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Experimental investigation on the eliminating astigmatism in off-axis parabolic mirror ring cavity

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HIGHLIGHTS

- Off-axis parabolic mirror used to eliminating the astigmatism in folded resonator.
- Without any astigmatically compensated elements.
- Optical elements can be inserted into the off-axis parabolic mirror resonator easily.
- The low sensitivity to misalignment kept for the off-axis parabolic mirror resonator.

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ABSTRACT

The astigmatism in a ring cavity has been eliminated based on the off-axis parabolic mirror, which was utilized as the folded mirror instead of the spherical mirror in the laser resonator. There are no astigmatism-compensated elements on the beam path of the laser resonator with very simple design. The experimentally measured results have shown that the ellipticity was more than 0.98 for this kind of design. The misalignment sensitivity for the ring cavity was equivalent to that of the spherical mirror ring cavity.

1. Introduction

For the folded laser resonator, astigmatism is one of the key factors that have to be considered, especially for folded ring resonator. Of course, there is no astigmatism in a simple three-plane-mirror ring cavity, but it is very sensitive to the mirror misalignment for these all-plane-mirror laser resonators that can affect the stability of lasers dramatically, because the alignment tolerances of the plane mirror resonator is more stringent than that of the curved mirror resonator [1]. The astigmatism can be neglected with very small incident angle of spherical mirror, but it is difficult for the necessary optical elements to be inserted into laser cavity, such as unidirectional device for ring cavity, and nonlinear crystal for ordinary folded resonator.

In practice, some special requirements can be best satisfied by a folded laser resonator, which is preferable because the reflection losses can be kept much smaller, such as the very small beam waist for intracavity nonlinear frequency conversion, and ring cavity for the travelling-wave oscillator design. Such a folded resonator, because of the oblique angle of incidence of the spherical mirror center, introduces astigmatism. Astigmatic beams have different spot sizes and beam waist positions in two orthogonal directions. In highly focused resonators of this type, the adjustment of mirror spacing is critical as the cavity is stable only over a small range of values. In a highly astigmatic resonator, a condition can exist where the resonator is stable in only one direction unless steps are taken to minimize astigmatism. So, the introduction of astigmatism influences the performances of laser such as beam quality and stability zone.

For the compensation of the astigmatism, a usual method is using the Brewster-angle plate [1,2]. With lens in the resonator [3], the astigmatism can also be compensated. Utilizing ABCD matrix law, the astigmatism compensation can be achieved in only one arm of the folded resonator or in the special region of the special shaped resonator [4,5]. Of course, the astigmatism in every arm can be compensated based on the Gaussian beam transmitting theory and the special design for resonator [6]. In 2015, the astigmatism free in parabolic mirror resonator was predicted in theory [7]. In this paper, a four-mirror ring cavity consisting of two plane mirrors and two off-axis parabolic mirrors was employed to confirm the prediction.

2. Experimental setup

For the off-axis parabolic mirror, its reflective surface is equivalent

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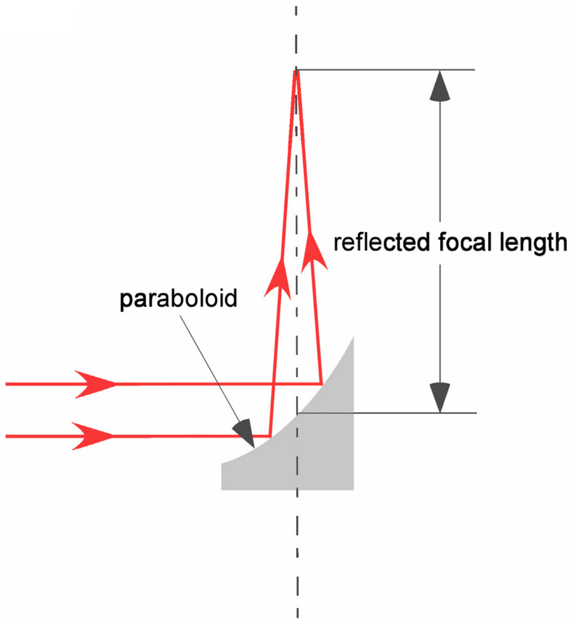

Fig. 1. Scheme of the off-axis parabolic mirror.

to segments of a parent parabolic mirror. It achromatically focuses a collimated beam or collimates a broadband point light source, and its off-axis design spatially separates the focal point from the rest of the beam path. As shown in Fig. 1, it is a scheme of the off-axis parabolic mirror. The angle between the focused beam and the collimated beam, which is called the "off-axis angle", that can be arbitrary based on all kinds of requirements, but it is 90° for this paper. Since the off-axis parabolic mirror can collimate a point source or focus a collimated beam without spherical aberration at the off-axis angle, the astigmatism can be eliminated if it can be employed in a folded resonator, or there is no astigmatism in this kind of folded resonator.

