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Modes of a laser resonator with a retroreflective mirror

Guo-Sheng Zhou and Lee W. Casperson

The self-consistent integral equation for the field distribution of the resonant modes in an inclined retroreflective grating resonator is solved in the limit of large Fresnel numbers. The transverse field distribution in the direction perpendicular to the grating grooves can be described in terms of Hermite-Gaussian functions provided that $\lambda \ll d \ll w$, where λ is the wavelength, d is the grating spacing, and w is the beam spot size.

I. Introduction

It has recently been pointed out that an array of corner-cube reflectors can act as an approximate phase conjugator in two dimensions.¹ The phase conjugation is only approximate because of the finite size of the conjugator elements, the inversion suffered by each plane wave, and the additional phase difference due to the varying reflector positions. Orlov *et al.* demonstrated that such an array can correct the dynamic index profile in optically pumped Nd:glass laser amplifiers.² Mathieu and Belanger³ showed recently that a retroreflective array of corner cubes can be used as a mirror to compensate for distorting elements inside a resonator, and they also pointed out that the laser operates normally for retroreflector tilts as large as 25° . Very severe distortion can be corrected if the distorting element is located close to the retroreflective array. The axial mode spacing is found to differ from the value $c/4L$ predicted for phase conjugation resonators,⁴ and these experimental results have not yet been analyzed.

It is reasonable to expect that a retroreflective grating (with 45° blazing angles) would act as an approximate phase conjugator in one dimension just as a corner-cube array does in two dimensions. Similarly, a resonator containing such a grating has in one dimension the same advantages as a resonator with a corner-cube retroreflector. Such a resonator might be used to compensate for distorting elements in one dimension as those often existing in transverse discharge CO₂ laser tubes. It may also be used to filter the distortion in one dimension and to study the distribution of inhomogeneity and nonuniformity. A retroreflective grating with grooves in

both x and y directions is also an approximate phase conjugator in two dimensions, and it is cheaper and easier to produce than a corner-cube array.

It is the purpose of this paper to present a self-consistent field analysis of a resonator containing a retroreflective grating and to demonstrate for large Fresnel numbers a complete description of the field distributions. The basic self-consistent integral equation is derived in Sec. II, and solutions are obtained in Sec. III. These solutions can be expressed in terms of Hermite-Gaussian functions, and several aspects of the results are considered in Sec. IV.

II. Self-consistent Integral Equation

The grating resonator is represented schematically in Fig. 1. It consists of a spherical mirror and a grating with both blazing angles at 45° and grating constant d . The reflectivity of the grating is assumed to be perfect. The spherical mirror has a radius of curvature R_2 and is square in cross section. The optical axis z passes through the centers of both the grating and the mirror and is perpendicular to the grating grooves and the mirror surface. L represents the distance between the centers of the mirror and grating. O is the center of the grating, and the y axis is parallel to the grating grooves. The angle between the x axis and the grating macroscopic surface is θ , which is positive when the macroscopic surface is turned counterclockwise from the x axis.

An incident ray from the point $P_2(x_2, y_2)$ passes through point $P_1(x_1, y_1)$ on the grating macroscopic surface and impinges at point A_1' on the groove. Then two processes happen. First, the ray diffracts back to the spherical mirror. This process is very weak as discussed in detail for common grating resonators,⁵ so we will not discuss it further here. Second, the ray experiences two reflections at A_1' and A_1 and goes to $P_1(x_1, y_1)$ at the grating macroscopic surface. This re-

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Fig. 1. Schematic representation of a light ray in a grating resonator.

flected ray is parallel to the incident ray P_2P_1' . The path length difference from P_1' through A_1 and A_1 to P_1 is approximately equal to the grating constant d and is independent of the ray directions when the small quantity $\tan\theta(x_2 - x_1)/L$ is ignored. However, the ray does experience a displacement from $P_1'(x_1', y_1')$ to $P_1(x_1, y_1)$. Let x_s be the coordinate of the middle point of the s th groove, $x_s = (s - 1/2)d \cos\theta$, where s is an integer. Let ξ be the distance between x_1 and x_s , which are at the same groove, $\xi = x_1 - x_s$, as shown in Fig. 2. It is also clear from the figure that $-(d/2)\cos\theta \leq \xi \leq d\cos\theta/2$. The path length difference from P_2 , through P_1' , A_1 , and A_1 to $P_1(x_1, y_1)$, can be expressed in the form

