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AN Ho:YAG LASER WITH DOUBLE-PASS PUMPING AND THE $ZnGeP_2$ OPO PUMPED BY THE Ho:YAG LASER

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Abstract

We report an efficient Ho:YAG laser end pumped by Tm:YLF lasers with double-pass pumping. We achieve the maximum continuous wave (CW) output power of 46.0 W with a single-pass pumping and 50.2 W with a double-pass pumping, corresponding to a slope efficiency of 58.0% and 62.8%, respectively. In addition, we use the Ho:YAG laser as a pumping source of the $ZnGeP_3$ optical parametric oscillator (OPO) and obtain the maximum average output power of 14.2 W with a linear cavity and 17.0 W with a ring resonator, respectively.

Keywords: double-pass pumping, OPO, solid state.

1. Introduction

Two-micron solid-state lasers have many attractive applications in medicine, laser ranging [1], remote sensing, laser radar, and optical communication [2]. Two-micron lasers are preferred as pump sources for optical parametric oscillators generating 3–5 μm mid-infrared radiation and farther in the mid-infrared range, which have prospective applications in spectroscopy, medicine, and defense [3]. Due to their high power and excellent beam quality, lasers operating at 1.91 μm [4, 5] with direct pumping of an Ho:YAG crystal with a diode-pumped Tm-doped bulk laser is an attractive route to achieve high power in the 2 μm regime [6]. With careful designing of the crystal length and doping concentration, 74% slope efficiency has been reported in a double-pass end-pump configuration [7]. Using the Tm-fiber laser as a pumping source, 81.2% slope efficiency has been reported in a four-pass end-pump configuration [8]. In addition, a slope efficiency of 82% has previously been reported in Ho:LuAG crystals; however, it is based on the absorbed pump power [9]. Generally, most of the reported laser slope efficiencies with respect to the pump power in holmium-doped YAG pumped by Tm-doped bulk solid-state lasers are around 60% [10]. We demonstrate an efficient Ho:YAG laser pumped by two Tm:YLF lasers in a novel double-pass configuration. Two Ho crystals are employed in the resonator due to the limit output power of each Tm pump.

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This paper presents a double-pass pumping Ho:YAG laser end-pumped by Tm:YLF lasers at room temperature. We achieve a slope efficiency of up to 62.8% and output power up to 50.2 W. Using the Ho:YAG laser as a pumping source, we demonstrate an efficient ZGP-OPO laser with a linear cavity and a ring cavity.

2. Experimental Setup

The experimental configuration we used is shown in Fig. 1. Two Ho:YAG crystals are used in the resonator, and each of them is end pumped by a Tm:YLF laser. The M^2 factor of the Tm beam is measured to be about 1.04. The maximum output power of each of the two Tm lasers is approximately 50 W. The laser resonator is L-shaped with two 45° flat dichroic mirrors M2 ($R > 99.6\%$ at 2.1 μm and $T > 97.7\%$ at 1.91 μm), which provides the pumping by the Tm laser; they also function as high reflectors. As shown in Figs. 1 a and 2 b, a 0° plane mirror M1 ($R > 99.8\%$ at 2.1 μm and $T > 99.7\%$ at 1.91 μm) and an output coupler M3 (with a transmission of 51% at 2.1 μm and 200 mm curvature) are employed in our experiment. The physical length of the resonator is about 210 mm. The pump beam is focused into the gain medium using a simple telescopic lens system (TLS) (not shown in the picture), consisting of a collimating lens and a focusing lens. After passing the TLS, a pump spot size ∼500 μm in diameter is formed in the center of Ho:YAG crystals. The Ho:YAG crystals with a holmium doping concentration of 0.5 at.% are 5 mm in diameter and 50 mm in length. Both end facets of the crystals are antireflection-coated for the pump and laser wavelengths.

