Diffraction losses reduction in multiapertured non-Hermitian laser resonators

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The behavior of diffraction losses in multiapertured laser resonators is theoretically and experimentally investigated. In the case of geometrically unstable resonators, it is shown that the combination of several apertures whose diameters have been independently optimized to reduce the laser diffraction losses leads to a still lower value for these losses. This puzzling fact is verified experimentally for a negative branch unstable resonator laser containing up to five intracavity apertures. In the case of geometrically stable resonators, it is shown that the introduction of a first intracavity aperture that selects the fundamental mode leads to modifications of the fundamental mode shape which, besides being relatively small, are sufficient to make the diffraction losses oscillate with the diameters of the following extra intracavity apertures. In particular, the diameters of these apertures can be optimized to reduce the diffraction losses below the value obtained with the first aperture only. These predictions are experimentally verified in the case of a dynamically stable cavity high power Nd:YAG (yttrium aluminum garnet) laser. In all cases, the calculations based on the Huygens-Fresnel principle exhibit a good agreement with the experimental results. [S1050-2947(97)03301-5]

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I. INTRODUCTION

Optical cavities are usually classified in two distinct classes, depending on whether they are geometrically stable or unstable [1]. In geometrically stable cavities, the nature and characteristics of the transverse modes are shown to be essentially determined by the characteristics of the optical elements (mirrors, lenses, free propagation, etc.) present inside the cavity. These modes are well approximated by Laguerre-Gaussian or Hermite-Gaussian functions, which both provide complete basis sets of orthogonal functions. In such stable resonators, discrimination between transverse modes is obtained by introducing a diffracting aperture inside the cavity. The fundamental TEM_{00} mode can then be selected by introducing a diffracting aperture that has a diameter several times larger than the fundamental mode diameter, introducing then only small disturbances on the Gaussian mode characteristics [1,2]. Besides, in the case of geometrically stable cavities, the diffraction losses introduced by the aperture decrease monotonically when the diameter of the intracavity aperture is increased [1,3–7]. On the contrary, in the case of a geometrically unstable cavity, diffraction effects play a major role in the shape of transverse modes [1]. In particular, their transverse expansion cannot be deduced from purely geometric considerations and more sophisticated computing techniques must be used to predict the shape of these modes [8–14] which, in general, do not provide a complete basis set of orthogonal functions. Moreover, in geometrically unstable cavities, the evolutions of the diffraction losses of the modes versus diameter of the intracavity aperture, i.e., versus cavity Fresnel number, exhibit complicated oscillating behaviors including mode crossings and anticrossings [1,15]. Indeed, it is well known that in the case of a geometrically unstable cavity containing one aperture, the losses of the fundamental mode oscillate around the value given by a purely geometric picture, with minima (maxima) corresponding to half-integer (integer) values of the equivalent Fresnel number of the cavity. Moreover, recently it was observed experimentally, thanks to a laser, that it is possible to reduce the losses for one round trip through an unstable cavity below this minimum value by, surprisingly, introducing more than one aperture inside the cavity [16]. This loss reduction in multiapertured cavities had already been observed in plane parallel microwave passive resonators [17], in connection with the focusing properties of a sequence of apertures [18]. This effect, which seems to be typical of non-Hermitian resonators, has, to our best knowledge, not yet been given a theoretical treatment in terms of resonator modes, which could lead to interesting comparisons with experiments.

Consequently, the first aim of this paper is to provide a theoretical calculation of the fundamental mode of a multiapertured unstable cavity, in order to isolate the optimum diameters of the apertures that lead to the largest reduction of the losses (Sec. II A). These results will then be compared with experiments similar to the one of Ref. [16] (Sec. II B). The second aim of this paper comes from the following observation: in a geometrically stable resonator, the introduction of the diffracting aperture that selects the fundamental TEM_{00} mode slightly modifies the resonator eigenmodes [2,19] and, in particular, makes the Huygens-Fresnel kernel corresponding to one round trip through the cavity non-Hermitian [1], leading, in general, to nonorthogonal eigenmodes. One can then wonder whether such a geometrically stable resonator containing one aperture will not behave like a geometrically unstable resonator. In particular, in Sec. III, we attempt theoretically and experimentally to reduce the losses of the cavity by introducing extra apertures inside this cavity and by optimizing the characteristics of these apertures.

