows stabilisation of radiation emitted by pulsed solid-state lasers at a level corresponding to the maximum compression of ultrashort pulses by a saturable absorber and provides a reproducibility of their parameters.

By switching off the outer electro-optical NFB synchronously with Q-switching of the resonator, the generation of $\sim 0.1-1$-mJ picosecond pulses can be attained. Moreover, radiation can be switched from one resonator to another with the help of an EOM [14]. This is done in order to protect the saturable absorber and to increase its service life. It is important that the EOM can control generation with a subnanosecond speed. The electro-optical control makes it possible to realise the active mode locking (AML) also. Low-voltage modulators based on the transverse Pockels effect, which are usually prepared according to a bicrystalline (bisectional) thermally compensated diagram, offer considerable promise for applications in repetitively pulsed lasers. When different control voltages are applied to the sections of such a modulator, the phase shifts are added, i.e., the control voltages are summed in fact. This makes it possible to use an intracavity modulator to perform control of various types such as AML, NFB, Q-switching of the cavity, and realisation of an external positive feedback (PFB) [15].

Pulsed or quasicontinuous diode pump systems can be used for developing simple and compact picosecond millijoule lasers with a relatively low pulse repetition rate (up to

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a few hundred hertz) without requiring any serious efforts for heat removal. However, the use of dye shutters for producing reliable picosecond lasers is unproductive in view of their low photostability and a limited service life.

In this paper, we present the results of the development of repetitively pulsed, diode-pumped, electro-optically controlled picosecond Nd : YAG lasers generating 0.5-mJ, 10 – 50-ps pulses with a maximum pulse repetition rate of 100 Hz without the use of passive laser Q switches. Two approaches can be used for generating picosecond pulses. The first is based on active-passive mode locking using SESAM and electro-optical control of generation, and a single EOM is used for realising AML and NFB. In the second approach, the self-mode locking and generation of picosecond pulses are obtained by using a combination of NFB and PFB produced by an EOM controlled by the photocurrent from fast semiconductor structures (FSSs).

2. Laser with NFB and active – passive mode locking using SESAM

Figure 1 shows the scheme of the laser. The generation of stable pulses with a pulse repetition rate up to 100 Hz was achieved by using a resonator configuration that minimises the effect of the thermal lens. For this purpose, we minimised the change in the mode diameter in the active element upon a change in the mean pump power. This was achieved by choosing the optimal radius of curvature of the spherical mirror and its position in the resonator. The active 5-mm long YAG : Nd crystal of diameter 5 mm was pumped longitudinally by a laser diode array (JOLD-35-QPXF) with a fibre pigtail ($\lambda = 0.809$ μm). The pump pulse duration was 200 μs for a peak pump power up to 30 W. The pumped region of diameter 1.5 mm was formed with the help of a collimator. One of the surfaces of the active crystal had a coating reflecting the lasing radiation at 1.064 μm and transmitting the pump radiation. This surface forms one of the highly reflecting mirrors (M1) in the cavity. The other surface of the active crystal is cut at an angle of 3° and has the AR coating for the lasing wavelength. The radius of curvature of the concave mirror M2 is 2 m. A SESAM was used as the second highly reflecting mirror. The total length of the resonator was about 1 m.

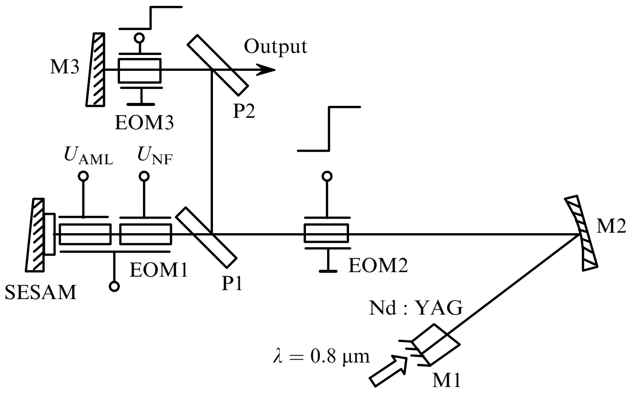

Figure 1. Scheme of a picosecond Nd : YAG laser with NFB and active – passive mode locking by using a SESAM: (P1, P2) polarisers; (M1 – M3) mirrors; (U_{AML}) control AML voltage; (U_{NF}) control negative feedback voltage.

