A resonantly pumped, Q-switched Ho:YLF laser with an output energy of 5 mJ at 1 kHz

J. Kwiatkowski,* J. Swiderski, W. Zendzian, J. K. Jabczynski, L. Gorajek, and M. Kaskow

Institute of Optoelectronics, Military University of Technology, Kaliskiego 2, 00-908 Warsaw

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Abstract—The continuous-wave (CW) and Q-switched operation of a Ho:YLF laser resonantly, single-pass pumped by a Tm: fiber laser operating at a wavelength of 1940nm is presented. At room temperature, for an output coupler of 40% transmission, a maximum CW output power of 11.5W for 32.5W of incident pump power was achieved, corresponding to a slope efficiency of 40%. Applying Q-switching operation, and under CW pumping regime, the pulse repetition frequency (PRF) was changed from 1 to 10kHz. The maximum average output power of 11.23W at the PRF of 10kHz was obtained. Lowering the PRF to 1kHz allows achieving a pulse energy of 4.97mJ in a 19ns pulse corresponding to the maximum peak power of 260kW. The Ho:YLF laser operated at the wavelength of 2050.5nm with a FWHM line width of 1.09nm. The output parameters of the laser radiation are sufficient enough to be used for range finding or for pumping mid-infrared optical parametric oscillators.

The mid-infrared (mid-IR) spectral region (wavelengths beyond 2 microns) has been one of the most explored research regions in laser technology in recent years [1]. A number of different molecules present in the atmosphere, such as H_2O, CO_2, N_2O, NH_3, have strong absorption lines laying in the mid-IR. The use of pulsed lasers delivering radiation at wavelengths fitted to particular absorption lines is the necessity, e.g. in detection of biologically hazardous and explosive materials, in detection of contamination and recognition or evaluation of atmosphere composition. Apart from that, these lasers offer unique and exceptional properties which are required in such applications as material processing or laser surgery and therapy. Excellent sources operating in the mid-IR are lasers based on thulium (Tm^{3+}) and holmium (Ho^{3+}) doped materials. They oscillate in the region of ~1.9µm and ~2µm, respectively. In recent years, high efficiency Ho-doped laser oscillators in different configurations based on hosts like YAG [2], YLF [3], YAP [4], LuAG [5], LLF [6], LSO [7], ceramics [8], and silica fiber [9] have been developed and reported.

It seems that the high gain cross section, long upper laser level lifetime (14ms), good thermo-mechanical behaviour (especially reduced thermal lensing) as well as the birefringent nature of an YLF host make Ho:YLF crystals particularly suitable to generate high energy laser pulses.

High absorption cross section of holmium doped media on $^5I_7$ energy level [10] makes Tm-doped fiber lasers operating at 1940nm one of the most attractive sources for direct pumping of Ho:YLF crystals. Additionally, the availability of high power commercial Tm:fibre lasers makes a Tm:fibre pumped Ho:YLF laser one of the most attractive candidates for producing Joule-level 2-micron pulses from a relatively compact 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 a high power Tm: fiber laser made by IPG Photonics operating at a wavelength of 1939.6nm with a FWHM line width of 0.9nm. It operated in the CW regime and could deliver up to 120W. The pump radiation was directed to a Ho:YLF crystal by an output facet of the collimator. The collimated beam diameter and divergence angle were 5.8 mm and 0.46mrad, respectively. The beam quality factor M^2 was measured to be 1.08.

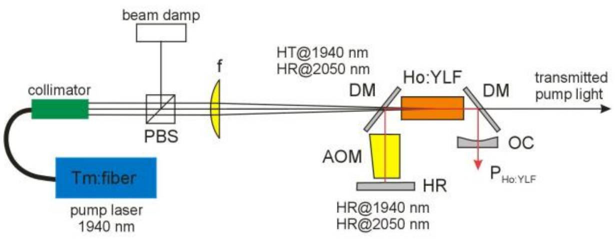

Fig. 1. Setup of the end-pumped Ho:YLF laser, where: PBS – polarizing beam splitter, DM – flat dichroic mirrors, anti-reflective at 1.94µm and 45-deg highly reflective at 2.05µm, OC – concave output-coupling mirror, AOM – acousto-optic modulator, HR – high reflector.

A 0.5%, a-cut Ho:YLF brick of 30-mm in length was used as an active medium. Its end facets were anti-reflection (AR) coated for the 1920-2100nm wavelength band. The crystal was wrapped with an indium foil and mounted in a water-cooled copper heat-sink. In the experiment, the temperature of the Ho:YLF crystal was held at 17°C. The same cooling system was applied to an

* E-mail: jkwiatkowski@wat.edu.pl

acousto-optic modulator (AOM). The unpolarized collimated pump radiation was firstly divided into two orthogonally polarized beams (by using a polarizing beam splitter plate) and then focused inside the Ho:YLF crystal by a plano-convex spherical lens of a focal length of f=600mm with an AR broadband coating. The Ho:YLF crystal was positioned between the flat dichroic mirrors (DM) with high transmission (T>96.5%) at the pump wavelength and high reflectivity for the 2040-2070nm wavelength band, inside a plano-concave resonator. The laser output mirror of 40% transmission with a curvature radius of R_{OC}=200mm was used. An acousto-optic modulator manufactured by Gooch & Housego was used to Q-switch the laser operation.

