Thermal analysis and CW laser operation at 1.998 μm in end pumped Tm:YAP lasers

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Abstract—We report on thermal analysis and continuous wave (CW) laser operation at (1.998μm) of an end pumped Tm: YAP cylindrical laser rod. The Tm: YAP laser rod is pumped at a wavelength of 1.064 μm emitting from an Nd: YAG laser source. A 3W incident pump power is used to generate a maximum laser output of 700 mW, representing 18% slope efficiency. The power of a thermally induced lens in a Tm:YAP laser rod is numerically analyzed and validated experimentally. The focal lengths of the thermally induced lens are directly measured using a Shack-Hartmann wavefront sensor. We have detected a blue up-conversion fluorescence emission before laser operation at 1.998 μm. The obtained experimental results were in good agreement with the numerical calculations.

Thulium doped yttrium-aluminum perovskite (Tm: YAP) has been utilized as a pulsed and continuous wave (CW) laser source in the 2 μm range, for various applications in medicine, atmospheric sounding and scientific research because of its ideal thermal-mechanical characteristics [1–4]. These characteristics represented in high mechanical strength and large heat conductivity of 0.11 W/cm·K [5], which allows high power operation with a reduced risk of fracture. Also, YAP crystal as a host for different rare earth ions exhibits a strong natural birefringence [6–8], which overwhelms the thermally induced birefringence and thus eliminates thermal depolarization problems commonly encountered with media such as Yttrium aluminum garnet (YAG) [8].

However, YAP crystal has a positive thermo-optical coefficient dn/dT of a value 14.6 K^{-1} [7], which induces strong positive thermal lensing. The presence of a thermal lens inside the laser resonator changes the optical path and beam properties resulting in an unstable resonator and degradation in laser beam quality [8]. Thermal effects in end and side pumped different types of solid-state lasers have been widely investigated to date [6–8]. However, few research works so far have been known for the investigation of a thermally induced lens and its compensation in Tm: YAP lasers [7], especially at a pump wavelength of 1.064 μm.

In this letter, we report, laser operation at 1.998 μm in a Tm:YAP laser rod under pumping at a wavelength of

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1.064 μm, which represents the first research we have known so far regarding this excitation wavelength.

In our experiment, the positive focal length of a thermally induced lens of the Tm:YAP laser rod verses incident pump powers were measured by a Shack-Hartmann wavefront sensor and compared to numerical calculations.

Figure 1 shows the experimental arrangement. The Tm:YAP rod is a 3 mm long, 3 mm in diameter and 3.5% atom dopant (Crytur no. P3363 [9]). The Tm:YAP rod is fitted in a copper house and is cooled by circulating water at 20 ° C, the two flat ends are cooled with air at 21°C room temperature. The two ends of the Tm:YAP rod are coated to configure a flat Fabry-Perot resonator. The pump source is a Nd:YAG laser at 1.064 μm, spatial mode TEM_{00} (laserlabcomponents no. 9082408 [10]).
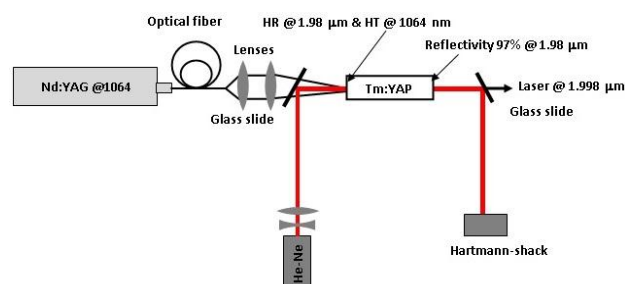

Fig.1. Experimental arrangement.

The Nd:YAG pump light was configured by optical fiber and two lenses to produce a circular shape point of 700μm in diameter on the first flat face of the Tm:YAP rod. This first flat face represents an input-coupling mirror with high reflectivity (HR) at the wavelength near 1.98 μm (R > 99.5%) and high transmittance at the pump wavelength (1.064 μm).

