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Evaluation of thermal effects on the beam quality of disk laser with unstable resonator

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ABSTRACT

In this paper thermal effects of the disk active medium and associated effects on the beam quality of laser are investigated. Using Collins integral and iterative method, transverse mode of an unstable resonator including a Yb:YAG active medium in disk geometry is calculated. After that the beam quality of the laser is calculated based on the generalized beam characterization method. Thermal lensing of the disk is calculated based on the OPD (Optical Path Difference) concept. Five factors influencing the OPD including temperature gradient, disk thermal expansion, photo-elastic effect, electronic lens and disk deformation are considered in our calculations. The calculations show that the effect of disk deformation factor on the quality of laser beam in the resonator is strong. However the total effect of all the thermal factors on the internal beam quality is fewer. Also it is shown that thermal effects degrade the output power, beam profile and beam quality of the output laser beam severely. As well the magnitude of each of affecting factors is evaluated distinctly.

1. Introduction

Improving the laser beam power and quality is the main aim in laser development. One of the serious problems in high power solid state laser development is thermal effects from view point of beam quality degradation. Thin disk lasers seems to be promising, because in them power scalability maintaining beam quality is possible in the first approximation [1]. Disk lasers in compare of rod type active media are shown superior beam quality. The reason is related to the lower thermal aberrations in disk geometry due to uniform cooling of active medium [2,3]. However thermal aberrations cannot be removed completely even in thin disk lasers [4–6].

A comprehensive study on the thermal effects in solid state lasers for the case of ytterbium-doped materials are conducted by Chénais et al. [7]. Chénais presented the theoretical formulations of thermal effects in laser active medium. Also he presented experimental setup for measurement of such effects. Although presented information in that paper generally are applicable to any kind of solid state laser but the geometry of active medium was not thin disk in their work. Thermal lensing in thin disk lasers is studied numerically by Sazegari et al. [8]. They predicted the optical and structural behavior in end-pumped CW Yb:YAG thin disk lasers using Monte Carlo ray-tracing method. Guangzhi Zhu et al. investigated thermal lens in disk laser more comprehensively [9–11]. They presented an analytical solution for heat conduction equation in thin disk laser. Based on the temperature distribution in the disk they estimated thermal lensing of the disk using OPD (Optical Path Difference) concept. Having temperature distribution in the disk medium it is possible to evaluate five factors influencing the OPD including temperature gradient, disk thermal expansion, photo-elastic effect, electronic lens and disk deformation. In the references [8–11], OPD of disk due to thermal effects of the disk is calculated. In our work however associated effects on the beam quality of disk laser is also evaluated. Mode dynamics and thermal lens effects of thin disk laser are also investigated by Mende et al. [12]. They studied laser beam profile dynamics due to variation of thermal lensing in a stable resonator but in this work an unstable resonator is considered in disk laser and the laser beam quality is achieved as well.

Using unstable resonator in a thin disk laser as a high power laser can be promising. Because of low gain (due to the thin disk) however there are some problems in application of unstable resonator with high magnification. Potential solutions to these problems are using modified unstable resonator [13] and variable reflectivity mirror [14]. In this paper a Yb:YAG disk laser in unstable resonator is considered and thermal affected beam quality is studied. Using Collins integral and iterative method, electric field distribution of the laser beam (transverse mode) is calculated. Using achieved transverse mode, the beam quality of laser is calculated by generalized beam characterization method [15,16].

In this paper, thermal induced OPD is calculated analytically based on the method presented in reference [9]. After calculation

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of total OPD, the associated phase difference is applied to our developed code for calculation of transverse mode resonator under influence of thermal aberrations and finally the beam quality is again calculated for recent thermal changed mode by generalized beam characterization method. Therefore we have estimated the effects of thermal aberrations on the laser beam quality. Calculations are conducted using our three developed codes. The first code calculates the electric filed distribution (transverse mode) of disk laser with unstable resonator. Second code calculates the beam quality factor based on the laser beam specifications and the third code calculates induced thermal aberrations in the disk. The accuracy of each code is confirmed by comparing with others and the calculations are validated.

The results show that thermal aberrations strongly affect the laser beam profile, beam quality and output power. By these calculations it is possible to evaluate the individual effects of each of thermal factors on the beam quality of the laser. Based on our calculations the destructive effect of disk deformation on the internal beam quality of laser is stronger than other four thermal factors.

2. Theory

The governing equations of the problem are presented in this section. For better presentation the theory part is divided to the three subsections.

2.1. Transverse mode of unstable resonator

Fig. 1 shows a schematic diagram of the thin disk laser with unstable resonator. Dominant transverse mode of an unstable resonator including ABCD optical elements can be obtained via Collins' integral as follows [15]:

$$E_2(x_2, y_2) = \frac{-ik\exp(-ikL)}{2\pi B} \iint E_1(x_1, y_1) \times \exp\left\{ \frac{-ik}{2\pi B}\left[A\left(x_1^2 + y_1^2\right) - 2\left(x_1x_2 + y_1y_2\right) + D\left(x_2^2 + y_2^2\right)\right]\right\} dx_1dy_1 \quad (1)$$

in which k is the wave number and L is the distance of beam propagation. A, B and D are the matrix elements of ABCD ray matrix of resonator including elements and spaces in beam propagation path. E_1 is the initial electric field of the laser beam (as an electromagnetic wave) and E_2 is propagated electric field at final screen. (x_1,y_1) and (x_2,y_2) are the coordinates of the points on initial and final screens respectively. In this paper integral (1) is solved numerically and iteratively to find the transverse mode profile of the laser. More details can be found in Ref. [17].

