Optimization of pumping conditions in end pumped Tm: YAP lasers with the consideration of thermal effects*

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In this work, we presented the measurements and calculations for the optimal pump conditions and their effects on thermal lens, fracture limit and laser efficiencies of end pumped Tm-doped yttrium aluminum perovskite (Tm: YAP) laser rod pumped at 1 064 nm. The results showed that the measured overall efficiency of produced laser at ~1.98 μm is enhanced from 3.9% to 6.9% when the pump spot diameter is reduced from 390 μm to 210 μm. The maximum output power and oscillation threshold are also enhanced with reduced pump spot size. The maximum thermal stress and focal length of thermally induced lens are also addressed.

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Laser sources around 2 μm have been used for various applications in biophoton, wind lidar and many other fields[1-5]. Laser sources operating in the 2 μm range, rare earth Tm-doped solid state hosts like yttrium aluminum garnet (YAG), yttrium lithium fluoride (YLF), yttrium aluminum perovskite (YAP) and fiber lasers have been demonstrated[6-12]. Among these different hosts, Tm-doped YAP (Tm: YAP) has proven to be one of the most preferable ~2 μm laser sources due to its unique physical and thermal properties[13,14]. These properties represented in natural birefringent medium that provides free depolarization effect that hindered the output laser power[8]. In addition, emission cross section of Tm in YAP host is twice compared to the most common laser crystal YAG[15]. In addition, the preference for this type of solid-state laser comparable to Tm-doped fiber lasers is based on the weakness of the upconversion processes that hindered laser emission at ~2 μm and allowance of power scaling in solid state YAP crystal[16-18].

A series of research works have been reported for Tm: YAP lasers operating at ~2 μm and pumped at a wavelength around 972 nm[19-21], but rare for a pump wavelength at 1 064 nm[18].

This work experimentally investigated the effect of pump spot size on performance of laser output at a wavelength of 1.98 μm laser pumped at 1 064 nm. We have previously studied the experimental and theoretical work on the effect of pump power on the focal lengths of thermally induced lens in end pumped regime at a fixed diameter of pump light.

However, in the end pumped laser configuration, the spot size of pump light strongly affects the efficiency of produced laser and the associated thermal effects[15]. On one hand, decreasing the pump spot size will increase the pump intensity, thereby raising the efficiency of the produced laser and lowering the oscillation threshold. On the other hand, increasing the pump intensity results in significant creation of thermally induced lens and its disfavored effect on laser stability, in addition to the risk of rod fracture[15].

In this work, we have investigated experimentally the effect of laser efficiency at ~1.98 μm in Tm: YAP laser rod pumped at 1 064 nm at different pump spot sizes of 210 μm, 270 μm, 330 μm and 390 μm. The experimental results showed that the reduction in pump spot increases the efficiency of produced laser. Additionally, we have calculated numerically the effect of pump spot size on the creation of thermally induced lens as well as maximum possible tensile stress. Also, we have presented the calculated focal lengths of thermally induced lens at different pump spot diameters. In this work, we have presented a new research result for Tm: YAP lasers under a new pumping wavelength of 1 064 nm. We have numerically emphasized the effect of different pump spot sizes on the focal lengths of thermally induced lens at different pump powers and the predicted fracture limits that may cause rod damage.

Fig.1 shows the experimental setup for producing laser in Tm: YAP rod. The pump source is an Nd: YAG laser operating at 1 064 nm. The emitted 1 064 nm pump light is focused onto an optical fiber with a large core diameter of 450 μm and a numerical aperture of 0.24. The

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emitted pump light from the other end of the optical fiber is shaped with different groups of focusing lenses to form different pump spot dimeters. The obtained pump spot is focused onto the first end of the 3.5 at.% Tm doped YAP with a diameter of 3 mm and a length of 3 mm. The Tm: YAP laser rod is water cooled at 20 °C and its two ends are air cooled at room temperature of 21 °C. The laser resonator is formed by coating mirrors on the two flat-flat ends of the Tm: YAP laser rod.

The input-coupling mirror is coated to achieve a high reflectivity (HR), reflectivity R>99.5% at the wavelength near 1.98 μm and high transmittance (HT), transmittance T>99.5% at pump wavelength of 1 064 nm. The output-coupling mirror has a reflectivity of 97% and transmittance of 3% at ~1.98 μm. The produced laser at 1.98 μm is reflected by a 45° mirror (HR at 1.98 μm and HT at 1 064 nm) and directed onto power meter to avoid residual pump light from measurements.