Control voltages from the NFB and AML are supplied to the sections of EOM1 placed near the SESAM. The NFB voltage is produced by a high-voltage amplifier at whose input the signal from a fast photodiode is supplied. Radiation from an intracavity beamsplitter is directed to this photodiode through fibreoptic delay line. After stabilisation of the pulse parameters under the action of AML and NFB, a voltage drop with a pulse front duration of 2 ns and amplitude equal to the half-wave voltage (1400 V) is applied to EOM2. In this case, the horizontally polarised radiation is transformed into vertically polarised one, and the vertically polarised radiation is directed towards a high-Q resonator formed by mirrors M1 and M3. Because the inversion is not completely consumed due to the bias voltage at EOM1, the pulse energy is enhanced by two orders of magnitude after switching of the resonators. The resonator switching prevents damage of the SESAM. When the pulse energy achieves its maximum, a voltage drop of amplitude equal to the quarter-wave voltage (700 V) is supplied to EOM3, and the radiation is coupled out from the resonator through polariser P2.

Low-voltage modulators based on the transverse Pockels effect and made of RTP and $LiTaO_3$ crystals were used as EOMs. These modulators consist of two thermally compensated crystals of length 10 mm (RTP) and 15 mm ($LiTaO_3$) with an aperture 3 × 3 mm. The half-wave voltages of the two-section EOM are 1400 V (RTP) and 450 V ($LiTaO_3$) at a wavelength of 1.06 μm. In the final version of the laser with active – passive mode locking, an EOM made of an RTP crystal was used because the capacitance of the sections of this modulator was 2.2 pF, while the capacitance of the sections of the $LiTaO_3$ modulator was 10 pF. This circumstance turned out to be significant for the realisation of AML and NFB schemes.

A harmonic voltage with a frequency equal to half the frequency determined by the axial period of the laser was used for AML. In the absence of a bias voltage across the modulator (Fig. 2a), pulses are generated at the instants corresponding to complete transparency of the modulator when the voltage across it passes through zero. If a harmonic voltage and a bias voltage produced by the NFB circuit (Fig. 2b) are supplied to the modulator, the transmission function of the modulator is modified and the separation of its peaks from one another is not equal to the axial period. It is important that the transmission averaged over two round trips in the resonator has maxima at the same positions as in the absence of a bias voltage. Transmission at the maximum and, hence, the introduced errors are determined by the action of the NFB.

The control AML voltage is produced by a tunable generator of harmonic signals (with a frequency stability $\Delta\nu/\nu = 2 \times 10^{-6}$) and is fed to a high-frequency amplifier, which is switched on only during lasing in order to reduce the consumed power and the power scattered in the sections of the modulator. The power consumed by the amplifier is also lowered by connecting the sections of the modulator in a series oscillatory circuit. The photodiode signal in the NFB circuit is amplified by using a specially designed high-voltage amplifier providing a delay time of 1 ns for a pulse front duration of 5 ns when a short pulse is supplied to the input. The decay time was chosen equal to three axial periods which turned out to be an acceptable compromise between the sensitivity requirements and the stability of the delayed NFB [16, 17]. The amplifier provided a maximum

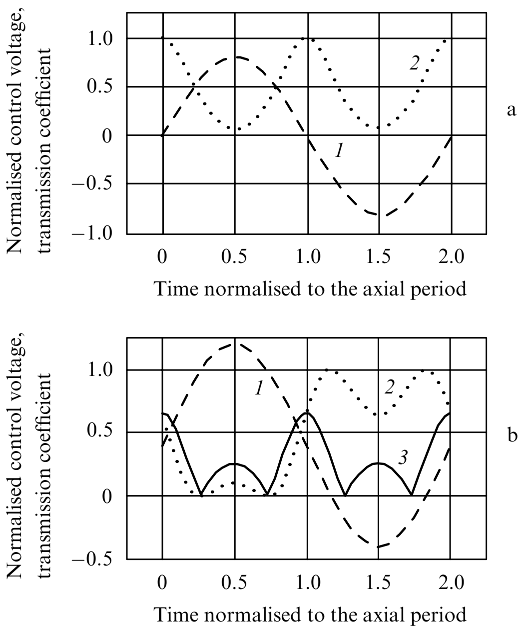

Figure 2. Time dependences of the control voltage across the EOM expressed in units of half-wave voltage (*1*), transmission coefficient of the EOM (*2*), and the EOM transmission coefficient averaged over two round trips in the resonator (*3*) for AML without a bias voltage (a) and with additional bias (b).

