

Reflection of a beam of finite size from a corrugated waveguide

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Abstract. The paper is concerned with the influence of the finite size of an incident beam upon both the anomalous-reflection spectrum and the shape of the energy distribution in a reflected beam. It is proved experimentally that the use of corrugated waveguides as a laser-resonator selective mirror improves the spatial coherence of radiation.

1. Introduction

In the excitation of a corrugated waveguide by a plane wave an anomalous reflection of light is observed [1-3]. The influence of the waveguide mode upon the zero orders of diffraction (the reflected and transmitted waves) turns out to be rather important: the reflection coefficient can be varied from zero to unity, and the reflected wave phase can be monotonically changed by 2π [4]. Owing to the resonant nature of the waveguide excitation such anomalies are concentrated in a fairly narrow spectrum interval

$$\Delta\lambda \approx \frac{\Lambda\lambda\alpha_r}{4\pi} \quad (1)$$

and with an angle of incidence

$$\Delta\theta \approx \frac{\lambda\alpha_r}{4\pi \cos \theta}, \quad (2)$$

where λ is the radiation wavelength, θ is the angle of light incidence, Λ is the grating period, and α_r is the radiative losses in the waveguide. Approximations (1) and (2) are valid far from normal and grazing incidence. It is assumed that the corrugation is shallow (that is $2\pi\lambda^{-1}\sigma \ll 1$, where σ is the corrugation half-depth), and that the corrugation period is such that there is only one radiative order in the corrugated waveguide. The spectral width of the reflection peak $\Delta\lambda$ cannot be infinitely small, since anomalous reflection is observed when $\alpha_r \gg \alpha_d$ (α_d are the dissipative losses in waveguide) [5]. Hence, according to equation (1), there is a lower limit on the value of $\Delta\lambda$ of $\sim \lambda^2\alpha_d$. For such waveguides whose parameters are experimentally achievable ($\alpha_d \sim 0.1 \text{ cm}^{-1}$), $\Delta\lambda \sim 0.1 \text{ \AA}$ is obtainable.

So, anomalous reflection is of interest in the construction of different devices, in particular, frequency filters.

Devices in practical use always operate with beams of finite size. This fact has induced us to analyse the influence of the finite size of incident beams upon anomalous reflection. The most important aspects of this analysis, for instance, the energy redistribution in a reflected beam cross-section (beam-shape modification),

and the change of the reflection spectrum with regard to variation of the size of the incident beam, are considered in this paper.

2. Theoretical approach to the description of the reflection of a finite-size beam

The behaviour of the reflection coefficient $\rho = r \exp i\psi$ (where r is the amplitude coefficient and ψ is the phase shift of the reflected wave) with respect to the angle of incidence θ leads to some specific features that occur in the reflection of a finite-size beam. The typical example of this kind of phenomena is the Goose-Hanchen shift at total internal reflection [6].

In the case of the anomalous reflection of light from a corrugated waveguide these phenomena can be expressed distinctly owing to the large values of the derivatives $dr/d\theta$ and $d\psi/d\theta$ due to the waveguide-mode excitation. In the work of T. Tamir and H. L. Bertoni [7], a general theoretical model was constructed for the reflection of a limited beam from the waveguide surface on excitation of the waveguide mode. A detailed analysis was, however, performed only for the case of a multilayer structure (a prismic method of waveguide excitation) with the assumption that the reflection coefficient ρ is equal to $|\rho(\theta)|=1$ for plane waves with a sufficiently broad range of values of the angle of incidence θ . In this case the waveguide excitation influences only the phase of the reflected plane wave. It was shown that at a specific phase-relationship between the components of the reflected wave, that is for the 'geometric-optic' component and the component due to light emission from the waveguide occurring only at $\theta=\theta_p$ (θ_p is the angle corresponding to the greatest mode excitation), the energy spatial distribution in the reflected beam has the specific form of two individual lobes.