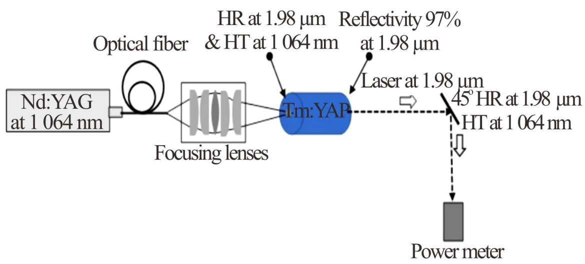

Fig.1 Experimental setup for Tm: YAP laser

Fig.2 shows the relationship between the input pump power and the laser output power at 1.98 μm for different spot diameters of pump light of 210 μm, 270 μm, 330 μm and 390 μm, respectively. For the maximum incident pump power of 3 W, the maximum output powers are 179 mW, 142 mW, 121 mW and 98 mW, and laser thresholds are 28 mW, 30 mW, 39 mW and 46 mW for pump spot diameters of 210 μm, 270 μm, 330 μm and 390 μm, respectively.

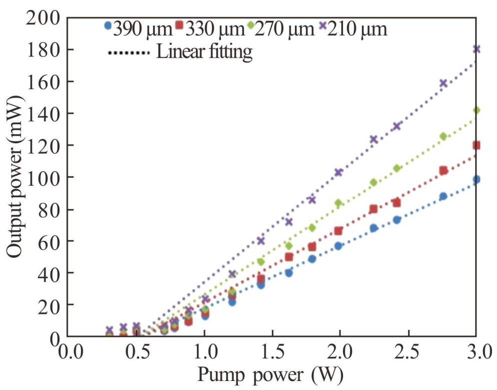

Fig.2 Relationship between laser output power at ~1.98 μm and input pump power at different pump spot diameters

The presented experimental results in Fig.2 indicate that high pump intensity or confinement of pump light over a small area will produce preferable low threshold and high efficiency of laser at 1.98 μm. Therefore, reducing the pump spot diameter can result in increased laser output before saturation occurs and reduced oscillation threshold.

The emitted spectra of Tm: YAP laser centered at 1.98 μm with a full width at a half maximum ($FWHM$) of about ~4 nm at a pump power of 2.5 W and spot sizes of 270 μm and 330 μm are shown in Fig.3.

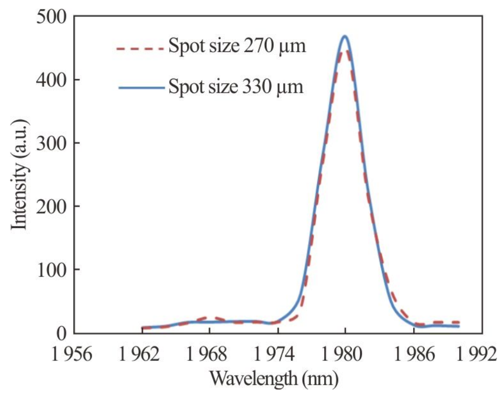

Fig.3 Emitted spectra of Tm: YAP laser at 1.98 μm

The maximum efficiency of the laser at 1.98 μm as a function of pump light spot diameter is presented in Fig.4. The obtained efficiencies are 6.9%, 5.52%, 4.6% and 3.391% for pump spot diameters of 210 μm, 270 μm, 330 μm and 390 μm, respectively. The efficiency of the produced laser tends to decrease as the pump light spot diameter increases.

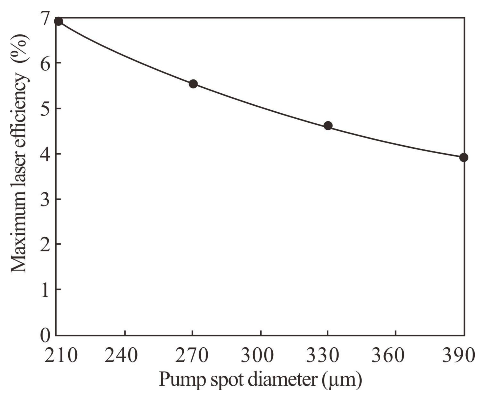

Fig.4 Relationship between the maximum laser efficiency at 1.98 μm and the spot diameter of pump light pumped at 3 W

The enhancement of produced laser efficiency is converged to around 51% when the diameter of pump spot size is reduced from 390 μm to 210 μm. We could not go further for smaller pump spot diameter due to limitation of focusing system of the pump light. However, the obtained laser output powers and overall efficiencies are considerably low. This is mainly due to low absorption coefficient at 1 064 nm, which will be discussed in the following part, non-optimized resonator and a low gain due to the small length of Tm: YAP rod. These results can be utilized in increasing output powers and lowering threshold by reducing pump spot size for the end pumped laser rod with better absorption and higher gain.

