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Continuous-wave and high repetition rate Q-switched operation of Ho:YLF laser in-band pumped by a linearly polarized Tm:fiber laser

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ABSTRACT

A study of Ho:YLF laser in continuous-wave (CW) and Q-switched operation, single-pass end-pumped by a Tm:fiber laser is presented. The research was made for two crystals of the same length and with different Ho dopant concentrations (0.5 at%, $3\times3\times30$ mm^3 and 1.0 at%, $5\times5\times30$ mm^3). The lasers operated on π-polarization. The lasers based on both crystals were examined under the same experimental circumstances. At room temperature, for an output coupling transmission of 40%, the maximum CW output powers of 11.5 W (0.5 at%) and 14.5 W (1.0 at%) were achieved, corresponding to slope efficiencies of 40.9% and 53.4% and optical-to-optical efficiencies of 35.4% and 44.6% with respect to the incident pump power, respectively. For a Q-switched operation, in a CW pumping regime, the pulse repetition frequency (PRF) was changed from 1 to 10 kHz. For this case, the maximum average output power of 14.2 W at the PRF of 10 kHz was obtained for a higher holmium-doping concentration crystal. For 1 kHz PRF, pulse energies of 5.7 mJ with a 11 ns FWHM pulse width corresponding to almost 520 kW peak power were recorded. The laser operated at the wavelength of 2050.08 nm with the FWHM line width of 0.86 nm delivering a near-diffraction-limited beam with M^2 values of 1.05 and 1.09 in the horizontal and vertical directions, respectively.

1. Introduction

The mid-infrared spectrum around 2 μm has been one of the most explored regions in laser technology in recent years [1,2]. High-power, short-pulse, high-repetition rate and high-energy 2-μm lasers have a wide range of potential applications in various fields such as medicine [3], military and science [4]. Due to the presence of strong absorption provided by different molecules, such as H_2O, CO_2, N_2O, NH_3 these lasers can be used in range finding, remote sensing [5,6], contamination detection and recognition, evaluation of atmosphere composition or water vapor profiling. Furthermore, due to the eye-safe feature, they offer unique and exceptional properties, which are required in such applications as material processing or laser surgery, dentistry and therapy. Additionally, 2-μm high peak power solid-state lasers are very effective pump sources of 3–10 μm optical parametric oscillators (OPOs), which are needed in advanced security and defense systems [7].

The most attractive and popular lasers are the ones based on thulium (Tm^{3+}) and holmium (Ho^{3+}) doped materials. They oscillate in the region of 1.9 μm and 2.1 μm, respectively. However, in high energy applications due to the high emission cross-section and relatively long upper-state lifetimes, Ho crystals are preferred when compared with Tm media.

Due to the lack of high power laser diodes operating at 1.9 μm (the absorption region of Ho-doped hosts), which can be used to pump Ho lasers directly, other approaches have been employed (however, recently, a Ho:YAG laser directly in-band pumped by a laser diode stack at 1.9 μm was demonstrated [8]). Initial works were concentrated on thulium–holmium co-doped lasers operation when pumped by 795 nm laser diodes [9]. Nowadays, holmium lasers are very often resonantly pumped by 1.9 μm Tm lasers [10], which have the advantage of minimal heating owing to the very low quantum defect between the pump and laser photons.

Recently, high efficiency holmium-doped lasers in different configurations based on hosts like YAG [11], YLF [12], YAP [13], LuAG [14], LuYAG [15], LLF [16], LSO [17], KLuW [18], KYF [19], ceramic [20], and silica fiber [21] have been intensively researched and reported. It seems that the high emission cross-section, long upper-laser level lifetime (~14 ms) [22], good thermal and mechanical properties, (i.e. a very weak thermal lens which helps to deliver diffraction limited beams even under intense end-pumping) as well as the natural birefringence of a YLF host,

