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Regular article

Transient thermal effect analysis and laser characteristics of novel Tm: LuYAG crystal

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ABSTRACT

Based on the actual working environment, the thermal model of novel Tm: LuYAG crystal is established, and the transient thermal effect of pulsed laser diode single-end pumped Tm: LuYAG laser under different spot radius, pump power, repetition frequency, pulse width and duty ratio are simulated, analyzed, and discussed theoretically. The output characteristics of pulsed-LD end-pumped Tm: LuYAG laser are achieved and analyzed at different repetition frequencies and duty ratios experimentally. At repetition frequency of 10 Hz, 100 Hz, 1000 Hz and duty ratio of 50 %, the maximum output energy is 724 mJ, 70 mJ, 6.36 mJ, with the slope efficiency is 39.4 %, 38.2 % and 35.5 %, respectively. Moreover, at repetition frequency of 10 Hz and duty ratio of 75 %, the maximum output energy of 900 mJ is achieved with slope efficiency of 34.6 %. The central wavelength of Tm: LuYAG laser is measured to be 2018.96 nm, and the beam quality is $M_x^2 = 1.96$, $M_y^2 = 1.98$. To our knowledge, it is the first time to analyze the transient thermal effect of Tm: LuYAG crystal pumped by pulsed laser diode in detail. As far as we know, this is the maximum output energy based on the novel Tm: LuYAG crystal.

1. Introduction

Due to the wide applications in laser radar, atmospheric remote sensing, medical treatment, the all-solid-state lasers directly achieved 2 μm laser output based on semiconductor pump has been rapidly developed resent years [1–4]. Up to now, garnet crystals, including YAG [5–6] and LuAG [7–8], are the most prominent kind of hosts since they have excellent mechanical and optical properties. In addition, the laser properties of the two have been widely researched and by substitution of Lu for Y in the host garnet (Tm, Y)$_3$Al$_5$O$_{12}$ thus novel mixed crystal Tm: LuYAG is been obtained, while this crystal retains good mechanical properties, its upper state lifetime will be extended, the emission spectrum will be broadened, and the central wavelength of its emission will have less consumption during atmospheric transmission. At the same time, the appearance of LuYAG mixed crystal also solved the problems of high cost and difficult processing of LuAG.

Recently, the Tm: LuYAG lasers have experienced a rapid development. In 1994, National Oceanic and Atmospheric Administration reported a Tm: LuYAG laser [9]. When the pump power was about 12 W, maximum output power of 3 W was obtained, with a slope efficiency of 33 %. In 2004, Tokyo University of Technology used a solar furnace to determine solidification points of LuYAG, and then grew LuYAG crystals by the Czochralski method and measured their lattice parameters, thermal and optical properties [10]. The results showed that the lattice parameters of LuYAG changed linearly with variations in composition. In 2012, Chinese Academy of Sciences reported on the first tunable Tm: LuYAG mixed crystal laser using a VBG for wavelength control [11]. The output wavelength could be tunable from 1935.3 to 1994.9 nm continuously and a maximum output power of 1.76 W was obtained at 1999.7 nm with pump power of 10.75 W and the corresponding slope efficiency of 21.41 %. In 2016, Jiangsu Normal University described a thulium-doped (Lu,Y)$_3$Al$_5$O$_{12}$ mixed crystal and investigated the spectrum characteristics and laser performance of a diode-pumped Tm: LuYAG crystal [12]. For continuous wave (CW) operation, the maximum output power was 3.05 W, with a slope efficiency about 33 %. And single pulse energy of 1.4 mJ and pulse duration of 89.5 ns was obtained under acoustic Q-switched operation. In 2018, Jiangsu Normal University discussed the first vortex laser in 2 μm spectral range directly generated

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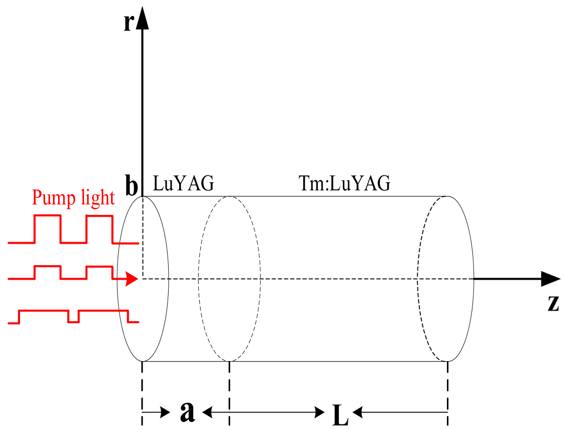

Fig. 1. The model of pulsed LD single-end pumped Tm: LuYAG crystal.

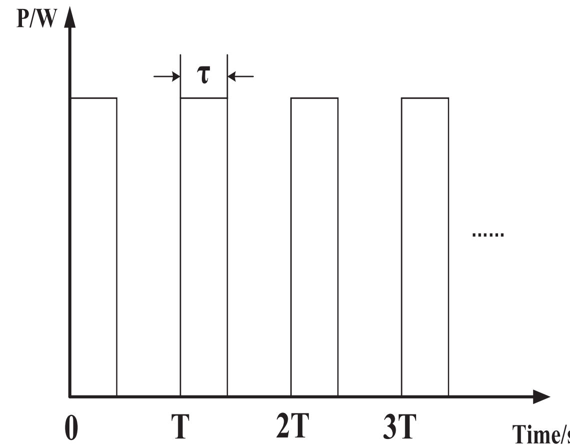

Fig. 2. Schematic diagram of pump pulse.

