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High beam quality in a HyBrID copper laser operating with an unstable resonator made of a concave mirror and a plano-convex BK7 lens

Madalena Alice Priante Gião[a], Walter Miyakawa[b,c], Nicolau André Silveira Rodrigues[b,*], Denise Maria Zezell[c], Rudimar Riva[b], Marcelo Geraldo Destro[b], Jaime Tsutomu Watanuki[b], Carlos Schwab[b]

[a]*Instituto Tecnológico de Aeronáutica, Centro Técnico Aeroespacial, São José dos Campos, São Paulo, Brazil*
[b]*Divisão de Fotônica, Instituto de Estudos Avançados, Centro Técnico Aeroespacia, 970 São José dos Campos, Caixa 604412-231, São Paulo, Brazil*
[c]*Centro de Lasers e Aplicações, Instituto de Pesquisas Energéticas e Nucleares, Trav. R. 400, Cidade Universitária, São Paulo, Brazil*

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Abstract

This paper presents a very simple unstable resonator, made of a concave mirror (total reflector) and a bare plane–convex BK7 lens working as a convex coupling mirror, which is quite efficient for HyBrID copper laser. In addition to a good quality factor ($M^2 = 4.9$), experimental results showed that it is possible to control the laser output power by introducing a variable aperture iris inside the cavity, close to the coupling lens, without spoiling beam quality. A rough theoretical model helped to explain these results as a combined effect of unstable resonator plus radial gain distribution.

Keywords: Laser beam quality; Unstable resonator; HyBrID copper laser

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1. Introduction

Beam quality is an extremely important issue in most laser applications because power and/or energy density usually are the parameters that must be controlled. In fact, since the advent of the laser in the 1960s, great effort has been made in studying, testing and developing laser resonators and in exploring gain medium characteristics aiming to improve beam characteristics.

An extensive discussion on laser resonators can be found in Refs. [1,2]. As a general rule, unstable resonators are suitable for lasers with high small signal gain and large transversal areas, like the copper lasers (copper vapour, copper salt or HyBrID copper laser) [3]. However, conventional unstable resonators introduce the so-called hard-edge effect: due to diffraction on the edge of mirrors and/or holes, a fraction of the output beam can be subtracted and the beam quality is somewhat deteriorated. In the particular case of HyBrID copper lasers, the gain profile has a bell-shaped radial distribution, i.e., the gain is maximum in the centre and diminishes as the radius increases [4]. Consequently, the deleterious effect of conventional unstable resonators is accentuated since the fraction of the beam that is subtracted is in the centre of the laser beam, where the intensity has its maximum. Coupling mirrors with variable (super-gaussian) reflectivity can avoid these hard edge effects. However, they are difficult to manufacture or obtain.

Barker and Loree [5] successfully used an extremely simple unstable resonator, made of a concave mirror and an ordinary uncoated plano-convex lens, in order to improve the beam quality of an excimer laser. This

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[*] Corresponding author.
E-mail address: nicolau@ieav.cta.br (N.A.S. Rodrigues).

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paper presents the results of tests of this kind of resonator with a HyBrID copper laser. Besides the resonator, an intracavity variable aperture iris is introduced close to the coupling mirror (lens) allowing the output power to be controlled. The M^2 quality factor is measured for different iris apertures and it is verified that the beam quality is not significantly spoiled. A numerical model based on Fresnell–Kirchhoff equations is used to analyse qualitatively the behaviour of this resonator.

2. Experimental set-up

Fig. 1 shows the schematic diagram of the experimental set-up used in this work. The unstable laser resonator is 1.47 m long and constituted of a total concave reflector (2.99 m curvature radius) and an uncoated convex–plane BK-7 lens (152 mm of focal length, or about 75 mm curvature radius). A variable aperture iris (3) was used to control the laser power and a convergent lens (6), to collimate the beam. The optical filter (7) reflects the yellow (578 nm) and transmits only the green (510 nm) emission. A CCD camera was attached to the laser beam sampler (LBS-100, Spiricon, UT, USA), which in turn was connected to a laser beam analyser (LBA-100, Spiricon, UT, USA). In order to avoid damages to the CCD sensor, only the reflected beam from the two quartz prisms was allowed to reach the camera. Neutral density optical filters were placed inside the sampler, in front of the camera, in order to control the light level on it.

