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108-W diode-end-pumped slab Tm:YLF laser with high beam quality

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Abstract Continuous-wave Tm:YLF laser with two slab crystals was double end pumped by four fiber-coupled laser diodes at room temperature. A maximum continuous wave output power of 108 W for the slab Tm:YLF laser was generated, corresponding to a slope efficiency of 39.0 % and an optical-to-optical conversion efficiency of 35.5 % with respect to the incident pump power. The laser operated at 1,908.1 nm with a beam quality factor of M^2 ~ 2.9 at the highest output power.

1 Introduction

Some of the applications of 1.9 µm Tm:YLF lasers are in laser surgery [1] and to pump high-power or high-energy Ho:YAG lasers [2–4] or high-energy Ho:YLF slab amplifiers [5]. Due to low multiphoton relaxation rates, Yttrium lithium fluoride (YLF) is a particularly attractive choice as the host medium for thulium, when it is utilized as pump source for a 2-µm Ho:YAG laser [6]. Compared to the rod geometry [7], the crystal with slab geometry allows for much higher pump power, and therefore much higher output power, by spreading out the heat load in the horizontal direction with spherical and elliptical pump beam [8]. Previously published results reported that 148 W average output powers was achieved from such a system at 1.912 µm [9], which was end pumped by diode stack. However, efficient pumping of Ho:YAG requires that the Tm:YLF output wavelength reasonably well match the strong absorption peak at 1,907.5 nm, and the Tm laser with high beam quality reasonably well meet the much longer Ho:YAG crystals. Volume Bragg Grating (VBG) mirror, which has a high reflectivity at a certain wavelength which fulfills the Bragg condition, offers a more precise and sure way to select a specific wavelength. The VBG was used to control and stabilize the emitting wave of diode pump Tm lasers [10], fiber lasers [11], and lasers where they can also facilitate single mode operation [12]. A 200 W Innoslab Tm:YLF laser was reported by Li et al. [13], while the laser was pumped by laser diode stack and thus had a bad beam quality in one direction. The output power of the above Innoslab Tm:YLF laser was only 100 W when inserted a Brewster plate in its resonator to select the laser emitting at 1,908 nm. Moreover, the fiber-coupled laser diodes pumping Tm:YLF laser allow better beam quality than the laser diode stacks pumping. Also, the efficiency of the end pumping scheme was much higher than the side pumping. We exhibit a Tm:YLF laser with slab crystal end pumped by fiber-coupled laser diodes, which allows high output power and good beam quality. The spectra of Tm-doped fiber laser has red shift with increasing the pumping power, As a consequence, the wavelength of the slab Tm:YLF solid-state laser with VBG was stable than the Tm-doped fiber laser.

In this paper, we report a Tm:YLF laser with two slab crystals using a VBG as a back-reflector. Each slab crystal was pumped by two 100 W, 791 nm fiber-coupled laser diodes using a dual-end-pumping scheme. It produced about 108 W of output power at 1908.1 nm and had a much better beam quality compared to slab laser. A beam quality factor of M^2 < 3 was found. To our knowledge, this is the highest output power from a slab Tm:YLF laser which was dual-end-pumped by fiber-coupled laser diodes.

