Pulsed laser diode dual-end pumped double-end bonded Tm:YAG transient thermal effect analysis

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Abstract. Based on heat transfer differential equations, by using integral transform we got the internal temperature distribution of pulse LD dual-end pumped Tm: YAG crystal and the thermal focal length of crystal was obtained by the temperature field. At pumped power of 11W and repetition rate of 100Hz, the maximum temperature inside crystal is 27.68℃. As repetition frequency varying from 100Hz to 200Hz, the maximum temperature inside crystal is increasing to 28.24℃. In the case of duty cycle unchanged, as the repetition rate increases, the thermal focal length is distributed in a saw-tooth pattern and gradually becomes shorter, eventually it tends to be periodical distribution. The theoretical analysis of the thermal focal of pulse LD dual-end pumped Tm: YAG crystal is demonstrated by the comparison between the theoretical results and the experimental results.

1. Introduction
Pulsed laser diode dual-end pumped double-end bonded Tm: YAG crystal produces 2-micron wavelength laser output, which plays an important role in the applications of laser imaging radar, doppler coherent wind-speed measuring radar and differential absorption radar for measuring the variations of Earth's Atmospheric Concentration and Temperature[1-2]. Because of the quasi-three-level laser system of Tm: YAG , on the one hand it has Low-gain cross section with long lifetime of the upper laser level ,on the other hand the 2-micron band belongs to the absorption peaks of water molecules and CO₂[3-4], which leads to serious thermal effects happened , affecting the stability of laser resonator, output power and beam quality, eventually restricting the development of 2 micron Tm: YAG laser, so studying the thermal effects is very important.

In this paper, the thermal effect of Pulsed laser diode dual-end Pumped double-end bonded Tm: YAG Laser crystal is analyzed. The Gauss-type pumping source is introduced and the transient thermal effect equation will be solved by integral transformation method. Then the distribution of light intensity in laser diode dual-end pumped double-end bonded Tm: YAG Laser crystal was obtained, and we also get the influence of pump power and repetition frequency. Finally, the thermal focal length is calculated and measured by simulation and experiment.

2. Pulsed laser diode dual-end-pumped double-end bonded Tm:YAG optical field analysis
Pulsed laser diode output by optical fiber, using a coupling lens group to constraint the pump light and it can be an approximated Gaussian function. Dual-end-pumped double-ended bonded Tm: YAG crystal is a rod structure, in the cylindrical coordinate system[5], model of double-end bonded Tm:YAG rod, as shown in Figure 1.
Fig. 1 Pulsing laser diode dual-end pumped double-end bonded Tm:YAG model

The \( r \) and \( z \) are the radial coordinate and the axial coordinate, respectively. \( b \) is the radius of double-end bonded Tm: YAG rod and \( L \) is the length of the doped \( \text{Tm}^{3+} \). \( a \) is the length of the undoped section where does not absorb pump light. \( z \) is the direction of pump light propagation. The two pulses LD is respectively driven into the crystal bonding interface along the \( z \)-axis direction.

The pump pulse is wavelength 785nm, duration time \( \tau \), cycle is \( T' \). \( P \) is the pumping intensity of Tm:YAG crystal, \( I(r,z,t) \) is given by (1)

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

where \( P \) is the power of coupled to the end face of the crystal bond, \( \omega \) is the Gaussian pumping light radius at the end face of the bond, in the calculation process, assuming that it is equal to the waist. The pump pulse periodic function is \( G(t) \) given by the formula (2).

\[
G(t) = \left[ \text{sqrt}(2\pi f, t/T') + 1 \right]^2/2
\]

Square is expressed as a square wave function, \( f \) denotes repetition frequency, \( t \) denotes time, \( \tau / T' \) denotes duty cycle.

The heat source distribution of pulsed Gaussian pump light in the rod produce can be used the (3) described.

\[
q(r,z,t) = \beta \eta I(r,z,t) = \frac{2P \beta \eta}{\pi \omega^2} \exp\left(-2r^2\frac{z^2}{\omega^2}\right) G(t) \{ \exp(-\beta z) + \exp(-\beta(L-z)) \}
\]

\( \eta \) is the partial conversion of pump.

When the repetition rate of pump laser is 100Hz, the pulse duration is 5ms, the pump energy is 120mJ, at the end of the single pulse, the double-end bonded Tm: YAG crystal Gaussian optical field distribution is shown in figure 2.