The second mirror is an output-coupling mirror which has 97% reflectivity at 1.98 μm and high transmittance at

1.064μm. The beam of an He-Ne laser is enlarged by a telescope to cover a spot of 3mm in diameter on the Tm: YAP laser rod and reflected by a glass slide to its end. Then it is reflected and directed by another glass slide to the Shacke-Hartmann (WFS1505C-Thorlabs) for measuring wavefront aberrations after passing the Tm:YAP cylindrical laser rod. The emission spectrum of fluorescence and laser operation recorded and measured with the aid of a monochromator, power meter, lock-in-amplifier, photodiodes, chopper wheel, and interference filters.
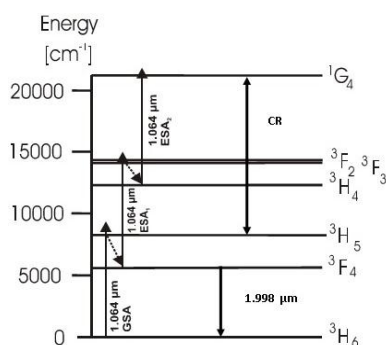

Fig. 2. Energy level scheme of Tm [11].

Figure 2 shows the energy levels of Tm ions and excitation mechanisms at a pump wavelength of 1064 nm. Excitation is produced by promoting the Tm ions from the ground state $^3H_6$ to $^3H_5$ level (ground state absorption, GSA) with fast non-radiative decay to $^3F_4$ level. The energy between $^3H_6$ to $^3H_5$ is 8230 cm^{-1} [11], which is far from the pump energy of 9398 cm^{-1}. The GSA is relatively small. However, the exploration of the value of ground state absorption cross section σ_{GSA}= 2.5×10^{-23}cm^2 [12], would lead to ~82% of incident pump power being absorbed. There are two unfavorable excited state absorption ESA$_{1,2}$ that promote the Tm ions to the levels $^3H_4$ and $^1G_4$, respectively. However, the population of the upper laser level $^3F_4$ might be supported by cross-relaxation (CR) $^3F_2$, $^3F_3$ → $^3H_5$, $^1G_4$ since no fluorescence at ~2.3 μm ($^3H_4$ → $^3H_5$ transition [11]) was observed. Under lasing conditions at 1.998 μm $^3F_4$ → $^3H_6$ transition, blue 480 nm up-conversion fluorescence [12] $^1G_4$ → $^3H_6$ (not shown in Fig. 2) becomes weaker because of the stimulated emission process that competes with the pump ESA$_{1,2}$.

The relation between the incident pump power and output laser is presented in Fig. 3. An abrupt appearance of laser emission is at ~650 mW of incident pump power. This high threshold is referred to the presence of unfavorable ESA$_{1,2}$ and a non-optimized resonator. The laser efficiency is ~18% with respect to incident pump power.

Also, as can be seen on the upper left of Fig. 3, the produced laser is cantered at 1.998 μm with a full width at a half maximum (FWHM) of about ~3.4 nm.
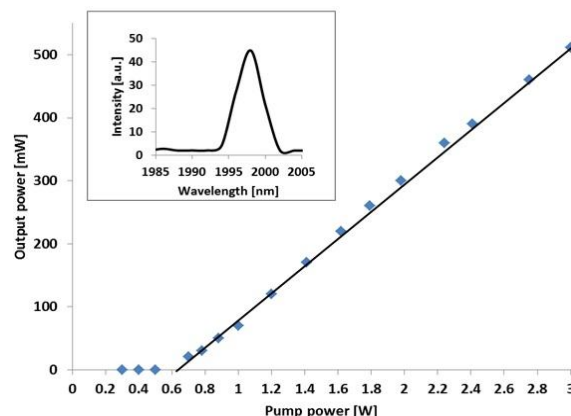

Fig. 3. A 1.998 μm laser output verses input power, the spectrum of the emitted laser on the top left.

The heat generated in solid state lasers due to quantum defect heating is removed by external cooling of the active medium. The resulting temperature gradient from the axis to the surface is responsible for the thermal effects in the active medium [8]. This nonuniform temperature distribution causes changes in the refractive index across the rod *dn/dT*, resulting in rod end faces bending and thermal stress. Hence, the wavefront of a generated laser beam is deformed and produces a thermal lens.
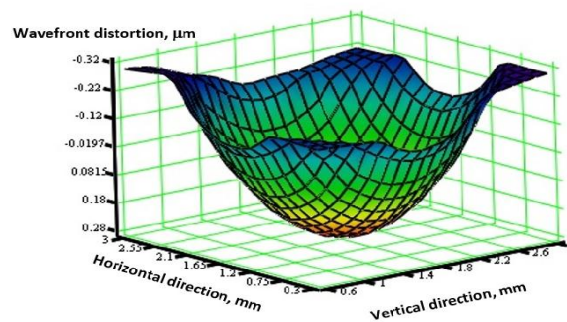

Fig. 4. Measurements of He-Ne wavefront aberration after passing a Tm:YAP laser rod pumped at 1.75 W.