II. GEOMETRICALLY UNSTABLE CAVITY

A. Theoretical predictions

In order to introduce the basic concepts and notations used in diffraction loss calculations, we first recall the well-

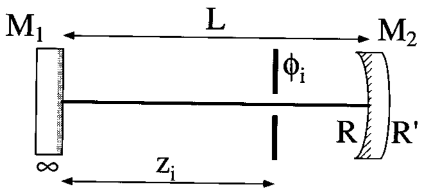

FIG. 1. Geometrically unstable two-mirror cavity of length L. M_1, plane mirror; M_2, concave mirror (radius of curvature R). The apertures of diameters ϕ_i are located at distances z_i from the plane mirror. We allow the rear of output mirror M_2 to have a radius of curvature R'.

known results obtained for a single aperture. The basic geometrically unstable cavity we consider here is schematized in Fig. 1. It consists in a plane mirror M_1 and a spherical mirror M_2 of radius of curvature R. This cavity is unstable as soon as its length L is larger than R. Starting from the spherical mirror, the $ABCD$ matrix for one round trip inside this cavity is then given by

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1-4L/R & 2L \\ -2/R & 1 \end{pmatrix}. \tag{1}$$

Then this negative-branch unstable resonator has a geometrical magnification given by

$$M = 1 - \frac{2L}{R} - \left[\frac{4L}{R} \left(\frac{L}{R} - 1 \right) \right]^{1/2}. \tag{2}$$

If we now introduce a circular aperture of diameter ϕ_1 on the spherical mirror ($z_1 = L$) and we assume a cylindrical symmetry for the resonator, the resonator eigenmode is the solution of the Huygens-Fresnel eigenequation [1] given by

$$\gamma u_1(r) = \frac{2\pi}{B\lambda} j^{l+1} \int_0^{\phi_1/2} dr' r' u_1(r') \times \exp\left[-j \frac{\pi}{B\lambda} (Ar'^2 + Dr^2) \right] J_l \left(\frac{2\pi}{B\lambda} rr' \right), \tag{3}$$

where the wave front on the aperture is $u_1(r)\exp[jl\phi]$ in the (r,ϕ) cylindrical coordinate system, γ the associated eigenvalue, λ is the vacuum wavelength of light, J_l is the Bessel function of order l, and l is an integer. In order to compute the lowest loss mode of the cavity, one can solve Eq. (3) with $l=0$ iteratively using a quasifast Hankel transform algorithm [20,21]. In particular, such a Fox-Li–type calculation [3,9] provides the modulus $|\gamma|$ of the eigenvalue that is related to the round trip intensity diffraction losses Γ of the fundamental mode in the following manner:

$$\Gamma = 1 - |\gamma|^2. \tag{4}$$

The result of the calculation of $|\gamma|$ versus ϕ_1 for $R = 0.6$ m, $L = 0.66$ m, and $\lambda = 3.39$ μm, is shown in Fig. 2(a). This figure exhibits the well-known evolution of the mode losses in an unstable cavity [1]. In particular, $|\gamma|$ oscillates around a constant value and exhibits maxima for half-integer values of N_{eq} and minima for integer values of N_{eq}, N_{eq} being the equivalent Fresnel number of the cavity given by

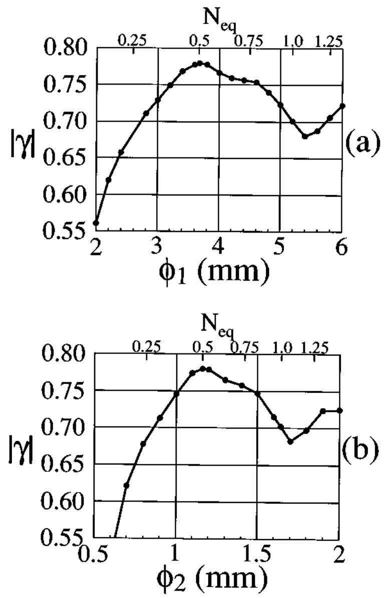

FIG. 2. Computed evolution of the modulus of the eigenvalue of the fundamental mode of the cavity of Fig. 1 versus diameter of the intracavity aperture. $\lambda = 3.39$ μm, $R = 0.6$ m, and $L = 0.66$ m. (a) The aperture is located on the spherical mirror: $z_1 = L$. (b) The aperture is located on the plane mirror: $z_2 = 0$. N_{eq} is the equivalent Fresnel number of the resonator.

