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Determination of thermal focal length under different depths of focus in asymmetrical flat-flat dynamically stable resonators

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ABSTRACT

A theoretical and experimental investigation on mode matching efficiency and thermal focal length in LD end-pumped Nd:YAG laser is presented. The laser rod thermal distribution and the mode matching efficiency on the waist size and the focus depth with different pump beam qualities are analyzed. An easy-to-use measurement method to obtain the focal length of asymmetric flat-flat dynamic cavities is proposed and then focal lengths at different depths of focus are measured revealing focal length apparently decreases with the decreasing of focus depth. Experimental results show the output power is not sensitive to telescope system and output coupler transmission when the depth of focus is small. There are better mode matching and higher output power at small focus depth, but shorter focal length and worse output beam quality will occur in this case. So depth of focus should be optimized, considering thermal lens effect, to scale output power referring to the cavity design.

1. Introduction

At the present time, fiber-coupled laser-diode (LD) end-pumped solid state lasers are still perceived as excellent coherent light sources in abundant application fields offering the advantages of high conversion efficiency and good beam quality, including super-precise measurement and detection, laser welding surface cleaning, photoelectric confrontation, laser holography, atom trapping and so on. Excellent spatial mode matching or pump-to-mode size ratio can maintain the beam quality at high-power operation [1]. However, power scaling of diode-end-pumped lasers is usually hindered by thermal effects from the small finite volume of the pump due to the presence of significant temperature gradients and axial stress strain in the gain medium. It is noted that thermal lens effect has a great influence on output parameters of the laser, such as appearance of multiple longitudinal modes, deterioration of beam quality, narrowing of the stable zone, especially reduction of output power [2]. In LD end-pumped solid-state lasers, output power is sensitive to both thermal effects and spatial mode matching, especially depth of focus. In lots of previous work, numerous publications have studied the influence of thermal effects or mode size matching on output parameters [3–5]. In addition, the influences of various thermal effects on spatial mode matching have been discussed in detail, including thermal induced diffraction loss [6], energy-transfer-up conversion effects (ETU), thermal loading [7], and so forth. The results show that thermal effects critically depend on the spatial mode matching. Still, to the best of the authors' knowledge, the mutual effects of spatial mode matching and thermal focal length on output parameters have not been published previously.

Several approaches, including calorimetric [8], interferometric [9], mode-degeneration methods [10], dynamic multimode analysis [11] and meta-stable cavity method [12] have been proposed for measuring thermal focal length in end-pumped solid-state lasers. Among them, meta-stable cavity method is a widely used method since laser crystal is usually equivalent to an auxiliary lens with variable focal length, which is useful to provide guidance for the interpretation of experimental results. Compared with other methods, the working state of crystal is consistent with the actual working state of the laser. When resonator is at the critical point between the stable and unstable zone, depending upon the relationship between focal length and cavity length, output power begins to decrease due to thermal effects. Then focal length at the corresponding pump power can be obtained according to the critical cavity length at which the output power is significantly lowered [13]. However, it is difficult to select the characteristic point in meta-stable cavity measurement. A formula, proposed by Chen, has been widely used for the determination of critical point in plano-concave resonant cavity [7]. However, none formulas have been presented applied to asymmetrical flat-flat

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dynamically stable resonator in experimental measurement of the focal length. Here a revised formula using to measure the focal length under the lasing condition was presented and verified for the asymmetrical flat-flat dynamically stable resonator, which is needed to facilitate the laser design.

In this paper, the simulation of mode matching efficiency factor with two different beam quality factors of the pump, and numerical calculation of thermal distribution in the laser rod are presented for comprehensive understanding of experimental results. An easy-to-use measurement method to obtain thermal focal length of asymmetric flat-flat dynamic cavities is proposed and then the focal length at different depths of focus will be measured. In addition, the variation of output power with incident pump power at different spatial mode matching, namely focusing systems and depth of focus, is analyzed.

2. Experimental setup

The laser field in the resonant cavity of spherical mirror is generated by interference between the two oppositely propagating traveling waves. Generally, the transverse modes of the two beams have the same intensity and phase distribution at a given plane. However, for a flat-flat cavity in which a positive lens is placed, the two beams traveling forward and backward have different spot sizes and intensities due to the diffractive effect produced by the aperture and the wave front variation generated by spherical aberration. Ye's stated that the laser beam emitted from the long arm is better than that from the short arm by using the theoretical and experimental validation [14]. Therefore, in the current experiment, laser crystal is placed as far as possible away from the output mirror. This cavity type of diode-end-pumped laser is called asymmetrical flat-flat dynamically stable cavity of which the stabilization is provided by a positive thermal lens.

