Optics & Laser Technology 67 (2015) 93–97

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

An efficient continuous-wave and Q-switched single-pass two-stage Ho:YLF MOPA system

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ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form
24 September 2014
Accepted 30 September 2014
Available online 24 October 2014

Keywords:
Mid-infrared lasers
Ho:YLF
Solid-state lasers

ABSTRACT

We report on the efficient operation of an Ho:YLF laser single-pass in-band pumped by a Tm-doped fiber laser. The research in a continuous-wave (CW) operation in an oscillator scheme was done for a crystal of 0.5 at% Ho dopant concentration and the length of 30 mm for the output coupler transmittances of T_{OC}=10%, 20%, 30% and 40%. At room temperature, for the output coupling transmission of 20%, the maximum CW output power of 24.5 W for 82.5 W of incident pump power, corresponding to the slope efficiency of 35.4% and optical-to-optical conversion efficiency of 29.7% was achieved. The highest slope efficiency of 81.6% with respect to absorbed pump power was obtained. Carrying out the measurements of the laser spectrum, for the out-coupling transmittance of T_{OC}=30%, we observed a very short time wavelength shift between 2051.5 and 2062.4 nm in an Ho:YLF laser operation. Trying to fully utilize the pump power unabsorbed by the active crystal in an oscillator stage, an amplifier system based on two additional Ho:YLF crystals was developed. For the output coupling transmission of 40% the slope efficiency increased from 31.5% in an oscillator scheme to 47.3% with respect to the incident pump power in a two-stage amplifier scheme with a beam quality parameter of M^2 better than 1.1. For a Q-switched operation, for the maximum incident pump power and the pulse repetition frequency (PRF) of 1 kHz, pulse energies of 18.5 mJ with a 22 ns FWHM pulse width corresponding to 841 kW peak power in the amplifier system were recorded.

1. Introduction

High-power, high-energy 2-μm laser sources are of great interest for a wide variety of scientific and technical applications. They offer properties, which are required in such applications as material processing, medicine [1], remote sensing [2], or in advanced security and defense systems [3]. The most attractive and popular 2-μm lasers, are the ones based on holmium (Ho^{3+}) doped materials, oscillating in the region of 2.1 μm [4]. It appears that in high energy applications due to the high gain cross section in combination with the relatively long upper laser level lifetime, 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 birefringent nature of a YLF host, allow the YLF host doped with Ho ions to become an excellent gain medium particularly suitable for producing high energy Q-switched pulses [5,6]. Nowadays, Ho:YLF lasers are very often resonantly pumped by 1.94 μm high power Tm-doped fiber lasers, which seem to be the most attractive sources for the direct pumping of Ho crystals, due to a very low quantum defect, an excellent mode matching resulting from the high quality of a pumping beam, compactness and modularity of an optical scheme. In addition, for further output energy scaling up a master oscillator power amplifier (MOPA) configuration with the use of high power Tm-fiber lasers can be employed relatively easy.

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 the case of high energy level systems, pulse repetition frequency is limited to a single Hz [7,8]. 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 a MOPA format can operate in various configurations and pumping schemes. In the first method, in the scheme presented e.g. by Dergachev et al. [9], the unpolarized high power pumping beam is split into two polarized beams to pump oscillator and amplifier stages separately. In the second approach proposed by Koen et al. [10] the collimated high power Tm:fiber laser pump radiation, unabsorbed in the oscillator crystal, can be subsequently used to pump the amplifier stage by applying another crystal rotated by 90° around the laser beam axis in comparison to the oscillator crystal. However, in such a configuration almost 22% of pump power

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http://dx.doi.org/10.1016/j.optlastec.2014.09.014
0030-3992/

was still unused and lost. In our approach for the similar incident pump power and in a compact Ho:YLF oscillator–amplifier configuration developed according to Koen's conception, trying to fully utilize pump power, we have used two-stage amplifier system based on two crystals with various lengths and a Ho doping concentration oriented perpendicular to each other. This allowed us to decrease unabsorbed pump power to single percentage points and significantly increase output power in a CW regime as well as pulse energies in a Q-switched operation.

The performance of the developed laser oscillator for various output coupler transmittances as well as the oscillator-two-stage amplifier system under CW and pulsed operation is presented.

