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Wavefront aberration analysis in misalignment passive positive-branch unstable laser resonators

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ABSTRACT

Eigenmode of resonators with asymmetric circular mirrors based on misalignment passive positive-branch unstable resonator is investigated in the paper. To do so, we use iterative algorithm to simulate the effect of intracavity phase perturbation on eigenmode structure properties of the passive confocal unstable resonator. On this basis, further experiment of output beam properties on a misaligned passive unstable laser resonator has been performed by adopting Hartmann–Shack (H–S) method and Zernike modal wavefront reconstruction. Wavefront distribution and the first 35-order Zernike coefficient included in the wavefront are obtained. The results show that intracavity tilt perturbation notably affects outcoupled beam intensity distribution, and will also increase some high-order aberrations of beam phase properties. However, low-order Zernike tilt aberration is the main component with phase-tilted perturbation is introduced into resonator cavity. Defocus, low-order astigmatism and coma aberration will all be brought with the augument of phase tilt aberration, which will obviously degrade output beam quality. When intracavity compensating elements are adopted for optical aberration correction, the correction of tilt aberration should be considered first.

1. Introduction

High beam quality is a key prerequisite in current laser application. Unstable resonators characterized by high power output, large fundamental mode volume and good spatial mode selection at high Fresnel numbers have been widely used in gas laser, solid-state laser and chemical laser oscillators [1–3]. Some investigations indicate that in some situations the brightness of a laser oscillator can be significantly increased by using an unstable resonator rather than a stable resonator [2,3]. However, some problems affect the mode properties and beam quality; mainly include the geometry misalignment of cavity mirrors, inhomogeneity of the gain medium, intracavity vibration and the thermal deformation of cavity mirrors [4–8]. So especially for a high-power laser with unstable resonators, the beam quality and output energy can be degraded obviously by such perturbations.

When the output energy of lasers is definite, it is very important to research the aberration of unstable resonators, and the effect on the beam quality and intensity distribution with intracavity perturbations such as phase tilted aberration, astigmatism, defocus and so on, which is the basis to research the problem of the intracavity aberration correction and built the control system [9–11]. However, there are very few research reports about the influence of intracaity perturbation on mode characteristics. In fact, it is not very explicit currently because beam wavefront aberration has not been decomposed to Zernike polynomial phase aberration, which is not acceptable for accurately wavefront correction and compensation by corresponding optical elements, and also the influence of low-order wavefront aberration on high-order aberration has not been illuminated [12,13].

In this study, firstly we presented the eigenmode distribution disturbed with the phase tilt aberration in a positive branch unstable resonator using asymmetric circular mirrors by iterated calculation in Section 2. The corresponding subtle wavefront aberration is achieved further by wavefront fitting using first 35-order Zernike polynomial coefficients. In Section 3, wavefront aberration of the output laser is analyzed accurately by adopting H–S wavefront detection and Zernike mode reconstruction. In this way, PV and RMS values of the wavefront distribution, the corresponding Zernike aberrations is acquired, and also the curve of circle energy can also be obtained by further calculation. Conclusions are given in Section 4. So it will be a further reference to establish that fairly

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simple devices based on adaptive optics (AO) are capable of eliminating many problems arising from intracavity perturbation in high-peak power lasers.

2. Theoretical analysis

2.1. Laser eigenmode with intracavity perturbed resonators

For researching the characteristic of an unstable resonator, the mode structure properties of aligned or maladjustment resonators should be analyzed theoretically. The eigenmode can be studied by adopting some mathematical methods [14–16]. Iterative method is usually adopted; namely, it needs to solve the integral equation as follows

$$\varphi(x,y)=\gamma\frac{\mathrm{i}}{\lambda L}\iint_S K(x,y,x\prime,y\prime)\varphi(x\prime,y\prime)\mathrm{d}S\prime \tag{1}$$

where φ and γ is the eigenfunction and eigenvalue respectively, K is called kernel of the integral equation, L is the resonator cavity length, and $k\equiv 2\pi/\lambda$. The modes of a general asymmetric circular mirror is expressed by the two coupled integral equations [15].

$$\begin{aligned}&\gamma_1\varphi_1(x)\\&=j^{l+1}\left(\frac{k}{L}\right)\int_0^{a_2} yJ_l\left(\frac{kxy}{L}\right)\exp\left[-j\left(\frac{k}{2L}\right)\times(g_1x^2+g_2y^2)\right]\varphi_2(y)\mathrm{d}y\\&\gamma_2\varphi_2(y)\\&=j^{l+1}\left(\frac{k}{L}\right)\int_0^{a_1} zJ_l\left(\frac{kxy}{L}\right)\exp\left[-j\left(\frac{k}{2L}\right)\times(g_2y^2+g_1z^2)\right]\varphi_1(z)\mathrm{d}z\end{aligned} \tag{2}$$

where g_1 and g_2 are defined as g parameter of resonators, L is the length of the resonator cavity, a_1 and a_2 are half apertures of convex mirror and concave mirror respectively, x, y and z are now unscaled radius coordinates on the two mirrors. However, diffraction integral equation will become more complex with intracavity phase perturbation in laser resonators, we analysis this problem by iterative calculation and further wavefront phase fitting with Zernike aberration coefficients.