At other angles of incidence, and not taking account of the other $\rho(\theta)$ function, as noted in [7], the energy distribution in the reflected beam would be different.

As for the limited beam reflection from the surface of a corrugated waveguide, all Tamir and Bertoni's analytical expressions are based on the assumption that the $\rho(\theta)$ dependence is known. However, the parameters involved in the formula for $\rho(\theta)$ were not determined by the authors for the case of a corrugated waveguide. Correspondingly, a detailed analysis of the energy distribution in the reflected beam for the case of a corrugated waveguide was also absent from their work.

Note that the $\rho(\theta)$ function for a corrugated waveguide appreciably differs from that for a multilayer structure. For instance, far from anomaly Fresnel reflection is observed, that is $|\rho(\theta)|^2 \ll 1$ (~ 0.04 for waveguides on a glass substrate), and in the vicinity of the excitation angle we have $|\rho(\theta_0)|=1$ at some $\theta=\theta_0$.

In this paper we study the influence of the limited dimensions of an incident beam upon the maximum reflection coefficient, the reflection spectrum, and the energy distribution in a reflected beam for the case of light reflection from just the surface of a corrugated waveguide. We employ the same approach as Tamir and Bertoni, but dwell in detail on these aspects omitted from their consideration.

We shall consider the beam to be limited by only one coordinate, that is along the direction of propagation of the waveguide mode. Such an assumption, generally speaking, does not correspond to the usual experimental conditions, however, it significantly simplifies the theoretical analysis, without obscuring the specific features of the limited beam reflection caused by excitation of the waveguide mode.

It is more suitable to take as an independent variable the projection on the waveguide plane of the incident wave-vector q

$$q = \frac{2\pi}{\lambda} \sin \theta, \tag{3}$$

rather than the angle of incidence θ (figure 1).

As plane-wave reflection from a periodically perturbed waveguide has been well investigated [1-5], the limited beam is best represented as a superposition of plane waves. Because of the linearity of the main electrodynamic equations, the amplitude reflection coefficient of each plane wave can be found independently. Then, by summing up the reflected waves, it is possible to obtain the reflection coefficient and energy distribution of the initial beam.

The electric-field distribution of the incident wave (we observe only TE-polarized waves) in the plane $Z=0$ may be determined with the help of the complex-valued function

$$E_i(x) = F(x) \exp(iq_0 x), \quad q_0 = \frac{2\pi}{\lambda} \sin \theta_0, \tag{4}$$

where θ_0 is the angle of incidence of the limited beam, $|F(x)|^2$ is the energy flux distribution of the incident beam at $Z=0$, and $\arg(F(x))$ gives the curvature of the incident-beam wavefront. The $E_i(x)$ expansion in terms of plane waves has the following form

$$E_i(x) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{+\infty} \hat{E}_i(q) \exp(iqx) dq, \tag{5}$$

where

$$\hat{E}_i(q) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{+\infty} F(x) \exp[i(q_0 - q)x] dx, \tag{6}$$

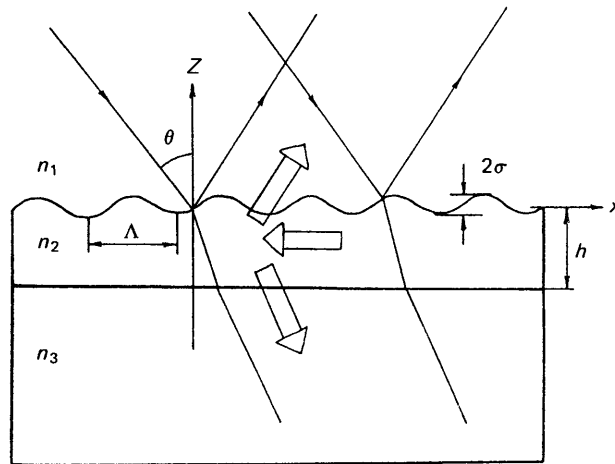


Figure 1. Corrugated dielectric waveguide.