The experimental device is shown in Fig. 1. The Nd:YAG laser crystal is pumped by an 808-nm fiber-coupled laser diode (nLIGHT laser, NL-P420-0808) with a core diameter of 0.4 mm, a numerical aperture of 0.22, spectral width of less than 3 nm, and the maximum output power is 20 W. The pump beam is reimaged into the laser crystal by a telescope system (composed of flat-convex lenses with focal lengths of 25 mm and 35 mm, respectively) and the spot size of the pump light is about 0.56 mm. The laser crystal is wrapped in indium foil and mounted on the micro-channel copper water-cooled blocks. The water temperature is maintained at 20 °C. The geometry size of laser crystal is Φ3 × 10 mm with 0.6-at.% and 1.0-at.% Nd-doping concentration. Both sides of the two crystals are coated for antireflection at 1064 and 808 nm (R = 0.16%). The entrance surface of the front mirror is coated for antireflection at the pump wavelength of 808 nm (R < 0.5%) and the other surface is coated for high-transmission at 808 nm (T > 90%) as well as high-reflection (R > 99.5%) at the lasing wavelength of 1064 nm. The flat output coupler has a transmittance of 10.3% used for the export of CW 1064 nm laser. The depth of focus z_0 is the distance between the focal plane of the pump mode and the bond facet of the laser crystal as shown in the Fig. 1. d_2 is the distance from the output mirror to the front surface of the laser crystal in the critical cavity, d_1 is the distance from the front cavity mirror to the front surface of the laser crystal, and the crystal length is l with refractive index of n.

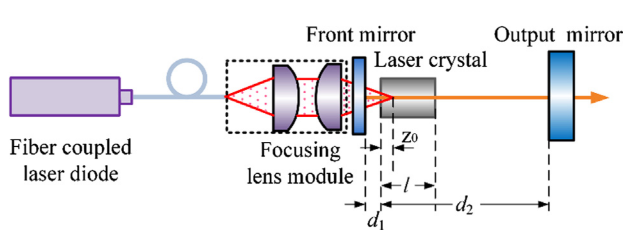

Fig. 1. Experimental setup of diode-end-pumped CW laser with asymmetrical flat-flat cavity.

3. Theoretical analysis

3.1. The simulation of mode matching efficiency factor

The mode matching of spot size between the oscillation beam and pump light has a crippling effect on the output power of diode-pumped solid-state laser. The degree of mode matching characterized by the spatial overlap of the pump and oscillating light field, is also called beam overlap efficiency or mode matching efficiency. Many theoretical researches on mode matching have been published by employing the average value of the pump spot size or the constant oscillation beam size to simplify mode-overlap integrals, which is not reasonable due to the large divergence angle of the pump beam.

In the simulation of mode matching efficiency, the spatial variations of both the pump and oscillating light field are taken into account. The mode matching efficiency factor S and output power are expressed as [15]

$$S = \frac{J_1^2}{J_2} = \frac{\left(\iiint \varepsilon(r,z) * g(r,z) dV\right)^2}{\iiint \varepsilon^2(r,z) * g(r,z) dV} \tag{1}$$

$$P_{out} = \eta_c * \eta_p \frac{J_1^2}{J_2} \frac{T}{\delta} (P_{in} - P_{th}) \tag{2}$$

Where $\varepsilon(r, z)$ and $g(r, z)$ are the normalized pump distribution and cavity mode distribution inside the active medium, respectively. η_c and η_p are the pumping efficiency and coupling efficiency, respectively. The waist size and its position of the pump are ω_{p0} and z_0, respectively.

A comparison of mode matching efficiency with two different beam quality factors of the pump is shown in Fig. 2. It is better to choose the pump beam with small M2-parameter because its mode matching efficiency is more insensitive to depth of focus than large M2 and changeless with the waist size, and the verification experiments will be done in the future work. Accordingly, it is necessary to consider the depth of focus in LD end-pumped lasers due to the large divergence angle of the pump. In this paper, the mode matching with different waist sizes and depths of focus of the pump is analyzed theoretically and experimentally. The maximum mode matching efficiency is located near the front-end-surface inside the gain medium, where exists the maximum output power theoretically. However, the lensing behavior in the gain medium may overfull counteract the output power improved by mode matching in certain cases. Therefore, it is great of importance to acquire the focal length at different depths of focus in asymmetric flat-flat cavity.

3.2. Measurement method of focal length

In formula for quantitative measurement of thermal focal length in an asymmetric flat-concave cavity [7], d_1 is a small variable in comparison with the cavity length, so the change of focal length caused by this parameter can be omitted in this formula. The modified formula can be used for quantitative measurement of the focal length of flat-flat cavity. Experimental measurement principle: the flat-flat cavity can be equivalent to a stable cavity containing an auxiliary lens, namely thermal lens. The correspondence between output power and cavity length can be obtained according to the relationship between cavity length and focal length of auxiliary lens. When output power is reduced to 70% of