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enabling the polarized light without an external polarizer, make Ho:YLF crystals particularly suitable for producing high energy pulses. In addition, for further output energy scaling up an master oscillator power amplifier (MOPA) configuration can be employed. An absorption spectrum of Ho:YLF at 1.94 μm [23] has a good overlap with the emission of many Tm lasers, so they can be used as efficient pump sources. At present, a variety of laser materials have been used to generate the 1.94 μm laser radiation, such as Tm:YLF [24], Tm:YAP [25], Tm:fiber (IPG Photonics). However, Tm-doped fiber lasers generating at 1.94 μm seem to be the most attractive sources for the direct pumping of Ho:YLF crystals, due to a very low quantum defect, an excellent mode matching resulting from the high quality of the pumping beam, compactness and modularity of the optical scheme. Furthermore, commercial availability of high power Tm:fiber lasers makes Tm:fiber-pumped Ho:YLF lasers one of the most attractive candidates for producing Joule level 2 μm pulses from a relatively compact setup. There are some reports on high power, high-energy Ho:YLF lasers operating in oscillator or MOPA configurations. To achieve hundreds of mJ pulse energies, extremely high pump powers, cryogenic cooling systems of Ho:YLF crystals, long cavity laser configurations and dry air atmosphere are needed. Furthermore, in case of high energy level systems, pulse repetition frequency is limited to a single Hz [26]. Such solutions are often presented as huge laser systems difficult to be commercialized. It is also worth adding that resonantly pumped Ho:YLF lasers in MOPA format can operate in various configurations and pumping schemes. In the first method, the collimated high power Tm:fiber laser pump radiation, unabsorbed in the oscillator, can be subsequently used to pump the amplifier stage [27]. In the second approach the reflected, unused in the oscillator stage, polarized beam radiation can be used to pump an amplifier stage by applying another crystal rotated by 90° around the laser beam axis, e.g. it was utilized in the scheme presented by Dergachev [28].

In this paper, we report on a CW and high repetition rate, acusto-optically Q-switched Ho:YLF lasers single-pass pumped by a linearly polarized, narrow line width of 1.94 μm Tm:fiber laser. The main goal of this research was to assess the maximum energy of generated pulses, applying a very compact oscillator configuration under operation in a room temperature. Therefore, the laser configuration was limited purposely to the use of only one output coupler transmittance. A detailed comparison of resonantly pumped Ho:YLF lasers in the dependence on the lengths of the crystals was made by Schellhorn [29]. This research was made for two crystals of the same length and with different Ho dopant concentrations (0.5 at%, $3\times3\times30\ mm^3$ and 1.0 at%, $5\times5\times30\ mm^3$).

For the CW mode of operation, 14.5 W of output power with 53.4% slope efficiency determined with respect to incident pump power was demonstrated. The Q-switched laser operated at a frequency ranging from 1 to 10 kHz and delivered pulses with 5.7 mJ energy and 11 ns duration (one of the shortest pulse durations observed in holmium-doped Q-switched lasers), corresponding to over 0.5 MW peak power. The performance of the developed lasers under CW and pulsed operation is described. Furthermore, we present what we believe to be the first report on the issues of timing jitter and pulse-to-pulse energy variations between generated pulses in Q-switched Ho:YLF lasers, which can be attributed to the fluctuations of pump radiation passing through a polarizing beam splitter.

2. Experimental setup

A Ho:YLF laser based on a longitudinal pumping scheme was developed according to the conception depicted in Fig. 1. In the experiment, the optical pumping was realized by high power Tm:fiber laser made by IPG Photonics operating at the wavelength of 1939.6 nm with a line width of 0.9 nm (FWHM). The fiber laser operated in a CW regime. The pump radiation was delivered to the Ho:YLF crystal by an output facet of the collimator. To modulate the optical cavity losses, an acusto-optic modulator (Gooch and Housego) was utilized.

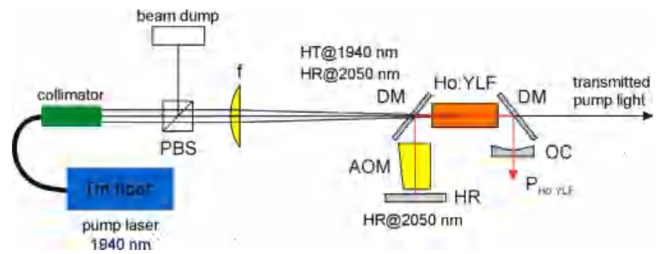

Fig. 1. Experimental setup of the end-pumped Ho:YLF laser: PBS – polarizing beam splitter, DM – flat dichroic mirrors anti-reflective at 1.94 μm and 45-deg highly reflective at 2.05 μm, OC – concave output-coupling mirror, AOM – acousto-optic modulator, HR – high reflector.

