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Adaptive, high-power, dynamically stable ring resonator

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ABSTRACT

Dynamically stable resonators have a stationary TEM00 beam waist inside the laser rod (w_{30}), which is minimal throughout the stability interval and insensitive to changes in pump power. For a given set of resonator parameters (mirror radii and distances between mirrors and rods), the stability interval parameters, which are the limits of the stability interval in terms of the rod's thermally induced focusing length are determined. In linear resonators, these stability interval parameters cannot be changed independently only by varying resonator distances, and mirrors of different curvature have to be employed. However, our group showed recently that for a symmetric ring resonator containing a pair of curved mirrors, the width of stability interval and the stability interval limit at maximum rod's focal length can be adjusted continuously and independently only by varying resonator distances once the mirror radius of curvature has been fixed. In this work we demonstrate a project of an adaptive ring resonator that allows the TEM00 -mode resonator to be continuously tuned throughout the whole range of pump powers utilizing standard electromechanics to move the mirrors. Additionally for a given value of pump power, w30 can be varied, thus allowing different beam qualities to be obtained from the same resonator.

Keywords: Dynamic stable resonators, ring lasers

1. INTRODUCTION

1.1 Dynamically stable ring resonator with a pair of curved mirrors

Silvestri et al demonstrated that a ring resonator has a single stability interval which is double the width regarding linear resonators and he presented expressions for a generic ring resonator containing one focusing rod [1]. The particular case of a symmetric ring resonator containing a pair of curved mirrors is shown in Figure 1 [2]. The resonator is characterized by the mirror curvature R and two distances *a* and *b*, with *a* being the distance between the focusing rod's principal planes and the curved mirrors and *b* being the complimentary travel distance (see Fig. 1). It is important to note that the resonator depicted in Fig. 1 is only one possible configuration. Also, only the resonator distances *a* and *b* are necessary for this characterization.

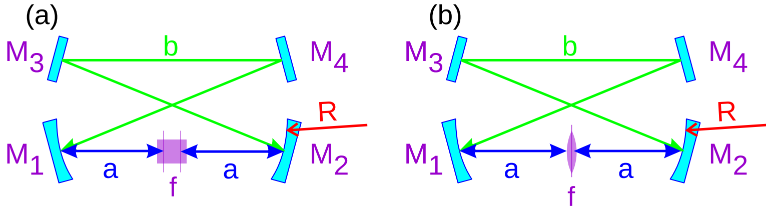

Figure 1. Scheme showing distances *a* and *b*.

The above-mentioned resonator has interesting characteristics regarding its stability interval. Distances *a* and *b* determine independently the position and width of the stability interval, respectively, as denoted by these simple expressions [2]:

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$$f_{\max} = \frac{2a - R}{4} \tag{1}$$

$$\Delta f = \frac{R^2}{4(b - R)} \tag{2}$$

where *fmax* thermal lens at maximum pump power and *Δf* is the width of the stability interval. Similar expressions for a resonator containing two focusing rods positioned closely to each other by a distance *d* between the rod's principal planes, that is d<< fmax, d<<fmin, are given by:

$$f_{\max} = a - \frac{R}{2} \tag{3}$$

$$\Delta f = \frac{R^2}{2(b - R)} \tag{4}$$

The fact that the position and the width of the stability interval may be independently adjusted by means of the distances *a* and *b* for a given value of *R* allows for the construction of adaptive resonators using electro mechanic components to set distances *a* and *b* as function of the necessary working conditions. In this work we present the design of a ring resonator that maintains the width of the stability interval in terms of dioptric power and thus maintains the same beam waist at the rod (w_{30}), and consequently the same beam quality, for a wide range of pump powers.

2. DESIGN PROCEDURE

2.1 Changing pump power while keeping the same beam quality

As pump power is changed, the rod's thermally induced focusing length changes non-linearly. To keep the beam waist constant during this change, the stability interval must have the same width as the pump power change in terms of dioptric power Δ(1/f). The stationary beam waist, which is in the middle of stability interval in terms of dioptric power. The limits of the stability interval in terms of the rod's focusing distance can be easily obtained and they are:

$$f_{\max} = \frac{2}{2/f - \Delta\left(1/f\right)} \tag{5}$$

$$f_{\min} = \frac{2}{2/f + \Delta\left(1/f\right)} \tag{6}$$

$$\Delta f = \frac{\Delta\left(1/f\right)}{\left(1/f\right)^2 - \left[\frac{1}{2}\Delta\left(1/f\right)\right]^2} \tag{7}$$

To obtain the corresponding *a* and *b* values, eq. (5) and eq.(7) are substituted in eq (1) and eq.(2), respectively, for a resonator with a single focusing rod or in eq.(3) and eq. (4), respectively, for a resonator with two rods. For our design we considered the case with two focusing rods. The expressions for distances a and b are:

$$a = \frac{R}{2} + \frac{2f}{f - f.\Delta\left(\frac{1}{f}\right)} \tag{8}$$

$$b = R + \frac{R^2\left\{\left(\frac{1}{f}\right)^2 - \left[\frac{\Delta(1/f)}{2}\right]^2\right\}}{2.\Delta(1/f)} \tag{9}$$

