Thermal-insensitive 1.06 μm laser by using the optimized concavo-convex cavity

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In this letter, we discussed the theoretical requirements of resonator stability, and found that resonator with $G_1^*G_2^*=1/2$ or closer to it was deep stable and insensitive to the thermal lens of laser crystal. The resonator was designed according to the obtained theoretical results. Laser with optimized concavo-convex cavity was found to meet the condition of violent change of environment temperature and the variation of thermal lens of laser crystal by our experiments.

1. Introduction

Q-switched, all-solid-state 1.06 μm lasers are widely used in various fields like ranging, remote sensing, microsurgery and so on [1-4]. Nd:YAG is one of the most extensively applied laser medium. However, the pump efficiency for the Nd^{3+} is rather low when using a broadband flash lamp. In case of pumping with flash lamp, compared with Nd:YAG, Ce:Nd:YAG is a better choice. The absorption band of Nd^{3+} ions matches well with the emission band of Ce^{3+}, resulting in the efficient energy transfer from Ce^{3+} to Nd^{3+}. It is believed that Nd^{3+} is efficiently sensitized by Ce^{3+}.

Much attention has been paid to the laser stability which is a most important property of laser in actual application. Improved stability of laser working for long and under different environmental conditions is one of high-motivated aim for scientists and engineers engaged in laser for a long time.

In this letter, we discussed the theoretical requirements of resonator stability, and applied the obtained theoretical results to the design of thermal-insensitive resonator. The laser was found to have excellent stability with an optimized concavo-convex cavity by our experiments.
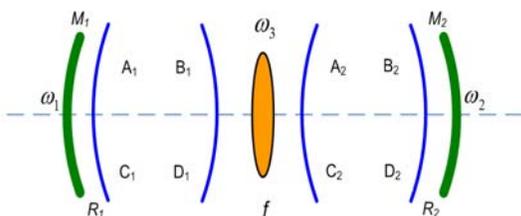
2. Theoretical requirement of cavity stability

Fig. 1. Sketch of linear cavity.

The sketch of linear cavity is showed in Fig. 1. The effect of pump-induced thermal lens of laser crystal can be treated as thin lens [5-7], and the ray transfer matrix is defined as

$$\begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{bmatrix} \qquad (1)$$

The ray transfer matrixes between M_i with R_i (i=1, 2), the radius of curvature of the mirrors, and thermal lens of laser crystal are indicated as

$$m_i = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}. \qquad (2)$$

The single-trip transfer ABCD matrix from M_1 to M_2 can be expressed as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}, \quad (3)$$

$$A = A_1A_2 + B_2C_1 - A_1B_2/f, \qquad (4)$$

$$B = A_2B_1 + B_2D_1 - B_1B_2/f, \qquad (5)$$

$$C = A_1C_2 + C_1D_2 - A_1D_2/f, \qquad (6)$$

$$D = B_1 C_2 + D_1 D_2 - B_1 D_2 / f . \qquad (7)$$

The G parameter of cavity is defined as

$$G_1^* = A - \frac{B}{R_1} , \qquad (8)$$

$$G_2^* = D - \frac{B}{R_2} . \qquad (9)$$

ω_2 is spot-size of the fundamental Gaussian beam inside the resonator at the output mirror M_2, and the expression is shown as follow

$$\omega_2{}^2 = \frac{\lambda B}{\pi} [\frac{G_1^*}{G_2^*(1 - G_1^* G_2^*)}]^{\frac{1}{2}} . \qquad (10)$$

Steffen et al [8] reported that the effect of pump-induced thermal lens on the cavity could be minimized, if the differentiation value of ω_2 with respect to the variable f is set as

$$\frac{d\omega_2}{df} = 0 . \qquad (11)$$

From Eq. (11) with the help of Eqs. (4)- (10), we obtain

$$G_1^* G_2^* = \frac{1}{2} . \qquad (12)$$

Hence, it is obvious that when $G_1^* G_2^* = 1/2$ or closer to it, the resonator is deep stable and is insensitive to the thermal lens of laser crystal.

3. Numerical calculation and experimental setup

In our experiments, the measured focal length of Ce:Nd:YAG crystal is 3000 mm at a certain pump energy. The value of $G_1^* G_2^*$ varies with radius of curvature of R_1 and R_2 is showed in Fig. 2.
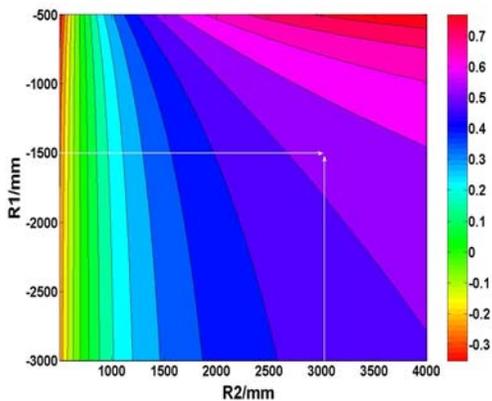

Fig. 2. Value of $G_1^* G_2^*$ varies with radius of curvature

of R_1 and R_2.