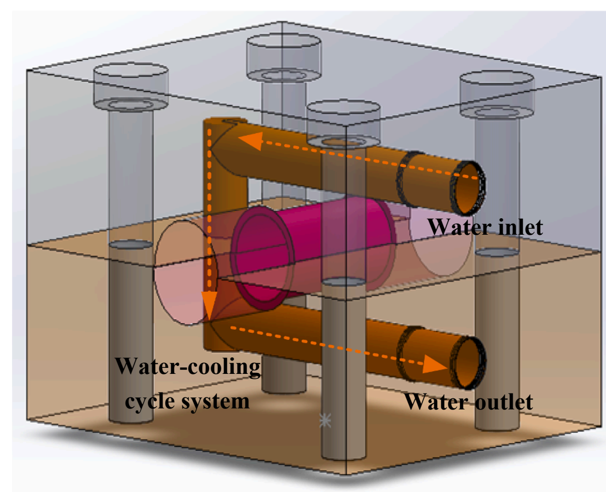

Fig. 3. The heat dissipation device of Tm: LuYAG crystal.

from a Tm: LuYAG oscillator [13]. The thresholds of different-order Laguerre-Gaussian modes are theoretically analyzed and discussed. Vortex lasers with orbital angular momentum of ħ and -ħ were experimentally produced with corresponding output powers of 1.75 W and 1.64 W, respectively. In 2020, Jiangsu Normal University continued to study direct generation of pulsed vortex beams at 2 μm CW acoustic Q-switched Tm: LuYAG laser [14]. At a repetition rate of 500 Hz, $LG_{0,+1}$ mode with 1.48 mJ pulse energy and $LG_{0,-1}$ mode with 1.51 mJ were produced. The same year that Changchun University of Science and Technology investigated the laser characteristics of LD end-pumped CW and Q-switched Tm: LuYAG laser [15]. Maximum output power of 3.7 W with slope efficiency of 54.6 % is obtained at pump power of 15 W under CW operation. For Q-switched operation, at repetition rate of 100 Hz and pump power of 9.12 W, a maximum single pulsed energy of 3.07 mJ and pulsed width of 100 ns was achieved. The slope efficiency was 27.05 %. In 2021, Changchun University of Science and Technology reported the output characteristics of acoustic Q-switched Tm: LuYAG laser [16]. The result indicated that, compared with using laser diode with central output wavelength of 788 nm as the pumping source, central wavelength of 785 nm light source was more suitable for pumping Tm: LuYAG crystal.

As mentioned above, there are few reports on novel Tm: LuYAG crystals. Moreover, to the best of our knowledge, it is the first time to analyze the transient thermal effect of Tm: LuYAG crystal pumped by pulsed laser diode in detail. The transient heat conduction equation is built, and the temperature distribution of Tm: LuYAG crystal are simulated under different condition, such as different pulse pump power, different operating repetition frequencies or various duty ratio. The output characteristics of pulsed LD end-pumped Tm: LuYAG laser are achieved in experiment. Maximum output energy of 900 mJ is obtained at repetition frequency of 10 Hz, with the slope efficiency of 34.6 %. As far as we know, this is the maximum output energy based on the Tm: LuYAG crystal. The beam quality is $M_x^2 = 1.96$, $M_y^2 = 1.98$. And the central output wavelength is 2018.96 nm.

2. Theoretical analysis

2.1. Thermal model of Tm: LuYAG crystal

The model of pulsed LD-pumped Tm: LuYAG crystal is established based on the cylindrical coordinate system, as shown in Fig. 1. The pulsed pump light propagates along the z-axis, which is the axial coordinate, and r is the radial coordinate. The radius of the single-end bonded Tm: LuYAG crystal is b, and the Tm^{3+} doped and undoped lengths are L and a, respectively. The absorption coefficient of Tm: LuYAG is α [17].

The pump pulse is rectangle pulse with pump duration time τ, period T, as shown in Fig. 2, in which the ordinate represents the output power of the pump source.

Assume that the absorption coefficient of single-end-bonded Tm: LuYAG crystal at pump wavelength is β [18], according to the Beer-Lambert law, the pump intensity at any location in Tm: LuYAG crystal is given by the formula (1).

$$I(r,z,t) = \frac{2P}{\pi\omega^2}\exp\left(-2\frac{r^2}{\omega^2}\right)\exp[-\beta(z-a)]G(t), a \le z \le L+a, -b \le r \le b \tag{1}$$

Where, P is the power of pump pulse, ω is the waist of pump-beam. r is the radial coordinate and z is the axial coordinate. $G(t)$ is a periodic function which describes pump pulse, as shown in formular (2).

$$G(t) = [square(2\pi ft, \tau/T + 1)]/2 \tag{2}$$

square is a rectangular square wave function, f is repetition frequency, τ is pump duration time, and $A = \tau/T$ is the duty cycle.

The heat source function which is caused by pulsed Gaussian pump light can be described as the expression (3) [19–20].

$$q_v(r,z,t) = \frac{2p\beta\eta}{\pi\omega^2}\exp\left(-2\frac{r^2}{\omega^2}\right)G(t)\{\exp(-\beta z) + \exp[-\beta(L-z)]\} \tag{3}$$

In order to alleviate the thermal problem of laser material, we use a water cooling radiator, the model of which is shown in Fig. 3. the side

Table 1
Parameters of Tm: LuYAG crystal for simulation [10]

Parameters	Value
Water cooler temperature (T_w) / K	291.15
Initial temperature (T_e) / K	296.15
Heat transfer coefficient of air (h) / $W \cdot cm^{-2} \cdot K^{-1}$	0.5×10^{-4}
Heat conductivity of Tm: LuYAG (k) / $W \cdot cm^{-1} \cdot K^{-1}$	7.5×10^{-2}
Pump beam waist (ω) / μm	400
Crystal radius (r) / mm	1.5
Non-doped part length (a) / mm	3
Doped part length (L) / mm	8
Density of Tm: LuYAG (ρ) / $kg{\cdot}cm^3$	5640×10^{-6}
Specific heat capacity of Tm: LuYAG (c) / $J \cdot kg^{-1} \cdot K^{-1}$	481
Absorption coefficient of 3.5 at. % Tm: LuYAG (α) /cm^{-1}	3.15

face of Tm: LuYAG crystal is packed by indium foil and placed in the copper heat sink, which is contacted with the cooling system and set at temperature of 291 K, and the yellow arrow is the water cooling circulation system. Two end faces of the crystal exchange heat with the air to transfer energy to the air.