2. Experimental setup

A Ho:YLF-MOPA laser based on a longitudinal pumping scheme was developed according to the conception depicted in Fig. 1. The optical pumping was realized by a CW single-mode high power Tm:fiber laser operating at a wavelength of 1940 nm. The unpolarized pump radiation was delivered to the active medium by an output facet of the collimator and focused with the use of a telescope consisting of two focal lenses with focal lengths of +250 mm and −75 mm. The spot radius of the pump beam in the crystal was measured to be ~750 μm. The ‘a-cut’ Ho:$YLF_{(1)}$ brick at 0.5 at% Ho doping concentration, the length of 30-mm and a cross-section of 3×3 mm^2 was used as an active medium in an oscillator configuration. The crystal was positioned between the two flat dichroic mirrors DM1 and DM2 at a 45-deg. 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 laser operated on π-polarization, forcing horizontally polarized radiation. The active medium was 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 a temperature of 16 °C. The rear cavity mirror HR was flat with a high reflectivity at a 2.05 μm wavelength. Plano-concave out-coupling mirrors OC of different transmissions with a curvature radius of $R_{OC}=400$ mm were used in the CW operation experiment. All the time during the experiments the humidity in the laboratory was kept below 20%. Laser Star Dual Channel meter with calibrated laser power and energy sensors were used in measurements.

3. Continuous-wave operation

The output powers of the laser in a CW mode of operation were measured for the output coupler transmittances of $T_{OC}=10\%$, 20%, 30% and 40%. The physical length of the Ho:$YLF_{(1)}$ laser cavity was approximately 400 mm, resulting in a calculated beam radius in the crystal of ~650 μm. Thermal lensing in this calculation was neglected. Due to the imperfect transmittance for the pump wavelength of the dichroic mirror DM2 small portion of the 1940 nm radiation was directed at the Ho:$YLF_{(1)}$ laser output. In order to measure only the pure holmium radiation, wavelengths below 2 μm were additionally separated and transmitted outside the cavity through the dichroic mirrors DM3 and DM4. The power meter in an oscillator scheme was placed in the position S1. At room temperature, for an output coupling transmission of 20% the highest output power and slope efficiency were achieved. For the maximum CW incident pump power of 82.5 W, the holmium laser yielded an output power as high as 24.5 W corresponding to a slope efficiency of 35.4% and an optical-to-optical conversion efficiency of 29.7%, determined with respect to the incident pump power (Fig. 2).

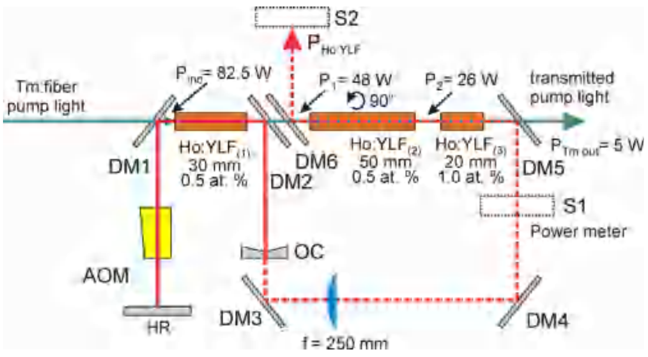

Fig. 1. Experimental setup of the end-pumped Ho:YLF-MOPA laser: DMs—flat dichroic mirrors anti-reflective at 1.94 μm and 45-deg highly reflective at 2.05 μm, OC—concave output coupling mirror, HR—high reflector at 2.05 μm, AOM—acousto-optic modulator used in a Q-switched operation.

