# Diode-end-pumped composite Tm:YAG rod with undoped ends at room temperature

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The lasing characteristics of composite Tm:YAG rod with undoped ends at room temperature are reported. The maximum output power at 2.015 $\mu$m is 6.97 W and the slope efficiency is 41.45%. Focusing point and output coupler are changed to find the optimization condition. The relationship between operation temperature and output power is discussed. Comparison between Tm:YAG and composite Tm:YAG testifies the superiority of composite crystal.

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In recent years, laser action in trivalent thulium ($Tm^{3+}$) has been developed rapidly. The main interest in the 2-$\mu$m laser on the $^3F_4 - {}^3H_6$ transition arises from its applications in medicine and remote sensing[1−8]. The upper laser level ($^3F_4$) is excited through the cross-relaxation process $^3H_4 + {}^3H_6 - {}^3F_4 + {}^3F_4$. Two $Tm^{3+}$ ions will be excited to $^3F_4$ level through this relaxation process for each photon absorbed in the $^3H_4$ level. $Tm^{3+}$ laser has high quantum efficiency ($\sim$ 2). This advantage can compensate its disadvantage in small emitting cross-section. YAG crystal has the advantages of high mechanical strength and large heat conductivity (0.13 W/(cm·K)) which allows high-power operation with reduced risk of fracture[9,10]. As Tm:YAG is a quasi-three-level laser material, the thermal population of the lower laser level cannot be avoided when the pump power becomes higher. Composite crystal with undoped ends can release thermal effect to some degree.

In 1991, Suni *et al.* made use of diode-pumped Tm:YAG to achieve 0.5-W output laser[11]. In 1998, Bollig *et al.* obtained 4.1-W output at 2.013 $\mu$m by using Tm:YAG crystal[12]. Later, Lai *et al.* achieved 120-W continuous-wave (CW) diode-pumped Tm:YAG laser with the slope efficiency of 31.2%[13]. In Lai's work, a 105-mm Tm:YAG rod consists of a central 65-mm section doped with 3 at.-% Tm and a 20-mm undoped YAG section diffusion bonded to each end.

In this work, we demonstrate the CW lasing in the 3.5 at.-% Tm-doped composite YAG crystal. A maximum output power of 6.97 W at 20-W pumping power is obtained. The slope efficiency is 41.45% and the free-running wavelength is 2.015 $\mu$m.

The absorption and fluorescence spectra of the Tm:YAG are shown in Fig. 1. The absorption peak around 785 nm and the fluorescence peak around 2.015 $\mu$m are obviously seen.

The experimental setup is shown in Fig. 2. The output beam from a fiber-coupled 785-nm laser diode (LD) is shaped and focused by a series of convex lenses. The laser is end-pumped. A Tm:YAG crystal with 3-mm diameter and 15-mm length is used as an active segment. Un-doped YAG crystals with 3-mm diameter and 5-mm length are diffusion bonded to both end faces of the active crystal. The whole composite Tm:YAG crystal is 25 mm long. The Tm concentration is 3.5%. Both sides of the crystal are polished plane, parallel, and anti-reflection coated ($T > 99.5\%$) at 785 nm and 2.02 $\mu$m. The other Tm:YAG crystal is 4 mm in diameter and 10 mm in length. The Tm concentration is also 3.5%, and the coating of both ends are the same to the composite Tm:YAG. The plane mirror is high reflective at the wavelength near 2.02 $\mu$m ($R > 99.5\%$) and high anti-reflective at the wavelength near 785 nm ($R < 0.5\%$). Different output couplers (OCs) were used in the experiment. The typical length of the cavity is 37 mm. In order to testify the superiority of composite crystal, relative experiment

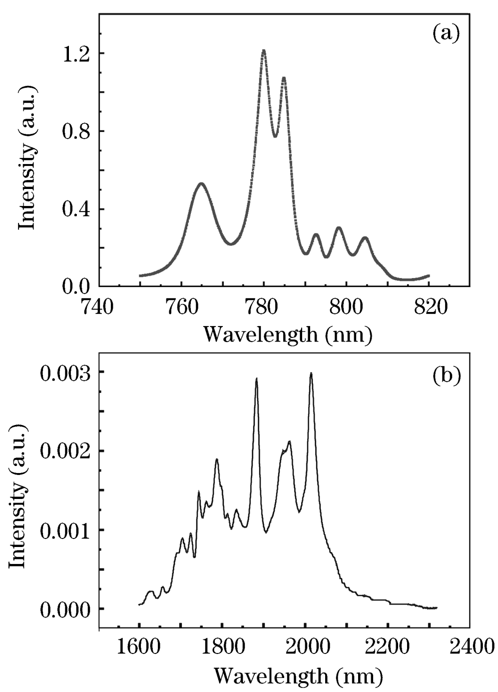


Fig. 1. (a) Absorption and (b) fluorescence spectra of Tm:YAG.