Fig. 2 Gaussian intensity distribution in double-end bonded Tm: YAG crystal

3. Pulsed laser diode dual-end-pumped double-end bonded Tm:YAG transient thermal effect

Tm: YAG crystal is isotropic, Tm: YAG rod is axially symmetric. Which the \( T_0 \) is the crystal initial temperature, \( T_1 \) is the single pulse pumping Tm: YAG rod produced the temperature, the transient
heat conduction equation is (4): When a pulse ends, $T_2$ is the end of the single pulse pumping Tm: YAG rod temperature, the transient heat conduction equation is (5).

$$\rho c \frac{\partial T_1}{\partial t} = \left( \frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r} \frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2} \right) + q_v $$  \hspace{1cm} (4)$$

$$\rho c \frac{\partial T_2}{\partial t} = \left( \frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r} \frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2} \right) $$  \hspace{1cm} (5)$$

Using integral transformation method to solve $T_1$, the integral transformation met

$$ T_1(r, z, t) = \sum_{m=1}^{n} \sum_{p=1}^{m} R_0(\beta_m, r) Z(\eta_p, z) e^{-\alpha(\beta_m + \eta_p)} \left[ \tilde{\tau}_n + \int_{-\infty}^{\infty} e^{\alpha(\beta_m + \eta_p)} A(\beta_m, \eta_p, t) dt \right] $$  \hspace{1cm} (6)$$

Using Separating Variable Method to solve $T_2$,

$$ T_2(r, z, t) = \sum_{m=1}^{n} \sum_{p=1}^{m} e^{\alpha(\beta_m + \eta_p) r} R_0(\beta_m, r) Z(\eta_p, z) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} R_1(\beta_m, r) Z(\eta_p, z) \int_{-\infty}^{\infty} B(\beta_m, \eta_p, t) dt dz $$  \hspace{1cm} (7)$$

Although we use the pulse pumping method, and we also need to give the Tm: YAG rod energy all the time, Then we need to calculate after $n \cdot (n \geq 2)$ pump pulses, the temperature distribution can be given as (8).

$$ T_{2n-1}(r, z, t) = \sum_{m=1}^{n} \sum_{p=1}^{m} R_0(\beta_m, r) Z(\eta_p, z) e^{-\alpha(\beta_m + \eta_p) r - (n-1)l} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} R_1(\beta_m, r) Z(\eta_p, z) \int_{-\infty}^{\infty} B(\beta_m, \eta_p, t) dt dz \times T_{2n-1}(r, z, nT - T) $$  \hspace{1cm} (8)$$

Analyzing the effect of pump power on Double-end bonded Tm: YAG rod transient thermal distribution. The two laser diodes are assumed to the repetition frequency 100Hz and pulse duration 5ms, the pump power is 7W, 9W and 11W, the temperature distribution in double-end bonded Tm: YAG rod are as shown in figure 3(a),(b),(c).

From figures 3, when the pump power is 7W, 9W and 11W, respectively. The position of the pump spot is 7.3mm from the crystal end face, the Quasi-thermal equilibrium temperature of the crystal rod is 25.04°C, 26.49°C and 27.68°C, respectively. When the re-frequency of pulse LD is unchanged, as the pump power increases, the temperature of Quasi-thermal equilibrium is higher, the temperature deviation between the Tm: YAG center and edge is bigger.

(a) 7W pump power (b) 9W pump power (c) 11W pump power

Fig.3 Repeated pulse LD dual-end pumped Tm: YAG crystal temperature distribution.

The repetitive frequency of pulsed LD is an important reason for the influence of crystal temperature. maintained duty ratio at 50%. When pump power is 11W, repetition frequency at 100Hz,
150 Hz and 200Hz, The LD dual-end pumped Double-end bonded Tm: YAG rod transient temperature distributions with repetition frequency shown in Fig.4(a),(b),(c).

\begin{align*}
\text{(a) 100Hz repetition frequency} & \quad \text{(b) 150Hz repetition frequency} & \quad \text{(c) 200Hz repetition frequency}
\end{align*}

Fig.4 Repeated pulse LD dual-end pumped Tm: YAG crystal temperature distribution.

From figure 4, when the repetition frequency is 100Hz, 150 Hz and 200Hz, respectively. The position of the pump spot is 7.3mm from the crystal end face, the highest temperature is located on 7.3mm, 7.1mm and 6.9mm from the crystal end face. The maximum temperature is 27.68℃, 27.95℃ and 28.24℃, respectively. When the pulse LD duty ratio is unchanged, as the pump power increases, the temperature of Quasi-thermal equilibrium is higher, the temperature deviation between the Tm: YAG center and edge is bigger.

4. Analysis and measurement of the pulsed laser diode dual-end-pumped double-ended bonded Tm: YAG thermal lens focal length

Usually, the Tm: YAG rod is wrapped in silver foil and place in the copper. The crystal is cooled by water. Due to the LD pumped the crystal absorbs heat and the cooling water cycle absorbs the crystal heat, the temperature distribution in the crystal is uneven. There is a temperature gradient, the uneven temperature distribution causes thermal stress in the crystal, which causes the crystal to become a lens-like lens and a focused laser.

