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Efficient lasing at 2.1 µm in a Ho : YAG laser pumped by a Tm : YLF laser

N.G. Zakharov, O.L. Antipov, V.V. Sharkov, A.P. Savikin

***Abstract*. A laser based on a Ho:YAG crystal operating at a wavelength of ~ 2.1 µm under pumping by Tm : YLF laser radiation with a wavelength of 1.908 µm is studied. The laser operates in cw and repetitively pulsed regimes with a high beam quality (quality factor $M^2 \leqslant 1.2$). The cw radiation power reached 15 W with the total optical efficiency of ~ 55 %. In the active *Q*-switched regime (achieved using an acousto-optic *Q*-switch), a highly stable repetitively pulsed lasing was obtained with a pulse repetition rate of 2.5 – 10 kHz, a pulse duration of 25 – 55 ns, and an average power up to 14.7 W. Using intracavity frequency selection, lasing was obtained at individual spectral lines in three wavelength regions, near 2.09, 2.097, and 2.123 µm.**

Keywords: *2-µm lasing, Ho : YAG crystal, Q-switching, frequency selection.*

Lasers based on crystals doped with Ho^{3+} ions operate at the wavelength ~ 2.1 µm, owing to which they are widely used in modern production technologies, medicine, remote probing of the atmosphere, and other fields [1 – 3]. Under lamp pumping, this generation is achieved in lasers based on crystals co-doped with Ho^{3+}, Tm^{3+}, and Cr^{3+} ions [4]. The pumping of Ho^{3+}-doped crystals by narrow-band laser radiation leads to a considerable increase in the laser power and efficiency, as well as to a better beam quality.

In this paper, we study a Ho : YAG laser pumped by a Tm : YLF laser. We study the cw and repetitively pulsed lasing in the Ho : YAG laser without selective elements and with an interference-polarisation filter (IPF).

The Ho : YAG laser elements (ELS-94, Moscow) were cut in the form of cylinders (30 mm long and 4 mm in diameter) from crystals grown by the Czochralski method with an ~ 1 % atomic concentration of Ho^{3+} ions; their faces were antireflection coated at the pump and laser wavelengths (1.9 and 2.1 µm, respectively). In some experiments, we used a segmented laser rod consisting of a Ho : YAG element and an undoped YAG rod (5 mm long and 4 mm in diameter) diffusion welded onto the pumped face of the Ho : YAG crystal, which ensured a lower temperature gradient. The Ho : YAG rods were wrapped with an indium foil and mounted in a copper heatsink, whose temperature was kept constant at ~ 12 °C with the help of a Peltier element and a temperature control system.

To pump the Ho : YAG crystals, we used the cw radiation of a diode-pumped Tm : YLF laser with an output power up to 30 W at $\lambda = 1.908$ µm (Fig. 1), which was described in [5]. The Tm : YLF laser, whose wavelength $\lambda = 1.908$ µm well coincides with the Ho : YAG crystal absorption band [5, 6], is the best source for pumping the Ho : YAG laser.

The Ho : YAG laser cavity was formed by three mirrors: a plane mirror M1 with a high reflectance at the laser (2.1 µm) and pump (1.8 µm) wavelengths, a dichroic mirror M2 with a high (above 99.5 %) reflectance at the laser wavelength and a high (~ 96 %) transmittance at the pump wavelength, and a spherical output mirror M3 semitransparent at the laser wavelength (Fig. 1). To obtain a higher gain, the Tm : YLF laser beam was focused by a lens system L into the Ho : YAG crystal through the dichroic mirror M2. The mirror M1 had a high reflectance at $\lambda = 1.908$ µm to increase the pump radiation absorption in the Ho : YAG crystal. The pump beam twice passed through the active element and was almost completely (~ 95 %) absorbed in it.

If the radiation reflected from the mirror M1 was not completely absorbed in the Ho : YAG crystal and fell back

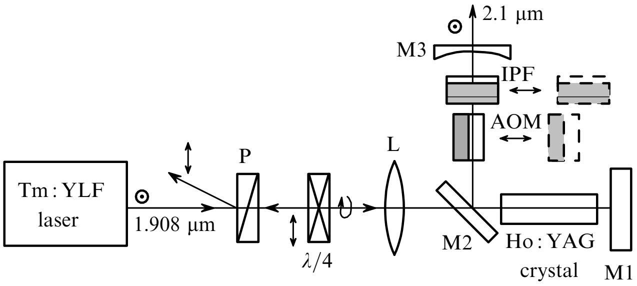

Figure 1. Scheme of the experimental setup: (P) polariser, (L) lens telescope, (M1) highly reflecting mirror, (M2) dichroic mirror, (M3) output mirror, (AOM) acousto-optic modulator, (IPF) interference-polarisation filter.