$$\rho'(x_1, x_2; y_1, y_2) = \rho'(x_1, x_2) + \rho(y_1, y_2), \quad (1)$$

$$\begin{aligned} \rho'(x_1, x_2) = & L/2 + d - (x_s + \xi)\tan\theta + 2x_s \tan\theta \\ & - (d/L)\tan\theta(x_2 \cos\theta + \xi - x_s) + (1/2L) \\ & \times [(-\xi + x_s)^2 + g_2 x_s^2 - 2x_2(-\xi + x_s)], \end{aligned} \quad (2)$$

$$\rho(y_1, y_2) = L/2 + \frac{1}{2L}(y_1^2 + g_2 y_2^2 - 2y_1 y_2), \quad (3)$$

where $g_2 = 1 - L/R_2$. The path length difference of P_1P_2 is given by

$$\rho(x_1, x_2; y_1, y_2) = \rho(x_1, x_2) + \rho(y_1, y_2), \quad (4)$$

$$\rho(x_1, x_2) = L/2 + (1/2L)[x_1^2 + g_2 x_2^2 - 2x_1 x_2] + x_1 \tan\theta. \quad (5)$$

Since the kernel of the self-consistent Fresnel Kirchhoff integral equation can be separated in the x and y directions, the field expressions may be written as follows:

$$\begin{aligned} \gamma_x E_x^{(2)}(x_2) = & (i/\lambda L) \int E_x^{(2)}(x_2') dx_2' \int dx_1' \frac{1}{\left(1 + \frac{x_1'}{L} \tan\theta\right)^2} \\ & \times \exp\{-ik[\rho'(x_1', x_2') + \rho(x_1', x_2)]\}, \end{aligned} \quad (6)$$

$$\begin{aligned} \gamma_y E_y^{(2)}(y_2) = & (i/\lambda L) \int E_y^{(2)}(y_2') dy_2' \int dy_1' \\ & \times \exp\{-ik[\rho(y_1', y_2') + \rho(y_1', y_2)]\}, \end{aligned} \quad (7)$$

$$E^{(2)}(x_2, y_2) = E_x^{(2)}(x_2) E_y^{(2)}(y_2), \quad (8)$$

$$\gamma = \gamma_x \gamma_y, \quad (9)$$

where $E^{(2)}$, $E_x^{(2)}(x_2)$, and $E_y^{(2)}(y_2)$ represent, respectively, the field and the field variations in the x and y directions on the surface of the spherical mirror with γ , γ_x , and γ_y as the corresponding eigenvalues. The wave number is $k = 2\pi/\lambda$, and λ is the wavelength in the resonator. According to the approximate rules used in the Huygens-Kirchhoff equation, in the integrand function small quantities to first order are kept, and in the exponential the small quantities to second order are kept. The factor $1/(1 + x_1' \tan\theta/L)^2$ comes from the distance P_1P_2 in the denominator. The limits of integration are assumed to approach infinity, which can be interpreted to mean that the modes of the resonator will be sufficiently confined about the axis so that the contributions to the integral from points other than those close to the axis may be neglected.

III. Solution of the Integral Equation

The integral equation (7) was solved previously in the limit that the Fresnel number $a^2/(L\lambda)$ approached infinity, where a is the width of the mirror, and the confinement criterion $0 < g_2 < 1$ was assumed to be satisfied. The solutions of Eq. (7) can be written in the form

$$E_y^{(2)}(y_2) = \phi_m(B_2 y_2), \quad (10)$$

where ϕ is the normalized Hermite-Gaussian function⁶

$$\phi_m(B_2 y_2) = N_m^{(2)} H_m(\sqrt{2} B_2 y_2) \exp(-B_2^2 y_2^2), \quad (11)$$

$$N_m^{(2)} = (\sqrt{2} B_2)^{1/2} (2^m m! \sqrt{\pi})^{-1/2}, \quad (12)$$

$$B_2 = (\pi/\lambda L)^{1/2} [g_2(1 - g_2)]^{1/4}, \quad (13)$$

where H_m is a Hermite polynomial of the order of m , $N_m^{(2)}$ is a normalization factor, and B_2 is the reciprocal of the beam spot size on the spherical mirror. The corresponding eigenvalue can be expressed as

$$\gamma_{ym} = \sigma_m, \quad (14)$$

where

$$\sigma_m = \exp\left\{-ikL + i(m + 1/2) \left[\frac{\pi}{2} + \tan^{-1} \frac{1 - 2g_2}{\sqrt{1 - (1 - 2g_2)^2}} \right] \right\}. \quad (15)$$

