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Numerical analysis of non-confocal configurations of a hybrid stable–unstable resonator

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ABSTRACT

The results of numerical simulations are reported modeling the behavior of a unidimensional Hybrid Stable–Unstable Resonator (HSUR) in strongly non-confocal configurations. Our analysis shows that such a resonator setup can produce cavity losses consistent with our design requirements and extract a Beam with Propagation Parameter better than 3 mm mrad.

1. Introduction

Hybrid Stable–Unstable Resonators (HSUR) have been largely used for thin and wide (slab-type) laser active media. Bourne and Dyer [1], in 1979, firstly adopted a spherical concave mirror and a cylindrical convex one, in combination with a rare gas halide slab active medium. Successively several gas [2] and solid state [3] lasers with slab shaped gain regions have been realized applying confocal HSURs. Confocal configurations either of the positive- or negative-branch types were experimentally tested as well as numerically analyzed in [4] and [5].

Nevertheless, when designing a laser, there are situations in which the use of a non-confocal configuration might be more desirable. This was for example the case of a recent work [6] of ours in which we experimentally investigated the adoption of a HSUR on a Nd:YAG slab with zig-zag internal propagation in the narrow cross-section transverse direction. In our case the stable transverse direction required a relatively short mirror radius of curvature (ROC). Indeed a zig-zag propagation in the active medium would have made the operation with longer mirror ROC too sensitive to misalignments in the stable transverse direction. The obvious advantage in the use of a simple concave spherical mirror and a cylindrical convex scraping one, brought us to the adoption of a definitely non-confocal configuration for the unstable transverse direction. Naturally this might be the case in many other situations, as for example when suitable optics are not available, or when thermal lens effects may bring out of the confocal configuration at certain power loading regimes. In 1995 Chandra et al. [7] adopted a non-confocal unstable resonator in a solid-state dye laser based on a gradient-reflectivity mirror (GRM). In their case, building a confocal resonator with the same cavity length and magnification, would have required a very short ROC GRM which is quite difficult to fabricate.

It is worth noting, that there is very little information in the literature about the structure of "modes" extracted from unstable resonators that do not have a simple "canonical" configuration. In this paper we show the results of a numerical analysis based on diffractive propagation algorithms performed to determine the expected cavity losses and extracted beam properties when adopting a non-confocal HSUR setup. Our analysis demonstrates that strongly non-confocal configurations can produce suitable values of resonator out-coupling coefficient with a good quality beam extraction, generously widening the acceptable range of design parameters such as mirror ROCs, cavity length and mirror tilts.

2. Numerical analysis method

Given the symmetry of the problem and the polarization selecting cavity we can simply consider the field distribution in our resonator to be scalar and separable into two x- and y-dependent complex amplitude functions. In ref. [6] we already demonstrated that the beam profile in the y-transverse direction, i.e. the direction parallel to the narrow cross-section of the YAG slab, is correctly described by a superposition of a limited (<8) number of low order Gaussian modes. This is a consequence of the HSUR producing a stable resonator configuration with a low Fresnel number in this transverse direction. The M_y^2 values reported in [6] are consistent with this modal analysis.

Our present study will be focused on the amplitude and phase x-dependent distributions in the lateral direction parallel to the larger

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cross-section of the YAG slab in which the HSUR determines an unstable resonator geometry. The analysis is performed by means of a numerical code based on Fresnel diffraction integral propagation algorithms in an iterative "Fox and Li" approach [4]. Referring to the experiments of ref. [6] we adopt in this numerical analysis a wavelength of 1.064 µm. With the purpose of understanding the viability of strongly non-confocal configurations we neglect the effects of the presence of a gain medium with the saturation and thermal lens effect that it generally produces. This assumption has various motivations. First of all it has been shown [8,9] that the general character of "loaded resonator" modes is very little changed from that of "bare resonator" ones, the main difference being the reduced amplitude of higher peaks. Secondly the cold cavity represents the simplest and most general model of the optical system, to which corrections such as thermal lens may be added as additional optical elements. Finally, our zig-zag face-pumped system proved to be scarcely affected by internal lens effects [10].

Our numerical algorithm reconstructs the resonator mode successively simulating the effect of mirror curvature, tilt (phase corrections) and apertures (amplitude truncations), and the effect of diffraction, applying an FFT based convolution with the impulse response function of e.m. propagation in the Fresnel approximation [4]:

$$u(x,L) = h(x,L)\otimes u(x,0) \tag{1}$$

where

$$h(x,z) = \frac{\exp(jkz)}{(jkz)^{1/2}}\exp\left(j\frac{kx^2}{2z}\right) \tag{2}$$

is the propagation impulse response function, and u(x,z) is the x-dependent complex field distribution after a z distance propagation.