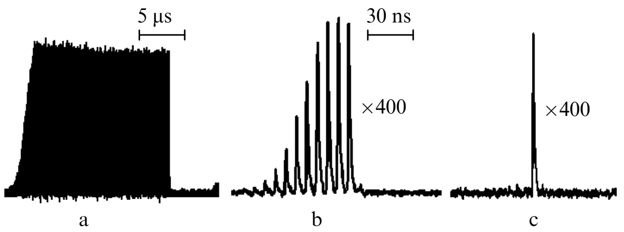

Figure 3. Dynamics of generation in a laser with active – passive mode locking: a picosecond pulse train before the switching of resonators (a); pulse energy growth after the switching of resonators (b); and a selected pulse (c).

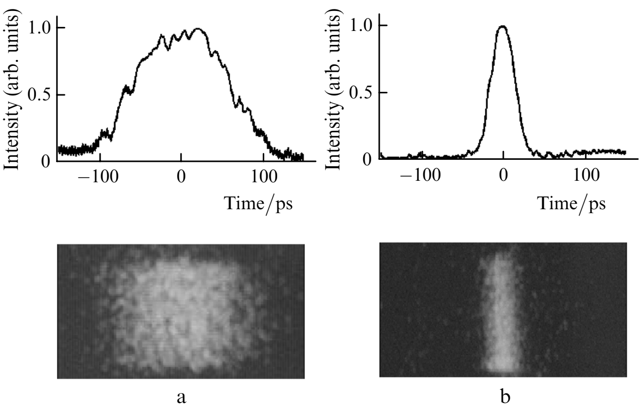

Figure 4. (a) Densito- and photochronograms of laser pulses in AML regime and (b) active – passive mode locking (AML and SESAM).

output power of 120 W. As a result, the NFB circuit made it possible to produce stable radiation both for active and active – passive mode locking. Gating of the NFB amplifier lowered its mean power consumption and heating, thus making it possible to mount it directly on the EOM.

As a rule, cw lasers producing ultrashort pulses employ SESAM with a low level of switching losses (0.5 % – 1.0 %). In the repetitively pulsed regime characterised by a higher gain, the required level of switched losses is also higher. However, an increase in losses raises the problem of switching the lasing regime to the generation of a train of giant pulses. The NFB circuit makes it possible to suppress the generation of giant pulses and stabilise the radiation power at an optimal level from the point of view of the highest decrease in the pulse duration. Consequently, the NBC circuit developed by us made it possible to use SESAM with a fairly high level of switching losses (up to 16 %).

Figure 3 shows the oscillograms illustrating the operation of the laser. Figure 3a shows a train of picosecond pulses with a nearly constant amplitude, formed under the action of SESAM, AML and NFB. The disruption of the pulse train at the instant $t = 15$ μs corresponds to the instant of switching of resonators, which is followed by the amplification of the pulse to the maximum amplitude in the high-Q resonator (Fig. 3b). After the achievement of the maximum amplitude, a single picosecond pulse is selected from the resonator (Fig. 3c). The use of AML (with a harmonic voltage amplitude of 500 V) together with NFB makes it possible to obtain pulses of duration $\sim$ 150 ps with an energy of 0.3 mJ and a maximum pulse repetition rate of 100 Hz. Figure 4a shows these pulses recorded with an AGAT-SF-3 streak camera. The pulse duration could be reduced considerably by using a SESAM (Fig. 4b). Thus the pulse duration was reduced to 10 ps by using SESAM whose initial absorption was $\sim$ 8 %. The choice of the resonator configuration minimising the effect of the thermal lens ensures a high stability of the amplitude of the selected pulse, which remained unchanged as the pulse repetition rate was increased from 1 to 100 Hz.