The electric field of the reflected wave in the plane $Z=0$ will be defined as follows

$$E_r(x) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{+\infty} \rho(q) \hat{E}_i(q) \exp(iqx) dq, \quad (7)$$

where $\rho(q) = r(q) \exp[i\psi(q)]$ is the reflection function of the plane wave. The refraction coefficient R of the finite-size beam will be defined as

$$R = \frac{\int_{-\infty}^{+\infty} |\hat{E}_i(q) \rho(q)|^2 dq}{\int_{-\infty}^{+\infty} |\hat{E}_i(q)|^2 dq}. \quad (8)$$

Using the well known relation between the normalizing factor for the function and its Fourier transform

$$\int_{-\infty}^{+\infty} |\hat{E}_i(q)|^2 dq = \int_{-\infty}^{+\infty} |E_i(x)|^2 dx,$$

we may write equation (8) as

$$R = \frac{\int_{-\infty}^{+\infty} |E_r(x)|^2 dx}{\int_{-\infty}^{+\infty} |E_i(x)|^2 dx}. \quad (9)$$

Finally, by 'energy distribution in the reflected beam' we mean the following function

$$I_r(x) = |E_r(x)|^2. \quad (10)$$

Note in particular that the incident and reflected beam parameters are determined in the $Z=0$ waveguide plane, rather than in the plane perpendicular to the beam axis. This is done to simplify the comparison of the beam and waveguide parameters.

Formulae (7)–(10) will allow us to calculate both the reflected-beam energy distribution and the integrated reflection coefficient.

3. Linear $\rho(q)$ approximation

The linear $\rho(q)$ approximation is acceptable for describing the reflection of beams that are limited in size for the case in which the diffractive divergence of an incident beam $\delta\theta = (\lambda/a) \cos\theta$ (a is the beam diameter in the waveguide plane) is far less than the angular width $\Delta\theta$ of the anomalous reflection, that is for $a\alpha_r/4\pi \gg 1$. In the vicinity of q_0 , the linear approximation for $\rho(q)$ has the form

$$\rho(q) = [r_0 + b(q - q_0)] \exp\{i[\psi_0 + \beta(q - q_0)]\}, \quad (11)$$

where $r_0 = r(q_0)$, $\psi_0 = \psi(q_0)$,

$$b = \left. \frac{dr}{dq} \right|_{q=q_0}, \quad \beta = \left. \frac{d\psi}{dq} \right|_{q=q_0}.$$

is defined as

(7)

From equations (5), (6) and (7) we have

$$E_r(x) = \left[r_0 \exp(i\psi_0) F(x') + b \exp \left[i \left(\psi_0 - \frac{\pi}{4} \right) \right] \frac{d}{dx'} F(x') \right] \exp(iq_0 x), \quad (12)$$

$$x' = x + \beta, \quad (13)$$

wave. The

Equation (12) clearly indicates that the dependence of the reflected-wave phase ψ on the angle of incidence leads to a shift of the reflected beam for

(8)

$$x' - x = \beta = \frac{d\psi}{dq}, \quad (14)$$

and the dependence of the amplitude of the reflection coefficient r on the same angle leads to a change in the beam shape (that is of the energy distribution in the beam cross-section) (see also figure 2). For the Gauss-Hermite modes we have

function and

$$F(x) = H_n \left(\frac{x}{a} \right) \exp \left[- \left(\frac{x}{a} \right)^2 \right], \quad (15)$$

$$\frac{d}{dx'} F(x') = - \frac{1}{a} H_{n+1} \left(\frac{x'}{a} \right) \exp \left[- \left(\frac{x'}{a} \right)^2 \right],$$