N.G. Zakharov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia;
N.I. Lobachevskii Nizhnii Novgorod State University, prosp. Gagarina 23, 603950 Nizhnii Novgorod, Russia;
O.L. Antipov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia;
e-mail: antipov@appl.sci-nnov.ru;
V.V. Sharkov, A.P. Savikin N.I. Lobachevsky Nizhnii Novgorod State University, prosp. Gagarina 23, 603950 Nizhnii Novgorod, Russia

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into the cavity of the Tm : YLF laser, the two oscillators become coupled. This changed the Tm : YLF lasing dynamics, namely, sharply (tenfold) increased the amplitude of pulses and decreased their total number. This, in turn, lead to a breakdown of the Tm : YLF crystal faces even at a low output power (~ 5 – 6 W). To decouple the Tm : YLF and Ho : YAG lasers, we placed a polarising wedge P and a quarter-wave plate in front of the focusing lens (Fig. 1). After a double pass through the quarter-wave plate, the Tm : YLF laser beam was polarised orthogonally to the initial polarisation and deflected from the cavity axis by the polarising wedge. This allowed us to completely eliminate the laser crystal breakdown (up to the operation with the maximum laser power).

The output power of the Ho : YAG laser was optimised by the best overlap of the cavity mode volume with the pumped volume (taking into account the lens induced in the Ho : YAG crystal by the pump radiation). We varied the pump beam diameter in the Ho : YAG crystal from 0.5 to 0.9 mm, the cavity length from 5 to 23 cm, the radius R of curvature of the output mirror from 150 to 300 mm, and the output mirror transmittance T from 50 % to 70 %. The maximum output power (~ 15.3 W) was achieved in the scheme with the segmented active element (with an undoped segment at the face) and the output mirror with $R \approx 150$ mm and $T \approx 64\,\%$ [curve (*1*) in Fig. 2]; in this case, the optical efficiency reached 55 %. The efficiency of a similar laser with a Ho : YAG crystal without an undoped section was 2 % lower [curve (*2*) in Fig. 2].

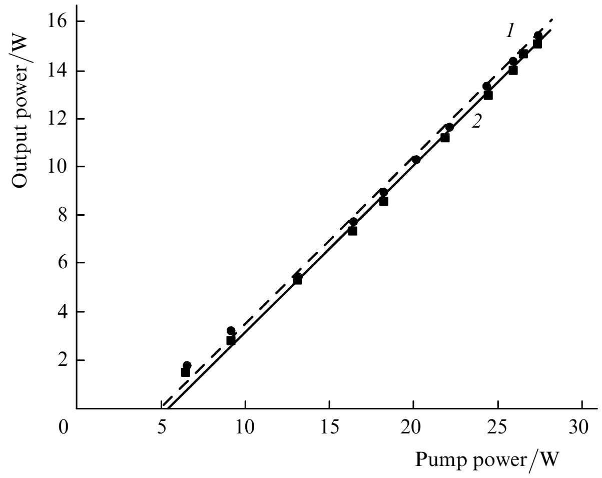

Figure 2. Dependence of the output power of the 2.1-μm lasers based on Ho : YAG crystals with (*1*) and without (*2*) undoped ends on the pump power (the measurement error is ~ 0.05 %).

The transverse spatial structure of the Ho : YAG laser beam was recorded on an IR Pyrocam III camera. The quality factor M^2, which characterises the coincidence of the beam profile with the Gaussian shape, was determined according to the method of the International Standards Organisation [7]. It was found that the beam quality remains close to the diffraction limit ($M^2 \leqslant 1.2$) even at the maximum output power.