3. Self-mode-locked laser based on a combination of optoelectronic PFB and NFB

The second method of pulse generation in a all-solid-state picosecond laser is based on the self-mode-locking regime using a combination of optoelectronic NFB and PFB. For generating pulses shorter than 100 ps in duration, the intracavity modulator must be controlled directly by the photocurrent of the FSSs located outside the cavity [18]. Calculations show [19] that under conditions of optimal relative sensitivity, delay and form of the controlling action, the double-circuit system (NFB and PFB) provides radiation stabilisation and a decrease in pulse duration to a few tens of picoseconds without using saturable absorbers and other intracavity nonlinear elements.

Unlike SESAMs, which are placed inside the resonator, only a small part of laser radiation is incident on FSS. Hence, even if the energy of picosecond pulses increased by two orders of magnitude (after switching off the NFB and Q-switching of the resonator), no degradation of FSS is observed. This leads to a considerable simplification of the laser circuit and the lasing control circuit. The direct use of photocurrent makes it possible to form quite simply on the EOM a saw-tooth shaped control voltage with a sharp subnanosecond wavefront and an exponential decay. The decay time, which is different for the NFB and PFB circuits, is chosen keeping in view the optimal stabilisation of radiation and a lowering of the pulse duration. For NFB, the pulse decay time is equal to $\sim(1.5-2)T_{\mathrm{r}}$, where T_{r} is the cavity round-trip transit time [19]. It is interesting to note that in this case, the Nd : YAG laser can autonomously ensure the generation of ultrashort pulses of duration ~ 100 ps simply through NFB control with an appropriate delay in the optical path [20]. However, the pulse formation time is equal to several thousand trips through the resonator, which is inadmissible in many cases. This drawback is eliminated by switching to a combination of NFB and PFB, which also makes it possible to decrease the pulse duration [16].

Generation of picosecond pulses as a temporal function of losses introduced as a result of controlled pulse formation by the intracavity modulator requires the creation of short transmission spikes having a duration of several hundred picoseconds. The voltage pulses formed in the PFB circuit may be saw-tooth-shaped with a steep sub-nanosecond front and a decay time equal to $\sim(0.5-1.5)T_{\mathrm{r}}$, as well as pulses whose duration is determined by the response of the FSS photocurrent. The version involving control with the help of short pulses was realised in [21], and the duration of a flashlamp-pumped Nd : YAG laser pulse was below 50 ps. A more than an order of magnitude increase in load resistance of the FSS connected in parallel to the modulator capacitance led to a transition to the saw-tooth shape of control voltages and made the FSS operation regime in the PFB circuit more reliable. The choice of delay times made it possible to realise quite a short EOM transmission spike as a result of the combined action of NFB and PFB. The formation of picosecond pulses can be presented in this case as follows (Fig. 5): the steep front of the NFB signal lowers the modulator transmission, while the steep front of the PFB signal increases it. If the delay times and sensitivities in the PFB and NFB circuits are optimised, a narrow 'window' on the time scale is formed on the modulator transmission [22]. For a quite low PFB voltage, such a 'window' does not prevent the NFB from playing its stabilising role. The presence of two EOM sections connected only through a common earthing offers a unique possibility to connect NFB and PFB independently to each section [15]. This lowers the load capacitances and parasitic inductances, and increases the speed of the NFB and PFB.

Figure 6 shows the scheme of the laser. The laser resonator of length 1.2 m consists of a 15-mm-long Nd : YAG active element of diameter 5 mm, highly reflecting mirror M1 deposited on the flat end face of the active element, two highly reflecting mirrors (spherical mirror M2 with a radius of curvature 2 m and flat mirror M3), a low-voltage bisectional EOM made of $\mathrm{LiTaO_3}$, polariser P and beamsplitter BS. The radiation needed for controlling generation was extracted from the resonator with the help of beamsplitter BS. After passing through the controlled optical delay line, the radiation was directed to the FSS in the NFB and PFB circuits. In spite of a considerable variation of the gain of the active element in the course of pulsed diode pumping,