The field variation in the y direction on the grating macroscopic surface has the same form as Eq. (11) except that B_2 is replaced by B_1 , where

Fig. 2. Expanded view of a single grating groove.

$$B_1 = \left(\frac{\pi}{\lambda L} \right)^{1/2} \left[\frac{1}{g_2} (1 - g_2) \right]^{1/4}. \quad (16)$$

Equation (6) can be simplified when $dw_2/(\lambda L) \ll 1$ and

$$d \sin \theta = p \lambda, \quad (17)$$

where w_2 is the beam spot size on the spherical mirror, $w_2 = 1/B_2$, and p is an integer, $p = 0, \pm 1, \pm 2, \dots$. Equation (17) is well known as the grating resonant condition. Then Eq. (6) reduces to

$$\begin{aligned} \gamma_x E_x^{(2)}(x_2) &= \frac{i}{\lambda L} \exp[-ik(L+d)] \int_{-\infty}^{\infty} dx'_2 E_x^{(2)}(x'_2) \exp\left[-\frac{ikg_2}{2L}(x_2^2 + x'^2_2)\right] \\ &\times \sum_{s=-\infty}^{\infty} \left(1 - \frac{2x'_s}{L} \tan \theta\right) \exp\left\{-\frac{ik}{L}[x'^2_s - (x_2 + x'_2 - d \tan \theta)x'_s - dx_2 \tan \theta]\right\} \\ &\times \int_{-d/2 \cos \theta}^{d/2 \cos \theta - d \sin \theta} \left(1 - \frac{2\xi}{L} \tan \theta\right) \exp\left\{-\frac{ik}{L}[\xi^2 - (x_2 - x'_2 + d \tan \theta)\xi]\right\} d\xi, \quad (18) \end{aligned}$$

where we have transformed the integration over x'_1 into an integration over one grating groove and a summation over all grooves. The term $-d \sin \theta$ in the upper limit of the integration comes from the fact that when $\theta \neq 0$ the ray incident on the surface AQ shown in Fig. 2 and parallel to the optical axis will not be reflected to BC , and thus the AQ part of the grating makes no contribution to the retroreflected rays.

When $\pi d^2/(2\pi \lambda L) \ll 1$, the ξ^2 term in the last exponential can be ignored; and if $2\pi w_2 d/(\lambda L) \ll 1$, the integration over one grating groove is approximately equal to

$$d \cos \theta (1 - \tan \theta) \exp\left[\frac{ik}{2L}(x_2 - x'_2 + d \tan \theta)d \sin \theta\right].$$

Thus the summation becomes proportional to

$$\begin{aligned} \sum_{s=-\infty}^{\infty} \left[1 - \frac{2 \tan \theta}{L} \left(s - \frac{1}{2}\right) d \cos \theta\right] d \cos \theta (1 - \tan \theta) \\ \times \exp\left\{-\frac{ik}{L} \left[\left(s - \frac{1}{2}\right)^2 d^2 \cos^2 \theta - (x_2 + x'_2 - d \tan \theta) \right. \right. \\ \left. \left. \times \left(s - \frac{1}{2}\right) d \cos \theta - dx_2 \tan \theta\right]\right\}. \end{aligned}$$

When $d \cos \theta = \Delta x_s$ is very small, this summation can be approximated by an integral

$$\begin{aligned} \exp\left(-\frac{ik}{L} dx_2 \tan \theta\right) (1 - \tan \theta) \int_{-\infty}^{\infty} \left[1 - \frac{2 \tan \theta}{L} x_s\right] \\ \times \exp\left\{-\frac{ik}{L} [x_s^2 - (x_2 + x'_2 - d \tan \theta)x_s]\right\} dx_s. \end{aligned}$$

