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HIGH PEAK POWER Ho : YLF AMPLIFIER AT 2.05 μm SEEDED BY AN ELECTRO-OPTICALLY DIODE-PUMPED Ho : $GdVO_4$ LASER

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Abstract

In this study, we present a high peak power Ho : YLF amplifier seeded by an electro-optically diode-pumped Ho : $GdVO_4$ laser operating at 2.05 μm. The diode-pumped Ho : $GdVO_4$ laser, operating under a continuous-wave (CW) regime, achieved an output power of 7.1 W at an absorbed pump power of 28 W, resulting in a slope efficiency of 41.4%. At a repetition rate of 1 kHz, the laser delivered an average output power of 3.6 W with a pulse width of 4.3 ns. By utilizing a Ho : YLF crystal as the amplification medium, with a seed power of 3 W and an incident pump power of 22.5 W, the amplifier generates an average output power of 15.5 W with a pulse width of 4.5 ns. We calculate the maximum pulse energy and peak power to be 15.5 mJ and 3.4 MW, respectively.

Keywords: high peak power, Ho : YLF amplifier, Ho : $GdVO_4$ laser, diode pumping.

1. Introduction

The solid-state lasers operating at 2 μm have many attractive applications such as Lidar, gas detection, in medicine, etc. [1–3]. Additionally, high peak power 2 μm laser pulses serve as excellent pump sources for middle-infrared nonlinear-optical-frequency conversions [4, 5]. Among the various laser media, Ho-based lasers utilizing the transition between $^5I_7$ and $^5I_8$ states are highly efficient for generating laser radiation at 2 μm. These lasers are typically pumped by Tm lasers at 1.9 μm due to the low quantum defect associated with this pump-lasing transition [6–9]. Alternatively, laser diodes (LDs) operating at 1.9 μm can also be used as pump sources for Ho lasers [10, 11].

The Ho : $GdVO_4$ crystal exhibits strong emission properties at 2 μm, making it a suitable medium for generating high-performance 2 μm lasers. The crystal has the absorption and emission peaks at 1.94 and 2.05 μm, respectively. In previous studies, the output characteristics of Ho : $GdVO_4$ lasers pumped by Tm lasers have been investigated [12–14]. Under LD pumping, CW and Q-switched characteristics of Ho : $GdVO_4$ laser were also investigated with output powers of several Watts [15–17]. However, there are fewer reports on the high peak power diode-pumped Ho lasers, because of the limitation of LD power and damage of coatings. A solution is the Ho amplifier method, which can provide more pump powers and reduce the risk of damage. The strong absorption and emission peaks of Ho : YLF crystal were also

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located at 1.94 and 2.05 μm, respectively; it is suitable to use it as an amplifying medium for 2.05 μm laser.

In this paper, we demonstrate for the first time an efficient Ho : YLF amplifier at 2.05 μm seeded by a diode-pumped electro-optically (EO) Q-switched Ho : $GdVO_4$ laser. At an absorbed LD power of 28 W, we achieve output powers of 7.1 and 3.6 W in Ho : $GdVO_4$ laser under CW and Q-switching regimes, respectively. At a repletion rate of 1 kHz and a seed power of 3 W, we obtain a maximum average output power of 15.5 W and a minimum pulse width of 4.5 ns with an incident pump power of 22.5 W, corresponding to a slope efficiency of 60.4%. We calculate the maximum pulse energy and peak power to be 15.5 mJ and 3.4 MW, respectively.

2. Experimental Setup

In Fig. 1, we schematically show the experimental setup for the Ho : YLF amplifier seeded by the diode-pumped Ho : $GdVO_4$ laser. An EO Q-switched diode-pumped Ho : $GdVO_4$ laser is used as the seed source; it is beneficial to reach high optical conversion efficiency, because the output wavelength of Ho : $GdVO_4$ laser matches the gain peak of Ho : YLF crystal. The fiber-coupled laser diode operating at 1.94 μm is the pump source of the laser oscillator, which has a maximum output power of 40 W, a core diameter of 0.6 mm, and NA of 0.22. The 1.0 at.%-doped Ho : $GdVO_4$ crystal is cut along a axis with dimension of 3×3×20 mm (in length). The end faces of crystal are coated for antireflection of the pump and lasing wavelengths. A water-cooling cooper heat sink and Indium foil are used to wrap the crystal and control the operating temperature at 15°C. A 1 : 1 telescope is used to focus the pump beam into the Ho : $GdVO_4$ crystal with a pump spot diameter of 0.6 mm. The single-pass pump absorption of Ho : $GdVO_4$ crystal is measured under no-lasing conditions. With an increase in the pump power from low to maximum level, the pump absorption efficiency is changed from 65% to 77%.

