# Thermal analysis and experimental study of end-pumped continuous-wave thulium-doped laser 

Chunting Wu ${ }^{\text {a,c, }, *}$, Fei Chen ${ }^{\text {b }}$, Tongyu Dai ${ }^{\text {c }}$, Youlun Ju ${ }^{\text {c }}$<br>${ }^{\text {a }}$ Jilin Key Laboratory of Solid-State Laser Technology and Application, Changchun University of Science and Technology, Changchun 130022, China<br>${ }^{\mathrm{b}}$ State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130031, China<br>${ }^{\text {c }}$ National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150080, China

## A R T I C L E I N F O

## Article history:

Received 1 July 2015
Accepted 5 December 2015

## Keywords:

Diode-pumped lasers
Tm:LuAG
Thermal lensing


#### Abstract

This paper focused on the analysis of thermal effect of Tm:LuAG crystal and its lasing characteristics under continuous-wave (CW) operation at room temperature. The temperature-distribution of Tm:LuAG rod was shown intuitively by using a software of COMSOL. The thermal focal length was calculated which was useful to design the resonator. In experiment, thermal focal length of Tm:LuAG crystal was measured, firstly. The experimental results were coinciding with the theoretical calculations. Then, laser characteristics of CW Tm:LuAG crystal were measured. Maximum output power of 6.34 W was obtained when the pump power was 25.7 W . To our best knowledge, it was the highest output power of CW Tm:LuAG laser. The output wavelength was 2023 nm and the beam quality factor was $M^{2}=3.8$ at the maximum power level.


© 2015 Published by Elsevier GmbH.

## 1. Introduction

All solid-state lasers operating at $2 \mu \mathrm{~m}$ are useful for the applications as coherent Doppler LIDAR, differential absorption LIDAR, and so on [1,2]. Thulium-doped $\mathrm{Lu}_{3} \mathrm{Al}_{5} \mathrm{O}_{12}$ (Tm:LuAG) crystal is isomorphic to YAG [3]. It is one of the attractive materials for it owns the advantages of high heat conductivity and the lower population density of the lower laser level. Compared with the wavelength of Tm:YAG $(2.015 \mu \mathrm{~m})$, the emission wavelength of Tm:LuAG $(2.023 \mu \mathrm{~m})$ is more closer to the optical transmission window.

In the past 10 years, many researchers reported their work on Tm:LuAG laser. For example, in 1995, an optical-to-optical differential efficiency of $23.6 \%$ was achieved by diode-pumped Tm:LuAG laser [4]. In 2000, the maximal output 0.92 W was obtained from diode-pumped Tm:LuAG laser under the pump power of 10 W [5]. And in 2008, the maximum output power of 4.91 W and the slope efficiency of $25.39 \%$ was obtained by diode-end-pumped Tm:LuAG laser [6]. Although there are many reports on the laser characteristics of Tm:LuAG laser, it was rarely seen the analysis of thermal

[^0]effect about Tm:LuAG crystal. In 2014, we reported the analysis of thermal effect about pulse LD pumped Tm:LuAG crystal and the lasing characteristics of pulsed Tm:LuAG at room temperature [7].

This paper focused on the analysis of thermal effect about Tm:LuAG crystal and the lasing characteristics of end-pumped continuous-wave Tm:LuAG laser at room temperature. The thermal model of Tm:LuAG crystal was built up. The temperaturedistribution of Tm:LuAG rod was shown intuitively by using a software of COMSOL. The thermal focal length was calculated and the resonator design was carried out considering the value-change of thermal focal length of Tm:LuAG crystal versus the pump power. In experiment, thermal focal length of Tm:LuAG crystal at different pump power were measured, which were coincide with the theoretical calculations. Finally, maximum output power of 6.34 W was obtained, with optical-to-optical conversion efficiency of $24.8 \%$ at the maximum power level. The output wavelength was 2023 nm . And the beam quality factor is $M^{2}=3.8$.

## 2. Analysis of thermal effect about Tm:LuAG crystal

### 2.1. Thermal model of Tm:LuAG crystal

The model of continuous-wave end-pumped Tm:LuAG rod was shown in Fig. 1.


