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Holmium laser with an acousto-optic paratellurite filter

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Abstract. **Experimental results on a solid-state holmium laser (Ho:YAG) with an intracavity acousto-optic paratellurite filter are presented. The laser power in cw and repetitively pulsed regimes is determined experimentally. It is shown that the use of an acousto-optic filter in the Ho:YAG laser cavity makes it possible to solve several important problems such as obtaining repetitively pulsed lasing, wavelength tuning and linearly polarised emission.**

Keywords: *holmium laser, acousto-optic filter, centre wavelength, controlling signal power.*

1. Introduction

Solid-state holmium laser (Ho:YAG) is of great interest for various scientific, industrial, medical and engineering applications [1]. This is explained by the fact that the radiation of these lasers falls into one of the atmospheric transparency windows and lies in the eye-safe wavelength region [2]. Holmium laser can be used to solve a number of applied problems, including pumping of optical parametric oscillators (OPOs) based on $ZnGeP_2$ crystals [3], which are efficient sources of near- and mid-IR radiation.

To achieve a maximum conversion efficiency in OPOs, the holmium laser must satisfy several requirements. These requirements include the stability of the laser pulse amplitude and the linear polarisation of radiation. It was shown in [4] that, to obtain single-wavelength operation of a Ho:YAG laser, one must use intracavity spectral selection. In the absence of selective elements, lasing may occur at two competing wavelengths, which leads to a strong amplitude instability of output laser pulses. As a spectral selector, one most often uses a Fabry–Perot etalon, i.e., a 100-μm-thick quarts plate [1].

In most practical schemes of holmium lasers, the repetitively pulsed regime is realised using a crystalline quartz acousto-optic modulator [2, 4]. One of the drawbacks of this modulator is a low (50%) modulation efficiency at a relatively high power of the controlling high-frequency signal. In some cases, one uses electro-optic modulators operating at controlling voltages of the order of a kilovolt [5].

The linearly polarised radiation of a holmium laser is most often produced using a dichroic mirror with an optical coating, which discriminates radiation with the spurious polarisation (to achieve emission with a close-to-linear polarisation, the discrimination must be no lower than 50%). However, the fabrication of such mirrors is a challenging technological problem.

In this work, we present the results of experimental studies of a holmium laser with a paratellurite intracavity acousto-optic filter (AOF), which is applied to achieve repetitively pulsed lasing. Our analysis of the literature allows us to conclude that this work is the first in which a paratellurite AOF is used for *Q*-switching, as well as for the spectral and polarisation selection of neodymium laser radiation. At the same time, it is known that the method of controlling the spectral and polarisation characteristics of radiation using an AOF has been for a long time successfully used in lasers of different types [6–8]. The use of paratellurite AOFs makes it possible to achieve amplitude-stable linearly polarised single-wavelength emission of a holmium laser without employment of additional intracavity elements.

2. Experimental setup

The scheme of the experimental setup is presented in Fig. 1. A Ho:YAG crystal was longitudinally pumped by a cw thulium laser at a wavelength of 1.908 μm. The pump beam passed twice through an active element 30 mm long with a Ho^{3+} concentration of 1 at % and was almost completely absorbed in the active element. The holmium laser cavity was formed by three mirrors, namely, by plane highly reflecting mirror M1 with a high reflection coefficient at wavelengths from 1.9 to

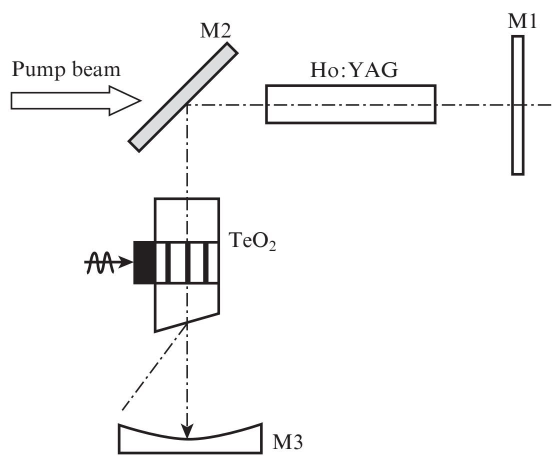

Figure 1. Scheme of the setup.

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2.1 μm, dichroic mirror M2 with a high reflection (approximately 99%) at the lasing wavelength and a high transmission (about 92%) at the pump wavelength, and output spherical mirror M3 with a curvature radius of 200 mm and a reflection coefficient of about 60% at the lasing wavelength. The physical cavity length was 100 mm. According to our calculations taking into account the induced thermal lens, the fundamental mode diameter in the crystal was ~0.55 mm. The beam diameter at the exit from the cavity was 0.8 mm. The pump beam was focused into a spot 0.6 mm in diameter (all diameters are given at the energy level e^{-2}).