$$N_{eq} = \frac{M^2 - 1}{2M} \frac{\phi_1^2}{4B\lambda}. \tag{5}$$

In particular, the lowest losses are obtained around the value $N_{eq} = 0.5$ [1], corresponding in the present case to a value of 39.3% for the diffraction losses Γ per round trip for $\phi_1 = 3.67$ mm. Obviously, the same computation gives a similar result when the aperture is located at a different plane inside the cavity. For example, Fig. 2(b) corresponds to the case where the intracavity aperture is located on the plane mirror ($z_2 = 0$). The case $N_{eq} = 0.5$ for which the diffraction losses are minimized now corresponds to an aperture diameter $\phi_2 = 1.16$ mm.

The question we wish to answer now is whether the diffraction losses for one round trip inside the cavity can still be reduced by introducing *several apertures*. We hence now consider the cavity of Fig. 1 containing both apertures, i.e., the one with diameter ϕ_1 located on the spherical mirror ($z_1 = L$) and the one with diameter ϕ_2 located on the plane mirror ($z_2 = 0$). Then the $ABCD$ matrices corresponding to propagation from aperture one to aperture two (via mirror M_2), and vice versa, are, respectively, given by

$$\begin{pmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{pmatrix} = \begin{pmatrix} 1-2L/R & L \\ -2/R & 1 \end{pmatrix}, \tag{6a}$$

$$\begin{pmatrix} A_{21} & B_{21} \\ C_{21} & D_{21} \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}. \tag{6b}$$

Then the fundamental mode of the resonator can be obtained by solving the following system of Huygens-Fresnel equations:

TABLE I. Locations and diameters of the apertures used in the calculations and the experiments on the cavity of Fig. 1. The diameters are chosen to minimize the losses of the cavity.

Aperture number	Position z_i (m)	Diameter ϕ_i (mm) (Theory)	Diameter ϕ_i (mm) (Experiment)
1	0.66	3.67	3.7
2	0	1.26	1.2
3	0.1	1.38	1.6
4	0.2	2.40	2.6
5	0.3	3.10	3.1

$$\gamma_{12}u_2(r_2)=\frac{2\pi}{B_{12}\lambda}\int_0^{\phi_1/2}dr_1 r_1 u_1(r_1)\times\exp\left[-j\frac{\pi}{B_{12}\lambda}(A_{12}r_1^2+D_{12}r_2^2)\right]\times J_0\left(\frac{2\pi}{B_{12}\lambda}r_1r_2\right), \tag{7a}$$

$$\gamma_{21}u_1(r_1)=\frac{2\pi}{B_{21}\lambda}\int_0^{\phi_2/2}dr_2 r_2 u_2(r_2)\times\exp\left[-j\frac{\pi}{B_{21}\lambda}(A_{21}r_2^2+D_{21}r_1^2)\right]\times J_0\left(\frac{2\pi}{B_{21}\lambda}r_1r_2\right), \tag{7b}$$

where $u_1(r_1)$ and $u_2(r_2)$ are the wave fronts on apertures one and two, respectively. The fundamental mode eigenvalue is then given by

$$\gamma=\gamma_{12}\gamma_{21}. \tag{8}$$

If we apply Eqs. (6)–(8) to the cavity of Fig. 1 containing the two preceding optimized apertures ($\phi_1=3.67$ mm and $\phi_2=1.16$ mm) we obtain $\gamma=0.798$, corresponding to $\Gamma=36.3\%$. This shows that the introduction of two optimized apertures permits us to reduce the resonator losses still below the minima obtained previously with only one aperture ($\Gamma=39.3\%$ losses per round trip). Actually, one can try to minimize these losses a little bit further by slightly modifying the diameters of the two apertures. In the present case, the best computed result is obtained with $\phi_1=3.67$ mm and $\phi_2=1.26$ mm, and leads to $\Gamma=35.0\%$. Anyway, it is striking to notice that the optimum is simply obtained by combining the action of the two apertures that have been optimized independently of one another.