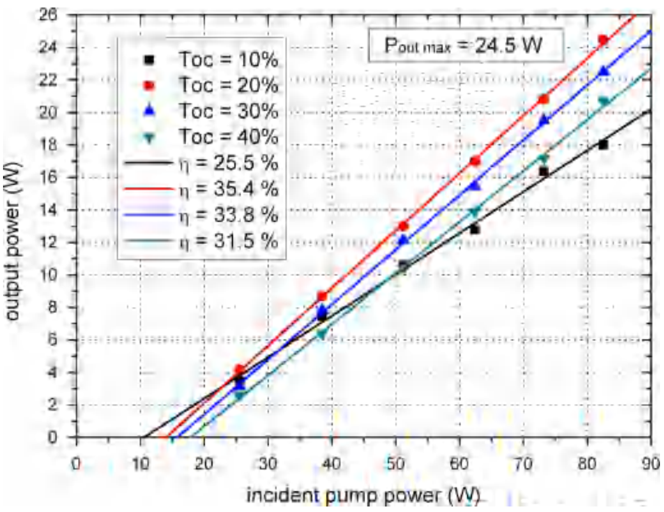

Fig. 2. Output powers of the Ho:YLF laser with a crystal length of 30 mm as a function of incident pump power for different output coupler transmittances. The results of a linear fit and the calculated slope efficiencies are given in the graph.

To calculate the absorbed pump power during the laser operation the transmitted pump radiation, unabsorbed in the crystal, was measured behind the dichroic mirror DM2 on-line. Due to the bleaching of the upper laser manifold and the ground state depletion for the high pump power the absorption efficiency of the pump light decreased with the increase of pump power. It resulted in a few percentage points in the decrease in the absorption efficiency within the whole range of pump power change. Furthermore, it was noticed that the absorption efficiency decreased with the increase of out-coupling transmission. For the Ho:$YLF_{(1)}$ laser pumped by maximum applied power the absorption determined for 10% and 40% out-coupling transmission was ~58% and ~42%, respectively (Fig. 3).

The highest optical-to-optical conversion efficiency of 59.8%, determined with respect to the absorbed pump power, for $T_{OC}=40\%$ was obtained. The slope efficiency for the same out-coupling mirror was even higher reaching 81.6% (Fig. 4).

The output spectra of the Ho:YLF lasers were measured with the integrating period below 1 s (with the use of an AQ6375 optical spectrum analyzer) with dependence on the output coupling transmittances. The increase of the output coupler transmission made the laser operate at shorter wavelengths. For the low values of output mirror transmission the laser operated at the characteristic wavelength of ~2064 nm. However, it was noticed that applying the out-coupling transmission of over 30%, the operating wavelength shifted to ~2050 nm. In the presented system, for the

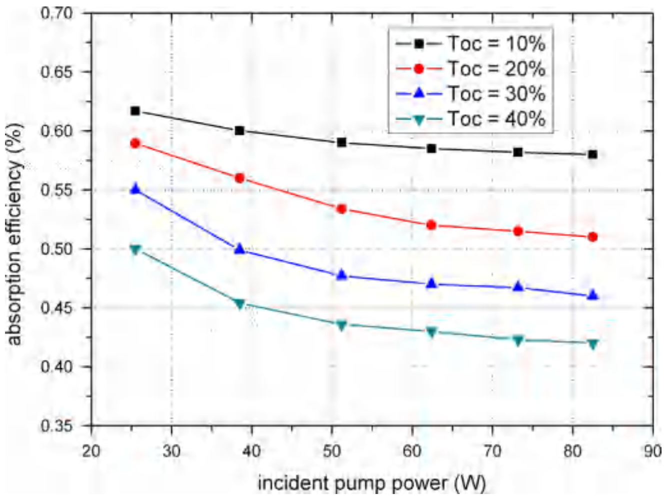

Fig. 3. Absorption efficiency vs incident pump power for different output coupler transmittances.

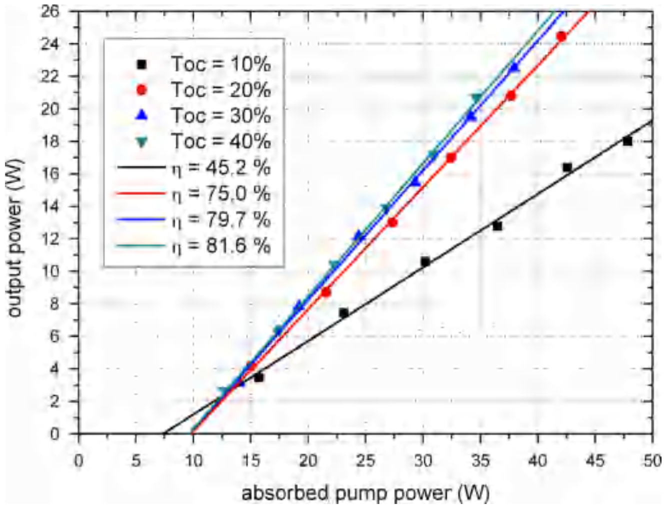

Fig. 4. Output powers of the Ho:YLF laser with a crystal length of 30 mm as a function of absorbed pump power for different output coupler transmittances.