Then the integral equation simplifies and has the form

$$\begin{aligned} \gamma_x E_x^{(2)}(x_2) &= \frac{\exp\left(\frac{\pi}{4} i\right)}{\sqrt{2\lambda L}} \exp[-ik(L+d)] (1 - \tan \theta) \\ &\times \int_{-\infty}^{\infty} dx'_2 E_x^{(2)}(x'_2) \left[1 - \frac{\tan \theta}{L} (x_2 + x'_2)\right] \\ &\times \exp\left\{-\frac{ik}{4L} [(2g_2 - 1)(x_2^2 + x'^2_2) - 2x_2 x'_2]\right\}. \quad (19) \end{aligned}$$

To solve this self-consistent integral equation, part

of the kernel can be expanded in terms of the products of eigenfunctions in both variables according to

$$\begin{aligned} \frac{\exp\left(\frac{\pi}{4} i - ikL\right)}{\sqrt{2\lambda L}} \exp\left\{-\frac{ik}{4L} [(2g_2 - 1)(x_2^2 + x'^2_2) - 2x_2 x'_2]\right\} \\ = \sum_m \sigma_m \phi_m(B_2 x_2) \phi_m(B_2 x'_2). \quad (20) \end{aligned}$$

Then Eq. (19) can be expressed in the form

$$\gamma_x E_x^{(2)}(x_2) = \exp(-ikd) (1 - \tan \theta) \left(1 - \frac{\tan \theta}{L} x_2\right) \sum_m \sigma_m C_m \phi_m(B_2 x_2), \quad (21)$$

where the coefficients C_m are given by

$$C_m = \int_{-\infty}^{\infty} \phi_m(B_2 x'_2) \left(1 - \frac{\tan \theta}{L} x'_2\right) E_x^{(2)}(x'_2) dx'_2. \quad (22)$$

Multiplying both sides of Eq. (21) by

$$\phi_n(B_2 x_2) \left(1 - \frac{\tan \theta}{L} x_2\right)$$

and integrating, we get an homogeneous linear algebraic equation system

$$\gamma_x C_n = \exp(-ikd) (1 - \tan \theta) \sum_m \sigma_m C_m R_{mn}, \quad (23)$$

where the coefficients R_{mn} are given by⁵

$$\begin{aligned} R_{mn} &= \int_{-\infty}^{\infty} \left(1 - \frac{\tan \theta}{L} x_2\right)^2 \phi_m(B_2 x_2) \phi_n(B_2 x_2) dx_2 \\ &= \begin{cases} 1 & n = m \\ -\frac{\tan \theta}{LB_2} \sqrt{m+1} & n = m+1 \\ -\frac{\tan \theta}{LB_2} \sqrt{m} & n = m-1 \\ \text{for the rest.} & \end{cases} \quad (24) \end{aligned}$$

The solution of Eqs. (23) is approximately expressed in the form

$$\begin{aligned} E_{xm}^{(2)}(x_2) &= \exp(-ikd) (1 - \tan \theta) \left(1 - \frac{x}{L} \tan \theta\right) [\phi_m(B_2 x_2) \\ &+ C'_{m-1} \phi_{m-1}(B_2 x_2) + C_{m+1} \phi_{m+1}(B_2 x_2)], \quad (25) \end{aligned}$$

where

$$C'_{m-1} = \frac{\tan\theta}{2LB_2} \left(\frac{m}{1-g_2} \right)^{1/2} \exp(i\chi), \quad (26a)$$

$$C_{m+1} = \frac{\tan\theta}{2LB_2} \left(\frac{m+1}{1-g_2} \right)^{1/2} \exp(-i\chi), \quad (26b)$$

$$\chi = \tan^{-1} \left(\frac{g_2}{1-g_2} \right)^{1/2}, \quad (26c)$$

and the corresponding eigenvalue is given by

$$\gamma_{xm} = (1 - \tan\theta)\sigma_m \exp(-ikd). \quad (27)$$

From Eq. (25) one can see that the mode components in the x direction are a superposition of Hermite-Gaussian functions and perturbation terms ϕ_{m-1} and ϕ_{m+1} , which result from the inclination of the grating. This inclination has influenced not only the beam length difference in the exponential but also the denominator of the integrand as indicated in Eq. (6).