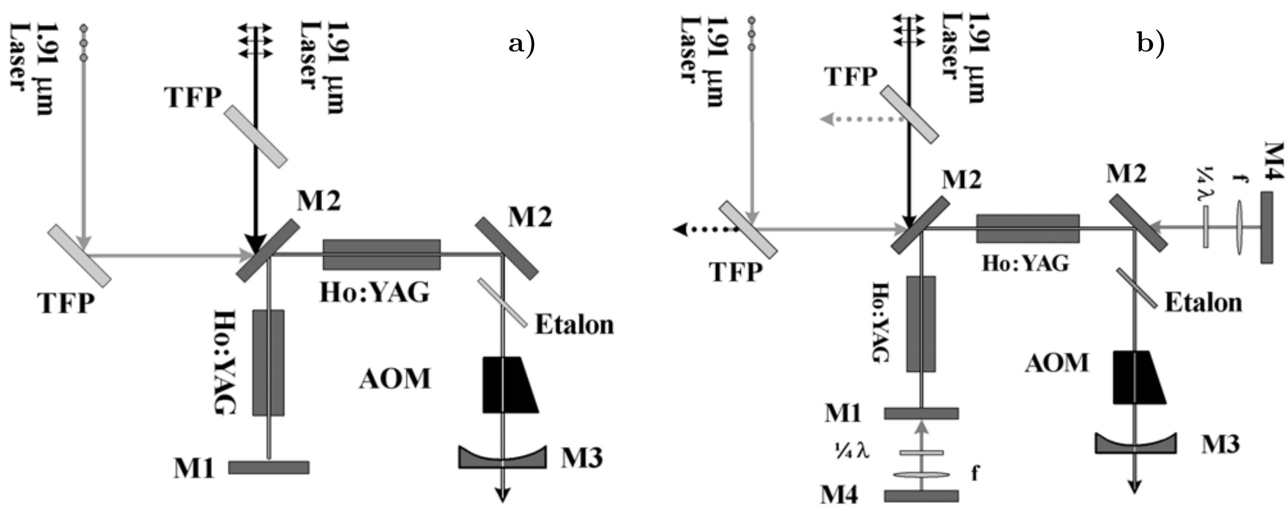

Fig. 1. Schematic diagram of the experimental setup of the Ho:YAG laser.

To increase the absorption efficiency, a focusing lens of 100 mm and a 0° flat mirror M4 highly reflective for 1.9 μm are employed, as shown in Fig. 1 b, which provides double-pass pumping. A $\lambda/4$ plate and thin film polarizer (TFP) are inserted in the resonator to avoid the Tm pump from being influenced by the feedback. The laser crystals are wrapped in indium foil to increase thermal contact and mounted in a copper holder and water-cooled to 18°C. A 0.1 mm thickness uncoated YAG etalon is used in the resonator to force the laser to emit at a single wavelength.

3. Experimental Results and Discussion

In the first experiments, the CW output powers are measured as a function of the incident pump power with single-pass and double-pass pumping, as shown in Fig. 2. The maximum output power of the Ho:YAG laser with single-pass pumping is 46.0 W, corresponding to a slope efficiency of 58.0%. However, when the Ho laser is operated with the double-pass pumping, a maximum output power of 50.2 W is achieved, which corresponds to a slope efficiency of 62.8%. Obviously, the efficiency of the Ho laser with double-pass pumping is higher than that with single-pass pumping. Unfortunately, the output power of the Ho laser is limited to the low Tm pump powers. Ongoing work should improve the output performance of the Tm lasers.

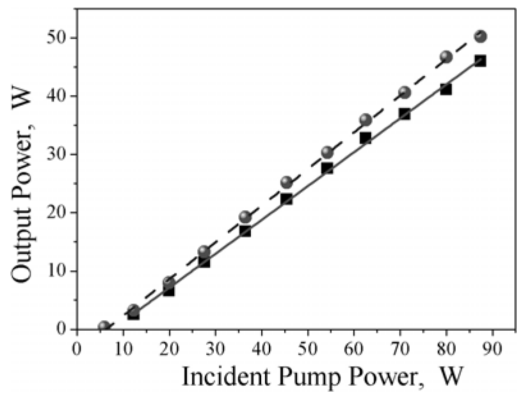

Fig. 2. Output power of the CW Ho:YAG laser with single-pass pumping (■), η_s = 58.0% and double-pass pumping (●), η_s = 62.8% .

In the case of the Q-switched Ho:YAG laser, a fused silica acoustic optical modulator (50DMA05-A, Gooch & Housego) with Brewster-angle end facets and an acoustic aperture of 1.8 mm is employed in the resonator. The radiofrequency (RF) is 41 MHz, and the RF power is 25 W. The output pulse energies and pulse widths of the Q-switched Ho:YAG laser are shown in Fig. 3. At a pulse repetition frequency of 20 kHz, we achieve a maximum output energy per pulse equal to 2.4 mJ with a peak power of approximately 77.4 kW. The temporal trace of the laser pulse (inset in Fig. 3) shows a pulse width of 31 ns (FWHM). The pulse duration demonstrates a steady decrease with incident pump power up to values of 40 W.

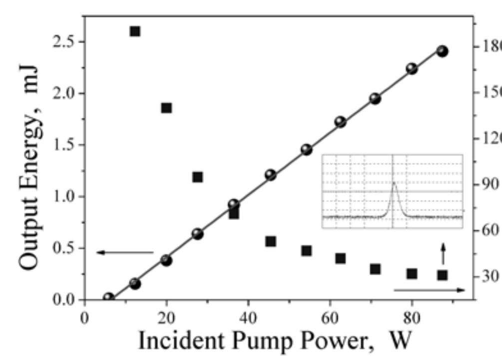

Fig. 3. Pulse widths (●) and pulse energies (■) versus the incident pump powers in the Q-switched regime. The inset shows the oscilloscope trace for an output energy per pulse equal to 2.4 mJ.