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2 Experimental setup

The details of the experimental setup are shown in Fig. 1. Two Tm:YLF slab crystals were dual-end-pumped by four fiber-coupled laser diodes with a fiber diameter of 400 µm and a numerical aperture of 0.22. The central wavelength of the pump light was measured to be 787.0 nm at threshold and increased linearly to 791 nm at the maximum output power of 100 W. The spectral width of the laser diode was 2.5 nm. The fiber-coupled laser diodes (Pearl Model P4-100-0790-3-A-R01-S0027) were made by *n*LIGHT Corporation. The absorption coefficient of the crystal at the pump wavelength of 790 nm was measured to be 1.6 cm^{-1} at the pump power of 2 W. The pump light was imaged 2.7:1 by use of standard optics to a diameter of about 1.08 mm, resulting in a Rayleigh length ($zr = \pi\omega^2 n/\lambda M^2$) of about 23 mm inside the crystal with refraction index $n = 1.44$. The pump waist is positioned about 7 mm inside the crystal. The two Tm:YLF slab crystals have a dimension of 12 mm width, 1.5 mm thickness and 20 mm lengths. The slab crystals had a doping of 2.5 at.% and were *a*-cut with the *c*-axis along the 1.5 mm direction. Both end faces of the Tm:YLF slab crystals were antireflection coated for the laser wavelengths in the range 1.9–2.0 µm and the diode pump wavelength around 790 nm. The slab crystals wrapped in 0.05-mm-thickness indium foils were sandwiched between two water-cooled copper heat sinks. The water temperature was kept constant at 291 K. The folded resonator consisted of three flat 45° dichroic mirrors (M1, M2 and M3) with high reflectivity ($R > 99.8$ %) in the wavelength range 1.9–2.0 µm and high transmission ($T > 97$ %) at the pump wavelength, a VBG (OptiGrate Corp.) mirror as the resonator back-reflector and a concave output coupler (M4). The VBG was designed to be HR at 1,908 nm and had a clear aperture of 6 × 8 (in cross section) × 6 (in thickness) mm^3. The VBG was mounted in a copper heat sink to stabilize its temperature at 291 K. The output coupler was a plano-concave mirror with a 180 or 200 mm radius of curvature, and they are all coated for 40 % transmittance at 1.91 µm. The physical length of the resonator was approximately 130 mm. To achieve high efficiency and high power, the end pumping and spherical pump beam were employed in the experiment. The calculated TEM_{00} beam waist in the slab crystals was 228 µm (180 mm) or 244 µm (200 mm), which was assumed to increase at higher pump power due to the effect of the weak negative thermal lensing in Tm:YLF. The 12 mm × 20 mm plane surfaces of the two Tm:YLF crystals were polished