Generally calculation of transverse mode of multi-element unstable resonator can be conducted by considering a transverse reference plane located inside unstable resonator just before the output mirror [18]. However in this work because we wanted to calculate the aberration effects of the disk active medium, we also considered another transverse reference plane just after the disk. In each iteration, firstly non-aberrational dioptric effects of the disk are calculated by Eq. (1) on this new reference plane. The electric field distribution of the laser beam is calculated on this reference plane in each iteration which is called $E(x,y)$. Then the aberrational effects of the disk are considered as an additional phase term based on the OPD concept as it will be explained following in subsection 3 “thermal effects”. The aberrated electric field of the laser beam due to passing through the disk can be written as $E(x, y)\exp(i\phi)$ where ϕ is the phase distortion due to disk thermal aberrations. This achieved aberrated electric filed is considered as initial electric field for next iteration. In this work we have used two reference planes, therefore ABCD matrixes are written for elements and spaces in the beam path between reference planes.

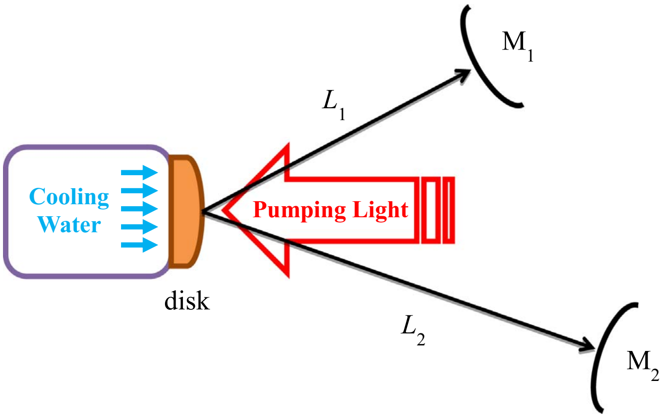

Fig. 1. Schematic diagram of V-shape unstable resonator for disk laser.

2.2. Laser beam quality

Having the electric field of laser mode, it is possible to calculate the M^2 factor of the beam based on the generalized beam parameters theory via following relations: [15,16]:

$$w(\mathrm{E}) = 2\sqrt{\frac{\int_{-\infty}^{\infty} |E(x)|^2 \left(x - x(\mathrm{E})\right)^2 dx}{\int_{-\infty}^{\infty} |E(x)|^2 dx}} \quad (2)$$

in which w is the width of the beam across the x-axis and x(E) is defined as the position of “center of intensity” of the beam which is given by

$$x(\mathrm{E}) = \frac{\int_{-\infty}^{\infty} |E(x)|^2 x dx}{\int_{-\infty}^{\infty} |E(x)|^2 dx} \quad (3)$$

The Fourier transform $\phi(\xi)$ of the amplitude distribution $E(x)$ is defined as

$$\phi(\xi) = \int_{-\infty}^{\infty} E(x)\exp(-i2\pi\xi x)dx \quad (4)$$

Angular width that can be taken as divergence of the beam can be expressed by

$$\theta_0(\phi) = 2\lambda\sqrt{\frac{\int_{-\infty}^{\infty} |\phi(\xi)|^2 \left(\xi - \xi(\phi)\right)^2 d\xi}{\int_{-\infty}^{\infty} |\phi(\xi)|^2 d\xi}} \quad (5)$$

in which λ is the wave-length and $\xi(\phi)$ is defined by

$$\xi(\phi) = \frac{\int_{-\infty}^{\infty} |\phi(\xi)|^2 \xi d\xi}{\int_{-\infty}^{\infty} |\phi(\xi)|^2 d\xi} \quad (6)$$

The generalized form of radius of curvature of the wave-front R (E) is expressed by

$$\frac{1}{R(E)} = \frac{i\lambda}{\pi w(E)^2 \int_{-\infty}^{\infty} |E(x)|^2 dx} \int_{-\infty}^{\infty} \left\{ \frac{\partial E(x)}{\partial x} E^*(x) - E(x)\frac{\partial E^*(x)}{\partial x} \right\} \times (x - x(E))dx \quad (7)$$

Finally the M^2 factor for generalized beams can be expressed as

$$M^2 = \frac{\pi w(E)}{\lambda}\sqrt{[\theta_0(\phi)]^2 - \frac{\left[w(E)\right]^2}{\left[R(E)\right]^2}} \quad (8)$$

In this way having electric field component of laser beam, it is possible to evaluate the M^2 factor. Any factor influencing the