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Stabilization of a single−frequency generation of the injection−seeded pulsed solid−state laser

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The article presents the results of developing the single−frequency pulsed Nd : YAG laser system at the 660 nm wavelength with a pulse duration of 50 ns and repetition rate of 1−10 Hz, operating in a Q−switched mode with injection of external radiation. Various schemes of forming a feedback system for controlling the spectral composition of the laser system are considered. It is shown that the method of locking the master oscillator frequency to the mode of the pulsed laser cavity has a number of advantages over the method of stabilizing the cavity length.

Keywords: Solid−state laser, Q−switching modulation, injection of radiation.

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High−power single−frequency solid−state lasers operating in the pulse regime find application in the laser interferometry, high−resolution laser spectroscopy, holography, etc. [1,2]. Such lasers enable obtaining visible or infrared pulses 10−100 ns long with the energy level of about millijoules and possibility to amplify them later up to the kilojoule level.

The possibility of obtaining single−frequency pulses extends significantly the area of pulsed lasers application in interferometry. For instance, radiation of lasers operating in single−frequency regimes possesses a considerably longer coherence than in the multifrequency mode. This allows using single−frequency radiation sources in creating unequal−arm interferometers. Such interferometers are used as measuring systems in experiments devoted to studying the effect of megabar shock waves on matter in the Physics of High Energy Densities [3–6]. In this case, short duration of the processes under study (~ 10 ns) requires using as radiation sources only pulsed lasers, since only they can provide the target illumination sufficient for detection.

The developed laser is intended to be used as a probing radiation source comprised in the LIV (Line Imaging Velocimetry) measuring system [7] in studying the interaction between the kilojoule laser radiation and matter. LIV is a system of two unequal−arm interferometers with the field visualization designed for experiments with a kilojoule laser setup „Luch“ (Sarov, Russia) [8]. To prevent the measuring path backlight by high−power radiation, the backlight radiation wavelength should be set apart from the setup „Luch“harmonics. Laser setup „Luch“into which the LIV module is integrated is used to generate transition $^4F_{3/2} \to {}^4I_{11/2}$ of ions Nd^{3+} ($1.06\,\mu$m). Therefore, transition $^4F_{3/2} \to {}^4I_{13/2}$ Nd^{3+} with the 1319 nm wavelength in the YAG matrix was chosen as a probing laser operating transition. Cross section of this transition is an order of magnitude smaller than that of the 1064 nm transition ($8.7 \cdot 10^{-20}$ and $4 \cdot 10^{-19}\,\mathrm{cm}^2$, respectively).

Fig. 1 presents the laser system layout.

The pulsed laser *1* cavity is 850 mm long. It is constrained by totally reflecting mirror $M1$ and mirror $M3$ with the reflection index of 70%, and comprises a quantron with two 5−mm Nd^{3+} : YAG crystals, mirror with polarization coating $M2$ used to inject the radiation into the cavity, and Pockels cell PC1. The cell and polarizer form a quarter−wave Q-switch for the 1319 nm radiation. For the transverse mode selection, diaphragm D is used.

The amplifier comprises the same quantron with two 5−mm Nd^{3+} : YAG crystals. After the double−pass amplification, frequency is doubled using crystal $\mathrm{KTiOPO_4}$ (KTP). The obtained radiation spectrum is sufficiently distant from the high−power harmonics of setup „Luch“ (1054 and 527 nm) and, at the same time, is visible for human eye, which makes the laser operation more convenient.

If no extra measures for the spectrum narrowing are taken, the laser works in the multimode regime and generates pulses 50 ns long. In this case, the spectrum width is > 120 GHz, which is almost three orders of magnitude larger than the intermode interval and matches with the coherence length of < 0.2 mm. This length is insufficient for operation of the unequal−arm LIV interferometer, since it is designed for longer time delay lines.

There are several ways of achieving the single−frequency regime. Continuous lasers employ intracavity filtration based on the Fabry−Perot etalon [9]. In the active Q−switched regime, the master oscillator−amplifier system is used. Two methods for implementing the master oscillator−amplifier system are possible: injection of single−frequency continuous radiation into the pulsed laser cavity [10,11] and amplification of the continuous laser radiation in a series of quantum amplifiers [3,4].