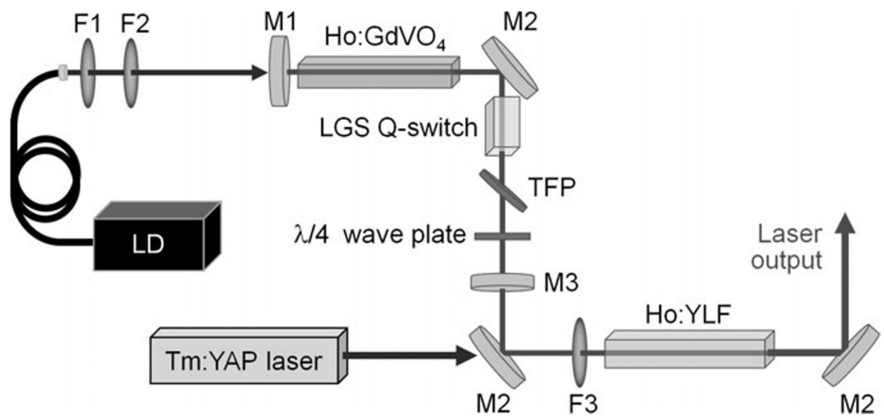

Fig. 1. The experimental setup of Ho : YLF amplifier seeded by a diode-pumped Ho : $GdVO_4$ laser.

The folded cavity consists of a flat 0° dichromatic mirror M1, a flat 45° dichromatic mirror M2, and an output coupler M3. Mirrors M1 and M3 are coated for antireflection of the pump wavelength and high reflection for lasing wavelength. The M3 is a plano-concave mirror with a radius of curvature of 500 mm and an output transmittance of 40%. A quarter wave plate is employed to change the polarization state of the oscillating beam. A z-cut LGS Q-switch (Dientech Corp.) with a length of 48 mm is used in the experiment. A thin film polarizer (TFP) is coated for a high reflection of s-polarized oscillating wavelength and high transmission for p-polarized oscillating wavelength. A homemade electro-driver with a rise time of 10 ns is used to drive the LGS Q-switch. The quarter-wave voltage is 2500 V. The EO Q-switch operates in the pulse-on mode. The cavity physical length of the oscillator is about 100 mm.

An a-cut Ho : YLF crystal with dimensions of 4×4×112 mm (in length) is used as the amplification medium. The Ho concentration is 0.3 at.%. Both end faces of Ho : YLF crystal are polished and coated for antireflection of the pump and seeding wavelengths. A water-cooling heat sink and Indium foil are used to mount Ho : YLF crystal and stabilize the operating temperature at $\sim 20^\circ$ C. As the pump source of Ho : YLF amplifier, we employ a homemade diode-pumped Tm : YAP laser operating at 1938 nm with a maximum output power of 25 W · s. Lens F3 with a focal length of 100 mm is used to focus the seed beam into the Ho : YLF crystal. The spot radius is about 0.3 mm. The Tm pump radius is kept at the same size. Two mirrors M2 are used to separate the pump, seed, and amplifying beams.