Let us now introduce inside the cavity a third aperture of diameter ϕ_3 at position $z_3=0.1$ m. If we introduce this aperture alone, we can optimize its diameter to minimize the round trip diffraction losses, leading to $\phi_3=1.28$ mm, $\gamma=0.697$, and $\Gamma=51.4\%$. Now, if we consider this aperture together with apertures one and two, the optimum is obtained for $\phi_3=1.38$ mm, and corresponds to $\gamma=0.816$, and $\Gamma=33.4\%$. To obtain this result, the eigensystem (7) must be extended to four propagation Huygens-Fresnel integrals. Here again, the diameter obtained by optimizing the aperture

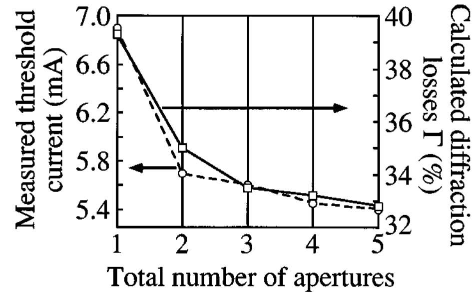

FIG. 3. Full line, calculated diffraction losses Γ versus number of intracavity apertures for the cavity of Fig. 1 with $R=0.6$ m, $L=0.66$ m, and $\lambda=3.39$ μm. Dotted line, corresponding experimental evolution of the laser threshold current. The positions and diameters of the apertures are summarized in Table I.

when it is alone inside the resonator is very close to the optimum diameter obtained in the presence of the two preceding apertures.

This optimization process can be continued. Table I summarizes the positions and diameters of five successively optimized apertures. The result of the computation of the fundamental mode diffraction losses is reported in Fig. 3 versus the number of intracavity apertures, these apertures being successively introduced inside the cavity according to the numbering of Table I. One can see that we hope to considerably reduce the diffraction losses of the resonator by introducing up to five circular apertures.

B. Experiments

To check the predictions of Sec. II A, we use a He-Ne laser oscillating at $\lambda=3.39$ μm. Mirrors M_1 (plane) and M_2 ($R=0.6$ m) have reflection coefficients 99% and 64%,

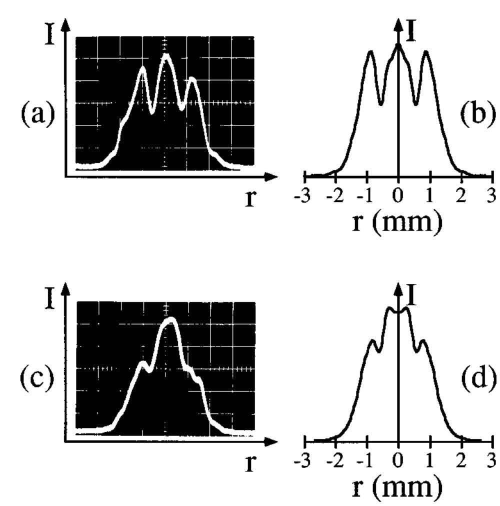

FIG. 4. Experimental (a),(c) and theoretical (b),(d) intensity profiles of the beam emerging from mirror M_2 of the geometrically unstable laser of Fig. 1 with $R=0.6$ m and $L=0.66$ m. (a) and (b) are obtained with one aperture of diameter $\phi_1=3.7$ mm located on mirror M_2 ($z_1=0.66$ m) and (c) and (d) with a second aperture of diameter $\phi_2=1.2$ mm located on mirror M_1 ($z_2=0$). The detector is located 30 cm behind mirror M_2, that has a rear radius of curvature $R'=19.1$ cm. (a),(c) 0.8 mm per division.

respectively. We choose $L=0.66$ m, as in the theoretical computations. The active medium is a 29-cm-long discharge tube filled with a 7:1 ^{3}He-^{20}Ne mixture at a total pressure of 1.1 Torr. We choose a large bore diameter (6.2 mm), so that we can neglect diffraction by the tube. A 250-μm-diameter circular InAs detector is located at the output of mirror M_2. To measure the total laser output power, a lens is introduced in front of this detector. We then successively introduce the five circular diffracting apertures at the positions z_i and in the order summarized in Table I. We optimize the diameters of the apertures in order to obtain the minimum threshold discharge current. The resulting experimentally optimized diameters are indicated in the last column of Table I. The agreement with the theoretically predicted optimimum diameters is quite good. Then, after introduction of each aperture, we measure the laser threshold current when the laser frequency is tuned at line center. The result of these measurements is reproduced in Fig. 3. One can see that each extra aperture permits us to reduce the laser threshold.