When the laser operated in a CW mode, two different a-cut Ho:YLF bricks of 30-mm in length were used as active media. The first one of $3\times3\ mm^2$ facet had 0.5 at% Ho concentration, whereas the other one of $5\times5\ mm^2$ was characterized by 1.0 at% Ho concentration. Their end facets were anti-reflection coated for 1.92–2.10 μm wavelength range. The crystals were wrapped with an indium foil and tightly mounted in a water-cooled copper heat-sink for better thermal contact. The temperature of the water was kept constant at 17 °C.

The same cooling system was applied to the acousto-optic modulator. The non-polarized collimated pump radiation was first divided into two orthogonally polarized beams and then focused inside the Ho:YLF crystals by a plano–convex, AR broadband coated, spherical lens of 600 mm focal length. The pump beam spot radius was measured to be ~200 μm.

The Ho:YLF crystal was positioned between the two flat dichroic mirrors DM at a 45° angle of incidence with high transmission ($T>96.5\%$) at the pump wavelength and high reflectivity for the 2.04–2.07 μm wavelength band, inside a U-shaped plano–concave resonator. The rear cavity HR mirror was flat with high reflectivity at 2.05 μm wavelength. The Ho:YLF laser plane–concave out-coupling mirror OC of 40% transmission with a curvature radius of $R_{OC}=200$ mm was used.

3. Results and discussion

The energetic characteristics of the laser in a CW mode of operation were measured with an acousto-optic modulator (AOM) inside the cavity, for the output coupler transmittance of $T_{OC}=40\%$ at 2050 nm. To optimize output values, the resonator length and the distance from the collimating lens *f* to the Ho:YLF crystal were adjusted. The physical length of the Ho:YLF laser resonator was approximately 145 mm. For the maximum CW incident pump power of 32.5 W, the holmium laser based on 1.0 at% crystal generated output power as high as 14.5 W with a slope efficiency of 53.4%, determined with respect to the incident pump power (Fig. 2). For the maximum system performance, the transmitted pump light behind the second dichroic mirror DM was measured to be 6 W and 14.3 W indicating pump absorption of nearly 82% and 56% for 1.0 at% and 0.5 at% Ho doping concentration crystals, respectively.

For the Q-switched operation, a fused silica, acousto-optic modulator was applied, as is shown in Fig. 1. It was driven by 20 W RF power at 40.68 MHz. The modulating signal was

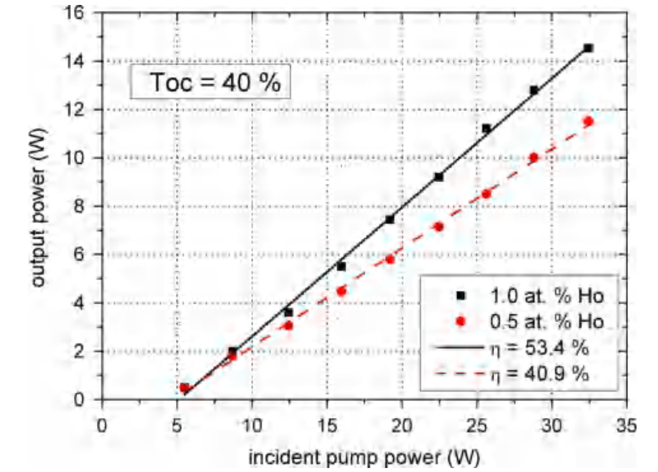

Fig. 2. Output powers of Ho:YLF lasers as a function of incident pump power for a lasers operating in the CW regime. The results of a linear fit and the calculated slope efficiencies are given in the graph.