Fig. 1. The model of continuous-wave end-pumped Tm:LuAG rod.
$r$ is the radial coordinate and $z$ is the axial coordinate. $b$ is the radius of rod and $L$ is the length of rod. Pump light propagated in the $z$ direction.

The heat source function in Tm:LuAG crystal could be described as formula (1) [8].
$q(r, z)=\frac{2 \alpha \eta_{\mathrm{h}} P_{i n} e^{-\alpha z}}{\pi w_{\mathrm{p}}^{2}} e^{-2 r^{2} / w_{\mathrm{p}}^{2}}$
Here, $\omega_{\mathrm{p}}$ is the waist radius of the pump beam, $\eta_{\mathrm{h}}$ is the heat fraction, $P_{i n}$ is the pump power, and $\alpha$ is the absorption coefficient of Tm:LuAG rod.

The boundary condition is shown as formula (2), (3), (4) and (5).
$\left.\frac{\partial T}{\partial r}\right|_{r=0}=0$
$\left.T\right|_{r=R_{0}}=T_{\mathrm{b}}$
$K_{\mathrm{c}}\left(T-T_{\infty}\right)-\left.h \frac{\partial T}{\partial n}\right|_{z=0}=0$
$K_{\mathrm{c}}\left(T-T_{\infty}\right)+\left.h \frac{\partial T}{\partial n}\right|_{z=L}=0$
where, $h$ is the heat transfer coefficient of the air. $K_{c}$ is the heat conductivity. $T_{\mathrm{b}}$ is the temperature of cooling water. $T_{\infty}$ is the room temperature.

The formula (2) could be simply to formula (6). And considering the formula (6), the temperature distribution within the end-pumped Tm:LuAG rod could be expressed as formula (7).
$\frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T(r, z)}{\partial r}\right)=-\frac{1}{K_{\mathrm{c}}} q(r, z)$
$T(r, z)=T_{\mathrm{b}}+\frac{\alpha \eta_{\mathrm{h}} P_{i n}}{4 \pi K_{\mathrm{c}}} e^{-\alpha z} \sum_{m=1}^{\infty} \frac{(-1)^{m}}{m m!}\left(\frac{2}{w_{\mathrm{p}}^{2}}\right)^{m}\left(\left(r^{2} / R_{0}^{2}\right)^{m}-1\right)$

### 2.2. Central temperature in Tm:LuAG crystal

The parameters of end-pumped Tm:LuAG laser would be used in simulation was shown in Table 1.

By using software of COMSOL, we could see the temperaturedistribution of Tm:LuAG rod intuitively, as shown in Fig. 2. When the scale of pump power was adjusted, the central temperature of Tm:LuAG rod changed correspondingly. At pump power of 5 W , the central temperature of Tm:LuAG rod was 303 K . And when the pump power was 30 W , the central temperature of Tm:LuAG rod increased to 361 K . The slope efficiency was about $2.3 \mathrm{~K} / \mathrm{W}$.

Central temperature of Tm:LuAG rod with different diameter versus pump power is shown in Fig. 3. The slope efficiency was about $1.1 \mathrm{~K} / \mathrm{W}, 1.9 \mathrm{~K} / \mathrm{W}, 2.3 \mathrm{~K} / \mathrm{W}, 2.6 \mathrm{~K} / \mathrm{W}$ and $2.8 \mathrm{~K} / \mathrm{W}$ of Tm:LuAG

Table 1
Parameters of end-pumped Tm:LuAG laser.

| Parameters | Value |
| :--- | :--- |
| Temperature of cooling liquid/K | 291 |
| Initial temperature/K | 295 |
| Heat transfer coefficient of air/(W cm |  |
| Heat conductivity of Tm:LuAG/(W cm $\left.{ }^{-1} \mathrm{~K}^{-1}\right)$ [8] | $8 \times 10^{-4}$ |
| Pump beam waist/cm | 0.079 |
| Pump power/W | 0.8 |
| Heat fraction | $1-30$ |
| Crystal radius/mm | 0.6 |
| The length of Tm:LuAG rod/mm | 1.5 |
| Density of Tm:LuAG/(g/cm $\left.{ }^{3}\right)[9]$ | 8 |
| Specific heat capacity of Tm:LuAG/(J Kg $\left.{ }^{-1} \mathrm{~K}^{-1}\right)$ | 6.32 |
| (similar to Tm:YAG) | 590 |
| Absorption coefficient of 3.5 at\% $\mathrm{Tm}: \mathrm{LuAG}^{-1} / \mathrm{cm}^{-1}$ |  |
| Thermo-optical coefficient $(d n / d T) /\left(\mathrm{K}^{-1}\right)[9]$ | 3 |
| Refractive index of Tm:LuAG rod | $8.9 \times 10^{-6}$ |
| Poisson's ratio | 1.81 |
| Thermal expansion coefficient/(K $\left.\mathrm{K}^{-1}\right)[9]$ | 0.3 |