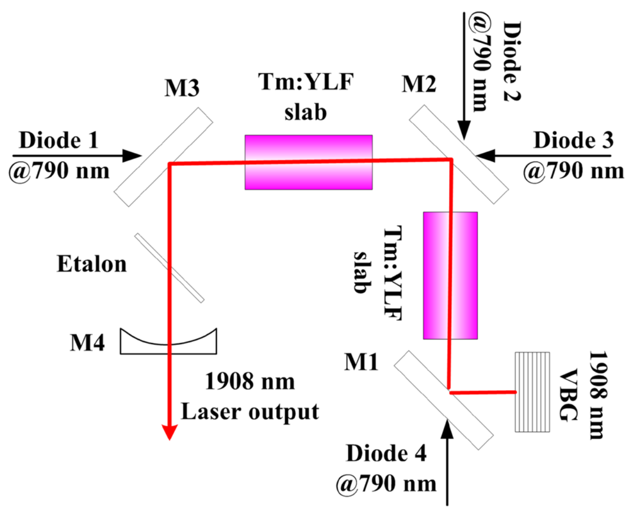


Fig. 1 Layout of the dual-end-pumped slab Tm:YLF laser with a VBG mirror

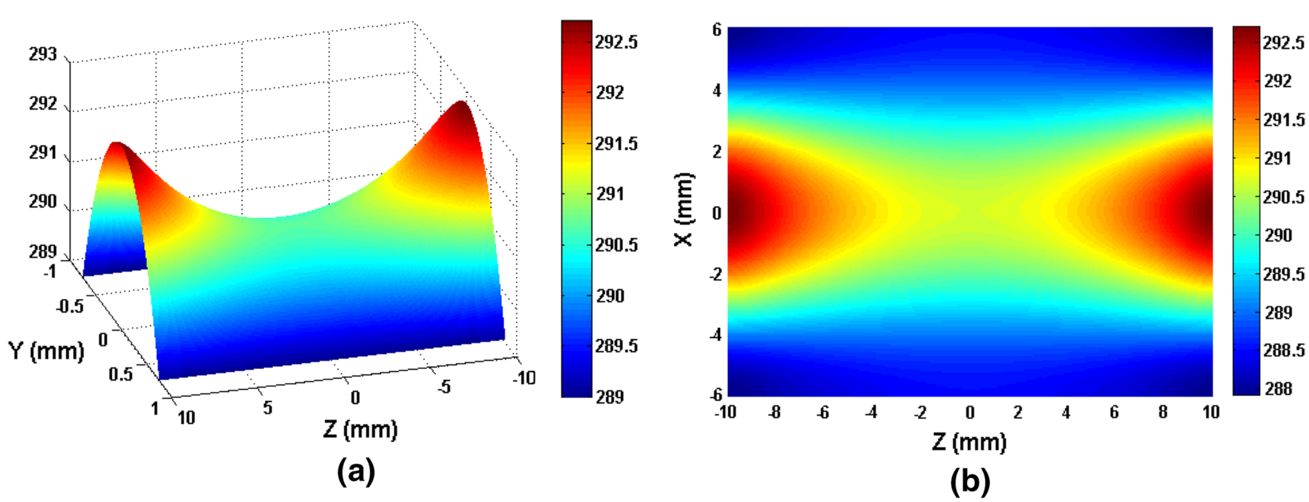


Fig. 2 Temperature distribution of the slab crystal, (**a**) y–z ($x = 0$), (**b**) x–z ($y = 0$)

and coated with Au film for effective and uniform thermal contact and cooling.

The local temperature distribution of the laser crystals can be achieved by solving the heat transfer Poisson equation. To simplify our calculation, we assume that the anisotropy for YLF is neglected, which is available to YLF since the thermal conductivity along the *a*-and *c*-axis for YLF has nearly the same value. The calculation results of the temperature distributions are shown in Fig. 2. Apparently, the heat mainly concentrates in the crystal where the pump beam passes through, and transfer to the *x*-axis is faster than that to *y*. The peak temperature of the slab crystal is about 292.7 K, and the temperature difference of the crystal was only 2.2 K. We can make a conclusion that the thin and wide crystal is available to heat dissipation, which leads to a small temperature gradient.