where H_n is the n th-order Hermite polynomial. That is higher order modes are

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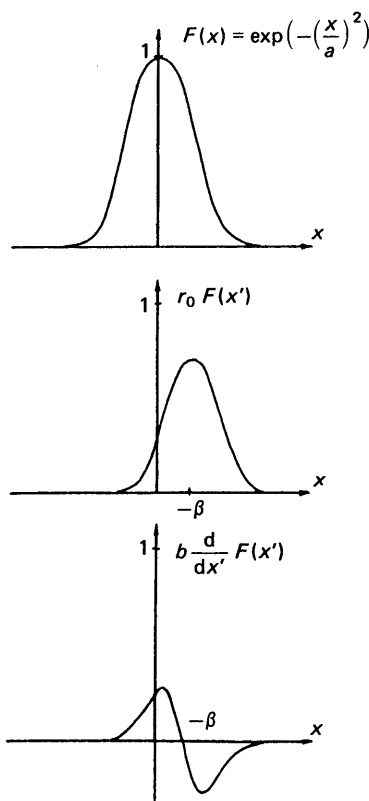


Figure 2. Shift and change of the beam shape upon reflection for the case of the linear $\rho(q)$ approximation.

present in the reflected beam. For the Gaussian beam

$$F(x) = \exp \left[-\left(\frac{x}{a} \right)^2 \right], \quad (16)$$

the energy transformation coefficient into the first-order mode is

$$\gamma = \frac{\int_{-\infty}^{+\infty} \left| b \frac{d}{dx} F(x) \right|^2 dx}{\int_{-\infty}^{+\infty} |F(x)|^2 dx} = \left(\frac{b}{a} \right)^2. \quad (17)$$

We must emphasize that equation (17) is derived by assuming $\rho(q)$ to be linear. Since $1/a$ is the divergence of the diffracted beam (on q -scale) and b is the inclination of the $r(q)$ curve, we may conclude that the value and the linear part of the inclination *versus* $r(q)$ define the Gaussian beam transformation coefficients into the Gauss-Hermite first-order mode.

Estimations for a $\text{SiO}_2\text{-Nb}_2\text{O}_5/\text{CaF}_2$ waveguide with a grating period $\Lambda = 0.38 \mu\text{m}$ and half-depth $\sigma = 0.02 \mu\text{m}$ have demonstrated that under the anomalous reflection regime the coefficient γ is 1.2×10^{-2} . The waveguide design is described in detail in section 7.

Note that in practical applications of anomalous reflection, the angle of incidence is chosen so as to achieve the maximum value of the reflection coefficient; thus, in the present case, $b=0$ and $\gamma=0$.

4. Oblique-incidence beam

In general, the $\rho(q)$ dependence is rather complicated. So, in the following, only the results of the numerical calculations for concrete structures will be presented.

We have chosen a waveguide with the parameters $n_1 = 1$, $n_2 = 1.46$, $n_3 = 1.4328$, $h = 1.41 \mu\text{m}$, $\Lambda = 0.29 \mu\text{m}$ and $2\sigma = 0.08 \mu\text{m}$, so that anomalous reflection is observed at $\lambda \approx 0.566$ and $\theta = 30^\circ$. The diffraction orders being irradiated are the waves which coincide with the transmitted and reflected waves. Radiative losses in this waveguide are $\alpha_r = 4.3 \text{ cm}^{-1}$.

The incident beam is considered to be Gaussian, equation (16). From expression (4), a is the size of the radiation spot on the waveguide surface, rather than the size of the Gaussian beam.

Observe now how the energy is distributed over the beam cross-section under anomalous reflection. The product $\alpha\alpha_r$ is naturally expected to be decisive in this problem, since $l = \alpha_r^{-1}$ is none other than a characteristic length, which is effective for the coupling of the waveguide mode with the incident and reflected waves. The results of the calculations are presented in figure 3. It is seen from analysis of the results that

- (i) if $\alpha\alpha_r \gg 1$, the shape of the incident beam is maintained on reflection without any distortions, and the beam is displaced by $\sim l$;
- (ii) if $\alpha\alpha_r \ll 1$, no anomalous reflection is observed;
- (iii) if $\alpha\alpha_r \approx 1$, the increase of the reflection coefficient caused by mode excitation is rather large, $R \approx 0.5$. In this case a considerable broadening of the reflected beam is observed in the direction of propagation of the waveguide mode.