The experiments can also provide another comparison with theoretical computations. We indeed mount the detector on a motorized translation stage, in order to record the output beam spatial profile. The detector (without the lens) is located at a distance $d=30$ cm behind the output mirror M_2. Figure 4 then reproduces the output beam profiles obtained with one [Fig. 4(a)] and two [Fig. 4(c)] optimized apertures. To compare these experimental profiles with theory, we must propagate the intracavity wave front $u_2(r_2)$ computed thanks to Eqs. (7) from the plane of aperture two to the detector plane. This is performed thanks to the following Huygens-Fresnel integral, which gives the resulting wave front $u_D(r)$ in the plane of the detector:

$$u_D(r)=\frac{2\pi}{B_D\lambda}\int_0^{\phi_2/2} dr_2 r_2 u_2(r_2) \times\exp\left[-j\frac{\pi}{B_D\lambda}(A_D r_2^2+D_D r_D^2)\right]J_0\left(\frac{2\pi}{B_D\lambda}r_2 r_D\right), \tag{9}$$

where the ABCD matrix corresponding to the propagation from the plane of aperture two to the detector is given by

$$\begin{pmatrix} A_D & B_D \\ C_D & D_D \end{pmatrix}=\begin{pmatrix} 1-(n-1)\left(\frac{e}{nR}+\frac{d}{R}-\frac{d}{R'}\right)-\frac{(n-1)^2}{n}\frac{ed}{RR'}, & \frac{e}{n}+d-\frac{n-1}{n}\frac{de}{R'} \\ (n-1)\left(\frac{1}{R}-\frac{1}{R'}\right)-\frac{(n-1)^2}{n}\frac{e}{RR'} & 1-\frac{n-1}{n}\frac{e}{R'} \end{pmatrix}. \tag{10}$$

This matrix takes the thickness e, refractive index n, and rear radius of curvature R' of the output mirror into account. With the experimental values $e=1$ cm, $n=1.409$, and $R'=19.1$ cm, one obtains the theoretical profiles of Figs. 4(b) and 4(d). These theoretical profiles have been smoothed to take the 250 μm diameter of the detector into account. The only parameter we slightly adjusted to improve the agreement between experiments and computations is d that we took equal to 28 cm in the calculations, rather than the experimental value of 30 cm. We attribute this small discrepancy to the fact that the apertures cannot be exactly located in the reflecting planes of the mirrors.

III. GEOMETRICALLY STABLE CAVITY

As stated in the Introduction, the diffraction losses of the fundamental mode of a geometrically stable cavity containing *one* aperture monotonically decrease when the diameter of this aperture is increased. Nevertheless, once this first aperture has been introduced inside the cavity, the cavity fundamental eigenmode is slightly modified with respect to the TEM$_{00}$ mode, and the Huygens-Fresnel kernel of this cavity is, in general, no longer Hermitian. Since these characteristics are identical to the ones of unstable cavities, we wonder in this section whether the diffraction losses for this fundamental mode can be reduced by introducing *several* apertures.

A. Theoretical predictions

In order to illustrate the fact that the reduction of diffraction losses in multiapertured lasers can exist in different kinds of lasers, we consider in this section the example of a standard high power solid-state Nd:YAG (yttrium aluminum garnet) laser, whose cavity is schematized in Fig. 5. This cavity of length L is closed by two convex mirrors M_1 and M_2 of identical radii of curvature R. The stability of this cavity is due to the presence of the lenslike effect [22] that occurs inside the active medium (length d, refractive index n) which is located in the middle of the cavity. We modelize this lenslike effect by a thin lens of focal length f located in the middle of the laser rod. Here, again, we allow this cavity to contain different circular apertures of diameters ϕ_i, located at distances z_i from mirror M_1.

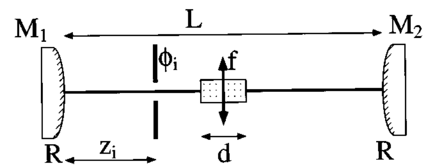

FIG. 5. Solid-state laser geometrically stable two-mirror cavity of length L. M_1, M_2, convex mirrors (radii of curvature R). The laser rod of length d creates a lenslike effect of focal length f. The apertures of diameters ϕ_i are located at distances z_i from mirror M_1.