The heat-transfer equation, the boundary conditions, and the initial conditions of the Tm: LuYAG crystal in the temperature-rise period are shown in formular (4)-(8).

$$\rho c\frac{\partial T_1}{\partial t} = k\left(\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r}\frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2}\right) + q_v, 0 \le t \le \tau, 0 \le z \le L + a, 0 \le r \le b \quad (4)$$

Boundary conditions,

$$T_1 = T_w, r = b \quad (5)$$

$$k\frac{\partial T_1}{\partial z} + hT_1 = hT_e \ \ z = 0 \quad (6)$$

$$k\frac{\partial T_1}{\partial z} + hT_1 = hT_e \ z = L + a \quad (7)$$

Initial condition

$$T_1 = T_0 \ t = 0 \ \ 0 \le z \le L + a \ 0 \le r \le b \quad (8)$$

The heat-transfer equation, the boundary conditions, and the initial conditions of the Tm:LuYAG crystal in the temperature-fall period are shown in formular (9)-(13).

$$\rho c\frac{\partial T_2}{\partial t} = k\left(\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2}\right), \tau \le t \le T, 0 \le z \le L + a, 0 \le r \le b \quad (9)$$

Boundary conditions

$$T_2 = T_w, r = b \quad (10)$$

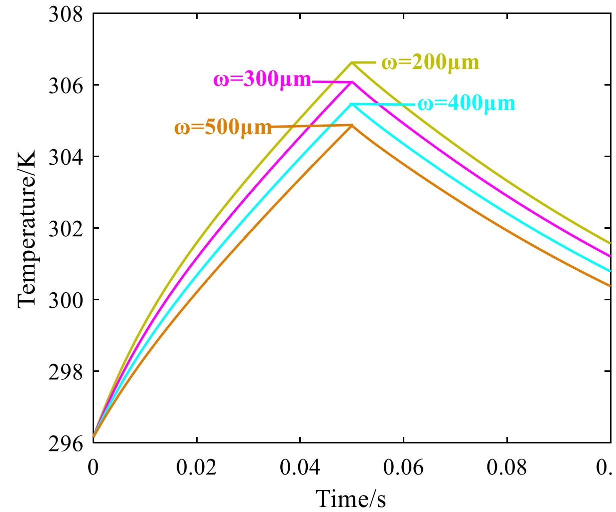

Fig. 5. Temperature of Tm: LuYAG crystal under different spot radius.

$$-k\frac{\partial T_2}{\partial z} + hT_2 = hT_e \ z = 0 \quad (11)$$

$$k\frac{\partial T_2}{\partial z} + hT_2 = hT_e \, z = L + a \quad (12)$$

Initial condition

$$T_2(r,z,t)|_{t=\tau} = T_1(r,z,t) \quad (13)$$

Here, ρ, c, *and* k are the density, the specific heat, and the heat conductivity of Tm: LuYAG crystal, respectively. h is the heat transfer coefficient of air. T_W is the temperature of water cooling. T_e is the initial temperature of Tm: LuYAG crystal, which equals to the room temperature T_0.

2.2. Analysis on transient thermal effect of Tm: LuYAG crystal

The parameters used in the simulation are shown in Table 1..

In the process of pulse pumping, the undoped part of Tm: LuYAG crystal will not generate heat, so we focus on the internal light field of Tm^{3+}-doped part. As the repetition frequency of pulsed laser diode is 10 Hz, the duty ratio is 50 %, the pulsed pump power is 50 W, and the other parameters used in the simulation are shown in Table 1, the optical field distribution of Tm: LuYAG crystal is shown in Fig. 4.

It can be seen from Fig. 4 that the light intensity internal the crystal is mainly distributed on the bonding surface which is close to the pump

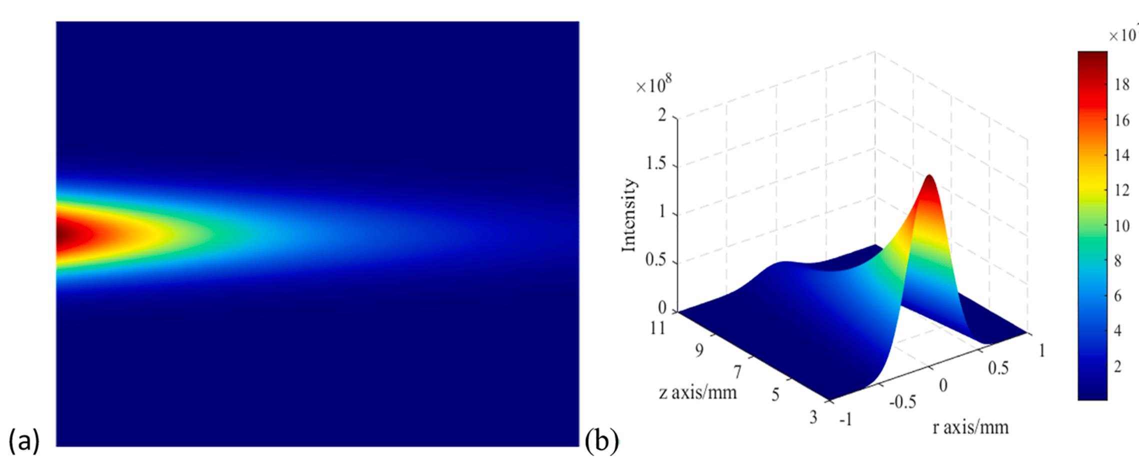

Fig. 4. Internal light intensity of Tm : LuYAG crystal (a) two-dimensional (b) three-dimensional.

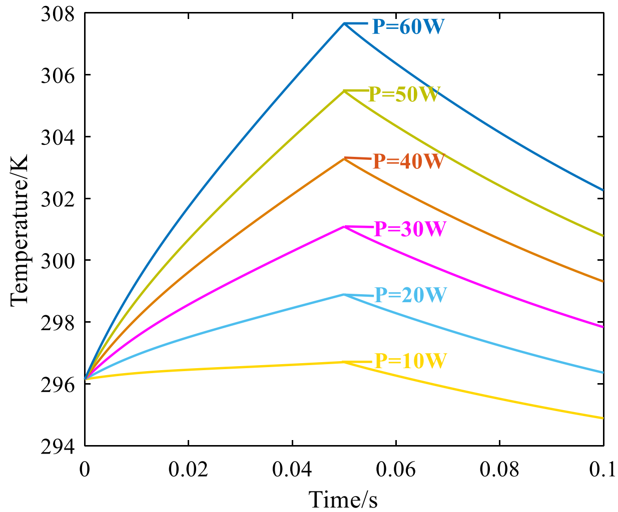

Fig. 6. Temperature of Tm: LuYAG crystal under different pump power.

source.

