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A method measuring thermal lens focal length of all rays polarized in radial and tangential direction of high power Nd:YAG laser

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Abstract

A novel method is applied to measure the focal length of thermal lens of a CW Nd:YAG laser. Using resonator critical stable point $G_1 * G_2 = 0$, by measuring output power as pumping power increasing, the laser rod thermal lens focal length f_r of all rays polarized in radial direction and the thermal lens focal length f_0 of all rays polarized in tangential direction can be calculated. The method can also be used to obtain the average effective thermal lens focal length f. The method requires no special equipment and is simple to implement. The measuring deviation of the method comparing with probe beam method is within the accuracy that is in the range of ±10%. It is less than the unstable-resonator method that is in the range of ±20%.

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1. Introduction

For high power laser operation, the focal length of thermal lens of laser crystal is a crucial parameter for optimizing the laser system. There are many techniques for measuring thermal lens focal length, such as using probe beam [1–4], interferometric method [5–7], unstable-resonator method [8–10], and transverse beat frequency method [11,12]. However, all these methods are used to measure the average thermal lens focal length. For perfect compensating thermal lens effect, it is more useful to know the thermal lens focal length f_r of all rays polarized in radial direction and the thermal lens focal length f_0 of all rays polarized in tangential direction.

In this paper, we present a novel method to measure thermal lens focal length of high power

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CW Nd:YAG laser. The methods can measure not only the average effective focal length of thermal lens f, but also the focal length f_r and f_θ of the thermal lens. The idea is based on the dependence of the critical stable point on the equivalent G parameter of the stable resonator, which depends on the thermal lens. Our method requires no special equipment and is simple to implement.

2. Analysis of measure method

According to the theory of resonators [1], a resonator is stable if $-1 \leqslant G_1G_2 \leqslant +1$, where G_1 and G_2 are the G parameters describing the design of the resonator. For a resonator with optical elements inside, the rod can be approximated to first order by a thin spherical lens of focal length f, and its G parameters are given as follows:

$$G_1 = \frac{a_1}{a_2}\left[1 - \frac{L_2}{f} - \frac{1}{R_1}\left(L_1 + L_2 - \frac{L_1L_2}{f}\right)\right], \quad (1)$$

$$G_2 = \frac{a_2}{a_1}\left[1 - \frac{L_1}{f} - \frac{1}{R_2}\left(L_1 + L_2 - \frac{L_1L_2}{f}\right)\right], \quad (2)$$

where a_1 and a_2 are the apertures of the mirrors, R_1 and R_2 are the radius of curvature of the mirrors, L_1 and L_2 are the distances from the principal planes to the mirrors, respectively.

The laser rod (of length l) can be approximated to a thin lens and two pieces of isotropic medium with refractive index n_0 and length h. The parameter h is the distance from the principal planes of the lens to the end of the laser rod [13], i.e., $h = l/2n_0$.

In our experiments, flat mirrors with identical apertures have been placed separately at equal distances from the Nd:YAG rod. Therefore, $a_1 = a_2$, $R_1 = R_2$, and $L_1 = L_2$.

Eqs. (1) and (2) were simplified as

$$G_1 = G_2 = 1 - \frac{L + (l/2)(1 - (1/n_0))}{f}. \quad (3)$$

Hence, the resonator stability is dependent only on the focal length of intra-cavity lens and length of the resonator.

The stability diagram of an optical resonator is shown in Fig. 1. Blank areas indicate regions of stable operation. The straight line (points A–C) corresponds to a symmetrical resonator with an internal lens of different focal length. Since the thermal lens of the rod is a function of input power, the configuration of the equivalent resonator changes from plane parallel to confocal and finally to concentric. Beyond this point the resonator becomes unstable. The point B (in Fig. 1), corresponds to $G_1 * G_2 = 0$, it is a critical stable point of resonator stable region. From Eq. (3), we have effective focal length:

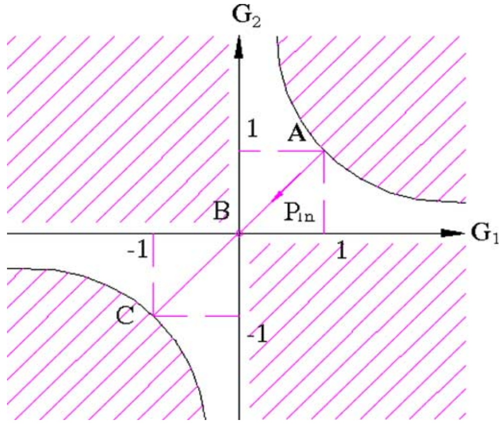

Fig. 1. Stability diagram of an optical resonator. Shaded areas indicate regions of unstable operation. Points A, B, C correspond to plane parallel, confocal, and concentric resonators, respectively.

$$f = L + (l/2)(1 - (1/n_0)). \quad (4)$$

At the critical stable point B, the focal length of the thermal lens f is the half of the resonator length. For a resonator length, the increment of output power will have a distinct decrease at the critical stable point as input powers increase. Using this method, we measured the thermal lens focal length with different resonator lengths.

In fact, the critical stable point is not simply a point. It can be found that is actually a region for careful adjustment of input powers. It is well known that the thermal lens focal length can be expressed as [14]:

$$f_i = \frac{AK}{P_{\text{in}}n_0}\left(\frac{1}{2n_0}\frac{\mathrm{d}n}{\mathrm{d}t} + n_0^2\beta C_{r,\theta} + \frac{r_0\beta(n_0 - 1)}{n_0 l}\right)^{-1}, \quad (5)$$

where there are two focal lengths f_r and f_θ, i.e., all rays polarized in radial direction and all rays polarized in tangential direction, respectively. And normally, there is $f_r/f_\theta = 1.2–1.5$ for Nd:YAG crystal. So we can measure not only the average thermal lens focal length f of the rod but also the radial and tangential direction thermal lens focal lengths f_r and f_θ, simultaneously.

3. Experiment and discussion

In our experiments, a ∅9 mm×155 mm AR coated Nd:YAG (science materials 0.8% Nd) laser rod was used in a diffuse reflecting cavity which was pumped by double Krypton flashlamps. The flashlamps were provided by a laser power supply rated up to 16 kW. The laser head was water cooled by a double cycle chiller, with constant experiments temperature of 20 °C (1 °C). A plane parallel resonator with an output coupling mirror of 20.5% was used in the experiments. Two apertures with a diameter of 9.5 mm were placed adjacent to the end of the laser rod, respectively.

The output power was detected by an Ophir Model 5000W-SH power meter. The critical stable points of the resonator were determined by detected output power curve. The critical stable points were founded when the output power does not linear increase as input pumped powers increase. In these experiments, the resonator alignment was strictly ensured. Every experiment curve was the average of detected output power as input pumped power changing from 0 to 16 kW and from 16 to 0 kW. For symmetrical resonator with length in a certain extent, the experimental results were obtained by drawing the function curve of laser output power and pump input power. Fig. 2 shows the measurement results for relationship between the output laser power and the pump power with five different resonator lengths. In the curves, it can be found that the output laser power increased linearly as pumping power increased at first, and then appeared a knee point followed by a plateau region, then increased linearly again, finally a decrease to zero. The changing process corresponds to the straight line in Fig. 1, in which pumping power increased and the focal length of the rod changed, as well as the configuration of the equivalent resonator changed from A point to B point and finally to C point.

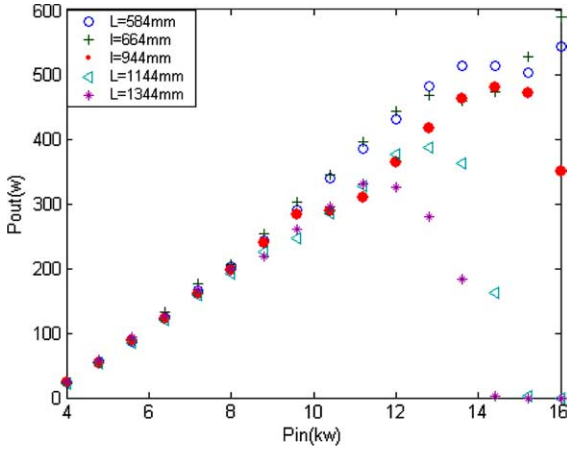

Fig. 2. The measurement results for the output laser power vs. the pump power with a plane parallel resonator at resonator lengths of 584–1344 mm.