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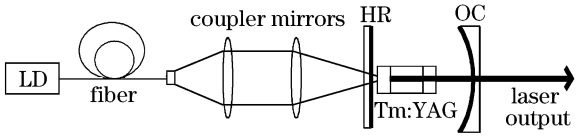


Fig. 2. Cavity configuration of the diode-pumped Tm:YAG laser.

**Table 1. Optimum Temperature of LD for Composite Tm:YAG**

| LD Temperature (°C) | 10 | 12 | 15 | 20 |
|---|---|---|---|---|
| Output Laser (W) | 6.58 | 6.75 | 6.86 | 6.80 |

**Table 2. Optimum Temperature of LD for Tm:YAG**

| LD Temperature (°C) | 14 | 15 | 17 | 20 |
|---|---|---|---|---|
| Output Laser (W) | 4.96 | 5.06 | 5.30 | 5.05 |

was also developed. Both crystals were laid on heat-sink and cooled by the thermoelectricity.

To find the optimum wavelength of pump laser, the LD temperature was changed (the wavelength can be changed by running temperature of diode in a small range) and the relationship between input power and output power was found. As shown in Tables 1 and 2, under the same pump power, the optimum running temperature for Tm:YAG crystal is 290 K, the corresponding central wavelength of the LD is about 785.5 nm. And the optimum running temperature for composite Tm:YAG crystal is 288 K, the central wavelength of the LD is about 785 nm under this temperature. The population density of the lower laser level is different between Tm:YAG and composite Tm:YAG. The capability of eliminating heat is stronger in composite crystal. It leads the absorption of Tm:YAG to shift to shorter wavelength.

Figure 3 illustrates the effect of different focus points. The result shows that the diameter of the focus point at 480 $\mu$m is more efficient than that at 630 $\mu$m when the pumped power is less than 14 W. It is quite accordant with the theoretical value of about 501.8 $\mu$m calculated by Matlab. But when the pumped power is higher than 14 W, the diameter of the focus point at 630 $\mu$m is more efficient than that at 480 $\mu$m. When the pumped power becomes higher, the thermal effect is more obvious. Reducing the pumping intensity can reduce the thermal effect to a certain degree.

Figure 4 gives the result of Tm:YAG laser with

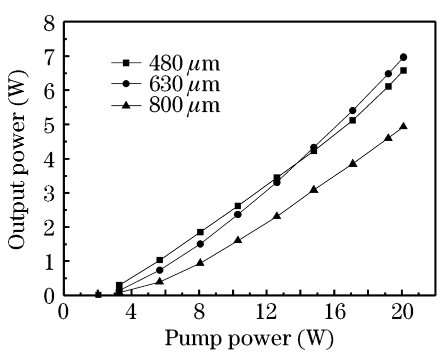


Fig. 3. Output power of composite Tm:YAG versus input LD power with different focus point diameters.

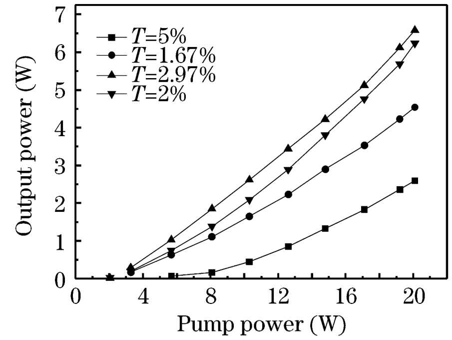


Fig. 4. Output power of composite Tm:YAG versus input LD power with different OCs.

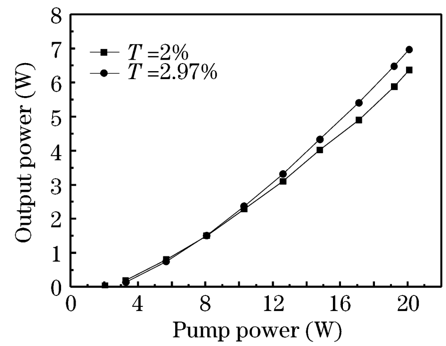


Fig. 5. Comparison between the output couplers of $T$ = 2% and $T$ = 2.97%. Focus point diameter is 630 $\mu$m.

