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The influence of misalignment of an axisymmetrical folded-combined CO_2 laser on output power

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ABSTRACT

The influences of misalignments of an axisymmetrical folded-combined (ASFC) CO_2 laser on the output power are studied in detail. The new cavity axes are established by using the misaligned matrixes corresponding to the misalignments of the output mirror and the discharge tube, and the diffraction losses of the cavity and the output powers are calculated. It is shown that the influences of the misalignments on the output power are significant when the misalignment angle of the output mirror exceeds 20 s. These calculated values afford references for the design of ASFC CO_2 lasers.

1. Introduction

Diffusion-cooled CO_2 lasers have developed rapidly. Examples of the lasers include the multi-channel slab CO_2 laser [1,2], the phase-locked radial array CO_2 laser [3,4], and the CO_2 waveguide laser [5,6]. Recently, a diffusion-cooled ASFC CO_2 laser has been proposed [7] and studied [8–13]. The near field distribution has been described in Ref. [8], the ability to combine the output beams has been predicted theoretically, and it can be used in industrial processing. A method for phase-locking was described [9,10,13] and the combination of the coherent beams in the far field has been studied.

We know that the theoretical prediction for the output power is about 60 W [7], but a maximum of only 21 W has been obtained experimentally [11,12]. The experiment indicated that the output power depends on the gas mixture and the discharge current is only a few watts [11]. Therefore, the difference must result mainly from misalignment of the cavity. The misalignment may increase the diffraction loss and decrease the output power. All cavities of the ASFC CO_2 laser possess a common output mirror. Therefore, the misalignment of the output mirror will influence the output powers of all laser beams. When a discharge tube is misaligned, the axes of two discharge tubes are no longer symmetrical. Therefore, the effective gain area will decrease and the output power will reduce. In this paper, we study the influences of the misalignments of the output mirror and the discharge tube on the output power.

2. Misaligned analysis of theoretical model

A three-dimensional (3D) ASFC CO_2 laser with thirteen discharge tubes is shown in Fig. 1(a). Mirror M is an output mirror, its thickness is d, the refractive index n, the reflectivity R, the transmissivity $T=1-R$, and the radius of curvature $\rho=\infty$. M_i $(i=0, 1, \ldots, 12)$ are all reflective mirrors, the radii of curvature are ρ_i $(i=0, 1, \ldots, 12)$. The thirteen discharge tubes are placed between mirrors M_i and M, their lengths are l_i $(i=0, 1, \ldots, 12)$, the radii are r_i. Let the distance between M_i and M all be the same at l_i. The straight line through the centers of M_i $(i=0, 1, \ldots, 12)$ and M is represented by $\overline{M_iM}$, and through M_i and M_0 by $\overline{M_iM_0}$. M_i-M-M_{i+6} $(i=1, 2, \ldots, 6)$ and $M-M_0$ denote the folded cavities and a plane concave cavity, respectively. The coordinate system (X, Y, Z) is established in Fig. 1(a). The angle included between beelines $\overline{M_iM_0}$ and $\overline{M_1M_0}$ is $\varDelta_i=(i-1)(\pi/6)$ $(i=1, 2, \ldots, 12)$. The angle between $\overline{M_iM}$ $(i=1, 2, \ldots, 12)$ and $\overline{MM_0}$ is θ_3^*.

In order to study the misalignment of the output mirror, we let the mirror M rotate an angle θ_1^* around X-axis. Therefore, the axis of the output mirror M will change from the Z-axis to the Z'-axis that intersects at point Q with Y-axis, θ_1^* is the angle included between the two axes, and a misalignment angle $\theta_{4(i)}$ ($\theta_{4(i+6,i)}$ or $\theta_{4(i,i+6)}$) of the mirror M is introduced to the cavity M_i-M-M_{i+6}. Similarly, for the misalignment of an arbitrary discharge tube (2), the misaligned angle displacement is θ_2 and the line displacement is θ'_2 (see Fig. 1(b)). We know that $\theta'_2 \approx l_2\sin(\theta_2)$ according to the corresponding geometrical relation. The new axes of the folded cavities M_i-M-M_{i+6} and plane concave cavity $M-M_0$ will be offset from the original axes. We use the 4×4 augmented matrices [14,15] to establish the new cavity axes of M_i-M-M_{i+6}