out-coupling transmittance of $T_{OC}=30\%$ it was possible to set a condition when the lasing wavelength self-switched between 2051.5 and 2062.4 nm with a very high repetition rate. Furthermore, it seems that during the switching between these two wavelengths, in a very short time, simultaneous generation on the two wavelengths is possible. The corresponding spectrum with double emission peaks is depicted in Fig. 5. It is worth noting that it was possible to record output spectra where two wavelengths had the same emission intensity.

The summarized data of slope efficiencies η_{slope}, optical-to-optical efficiencies $\eta_{\text{opt-opt}}$, with respect to the incident pump power, as well as the generated laser wavelengths obtained for the Ho:YLF$_{(1)}$ crystal with different transmittances of the output coupler T_{OC} are presented in Table 1.

The high pump power and natural birefringence of the YLF host made the pump power absorption in the laser crystal achieve a value of tens of percentage points. Due to the lowest value of absorption efficiency for $T_{OC}=40\%$ such laser configuration was chosen for MOPA measurement. For the maximum incident pump power and the output coupler of 40% about 48 W was transmitted through the dichroic mirrors DM2 and DM6. Since the absorption in the Ho:YLF$_{(1)}$ is strongly polarization dependent, transmitted pump radiation was partially polarized in the vertical direction. Therefore, in order to utilize the pump power as much as possible in the amplifier stage the second Ho:YLF$_{(2)}$ brick at 0.5 at% Ho doping concentration and the length of 50-mm, rotated by 90° with respect to the oscillator crystal Ho:YLF$_{(1)}$ was used. The cross-section of this crystal was 3×3 mm^2. A lens with a focal length of 250 mm was used to focus the holmium oscillator radiation in the amplifier crystal. For the maximum incident pump power, the amplifier system based on the Ho:YLF$_{(2)}$ crystal yielded an output power of 26.6 W (corresponding to a gain of the amplifier of almost 1.3) with a slope efficiency of 41.4% and an optical-to-optical conversion efficiency of 32.2%, determined with respect to the incident pump power. However, with the use of one crystal in the amplifier stage about 26 W of pump light was unused and lost through the mirror DM5. The transmitted pump beam indicated partially polarized radiation in the horizontal direction in this case. Thus, we decided to use the third Ho:YLF$_{(3)}$ crystal at 1.0 at% Ho doping concentration and the length of 20-mm, rotated by 90° with respect to the amplifier crystal Ho:YLF$_{(2)}$. A two-stage amplifier system yielded an output power of 30.5 W with a slope efficiency of 47.3% and an optical-to-optical conversion efficiency of 37%. The energetic characteristics of the Ho:YLF-MOPA system are presented in Fig. 6. In such a configuration both amplifier crystals absorbed 43 W of the pump radiation transmitted through the oscillator crystal leaving only 5 W of the total pump light unused.

To determine the beam quality factor in a CW regime we directed the Ho laser amplified radiation through a 350-mm focal length lens and measured the beam diameter along the propagation direction with the use of a pyroelectric NanoModeScan—scanning-slit laser beam profiler, making the measurements in accordance with ISO 11146. With standard beam propagation expressions, the curves applied to the data measured at the maximum incident pump power yielded a nearly diffraction limited amplified beam with an excellent M^2 parameter better