(16) Thus, one more condition should be added to the well known conditions for anomalous reflection. Not only must the angle of incidence, wavelength, grating period and effective refractive index n^* correspond to the excitation of the waveguide mode

$$n^* = \sin \theta + \frac{\lambda}{\Lambda},$$

(17) and the dissipative losses be small compared with the radiative ones $\alpha_d \ll \alpha_r$, but also the incident beam diameter should be sufficiently large $a \gg 1$.

5. Normal incidence

Normal incidence may be more applicable for practical use. Its specific feature is the simultaneous excitation of two waveguide modes propagating in opposite directions and interacting with one another in the second-order diffraction. Let us consider how the finite size of a reflected beam affects the spectral dependence of the reflection coefficient and the energy distribution in the reflected beam.

As an object of investigation we have taken the same waveguide (substrate $n_3 = 1.4328$, waveguide layer $n_2 = 1.46$, $h = 1.41 \mu\text{m}$, $2\sigma = 0.08 \mu\text{m}$) except that the grating period $\Lambda = 0.388 \mu\text{m}$ was chosen so that anomalous reflection at normal incidence was observed for $\lambda \approx 0.565 \mu\text{m}$.

It was previously noted [8] that at close to normal angles of incidence, the curve $r^2(\lambda)$ (for $\theta = \text{constant}$) has two typical shapes which are caused by excitation of the waveguide mode excitation of the +1 and -1 diffraction orders, the spectral distance between them being limited by a value proportional to the coupling coefficient of these modes. As $\theta \rightarrow 0$, the spectral width of the longwave reflection peak tends to zero, and with increasing dissipative losses its amplitude reduces at a higher rate than the amplitude of the shortwave reflection peak. This undoubtedly

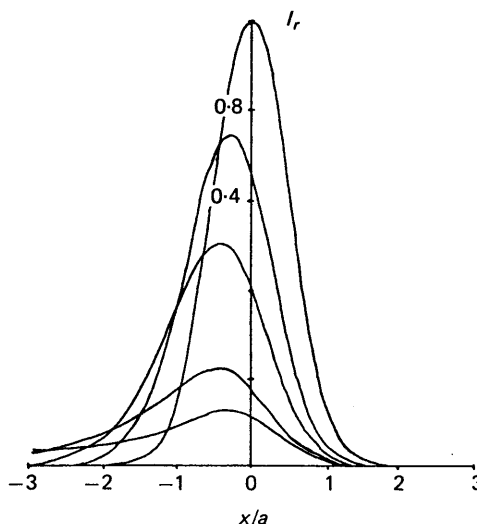


Figure 3. Shift and change of the beam shape upon anomalous reflection from a corrugated waveguide for different incident beam sizes: $a = \infty, 10 \text{ mm}, 5 \text{ mm}, 2 \text{ mm}$ and 1 mm (from highest to lowest peaking).

improves the spectral characteristics of a filter based on a corrugated waveguide. On the other hand, the angular width $\Delta\theta$ of the longwave reflection peak (an $r^2(\theta)$ dependence is observed for $\lambda = \text{constant}$) also tends to zero as $\theta \rightarrow 0$. This case is illustrated in figure 4, where the constant reflection-coefficient lines of the homogeneous plane TE-wave $r^2(\lambda, \theta) = \text{constant}$ are presented with coordinates (λ, θ) .

The angular width of the reflection peak is restricted by the beam diameter $(a/\lambda)\Delta\theta \gg 1$ (that is its diffraction divergence must be far less than $\Delta\theta$). Therefore, for constant a , the long-wavelength reflection peak disappears with decreasing angle of incidence. Figure 5 illustrates the spectral curves $R(\lambda)$ for $\theta = 5 \times 10^{-5}$ rad for a beam of infinite size and for two beams of Gaussian profile with dimensions $a = 10 \text{ mm} - 2 \text{ mm}$. Note that the possibility of avoiding the long-wavelength reflection peak is very important for corrugated waveguides used as frequency filters operating for reflection.

