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Theoretical study on phase-locking of a radial array CO_2 laser

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ABSTRACT

The phase-locking of the radial array CO_2 laser (RAL) is introduced based on the injection-locking principle. The characteristic parameters of laser beams used in the phase-locking are described, and the coupling coefficient c_{00} between the injected mode and the eigenmode of RAL is calculated. The laser modes from RAL are the low-order Hermite Gaussian modes due to the diffraction loss. The analytical formula for the output beam through an ABCD optical system is derived according Collins formula. The numerical examples are given to illustrate our analytical results.

1. Introduction

The RAL [1–4] was proposed and studied in order to obtain the high-power laser output due to the large gain area and compact structure. And the phase-locking of multichannel radial array CO_2 laser has been studied [5–7] for fulfilling the coherent combination of the array beams. So far, the research works on high-power CO_2 laser [8–14] are still continuous. A new type of toric concave mirror laser resonator with a big Fresnel number [8] has been designed, and 3.2 kW laser beam with an M^2 factor of 1.9 was obtained in a high-power transverse flow CO_2 laser. Unstable resonator is capable of providing a diffraction-limited beam, the intensity and phase distribution are almost uniform [9,10]. Axisymmetric-fold combination CO_2 laser [11–14] can obtain the high-power laser beam, and the phase-locking can be fulfilled by using the method of reflection-injection-locking.

There are many useful reports on the phase-locking of RAL [1–6] according to the above descriptions. However, the main works aim at the qualitative analysis, the phase-locking principle and the properties of output beam are not still introduced. Therefore, this paper will study quantitatively the phase-locking in RAL and combination of output beam, the analytical formula for the output beam through an ABCD optical system is derived in detail. The phase-locking of the multiple independent lasers has been studied since the phenomenon was first proposed by Basov [15], and later demonstrated by Stover and Steier [16]. Then a variety of methods on phase-locking has included the injection-locking and master-oscillator-power amplifier approaches [17–20], adaptive optical techniques [21], intra-cavity spatial filtering or Talbot cavity methods [22], nonlinear optical coupling techniques [23,24]. In this paper, the injection-locking method is the most efficient method according to the structure of RAL. The injected signal can be reflected by the internal cavity [14] or the external cavity [11]. The former can make the laser compact, but the injected signal is too poor that the effect of phase-locking will be influenced. However, the latter can provide the intense injected signal because the reflected beam will be injected divergently into the RAL. Therefore, in this paper, we will use the second method in order to obtain the intense injected signal.

What is pointed out especially is that this paper is different from Refs. [5–7,11–13]. (1) First, the principles of phase-locking are different between this paper and Ref. [7]. The signal from the spontaneous emission is considered as the control source used for the phase-locking in [7]; however, in this paper, the external cavity is used, and the signal used for the phase-locking is from the reflection of the external cavity. Second, it is well known that the output laser mode from slab discharge laser is the Hermite – Gaussian mode. The simple expression (see [7, Eq. (12)]) is used for calculating the output light intensity. However, in this paper, the complex analytical formula is derived to describe the output laser beam (see Eq.(9) in this paper) and the corresponding numerical calculations are given. (2) Yelden et al. have studied experimentally the phase-locking of CO_2 laser in [5,6]. The experimental results are important for the development of CO_2 laser, the works aim at the experimental study and the qualitative analysis. However, in this paper, the quantitative descriptions of the output beams are studied, the numerical examples are given to describe the output beam. (3) The fundamental mode Gaussian beams from the discharge tube CO_2 lasers [11–13] are studied.

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However, in this paper, the output beams from the slab CO_2 laser are the complex Hermite – Gaussian beams; therefore, the effect of phase-locking is different for the two CO_2 lasers.

2. Phase-locking principle and property of beam in RAL

2.1. Phase-locking principle

The phase-locking principle can be illustrated as follows: first the two mirror cavity M_3-M_4, which lies the symmetry axis of the system, is excited by the pumping source, and the laser beam will be obtained from the plane-concave cavity. Then the beam will be reflected by the reflection mirror M_5. And it will become a control-source (see the dashed line between M_4 and M_5) and inject divergently into every discharge channel in RAL under the condition of the paraxial approximation. Therefore, the eigenmodes will be excited if the injected signal is intense enough in RAL. And the eigenmode of RAL will be controlled by the injected mode if the injected mode can establish the oscillation in RAL. Therefore, the array beams exported from output-mirror have a fixed phase relation to each other. Therefore, in this paper, we will select the appropriate parameters in order to provide the intense injected signal, the place and curvature radii of mirror M_3 and M_5 will influence directly the effect of phase-locking. In order to study the properties of the oscillation beams and phase-locking, we set $L_1 = 1.5$ m, $L_2 = 0.9$ m, $L_3 = 0.6$ m, and $\lambda = 10.6$ μm.