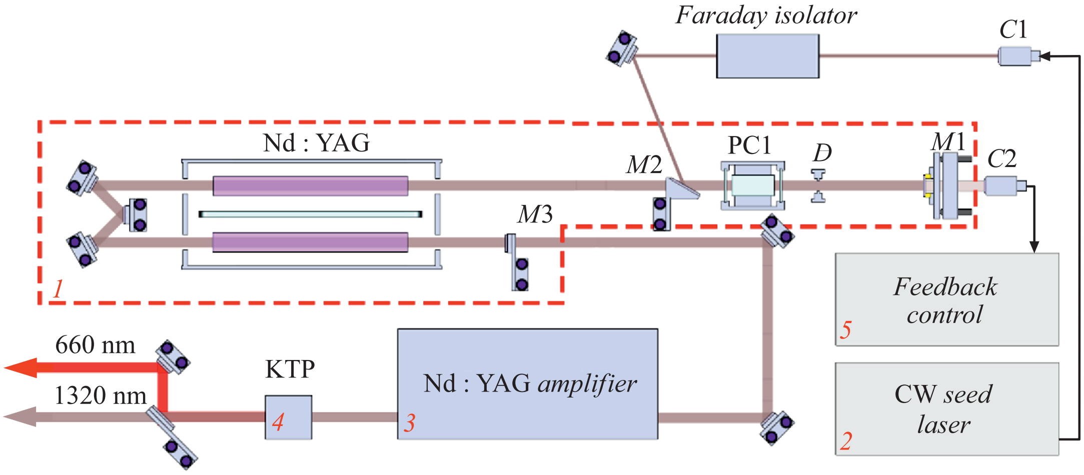

Figure 1. Laser system. *1* — Q–switched pulsed laser Nd : YAG, *2* — semiconductor injection–seeded laser, *3* — double–pass amplifier, *4* — second harmonic converter, *5* — stabilization system, $M1$–$M3$ — mirrors, $C1$, $C2$ — collimators, D — diaphragm, PC1 — Pockels cell.

As a master oscillator of the laser system described here, a 20 mW single–frequency semiconductor laser was used. The central wavelength of its operating range was 1310 nm. Thereat, its offset by 20 nm both towards short and long waves is possible. Radiation of this laser was injected into the pulsed laser cavity. As compared with the case when a chain of amplifiers is used, such a system is much more compact and less cost–effective; in addition, it is less demanding of the wave front quality and maximal power of the master oscillator. The semiconductor laser radiation intensity exceeds the spontaneous noise intensity by a few orders of magnitude, which allows initiation of a high–power single–frequency pulse. This regime may be realized only when the semiconductor laser frequency gets into one of the transverse modes of the pulsed laser cavity. As a rule, the task of coupling the master oscillator and pulsed laser modes is not considered [11], though just this task is determinative in the problem of using such a laser system as a stable source of high–power single–frequency radiation.

To ensure single–frequency generation, it is necessary to stabilize with respect to each other the pulsed laser and master oscillator frequencies. To compensate their difference caused by thermal and vibrational noise, an automatic frequency–locking system was used.

The frequency–locking system is based on locked–in detection of the optical system modulated response that is converted to the control signal by using properly fitted gain factors of the proportional–integral–derivative controller. The modulation is performed by displacing the $M1$ mirror fixed on piezoelectric element PP–12 with the frequency of 20 kHz. The task of the feedback system is to continuously monitor the shape of the optical system response derivative and to create a control signal that reduces the error signal to zero. The feedback signal is formed based on the interferential signal from the cavity with the master oscillator as a radiation source. The interferential maximum is searched for between the pumping pulses. The injected radiation reflects from mirror $M1$, passes through all the intracavity optical elements, reflects from output mirror $M3$ and returns back to totally reflecting mirror $M1$ (Fig. 1). A small portion of the master oscillator radiation that is a result of the radiation interference during the first and second passages through the $M1$–$M3$ cavity passes through mirror $M1$ and gets into photoreceiver $C2$. Just this radiation portion serves as the error signal.

Two versions of the master oscillator and cavity frequency locking were implemented. In the first version, the pulsed laser cavity length was adjusted to the master oscillator frequency by linearly displacing the totally reflecting mirror using piezoelectric element PP-12; the displacement range was up to 2.4 μm (Fig. 2, left scheme). In this scheme, the master oscillator was additionally equipped with the system of locking the frequency to the transmission band of the thermostabilized Fabry–Perot etalon, which allowed excluding the drift of the master oscillator frequency beyond the adjustment range of the pulsed laser cavity length.

In the second version of the automatic frequency locking system, the single–mode generation regime was achieved by adjusting the master oscillator frequency to the variation in the unstabilized cavity length (Fig. 2, right scheme). The master oscillator frequency could be controlled by the pumping current in the range 15 GHz wide. Thus, the pulsed laser intermode interval was 176 MHz; this range of the master oscillator spectral tuning made it possible to continuously monitor the mode position during the cavity length variation within the range of 56 μm. This was more than enough higher than thermal and vibrational interference really existing during the laser system operation (when the cavity is warmed–up).

