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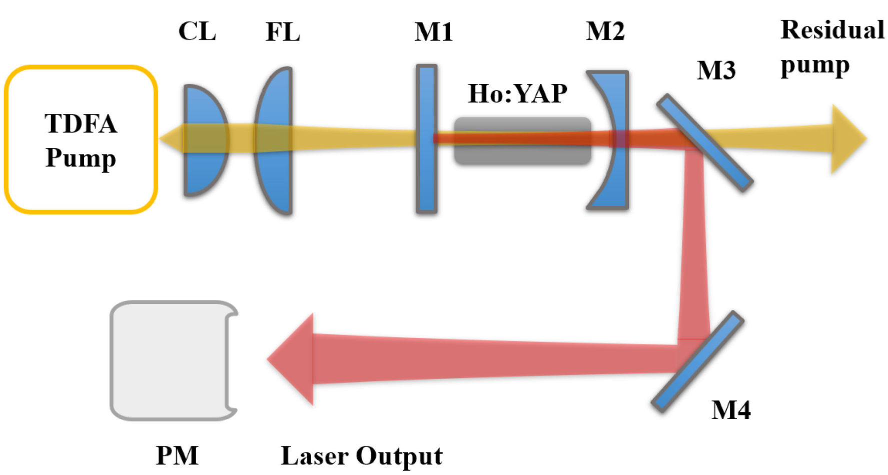

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High Power Ho:YAP Laser With 107 W of Output Power at 2117 nm

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Abstract: A high power Ho:YAP laser in-band pumped by a home-constructed Tm doped all fiber master oscillator power amplifier (MOPA) is reported. The optically polished and uncoated Ho:YAP laser yielded over 107 W of output power at ∼2117.1 nm with 215.4 W of absorbed pump power, corresponding to a slope efficiency of 50.6% with respect to the absorbed pump power. The beam quality M^2 parameter was measured at 80 W of output power to be ∼3.2 and ∼2.6 in x- and y-directions, respectively.

Index Terms: Solid-state laser, high power, Tm doped MOPA system, Ho:YAP.

1. Introduction

Laser sources operating in ∼2.1 μm wavelength regime have a wide range of applications in fields of medical treatment, photoelectric countermeasure, laser range finder and laser radar as well as 3–5 μm mid-infrared laser generation via pumping optical parametrical oscillators, amplifiers and Raman lasers [1]–[3]. Several methods, such as rare-earth ions Tm, Ho co-doped solid-state lasers, Ho doped solid-state lasers and optical parametrical oscillators are proposed to obtain the ∼2.1 μm lasers. Among them, diode pumped Tm, Ho co-doped solid-state lasers are effective methods to generate ∼2.1 μm lasers directly, but this kind of system experiences serious thermal effects due to high up-conversion rate and energy transferring effects between Tm^{3+} ions and Ho^{3+} ions, making it require more critical working conditions when operating at high output power, e.g., low working temperature (77 K) [4]–[6]. The optical parametrical oscillators transferring from ∼1 μm to ∼2 μm need a high energy pump source, and besides, it still faces the problem of low conversion efficiency [7]. For the past few years, in-band pumped Ho doped solid-state lasers have drawn more attention with the rapid development of ∼1.9 μm lasers. In-band pumping Ho doped materials between $^5I_8$ and $^5I_7$ levels has minimal thermal loading due to the inherent high quantum efficiency, making it attractive approach to obtain ∼2.1 μm lasers. So far, high power and efficient laser operation of Ho^{3+}-doped Ho:YAG [8]–[10], Ho:LuYAG [11], [12], Ho:LuAG [13]–[15], Ho:YLF [16] and Ho:LLF [17] lasers have been successfully demonstrated. Employing four high power Tm:YLF laser pump