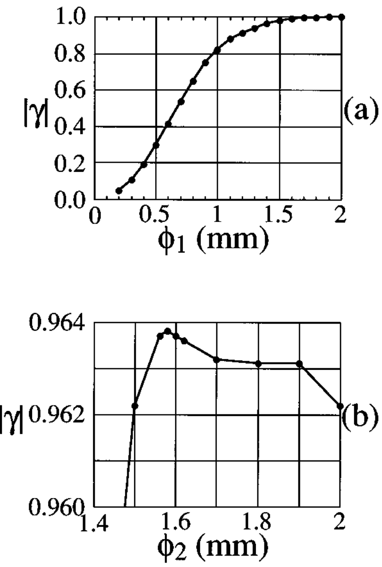

FIG. 6. Computed evolution of the modulus of the eigenvalue of the fundamental mode of the cavity of Fig. 5 versus diameter of the intracavity aperture. $R=-1.2$ m, $L=0.44$ m, $f=0.55$ m, $d=0.06$ m, $n=1.8$, and $\lambda=1.064$ μm. (a) The aperture is located on the mirror M_1: $z_1=0$. (b) We choose $\phi_1=1.4$ mm and introduce a second aperture of diameter ϕ_2 located on mirror M_2: $z_2=L$.

To compute the fundamental eigenmode of the cavity of Fig. 5, we choose the following values for the different parameters: $L=0.44$ m, $R=-1.2$ m, $f=0.55$ m, $d=0.06$ m, $n=1.8$, and $\lambda=1.064$ μm. In these conditions, the cavity is stable with a mode size $w=515$ μm on the mirrors. In a manner similar to what we did in Sec. II for the unstable cavity, we can compute the modulus of the eigenvalue γ associated with the fundamental eigenmode when an aperture of diameter ϕ_1 is introduced in front of mirror M_1 $(z_1=0)$. The result of such a calculation is reproduced in Fig. 6(a). One can see that as is usual in the case of stable cavities [1], the diffraction losses decrease monotonically when ϕ_1 is increased. Let us now fix the value of ϕ_1 at 1.4 mm, a value that should permit us to select the fundamental mode. As can be seen from Fig. 6(a), this leads to $|\gamma|=0.961$, corresponding to $\Gamma=7.6\%$ diffraction losses per round trip. Although this value is relatively low, it is sufficient to slightly alter the wave front of the fundamental mode of the cavity. Let us now introduce a second circular aperture of diameter ϕ_2 on mirror M_2 $(z_2=L)$. Using two Huygens-Fresnel integrals per round trip, we can compute the evolution of $|\gamma|$ versus ϕ_2, as can be seen in Fig. 6(b). Notice that now the situation looks like what we obtained earlier (see Fig. 2) in the case of an unstable cavity; the mode losses oscillate when the diameter of the aperture is increased. In particular, we predict the existence of an optimum for $\phi_2=1.58$ mm, leading to $|\gamma|\approx 0.964$, i.e., $\Gamma=7.1\%$ diffraction losses per roundtrip.

Similar to what we did in the case of the unstable cavity, we can continue to introduce new apertures inside the cavity. The positions and optimum diameters of the four successive apertures we consider are summarized in Table II. Figure 7 then reproduces the computed evolution of the diffraction losses versus number of intracavity apertures, which are successively introduced inside the cavity following their numbering order (see Table II). Notice that each aperture is expected to reduce the diffraction losses of the cavity.

TABLE II. Locations and diameters of the apertures used in the calculations and the experiments on the cavity of Fig. 5. The diameters are chosen to minimize the losses of the cavity.

