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Investigation of two-frequency Nd^{3+} : YAG laser*

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Abstract. **A repetitively pulsed two-frequency laser is developed. Pulsed operation of a laser based on a Nd^{3+} : YAG crystal with simultaneous amplification of radiation at two wavelengths in a single-pass amplifier is studied.**

Keywords: *two-frequency lasing, repetitively pulsed regime.*

1. Introduction

At present, the most frequently used active medium of high-power repetitively pulsed laser amplifiers is the Nd^{3+} : YAG crystal. In this crystal, the stimulated radiative transition from the upper laser level $^4F_{3/2}$ can occur to several levels, including the $^4I_{13/2}$ and $^4I_{11/2}$ levels. The wavelengths of lasing on these transitions are 1.33 and 1.06 μm, respectively. Since the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition has the largest stimulated emission cross section, it is most frequently used for lasing. The $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition cross section (λ = 1.06 μm) varies from 1.8×10^{-19} to 8.8×10^{-19} cm^2 for different batches of crystals [1], while the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition cross section reaches 1.5×10^{-19} cm^2 [1]. The stimulated emission cross sections of other transitions in Nd^3+ : YAG crystals are considerably smaller, because of which the creation of a laser source emitting radiation simultaneously at two wavelengths is a rather difficult scientific and technical problem.

Let us consider several examples of realisation of such a system. The authors of paper [2] reported on the creation of an end-diode-pumped cw solid-state laser operating at two wavelengths and demonstrated highly efficient lasing in a two-mirror cavity at wavelengths of 1.064 and 1.112 nm, which correspond to different upper laser levels. To create a Q-switched repetitively pulsed laser, the authors of [3] used intracavity spectral separation of generated frequencies with pulse synchronisation by varying the lengths of cavity arms; this scheme was rather difficult to align and had significant intracavity losses due to a large number of used optical elements.

The aim of the present work was to create a simply aligned repetitively pulsed laser with simultaneous lasing at λ = 1.06 and 1.33 μm in order to use it as a base for developing a multifrequency laser system. This laser can considerably extend the potentials and increase the accuracy of measurement methods used in optical probing of the atmosphere, in ecological monitoring, and in medical and biological express analysis of biological objects.

2. Two-frequency laser

To obtain laser radiation simultaneously at two wavelengths, we proposed and realised a scheme shown in Fig. 1. The two-frequency laser has two cavities with a common output mirror (*8*), a Q-switch (*7*), and highly reflecting mirrors (*1*) (shoulder II) and (*3*) (shoulder I). Shoulder II contains an active element (*2*), which emits at λ = 1.33 μm, while the active element (*4*) positioned in shoulder I operates at λ = 1.06 μm. The aperture (*5*) with a diameter of 3 mm is used to match the apertures of beams with λ = 1.06 and 1.33 μm. The deflecting mirror (*6*) has the reflectance R = 99 % at λ =

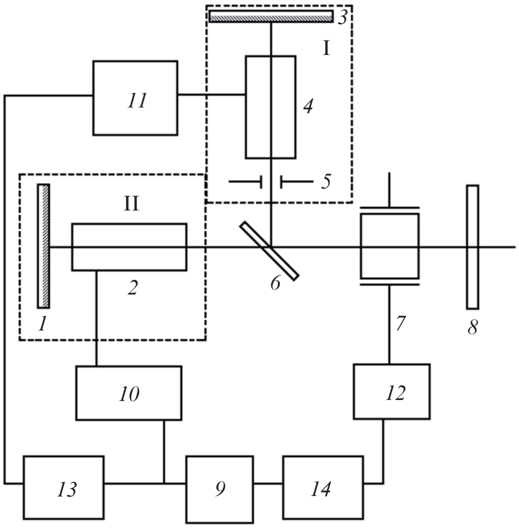

Figure 1. General scheme of a Q-switched two-frequency laser with a common output mirror: (*1*) rear cavity mirror for λ = 1.33 μm (R = 99 %); (*2*) active element 3 mm in diameter; (*3*) rear cavity mirror for λ = 1.06 μm (R = 98 %); (*4*) active element 5 mm in diameter; (*5*) aperture 3 mm in diameter; (*6*) deflecting mirror for λ = 1.06 μm (R = 99 %); (*7*) Q-switch; (*8*) output mirror; (*9*) master oscillator; (*10*, *11*) pump units; (*12*) Q-switch control unit; (*13*, *14*) delay units.