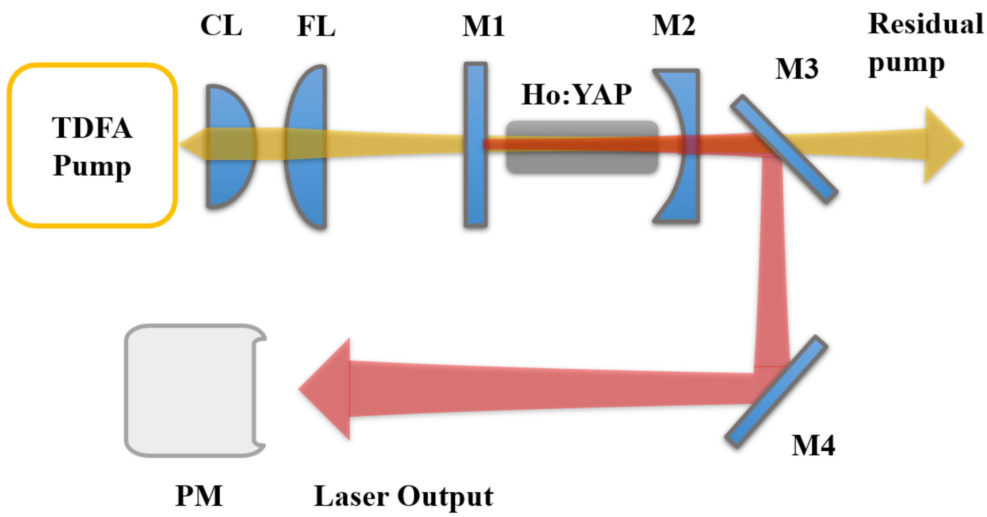

Fig. 1. Experimental setup of the Ho:YAP laser pumped by a 1930.5 nm TDFA. The components are as follows: CL- collimated lens. FL- focus lens. M1- input coupler. M2- output coupler. M3, M4- dichroic mirrors. PM- optical power meter.

sources and an oscillator containing two pieces of Ho:YAG in tandem, over 100 W of CW output has been generated with a slope efficiency of ~68% [9].

Yttrium aluminum oxide (YAP, YAlO) is another promising material owing to its high thermal conductivities (~11 W/m·K), low maximum phonon energies (~570 cm^{-1}) and high laser damage threshold [18]. The orthorhombic symmetry and a perovskite structure make the YAP crystal birefringence character, resulting in linearly polarized output and free of depolarization degradation when operating at high power level. For 3–5 μm nonlinear frequency conversion lasers such as optical parametrical oscillators and Raman lasers, high peak power or high average power linearly polarized laser sources are demanded for pumping the nonlinear optical materials, hence the highly robust Ho:YAP laser is quite a suitable choice as the pump source. To date, several studies have been carried out to investigate the performance of Ho:YAP laser in-band pumped by Tm-doped solid-state lasers or all-fiber lasers, showing great potential of Ho:YAP as a gain material for high power and efficient ~2.1 μm lasers [19]–[23]. So far, generation of over 20.2 W of CW output power at 2118 nm has been demonstrated from a Ho:YAP laser with a slope efficiency of 72% with respect to absorbed pump power [24].

In this letter, we report on power scaling of Ho:YAP laser in-band pumped by a home-constructed high power Tm-doped all fiber MOPA system generating over 107 W of linearly polarized output power at ~2117 nm. The Ho:YAP is optically polished but uncoated, and lasing slope efficiency with respect to absorbed power is ~ 50.6%. The beam quality factor M^2 was measured at 80 W of output power to be ~3.2 and ~2.6, respectively in x- and y-directions. To the best of our knowledge, this is the highest output power so far obtained from Ho:YAP laser operating in the ~2.1 μm wavelength regime.

2. Experimental Setup

The configuration of the Ho:YAP laser pumped by a Tm-doped all fiber MOPA is illustrated in Fig. 1. A simple two-mirror resonator was employed which comprised a plane input mirror (M1) with high reflectivity (HR>99.8%) at 2050–2160 nm and high transmission (HT>99.5%) at 1800–1940 nm, and an output coupler (M2) with a transmission of 20% or 50% at 2050–2160 nm and high transmission (HT>95%) at 1880–1950 nm. The M3 and M4 are dichroic mirrors with high

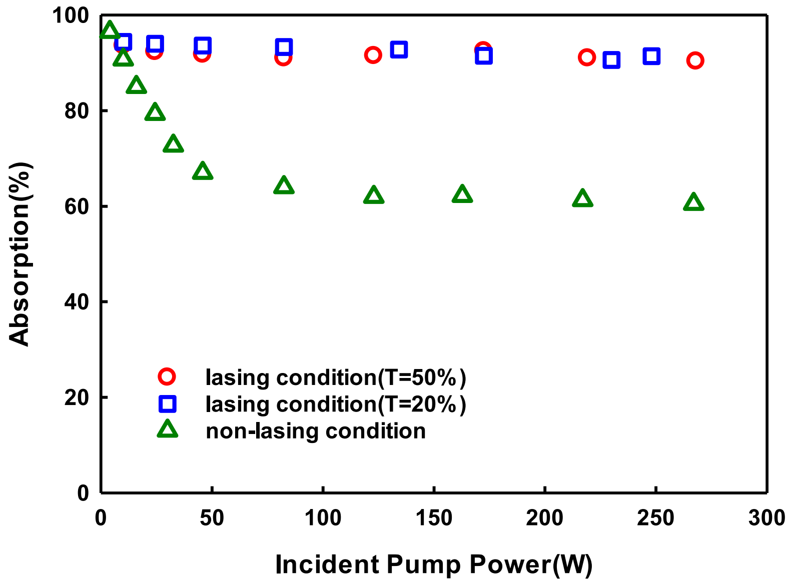

Fig. 2. Absorption efficiency of Ho:YAP crystal under lasing (T = 20%, T = 50%) and non-lasing conditions.

