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Thermal focal length determination of a laser crystal by modulating the pump source

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Abstract
A simple method for determining the thermal focal length of a laser crystal is developed only by modulating the pump source to the pulse operation mode. The maximum output energy of a laser pulse is initially measured with the modulated pump source at 1 Hz repetition rate, where the thermal effects are negligible. Therefore, the beam waist of the resonator mode is equal to that of the pump laser beam, and a relationship between the energy and cavity waist is deduced. Then, the output energies at different repetition rates of the pump source are measured and the corresponding cavity waist sizes are calculated using the above relationship. Eventually, the thermal focal length of the laser crystal is directly determined by using a formula for the cavity mode radius of the resonator with an internal lens. The present method paves the way to determine the thermal focal length for different laser crystals and hence appropriate laser resonator cavity can be designed for higher energy with good beam quality.

Keywords: thermal focal length, pump modulation, microchip laser

(Some figures may appear in colour only in the online journal)

1. Introduction

Diode-pump solid-state (DPSS) laser is a very important laser source and has been broadly applied in various fields including laser engineering, quantum optics, metrology, military and defense [1, 2]. However, in the development of DPSS lasers, the thermal lens effect of the laser crystals has always restricted the output power and affected the beam quality of the lasers, and has even caused damage to the laser crystals [3, 4]. Therefore, a few methods were developed to determine the thermal lens effects of laser crystal and used in order to optimize the performance of the lasers and protect the laser crystals. The most common technique is to pass a weak collimated probe beam through a laser crystal, which undergoes thermal loading resulting from the pump source [5]. After measuring the distance between the laser crystal with the focal point, the focal length of the laser crystal is determined. Although the method is simple, the measured thermal focal length values in this arrangement are far different from the actual value, thus lacking accuracy. The thermal focal length can also be determined by employing a critical [6] cavity and the distance between the input and output couplers is changed with the variation of pump power. However, the measurement process is very tedious and its precision heavily depends on the alignment of the resonator. Despite the recent development of several methods such as wave-front measurement [7], coherent measurement [8], etc, to determine the thermal focal length, there is considerable interest to form a technique for passively Q-switched (PQS) microchip laser since it is free of alignment, high peak power and short pulse duration from the extremely compact monolithic microchip laser. PQS microchip laser, which has been used for many applications,

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is fabricated by thermally bonding the thin laser crystal with saturable absorber (SA) and both surfaces are polished flat and parallel on two sides. Furthermore, the input and output dielectric mirrors are directly deposited on the polished surfaces. In addition to the laser crystal, the thermal lens effect caused by oscillating laser pulse on the SA is also severe. Moreover, the thermal lens effect of SA is complex and constantly changing during the operation of the laser [9] because the absorption coefficient of the SA is dynamic and acts as a Q switch. Therefore, it is important to develop an innovative method to determine the thermal focal length of the laser crystal, which varies with the thermal lens effect induced radius of curvature. By taking into account all of these effects, the output performance of the PQS microchip laser can be further improved. In this paper, we develop a new method to precisely determine the thermal focal length of the laser crystal, which can be deduced by modulating the pump source.

2. Theoretical analyses

In order to achieve the precise measurement of the thermal focal length of a laser crystal by modulating the pump source, we designed the microchip laser shown in figure 1. A fiber-coupled laser diode (LD) with the emitting wavelength of 808 nm and maximal output power of 50 W (BWT Inc.) is used as the pump source. The numerical aperture and diameter are 0.22 and 200 μm, respectively. The pump laser beam is delivered to the microchip laser resonator by a coupling system constructed of two lenses f_1 and f_2. The focal lengths of f_1 and f_2 are 11 and 25 mm, respectively, and the corresponding pump laser beam waist radius of 227 μm is obtained on the laser crystal. A compact monolithic microchip laser, which consists of Nd:YAG/Cr:YAG composite crystal by diffusion bonding technologies with both surfaces coated with the dielectric films, is used in this study. The aperture of the composite crystal is a square with 3 mm sides. The lengths of the Nd:YAG and Cr:YAG are 4.5 and 0.45 mm, respectively. The Nd ion doping concentration of the Nd:YAG and the initial transmission of the Cr:YAG are 1.1 at.% and 90%, respectively. The front surface of the Nd:YAG crystal is coated with the high-transmission film at 808 nm and high-reflectivity film at 1064 nm, and acts as the input coupler. Similarly, the rear surface of the Cr:YAG is coated with the partial-reflectivity film at 1064 nm (R = 60%@1064 nm) and acts as the output coupler.