In Fig. 1, Let R_x and R_y denote the magnitudes of the unperturbed radius of curvature of the convex mirror, and let M_x and M_y denote the geometric magnifications of undisturbed optical cavity in the x and y meridional planes, respectively. The intracavity perturbation surface is indicated by the plate H, δ is the x directional perturbation and L_1 is the distance between the intracavity phase perturbation plane and the concave mirror. The integral equation for the phase-tilt-aberrated cavity with convex mirror feedback aperture S may be directly obtained through the augmented paraxial ray transfer matrix for a single round-trip iteration [16]. The result is.

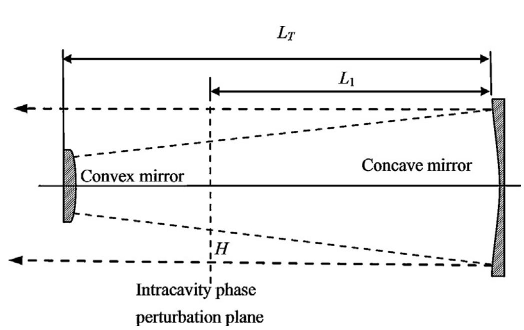

Fig. 1. Positive-branch confocal unstable resonator structure with an intracavity phase perturbation plane.

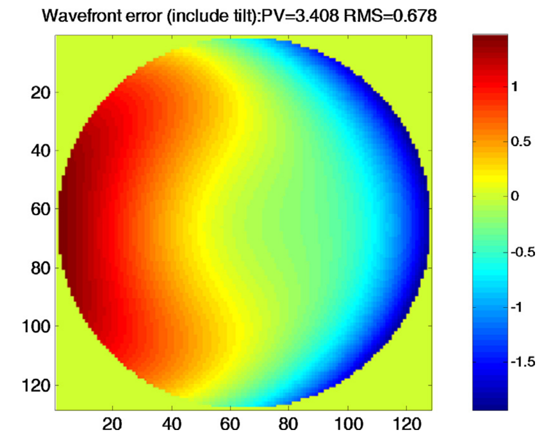

Fig. 2. Mode wavefront distribution by introducing a $\lambda/2$ intracavity phase-tilted perturbation, PV = 3.408λ, RMS = 0.678λ.

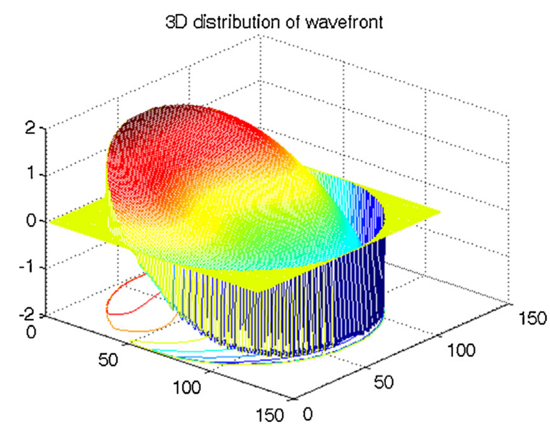

Fig. 3. Wavefront 3-D distribution of the eigenmode by introducing a $\lambda/2$ intracavity phase-tilted perturbation.

$$\begin{aligned}&\gamma u(x_2,y_2)\\&=-\frac{i}{2\lambda L_T}e^{i2kL_T}\exp\left\{-i\frac{\pi}{\lambda}\frac{2\delta M_x\left[1-(1/M_xR_x)L_1\right]}{M_x+1}x_2\right\}\\&\times\iint_S u(x_1,y_1)\exp\left\{-i\frac{\pi}{\lambda}\frac{2\delta M_x\left[1-(1/M_xR_x)L_1\right]}{M_x+1}x_1\right\}\\&\times\exp\left\{i\frac{\pi}{\lambda L_T}\left[\frac{(x_2-M_xx_1)^2}{M_x+1}+\frac{(y_2-M_yy_1)^2}{M_y+1}\right]\right\}\mathrm{d}x_1\mathrm{d}y_1\end{aligned} \tag{3}$$

2.2. Theoretical calculation and discussion

The parameter of the unstable resonator is $g_1=1.50$, $g_2=0.75$, $M=2.0$, the half aperture of the convex mirror is 10 mm, the Fresnel number $N_{eq}=(M-1)a^2/2\ \lambda$. $L=0.31$, the phase tilted perturbation along the x direction is $\delta=\lambda/2$, and the distance between the intracavity phase perturbation plane and the concave mirror is $L_1=L/3$, in which L is the length of the resonator cavity. Figs. 2 and 3 show that the eigenmode distribution by using Fox–Li iterative method. In our calculation, the first 35-order Zernike aberration have been obtained by decomposing the aberrated wavefront with Zernike circle orthogonal polynomials, and the first 12-order Zernike coefficients are shown in Fig. 4. It is verified Z_1 coefficient (x directional tilt aberration) is the main aberration; Z_1 is −0.742,