reflectivity (HR>99.8%) at 2050–2160 nm and high transmission (HT>95%) at 1880–1950 nm coated at 45° angle of incident. A Ho:YAP rod with a relatively low doping concentration of 0.5 at.% grown by the Czochralski technique was cut along the b-axis in a diameter of 3 mm and a length of 50 mm, both end faces were polished plane and parallel, but with no antireflection coating at either the pump or the oscillating wavelength. The plane input mirror M1 was positioned as close as possible to the rod and the total physical length of the resonator was about 68 mm. The Ho:YAP rod was water cooled at a temperature of 20 °C.

The pump source was a home-constructed high power and wavelength stabilized Tm-doped all fiber MOPA that can deliver over 280 W of output power with $M^2 \approx 1.2$. The output wavelength of the TDFA was stabilized by a femtosecond laser direct write fiber Bragg grating in the seed oscillator to be 1930.5 nm with a linewidth (FWHM) of <0.2 nm. The pump beam from the TDFA was collimated by a plano-convex lens with focal length of 20 mm and then focused to a beam radius of ~310 μm in the center of the Ho:YAP rod by a plano-convex lens with focal length of 500 mm. The confocal parameter of the pump beam inside the Ho:YAP crystal was estimated to be ~480 mm. A relatively large pump beam size was deliberately chosen for power scaling and alleviating ground state bleaching effects at very high power levels. In this fiber-bulk laser system, the weak reflection from each surface of mirrors and crystal may couple back into the core of the fiber laser, and then can be amplified in reverse by the gain fiber and hence causing unfavorable effects on the TDFA. Therefore, an aperture was placed behind the focus lens and the resonator axis was misaligned from the pump axis by approximately 1.5° to prevent feedback to the TDFA pump source.

3. Experimental Results and Discussion

Single-pass pump absorption of the Ho:YAP crystal was measured with a pump beam of ~620 μm diameter under both lasing and non-lasing conditions, as shown in Fig. 2. Under non-lasing condition, by measuring the incident pump power in front of the input coupling mirror (M1) and unabsorbed pump power behind the crystal, small-signal pump absorption (with no ground state bleaching) was estimated to be ~97% under non-lasing condition, and drops to ~62% as the incident pump power increased to higher than 150 W due to ground state bleaching. It can be seen

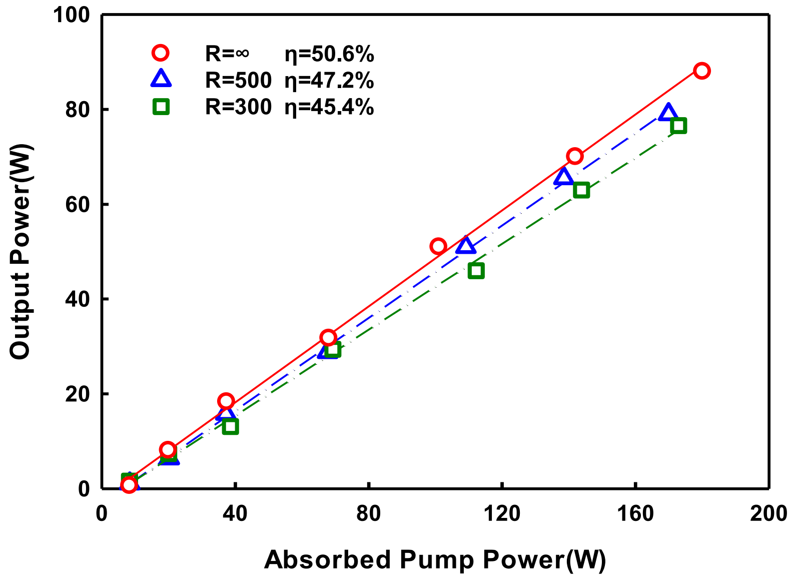

Fig. 3. CW output power of Ho:YAP laser versus absorbed pump power at various radius of curvature of OCs.

from Fig. 2 that pump absorption under lasing condition is very close to that of the small-signal absorption at all pump power levels for output couplers of both 50% and 20% transmission, this is mainly attributed to the relatively long crystal length and large pump beam which can ensure a high absorption rate and provide sufficient gain at high power levels.