When the pump source LD is modulated with a square signal, it works in a pulse mode. According to the fluorescence lifetime of the Nd:YAG, the pump pulse duration is set to 250 μs and thus the maximal output energy E_p of the microchip laser can be estimated by [10],

$$E_p = J_{sat}\frac{A_g}{\gamma_g}\ln R \ln \delta_f, \tag{1}$$

where $J_{sat} = h\nu/2\sigma_g$ is the saturation fluence of the laser crystal, $h\nu$ is the photon energy at 1064 nm and σ_g is the laser-stimulated emission. $A_g = \pi\omega^2$ is the effective area of the resonator mode at the center of the laser medium and ω is the beam waist size at the laser crystal. R is the reflectivity of the output coupler and δ_f is the ratio of the final and initial population inversion density. From equation (1), it was clear that the output energy E_p is decided by the beam waist size at the laser crystal when the parameters of the laser crystal and the SA as well as the output coupler are kept constant. So equation (1) can be further expressed as,

$$E_p = k\omega^2, \tag{2}$$

where,

$$k = J_{sat}\frac{\pi}{\gamma_g}\ln R \ln \delta_f. \tag{3}$$

Meanwhile, it is important to note that the cavity beam waist size depends on the thermal focal length of the laser crystal when the length of the composite crystal is kept constant, and can be expressed as [11],

$$\omega^2 = \frac{\lambda L_{cav}}{\pi}\sqrt{\frac{f^2}{(f - L_{cav})L_{cav}}}, \tag{4}$$

where λ is the wavelength of the laser.

From equations (2) and (4), it is easy to find the relationship between the output energy and thermal focal length, which can be expressed as,

$$E_p = \frac{k\lambda L_{cav}}{\pi}\sqrt{\frac{f^2}{(f - L_{cav})L_{cav}}}. \tag{5}$$

Equation (5) clearly implies that the output energy mainly depends on the thermal focal length of the microchip laser. In other words, the thermal focal length of the crystal can be determined only by measuring the output energy of the PQS microchip laser.

3. Results and discussion

In the experiment, initially the maximum output energy of the microchip laser is measured at the repetition rate of 1 Hz, as depicted in figure 2. It is clear that the total output energy of the microchip laser's pulse train increases linearly with the pump power, and maximum energy of 3.18 mJ is observed at 45 W. The pump power is not increased further, since a LD with maximum power of 50 W has been used in this experiment. As the repetition rate of 1 Hz is used, the injected average pump power is only about 0.01 W. Thus, the thermal lens effect is too small to be considered. Meanwhile, laser pulse with good beam quality is observed and therefore, it is presumed that the initial cavity waist size of the resonator mode is equal to that of the pump laser beam of 227 μm. Therefore, using equation (2), the value k of 6.17 J m^{-2} is obtained.

Similarly, by changing the repetition rate of the pump source (LD), the maximum output energy is recorded at fixed pump power of 45 W, as illustrated in figure 3. It can be seen that the maximum output energy of the microchip laser has decreased from 3.18 to 1.24 mJ when the repetition rate is

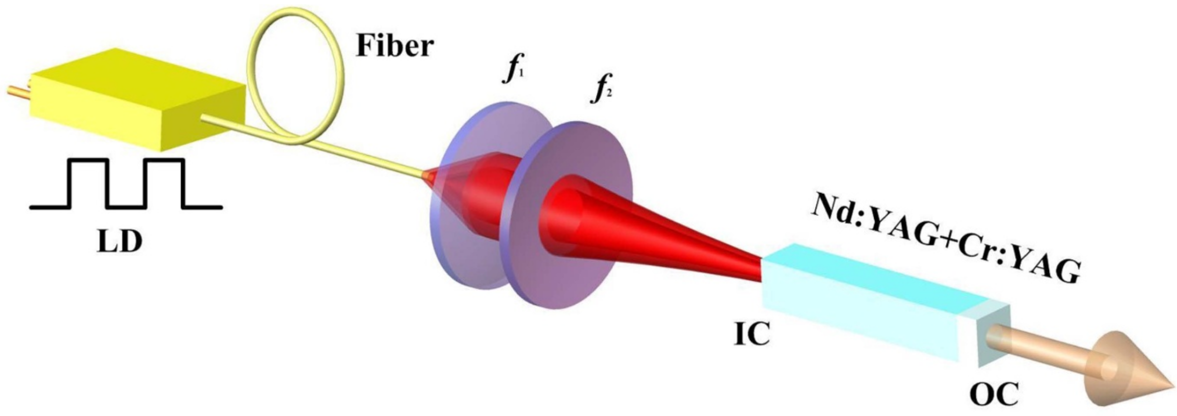

Figure 1. Experimental setup for determination of the thermal focal length.

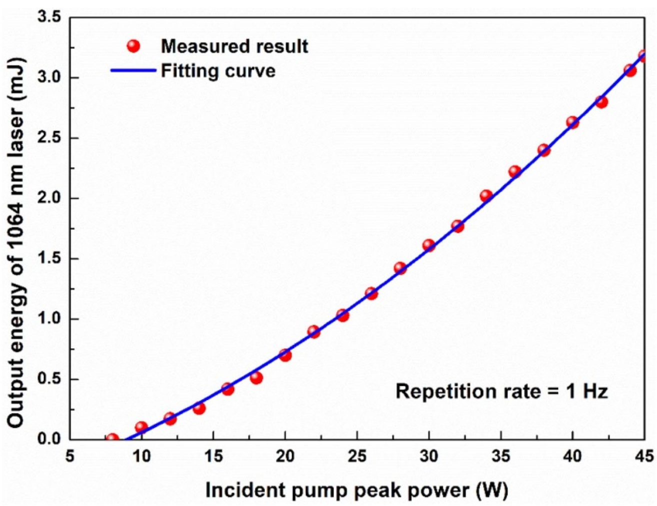

Figure 2. Output energy of the microchip laser at the repetition rate of 1 Hz.