Using the LBA-100 facilities, the spatial profile and the beam diameter for several positions along the ruler (item 10 in Fig. 1) were obtained and directly recorded into a floppy disk. Each diameter data corresponds, in fact, to the mean value taken over 50 measurements.

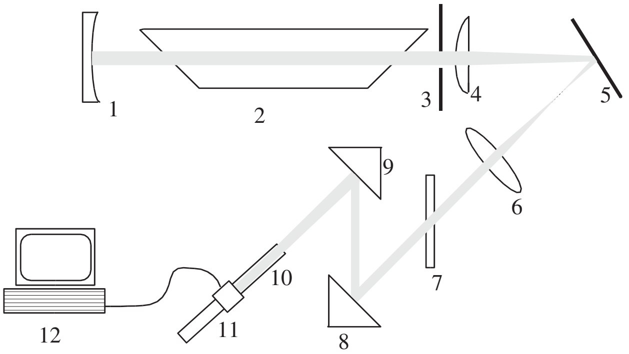

Fig. 1. Schematic diagram of the experimental set-up: (1) resonator concave total reflector (2.99 m curvature radius), (2) laser discharge tube, (3) variable aperture iris, (4) resonator coupling mirror (convex-plane, $f = 152$ mm, uncoated BK7 lens), (5) plane mirror, (6) $f = 250$ mm convergent lens, (7) optical filter, (8) and (9) quartz prisms, (10) ruler, (11) LBS-100 laser beam sampler and (12) LBA-100 laser beam analyser.

From the experimental data, the curve of the square beam radius versus z position was fitted to the second-degree polynomial that describes the propagation of high-order beams [6]

$$W^2(z) = W_0^2 + \theta^2(z - z_0)^2, \quad (1)$$

where $W(z)$ is the beam radius, z_0 is the position of the beam waist W_0, $\theta = M^2\lambda/(\pi W_0)$ is the far-field beam divergence and M^2 is the beam quality factor. The laser beam parameters were then calculated from this fitting and the procedure was repeated to the six iris apertures shown in Table 1.

By inserting an aluminium foil screen in the optical path after the first prism, the temporal characterization was also made. The beam scattered by this aluminium foil was detected by a photodiode (040-B, EGG) detector and the signal was sent to an oscilloscope (TDS 450A, Tektronics).

3. Results and discussions

Fig. 2 shows the experimental data (squares) and fitted (dashed) curves of the squared beam radius $W(z)^2$, for the iris widely open, together with the fitted M^2, W_0

Table 1
Iris aperture in millimeters and respective total (green + yellow) laser average output power in watts

	Diameter (mm)	Power (W)
P1	Totally open	6.7
P2	11.8	6.1
P3	10.3	5.0
P4	8.8	4.5
P5	7.5	4.0
P6	6.5	3.0

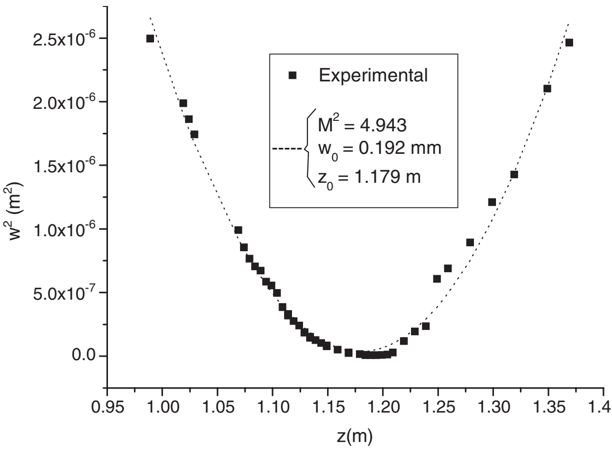

Fig. 2. Experimental data (squares) and fitted curves (dashed) of W^2 versus z position, according to Eq. (1), for the iris totally open. The same measurements were made with apertures of 11.8, 10.3, 8.8, 7.5 and 6.5 mm.

and z_0 parameters. Firstly, some discrepancy is observed when comparing experimental and fitted curves, probably due to the combination of two factors: the reduction in beam intensity produced by the iris diameter reduction (consequently, decreasing the CCD accuracy [7]) and the poor reproducibility in the iris aperture. The same experiment was repeated for every aperture given in Table 1.