Lasing characteristics of the Ho:YAP were first examined employing a simple two-mirror resonator design with output couplers of 50% transmittance and different radius of curvature ($R = 300$ mm, 500 mm and $R \rightarrow \infty$), and the result is presented in Fig. 3. The absorbed pump power is estimated under lasing condition, by taking the same incident pump power of non-lasing condition and measuring the unabsorbed pump power behind the dichroic mirror (M3). Lasing thresholds with output couplers of 300 mm, 500 mm and ∞ radius of curvature are ~4.5 W, 5.1 W and 5.6 W, respectively. Lasing slope efficiency with the plane-plane resonator design reaches 50.6% owing to better pump-resonator mode matching.

Figure 4 shows output power as a function of absorbed pump power using a plane-plane resonator design and output couplers of 20% and 50% transmittance. The laser reached threshold at a pump power of 4.6 W for $T = 20\%$ and 5.6 W for $T = 50\%$, respectively. The laser can generate a maximum CW output power of 107.3 W with absorbed pump power of 215.4 W for the output coupler with a reflectivity of 50%, corresponding to an optical conversion efficiency of 49.9%. Output slope efficiency with respect to the absorbed pump power was 50.6%. As depicted in Fig. 4, the output power shows a nearly linear dependence on the pump power, even at the highest pump power, suggesting that there is scope for further power scaling by simply increasing the incident pump power. Because of the birefringence nature of Ho:YAP crystals, the laser was operating at linear polarization along c-axis of the crystal rod and the polarization extinction ratio (PER) was estimated to be ~20.8 dB at 10 W of output power using a Glan-laser calcite polarizer.

Lasing emission spectrum of the Ho:YAP laser was monitored with an optical spectrum analyzer (AQ6375, Yokogawa) with a resolution of 0.05 nm and a typical output spectrum is shown in Fig. 5. It can be seen that the Ho:YAP laser emits in most cases multiple wavelengths with a wavelength span of a few nanometers. Lasing center wavelength and spectral width at 20 mW and 50 W of output power were 2116.6 nm, 3.0 nm and 2117.9 nm, 3.1 nm for the 20% output coupler, and 2116.9 nm, 0.8 nm and 2118.0 nm, 2.4 nm for the 50% output coupler, respectively. When the output coupler was 50%, the laser spectral width at 20 mW was 0.8 nm, which was much narrower

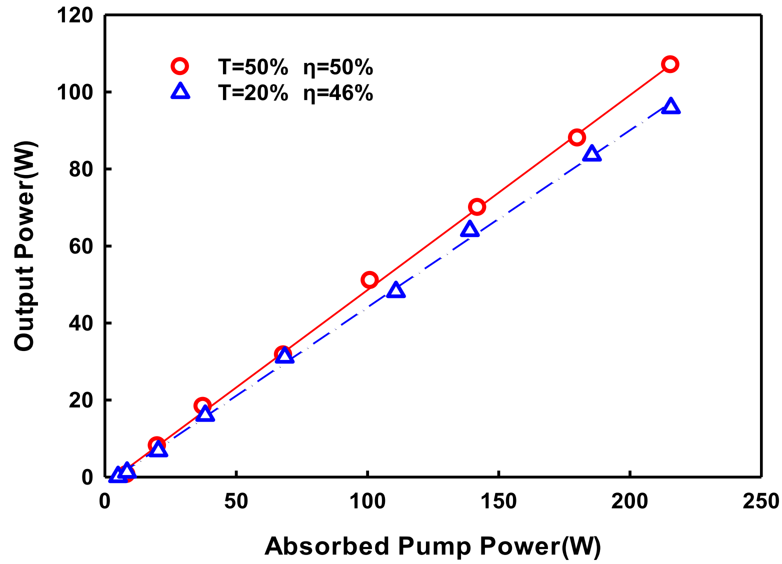

Fig. 4. CW output power of Ho:YAP laser versus absorbed pump power with transmittance of 20% and 50%.