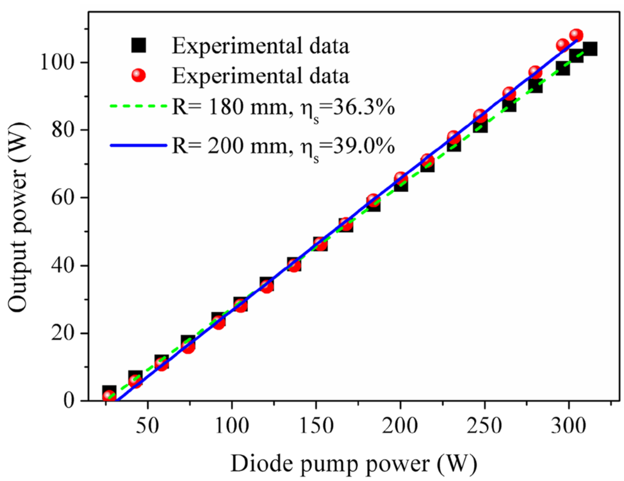


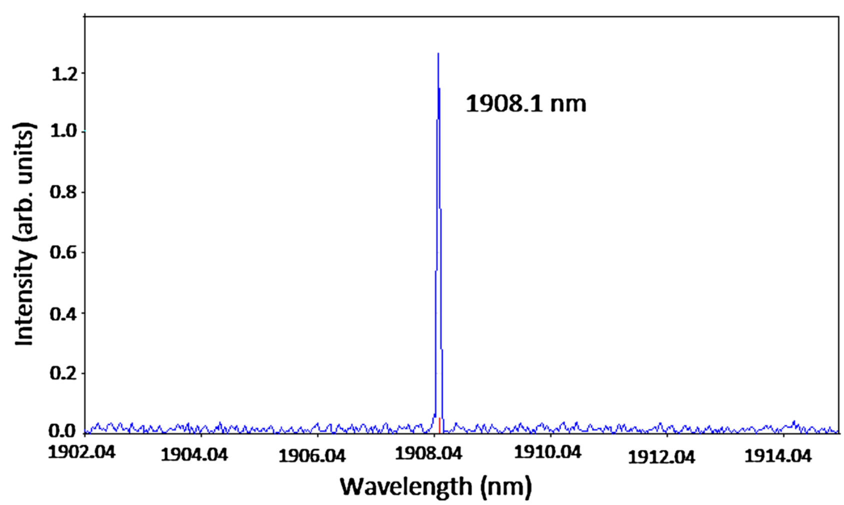
Fig. 3 Output power of the slab Tm:YLF laser

3 Experimental results and discussion

The output power as a function of the diode pump power incident on the slab crystals is plotted in Fig. 3. The threshold pump power of the slab Tm:YLF laser was approximately 25 W. A maximum laser output power of 108 W was achieved at the incident pump power of 304.5 W with a 200 mm curvature output coupler. This corresponds to a slope efficiency of 39.0 % and an optical-to-optical efficiency of 35.5 %. The slope efficiency was comparable to previously demonstrated values of end-pumped Tm:YLF slab laser [8], however, the optical conversion was much higher than them. The laser beam was σ-polarized (polarization parallel to the *a*-axis of the YLF slab crystals). While for the 180 mm curvature output coupler, 104 W output power was achieved, corresponding to a slope efficiency of 36.3 % and a conversion efficiency of 33.3 %. The efficiency of the slab Tm:YLF laser with 180 mm curvature output coupler was obviously lower the 200 mm, which can be attribute to the unmatched ratio of the diode pump beam to the oscillator laser waist. No fracture of the slab was observed in the experiments.

As shown in Fig. 4, the output spectrum of the Tm slab laser at the highest output power was measured with a Burleigh A-650 spectrum analyzer combined with a WA-1500 wavemeter (0.7 pm resolution). The water vapor absorption in the spectrum leads to amplitude instabilities at higher output powers, which can be improved by inserting a 0.3-mm-thick uncoated YAG etalon into the resonator (between M3 and M4). The laser was tuned to 1,908.1 nm by adjusting the angle of the etalon combined with the effect of the VBG in the resonator, which is well coincide with the Ho:YAG absorption peak [6]. The shift of the emitting wavelength of the slab Tm:YLF laser was

Fig. 4 Output spectrum of the slab Tm:YLF laser



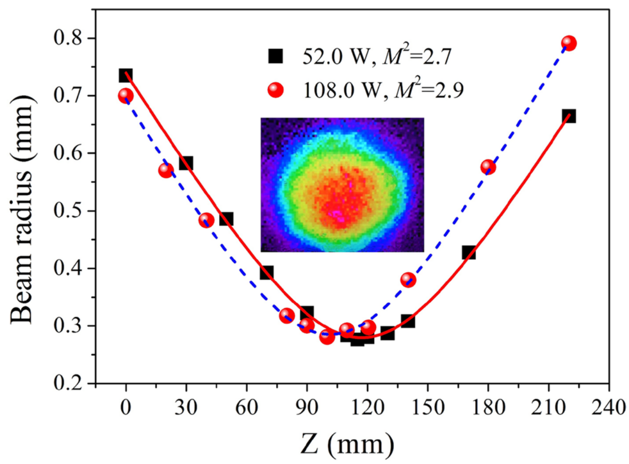


Fig. 5 Beam quality of slab Tm:YLF laser under two different output powers. Insert is the typical 2D beam profiles