As shown in Fig. 4, we route the Ho:YAG laser radiation through a 200 mm focal length lens and measure the 1/e^2 beam radius along the propagation direction at different CW output powers using the 90/10 knife-edge technique. By fitting the Gaussian-beam standard expression to these data, we see that the fit yields $M^2 = 2.27$ at an output power equal to 50.2 W.

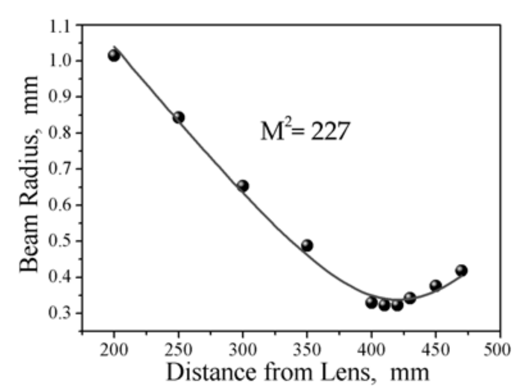

Fig. 4. The M^2 measurement of the CW Ho:YAG laser.

An important application of 2 μm lasers is in pumping the ZGP OPO in order to obtain mid-infrared generation. Using the Ho:YAG laser as a pumping source, we demonstrated a ZGP OPO operating at room temperature. The experimental setup of the ZGP-OPO laser with linear cavity and ring cavity is shown in Fig. 5. Both end facets of the crystal are antireflection-coated at 2.1 μm and in the range of 3–5 μm. The ZGP crystal with dimensions 6×8×18 mm^3 is cut at 55° with respect to the optical axis, which provides I-type phase matching. It is wrapped with indium foil and fixed in a copper support with water cooling.

The linear cavity uses two 0° flat mirrors arranged and configured as a doubly resonant oscillator (DRO); this provides simultaneous feedback for both the signal and the idler waves. The input dichroic mirror M6 is HR coated at 2.1 μm and in the range of 3–5 μm. The output coupler M7 is HR coated at 2.1 μm and has reflectivity approximately 50% over the entire 3–5 μm region. The physical resonator length is approximately 30 mm. The input mirror M6 is placed at a small angle combined with an aperture to avoid the Ho pump from being influenced by the feedback.

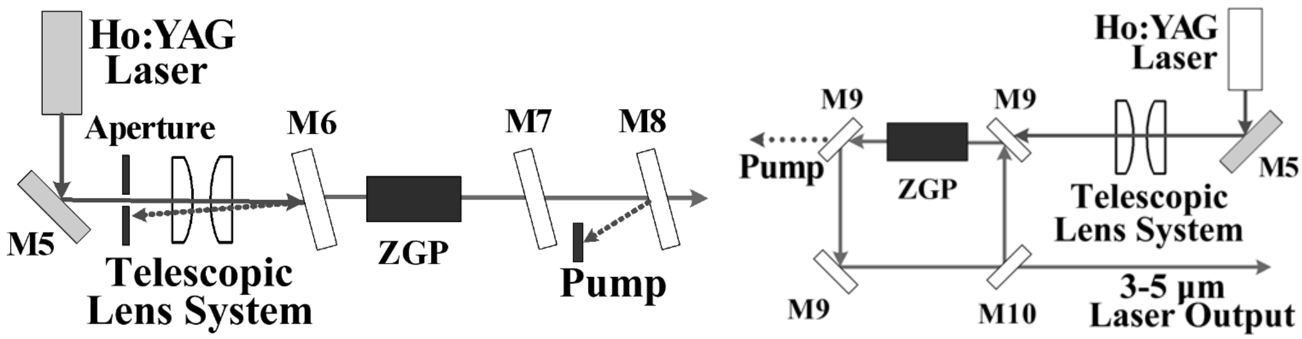

Fig. 5. Schematic diagram of the experimental setup of the ZGP OPO.

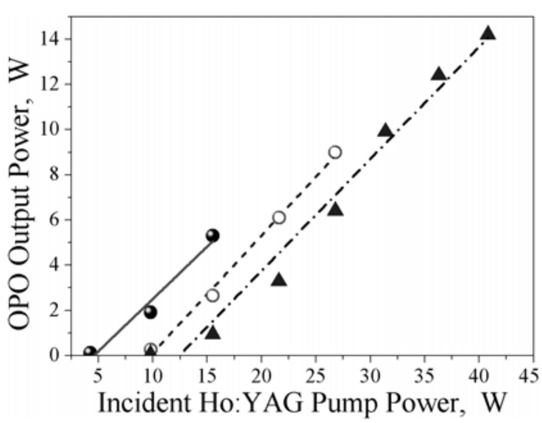

Fig. 6. Output power of the ZGP OPO with the linear cavity and three different repetition frequencies: 5 kHz (●), $\eta_s = 46.2\%$, 10 kHz (○), $\eta_s = 52.0\%$, and 15 kHz (△), $\eta_s = 49.6\%$.