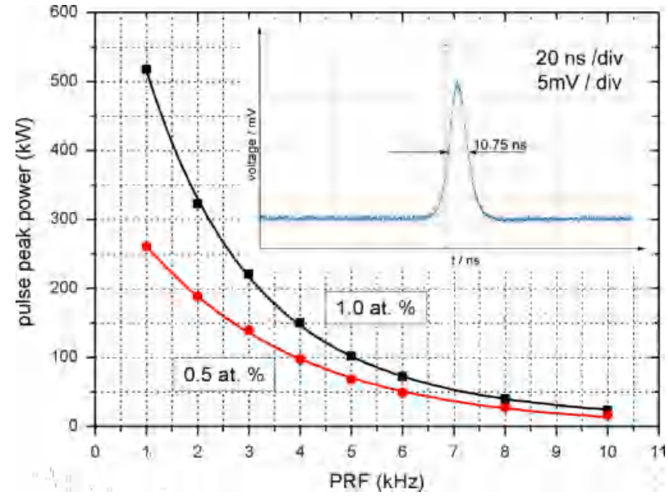

Fig. 4. Pulse peak power as a function of the pulse repetition rate for the maximum pump power of 32.5 W. The inset shows the scope of the shortest (10.75 ns) recorded pulse.

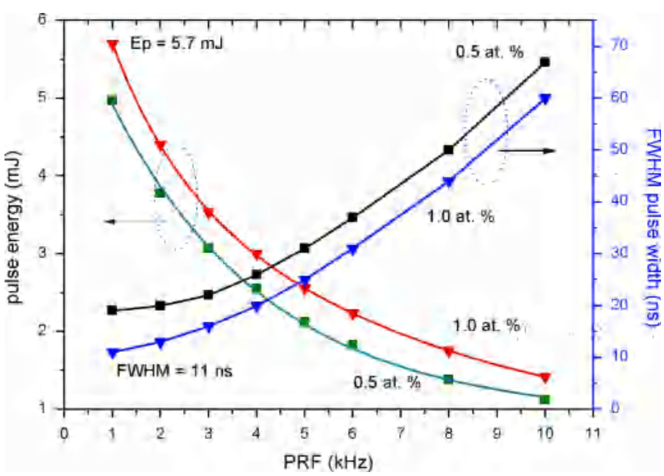

Fig. 3. Pulse energy and pulse width as a function of pulse repetition rate for the maximum pump power of 32.5 W.

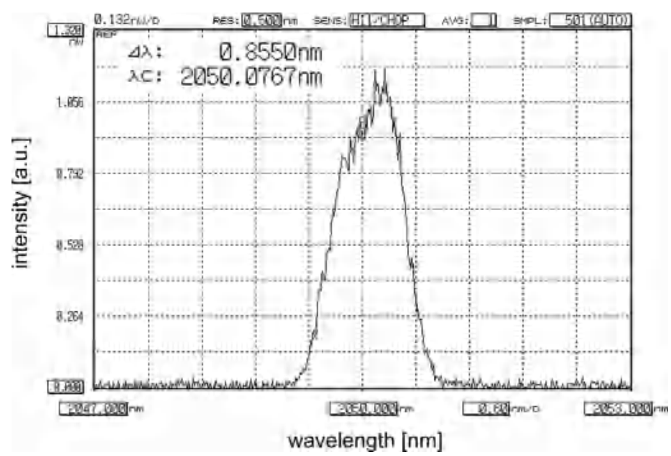

Fig. 5. Emission spectra of the Q-switched 1.0 at% Ho:YLF laser.

synchronized with an external generator. The same out coupling mirror OC (used in the experiment on a CW operation) was applied. The best results, for the incident pump power of 32.5 W, were achieved for Ho crystal with higher doping concentration. The pulse energies and FWHM pulse widths for both crystals are presented in Fig. 3.