In general, the focusing pump spot over a small size will dominate the thermal effects that hindered the laser performance like fracture effects, and the thermally induced lens should be considered.

In the following part, we present the calculations of the maximum tensile stress and focal length of the thermally induced lens. The maximum tensile stress σ_{max} across the rod section is given by[15]

$$\sigma_{max}=\frac{1}{2}(T-T_0)\cdot\frac{\beta E}{1-\nu}, \tag{1}$$

where β, E, ν and $(T-T_0)$ are the expansion coefficient, Young's modulus, Poisson ration and temperature difference between the rod center and its circumference, respectively. For calculation of σ_{max}, we select β=4.2×10^{-6} K, E=220 GPa, and ν=0.3[15]. For incident pump power of 3 W, the calculated σ_{max} is 0.41 GPa, 0.037 GPa, 0.031 GPa and 0.028 GPa for pump spot diameters of 210 μm, 270 μm, 330 μm and 390 μm, respectively. However, the calculated values of σ_{max} are in a safe range and far away from the fracture limit of Tm: YAP crystal, which is ~160 MPa[15].

The heat dissipated inside laser rod resulting from quantum defect heating and cooling the outer surface of laser rod produces nonuniform temperature distribution[15]. This nonuniform temperature distribution alters the refractive index of the active medium (thermal dispersion dn/dT) with the thermal expansion of pumped end face, and is responsible for forming the thermally induced lens. The presence of thermal lens inside laser resonator affects the laser beam properties and resonator stability.

We have numerically calculated the focal lengths using the analytical equation[15] of

$$f=\frac{\pi K r_{\mathrm{p}}^2}{P_{\mathrm{heat}}\cdot(\mathrm{d}n/\mathrm{d}T)}\left(\frac{1}{1-\mathrm{e}^{-\alpha L}}\right), \tag{2}$$

where P_{heat} is the fraction of pump power dissipated in the laser rod as heat according to Eq.(3)[15]:

$$P_{\mathrm{heat}}=\left(1-\frac{\lambda_{\mathrm{pump}}}{\lambda_{\mathrm{laser}}}\right)\cdot P_{\mathrm{inputpower}}, \tag{3}$$

where λ_{pump}, λ_{laser} and $P_{inputpower}$ are wavelength of pump light, wavelength of produced laser and input pump power, respectively.

The calculation results of focal lengths of thermally induced lens for Tm: YAP laser rod at different pump powers and different pump spot diameters of 210 μm, 270 μm, 330 μm and 390 μm are presented in Fig.5. The input parameters in Eq.(2) are P_{heat}=~0.46 W under lasing condition for incident pump power, K=0.11 W/(cm·K), dn/dT=14.6 K^{-1}, and the Tm: YAP rod length L is 3 mm. The absorption coefficient α is equal to 0.47 cm^{-1}, and it is measured experimentally herein for 3.5 at.% Tm doped YAP at a wavelength of 1 064 nm.

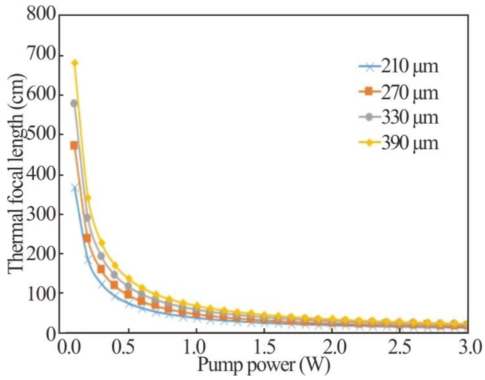

Fig.5 Focal lengths of the created thermally induced lens in end pumped Tm: YAP laser rods for different pump diameters at 3 W of incident pump power

In conclusion, the laser generation at ~1.98 μm in end pumped Tm: YAP laser rod pumped at 1 064 nm is presented. The laser performance is investigated under different pump spot diameters. An enhanced laser performance concerned in higher output power and lower threshold is achieved. We obtained a maximum output laser power of 179 mW at 28 mW of oscillation threshold instead of 98 mW output laser at 46 mW threshold, when the pump spot size is reduced from 390 μm to 210 μm. A further enhancement could be reached when using even smaller pump spot size and another pump wavelength with a better absorption coefficient like 792 nm. Also, we have presented the calculated focal lengths of thermally induced lens at different pump spot diameters. In this work, we have presented a new research result for Tm: YAP lasers under a new pumping wavelength of 1 064 nm.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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