3. Experimental Results

When the EO driver is off, the CW output power of the diode-pumped Ho : $GdVO_4$ laser is measured by a power meter (Coherent PM30); see Fig. 2 a. With an absorbed pump power of 28 W, a CW output power of 7.1 W is achieved, corresponding to a slope efficiency of 41.4% with respect to the absorbed pump power. Turning on the EO driver, a maximum average output power of 3.6 W is achieved with a repetition rate of 1 kHz, corresponding to a slope efficiency of 21.2% with respect to the absorbed pump power. The output spectra of the diode-pumped Ho : $GdVO_4$ laser under CW and Q-switching regimes are measured by a spectrometer (Wavescan, APE). The central wavelength and FWHM line width are 2047.9 and 0.2 nm, respectively; see the insert in Fig. 2 a. No obvious difference between the CW and Q-switching regimes is recorded. A fast InGaAs photodiode (ET-5000, EOT) connected with an oscilloscope (DPO 4000, Tektronix) is used to measure the pulse width of the diode-pumped Ho : $GdVO_4$ laser under Q-switching regime. At the maximum pump power, a minimum pulse width of 4.3 ns is obtained; the corresponding pulse profile is shown in Fig. 2 b. In addition, using a 90/10 knife-edge method, we estimate the M^2-factor at the maximum output level of the diode-pumped EO Q-switched Ho : $GdVO_4$ laser to be about 1.9.

In Fig. 3 a, we present the output powers of Ho : YLF amplifier, when the seed power is 3 W. When the incident pump power is 22.5 W, we achieve an output power of 15.5 W, corresponding to a slope

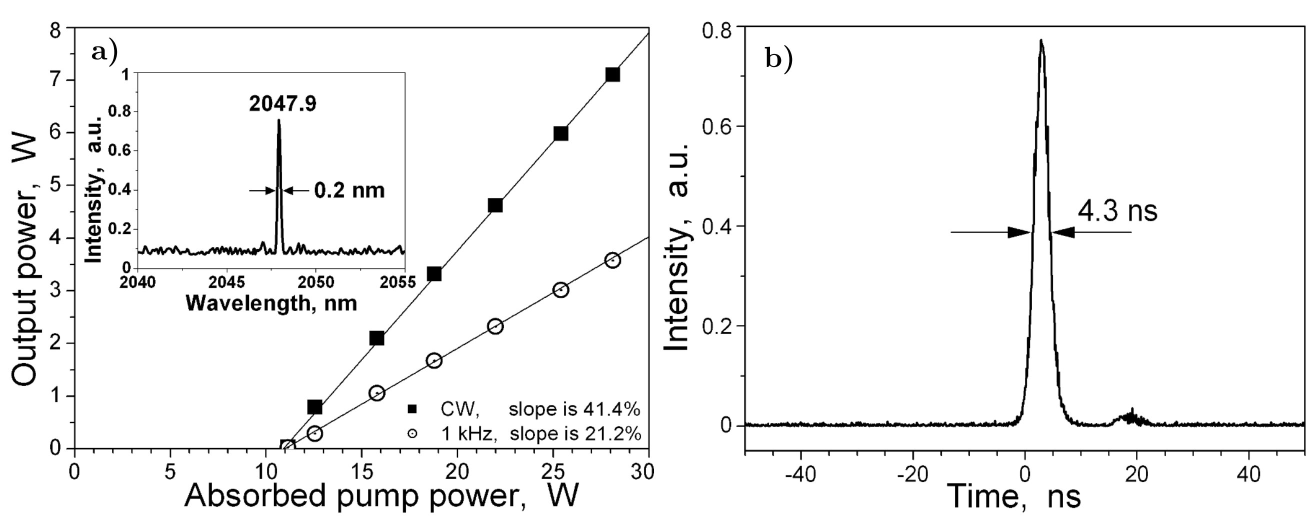

Fig. 2. The output characteristics of diode-pumped Ho : $GdVO_4$ laser; here, the output power (a) for continuous wave (■) and 1 kHz pulse (⊙) and the minimum pulse profile (b).

