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Transversely diode-pumped *Q*-switched Nd : YAG laser with injection of radiation from a single-frequency semiconductor laser

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Abstract. **A *Q*-switched Nd : YAG laser with a high-power transverse diode pumping and injection of seed radiation generated by a single-frequency semiconductor laser is described. The threshold seed radiation power at which the *Q*-switched Nd : YAG switches to the single-frequency mode is 0.44 mW (radiation intensity 5.6×10^{-2} W cm^{-2}). With increasing injection power, the spectral and power characteristics of the *Q*-switched laser almost do not change at a constant excitation of its active medium. The spectral linewidth of the *Q*-switched Nd : YAG laser with injection from a TLD-1060-14BF single-frequency semiconductor laser module does not exceed 90 MHz (wavelength 1064 nm).**

Keywords: *solid-state laser, diode pumping, semiconductor laser module, injection of narrowband radiation.*

Single-frequency pulsed solid-state lasers based on a Nd : YAG crystal with a linewidth of 100 MHz and a pulse energy from units to tens of millijoules are promising sources for high-resolution lidars (wind lidars) [1, 2]. One of the efficient methods of generation of time-synchronised narrowband light pulses is the injection of radiation from an external source into a high-power laser cavity [3 – 8]. In most cases, this approach is implemented within the superregenerative amplification mechanism [3]. In this case, as an external (seed) source one uses single-frequency lasers with the spectral characteristics of their active media identical or close to the characteristics of high-power lasers to which the seed radiation is injected [1, 3 – 8].

As was shown in [8], the threshold power of a cw injector above which a high-power multimode Nd : YAG laser switches to a single-frequency regime does not exceed 0.14 mW. This allows one to use single-frequency semiconductor lasers with an external fibre Bragg grating as seed radiation sources [9 – 11].

The present work is devoted to the study of the possibility of using a semiconductor single-frequency laser module (SLM) of the TLD-1060-14BF type as a seed radiation source for a *Q*-switched transversely diode-pumped Nd : YAG laser.

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The spectral characteristics of the Nd : YAG laser are studied in detail in the free-running and *Q*-switched regimes, as well as in a *Q*-switched regime with injection of single-frequency seed radiation.

The block-scheme of the laser (Fig. 1) includes a high-power laser (*1 – 8*) and a low-power cw laser injector (*9 – 15*). The high-power *Q*-switched laser is based on a Nd : YAG active element transversely excited by three laser diode arrays (LDAs) positioned symmetrically with respect to the longitudinal *X* axis near the lateral surface of the cylindrical active element (AE) 5 mm in diameter and 500 mm long. The summed output pulse energy of LDAs was varied within the range 1.5 – 3.0 kW. The rectangular pump pulse duration was 250 μs (the length of the leading and trailing pulse edges did not exceed 5 μs) at a pulse repetition rate of 10 – 30 Hz. The AE edges were antireflection coated for a wavelength of 1064 nm. The concentration of neodymium ions in the AE of the *Q*-switched laser was 1.1%. *Q*-switching was performed by an electro-optical element based on the DKDP crystal. The *Q*-switched laser cavity was 270 mm long.

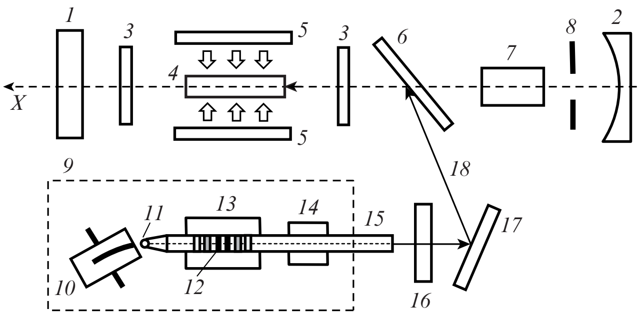
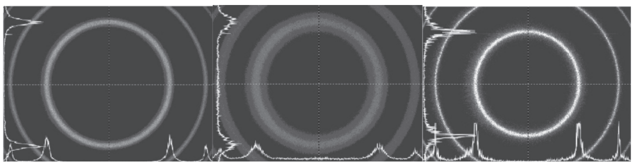


Figure 1. Experimental scheme: (*1*) plane output mirror; (*2*) highly reflecting spherical mirror (curvature radius 1 m); (*3*) quarter-wave phase plate; (*4*) AE of the *Q*-switched laser; (*5*) diode pump unit; (*6*) polariser; (*7*) Pockels cell; (*8*) aperture; (*9*) SLM; (*10*) two-pass amplifier; (*11*) microlens; (*12*) FBG; (*13*) piezoceramics; (*14*) optical isolator; (*15*) single-mode fibre output; (*16*) collimating system; (*17*) folding mirror; (*18*) seed radiation.