In Fig. 3 the measured M^2 against iris aperture is plotted. The M^2 quality factor obtained for totally open iris was 4.9 and, roughly speaking, M^2 decreases as the iris aperture diminishes, with a peak for an iris diameter of about 8.5 mm. It is reasonable, since the iris works as a spatial filter inside the cavity; the iris eliminates the edge modes and favours the lower order ones. This behaviour was understood as follows. For very large iris aperture, the mode formation has two main contributions: the gain distribution and the ASE. While the iris diameter is decreased, the ASE is filtered out and the beam quality is improved, until the iris diameter equals the gain distribution diameter. At this point the laser mode is determined by the radial gain distribution and has a bell-shape. If the iris diameter decreases, the bell-shaped mode will be truncated, spoiling the beam quality, with an increase in the M^2 factor. For iris diameter much smaller than the gain region diameter, the coupled beam will have a diffraction pattern equivalent to a uniformly illuminated circular aperture and the M^2 decreases (the spatial coherence increases) as the iris diameter decreases. Thus, to our understanding, this explains the M^2 peak for the iris diameter of about 8.5 mm. This behaviour is still being numerically studied and the detailed results will be opportunely presented.

Another interesting behaviour, shown in Fig. 4, is that the beam waist W_0 after the lens does not change considerably with iris aperture, within a fluctuation of about 10%. This behaviour is very interesting in experiments because, once W_0 after the lens is determined for one of the experimental conditions, the intensity will be proportional to the total laser power. Thus, only the laser total power must be monitored during experiments.

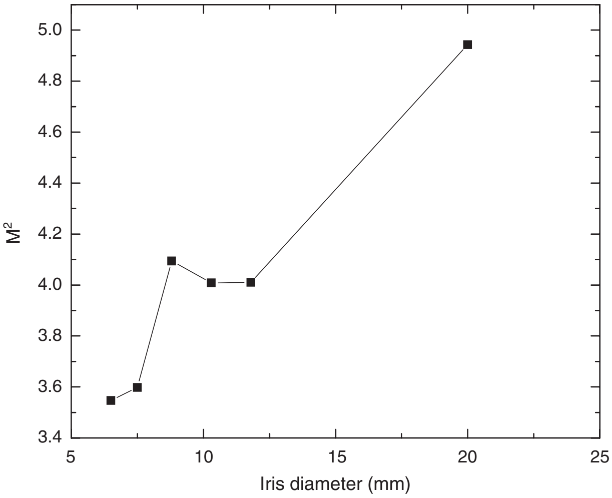

Fig. 3. M^2 versus iris diameter. For the widely open iris, the inner discharge tube diameter (20 mm) was taken.

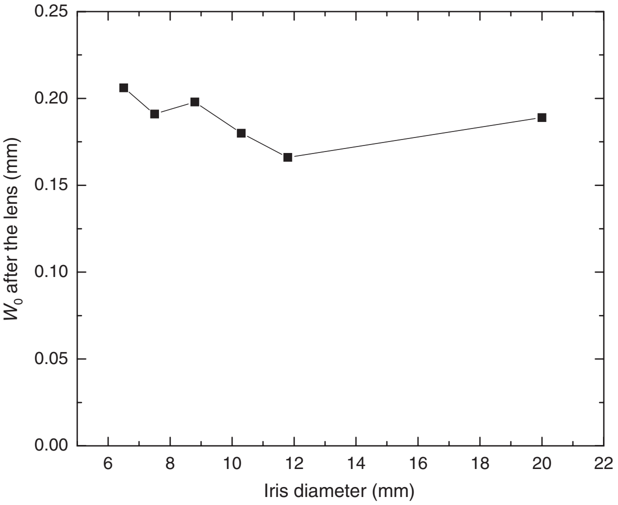

Fig. 4. W_0 against iris aperture. It is interesting to observe that although the iris aperture varied by a factor of about 3, the spot size after the lens did not change considerably.