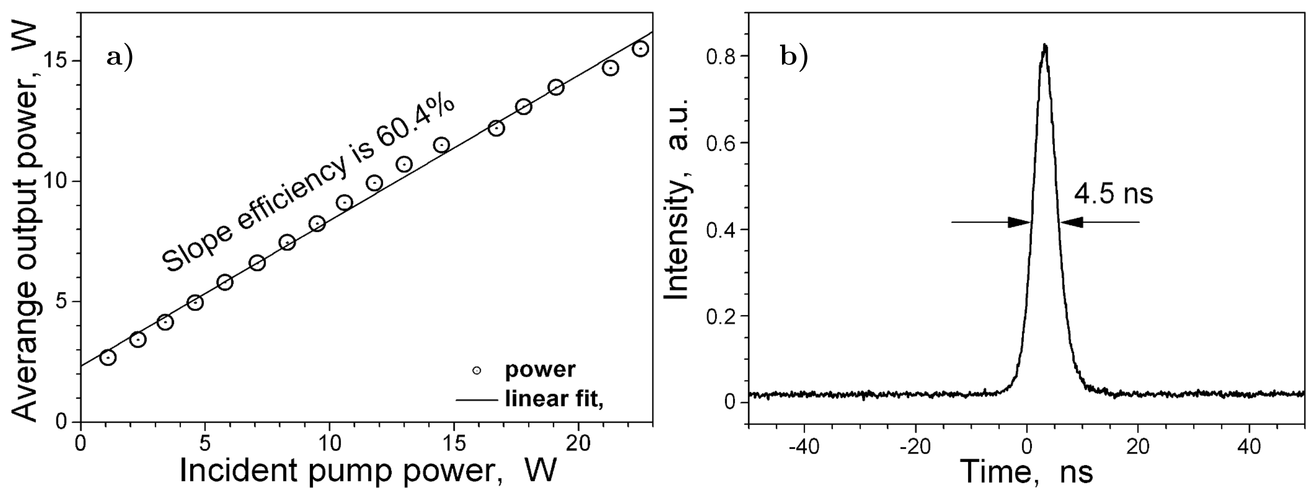

Fig. 3. Output power (a) and minimum pulse width (b) of Ho : YLF amplifier with a seed power of 3 W.

efficiency of 60.4%. The output spectrum of Ho : YLF amplifier and M^2-factor are the same as for the Ho : $GdVO_4$ oscillator. The minimum pulse width slightly increases to 4.5 ns; see Fig. 3 b. In Fig. 4, we show the calculating pulse energy and peak power of Ho : YLF amplifier; the maximum pulse energy and peak power are 15.5 mJ and 3.4 MW, respectively.

4. Conclusions

In conclusion, in this work we demonstrated an efficient Ho : YLF amplifier operating at 2.05 μm. The diode-pumped EO *Q*-switched Ho : $GdVO_4$ laser was used as the seed source. At a repetition rate of 1 kHz, an average output power of 3.6 W was achieved with a slope efficiency of 21.2% with respect to the absorbed pump power. Using a Ho : YLF crystal as the amplification medium, with a seed power of 3 W and an incident pump power of 22.5 W, we obtained a maximum average output power of 15.5 W, corresponding to a slope efficiency of 60.4%. In addition, the minimum pulse width was equal to 4.5 ns. Calculating maximum pulse energy and peak power were 15.5 mJ and 3.4 MW, respectively. These results indicate that designed Ho : YLF amplifier is a promising candidate for generating high efficiency and high peak power laser operating at 2.05 μm. While the current pump power limited the achievable pulse energy, in this work, we anticipate that our setup can achieve pulse energies exceeding 50 mJ at 2.05 μm with additional Tm-pump powers, due to low quantum defect and high optical conversion efficiency.

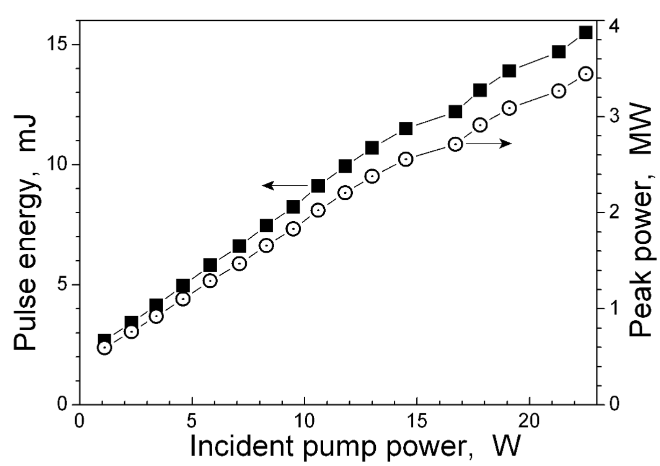

Fig. 4. Pulse energy (■) and peak power (⊙) of Ho : YLF amplifier.

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