As a seed radiation source for the high-power *Q*-switched laser, we used a TLD-1060-14BF (NOLATECH, Moscow) single-frequency semiconductor laser module [11, 12]. The SLM scheme included a two-pass amplifier based on a InGaAs/GaAs heterostructure with quantum-dot layers and coupled to a single-mode fibre using a microlens (see Fig. 1). A fibre Bragg grating (FBG) was formed in the fibre near the microlens. The fibre segment with the FBG was mounted on piezoceramics. For protection from external reflections, we placed an optical isolator at the SLM fibre output. A stable cw single-frequency regime of the module was ensured by precision stabilisation of the pump current and the operating temperature of the semiconductor amplifier mounted on a Peltier element. The SLM spectrum consisted of one line with a halfwidth smaller than 0.5 MHz (the laser wavelength at room-temperature is 1064 nm) in the entire studied range of the injector output power P (0–12 mW). Polarised radiation from the fibre output was collimated into a beam 5 mm in diameter and directed to the Q-switched laser cavity using an intracavity polariser.

The maximum of the injection lasing line was tuned to one of the intrinsic modes of the Q-switched laser (spaced by 575 MHz) by varying the pump current and the SLM amplifier temperature, as well as the voltage applied to the FBG piezocorrector. The moment of coincidence of the injection lasing line and the Q-switched laser mode was determined by the interference pattern formed by a Fabry–Perot interferometer (with a free dispersion region of 1 GHz) and observed using a CCD camera. The interferometer mirrors were designed for operation in the region of 532 nm. The interferometer base length was 150 mm, and the reflection coefficient of interferometer mirrors was 85%. In experiment, the Q-switched laser radiation was converted by a nonlinear $KTiOPO_4$ crystal to the second harmonic. The Q-switched laser linewidth (wavelength 1064 nm) was determined by measuring the second harmonic linewidth (532 nm). In the case of Gaussian lines, the widths of the 1064-nm line $\Delta\nu_{1064}$ and the second-harmonic line $\Delta\nu_{532}$ relate to each other as $\Delta\nu_{1064}/\Delta\nu_{532} = 1/\sqrt{2}$ [13, 14]. Measuring the parameters of interference fringes, one can determine the Q-switched laser linewidth.

The interference patterns of the Nd:YAG laser radiation recorded under different conditions of LDA excitation are presented in Fig. 2. The radiation linewidth at half maximum $\Delta\nu$ in the free-running regime was 3.68 GHz (Fig. 2a). The laser linewidth in the Q-switched regime increased to 6.82 GHZ (Fig. 2b), which is probably caused by a decrease in the Q-switched Nd:YAG laser pulse duration by more than four orders of magnitude (up to 10.6 ns). When the power injected into the Q-switched laser cavity was $P \geqslant 0.44$ mW (radiation intensity no lower than 5.6×10^{-2} W cm^{-2}), we observed a single-frequency Q-switched regime. It should be noted that the interferograms shown in Figs 2a, 2b are obtained using a Fabry–Perot interferometer with a base of 5 mm and a spectral resolution that allowed us to estimate linewidth only in the free-running and the Q-switched regimes without injection of an external signal. The laser spectrum in the Q-switched regime with injection of single-frequency cw radiation (Fig. 2c) is presented only as an illustration. Its real spectral width was estimated using a Fabry–Perot interferometer with a base of 150 nm and was smaller than 90 MHz for a wavelength of 1064 nm.



a b c

Figure 2. Spectra of a transversely diode-pumped Nd:YAG laser recorded using a Fabry–Perot interferometer with a 5-mm base in (a) the free-running regime (linewidth $\Delta\nu$ = 3.68 GHz), (b) Q-switched regime ($\Delta\nu$ = 6.82 GHz), and (c) Q-switched regime with injection of cw single-frequency radiation ($\Delta\nu$ < 90 MHz).

As is found, it is not necessary to precisely tune the seed laser line to one of the intrinsic modes of the Q-switched Nd:YAG laser within the AE gain profile with a width of ~180 GHz [15, 16]. This can be probably explained by the fact that generation of an actively Q-switched solid-state laser is developed for about ten cavity roundtrips. As a result, the intrinsic steady-state modes have no time to form, and the radiation spectrum is quasi-continuous [5, 17].

Like in the case considered in [8], the Nd:YAG laser switches from Q-switched to single-frequency operation as the injection power reaches some threshold value. An increase in the threshold power by 0.3 mW in our case compared to the value found in [8] is explained by incomplete coincidence between the spatial characteristics of the injection radiation and the Q-switched laser cavity. At higher injection powers P, the spectral and power output characteristics of the Q-switched laser almost did not change if the LDA excitation was constant.

An increase in the Q-switched laser pump power from 1.5 to 3.0 kW led to an increase in the output single-frequency pulse energy E. At a maximum LDA pump power, this energy was achieved to be E = 57 mJ.

It is found that the temporal stability of the Q-switched laser frequency is almost entirely determined by the stability of the injector frequency (the SLM frequency shift in our experiments did not exceed 720 MHz per hour of continuous operation).

Thus, it is experimentally shown that a TLD-1060-14BF single-frequency semiconductor laser module can be used as an efficient seed radiation source for narrowband Q-switched Nd:YAG laser with high-power transverse diode pumping. The threshold injection power at which the Q-switched Nd:YAG laser switches to a single-frequency regime does not exceed 0.44 mW (radiation intensity 5.6×10^{-2} W cm^{-2}). With increasing injector power, the spectral and power characteristics of the Q-switched laser almost do not change under the condition of constant LDA excitation. The spectral linewidth of the Nd:YAG laser in the Q-switched regime with injection of radiation from a TLD-1060-14BF semiconductor laser module does not exceed 90 MHz (wavelength 1064 nm).

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