The AOF was placed into the output shoulder of the cavity between the dichroic (M2) and output (M3) mirrors. The paratellurite crystal was 28 mm long. The piezoelectric transducer dimensions were 17×1.8 mm. The optical axis of the AOF made an angle of ~14° with the acoustic wave front [9]. The angle of incidence of laser radiation on the acoustic wave front was ~20°. The working faces of the crystal were antireflection coated for the wavelength $\lambda = 2$ μm. The output face of the crystal was cut at a small angle. Owing to this, the angle between the diffracted and passed laser beams at the exit from the crystal was ~7°. The optical axis of the cavity was coupled to the diffracted beam, and lasing occurred only at the open AOF. The laser wavelength was determined by the frequency of the controlling signal applied to the AOF.

In the first experimental series, we determined the controlling signal parameters suitable for the Ho:YAG laser wavelengths. For this purpose, the holmium laser was tuned to a required wavelength using an etalon. In the second series of experiments, the AOF was placed into the cavity in order to obtain a repetitively pulsed regime and wavelength tuning.

3. Experimental results and discussion

Table 1 presents the experimental values of controlling signal frequencies needed for operation of the Ho:YAG laser at particular wavelengths. The centre wavelengths are found by approximating the experimental dependences. The measurements were performed at room temperature. It is necessary to note that an increase in the crystal temperature by 20 °C led to a frequency shift of 50 kHz.

Table 1. Controlling signal frequencies for different Ho:YAG laser wavelengths.

Wavelength/μm	Centre frequency/MHz
2.091	49.40
2.097	49.28
2.123	48.66

To decrease the random error, the AOF efficiency was measured using a two-channel optical scheme. The controlling signal power did not exceed 2 W. The maximum AOF efficiency achieved in the experiments was 87%. According to the experimental data, the acoustic transmission band of the AOF was ~160 kHz. The transmission band width at half maximum was ~7 nm [10].

Figure 2 shows the dependence of the cw Ho:YAG laser power on the pump power. The laser power at the wavelength $\lambda = 2.091$ μm turned out to be somewhat lower than at $\lambda = 2.097$ and 2.123 μm. The maximum output laser power density at these wavelengths was almost identical and equal to 2.6 kW cm^{-2}, and the corresponding conversion efficiency was 52%. The slope conversion efficiency exceeded 60%. The study of the polarisation degree showed that the Ho:YAG laser radiation was completely linearly polarised in the vertical plane. This is explained by the fact that the diffracted beam at the AOF exit was also polarised in the vertical plane.

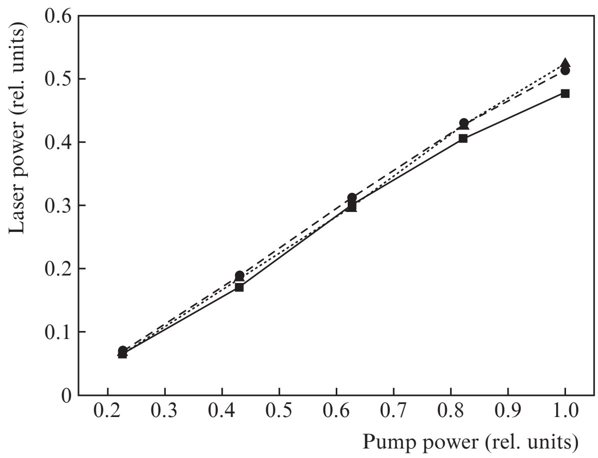

Figure 2. Dependences of the cw Ho:YAG laser power on the pump power for wavelengths λ = (■) 2.091, (●) 2.097 and (▲) 2.123 μm.

Our investigations of the laser spectrum showed that lasing occurred at one wavelength dependent on the frequency of the controlling signal applied to the AOF. By changing the controlling signal frequency according to Table 1, we obtained tuning of the laser wavelength. At the same time, it should be noted that lasing without an AOF occurred randomly at two wavelengths, 2.091 and 2.097 μm.

Figure 3 presents the dependence of the average repetitively pulsed Ho:YAG laser power on the pump power. The pulse repetition rate of 10 kHz was chosen based on the radiation resistance of the coatings of the cavity mirrors.

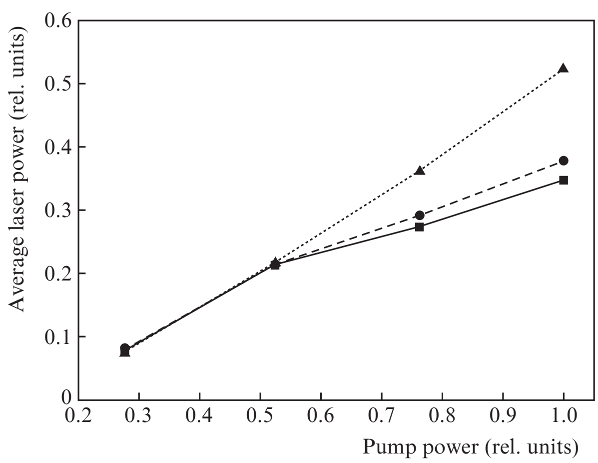

Figure 3. Dependences of the average power of the repetitively pulsed Ho:YAG laser on the pump power for λ = (■) 2.091, (●) 2.097 and (▲) 2.123 μm.

The measurements of the average power and energy showed that the entire output radiation was emitted in the form of short laser pulses with a duration of 35 ns and a repetition rate of 10 kHz.