To confirm the analysis above, a diode-end-pumped single-longitudinal-mode $Nd:GdVO_4$ laser at 912 nm was employed in the experiment. The experimental setup is schematically depicted in Fig. 2a. The ring resonator was formed by two plane mirrors (M1, M4) and two off-axis parabolic mirrors (M2, M3) with 90° off-axis angle (as shown in Fig. 2a, the off-axis parabolic mirrors M2 and M3 are from Thorlabs, they are fabricated by using aluminum substrates and the diamond-turned parabolic surface has a gold coating that provides more than 96% average reflectance from 800 nm to 20 μm. The bottom of each mirror has three tapped mounting holes in a triangle pattern and an alignment hole for use with a mounting adapter.). M1 was high-reflection (HR)-coated at 912 nm ($R_{912\ nm} > 99.8\%$) and high-transmission (HT)-coated at 808 and 1064 nm ($T_{808\ nm} > 99\%$, $T_{1064\ nm} > 95\%$). M4 is an output coupler with transmission of 3%. The reflected focal length of both off-axis parabolic mirrors is 50.8 mm. The resonator length between off-axis parabolic mirrors M2 and M3 via plane mirror M4 is 190 mm. The distances from laser medium to M2 directly and to M3 via M1 are all 90 mm. The distance between M2 and M4 is 60 mm. The laser medium is an *a*-cut composite $Nd:GdVO_4$ crystal with cross section dimensions of 2.5 mm × 2.5 mm. The composite $Nd:GdVO_4$ crystal has a length of 11 mm, which consists of a 5 mm long, 0.1 at.% Nd-doped part and two 3 mm long undoped end caps. The pump source is a fiber-coupled 808 nm laser diode with a fiber core diameter of 300 μm and a numerical aperture of 0.12. Both end faces of the $Nd:GdVO_4$ crystal were antireflection (AR)-coated at 912 nm ($R_{912\ nm} < 0.2\%$) and HT-coated at 808 nm ($T_{808\ nm} > 99\%$) and 1064 nm ($T_{1064\ nm} > 95\%$). The whole $Nd:GdVO_4$ crystal was tightly wrapped with indium foil for reliable heat transfer and mounted in a copper block, which was temperature-controlled by a temperature controller with an accuracy of 0.01 °C, and the temperature of the $Nd:GdVO_4$

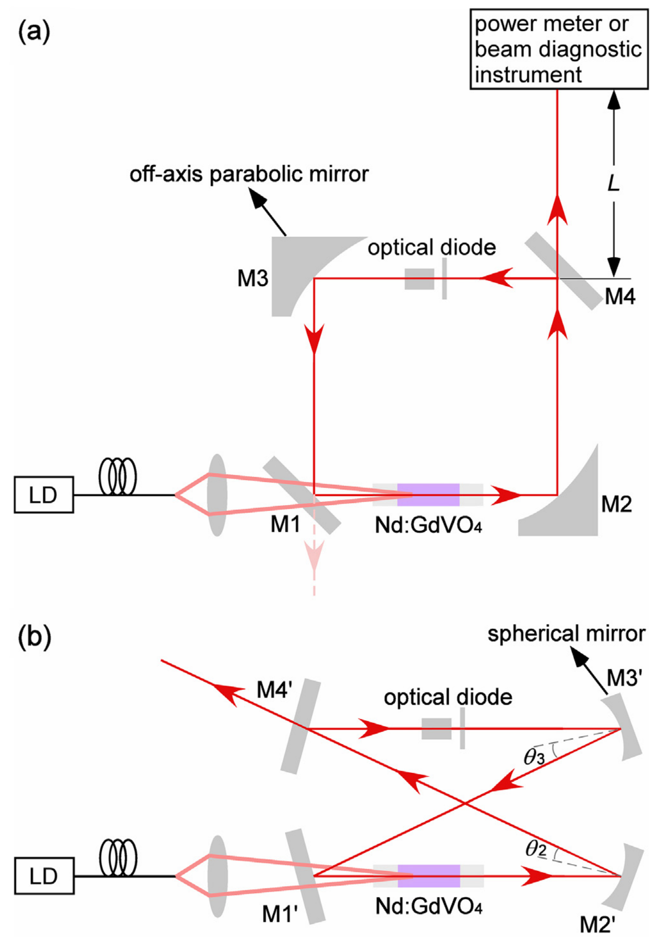

Fig. 2. Schematic of single-longitudinal-mode laser. (a): off-axis parabolic mirror ring resonator; (b): the equivalent spherical mirror ring resonator.

crystal was controlled at 20 °C in the experiment. To obtain the single-longitudinal-mode operation laser, an optical diode was used in the resonator to constrain the laser beam to be unidirectional-propagating, which eliminates the spatial-hole-burning effect within the active medium. The optical diode was formed by a half-wave plate and a magneto-optical crystal located within a magnetic field. Obviously, it is very easy for the optical diode to be inserted into the cavity for the special design because of the 90° angles between incident beams and reflected beams. The output laser could be measured by the power meter or the beam diagnostic instrument (CCD camera) at a distance *L* from the output coupler.

The equivalent spherical mirror folded ring resonator is shown in Fig. 2b. Similarly, it was formed by two plane mirrors (M1′, M4′) and two spherical mirrors M2′ and M3′ with the identical cavity lengths. Of course, the pump source and laser medium were the same to that in the off-axis parabolic mirror ring resonator. M1′ was HR-coated at 912 nm ($R_{912\ nm} > 99.8\%$) and HT-coated at 808 and 1064 nm ($T_{808\ nm} > 99\%$, $T_{1064\ nm} > 95\%$), with the coating incident angle of 0° that is different from M1, in which the incident angle is 45°. Both M2′ and M3′ are plano-concave mirrors with HR-coating at 912 nm ($R_{912\ nm} > 99.8\%$). The radius of both M2′ and M3′ is 100 mm. M4′ is an output coupler that is equivalent to M4. θ_2 and θ_3 are the incident angle of spherical mirrors M2′ and M3′, respectively. The θ_2 and θ_3 should be kept as same as possible, and both of them were 10° in the experiment. Obviously, the astigmatism exists in this kind of ring resonator design.