2.2.1. Transient thermal effect of Tm: LuYAG crystal under different spot radius

In order to achieve high optical efficiency and good beam quality of Tm: LuYAG laser, the mode matching between pump light and oscillating light has been adjusted. The repetition frequency of pulsed laser diode is 10 Hz, the duty ratio is 50 %, the pulsed pump power is 50 W, and the other parameters used in the simulation are shown in Table 1. The transient temperature distribution in the central bonding surface of Tm: LuYAG crystal in one cycle is stimulated, as shown in Fig. 5.

It can be seen from Fig. 5 that when the spot radius is 200, 300, 400, 500 μm, the transient temperature distribution in the central bonding surface of Tm: LuYAG crystal in one cycle is 306.63, 306.09, 305.47, 304.86 K, respectively. With the decrease of beam waist, the pump power density is increases, which leads to the temperature increasing in the central bonding surface of Tm: LuYAG crystal correspondingly.

2.2.2. Transient thermal effect of Tm: LuYAG crystal under different pump power

The pump source is a pulsed laser diode. The repetition frequency is 10 Hz and duty ratio is 50 %, and the other parameters used in the simulation are shown in Table 1. The transient temperature distribution in the central bonding surface of Tm: LuYAG crystal in one cycle is stimulated, as shown in Fig. 6.

As shown in Fig. 6, when the pump power is 10, 20, 30, 40, 50, 60 W, the transient temperature distribution in the central bonding surface of Tm: LuYAG crystal in one cycle is 296.69, 298.89, 301.07, 303.28, 305.47and 307.66 K, respectively. In other words, with the increasing of pump power, the pump energy absorbed by the crystal increases gradually, the transient temperature in the central bonding surface of Tm: LuYAG crystal is increasing correspondingly.

2.2.3. Transient thermal effect of Tm: LuYAG crystal under different duty ratio

The pump source is a pulsed laser diode. When the pump power is 50 W, the pulse width is 25 ms, the duty ratio is 25 %, 50 %, 75 %, then the repetition frequency is 10 Hz, 20 Hz, 30 Hz, respectively. While, the pulse energy remains at 1.25 J. The other parameters used in the simulation are shown in Table 1. The transient temperature distribution in the central bonding surface of Tm: LuYAG crystal is stimulated, as shown in Fig. 7.

According to Fig. 7 (a), the highest transient temperature in the central bonding surface of Tm: LuYAG crystal under repetition frequency of 10 Hz, 20 Hz, 30 Hz and duty ratio of 25 %, 50 %, 75 % are 302.19, 307.6, 313.58 K, respectively. As the pump energy is constant, the higher the duty ratio is, the shorter cooling time the crystal owns. The higher the residual temperature left by the previous pulse pump is, means the higher internal temperature in the crystal is. Therefore, when the pump energy and the pulse width are the same, with the increasing of the duty ratio, the transient temperature in the central bonding surface of Tm: LuYAG crystal is increasing correspondingly.

In order to further verify the effect of duty ratio on transient temperature distribution of crystal, as the pulsed pump power is 50 W, the repetition frequency is 10 Hz, the duty cycle is 25 %, 50 %, 75 %, and the other parameters used in the simulation are shown in Table 1. The transient temperature distribution in the central bonding surface of Tm: LuYAG crystal is stimulated, as shown in Fig. 7 (b).

According to Fig. 7 (b), the highest transient temperature in the central bonding surface of Tm: LuYAG crystal in one cycle under duty ratio of 25 %, 50 %, 75 % are 301.58, 305.55, 308.99 K, respectively. As the pump power and the frequency are constant, the increase of duty ratio means the increasing of the pump energy, the thermal effect of the crystal becomes more seriously. Therefore, at the same repetition frequency but different duty ratio, the transient temperature in the central bonding surface of Tm: LuYAG crystal will increase as the increase of duty ratio.

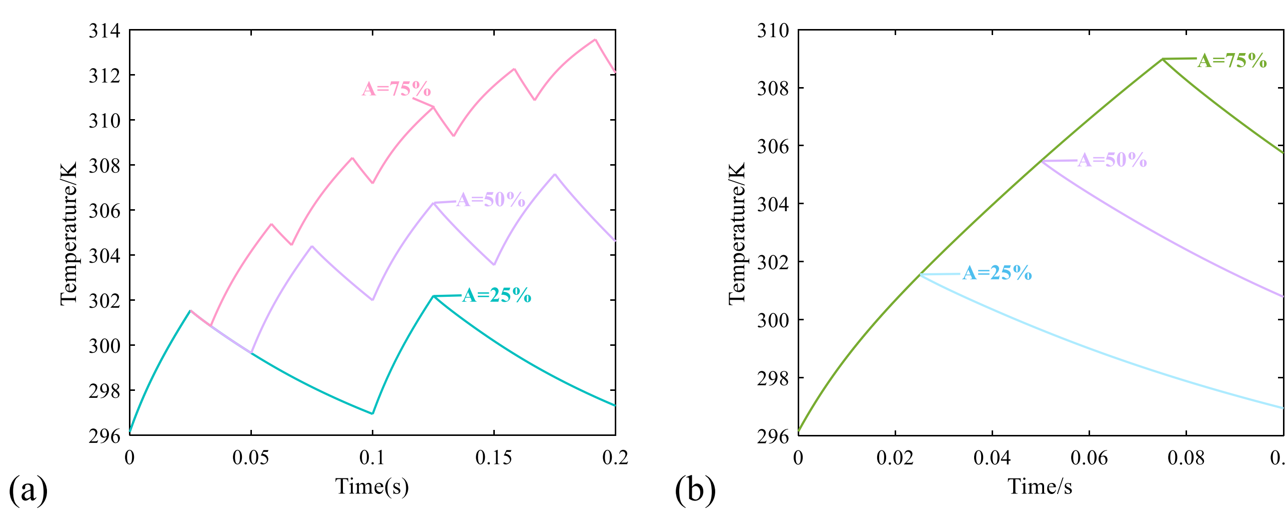

Fig. 7. Transient temperature distribution in the central bonding surface of Tm: LuYAG crystal under different duty ratio (In the figure, A represents the duty ratio).