The thermal lens of the modules was measured by passing a collimated He-Ne laser while the module was pumped [3]. Results are shown on Fig.2

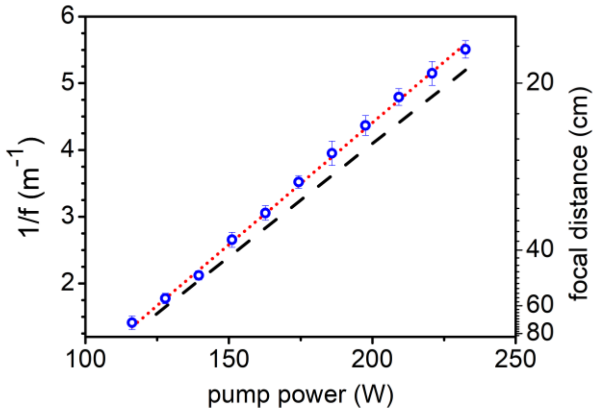

Figure 2. Measured dioptric power and corresponding focal length of thermal lens for the laser module. Points: measured values; red dotted line: linear adjust; dashed line: expected value when lasing.

To choose the best mirror radii, maximum and minimum values of expressions (8) and (9) for the possible *f* values were plotted to check feasibility. Results are shown on Fig. 3. For this plot *f* values are in the range of 21 cm (focusing length at maximum pump power) and 700 cm. The 700 cm limit was chosen because distance *a* goes to unacceptable high values above this limit. In the below graphic the maximum and minimum values of *a* and *b* (occurring at the *f* = 700 cm and *f* = 21 cm limits) are plot for different values of mirror curvature radius between -1000 mm and 1000 mm. *a* and *b* values are smaller for negative radii however, both, a and b assume negative values thus not allowing the use of negative curvature mirrors. For positive mirrors, it can be seen that the maximum value of distance *a* grows as radius of curvature increases. For R close to zero, *a* assumes smaller values allowing the construction of more compact resonators however, distance *b* assumes very small values that are not feasible for assembly. The chosen mirror radius was 200 mm with distance *a* ranging from 33.9 cm to 128.7 cm and *b* ranging from 22.9 cm and 58.1 cm.

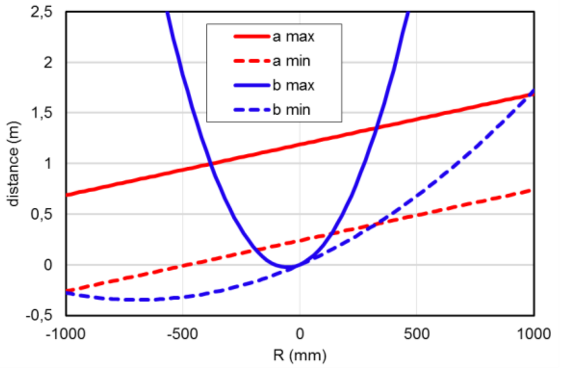

Figure 3. Calculated maximum and minimum distances *a* and *b* for (21 cm < f < 700 cm) for different mirror radii of curvature.

Next, the curves of distances *a* and *b* as *f* changes were plotted in Fig. 4. The distance *a* forces the resonator to assume larger values for smaller focusing powers. The resonator length L' = 2a+b assumes a maximum value of 3.42 m.

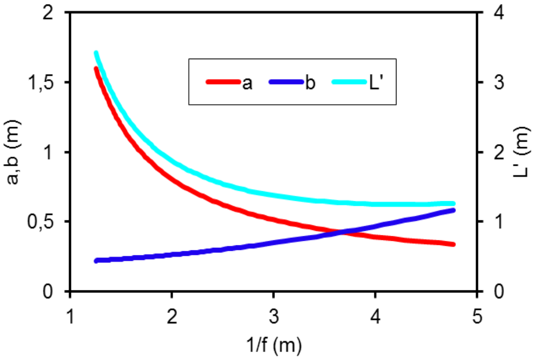

Figure 4. Scheme showing distances a and b and resonator length L' as rod's focal length is varied.

2.2 Change beam quality while keeping the same pump power

Another feature of the adaptive resonator is the capability of changing the stability interval width and consequently the stationary beam waist and, therefore, beam quality by changing resonator distances, which is done by means of changing $\Delta(1/f)$ in eq. (8) and eq. (9). The results are plotted in Fig. 5 where the corresponding distances *a* and *b* as well as resonator length L' are plotted as a function of the stationary beam waist w_{30} at different pump powers, whose equivalent rod's focusing length are 21 cm (a), 45 cm (b) and 70 cm (c). In fig. 5 (a) it can be seen that stationary waists in the range of 300 µm to 1200 µm can be obtained at maximum pump power for a distance *a* < 1.5 m. In Fig. 5 (b) and Fig. 5 (c) it can be seen that the minimum achievable beam waist is limited to approximately 490 µm and 705 µm for a distance *a* < 1,5 m at f = 45 cm (b) and f = 70 cm (c), respectively.