In addition to the cw regime, we achieved the Q-switched operation of the Ho : YAG laser. For this purpose, we placed an acousto-optic Q-switch into the output arm of the cavity between the dichroic (M2) and output (M3) mirrors (Fig. 1). We obtained repetitive short (25 – 55 ns) pulses with a repetition rate of 2.5 – 10 kHz (Fig. 3). In this pulse repetition rate region, we observed a high duration and amplitude stability of pulses (the amplitude instability below 3 % and the duration instability below 2 ns). A decrease in the pulse repetition rate (within the above range) at a constant pump power, as well as an increase in the pump power at a constant repetition rate, lead to a decrease in the pulse duration and an increase in the pulse amplitude. The average power and the pump conversion efficiency in the repetitively pulsed regime within the mentioned repetition rate region were constant and comprised 98 % of the corresponding values in the cw mode. The beam quality in the repetitively pulsed regime remained close to diffraction limit. At the acousto-optic modulation frequency below 2.5 kHz, the average output power decreased (by ~ 6 % at 2 kHz). At higher modulation frequencies (10 – 20 kHz), we observed a strong increase in the amplitude instability of pulses.

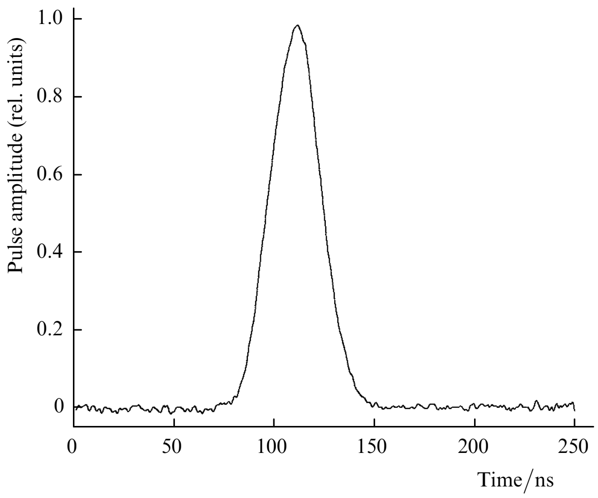

Figure 3. Oscillogram of a pulse of the Q-switched Ho : YAG laser at the pulse repetition rate of 3 kHz and the output power of 14 W.

The spectral composition of the output radiation of the Ho : YAG laser was measured using an MDR-41 monochromator with a resolution of 0.1 nm. The spectra showed that the lasing occurred simultaneously in two spectral regions with maxima at $\lambda = 2.09$ and 2.097 μm in both cw [curve (*1*) in Fig. 4] and repetitively pulsed [curve (*2*) in Fig. 4] regimes. The intensity ratio of the spectral lines depends on the laser operation mode, the crystal temperature, and the cavity Q-factor. For spectral selection of the output radiation, we placed an IPF (a plane-parallel sapphire plate oriented at the Brewster angle to the cavity axis) into the cavity arm between the M2 and M3 mirrors. This allowed us to obtain lasing in both cw and repetitively pulsed regimes at a selected spectral line in each of the three wavelength ranges, near 2.09, 2.097, and 2.123 μm (with the linewidth below 0.5 nm). The decrease in the average power was minimal (not exceeding 1 %) in the case of selection of the line at $\lambda = 2.097$ μm. The selection of lines at $\lambda = 2.09$ or 2.123 μm decreased the average power stronger, by ~ 10 % and ~ 15 %, respectively, at the maximum power.

Thus, we have demonstrated high-power cw and repetitively pulsed two-micron lasing with a high beam quality

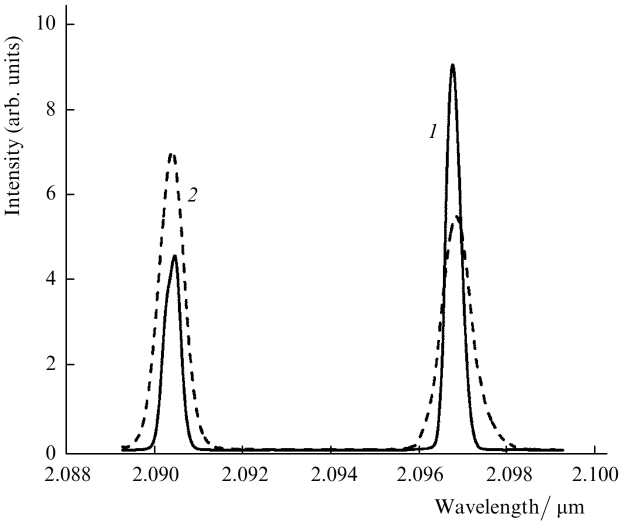

Figure 4. Spectra of the Ho : YAG laser in the absence of selecting elements for the cw (*1*) and *Q*-switched (*2*) modes at the output power of ~ 14 W.

and highly stable characteristics (power, pulse duration, pulse repetition rate, wavelength, and spectral linewidth).

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