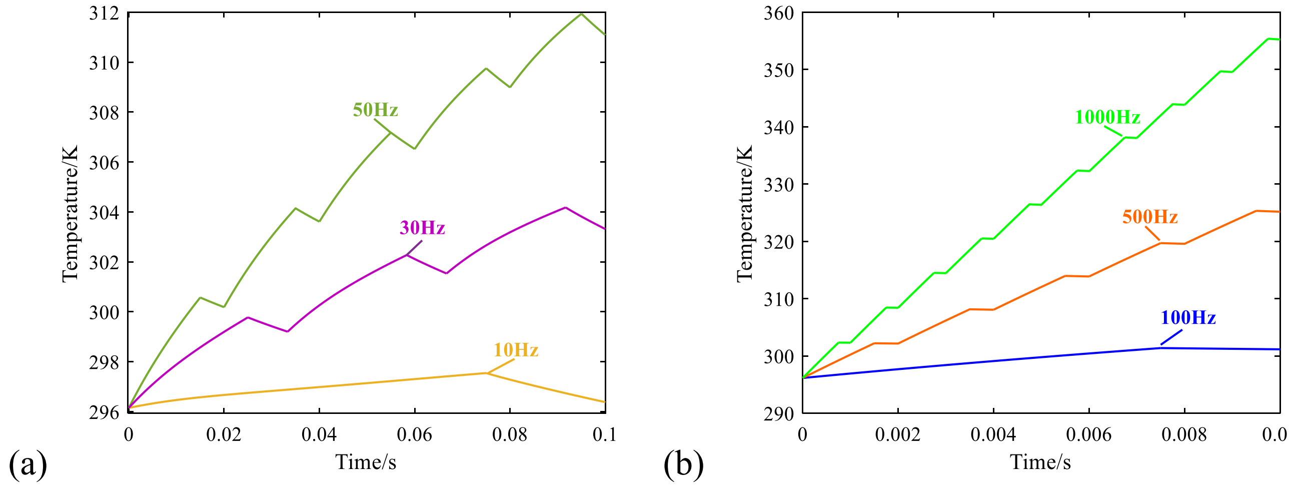

Fig. 8. Transient temperature distribution in the central bonding surface of Tm: LuYAG crystal under different repetition frequency.

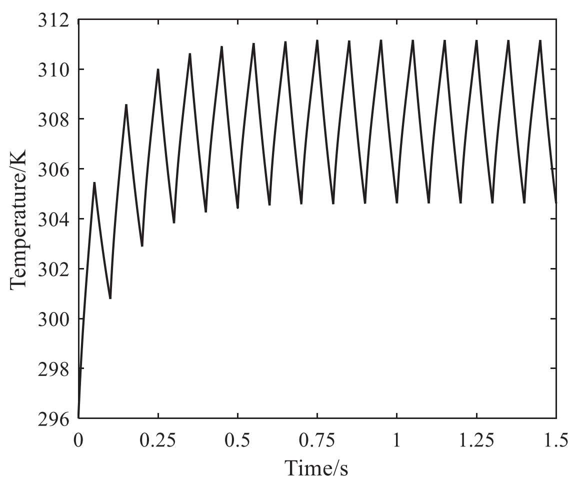

Fig. 9. The center temperature of Tm: LuYAG crystal in bonding surface.

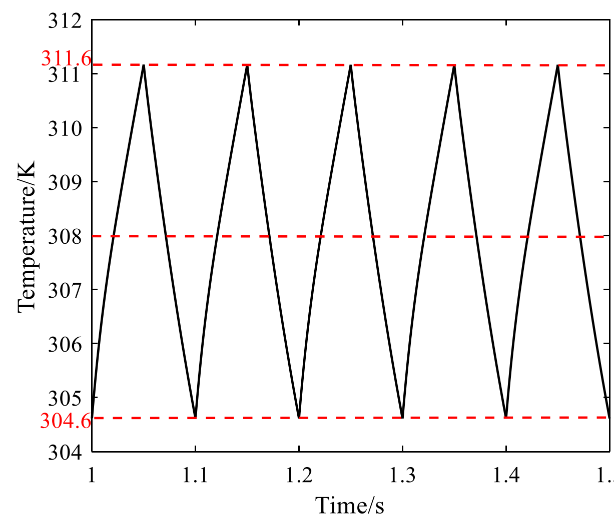

Fig. 10. The center temperature of Tm: LuYAG crystal in bonding surface under the quasi-thermal equilibrium state.

2.2.4. Transient thermal effect of Tm: LuYAG crystal under different repetition frequency

As the pulse pump is energy is 900 mJ, the duty ratio is 75 %, the repetition frequency is 10 Hz, 30 Hz, 50 Hz, 100 Hz, 500 Hz, 1 kHz, the other parameters used in the simulation are shown in Table 1. Then the transient temperature distribution in the central bonding surface of Tm: LuYAG crystal is stimulated, as shown in Fig. 8.

It can be seen from Fig. 8, that the central temperature in the Tm: LuYAG crystal bonding surface is gradually increases with the time. And the higher the repetition frequency, the faster the temperature rise rate of the crystal. As at time of 0.1 s, the highest transient temperature in the central bonding surface of Tm: LuYAG crystal under repetition frequency of 10 Hz, 30 Hz, 50 Hz are 297.52, 304.18, 311.91 K, respectively. While, within time of 0.01 s, the highest transient temperature in the central bonding surface of Tm: LuYAG crystal under repetition frequency of 100 Hz, 500 Hz, 1000 Hz attach to 301.37, 325.32, 355.37 K, respectively. This is because when the pump energy and duty ratio is constant, the higher repetition frequency, the pulse width is narrower, resulting in the increase of peak power and the gradual accumulation of heat in the crystal internal.