To estimate the stability of the obtained single–frequency regime, the laser pulse temporal profiles and pulse repetition

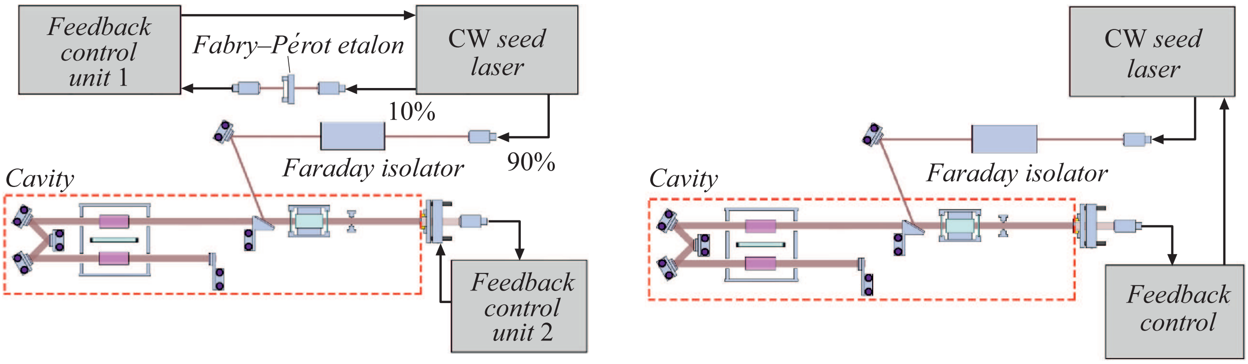

Figure 2. The scheme of locking the cavity to the stabilized master oscillator radiation (left) and locking the master oscillator frequency to the pulsed laser cavity modes (right).