The maximum laser power density at the cavity exit in the repetitively pulsed regime was observed at a wavelength of

2.123 μm and reached 2.6 kW cm^{-2}. The conversion efficiency at this wavelength in the repetitively pulsed regime was the same as in the cw regime. Further increase in the laser power enhances the probability of breakdown of the coatings of mirrors. The maximum achieved pulse power density at the cavity exit was 0.26 J cm^{-2}. In the case of the Ho:YAG laser operation at the wavelengths λ = 2.097 and 2.091 μm, we observed a noticeable decrease in the conversion efficiency, which was related to insufficiently fast response of the AOF. The matter is that the effective gain cross section at λ = 2.091 and 2.097 μm is almost twice as high as the corresponding value for λ = 2.123 μm. Because of this, the laser pulses at λ = 2.091 and 2.097 μm build up more rapidly than at λ = 2.123 μm and, at some pump power, the build-up time begins to exceed the AOF response time, which decreases the conversion efficiency (Fig. 3). The AOF response time can be estimated as the ratio of the laser beam diameter to the acoustic wave velocity. It should be noted that the parameter that determines the AOF response time is the acoustic wave velocity, which in our case was ~800 m s^{-1}. At a typical beam diameter of 0.55 mm, the AOF response time is ~0.7 μs.

Figure 4 shows the oscillogram of laser pulses at a fixed pump power density. Time was measured from the triggering pulse applied to the AOF. This dependence allows one to estimate the time intervals proportional to the build-up rate of laser pulses.

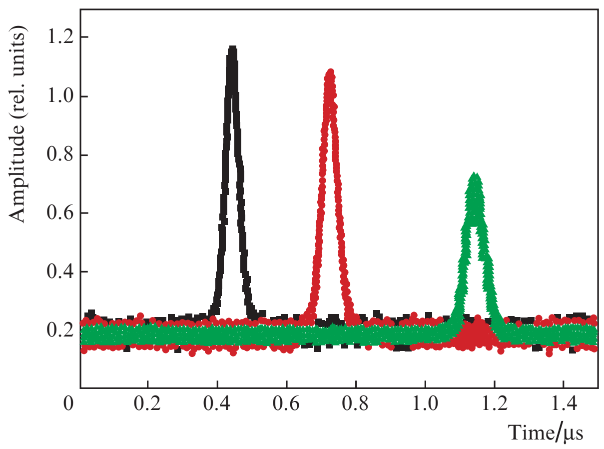

Figure 4. Oscillograms of laser pulses at λ = (■) 2.091, (●) 2.097 and (▲) 2.123 μm.

The experiments also showed that the repetitively pulsed radiation at the laser exit had the maximum contrast. This was achieved owing to the spatial separation of beams in the AOF.

4. Conclusions

We presented the results of experimental investigations of a solid-state holmium laser with a paratellurite intracavity AOF. The most efficient lasing occurred at a wavelength of 2.123 μm. The maximum achieved power density at the cavity exit was 2.6 kW cm^{-2}, while the maximum pulse energy density was 0.26 J cm^{-2}.

Our experiments showed that the use of a paratellurite AOF in the Ho:YAG laser cavity allows one to solve the most important problems related to its application in the systems used to pump OPOs based on the $ZnGeP_2$ crystal. It is necessary to note that this paper reports for the first time the use of a paratellurite AOF for *Q*-switching, as well as for the spectral and polarisation selection of holmium laser radiation. The use of the AOF allows one to achieve amplitude-stable linearly polarised single-wavelength laser radiation without employing additional intracavity elements.

References

1. Walsh B.M. *Laser Phys.*, **19** (4), 855 (2009).
2. Grachev S.V. *Ho:YAG lazer v meditsine* (Ho:YAG Laser in Medicine) (Moscow: Triada-X, 2003).
3. Budni P.A., Pomeranz L.A., Lemons M.L., Miller C.A., Mosto J.R., Chicklis E.P. *J. Opt. Soc. Am. B*, **17**, 723 (2000).
4. Lippert E., Nicolas S., Arisholm G., Stenersen K., Rustad G. *Appl. Opt.*, **45**, 3849 (2005).
5. Hemming A., Richards J., Bennetts S. *Opt. Commun.*, **283**, 4041 (2010).
6. Stel'makh M.F., Dmitriev V.G., Mikhailov L.K., et al. *Zh. Prikl. Spektrosk*. **40** (2), 181 (1984).
7. Mazur M.M., Makhmudov Kh.M., Pustovoit V.I. *Kvantovaya Elektron.*, **15** (4), 711 (1988) [*Sov. J. Quantum Electron.*, **18** (4), 453 (1988)].
8. Baburin N.V., Galagan B.I., Danileiko Yu.K., et al. *Kvantovaya Elektron.*, **31** (4), 303 (2001) [*Quantum Electron.*, **31** (4), 303 (2001)].
9. Chang I.C. *Appl. Phys. Lett.*, **25**, 370 (1974).
10. Magdich L.N., Molchanov V.Ya. *Akustoopticheskie ustroistva i ikh primenenie* (Acousto-optic Devices and Their Application) (Moscow: Radio i svyaz', 1978).