2.2.5. Transient thermal effect analysis of Tm: LuYAG crystal

When the repetition frequency is 10 Hz, duty ratio is 50 %, and the pump power is 50 W, the center temperature of Tm: LuYAG crystal in bonding surface versus the time is stimulated by software of MATLAB, as shown in Fig. 9.

As shown in Fig. 9, the center temperature of Tm: LuYAG crystal in the bonding surface increases gradually and shows a zigzag distribution, finally tends to a critical stable state, and fluctuates in a small range around the temperature. As shown in Fig. 10, the center temperatures in the Tm: LuYAG crystal bonding surface varies from 304.6 K to 311.6 K and fluctuates around 308 K. And the whole quasi-thermal equilibrium shows a zigzag distribution.

In addition, when the repetition frequency of pulsed pump is 100 Hz and 1000 Hz, and other conditions remain unchanged, the center temperature of Tm: LuYAG crystal in bonding surface under the quasi-thermal equilibrium state is also worthy of reference, as shown in Fig. 11.

It can be seen from Fig. 11 (a), the repetition frequency is 100 Hz, the center temperatures of the Tm: LuYAG crystal in bonding surface varies from 310.2 K to 311 K and fluctuates around 310.6 K. According to Fig. 11 (b), the repetition frequency is 1000 Hz, the center temperatures of the Tm: LuYAG crystal in bonding surface varies from 310.742 K to 310.828 K and fluctuates around 310.784 K. And the whole quasi-thermal equilibrium shows a zigzag distribution.

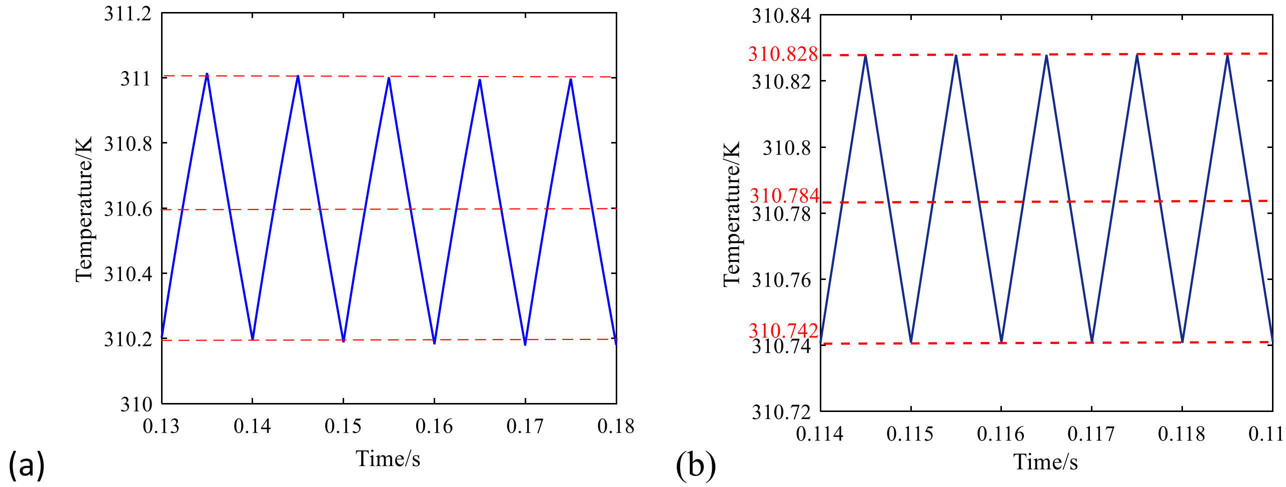

Fig. 11. The center temperature of Tm: LuYAG crystal in bonding surface under the quasi-thermal equilibrium state (a) 100 Hz, (b) 1000 Hz.

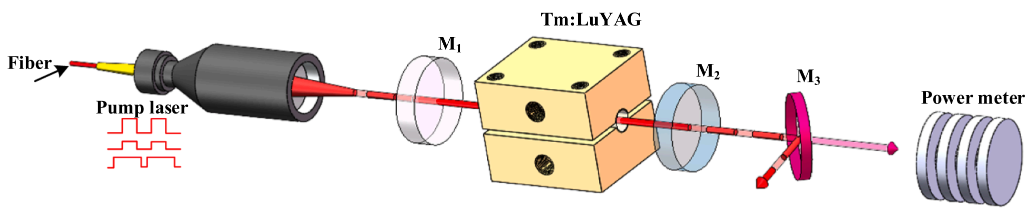

Fig. 12. Experimental setup of Tm: LuYAG laser.

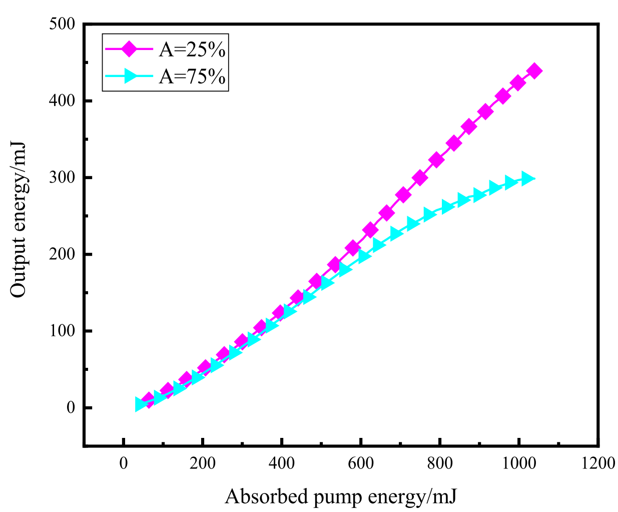

Fig. 13. Output energy versus the pump energy under different duty ratio.

3. Experimental research and analysis

3.1. Experimental setup

The experimental setup of pulse LD end-pumped Tm:LuYAG laser is shown in Fig. 12.