After further calculations and use of the recursion relation $H_{n+1}(x) = 2x H_n(x) - 2nH_{n-1}(x)$, one finds that the amplitude distribution of the eigenmodes can be expressed in the form

$$\begin{aligned} |E_{xm}^{(2)}(x_2)| &= (1 - \tan\theta) |\phi_m(B_2x_2)| \\ &= (1 - \tan\theta) N_m^{(2)} |H_m(\sqrt{2}B_2x_2) \exp(-B_2x_2^2)|, \end{aligned} \quad (28)$$

which is essentially the same as the amplitude distribution of an ordinary Hermite-Gaussian mode. The phase distribution, however, is different. For an ordinary mirror-mirror stable resonator the mirror surfaces are equiphase surfaces, but now for the retroreflective grating resonator the spherical mirror is not an equiphase surface. Thus the amplitude distribution of the eigenmode at a remote plane is not the same as that of an ordinary Hermite-Gaussian function, and one finds that asymmetries develop with respect to the optical axis.

After the field distribution on the mirror has been determined, the field on the grating macroscopic surface before retroreflection can be derived by a Fresnel integration

$$\begin{aligned} E_{xm}^{(1)}(x_1) &= \exp\left(-ikd - ik\frac{L}{2}\right) \exp(-ikx_1 \tan\theta)(1 - \tan\theta) \\ &\times \left(1 - \frac{x_1}{L} \tan\theta\right) [\chi'_m \phi_m(B_1x_1) + A'_{m-1} \chi'_{m-1} \\ &\times \phi_{m-1}(B_1x_1) + A_{m+1} \chi'_{m+1} \phi_{m+1}(B_1x_1)], \end{aligned} \quad (29)$$

where

$$A'_{m-1} = iC'_{m-1}g_2^{1/2} \exp(-i\chi) \quad (29a)$$

$$A_{m+1} = -iC_{m+1}g_2^{1/2} \exp(i\chi) \quad (29b)$$

$$\chi'_m = \exp\left[i\left(m + \frac{1}{2}\right)\left(\frac{\pi}{2} - \tan^{-1} \frac{\sqrt{g_2}}{\sqrt{1-g_2}}\right)\right]. \quad (29c)$$

IV. Characteristics of the Retroreflective Grating Resonator

Even when the grating is not perpendicular to the optical axis, from Eq. (25) there still exist confined modes in the resonator. This property has been recently proved by an experiment with a retroreflective corner-cube array resonator.³ The field variations in the y direction are simply the Hermite-Gaussian functions, and the field variations in the x direction are a superposition of Hermite-Gaussian functions together with the perturbation terms ϕ_{m-1} and ϕ_{m+1} . For the fundamental mode the field variation in the x direction is the superposition of ϕ_0 and the perturbation term ϕ_1 .

The perturbation terms are caused by the inclination of the grating. They are proportional to $\tan\theta/(LB_1)$. However, if the following condition is satisfied,

$$\left(\frac{\pi L}{\lambda}\right)^{1/2} \left[\frac{1}{g_2}(1-g_2)\right]^{1/4} \gg \sqrt{m} \tan\theta, \quad (30)$$

then $C'_{m-1} \ll 1$, $C_{m+1} \ll 1$, $A'_{m-1} \ll 1$, $A_{m+1} \ll 1$, and the distribution on the mirror and the grating macroscopic surface can be approximately expressed in the form

$$E_{mn}^{(2)}(x_2, y_2) = \exp(-ikd)(1 - \tan\theta)\phi_m(B_2x_2)\phi_n(B_2y_2), \quad (31)$$

$$\begin{aligned} E_{mn}^{(1)}(x_1, y_1) &= \exp(ikd - ikL/2)(1 - \tan\theta) \\ &\times \exp(-ikx_1 \tan\theta)\phi_m(B_1x_1)\phi_n(B_1y_1). \end{aligned} \quad (32)$$

The phase factor $\exp(-ikx_1 \tan\theta)$ is caused by the inclination of the grating. In this case the field distributions on both the mirror and the grating macroscopic surface are simply the ordinary Hermite-Gaussian functions except for a phase factor, and the field calculation can be simplified by replacing the inclined plane grating by an equivalent plane mirror perpendicular to the optical axis at the center of the grating.