With a plane wave as the initial condition, resonator round trips are repeated up to the convergence of the "eigen-value" defined as the ratio between the amplitudes of two successive self-similar distributions. An eigen-value is considered to have reached convergence when its recursive calculation determines relative variations of less than 10^{-4}. A set of more than one hundred different initial conditions was actually tested in a number of resonator configurations in order to be sure that the procedure converges towards the lowest loss spatial distribution. In Fig. 1 the typical outputs of our code are shown proving the correct reconstruction of "geometrical" and "diffractive" properties of the intracavity field distributions. These outputs refer to the confocal resonator configuration, schematically depicted on the upper right corner. The mirror ROCs adopted in all the numerics presented in this paper are those of the optical setup of ref. [6]. Namely R1 = −1000 mm (diverging cylindrical) and R2 = 1250 mm (converging spherical). As a consequence the confocal cavity length is 125 mm. Our active medium slab has a 10 mm wide larger cross-section and the output aperture turns out to be 2 mm in the one-sided HSUR confocal configuration.

In the resonator scheme two planes, P1 and P2, are evidenced on which we characterize four different intracavity field distributions. Intensity and phase distributions plotted in bold and blue, are related to the field number one, that is coupled out of the resonator. The phase distributions plotted in the lower part of the figure clearly show how the recursive code correctly reconstructs the wavefront curvature. Left-propagating wavefronts (with respect to the resonator scheme in the figure) are flat, indicating a collimated beam. As in previous numerical analysis [4,5] the intensity distributions present deep ripples caused by the diffraction from mirror hard edges.

A similar analysis has been performed for various resonator configurations. Fig. 2 shows an example of non-confocal resonator distributions. These distributions correspond to a cavity length of 225 mm, close to the value of the resonator adopted in [6]. As in Fig. 1 the bold and blue profiles refer to the field from which the resonator extracts the output beam. Different from the case of the confocal resonator, the left-propagating fields (1 and 4) do not have a flat wavefront but a concave one indicating a converging beam. Correspondingly, the intensity distribution on the out-coupling mirror (top-left corner of the figure) doesn't extend in the whole 10 mm wide resonator cross-section, unless some tilt is given to the mirror alignment. Thus the extracted beam turns out to have a much thinner cross-section. In the following paragraph we present the results of a detailed analysis of non-confocal configurations performed varying two resonator parameters: the cavity length and the tilt of the rear mirror.

3. Field distributions and cavity losses in non-confocal configurations

In Fig. 3 we show some typical intensity and phase distributions on the resonator output plane for strongly non-confocal configurations.

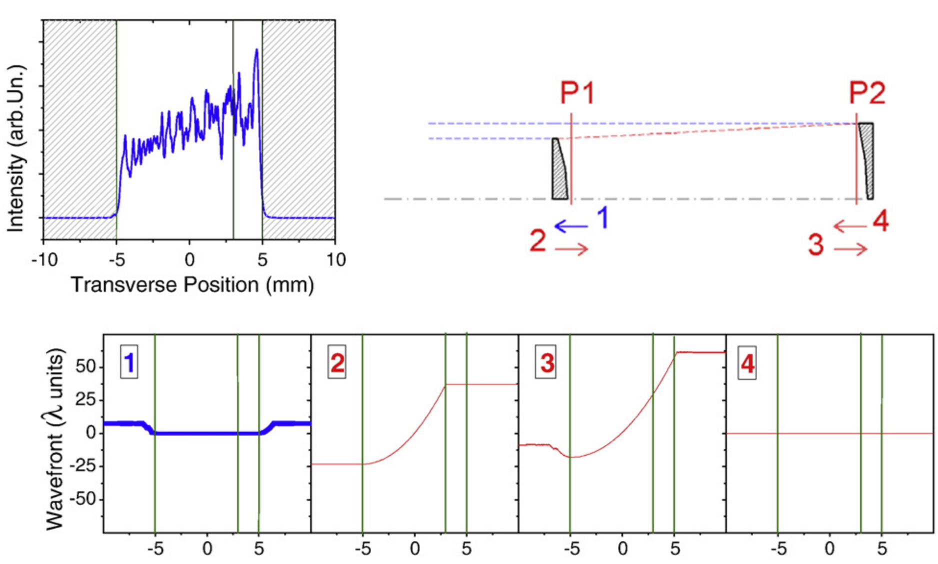

Fig. 1. Top-left: Intensity distribution of the left-propagating field on plane P1. Top-right: Confocal HSUR scheme. Bottom: Wavefront (field phase distribution) of the 1-2-3-4 beams propagating in the resonator as specified by the arrows in the scheme. The output wavefront (1) is plotted in bold and blue.