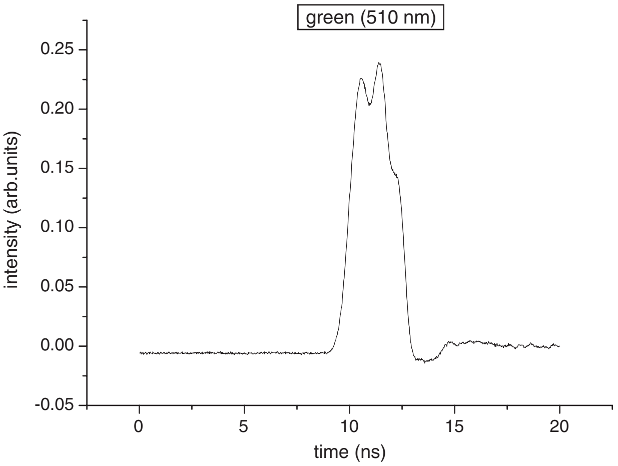

Fig. 5. Pulse temporal profile of the Cu–HBr laser for the green line.

The temporal laser beam profile for the green line is displayed in Fig. 5. Since the resonator is 1.47 m long, the laser pulse is built during 2 or 3 round trips, and hence it is very mode-selective because, with only a few round trips, it is possible to have a beam with M^2 lower than 5. This cannot be explained by considering only the resonator geometry; it is necessary to consider the active medium geometry and the radial gain distribution.

4. Qualitative analysis

A numerical simulation was performed in order to analyse qualitatively the experimental results. The one-dimensional Fox and Li procedure [8] was applied to the resonator configuration, except that only few round trips were calculated, instead of repeating the calculation until the field pattern converges to one of the resonator modes. The equivalent sequence of lenses and apertures is shown in Fig. 6.

The optical field propagation between mirrors is calculated by using the one-dimensional Fresnell–Kirchhoff equation, given by [9]

$$u(x) = \frac{\exp[\mathrm{i}(kz - \pi/4)]}{\sqrt{\lambda L}} \int_{-\infty}^{\infty} u(x_0) \times \exp\left[\frac{\mathrm{i}k(x - x_0)^2}{2L}\right] \mathrm{d}x_0, \tag{2}$$

where $u(x_0)$ is the input field, $u(x)$ is the propagated field, $k = 2\pi/\lambda$ is the propagation constant and λ is the wavelength. This expression was calculated by using the convolution theorem together with fast fourier transform (FFT) routines, in order to speed up computer calculation. The effect of the lenses and apertures over the field is given by the relation

$$u(x) = \begin{cases} u(x_0)\exp\left(\dfrac{-\mathrm{i}kx_0^2}{2f_i}\right) & \text{for } x_0 \text{ inside aperture,} \\ 0 & \text{for } x_0 \text{ outside aperture,} \end{cases} \tag{3}$$

where $u(x_0)$ is the input field, $u(x)$ is the field after the equivalent lens (after reflection on the mirror) and f_i is the focal length for the ith lens (mirror).

The process was considered to begin near the coupling mirror and the input optical field was simulated by a random distribution of amplitude and phase, in order to simulate the random spontaneous emission. The input field is reflected by the coupling mirror, propagates until the concave mirror, reflects, and propagates back to the coupling mirror, completing one round trip. After every round trip the beam quality M^2 was calculated and plotted against the number of round trips. The M^2 calculation is performed as follows.

Since the field profile $u(x)$ is known, the intensity profile is determined by doing $I(x) \propto |u(x)|^2$ and then the beam radius can be calculated by using the second moment method [6]. One calculates the beam radius w just before it strikes the coupling mirror; after that, the effect of the lens (coupling mirror) on the beam after it is coupled out is calculated; the propagation until the focal plan is calculated and finally the beam radius w_0 at the focal plane is calculated. The beam quality factor is then given by [6]

$$M^2 = \frac{\pi w_0 w}{\lambda f}. \tag{4}$$

The HyBrID-Cu laser has a bell-shaped radial gain distribution, with a very high small signal gain on the axis of the active medium. In order to qualitatively describe the contribution of this gain distribution on the mode formation, it was considered a parabolic reflectivity on the coupling mirror surface, with the maximum at the centre and vanishing for a 12 mm radius. So, it was considered that the very high gain, with the bell-shaped distribution acts in the mode formation as a resonator with variable reflectivity mirror [10].