The semiconductor pump source was developed by American n-Light company, which is a fiber-coupled output laser with a center wavelength of 785 nm and a maximum output power of 50 W. The fiber diameter is 400 μm, with a numerical aperture is 0.22. The resonator cavity length is 55 mm. M_1 is a plane mirror, coated with high reflection (HR) at 2.02 μm (R > 99.5 %) and antireflection (AR) at 785 nm (R < 0.5 %). M_2 is a concave output coupler, the curvature of which is 500 mm, coated with transmission of 5 % at 2 μm. M_3 is a 45°mirror, coated with AR at 785 nm (R < 0.5 %) and HR at 2.02 μm (R > 99.5 %). A composite Tm: LuYAG crystal with a Tm^{3+} doping concentration of 3.5at. % and the dimension of $3\times(3+8)$ mm^3 has been chosen as the laser material. Both end faces are coated with AR at 785 nm (R < 0.5 %) and 2.2 μm (R < 0.5 %), The absorption efficiency of Tm: LuYAG crystal at 785 nm is measured as 84 %. The composite Tm: LuYAG crystal is wrapped in indium foil ($d = 0.05$ mm) and put in a water-cooled copper apparatus, the temperature of which is maintained at 291.15 K.

3.2. Experimental results and analysis

The pumping source is the pulsed laser diode mentioned above. The average output power is measured by a power meter (F150A-BB-26, Ophir). Then the output energy is calculated according to the relationship between energy and average power.

3.2.1. Output energy of Tm: LuYAG laser under different duty ratio

As the pulse width of laser diode is 25 ms, the peak power of which is ranged from 3.06 to 49.5 W, the output energy of Tm: LuYAG laser versus pump energy under duty ratio of 25 % and 75 % is shown in Fig. 13.

As shown in Fig. 13, under the condition of the same pulse width but different duty ratio, the output energy increases with the absorbed energy. Under pump energy of 1.04 J, the maximum output energy of 439 mJ and 298 mJ is obtained, respectively, with the threshold pump energy of 64.26 mJ and 41.16 mJ. The slope efficient is 47.7 % and 33.2 %, respectively. When the duty ratio is 75 %, the output energy of Tm: LuYAG laser tends to be saturated with the increase of pump energy. However, when the duty ratio is 25 %, the linearity of the laser output energy is better, and there is no phenomenon of output energy saturation. It because that with the increase of duty ratio, the internal temperature of Tm: LuYAG crystal increases gradually, and the heat accumulation in the crystal is unable to dissipate in time, resulting in the decrease of thermal focal length and the increase of resonator cavity

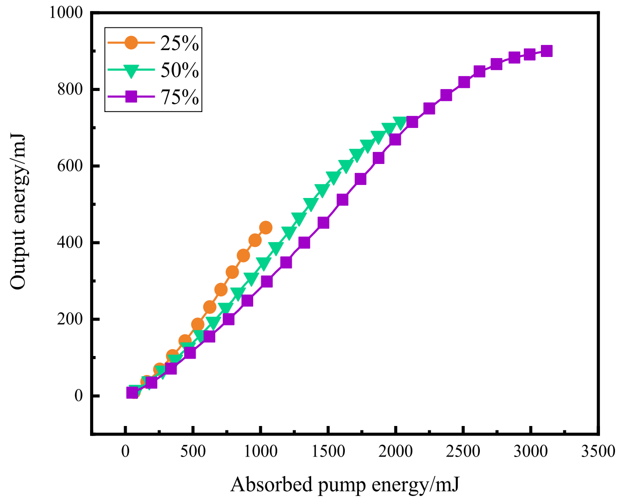

Fig. 14. Output energy versus pump energy under different duty ratio at 10 Hz.

loss.

As the repetition frequency of laser diode is 10 Hz, the output energy of Tm: LuYAG laser versus pump energy under duty ratio of 25 %, 50 %, 75 % are achieved, as shown in Fig. 14. When the pump duty ratio is 25 %, the slope efficiency of output energy is higher. However, limited by the peak power the pumping source supplied, the maximum output energy that can be obtained is also limited at duty ratio of 25 %. The maximum output energy of 439 mJ, 724 mJ, 900 mJ are obtained, under pump energy of 1.04 J, 2.08 J, 3.1 J, respectively, corresponding the slope efficiency are 47.7 %, 39.4 %, 34.6 %. At the same time, when the pump duty cycle is 50 % and 75 %, the output laser energy is saturated in varying degrees.

3.2.2. *Output energy of Tm: LuYAG laser under different repetition frequency*

In order to clarify the influence of repetition rate on the output performance of Tm: LuYAG laser, The output energy of Tm: LuYAG laser under repetition frequency of 10 Hz, 30 Hz, 50 Hz, 100 Hz, 500 Hz, and 1000 Hz are achieved, as shown in Fig. 15. The duty ratio is 50 %.

It can be seen from Fig. 15 (a) that when the duty ratio is 50%, the maximum output energy of 724 mJ, 251.7 mJ, 145.6 mJ are obtained, under pump energy of 2.08 J, 690 mJ, 415.8 mJ, respectively, corresponding the slope efficiency are 39.4 %, 40.5 %, 38.3 %. As shown in Fig. 15 (b), the maximum output energy of 70 mJ, 11.88 mJ, 6.36 mJ are obtained, under pump energy of 207.9 mJ, 41.58 mJ, 20.79 mJ, respectively, corresponding the slope efficiency are 38.2 %, 33.7 %, 35.5 %. The higher the repetition rate of the laser, the closer the output performance is to that in continuous wave operation, which means a more serious thermal lens effect of Tm: LuYAG crystal.