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1.06 µm at the angle of incidence of 45°, while the transmittance of this mirror at the same angle of incidence and λ = 1.33 µm is 90%. The reflectance of the output mirror is 20% at λ = 1.06 µm and ~70% at λ = 1.33 µm. The estimates obtained using the expression [4]

$$R_{\rm opt} = \exp\left[-2\gamma L\left(\sqrt{\frac{GA}{\gamma L}} - 1\right)\right]$$

(γ is the internal loss coefficient, L is the active zone length, G is the gain, and A is the excess over the pumping threshold) show that this mirror is close to optimal for both wavelengths.

Active Q-switching used in the laser was based of frustrated total internal reflection (FTIR). The nominal switching time of the Q-switch was 600 ns. The active elements were pumped by laser diode arrays. The operation of pump units (*10*, *11*) and Q-switch control unit (*12*) was synchronised by the master oscillator (*9*) and delay units (*13*, *14*).

The output energy of each resonator and of the entire laser system with simultaneous operation of both resonators was measured using an Ophir PE-50 energy meter. The measurement results are given in Table 1.

Table 1. Laser energy in different operation regimes.

Operation regime	Energy/mJ		
	Shoulder I	Shoulder II	Simultaneous operation of shoulders
Free-running regime	45 ± 2	30 ± 2	75 ±3
Q-switched regime	34 ± 2	15 ± 1	49 ± 2

In addition, we measured the time characteristics of the laser output radiation. The laser pulses were recorded by a FEK-15 photodetector and a TDS 6604 oscilloscope both separately for each resonator and for simultaneous operation of both resonators. Figure 2 presents the oscillograms of laser pulses in the case of separate operation of each resonator. One can see that the pulse durations at the two wavelengths are approximately the same. This can be explained by insufficiently fast Q-switching [5].

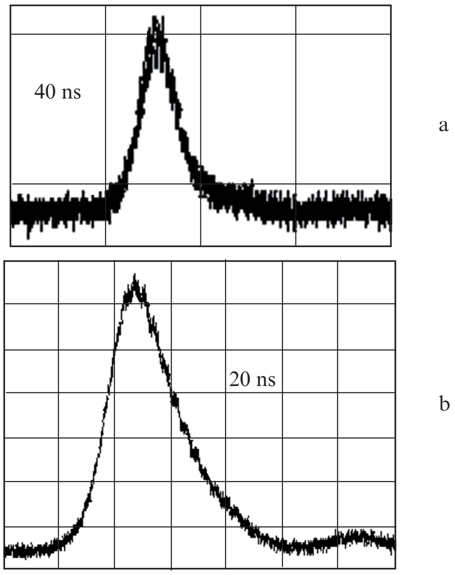

Figure 2. Typical oscillograms of radiation pulses at λ = 1.06 µm with a half-height duration of ~20 ns (a) and at λ = 1.33 µm with a half-height duration of ~27 ns.

Figure 3 shows the pulse oscillogram in the case of simultaneous lasing at two wavelengths. It is seen that pulses with different wavelengths are emitted at different time moments. The delay between the pulses is ~380 ns, which may occur due to different lasing conditions in cavities I and II.

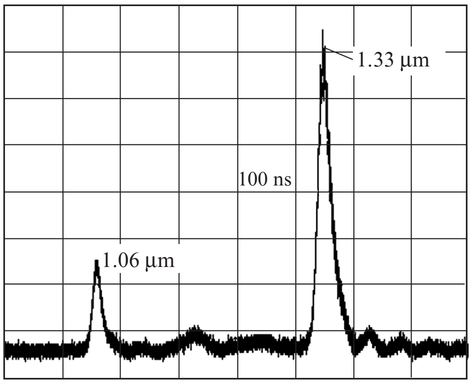

Figure 3. Oscillogram of radiation pulses at simultaneous operation of two resonators.

To synchronise laser pulses in the channels, the electric signal controlling the pump unit (*11*) was delayed using the delay unit (*13*) (Fig. 1). Figure 4 shows the time diagram of electric signals controlling the pump units, Q-switch, and FEK-15. Approximately 180 µs after beginning of pumping of the active element in the channel with λ = 1.33 µm [signal (*1*)], pumping of the active element emitting at λ = 1.06 µm [signal (*2*)] begins. Then, ~240 µs from the initial instant, the Q-switch opens [signal (*3*)] and lasing occurs [signal (*4*)].

The oscillogram of a FEK-15 signal obtained using synchronisation of pulses at the two wavelengths is shown in Fig. 5.

The emission spectrum of the two-frequency laser was studied using a spectrum analyser. The obtained data are presented in Fig. 6.

