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Influence of thermal deformation in cavity mirrors on beam propagation characteristics of high-power slab lasers

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ABSTRACT

Owing to their good diffusion cooling and low sensitivity to misalignment, slab-shape negative-branch unstable-waveguide resonators are widely used for high-power lasers in industry. As the output beam of the resonator is astigmatic, an external beam shaping system is required. However, the transverse dimension of the cavity mirrors in the resonator is large. For a long-time operation, the heating of cavity mirrors can be non-uniform. This results in micro-deformation and a change in the radius of curvature of the cavity mirrors, and leads to an output beam of an offset optical axis of the resonator. It was found that a change in the radius of curvature of 0.1% (1 mm) caused by thermal deformation generates a transverse displacement of 1.65 mm at the spatial filter of the external beam shaping system, and an output power loss of more than 80%. This can potentially burn out the spatial filter. In order to analyze the effect of the offset optical axis of the beam on the external optical path, we analyzed the transverse displacement and rotational misalignments of the spatial filter. For instance, if the transverse displacement was 0.3 mm, the loss in the output power was 9.6% and a sidelobe appeared in the unstable direction. If the angle of rotation was 5°, the loss in the output power was 2%, and the poles were in the direction of the waveguide. Based on these results, by adjusting the bending mirror, the deviation angle of the output beam of the resonator cavity was corrected, in order to obtain maximum output power and optimal beam quality. Finally, the propagation characteristics of the corrected output beam were analyzed.

1. Introduction

Slab lasers use diffusion cooling to achieve good cooling for high-power outputs; thus, they are widely used in solid and gas lasers [1–7]. However, a negative-branch unstable resonator exhibits lower misalignment sensitivity compared to a positive-branch unstable resonator; therefore, it is also used in industrial high-power lasers. For example, the 2 kW RF slab CO_2 lasers developed by our research group use negative-branch unstable-waveguide resonators [8–10]. Nevertheless, in Refs. [2,9], the output beam of the negative-branch unstable-waveguide resonator exhibits astigmatism. Consequently, an external beam shaping system is required to obtain a fundamental mode Gaussian beam suitable for laser processing. Therefore, the influence of the external beam shaping system on the beam propagation needs to be considered together with that of the resonator cavity.

In high-power slab lasers, the aspect ratio of the cavity mirrors is approximately 1:13; thus, the transverse size of the cavity mirrors is larger. In a long-time operation, the heating of cavity mirrors can be non-uniform. This can lead to micro deformation of the mirrors, and change their radius of curvature, which affects the output beam of the cavity. Finally, if the beam passes through an external beam shaping system without adjusting the misalignment, the beam quality can be degraded. In the designing process, corrections of these effects have to be considered.

In this paper, firstly, we study RF slab CO_2 lasers with negative-branch unstable-waveguide hybrid resonators and their external beam shaping system. Secondly, the effects of thermal deformation of the cavity mirrors on the cavity output beam is investigated. It is found that when the thermal deformation of the cavity mirrors is changed by 0.1% (1 mm), the relative phase of the output beam changes slightly, while the output beam offset optical axis 1.5 mrad. Thirdly, in the external beam shaping system, the deviation of the optical axis of the cavity output beam is equivalent to the misaligned spatial filter. Thus, the transverse displacement and rotational misalignment of the spatial filter can be explored. Fourthly, these problems, are addressed by using a bending

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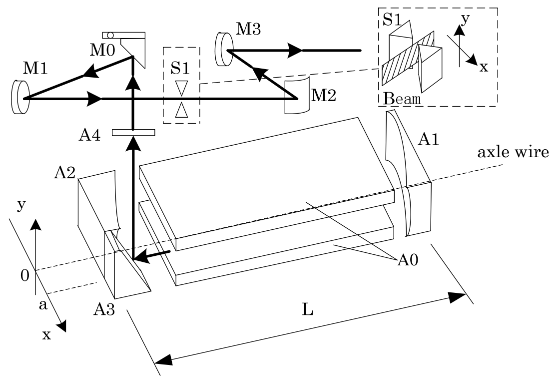

Fig. 1. Schematic of the experimental system. A0: electrode, A1: reflecting mirror, A2: resonator output mirror, A3: 45° mirror, A4: windows mirror, M0: bending mirror, M1: spherical focusing mirror, S1: spatial filter, M2: cylindrical mirror, M3: spherical mirror. x: unstable direction, y: waveguide direction.

mirror adjustment device, which reduces the loss of the output power and improve the beam quality. Finally, the propagation characteristics of the beam after passing through the spatial filter are analyzed. These analysis methods and results are useful for the design of gas and solid slab lasers using a hybrid resonator.

2. Experimental system

A 2 kW diffusion cooling RF CO_2 laser was used in the experimental system. First, the configurations of the negative-branch unstable-waveguide hybrid resonator and the external beam shaping system are presented. Then, the intensity distributions of the unshaped output beam of the hybrid resonator are given.