The resonant frequency ν can be found from Eqs. (9), (14), (15), and (27). When the perturbation terms are omitted, the frequency ν is given by

$$\nu = \frac{c}{2L+d} \left[q + \frac{1}{\pi} (m+n+1) \cos^{-1} \sqrt{g_2} \right], \quad (33)$$

where q is an integer, and c is the velocity of light in the resonator. This expression for ν is just the same as for a common resonator with two mirrors and a mirror spacing $L + d/2$. The axial frequency spacing is $\Delta\nu = c/(2L + d)$ when the grating is perpendicular to the optical axis, and this was proved by the experiment with a retroreflective corner-cube array resonator.³ Thus this type of resonator is not a typical phase conjugation resonator, which would have the axial frequency spacing $\Delta\nu' = c/4L$.⁴ The resonant frequency must satisfy the grating resonant condition when the grating is inclined to the optical axis

$$\nu = pc/(2d \sin\theta), \quad (34)$$

where p is an integer. Hence this resonator can be used to select frequency just as a common grating resonator.

For an ordinary resonator the diffraction losses per round trip are equal to zero when the Fresnel number

approaches infinity. However, the losses per round trip δ for the present grating resonator are equal to

$$\delta \approx 2 \tan \theta. \quad (35)$$

This results from the fact that only part of the grating area contributes to the retroreflected ray.

For common grating resonators there are several diffracted principal maximum waves away from the grating. For this retroreflective grating resonator there is only one significant diffracted wave, which is the retroreflective wave.

V. Conclusion

We have solved the self-consistent Fresnel-Kirchhoff integral equation for the field distribution of the resonant modes in a retroreflective grating resonator in the limit of infinite Fresnel number, and the characteristics of this resonator have been described. The modes are similar in many respects to the modes of conventional laser resonators. The main restriction on the use of the final results is that the grating constant d should be large compared with the wavelength and small compared with the beam spot size on the grating. If needed, the calculations can be generalized and this restriction relaxed.

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Archivist Compares Manual with Computer Retrieval

Achivists who hope to expand their capacity to locate larger percentages of relevant archival documents by converting to expensive computerized retrieval systems may find the results disappointing, Smithsonian Archivist Richard H. Lytle says.

Lytle believes that his recent study comparing two retrieval systems—one manual and one computerized—may be the first such experiment carried out in a real-life archival setting. His findings, that neither system produces consistent or reliable results, were presented in the *American Archivist* (Winter and Spring 1980).

The two archival methods tested were the traditional provenance method, wherein records are organized via descriptions of the activities of the person or organization which created them, and the computerized content indexing method, which is set up electronically to match information in the request with information that may be contained in the documents.

While the content indexing method has the potential for much greater thoroughness and precision, its effectiveness is entirely dependent upon the accuracy and appropriateness of the system's vocabulary. The system will be usable only if the person who set it up had a clear, comprehensive view of the system users' needs.

The manual provenance method, on the other hand, depends heavily on the expertise of current archives staff and their knowledge of the archives collection.

Lytle ran his evaluation in an actual archival setting because he believes that similar studies made in controlled laboratory conditions have had questionable practical value. The person who sets up a controlled test, for example, also chooses relevant documents that are to be retrieved. In an actual archival situation, it is impossible to determine how many documents are relevant to a given question.

Lytle conducted his study at the Baltimore Institutional Studies Center, a division of the University of Baltimore which conducts urban research. Four archivists alternated in using manual and computerized methods to answer 20 retrieval questions.

Surprisingly, the relative performance of the two methods was approximately equal, with neither method retrieving a high percentage of relevant documents. "This result," Lytle believes, "is probably typical of retrieval from archives."

He admits to the possibility of distortion in his study, due to the small number of questions run, but he adds that there is evidence that the methodology of the research design is sound. With modifications, it could be used to evaluate and compare two or more archival or museum retrieval systems on the same collection.

Lytle points out the similarities between museum and archival retrieval systems and the implications of his findings for both types of institutions.

Specifically, the experiment suggests that research is needed on how the provenance method can be systematized and improved to the extent it could be computerized. This might be the most cost-effective retrieval device for a museum or archives system, Lytle says.

And, agencies considering the content indexing method should be sure of potential user needs as they develop a system vocabulary.