The output power of the laser was measured in a CW mode of operation in a cavity with the AOM, for the same output coupler transmittance as in the Q-switch regime (T_{OC}=40% at 2050nm). To optimize the best output values, the length of the resonator and distance from the collimating lens f to the Ho:YLF crystal were adjusted properly. The physical length of the resonator was 145mm. For the maximum applied CW pump power of 32.5W, the holmium laser generated output power as high as 11.5W with a slope efficiency of 40%, determined with respect to incident pump power (Fig. 2).

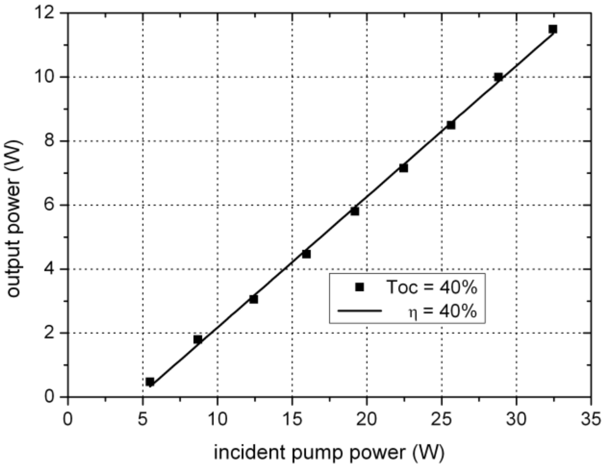

Fig. 2. Output power vs. incident pump power for a laser operating in the CW regime.

In the Q-switch regime a fused silica, conduction cooled AOM was inserted into the cavity. It was driven by a 20 W RF power at 40.68 MHz. The modulating signal was synchronized with the external generator. The best results for the incident pump power of 32.5 W are listed in Table 1 and presented in Fig. 3.

Table 1. Best results of Q-switching for the CW pumping regime.

PRF (kHz)	Pulse width (ns)	Average power (W)	Pulse energy (mJ)	Peak power (kW)
1	19	4.97	4.97	261.58
2	20	7.55	3.78	188.75
3	22	9.20	3.07	139.39
4	26	10.20	2.55	98.08
5	31	10.60	2.12	68.39
6	37	10.94	1.82	49.28
8	50	11.03	1.38	27.58
10	67	11.23	1.12	16.76

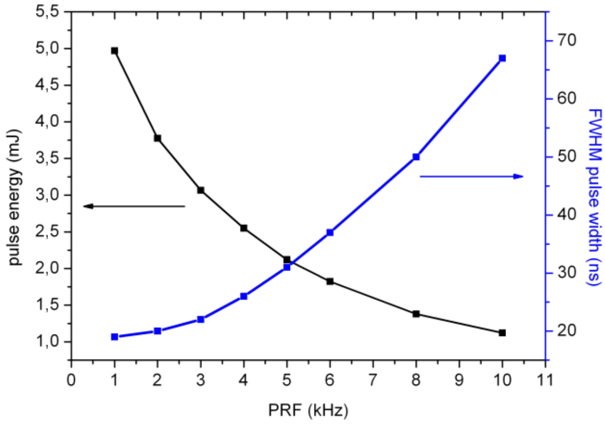

Fig. 3. Pulse energy and pulse width as a function of PRF measured for the maximum pump power of 32.5W.

The PRF was varied from 1 to 10kHz. For the minimum applied frequency, pulses of almost 5mJ energy were achieved. For the maximum incident pump power (at 10kHz), the highest average output power of 11.23W was measured corresponding to optical-to-optical conversion efficiency of 34.5%. A >12.5GHz high-speed detector with a rise/fall time of 28ps made by Electro-Optics Technology (ET-5000) was used to measure the 2-μm laser output pulses. For the PRF of 1kHz, the shortest pulses of 19ns FWHM duration and 261kW peak power were recorded.

The output spectrum of the Ho:YLF laser was measured with the use of an AQ6375 optical spectrum analyzer made by Yokogawa with a resolution of 0.5nm. The laser operated at the wavelength of λ=2050.5nm (transition between $^5I_7 \rightarrow {}^5I_8$ energy levels). The spectrum FWHM width was 1.09nm (Fig. 4).

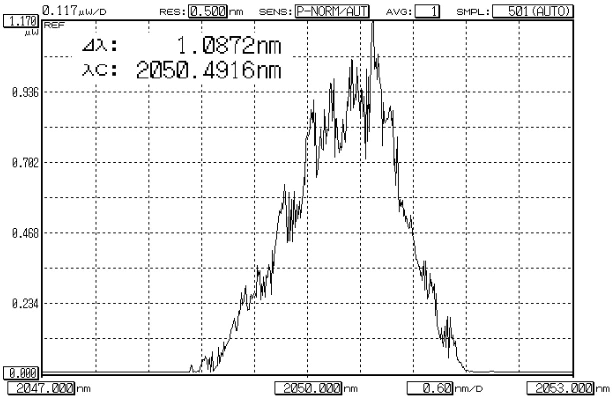

Fig. 4. Emission spectrum of the Q-switched Ho:YLF laser.

In conclusion, a single-pass, Q-switched Ho:YLF laser pumped by a commercially available thulium-doped fiber laser, with the maximum peak power of 260 kW, was demonstrated. Under CW pumping, the output power of 11.5 W with a 40% slope efficiency, determined with respect to incident pump power, was observed. However, the maximum available pump power was not applied. Using the fiber laser to end pump the Q-switched Ho:YLF laser, pulses of 19 ns in duration and with an energy of 4.97mJ (at 1kHz) were obtained. The experiments on output power scaling up are planned to be performed in the near future. The output parameters of the developed Ho:YLF laser seem to be satisfactory for pumping ZGP-OPOs operating in the mid-infrared range.

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