The thermal focal length formula is written as:

\[ f = \frac{r_e^2}{2\Delta \alpha} = \frac{r_e^2}{2\int\left[\frac{dn}{dT} + (n-1)(\nu + 1)\alpha_{00}\right] \times \int_{0}^{t} \left[T(0,z,t) - T(r_e,z,t)\right] dz} \]

(9)

When \( \frac{dn}{dT} \) is thermo-optical coefficient, \( r_e \) is the Gaussian pumping beam effective radius. When the pump power is 7W, duty ratio at 50%, frequency at 100Hz, 150 Hz and 200Hz, The laser diode dual-end pumped double-end bonded Tm: YAG rod thermal focal length as shown in Fig.5(a),(b),(c)

\begin{align*}
\text{(a) 100Hz repetition frequency} & \quad \text{(b) 150Hz repetition frequency} & \quad \text{(c) 200 Hz repetition frequency}
\end{align*}

Fig.5 Pulse LD dual-end pumped Tm: YAG crystal time-varying thermal focal length.

From figure 5, the thermal focal length shows a zigzag distribution, when the frequency at 100Hz, the pulse duration is 5ms, Quasi-thermal equilibrium state, the double-end bonded Tm: YAG rod thermal focal length with the range of 21.62cm-23.1cm. When the frequency at 150Hz, the pulse duration is 3.4ms, the thermal focal length range of 16.85cm-17.61cm. When the frequency at 200Hz, the pulse duration is 2.5ms, the thermal focal length range of 10.97cm-11.35cm. Experiment verification. Fig. 6 is an experimental setup of thermal focal length measurement.
Fig.6 The experimental setup of thermal focal length measurement
1 is a He-Ne laser; 2 is a beam expander system; 3, 4 are LD pumping sources; 5, 6, and 7 are f=35 mm plano-convex focusing lenses; 8, 9, 10 are f=75 mm plano-convex focusing lenses 11, 12, 13 are 45° mirrors; 14 is double-ended composite Tm: YAG crystal; 15 is a light barrier.

In the thermal focal length measurement system of pulsed LD double-end-pumped bonded Tm: YAG crystal, the temperature of the water-cooled circulatory system is set at 18℃, room temperature is 21℃, and the output wavelengths of the two LD are 785.26nm and 784.71nm, and the line width are 1.2nm and 1.5nm, respectively. Fig. 7 (a) (b) (c) show the comparison of experimental measurement and theoretical simulation with the pumped light repetition frequency of 100Hz, 150Hz and 200Hz and the pumped light pulse width of 5ms, 3.4ms and 2.5ms.

It can be seen from the figure that the experimental results are in good agreement with the theoretical simulation results. The duty cycle is 50% and the single pulse energy is 20mJ. When the repetition frequency is 100Hz, the corresponding injection power is 4W, and the thermal focal length of the crystal is 290mm. When the repetition frequency is 150Hz, the corresponding injection power is 6W, and the thermal focal length of the crystal is 260mm. When the repetition frequency is 200Hz, the corresponding injection power is 8W, and the thermal focal length of the crystal is 105mm. It can be concluded that when the single pulse energy is constant, the thermal focal length becomes shorter with the change of repetition frequency, and the thermal effect becomes serious.

(a) 100Hz repetition frequency (b) 150Hz repetition frequency (c) 200 Hz repetition frequency
Fig.7 Pulse LD dual-end pumped Tm:YAG crystal experiment and theory thermal focal length.

Based on the above experimental measurements and numerical simulation comparison curves, the possible reasons for the errors are analyzed. The experimental results show that the thermal focal length is measured without cavity formation. In fact, after cavity formation, part of the pumped light absorbed by the crystal is converted into laser output, and non-radiative transition occurs. The actual thermal focal length should be slightly larger than that measured under this condition.

5. conclusions
In this paper, a thermal model of a double-end bonded Tm: YAG laser system with dual-end-pumped pulsed LD is established, considering that the two ends of Tm: YAG crystal rod are in contact with air and the side of the crystal rod is water-cooled. Based on the integral transformation, the transient heat conduction equation of the crystal is solved. When the duty cycle is 50%, the effect of repetition
frequency on thermal focal length is analyzed and verified by simulation and experiment. The results show that with the increase of the number of pulses pumped, the thermal focal length shows a zigzag distribution and finally tends to a stable periodic distribution. In addition, the thermal focal length under different parameters of pulse pumping light is further measured and compared with the theoretical simulation results. The results show that the two methods are in good agreement. With the increase of repetition frequency, the thermal focal length decreases gradually, and the thermal lens effect of the crystal increases gradually. The research results provide a theoretical basis for further research on thermal effect compensation and resonant cavity design.

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