3.2.3. *Laser characteristics of Tm: LuYAG crystal under repetition frequency of 10 Hz*

As mentioned above, at pulse repetition rate of 10 Hz and duty ratio of 75 %, maximum output energy of 900 mJ is achieved at pump energy of 3.1 J by Tm: LuYAG crystal for the first time. The threshold pump energy is 50.15 mJ and the slope efficiency is 34.6 %. A spectrometer (AQ6375, Co. YOKOGAWA) with wavelength range 1.2 ~ 2.4 μm and accuracy of 0.05 nm is used to measure the output wavelength of Tm: LuYAG laser. As shown in Fig. 16, the central wavelength of Tm:LuYAG laser is 2018.96 nm. Then, a beam-quality analyzer (Pyrocam III Co. Spiricon, Duma Optronics) is used to measure the spot pattern of the output laser and the beam quality. And the result is that $M_x^2 = 1.96$ and $M_y^2 = 1.98$, respectively, as shown in Fig. 17. Output characteristics of Tm: LuYAG laser under higher duty cycle at repetition frequency 10 Hz are tried. But unfortunately, the output energy of the laser appeared the trend of saturation soon. In order to improve the output energy of Tm: LuYAG laser, a pump source with higher peak power will be used in the

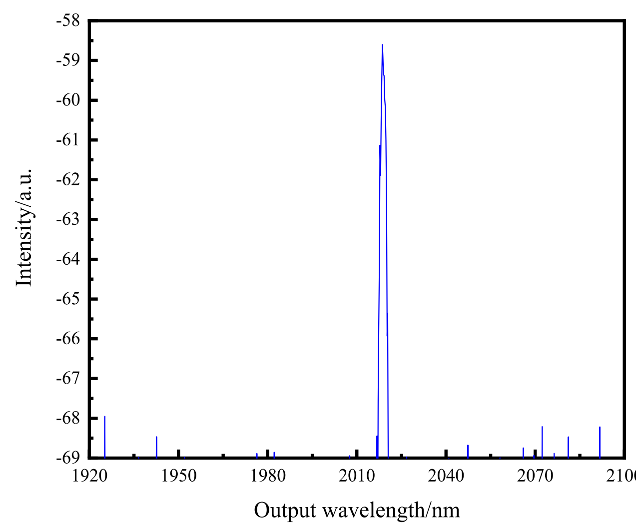

Fig. 16. Output wavelength of Tm: LuYAG laser.

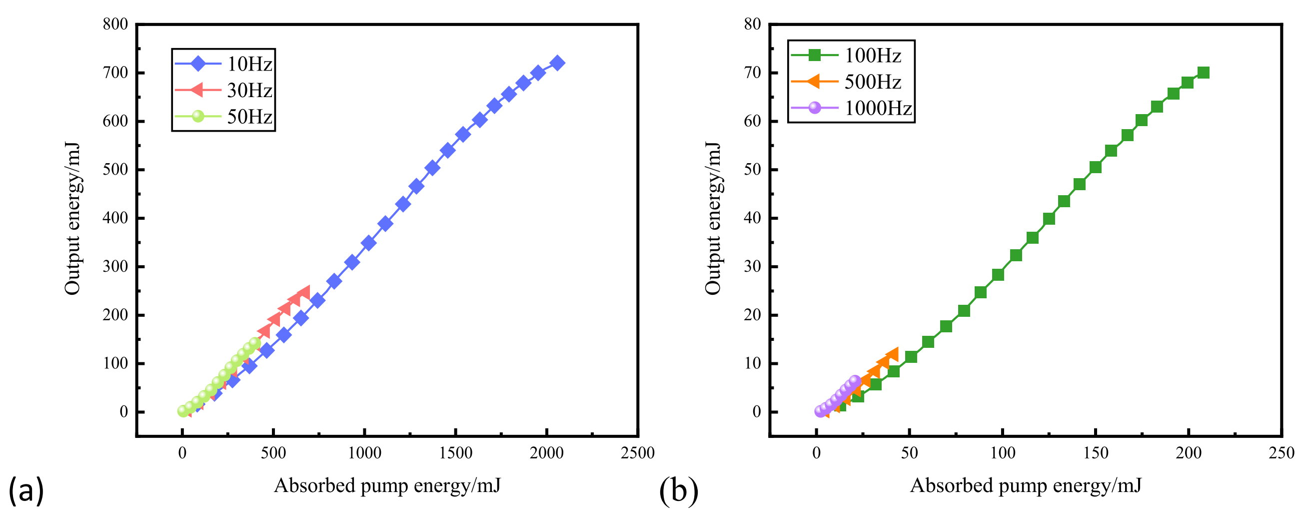

Fig. 15. Output energy versus the pump energy under different repetition frequency.

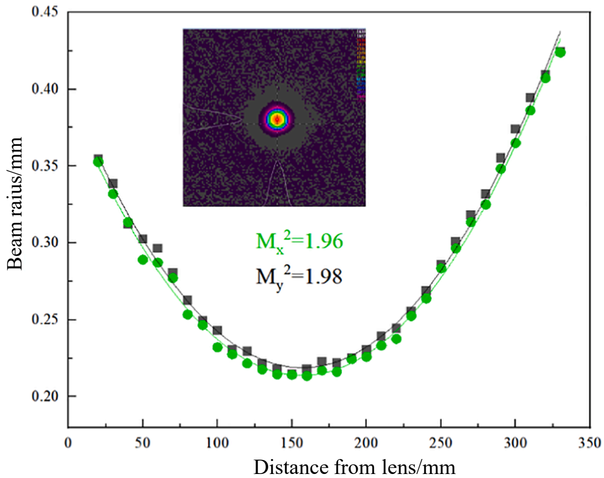

Fig. 17. Beam quality of Tm: LuYAG laser.

further.

4. Conclusion

In summary, based on the actual working situation of Tm: LuYAG crystal, the effects of spot radius, pump power, repetition frequency, and duty ratio on axial transient temperature distribution in a Tm: LuYAG laser with a pulsed single-end-pumped structure are analyzed. The result indicates that with the increasing of pump power, repetition frequency, duty ratio, and with the decrease of beam waist, the transient temperature in the central bonding surface of Tm: LuYAG crystal is increasing correspondingly. With the increase of pulses number, the temperature distribution of crystal rod appears jagged, but the whole temperature of rod keeps rising until it gets to steady state. For the experimental, when using the 785 nm pulsed LD with repetition frequency of 10 Hz, pulse width of 75 ms, duty ratio of 75 % and the pump energy of 3.1 J, the maximum pulse energy of 900 mJ is obtained for the Tm: LuYAG laser for the first time. The slope efficiency is 34.6 %. The beam quality is $M_x^2 = 1.96$ and $M_y^2 = 1.98$, the center wavelength is 2018.96 nm. The result show that Tm: LuYAG mixed crystals have higher research significance and practical application value.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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