The PRF was varied from 1 to 10 kHz. Applying lower repetition rates resulted in an unexpected output coupling mirror damaged, and therefore, they are not discussed in this paper. For the minimum applied frequency, pulses of 5.7 mJ energy were achieved. For the maximum incident pump power (for 10 kHz), the highest average output power of 14.2 W was measured corresponding to the optical-to-optical conversion efficiency of 43.7% with respect to the incident pump power. A >12.5 GHz high-speed detector made by Electro-Optics Technology (ET-5000) was used to measure the 2-μm laser output pulses. The shortest pulses of 11 ns FWHM width and almost 520 kW peak power (Fig. 4) were achieved for the PRF of 1 kHz.

It is worth mentioning the timing jitter of output pulses generated by the developed actively Q-switched laser. The origin of this jitter can be attributed to the fluctuations of pump radiation passing through a polarizing beam splitter. Short-time power instabilities of linearly polarized pump radiation passing through the beam splitter induced the instabilities of energy and FWHM pulse duration of the generated 2 μm pulses. For the maximum applied pump power we observed the maximum timing jitter equal to ~200 ns, causing a significant decrease in pulse peak power. It was especially visible for the higher holmium doping concentration crystal. For lower pump power levels and higher PRFs, the instabilities even led to the interruption of laser generation.

The output spectra of the Ho:YLF lasers for the maximum pump power and 2 kHz PRF were measured with the use of an AQ6375 optical spectrum analyzer with a resolution of 0.5 nm. The lasers operated at 2050.49 nm with the FWHM linewidth of 1.09 nm (0.5 at% Ho crystal) and 2050.08 nm with the FWHM linewidth of 0.86 nm (1.0 at% Ho crystal). Fig. 5 shows the spectrum of the Ho:YLF laser based on 1.0 at% holmium doping concentration crystal.

The beam quality of the Q-switched Ho:YLF laser based on 1.0 at% Ho was measured with the use of a pyroelectric NanoScan – scanning-slit laser beam profiler, making measurements according to ISO 11146. The beam quality parameter M^2 at the 5 kHz PRF and maximum pump power was measured to be 1.05 and 1.09 in horizontal and vertical directions, respectively (Fig. 6). A nearly perfect Gaussian beam profile inside the resonator within the whole scan resulting from the single-mode pump laser operation

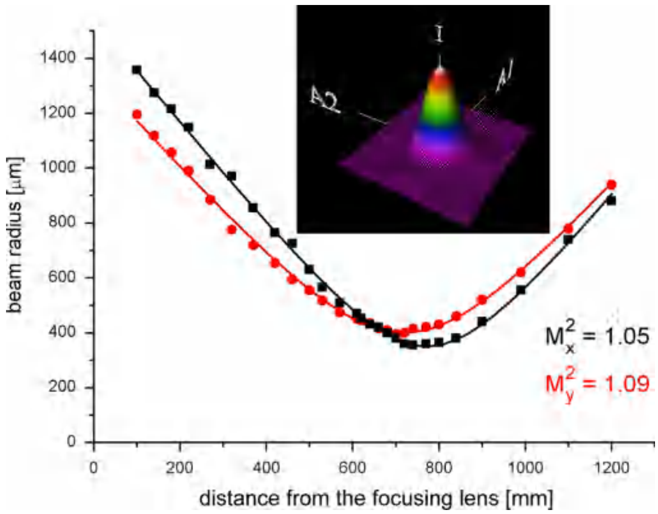

Fig. 6. Caustic determination for the Ho:YLF laser at the 5 kHz PRF and maximum pump power. The inset shows a spatial distribution of the Q-switched Ho:YLF laser beam.

was created. The beam profile in 3D dimension is shown in Fig. 6 as an inset.

4. Conclusions

An efficient single-pass pumped, Q-switched Ho:YLF laser based on a commercially available thulium-doped fiber laser was demonstrated. The maximum output powers in a CW regime of 11.5 W (0.5 at% Ho concentration) and 14.5 W (1.0 at% Ho concentration) were achieved, corresponding to slope efficiencies of 40.9% and 53.4% and optical-to-optical efficiencies of 35.4% and 44.6% determined with respect to incident pump power, respectively. The pulse energies of 5.7 mJ with a 11 ns FWHM pulse width at 1 kHz PRF corresponding to almost 520 kW peak power were obtained.

Acknowledgments

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