2.1. Complete configuration

The hybrid resonator uses an off-axis negative-branch unstable schematic in the transverse direction and a waveguide scheme in the perpendicular direction. The diffraction-limit beam can be obtained in the unstable direction of the hybrid resonator, and the best beam quality can be obtained in the waveguide direction. Thus, an external beam shaping system is needed to transform the astigmatic beam into a nearly circular Gaussian-shaped beam with no side lobes. The experimental system based on this, including a spatial filter illustrated in Fig. 1.

The configuration of the negative-branch unstable-waveguide hybrid confocal resonator was composed of a reflection mirror (A1), an output-coupling mirror (A2), a 45° mirror (A3), and an output window (A4). Along the x-axis, the cavity is unstable, and along the y-axis, it is a waveguide. A1 and A2 are concave mirrors. The radius of curvature of A1 is R1 = 1040 mm, and A2 is R2 = 920 mm. The length of the confocal resonator is L = (R1 + R2)/2, and a = 81 mm is the half-width of the output-coupling mirror. The parallel copper electrodes (A0) were internally water-cooled using a multichannel, with an active area of 200 mm × 965 mm. The discharge gap was 1.5 mm. A 30 kW RF power supply operating at a frequency of 81 MHz was used in the system. The gas pressure in the laser vessel was about 135 Torr, with a gas mixture mainly containing 19% N_2, 4% CO_2, 6% CO, 3% O_2, and 3% Xe in He (supplied by the Linde Gas Company). The laser wavelength was λ = 10.6 μm. This type of resonator cavity structure is sensitive to the change of the radius of curvature of the cavity mirrors.

The primary function of the bending mirror (M0) is to change the direction of propagation of the beam. The beam propagated from the diamond window mirror (A4) to the bending mirror, and the output beam from M0 with a smaller incident angle into the spherical mirror M1.

The spherical focusing mirror (M1) has two main functions: (1) focusing the output beam in the unstable direction, (2) collimating the output beam in the waveguide direction.

The spatial filter (S1) is the core component of the shaping system. The side lobes of the output beam were eliminated, thus the beam quality of the unstable direction was improved.

The cylindrical mirror (M2) has two functions: (1) to compress the divergence angle, (2) to make the beam waist in the two directions equal.

The spherical mirror (M3) is used at the output beam collimation. The position of the beam waist can be adjusted by changing the radius of curvature and location of the spherical mirror.

2.2. Output beam of the cavity

The intensity distribution of the unshaped output beam from the hybrid resonator at the free space along the distance z was calculated by using the modified virtual source method and approximate analytical expressions of the rectangular waveguide [11,12]. It was assumed that on the plane of A4 (the output window of the resonator) $z = 0$. The simulation parameters are listed as follows. Along the unstable axis, the magnification ratio was $M = -1.13$, and the equivalent Fresnel number of this cavity was $N_{eq} = 673$. Other parameters are described previously. Fig. 2 illustrates the simulation and corresponding experimental results at $z = 400$ mm, and the intensity distributions in the far field that were obtained by the focus lens, respectively. As can be seen in Fig. 2, the unshaped output beam from the hybrid resonator was simply astigmatic with many high-spatial-frequency oscillations along the unstable axis. Fig. 2(a) shows the numerical simulation result at $z = 400$ mm, Fig. 2(b) shows the experimental result at $z = 400$ mm, Fig. 2(c) shows the intensity distributions of the unshaped beam at the far field that was obtained by the focus lens in the unstable direction, and Fig. 2(d) shows the intensity distributions in the direction of the waveguide.

3. Influence of thermal deformation of the cavity mirrors

The cavity mirrors considered in this section are reflector mirror A1 and output-coupling mirror A2. There are three main reasons for the thermal deformation of the cavity mirrors. Firstly, the cooling channel is parallel to the transverse direction of the mirror, with a length of 200 mm, while there is a temperature difference between the water inlet and the water outlet. Secondly, the width of body of the cavity mirror A1 is 35 mm, the width of the mirror A1 is 15 mm, the beam width which actual role on the mirror is about 1.5 mm. Thus, the power density is very high. Thirdly, the distribution of the beam intensity in the transverse direction on the mirror is non-uniform, the minimum value can be half of the maximum value, and the distribution varies with the thermal deformation of the cavity mirrors, as shown in Fig. 4(a), (d), and (g). Therefore thermal deformation occurs, and the radius of curvature (R1) of A1 and R2 of A2 are modified, resulting in a non-confocal cavity. This affects the quality of the output beam from the cavity.

3.1. Analytical method

As an example, the thermal deformation of mirror A1 was analyzed by using finite element analysis in ANSYS.

First, an entity model of mirror A1 was built in ANSYS. Then, the SOLID5 coupling cell was selected, and the material was set as copper, assuming that there was no exchange of heat between A1 and the surrounding environment. The room temperature was set as 20 °C, and the weight of A1 was ignored [13,14].

In order to simplified analyze the thermal deformation of the cavity mirrors, the effect of cooling was considered only, and the effect of the intensity distribution of the beam on the mirror was ignored. It was assumed that the intensity and distribution of the beam on A1 were uniform [15,16]. Thus, a uniform heat source was brought to A1 in