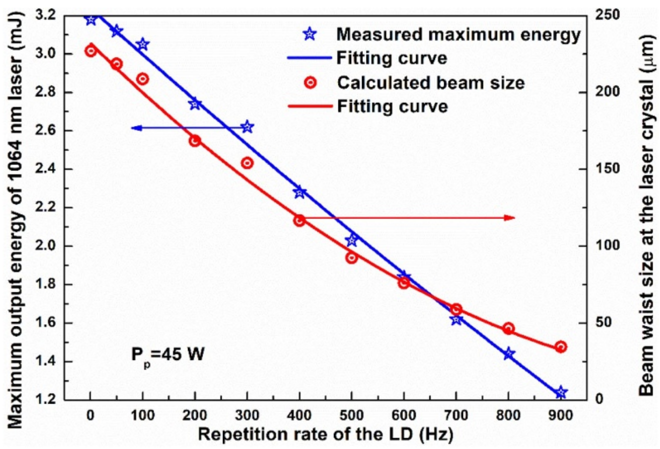

Figure 3. Measured maximum output energy and achieved corresponding beam waist radius at the laser crystal for different repetition rates.

increased from 1 to 900 Hz. Using the deduced value of k at 1 Hz repetition rate, the laser beam waist radius at different repetition rates can be calculated and also depicted in figure 3. It is found that the laser beam waist shrank rapidly from 227 to 34.5 μm when the repetition rate increased from 1 to 900 Hz, which is mainly due to the thermal lens effect of the composite crystal. In particular, the laser beam quality and resonator mode matching ability deteriorated rapidly and high-order modes would become more and more apparent with the increase of the repetition rate of the quasi-continuous-wave pumping.

By substituting the obtained beam waist values at different repetition rates for the same length of composite crystal to equation (5), the thermal focal length can be determined successfully, and the results are depicted in figure 4. When the repetition rate of the LD is kept as low as 1 Hz, the measured thermal focal length is as large as 4.6 m, so that the thermal lens effect of the composite crystal can be ignored. In contrast, when the repetition rate of the microchip laser is increased to 700 Hz, the thermal focal length is only 13.3 mm, which clearly explains that the thermal lens effect is very severe. At the same time, the high-order transverse modes are more prominent, which also shows that the mode matching is severely degraded. When the repetition rate of the LD is continuously increased to 800 and 900 Hz, the output energy of the PQS microchip laser can no longer completely represent the size of the laser beam waist, since the thermal effect of the laser crystal cannot be regarded as a simple thin lens in this case.

4. Conclusions

In summary, a simple and new method to measure the thermal focal length of the laser crystal has been demonstrated by manipulating the pump source to a pulse operation mode. By deducing the relationship between the observed maximum energy and cavity waist size at the low repetition rate of 1 Hz, cavity sizes have been calculated for different repetition rates and hence the corresponding thermal focal lengths are determined using a formula which relates the cavity mode radius and the inner lens of the resonator. The developed method is a simple and convenient way to evaluate and measure the thermal focal length of the laser crystal, and can pave the way to measure the thermal focal length of other laser crystals made

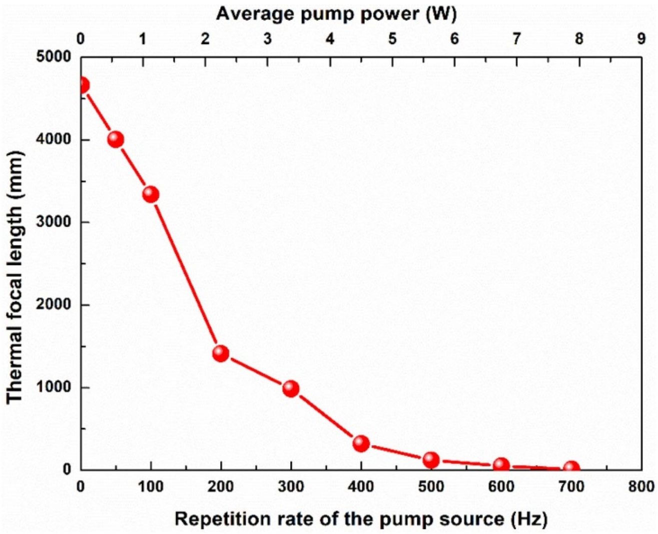

Figure 4. Thermal focal length of the laser crystal measured in the experiment.

up of different materials. Once the thermal focal length is easily determined, it is easy to further optimize the laser performances including the output energy and beam quality.

Acknowledgments

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