Fig. 2. Central temperature of Tm:LuAG crystal at different pump power.


Fig. 3. Central temperature of $T m: L u A G$ rod versus pump power with different diameter.
rod with diameter of $1 \mathrm{~mm}, 2 \mathrm{~mm}, 3 \mathrm{~mm}, 4 \mathrm{~mm}$ and 5 mm , respectively. Small cross section of laser rod was conducive to cooling. However, due to the limitations of mechanical dimensions and the gain extraction, the cross section of laser rod should be proper.

### 2.3. Thermal focal length Tm:LuAG crystal

In Tm:LuAG rod, thermally induced optical path difference caused by the change of refractive index with temperature. The thermally induced optical path difference (OPD) [10] in the slice $z$


Fig. 4. Thermal focal length versus pump power.


Fig. 5. Resonator design.
to $\mathrm{d} z$ is written by the expression (8).

$$
\begin{align*}
\operatorname{OPD}(r)= & 2 \int_{0}^{L}\left[\frac{\partial n}{\partial t} \Delta T(r, z)+\left(n_{0}-1\right)(1+v) \alpha_{T} \Delta T(r, z)\right. \\
& \left.+\sum_{i, j=1}^{3} \frac{\partial n}{\partial \varepsilon_{i, j}(r)} \varepsilon_{i, j}\right] \mathrm{d} z \tag{8}
\end{align*}
$$

The time-varying thermal focal length is written as the expression (9) [8].
$f_{\mathrm{th}}=\frac{\pi K_{\mathrm{c}} \omega_{\mathrm{p}}^{2}}{\alpha \eta_{\mathrm{h}} P_{\text {in }} \partial n / \partial t} \frac{1}{1-\exp (-\alpha L)}$

As shown in Fig. 4, the thermal focal length became shorter when the pump power increased. During the power range of $1-30 \mathrm{~W}$, the thermal focal length was in the range of $21-613 \mathrm{~mm}$. When the pump power was high, the thermal focal length was shorter than 50 mm . It meant that the thermal effect of Tm:LuAG crystal was quite seriously. The data were very useful to design the cavity.

### 2.4. Resonator design

To lower the threshold of the low gain transition quasi-threelevel laser and increase the output power, the cavity length was designed as short as possible. The value-change of the thermal focal length should be considered as designing the resonator, as shown in Fig. 5. Plane mirror M1 and concave mirror M2 were set on the sides of the laser crystal. The thermal lens of the crystal was seen as a parabolic thin lens which was convenient for resonator design using ABCD matrices, as shown in formula (9). Considering the thermal focal lens in the gain medium, the stability of the cavity versus the thermal focal length is expressed by $\frac{A+D}{2}$ in Fig. 6. We could


Fig. 6. The stability of the cavity versus the thermal focal length.


Fig. 7. Experimental setup.
see that the laser cavity was insensitive to the thermal lens and the cavity was stable even operated at high pump level.