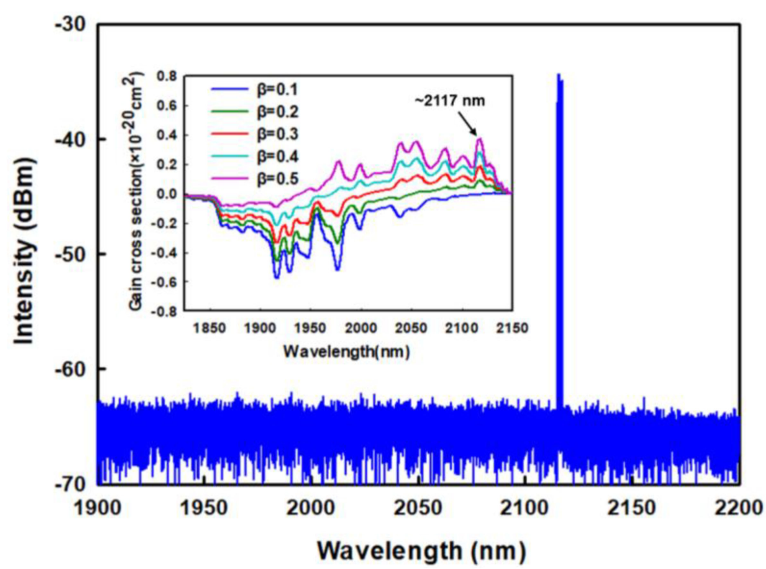

Fig. 5. Output spectrum of the Ho:YAP laser. Inset: gain cross sections of 0.5 at.% Ho:YAP with different population inversion ($\beta = N_2/(N_1 + N_2)$, where N_1, N_2 represent the populations of $^5I_8$ and $^5I_7$ levels, respectively).

due to less oscillating wavelengths at lower output power and a sharp gain peak at high population inversion level (see the inset of Fig. 5). And a small wavelength shift with increased output power may be attributed to the elevated crystal temperature and hence increased reabsorption at high power levels.

Behind the second 45° dichroic mirror (M4), a plano-convex lens with focal length of 200 mm was placed and the laser beam was focused. A beam profiler (Nanoscan, Photo Inc.) was utilized to measure the $1/e^2$ beam radius at different positions and the M^2 parameter of the laser beam was Gaussian-fitted to be ∼1.4 at output power of 20 W, and increased to ∼3.2 when the output

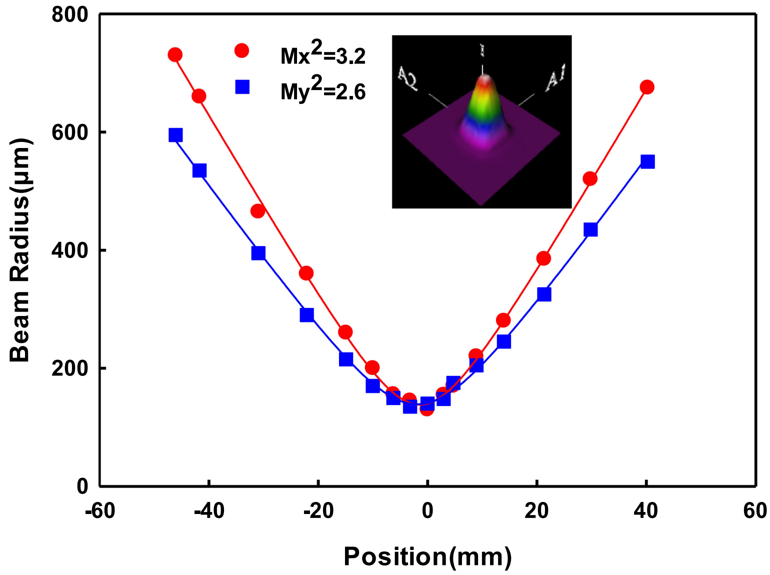

Fig. 6. Beam radius versus positions of the Ho:YAP laser at 80 W of output power. Inset: 3D profile of laser beam near the focus.

power was 80 W, as shown in Fig. 6. A small beam quality degradation with increased power level is induced mainly by the thermal induced phase aberration at high power levels. The difference of M^2 factor between x- and y-directions can be explained by the misalignment of the pump axis and oscillation axis in the horizontal dimension, which will cause more high-order transverse modes in x-direction.

4. Conclusions

In conclusion, we have experimentally demonstrated power scaling of Ho:YAP laser end pumped by a home-constructed 1930.5 nm Tm-doped all fiber MOPA. Maximum output power of 107.3 W at ∼2117 nm with optical conversion efficiency of 49.9% have been achieved. Lasing slope efficiency with respect to the absorbed pump power was 50.6%. The polarization extinction ratio was ∼20.8 dB and the M^2 parameter was measured at 80 W of output power to be ∼3.2 and ∼2.6, respectively in horizontal and vertical directions. Further improvement of the lasing efficiency and power scaling should be possible by AR-coating the crystals and simply improving the pump power.

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