Aperture number	Position z_i (m)	Diameter ϕ_i (mm) (Theory)	Diameter ϕ_i (mm) (Experiment)
1	0	1.40	1.4
2	0.44	1.58	1.5
3	0.10	1.76	1.7
4	0.34	1.82	1.8

B. Experiments

To check the predictions of Sec. III A, we use a commercial flashlamp-pumped cw Nd:YAG laser (Quantronix model 114). Its mirror M_1 and M_2 have transmission coefficients equal to 9% and 0.5%, respectively. Its other characteristics are the ones we used in the theoretical calculations. In particular, we measured the equivalent focal length of the flashlamp-induced lenslike effect to be $f=0.55$ m in the range of discharge currents we use in the present experiments ($I\approx 20$ A). In these conditions, the introduction of the first aperture of diameter $\phi_1=1.4$ mm in front of mirror M_1 $(z_1=0)$ is sufficient to select the fundamental transverse mode of the cavity. One can then record the evolution of the laser output power versus discharge current (● in Fig. 8). We then introduce successively other apertures inside the cavity at the positions indicated in the second column of Table II. At every introduction of a new aperture, we look for the aperture diameter that minimizes the laser threshold. The resulting experimentally optimized aperture diameters ϕ_i are indicated in the last column of Table II. The corresponding output power versus current characteristics are reproduced in Fig. 8. From these characteristics, we can in each case extrapolate the value of the threshold current. The evolution of this threshold current versus number of apertures is reproduced in Fig. 7. We can make the two following remarks. First, the experimentally optimized aperture diameters are in good agreement with the ones expected from theory (compare third and fourth columns in Table II). Sec-

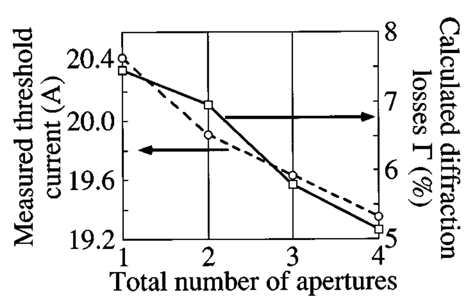

FIG. 7. Full line, calculated diffraction losses Γ versus number of intracavity apertures for the cavity of Fig. 5 with $R=-1.2$ m, $L=0.44$ m, $f=0.55$ m, $d=0.06$ m, $n=1.8$, and $\lambda=1.064$ μm. Dotted line, corresponding experimental evolution of the laser threshold current. The positions and diameters of the apertures are summarized in Table II.

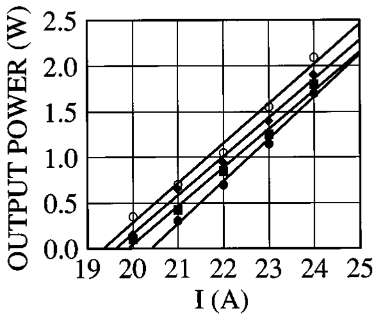

FIG. 8. Experimental evolution of the output power versus excitation current for the Nd:YAG laser schematized in Fig. 5. ●, one aperture; ■, two apertures; ♦, three apertures; and ○, four apertures. The positions and diameters of the apertures are summarized in Table II.

ond, one can see from Figs. 7 and 8 that the introduction of a new aperture always permits us to reduce the laser threshold and, for a fixed current, to increase its output power. Notice, by the way, that this output power increase mechanism is different from the one suggested in Ref. [23] which is due to an increase of the laser mode volume. Here, this increase is due to a reduction of the laser losses thanks to diffraction.

IV. DISCUSSION AND CONCLUSION

In conclusion, we have shown theoretically and experimentally that the introduction of several apertures inside laser cavities can lead to a reduction of diffraction losses. In the case of an unstable cavity, we have seen that the combination of several apertures that are individually optimized to minimize diffraction losses leads to an overall reduction of these losses. More precisely, it is particularly convenient to choose aperture diameters which, individually, correspond to the value 0.5 for the equivalent Fresnel number of the cavity. In the case of geometrically stable cavities, although the cavity diffraction losses evolve monotonically with the diameter of the first aperture, we have seen that the small modifications of the fundamental mode wave front introduced by this aperture are sufficient to make the following aperture behave as if the cavity was unstable. In particular, these apertures have been shown to be able to reduce the diffraction losses of the cavity. In this case, the first aperture plays the role of a ''fundamental mode selector'' and the following apertures are used to reduce the diffraction losses. In all cases, a good agreement has been obtained between experiments and the calculations based on Huygens-Fresnel diffraction integrals.