Figure 4, shows the measurements of a Shack-Hartmann sensor for the deformation occurred in the wavefront of an He-Ne laser beam after passing the pumped Tm:YAP laser rod at 1.75 W. As can be seen in Fig. 4, the hotter part is at the rod center and the cooler part at the circumference resulting in a thermally induced lens, which is stronger compared to the outer region. The deformation occurred in the wavefront of an He-Ne laser beam is fitted to a second order polynomial equation, Eq. (1) [13–14]:

$$z(x,y) = a \cdot x^2 + b \cdot y^2 + c \cdot x \cdot y + d \cdot x + e \cdot y + f \qquad (1)$$

The thermal focal length of the thermally induced lens is proportional to the curvature of parabola and the coefficients a and b. Depending on the pump light focus on the laser rod end and its shape, the thermal lens may become asymmetric. This leads to an astigmatic thermal lens with two focal lengths in horizontal and vertical directions, respectively (f_x) and (f_y).

Figure 5 shows the measurements and calculations of the positive focal length of a thermal lens against incident pump powers. As can be seen in Fig. 5, the measured thermal focal lengths are an astigmatic thermal lens with two focal radii f_x (dashed line) and f_y (dotted line). This is mainly because the beam shaping of pump light must be radially symmetric. It is clearly seen that the power of a created thermally induced lens becomes stronger relative to pump powers.

In Fig. 5, the numerical calculations (solid line) of the mean value of the thermally induced lens in a Tm: YAP laser are acquired from analytical equation, Eq. (2) [15]:

$$f = \frac{\pi \cdot K \cdot r_p^2}{P_{heat} \cdot \left(\frac{dn}{dT} \right)} \left(\frac{1}{1 - e^{-\alpha \cdot L}} \right) \qquad (2)$$

where, r_p is the pump radius (350 μm), P_{heat} is the part of absorbed pump power converted to heat under lasing condition 0.22, while the heat conductivity (K) is 0.11 W/cm·K, thermal dispersion (dn/dT) 14.6 K^{-1}, Tm:YAP rod length (L) is 3mm and the estimated absorption coefficient of the laser medium α is 2 cm^{-1} [5, 7].
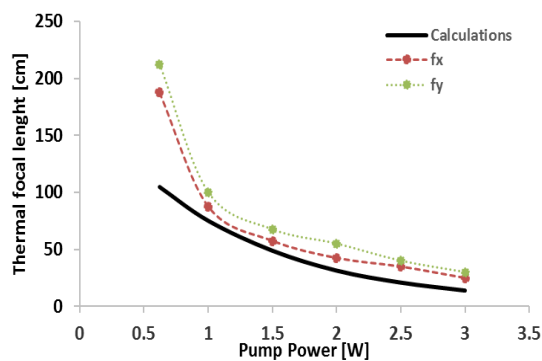

Fig. 5. Measurements and calculations of the focal lengths of a created thermally induced lens in end pumped Tm: YAP laser rods verses incident pump powers.

As can be seen in Fig. 5, the experimental values of the thermal focal lens are higher than numerical calculations. The deviation between the experimental work and calculations is attributed to the influence of the end face effect (curvature thermal expansion) which is neglected in Eq. (2). Furthermore, upconversion process that promoted Tm ions to $^1G_4$ level generates significant heat dissipation [16] in the Tm: YAP rod, which is also ignored in equ. (2). The effect of undesired $ESA_{1,2}$ increases strongly under non-lasing conditions, which means that a large deviation between the experimental data and numerical calculation is near the laser threshold. Under lasing conditions, the $ESA_{1,2}$ that evacuate the upper laser level at 1.988 μm is weakened, causing a close correlation between measurements and calculations.

In conclusion, the laser is demonstrated at 1.998 μm in a Tm: YAP laser rod under pumping at 1064 nm. This presents the first laser emission so far we know in Tm:YAP lasers under pumping at 1064 nm. A 700 mW output laser is obtained with 18% slope efficiency. The low efficiency is mainly referred to undesired upconversion processes $ESA_{1,2}$. We have also analyzed the thermal effects and creation of a thermally induced lens in a Tm:YAP laser numerically and experimentally. We found that the agreement between numerical and experimental results was below the threshold. Before the lasing condition, the upconversion processes should be included in mathematical equations and need more study. Also, we have presented a direct and accurate experimental method for measuring the focal length of a thermally induced lens.

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