Fig. 7 shows the calculated M^2 against the number of round trips for four different situations: (a) an empty unstable resonator, according to the equivalent sequence of lenses and apertures shown in Fig. 6; (b) the same resonator plus a 12 mm iris; (c) a plane-parallel resonator with the parabolic reflectivity on the coupling mirror and (d) the unstable resonator plus the parabolic

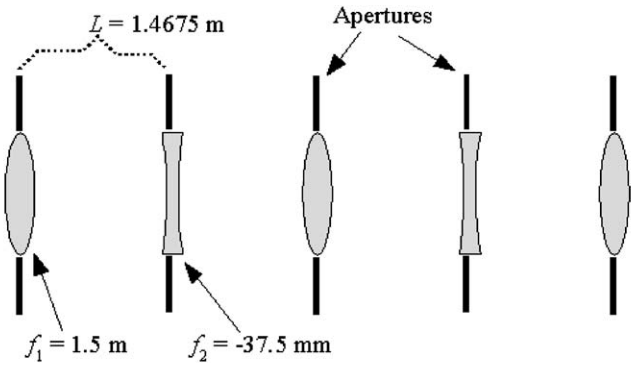

Fig. 6. Equivalent sequence of lenses and apertures for the calculated resonator. It was considered a confocal negative branch unstable resonator with a 3 m curvature radius concave mirror and a 75 mm curvature radius convex mirror. The aperture for both mirrors is 20 mm.

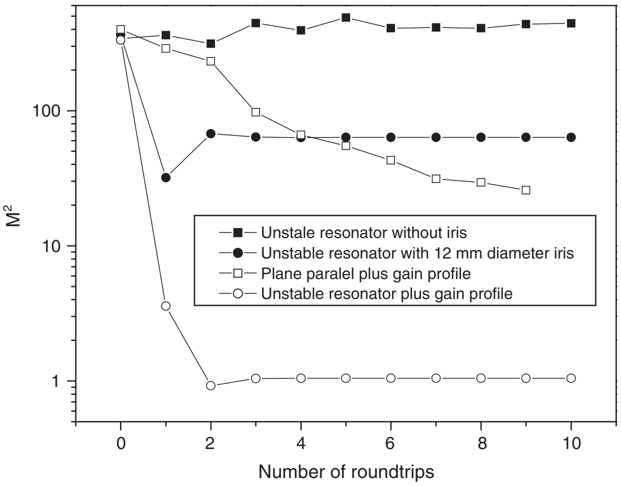

Fig. 7. Calculated M^2 against number of round trips considering: (a) an ordinary unstable resonator, (b) the same resonator plus a 12 mm intracavity iris, (c) plane-parallel resonator plus the gain profile and (d) the same resonator as in (b) plus the gain profile.

reflectivity coupling mirror. In the first situation only the empty resonator was considered and it can be seen that, at least in the 10 first round trips, the beam quality remains in the order of 300. In the second situation, the beam was confined to the gain region (of about 12 mm diameter), or rather, it was considered that the gain works as an iris, constraining the laser beam by gain (instead of by losses, in the case of an ordinary iris). In this situation the M^2 drops down to about 60 in just one round trip and remains at this level. In the third case a plane-parallel resonator plus the parabolic reflectivity in the coupling mirror was considered, and it is verified that the gain distribution alone cannot explain the good quality obtained with the HyBrID copper laser plus the resonator presented in this paper. At last, the effect of the unstable resonator combined with the gain distribution was considered: now, M^2 drops down to unity after two round trips. The conclusion is that neither the resonator geometry nor the gain distribution alone can explain the good beam quality that is obtained with this resonator. It is necessary to take into account the geometrical aspects (including here the diffraction) plus the effect of the gain radial distribution.

5. Conclusions

In this work, a very simple optical resonator made of a concave total reflector, a convex-plane BK7 lens acting as the coupling reflector and an intracavity iris placed close to the coupling mirror was presented in order to control the laser power. This resonator was installed in a HyBrID copper laser and the performance of the set-up was analysed. The beam quality M^2 factor was measured for different iris apertures and $M^2 = 4.9$ for a widely open iris and $M^2 = 3.52$ for the iris with a diameter of 6.2 mm was obtained. The beam quality was considered very good for this kind of laser and the reduction of M^2 value as the iris aperture decreased is reasonable, since inside the cavity the iris works as a spatial filter. The temporal beam profiles were recorded for the green (510 nm) and yellow (578 nm) emissions and pulse widths of, respectively, 17 and 25 ns were found. A qualitative analysis was performed, by using a Fox-and-Li-like method, considering the radial gain distribution in the active medium, and it was understood that the combination of a negative branch unstable resonator plus the concentration of the gain on the optical axis assures the high-quality beam for this laser.

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