Finally, in both cases—stable and unstable cavities—the propagation along one round trip through the cavity corresponds, in general, to a non-Hermitian kernel. Consequently, the transverse eigenmodes of the cavity are not orthogonal to each other. One can consequently expect interesting and novel features from the excess noise factors [24] in such cavities, especially multiapertured stable cavities that could reach excess noise factors as large as the one already obtained in unstable resonators.

ACKNOWLEDGMENTS

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[1] A. E. Siegman, *Lasers* (University Science Books, Mill Valley, CA, 1986).
[2] A. Le Floch, R. Le Naour, J.-M. Lenormand, and J. -P. Taché, Phys. Rev. Lett. **45**, 544 (1980); A. Kellou and G. Stéphan, Appl. Opt. **26**, 76 (1987); B. Lissak and S. Ruschin, *ibid.* **29**, 767 (1990); O. Haderka, J. Opt. Soc. Am. A **12**, 340 (1995); Appl. Opt. **34**, 7656 (1995).
[3] A. G. Fox and T. Li, Proc. IEEE **51**, 80 (1963).
[4] H. Kogelnik and T. Li, Appl. Opt. **5**, 1550 (1966).
[5] M. Piché, P. Lavigne, F. Martin, and P.-A. Bélanger, Appl. Opt. **22**, 1999 (1983).
[6] W. W. Rigrod, IEEE J. Quantum Electron. **QE-19**, 1679 (1983).
[7] J. -P. Taché, Opt. Quantum Electron. **16**, 71 (1984).
[8] A. E. Siegman, Proc. IEEE **53**, 277 (1965).
[9] A. G. Fox and T. Li, Bell Syst. Tech. J. **40**, 453 (1961).
[10] A. E. Siegman, IEEE J. Quantum Electron. **QE-3**, 156 (1967).
[11] P. Horwitz, J. Opt. Soc. Am. **63**, 1528 (1973).
[12] P. Horwitz, Appl. Opt. **15**, 167 (1976).
[13] R. R. Butts and P. V. Avizonis, J. Opt. Soc. Am. **68**, 1072 (1978).
[14] W. H. Southwell, J. Opt. Soc. Am. A **3**, 1885 (1986).
[15] A. E. Siegman and H. Y. Miller, Appl. Opt. **9**, 2729 (1970).
[16] F. Bretenaker and A. Le Floch, C. R. Acad. Sci. (Paris) **321**, 97 (1995).
[17] P. Gosselin, Thèse de Maîtrise, Département de Physique, Université Laval, Québec, 1967 (unpublished); R. Boulay, J. W. Y. Lit, R. Tremblay, and N. Beaudry, Opt. Commun. **5**, 82 (1972).
[18] R. Tremblay and M. De, Appl. Phys. Lett. **9**, 136 (1966); M. De, J. W. Y. Lit, and R. Tremblay, Appl. Opt. **7**, 483 (1968); J. W. Y. Lit and R. Tremblay, J. Opt. Soc. Am. **59**, 559 (1969); J. Y. W. Lit, R. Boulay, and R. Tremblay, Opt. Commun. **1**, 280 (1970); G. Otis, J. -L. Lachambre, and P. Lavigne, Appl. Opt. **18**, 875 (1979); F. Bloisi and L. R. M. Vicari, *ibid.* **30**, 1595 (1991).
[19] K. Ait-Ameur and H. Ladjouze, J. Phys. D **21**, 1566 (1988); K. Ait-Ameur, H. Ladjouze, and G. Stéphan, Appl. Opt. **31**, 397 (1992); K. Ait-Ameur and G. Stéphan, Opt. Lett. **18**, 938 (1993).
[20] A. E. Siegman, Opt. Lett. **1**, 13 (1977).
[21] To perform such computations, we used the software PARAXIA developed by J. -L. Doumont, A. E. Siegman, and J. A. Ruff, and distributed by SCIOPT Enterprises, 7189 Wooded Lake Dr, San Jose, CA 95120.
[22] W. Koechner, Appl. Opt. **9**, 2548 (1970).
[23] K. Ait-Ameur and G. Stéphan, Appl. Opt. **34**, 7662 (1995).
[24] A. E. Siegman, Phys. Rev. A **39**, 1253 (1989); **39**, 1264 (1989); P. L. Mussche and A. E. Siegman, Proc. Soc. Photo-Opt. Instrum. Eng. **1376**, 153 (1990).