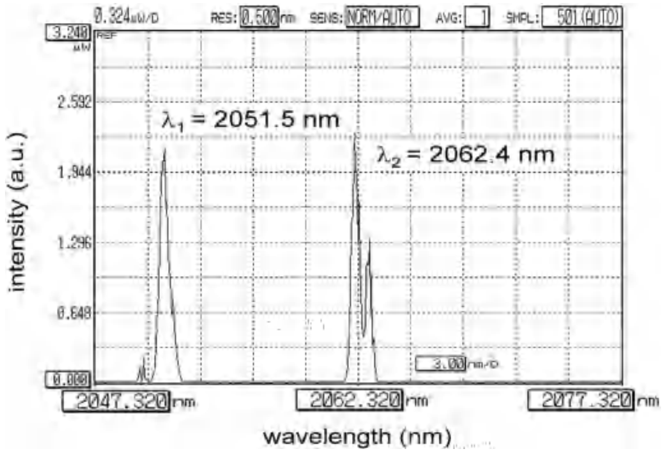

Fig. 5. Generation on two wavelengths of the 30-mm-long Ho:YLF laser working with the output coupler transmission of $T_{OC}=30\%$.

Table 1
Comparison of slope efficiencies η_{slope} and optical-to-optical efficiencies $\eta_{\text{opt-opt}}$ of a Ho:YLF oscillator in CW operation with respect to the incident (inc) and absorbed (abs) pump power with different transmittances of the output coupler T_{OC}. The generated laser wavelengths are also presented.

	$T_{oc}=10\%$	$T_{oc}=20\%$	$T_{oc}=30\%$	$T_{oc}=40\%$
η_{slope}(inc/abs) [%]	25.5/45.2	35.4/75.0	33.8/79.7	31.5/81.6
$\eta_{\text{opt-opt}}$(inc/abs) [%]	21.8/37.6	29.7/58.1	27.3/59.3	25.1/59.8
Wavelength [nm]	2063.1	2062.6	2062.4/2051.5	2051.4

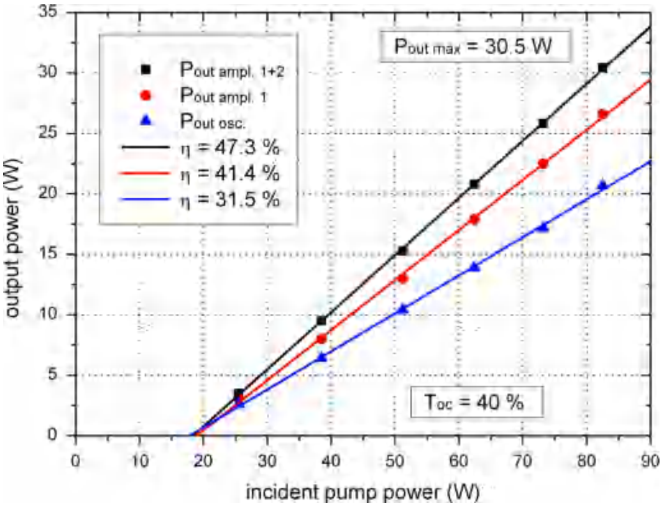

Fig. 6. Output powers of the Ho:YLF-MOPA system based on the two-stage amplifier scheme as a function of incident pump power for an output coupler transmittance of 40% in a CW regime.

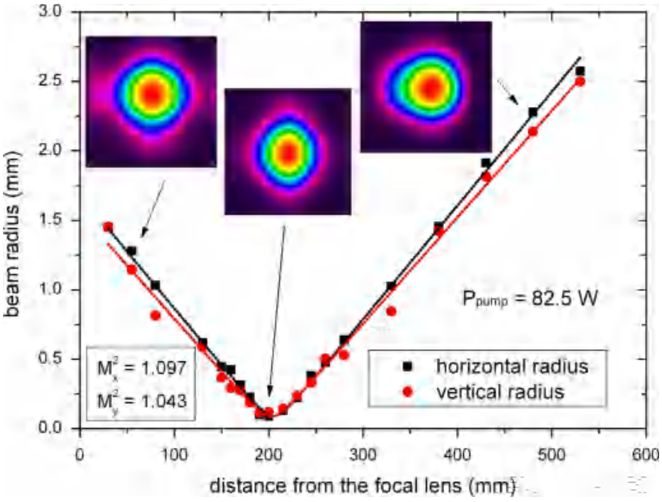

Fig. 7. Beam propagation factor measurement of a CW Ho:YLF-MOPA laser beam. The insets show 2D spatial profiles of the amplified laser beam.

than 1.1 in both horizontal and vertical directions (Fig. 7). Circularly symmetric beam profiles (shown in Fig. 7 as insets) with the Gaussian distributions within the whole scan were recorded.