$$
\begin{align*}
T=\left[\begin{array}{ll}
A & B \\
C & D
\end{array}\right]= & {\left[\begin{array}{ll}
1 & 0 \\
0 & 1
\end{array}\right]\left[\begin{array}{ll}
1 & L 1 \\
0 & 1
\end{array}\right]\left[\begin{array}{cc}
1 & 0 \\
-\frac{1}{f} & 1
\end{array}\right] } \\
& {\left[\begin{array}{ll}
1 & \frac{L 2}{n} \\
0 & 1
\end{array}\right]\left[\begin{array}{ll}
1 & L 3 \\
0 & 1
\end{array}\right]\left[\begin{array}{cc}
1 & 0 \\
-\frac{R}{2} & 1
\end{array}\right] }  \tag{10}\\
& {\left[\begin{array}{ll}
1 & L 3 \\
0 & 1
\end{array}\right]\left[\begin{array}{ll}
1 & \frac{L 2}{n} \\
0 & 1
\end{array}\right]\left[\begin{array}{cc}
1 & 0 \\
-\frac{1}{f_{i}} & 1
\end{array}\right]\left[\begin{array}{ll}
1 & L 1 \\
0 & 1
\end{array}\right] } \tag{11}
\end{align*}
$$

$-1<\frac{A+D}{2}<1$

## 3. Experimental setup

Fig. 7 showed the experimental setup of diode-end-pumped Tm:LuAG laser.

In experiment, a fiber-coupled laser diode (LD) was employed as the pump source. The central wavelength of the LD could be matched the absorption of Tm:LuAG laser at 788 nm by changing the temperature of the LD. The core diameter and numerical aperture (NA) of the fiber was 400 and $0.22 \mu \mathrm{~m}$. The output beam of the pump laser was shaped and focused by two simple lenses. The mode matching between pump mode and laser mode was optimized by changing the pump beam waist radius and its location.

The dimension of $3.5 \% \mathrm{Tm}$-doped LuAG was $\phi 3 \times 8 \mathrm{~mm}^{2}$. In fact, optimizing the doping concentration was quite necessary to improve the output power of Tm:LuAG laser. The faces were polished planes, parallel and coated with antireflection at the wavelength near $790 \mathrm{~nm}(R<0.5 \%)$ and $2023 \mathrm{~nm}(R<0.5 \%)$. The side face of Tm:LuAG crystal was packed by indium foil and placed in the copper heat sink. The copper heat sink was contacted with the cooling system. The outer cylindrical surface of the crystal rod assumed to keep constant temperature which was set as 291 K , and the two end faces exchange heat with the air.

The resonator geometry used was plane-concave. The plane mirror was high reflective at the wavelength near $2023 \mathrm{~nm}(R>99.5 \%)$
and high antireflective at the wavelength about $788 \mathrm{~nm}(R<0.5 \%)$. The radius of curvature and the transmissivity at 2023 nm of the output coupler were 100 mm and $3.5 \%$, respectively. The physical length of the cavity was 23 mm . Another plane mirror with transmissivity of $3.5 \%$ near 2023 nm was used as output mirror to measure the thermal focal length of Tm:LuAG crystal.

## 4. Experimental results and discussion

Firstly, the experiment of measuring thermal focal length of Tm:LuAG crystal was carried out. A plane-plane resonator was used. The Tm:LuAG crystal was placed closely to the high reflective plane mirror. Another plane mirror with transmissivity of 3.5\% was placed on the other side of the crystal. The cavity length was 23 mm . The laser oscillation began after carefully adjustment and the threshold was 2.6 W . At pump power of 5 W , the output coupler was kept away from the laser crystal by adjust the position of the output mirror. When the cavity length was 126 mm , the laser oscillating termination happened suddenly. In other words, the thermal focal length of Tm:LuAG crystal was 126 mm at pump power of 5 W . By this method, the thermal focal length of Tm:LuAG crystal at pump power of $10 \mathrm{~W}, 15 \mathrm{~W}, 20 \mathrm{~W}$ and 25 W were measured.

Fig. 8 gave the calculated results and experimental results about thermal focal length of Tm:LuAG crystal versus pump power. The experimental results were coinciding with the theoretical calculations. At pump power of 25 W , the thermal focal length of Tm:LuAG crystal was 25 mm experimentally. At pump power of 30 W , no output power at all. However, if we keep the pump power out firstly, then let the pump power act on the crystal suddenly, the output power data would be displayed on the power meter instantly but disappeared at once, which meant that the thermal focal length was too short to keep the stability of the cavity.