The changes in the shape of the energy distribution in the reflected beam are very similar to those described for the case of oblique incidence. Namely: if $\alpha\alpha_r \gg 1$, the energy distribution in the reflected beam is identical to that in the incident beam; if $\alpha\alpha_r \ll 1$, no anomalous reflection is observed; while if $\alpha\alpha_r \approx 1$ the reflection is sufficiently large ($R \approx 0.5$) and the reflected beam is significantly broadened (figure 6). For normal incidence no beam displacement is observed and, compared with oblique incidence, the broadening is symmetric.

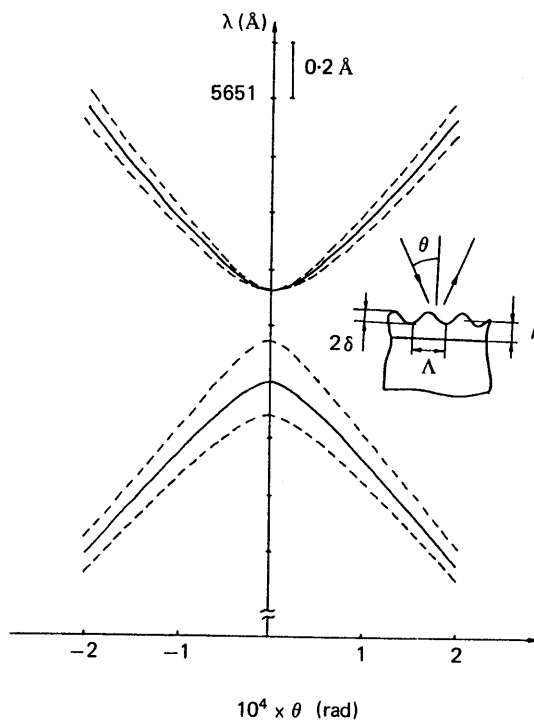


Figure 4. Curves of constant reflection coefficient ($r^2(\lambda, \theta) = \text{constant}$) for small angles of incidence: ($r^2(\lambda, \theta) = 1$ (solid curves); $R^2(\lambda, \theta) = 0.5$ (dashed curves).

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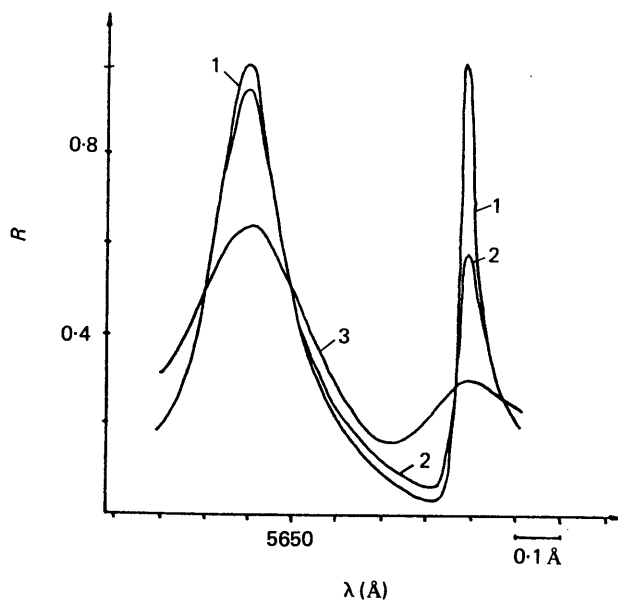


Figure 5. The influence of the finite size of the incident beam upon the anomalous reflection spectrum for: $a = \infty$ (solid curve), 10 mm (dashed curve), 2 mm (dot-dashed curve).