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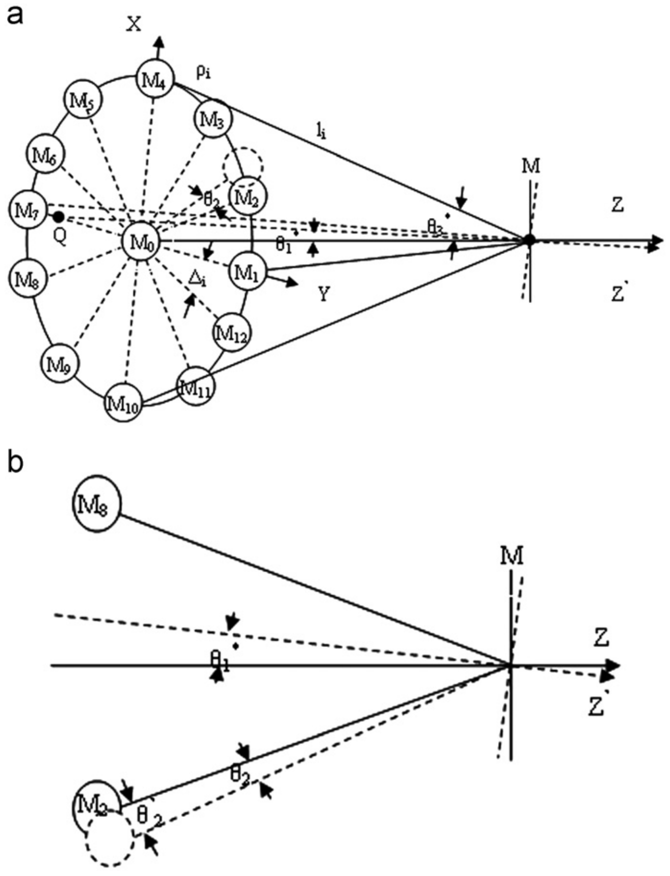

Fig. 1. (a) Diagram of the model of ASFC CO_2 laser: M is output mirror; M_i $(i=0, 1, \ldots, 12)$ are all reflective mirrors, the curvature radii are ρ_i, the discharge tubes are placed between mirrors M_i and M, their lengths are l_i, the radii are r_i. The straight line through the centers of M_i $(i=0, 1, \ldots, 12)$ and M is represented by $\overline{M_iM}$, and through M_i and M_0 by $\overline{M_iM_0}$. (b) Geometrical optical diagram of misalignments.

and $M-M_0$. For the folded cavities M_i-M-M_{i+6} $(i=1, 2, \ldots, 6)$, the line deviations $\Delta d_{(i,i+6)}$ and the angle deviations $\Delta\theta_{(i,i+6)}$ satisfy the following relation:

$$\begin{pmatrix}\Delta d_{(i,i+6)}\\ \Delta\theta_{(i,i+6)}\\ 1\\ 1\end{pmatrix}=\begin{pmatrix}1&0&0&0\\0&1&0&-2\theta_{4(i+6,i)}\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&l_i&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}$$
$$\begin{pmatrix}1&0&0&0\\-\dfrac{2}{\rho_i}&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&l_i&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\times\begin{pmatrix}1&0&0&0\\0&1&0&-2\theta_{4(i,i+6)}\\0&0&1&0\\0&0&0&1\end{pmatrix}$$
$$\begin{pmatrix}1&l_i&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&0&0&0\\-\dfrac{2}{\rho_i}&1&\dfrac{2\theta'_j}{\rho_i}&-2\theta_j\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&l_i&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}\Delta d_{(i,i+6)}\\ \Delta\theta_{(i,i+6)}\\ 1\\ 1\end{pmatrix}. \tag{1}$$

where $i=1, 2, \ldots 6$. θ_j and θ'_j result from the misalignment of the discharge tube (2). Therefore, $\theta_j \neq 0$ and $\theta'_j \neq 0$ when $j=2$, and $\theta_j=\theta'_j=0$ when $j=1, 3, \ldots, 12$. We know that $\theta_{4(i)}$ are the misaligned elements resulting from the misalignment of the output mirror for the different folded cavities M_i-M-M_{i+6}. It should be noted that there are a few peculiar values: $\theta_{4(0)}=\theta_{4(1)}=\theta_1^*$, and $\theta_{4(7)}=3\theta_1^*$ because $\overline{M_{0,1,7}M}$ and $\overline{QM}$ are in the same $Y-Z$ plane as mirrors $M_{0,1,7}$. $\theta_{4(i+6,i)}$ or $\theta_{4(i,i+6)}$ is the same order of magnitude as $\Delta\theta_{(i,i+6)}$. Therefore, we set $\theta_{4(i)}$ to be the angle of the two planes a_i and b_i. Plane a_i is determined by lines $\overline{M_iM}$ and $\overline{MM_0}$, and plane b_i is given by lines $\overline{M_iM}$ and $\overline{MQ}$. According to the geometrical relation, we know $\theta_{4(i)}$ satisfies the following expression:

$$\theta_{4(i)}=\arccos\left\{\frac{\sin^2\theta_3^*+\cos^2\theta_3^*\times\tan^2\varphi_i-\left[1+\frac{\cos^2\theta_3^*}{\cos^2\varphi_i}-2\left(\frac{\cos\theta_3^*}{\cos\varphi_i}\right)\cos\theta_1^*\right]}{\sin(2\theta_3^*)\times\tan\varphi_i}\right\}. \tag{2}$$

where

$$\varphi_i=\arccos(\cos\theta_1^*\times\cos\theta_3^*+\sin\theta_1^*\times\sin\theta_3^*\times\cos\Delta_i). \tag{3}$$

Substituting Eqs.(2) and (3) into Eq.(1), we can obtain the values of $\Delta d_{(i,i+6)}$ and $\Delta\theta_{(i,i+6)}$. Similarly, for the plane concave cavity $M-M_0$, the line deviation Δd_0 and the angle deviation $\Delta\theta_0$ satisfy the following relation:

$$\begin{pmatrix}\Delta d_0\\ \Delta\theta_0\\ 1\\ 1\end{pmatrix}=\begin{pmatrix}1&0&0&0\\0&1&0&-2\theta_{4(0)}\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&l_0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}$$
$$\begin{pmatrix}1&0&0&0\\-\dfrac{2}{\rho_0}&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&l_0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}\Delta d_0\\ \Delta\theta_0\\ 1\\ 1\end{pmatrix}. \tag{4}$$

We know that these line deviations Δd_i $(i=0, 1, \ldots, 12)$ will increase the diffraction losses [16] of the corresponding cavities and reduce the output powers [7]. In this paper, we study only the influences of misalignments on the output power of the fundamental mode. Diffraction loss of the mode can be given by

$$\alpha_l(\Delta d_i)=\exp\left[-\frac{2(r_i-|\Delta d_i|)^2}{\omega_i^2}\right]. \tag{5}$$

where the beam radii ω_i at the all reflective mirrors M_i [16] satisfy

$$\omega_i=\left(\frac{\lambda l_i\rho_i}{\pi}\right)^{1/2}\left[\frac{1}{l_i(\rho_i-l_i)}\right]^{1/4}. \tag{6}$$

$\alpha_l(\Delta d_i)$ denote the diffraction losses when the line deviations are Δd_i. These values will influence the output power [7,17] that is given by

$$P_{out}=\frac{72\pi T^2\times(1-\alpha_t)^{1/2}\times\left\{g_0 l_i+\ln[(1-\alpha_t)(1-\alpha_t-T)]^{1/2}\right\}}{[(1-\alpha_t)^{1/2}+(1-\alpha_t-T)^{1/2}]\times[1-(1-\alpha_t)(1-\alpha_t-T)^{1/2}]}. \tag{7}$$

where g_0 is the small-signal gain coefficient, the total loss $\alpha_t=\alpha_l(\Delta d_i)+\alpha_{other}$, and α_{other} represents all other losses except the diffraction loss. We set these parameters as $\rho_i=1.8$ m, $l_i=1.5$ m, $d=5$ mm, $n=2.4$, $\lambda=10.6$ μm, $R=80\%$, $T=20\%$, $r_i=5$ mm, $g_0=0.012\ \text{cm}^{-1}$, and $\alpha_{other}\approx 0.005$. The line deviations Δd_i, diffraction losses $\alpha_l(\Delta d_i)$, and output power P_{out} can be obtained easily. The calculated values are shown in Table 1.

We know from Table 1 that the total output power can reach about 800 W for the laser with thirteen discharge tubes under the ideal case (without the misalignments). However, it depends on the misaligned angles to a great extent, especially for output mirror misalignment. The output power can exceed 630 W when $\theta_1^*\leq 20$ and $\theta_2=100$ s; but it is only 372 W when $\theta_1^*\approx 50$ and $\theta_2=100$ s, and it is far less than the output power under the ideal case. However, it is only 360 W when $\theta_1^*\approx 50$ s for $\theta_2=500$ s and