We could survey the experiment curves. When the first knee point appears, the resonator enters the critical stable points (near B point). So in our experiment curves, the output power decreased gently. According to (5), the effective focal length f_θ is relative to the pump power. At second knee, the resonator departs from the critical stable point, and the effective focal length is f_r in relation to the pump power. Between the two knees, there is a plateau region and average the effective thermal lens focal length f is in the center of the region.

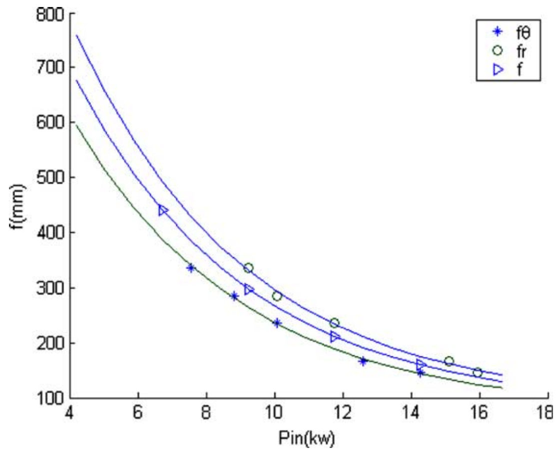

Fig. 3. Measured thermal lens focal length of YAG crystal rod as a function of lamp input power. Each point represents the calculated effective focal length of YAG crystal for f_r (○), f_θ (∗), and average f (▹), respectively.

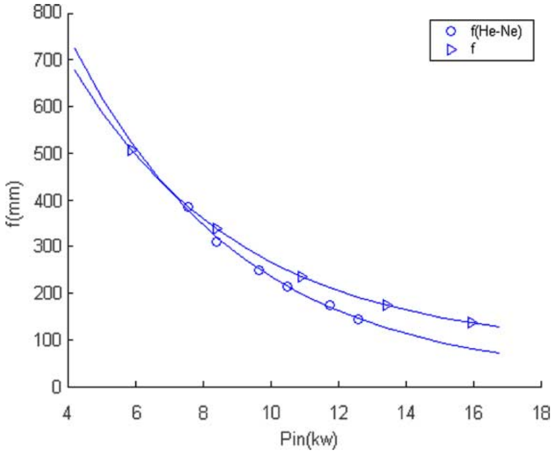

Fig. 4. Effective focal length of YAG crystal as a function of lamp input power. The average focal length of experimental values are obtained by resonator critical stable points (▷) and values obtained with a He–Ne laser (○).

Using Eqs. (5) and (4), the effective thermal lens focal lengths f_r, f_θ, and average f, can be calculated, respectively. The results are shown in Fig. 3.

In order to check the accuracy of the method, the measurement results were compared with those of probe beam method [3] with He–Ne laser in the same condition (Fig. 4). The values of the average effective focal length obtained with our method were a little higher than the values obtained with probe beam method, especial as pumping power increase and the focal length of the thermal lens decrease. The deviation is within the accuracy of the method, which is in the range of ±10%. The limitation for the accuracy of the measurement is attributed to the experiment deviation. The distance deviation of the two mirrors placed separately from the Nd:YAG rod. However, it is less than the unstable-resonator method [8] of ±20%.

4. Conclusion

We have presented a novel method to measure the average effective focal length of a flash-lamp-pumped CW Nd:YAG laser. Because critical stable points of stability resonator are used, the result is more precise than unstable-resonator method, and the method is very simple. Especially for measuring the thermal lens focal length f_r and f_θ, to our knowledge, this is the practical one so far.

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