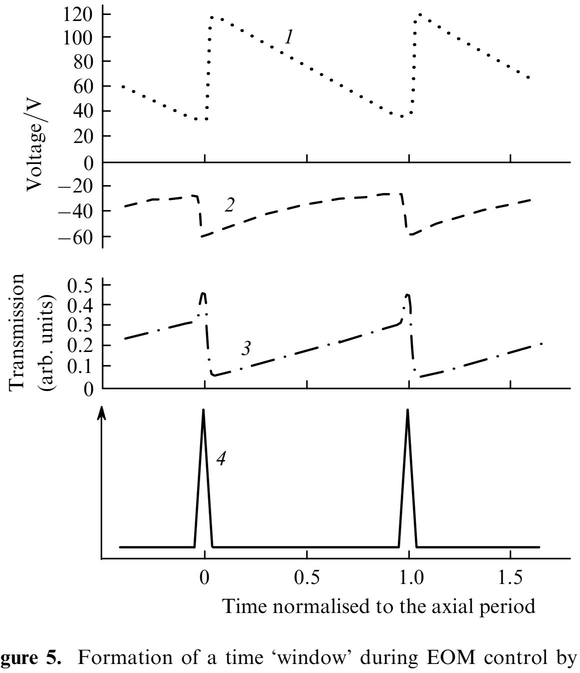

Figure 5. Formation of a time 'window' during EOM control by saw-tooth-shaped NFB and PFB voltages: (*1*) NFB control voltage; (*2*) PFB control voltage; (*3*) modulator transmission; (*4*) optical pulses.

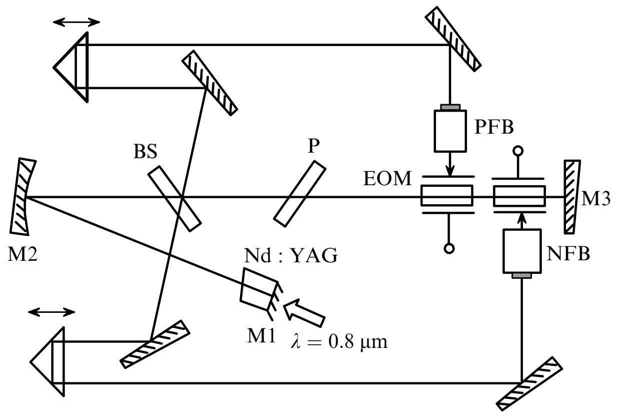

Figure 6. Scheme of a picosecond Nd : YAG laser controlled by a combination of NFB and PFB: (M1 – M3) mirrors; (BS) beamsplitter; (P) polariser.

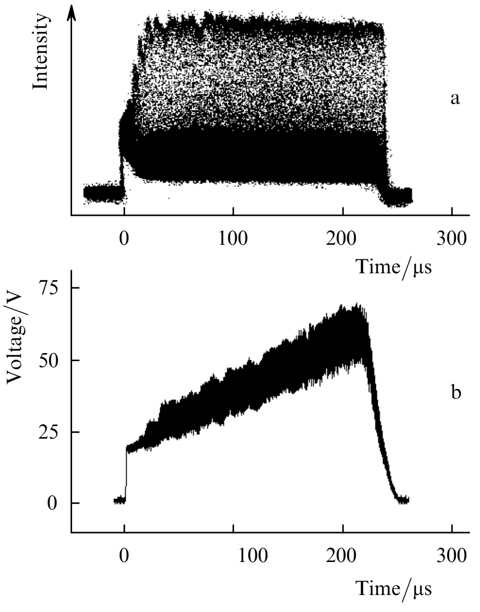

Figure 7. (a) Time dependence of the laser radiation intensity controlled by a combination of NFB and PFB; (b) NFB voltage during lasing.

effective stabilisation of radiation led to the formation of picosecond constant-amplitude pulse trains of duration exceeding 200 μs (Fig. 7a). The time dependence of the controlling NFB voltage is shown in Fig. 7b. The duration of picosecond pulses measured with the help of an AGAT-SF-3 streak camera was 30 ps.

4. Conclusions

Two versions of all-solid-state diode-pumped, electro-optically controlled picosecond Nd : YAG lasers have been developed and studied experimentally. The obtained results lead to the conclusion that the lasers developed by us will be used widely in various fields of science and technology.

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