2.2. Property of beam used in phase-locking

The structure of high-power RAL is shown in Fig. 1a. Toric concave mirror M_1 is the holophote (curvature radius is ρ_1), the curvature radii of concave mirrors M_2 and M_3 are ρ_2 and ρ_3, respectively. L_1, L_2 and L_3 are the distances between two mirror cavities M_1-M_2, M_2-M_3 and M_3-M_4, respectively. We know from the parameters set above that mirror cavity M_3-M_4 is a stable cavity if $\rho_3 > L_3$, and the eigenmode is the Gaussian beam. M_5 is the control mirror (curvature radius is ρ_5), it can reflect the control-source beam from cavity M_3-M_4 and control the oscillation in RAL. M_6 is the convergent lens (focal length is f). The geometrical optical pathway diagram of oscillation beam in resonator is shown in Fig. 1b. The distances between parallel beams from cavities M_1-M_2 (M_3-M_4) and z axis are r_1 (r_2), the incident angle in mirror M_2 is θ. The ray matrix of the oscillation beam for the single-pass trip with reference to mirror M_1 is given by

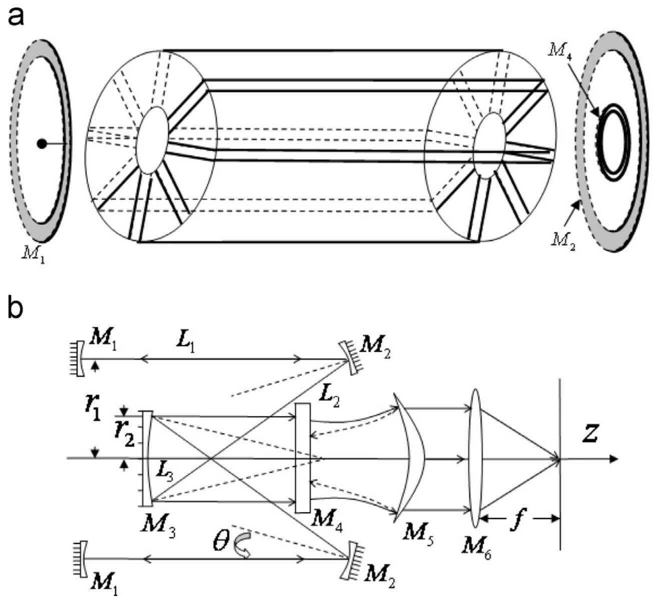

Fig. 1. Diagrams of RAL, (a) stereograph diagram of laser, (b) section diagram and geometrical optical pathway diagram of oscillation beam.

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} 1 & L_3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/\rho_3 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/\rho_2 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix}. \tag{1}$$

Therefore, the ray matrix for one complete round-trip through four mirrors stable cavity $M_1-M_2-M_3-M_4$ is expressed as

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} d & b \\ c & a \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/\rho_1 & 1 \end{pmatrix}. \tag{2}$$

What is pointed out especially is that the curvature radii of mirrors M_3 and M_5 is important for the properties of the oscillation beams in RAL according to Refs. [11–14]. The beam width w_1 of the oscillation beam [14] at mirror M_1 is given by

$$w_1 = \left(\frac{2\lambda B}{\pi \sqrt{4-(A+D)^2}} \right)^{1/2}. \tag{3}$$

Obviously, values of w_1 will be determined by the curvature radius ρ_3 of mirror M_3 according to the complex parameter formula of oscillation beam [12], the curve diagrams between w_1 and ρ_3 are shown in Fig. 2. The phase-locking should be considered firstly in order to fulfill the coherent combination of the multi-beams from RAL according to the injection-locking of the stable cavity [11–14]. The coupling coefficient [25] of the injected mode and the eigenmode in RAL is given by

$$c_{mn} = \left(\frac{2}{2^{m+n} \pi w_0 w_1 m! n!} \right)^{1/2} \int_{-\infty}^{\infty} H_m\left(\sqrt{2/w_0^2}\, s\right) H_n \times \left(\sqrt{2/w_1^2}\, s\right) \exp\left(-ps^2\right) ds. \tag{4}$$

where, $s = x, y$,

$$p = \frac{1}{w_0^2} + \frac{1}{w_1^2} + i\frac{k}{2}\left(\frac{1}{R_0} - \frac{1}{R_1} \right). \tag{5}$$

where, k is the wavenumber, R_1 is the curvature radius of the equiphase surface the oscillation beam at mirror M_1, w_0 and R_0 are the beam radius and curvature radius of the equiphase surface of the injected beam, respectively. We know from Eq. (4) that the

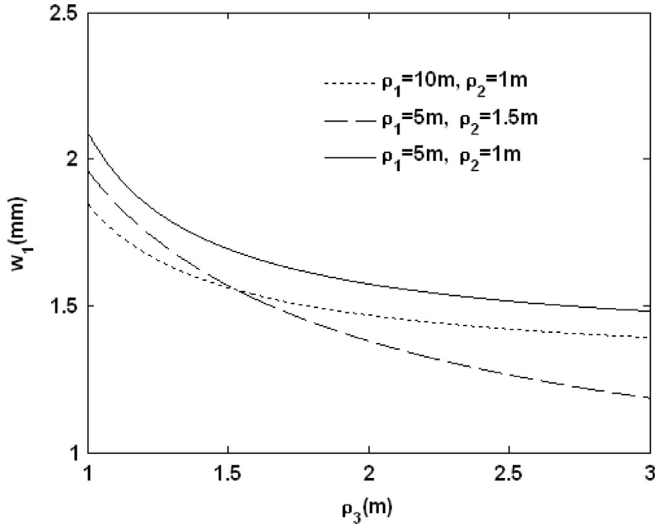

Fig. 2. Curve diagrams between beam radius w_1 at mirror M_1 and curvature radius ρ_3 for the different parameters.