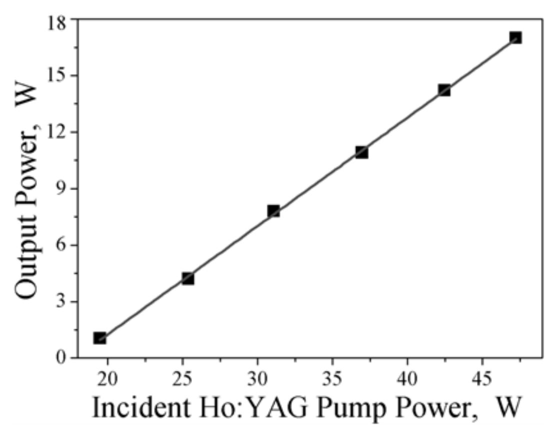

Fig. 7. Measured output power of the ZGP OPO with the ring cavity, $\eta_s = 57.6\%$.

The ring cavity uses four 45° flat mirrors arranged in a rectangle configuration. The output coupler M10 has a high transmission ($T > 95\%$) for the pump wavelength and a reflectivity of 50% for the signal and idler waves. The other three mirrors M9 are highly transparent ($T > 95\%$) for pump and highly reflective ($T > 99\%$) for the oscillating signal and idler. After passing through the telescopic lens system, the pump Ho:YAG laser beam is focused to a diameter of approximately 800 μm in the ZGP crystal.

Figure 6 shows the output performance of the ZGP-OPO laser with the linear cavity, whose output power is the sum of the signal (3.9 μm) and idler (4.6 μm), both in the mid-IR region. The linear-cavity ZGP-OPO laser with three different repetition frequencies shows similar performance in terms of the slope efficiency. We achieved 14.2 W output power of the linear-cavity ZGP-OPO laser with a pulse repetition frequency of 15 kHz, corresponding to a slope efficiency of 49.6%.

Figure 7 shows the output performance of the ZGP-OPO laser with the ring cavity, whose output power is also the sum of the signal (3.82 μm) and idler (4.63 μm). We achieved 17.0 W output power of the ring cavity ZGP-OPO laser with a pulse repetition frequency of 20 kHz, corresponding to a slope efficiency of 57.6%. Based on the above investigation, we conclude that the performance of the ring cavity is better than that of the linear cavity, which can be attributed to the fact that the ring cavity is not influenced by the pump feedback.

In Fig. 8, we show the M^2 values of the ZGP OPO with the ring cavity measured by the 90/10 knife-edge technique at the maximum output power. The M^2 measurement combines the signal and idler beams, and the experimental data yield a beam quality of $M^2 \sim 3.0$ for the signal beam and 2.5 for the idler beam. Based on the above investigation, we achieved a beam quality of $M^2 \leq 3$.

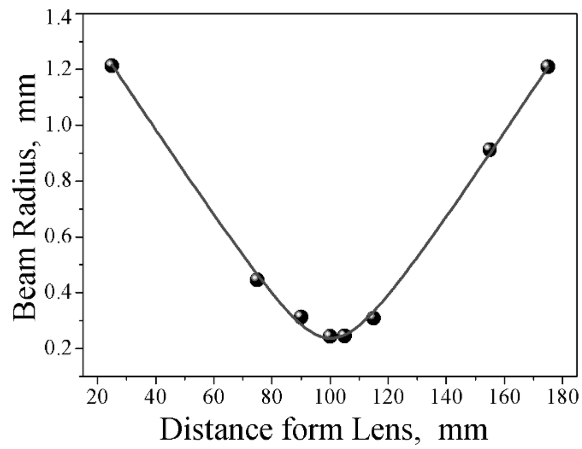

Fig. 8. The M^2 measurement of the ZGP OPO with the ring cavity. $M^2 = 3.0$ at 3.82 μm and $M^2 = 2.5$ at 4.63 μm.

4. Conclusions

In conclusion, we investigated the performance of the double-pass pumping Ho:YAG laser. We obtained an output power of 46.0 W with single-pass pumping and 50.2 W with double-pass pumping. The maximum slope efficiency in terms of the incident pump power reached approximately 62.8% for double-pass pumping. At a pulsed repetition frequency of 20 kHz, we achieved a maximum output energy per pulse equal to 2.4 mJ with a pulse width of 31 ns (FWHM). In addition, using the Ho:YAG laser as a pumping source, we achieved 17.0 W output power of the ZGP-OPO laser with the ring cavity and a beam quality of $M^2 \leq 3$.

Acknowledgments

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