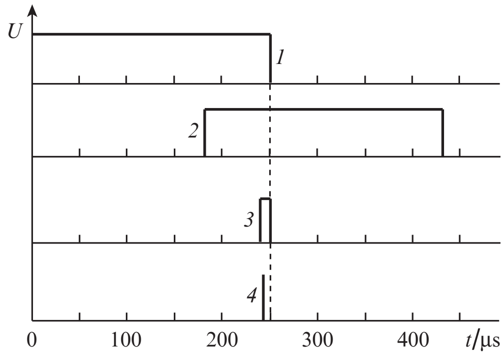

Figure 4. Time diagrams of signals U controlling pump unit (*10*) [signal (*1*)], pump unit (*11*) [signal (*2*)], Q-switch (12) [signal (*3*)], and FEK-15 [signal (*4*)].

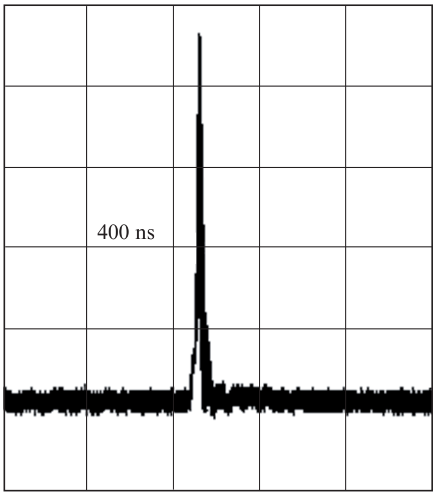

Figure 5. Pulse oscillogram in the case of simultaneous lasing at two wavelengths.

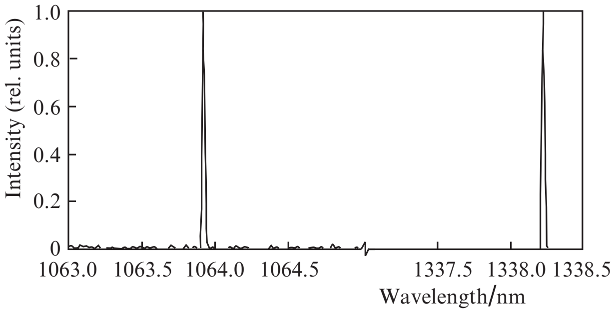

Figure 6. Spectrum of the two-frequency laser.

3. Single-pass two-frequency amplifying system

We experimentally studied a single-pass laser amplifier. The above-described two-frequency laser was used as a master oscillator, and an 'Igla-M2-6.3' quantron with a Nd^{3+}:YAG active element 6.3 mm in diameter was used as an amplifier. The small signal gain per pass through the active element was ~4 at $\lambda = 1.06$ μm and ~1.5 at $\lambda = 1.33$ μm.

The amplifier output energy at $\lambda = 1.06$ μm in the absence of lasing at $\lambda = 1.33$ μm was 134±7 mJ, while the radiation energy at $\lambda = 1.33$ μm in the absence of lasing at $\lambda = 1.064$ μm was 24±1 mJ. At simultaneous amplification of radiation at both wavelengths, the amplifier output energy was 158± 7 mJ.

The saturation energy density of an active medium can be determined by the formula $E_s = h\nu/\sigma$, where σ is the stimulated emission cross section. For the used crystal, $E_s = 1.044$ J cm^{-2} for radiation at $\lambda = 1.06$ μm and 4.26 J cm^{-2} for radiation at $\lambda = 1.33$ μm.

4. Conclusions

The proposed laser configuration allows Q-switched lasing at two wavelengths with time synchronisation of pulses with an accuracy to the pulse duration. More precise synchronisation can be obtained using spectral separation of output beams and a two-channel scheme of recording of the laser pulse duration. The studied laser has a common output mirror for both cavity shoulders. This is believed to be helpful for matching of directional diagrams of beams with different wavelengths; however, this statement needs additional investigation.

Simultaneous amplification of laser radiation at two wavelengths in a Nd^{3+}:YAG crystal was studied. The comparison of obtained results with the results of amplification at individual wavelengths shows that the amplifier operates in a saturated regime at $\lambda = 1.06$ μm and in an unsaturated regime at $\lambda = 1.33$ μm.

The radiation with the reported parameters can be used for generation of sum and difference frequencies, as well as for parametric light generation. It should be noted that the difference frequency generation using the studied two-frequency laser will allow one to obtain radiation with a frequency of ~1823 cm^{-1}, which falls into the atmospheric transparency window [6] and can be used in communication technologies (laser communication lines).

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