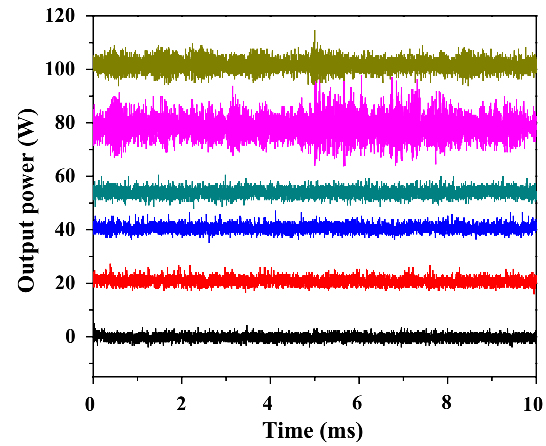


Fig. 6 Typical temporal waveform of the double slab Tm:YLF laser at different output powers

only about 0.3 nm from the threshold to the highest output power.

The output beam at two different output powers was characterized by scanning it with 90/10 knife-edge technique after pass through a focusing lens with focal length of 200 mm along the propagation direction. The beam radius was measured along the x direction paralleled to the a-axis of the Tm:YLF crystals. By fitting the standard Gaussian beam propagation expression to the measured data, as shown in Fig. 5, the fit yields M^2 ~ 2.7 and M^2 ~ 2.9, at the output power of 52.0 W and 108.0 W, respectively. Based on the above investigation, a beam quality factor of $M^2 < 3$ was found. From the data, we note that the shift of the beam waist is about 15.5 mm along the propagation direction as the output power from 52.0 to 108.0 W, which can be contribute to the thermal lensing effect of the Tm:YLF slab crystals. The output 2D laser beam profile (insert in Fig. 5) at the highest output power was observed by a pyroelectric camera. Due to the end-pumped configuration, the output 2D beam profile was observed as a circular spot. The heat dissipation is different in the two directions, as shown in Fig. 2. Apparently, the temperature gradient of the y direction was lager than the x direction, which means the thermal lens effect was strong in y direction. In other words, the beam quality of the output beam along the y direction was worse than the x direction.

The slab Tm laser was mounted in a dry box filled with nitrogen. Due to the several milliseconds lifetime of the $^3F_4$ upper state of Tm-doped laser host, it takes several tens of milliseconds to dampen the relaxation oscillation to a steady state after the pump is turned on. Any slight mechanical or acoustic perturbation to the laser resonator leads to the intrinsic amplitude instability observed in solid-state lasers. The power fluctuations of the double slab Tm:YLF solid-state laser were measured with an InGaAs detector and a Lecroy digital oscilloscope (Wavesurfer 64 Xs, 2.5 G-samples/s, 600 MHz bandwidth).The results are shown in Fig. 6 at different power levels. The results take the form of fluctuating signal oscillating around several different stable continuous wave power levels. There is no obvious signal spiking in the output under the power level of 80 W, while several spiking pulse are observed equal and greater than the power of 80 W which can be improved by larger ratio of pump beam waist to laser beam waist. The future work will address the matter. In addition, if we do not put the laser in a dry air box, the instabilities may be much stronger. A modulation down to zero value level may be cause damage of the AR coatings.

4 Conclusion

In conclusion, a 108-W slab crystal Tm:YLF laser dual-end-pumped by fiber-coupled laser diodes has been demonstrated with a beam quality of $M^2 < 3$ which was better than previous reports in slab geometry. The laser output wavelength was centered at 1,908.1 nm by a VBG mirror combined with a 0.3-mm-thickness YAG uncoated etalon. This corresponded to a slope efficiency of 39.0 % and a total optical conversion of 35.5 %. This Tm laser is ideal to be used as a pumping source of a high-power and high-efficiency Ho:YAG laser. The end pumping scheme and slab crystal geometry combined with fiber-coupled laser diodes can be scaled to higher output powers and good beam quality, which is the subject of future work.

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