Then a plane-concave resonator was used as designed to achieve stable laser output. Fig. 9 showed the output power of Tm:LuAG laser versus pump power. The lasing threshold was 2.1 W . Under a pump power of 25.7 W from the laser diode, the maximum power of 6.34 W was achieved. The slope efficiency was $45.2 \%$. The optical-to-optical conversion efficiency at the maximum power level was approximately $24.8 \%$. Because of the power saturation trend, higher pump power was not used for protecting Tm:LuAG crystal.

The wavelength of the Tm:LuAG laser was measured with a monochrometer ( $300-\mathrm{mm}$ focal length, 300 lines $/ \mathrm{mm}$, grating blazed at 2000 nm ). The chopped-input laser was detected by an InGaAs detector connected with a phase-lock amplifier. Fig. 10 showed the measured laser spectrum of the Tm:LuAG laser.


Fig. 8. Thermal focal length versus pump power.


Fig. 9. Output power versus pump power.


Fig. 10. Output wavelength of Tm:LuAG laser.

At the maximum output power, the beam quality factor $\left(M^{2}\right)$ of Tm:LuAG laser was measured by the traveling knife-edge method. The $M^{2}$ was equal to 3.8 . It is because the cavity was too short to restrain multimode oscillation. The severe thermal effects would also reduce the beam quality.

## 5. Conclusion

In summary, we reported an analysis of thermal effect about Tm:LuAG crystal and its lasing characteristics under continuouswave operation at room temperature. The thermal model of Tm:LuAG crystal was built up. The temperature-distribution of Tm:LuAG rod was shown intuitively by using software of COMSOL. Central temperature of Tm:LuAG rod with different diameter versus pump power had also been obtained, result in that small cross section of laser rod was conducive to cooling. The thermal focal length was calculated which was useful to design the resonator. In experiment, thermal focal length of Tm:LuAG crystal at different pump power were measured, which were coincide with the theoretical calculations. Maximum output power of 6.34 W was obtained. The output wavelength was 2023 nm and the beam quality factor was $M^{2}=3.8$ at the maximum power level. Compared with the experimental result before ( $M^{2}=1.17$ ), it proved that the pulse LD pumped technology is a good method to relieve thermal effect and improve the beam quality of Tm:LuAG laser.

## Acknowledgments

We gratefully acknowledge support from the National Natural Science Foundation of China (Grant no. 61405017).

## References

[1] Y.F. Li, B.Q. Yao, Z.G. Wang, Y.Z. Wang, Y.L. Ju, Chin. Optik Lett. 4 (2006) 470-472.
[2] B.Q. Yao, L.Q. Dong, Y.Z. Wang, Y.L. Ju, X. Yu, W.F. Sun, Y.F. Li, Acta Optik Sin. 24 (2004) 79-82 (in Chinese).
[3] J.D. Kmetec, T.S. Kubo, T.J. Kane, C.J. Grund, Optik Lett. 19 (1994) 186-188.
[4] N.P. Barnes, M.G. Jani, R.L. Hutcheson, Appl. Optik 34 (1995) 4290-4292.
[5] V. Wulfmeyer, M. Randall, A. Brewer, R.M. Hardesty, Optik Lett. 25 (2000) 1228-1230.
[6] C.T. Wu, Y.L. Ju, Y.F. Li, Z.G. Wang, Y.Z. Wang, Chin. Optik Lett. 6 (2008) 415-416.
[7] C.T. Wu, F. Chen, R. Wang, Y.L. Ju, Optik Commun. 333 (2014) 115-118.
[8] M.E. Innocenzi, H.T. Yura, C.L. Fincher, R.A. Fields, Appl. Phys. Lett. 56 (1990) 1831-1833.
[9] X.D. Wang, X.D. Xu, T.C. Zang, C.L. Ma, Z.W. Zhao, J. Xu, Rare Earth Soc. 27 (2009) 745-748 (in Chinese).
[10] X.L. Song, B.B. Li, S.Y. Wang, D.F. Cai, J.G. Wen, Z. Guo, Chin. J. Lasers 34 (2007) 1476-1479 (in Chinese).


[^0]:    * Corresponding author at: Jilin key Laboratory of Solid-State Laser Technology and Application, Changchun University of Science and Technology, Changchun, 130022, China. Tel.: +86 431 85582819; fax: +86 43185582465.

    E-mail address: bigsnow1@126.com (C. Wu).