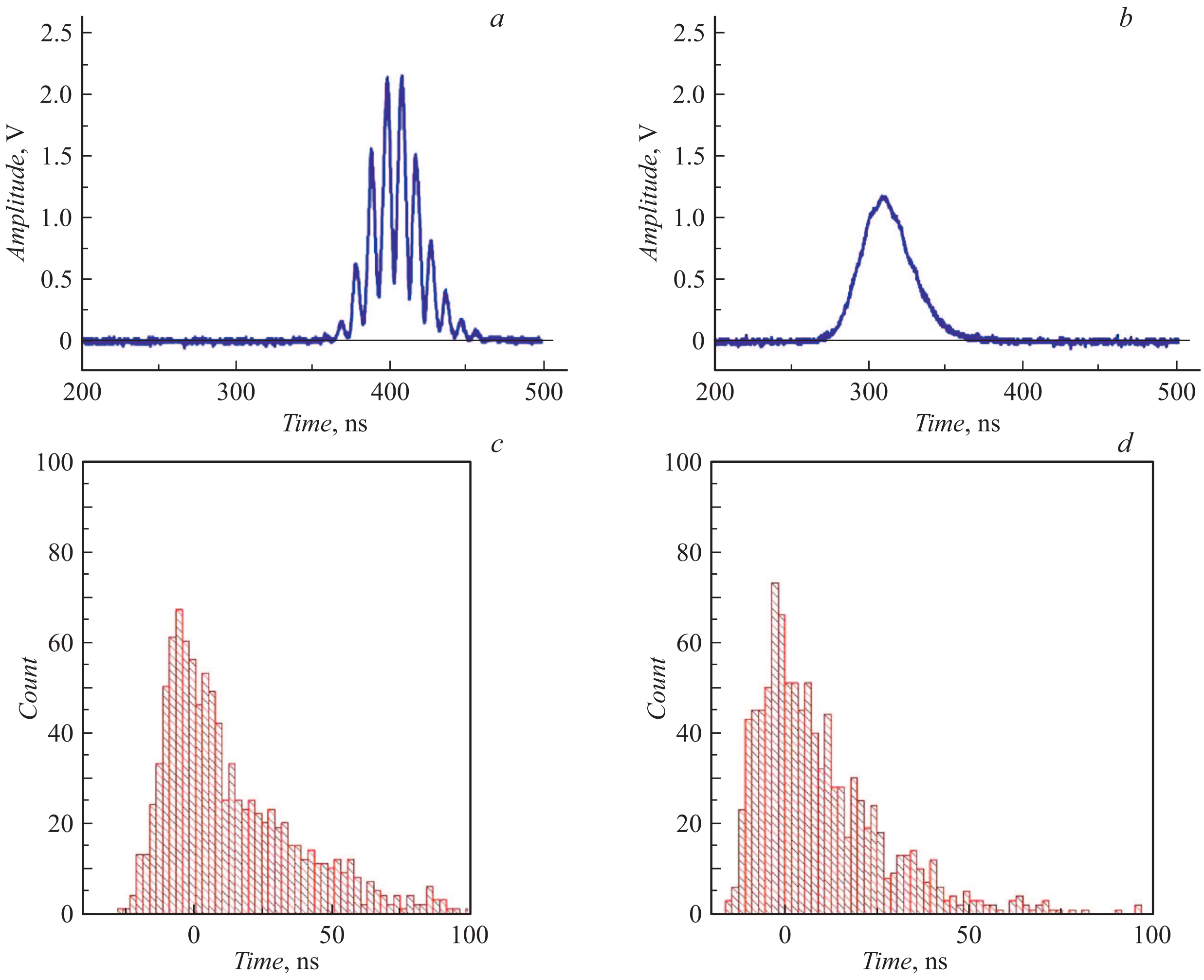

Figure 3. Generation in the multifrequency (a) and single–frequency (b) regimes, histograms of the time delay between the Q–switch opening and generation pulse for a series of 1000 pulses in fitting the cavity length to the master oscillator (c) frequency and in locking the master oscillator frequency to the free cavity (d).

rates were compared for the regimes of multifrequency and single–frequency generation with two stabilization regimes. Due to the mode interference, the multifrequency regime generation had the shape shown in Fig. 3, a. The band of the used photoreceiver HFBR-2416 was 125 MHz, which restricted the number of observed modes participating in beats. In the case of the single–frequency generation, the signal is a smooth pulse ∼ 50 ns long with the repletion rate of 1 to 10 Hz. The signal shape is shown in Fig. 3, *b*. After passing the amplifier and second−harmonic converter, a pulse up to 30 mJ in energy is formed. One can see that the single−frequency injection−seeded regime provides pulse generation about 100 ns earlier than the multifrequency generation onset. This is caused by an accelerated evolution of generation in the presence of the master oscillator radiation. The time of the generation development after closing the Q−switch characterizes the efficiency of locking the master oscillator and pulsed laser modes. This makes possible creation of the cavity frequency locking system based on the criterion of minimizing the generation development time. However, this approach provides information on the laser system state only during a pulse and is unable to monitor its state between pulses, which significantly decreases the spectrum of compensable excitations.

As a parameter for estimating the laser system operating mode, the dispersion of time delay of the laser pulse generation (maximum radiation intensity) relative to the time of the Q−switch opening was chosen. The delay dependence on other factors was studied separately. In the multimode regime with the absence of external radiation injection, the time delay dispersion did not exceed 2 ns, which evidences for a good stability of the laser system. A significant difference between stabilities of the multimode and single−mode regimes is caused by the relationship between the time delay and radiation injection efficiency. In the multimode regime, the stability is not related to the positions of specific cavity modes, while in the single−mode regime the moment of the generation development onset depends on the extent of overlapping of the master oscillation radiation spectrum and cavity longitudinal mode. Fig. 3, *c* and *d* presents the measurements of the time delay dispersion for the first and second frequency locking versions for a series of 1000 pulses with the repetition rate of 1 Hz. In the regime of stabilizing the pulsed laser cavity length, the delay dispersion was 20.1 ± 0.2 ns, while that in the regime of the master oscillator locking to the pulsed laser cavity was 14.3 ± 0.2 ns.

The cavity locking to the master oscillator appeared to be rather labor−consuming in the case of the primary manual tuning of the master oscillator frequency. Restriction of the range of the mirror linear displacement ($< 2\,\mu$m) have led to the necessity of introducing the second feedback loop (stabilization of the master oscillator wavelength) and impossibility of compensating single excitations. In its turn, the feedback system based on controlling the master oscillator wavelength had a wide range of the master oscillator tuning (> 15 GHz), which allowed compensation of excitations getting beyond the operating range of the first version of the scheme.

For interferometric measurements in the field of Physics of High Energy Densities at high−power laser setups with the kilojoule energy level, a single−frequency system was developed for the target illumination with a laser at the wavelength of 660 nm, pulse length of 50 ns, and pulse energy of up to 30 mJ.

It was shown that the method of the master oscillator frequency locking to the pulsed laser cavity mode provides higher stability of the single−frequency generation as compared to the method of the cavity tuning by mirror displacement.

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Conflict of interests

The authors declare that they have no conflict of interests.

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