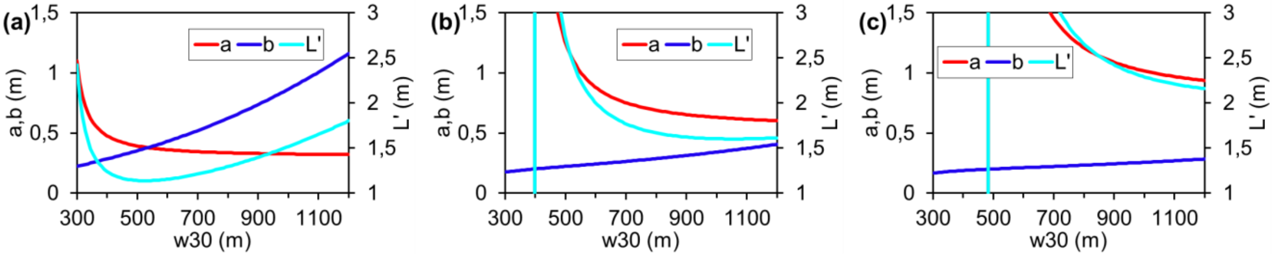

Figure 5. Scheme showing distances a and b and resonator length L' as rod's focal length is varied at maximum pump power. (a) f = 21 cm; (b) f = 45 cm; (c) f = 70 cm

2.3 Resonator design

The resonator uses transversally diode pumped modules with 225 W of optical pump power at 808 nm. The modules contain a Ø 3 mm x 78 mm Nd:YAG rod doped with 0.6 at.% Nd. Resonator design consists in a rectangle with 45° incidence mirrors. The use of intracavity lenses instead curved mirrors allows for translation with normal incidence. The lenses are mounted on a travelling stage to control distance *b*. The laser modules with two mirrors with 45 incidence angle are fixed to another translation stage to control distance *a*. Both travelling stages move along a linear guide and are moved by fuses attached to stepper motors. A thin-film polarizer with 45° incidence is utilized for obtaining a linearly polarized output and by utilizing this polarizer it is possible to select radial and tangential thermally induced lens components closer to each other as demonstrated in reference [4]. A feedback mirror is utilized to allow unidirectional output The position of the output coupler corresponds to the position of the image of the waist of the beam and thus there is always a plane wavefront on it, allowing for the required changes in distances a and b (the waist is always located at the same position). The resonator scheme is shown on Fig. 6.

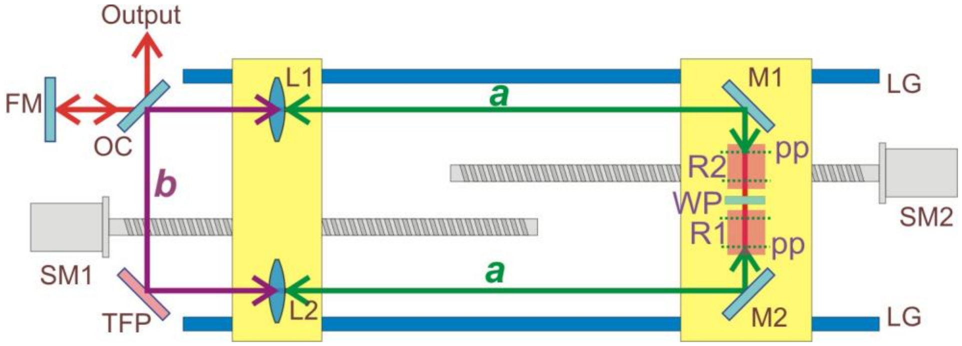

Figure 6. Scheme of the adaptive resonator. R1, R2: Nd:YAG laser rods; pp: principal planes of the laser rod; L1, L2 intracavity lenses; M1, M2: flat HR mirrors; OC: Output coupler; TFP: Thin-film polarizer; FB: feedback mirror; WP: half wave plate; LG: Linear guides; SM1 and SM2:stepper motors attached to fuses to control resonator distances *a* and *b*.

3. DISCUSSION

The concept of mode-filling, in which the objective is to increase spatial overlap with the population inversion (and therefore efficiency) and at the same time to increase the beam quality can be effectively applied to standing resonators that use diode-pumped rod modules [5,6]. It also can be very effectively employed in diode-side pumped slab configurations [7,8], where the highest reported efficiencies for neodymium lasers have been achieved [9,10], using fluoride and vanadate hosts [11,12], while maintain almost diffraction limited laser output.

4. CONCLUSIONS

The use of ring resonator with a pair of curved mirrors allows the positioning of the stability interval by changing only distances. Based on this we demonstrate the possibility of building an adaptive resonator utilizing diode side pumped laser modules. The resonator has the possibility of keeping the same beam waist size while changing the thermally induced lens in the range of 70 cm to 21 cm focal length. Additionally, the beam quality can be chosen by changing the stability interval width and, therefore, stationary beam waist from 300 µm to 1200 µm operating always at maximum pump power.

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