4. Q-switched operation

In a Q-switched operation a fused silica acousto-optic modulator made by the Gooch and Housego company was utilized. The AOM was driven by 20 W RF power at 40.68 MHz. In order to avoid any damage of the output coupling mirror, experiments were carried out with the highest transmission of the output coupler T_{OC}=40%. The pulse repetition frequency was varied from 1 to 6 kHz. The generated pulse energies of the oscillator and amplifiers as well as FWHM pulse widths as a function of pulse repetition frequency for maximum incident pump power of 82.5 W are presented in Fig. 8. For the minimum applied frequency in a two-stage amplifier configuration, pulses of 18.5 mJ energy were achieved corresponding to a gain of almost 1.75 with respect to the oscillator scheme. $A>12.5$ 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 22 ns FWHM width and 841 kW peak power were achieved for the PRF of 1 kHz. In comparison with the oscillator configuration the amplifier system did not change the pulse width of the generated pulses in any measurable way.

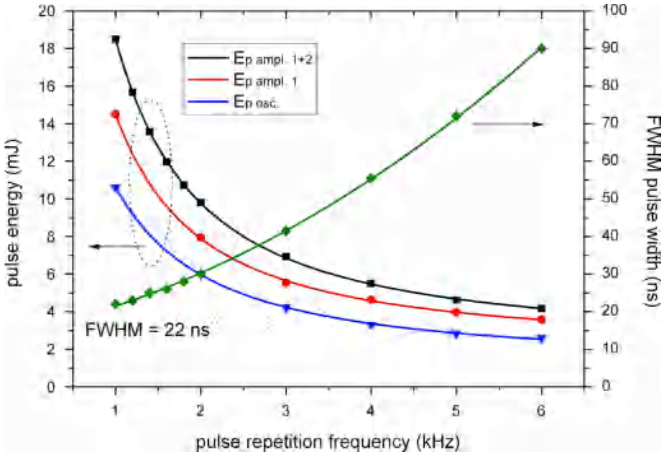

Fig. 8. Pulse energy and pulse width as a function of pulse repetition frequency for the maximum incident pump power of 82.5 W.

5. Conclusions

An efficient, single-pass pumped, CW and Q-switched Ho:YLF-MOPA laser pumped by a thulium-doped fiber laser was demonstrated. In this scheme the pump radiation unabsorbed in the oscillator crystal was used to pump the two-stage optical amplifier. A 0.5 at% Ho doped crystal with a length of 30 mm was tested during the experiment in an oscillator scheme. In a CW regime for an output coupling transmission of 20%, the maximum output power of 24.5 W for 82.5 W of incident pump power, corresponding to a slope efficiency of 35.4% and optical-to-optical conversion efficiency of 29.7% was achieved. The highest slope efficiency of 81.6% and optical-to-optical conversion efficiency of 59.8% for an output coupling transmission of 40% with respect to absorbed pump power were obtained. For a Ho:YLF laser, the main emission wavelength on a π-polarization of 2064 nm shifted to the shorter wavelength of 2050 nm with an increase in output coupling transmittances. For an output coupling transmission of 30% we demonstrated, two wavelengths generation at 2051.5 nm and 2062.4 nm. To utilize pump power transmitted through a oscillator stage an amplifier system based on two orthogonally rotated Ho:YLF crystals was developed. For the output coupling transmission of 40% the slope efficiency was increased from 31.5% in an oscillator scheme to 47.3% with respect to the incident pump power reaching the maximum output power of 30.5 W in a two-stage amplifier scheme with a beam quality parameter M^2 better than 1.1. For a Q-switched operation for the maximum incident pump power at the PRF of 1 kHz, pulse energies of 18.5 mJ with a 22 ns FWHM pulse width corresponding to 841 kW peak power in the amplifier system were recorded corresponding to a gain of almost 1.75 comparing the oscillator scheme.

Acknowledgments

This research has been supported by the National Science Centre of Poland under Contract no. 2011/03/B/ST7/00256 and partially funded by the European Union from the European Regional Development Fund, Project number: WND-POIG 02.01.00-14-095/09.

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