In Fig. 2, different color area represents different value of $G_1^* G_2^*$, and the right color-bar is value of the color. From Fig. 2, we can see that when $R_1 = -1500$ mm and $R_2 = 3000$ mm, the value of $G_1^* G_2^*$ is closer to 1/2. For another reason, mirrors with radius of curvature of -1500 mm and 3000 mm already existed in our laboratory. So we chose $R_1 = -1500$ mm and $R_2 = 3000$ mm to serve as input mirror and output mirror in our experiments. The LiNbO$_3$ crystal forming a Pockels cell is z-cut. The experimental configuration is shown in Fig. 3.
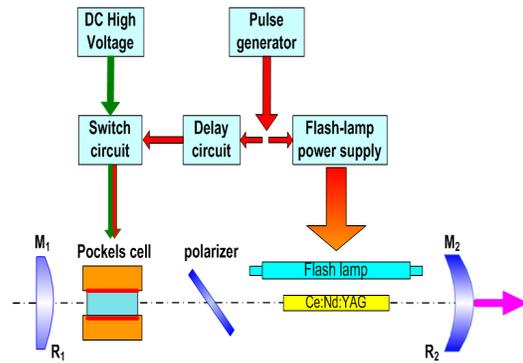

Fig. 3. Schematic of Ce:Nd:YAG laser oscillator with concavo-convex cavity.

4. Experimental results

The electro-optically Q-switched Ce:Nd:YAG laser is at a repetition rate of 20 Hz and run for 6 cycles under different environment temperature. Each cycle consists of a 60-second of working period and a 60-second rest period. The average output pulse energy was detected by the power meter under different environment temperature of -45 °C, 25 °C and 55 °C, respectively. The measuring results are shown in Fig. 4.
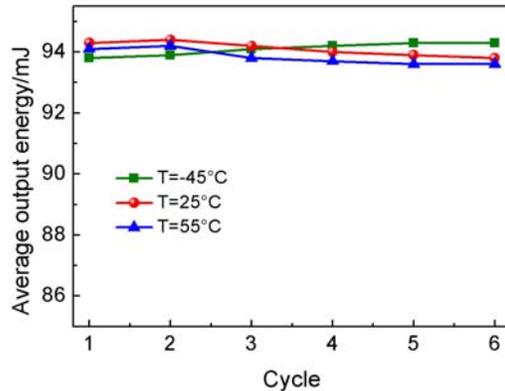

Fig. 4. The average output pulse energy within 6 cycles under different environment temperature.

The fluctuations within 6 cycles are 0.53%, 0.64%

and 0.64% at environment temperature of -45 °C, 25 °C and 55 °C, respectively. Compared with the average output pulse energy at room temperature (T = 25 °C), the maximum fluctuations of energy at T = - 45 °C and T = 55 °C are 0.64% and 0.85%.

There is a fact that the thermal lens of the laser crystal becomes more serious increasing with the pumping time [9], so that the average output pulse energy will become lower along with increasing of the pumping time using usual laser cavities without taking stability into consideration, and the thermal lens of the laser crystal also changes as environment temperature is different. Because laser resonator with $G_1^*G_2^*=1/2$ or closer to it is insensitive to the thermal lens of laser crystal, so that the fluctuations of average output pulse energy within 6 cycles and under different environment temperature of -45 °C, 25 °C and 55 °C are very small.

The laser divergence angle was measured by the pinhole method [10]. Because optimized concavo-convex cavity is insensitive to the thermal effect of laser crystal, the beam divergence angle fluctuates slightly. The fluctuation of divergence angle is 0.03 mrad at room temperature (T=25 °C) within 6 cycles, as shown in Fig. 5.

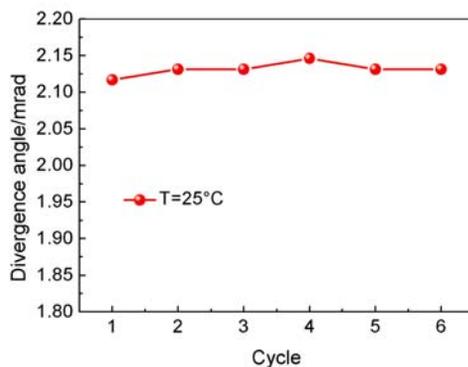*Fig. 5. The beam divergence angle within 6 cycles at T=25°C.*

5. Conclusions

In summary, we discussed the theoretical requirements of cavity stability, and found that resonator with $G_1^*G_2^*=1/2$ or closer to it was deep stable and was insensitive to the thermal lens of laser crystal. The resonator was designed according to the obtained theoretical requirements of resonator stability. The fluctuations of laser average output energy and beam divergence angle with optimized concavo-convex cavity were very small. The laser was found to meet the condition of violent change of environment temperature and the variation of thermal lens of laser crystal by our experiments and it was developed up to practical application level.

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