different transmission coefficients of couplers. The maximum output powers of 4.54 W ($T$ = 1.67%), 6.24 W ($T$ = 2%), 6.58 W ($T$ = 2.97%), and 2.60 W ($T$ = 5%) are obtained under pump power of 20 W at 785 nm. The thresholds are 2.67, 2.05, 2.05, 5.67 W and the slope efficiencies are 26.23%, 34.56%, 36.23%, 18.44%, respectively. The above results reveal that it is negative to use OC with transmission larger than 5%. The maximum output power of 6.97 W is achieved when the diameter of the focus spot is 630 $\mu$m and the OC transmission is 2.97%. The slope efficiency is 41.45%. Figure 5 gives the comparison with $T$ = 2% and $T$ = 2.97%. With the pump power becomes higher, $T$ = 2.97% is more efficient than $T$ = 2%. Tm:YAG is a quasi-three-level laser material. When the pump power becomes higher, the thermal population of the lower laser level becomes serious. For high power output laser, increasing the OC transmission properly can reduce the heat of the cavity and improve the efficiency of the laser.

When the scale of temperature controller is adjusted, the output power changes correspondingly. The output power change is fitted linearly in the range of room temperature. As Fig. 6 shows, the slope is about −29.5 mW/K. It means that increasing the temperature of the laser crystal is unfavorable to emit the heat at room temperature. Tm:YAG which is operating on the $^3F_4-{}^3H_6$ transition is a quasi-three-level laser. The ground state is thermally populated. When the temperature becomes higher, the number of reversal particles will decrease. And the high temperature will increase the threshold and reduce the output power.

Figure 7 shows the input-output characteristics of Tm:YAG and composite Tm:YAG operated at 285 K.

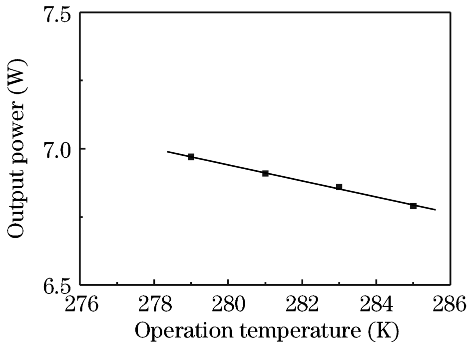


Fig. 6. Output power versus operation temperature.

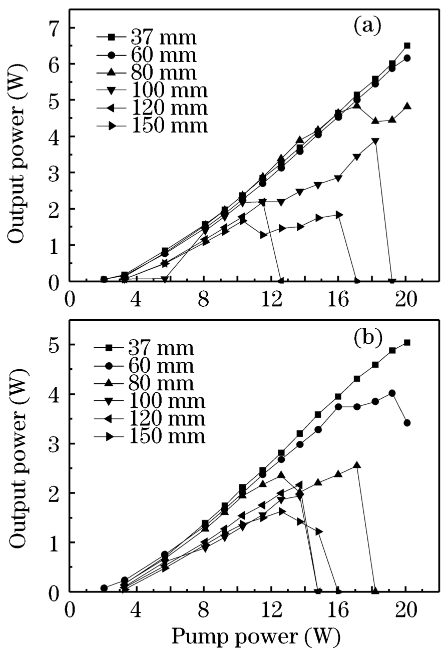


Fig. 7. Comparison between composite Tm:YAG and Tm:YAG for different cavity lengths. (a) Composite Tm:YAG; (b) Tm:YAG.

Here the cavity length is changed in the range of $37-150$ mm. As the cavity length becomes longer, the thermal effect turns to be more obvious. For composite Tm:YAG, when the cavity length is less than 60 mm, the thermal lensing does not affect the laser performance. But for Tm:YAG, when the cavity length is 60 mm, the output power becomes unstable. For the pumped power higher than 15 W, the slope efficiency of Tm:YAG is descending. When the length of the cavity is longer than 80 mm, the superiority of composite crystal becomes obvious. Also, the threshold of composite crystal is lower. All of these testify the composite crystal is more efficient for its capability of releasing thermal effect.

In conclusion, the lasing characteristics of composite Tm:YAG at room temperature are obtained. The maximum output power at 2.015 $\mu$m is 6.97 W and the slope efficiency is 41.45%. The focus spot of 480-$\mu$m diameter is more efficient than the 630-$\mu$m one when the pump power is less than 14 W, but for the pump power higher than 15 W the 630-$\mu$m focus point is more efficient. Limited by the experiment condition, the optimum output coupler transmission is 2.97%. At room temperature, the higher temperature the laser crystal operates on, the lower power it produces. Comparison between Tm:YAG and composite Tm:YAG with the cavity length changing from 37 to 150 mm testifies the superiority of composite crystal.

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