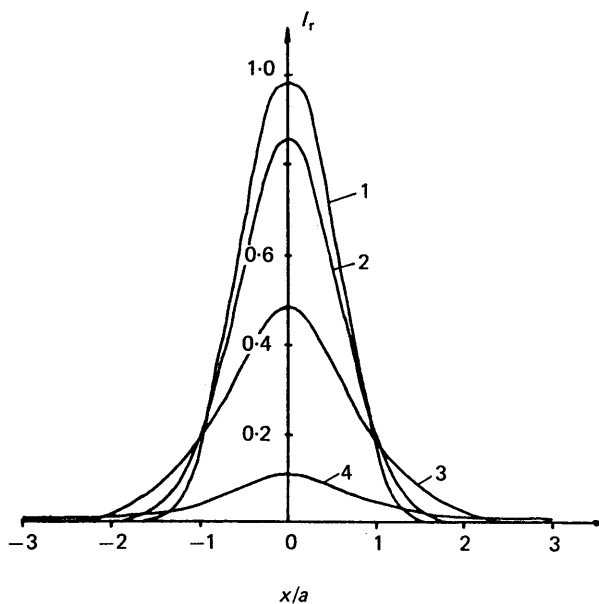


Figure 6. Energy distribution in the reflected beam cross-section for anomalous reflection at normal incidence for: $a = 10$ mm, 5 mm, 2 mm and 0.5 mm (from highest to lowest peaking).

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6. Bulk dielectric grating waveguide

Anomalous light reflection is caused by the excitation of the waveguide modes and is observed for both corrugated and bulk dielectric grating waveguides. Much work has been devoted to corrugated waveguides, whereas bulk dielectric grating waveguides have remained practically unstudied. Without going into details about the method of calculating $\rho(q)$ (it is not an issue for this paper) let us give the typical curves for $r^2(\theta)$ for a structure whose dielectric permeability is given by

$$\varepsilon = \begin{cases} \varepsilon_1, & z > 0, \\ \varepsilon_2 + \Delta\varepsilon \cos Kx, & -h < z < 0, \\ \varepsilon_3, & z < -h, \end{cases} \quad (18)$$

where $\varepsilon_1 = 1.0$, $\varepsilon_2 = 3.92$, $\varepsilon_3 = 2.286$, $\Delta\varepsilon/\varepsilon_2 = 0.0125$, $\lambda = 0.6328 \mu\text{m}$ and $\Lambda = 2\pi/K = 0.44 \mu\text{m}$. Figure 7 demonstrates the characteristic dependence of the reflection coefficient r^2 on the angle of incidence at different values of the waveguide depth h . Such a variety of shapes for this dependence $r^2(\theta)$ is caused by the fact that anomalous reflection is an interference phenomenon. Altering the waveguide thickness leads to a change of the phase of the waves propagating within the waveguide layer and ultimately to a change in the shape of $r^2(\theta)$.

Taking the finite size of the incident beam into account, we come to the same conclusion as we did in the case of the corrugated waveguide: the result of reflection is defined by the value of ad_r (figure 7(b)).

We thus emphasize that anomalous reflection is a general property of periodically perturbed waveguides. However, for waveguides with a bulk dielectric grating providing a one-sided radiation output from the waveguide, no anomalous reflection is likely to be observed, as in the case of two-sided corrugated thin-film waveguides with a unidirectional radiation output [9].

7. Experiment

The effect of beam broadening upon reflection can be used to improve the spatial coherence of laser radiation. In other words, it is easier to achieve coherent operation of the whole active medium in a laser with such a mirror, than it is in a laser with ordinary mirrors. This fact is confirmed experimentally. We used a dye laser (rhodamine 6G) (see figure 8(a)). For dye pumping, second-harmonic radiation ($\lambda = 0.53 \mu\text{m}$) from a YAG-Nd-glass laser was used. Figure 8(b) illustrates the spectrum of the dye-laser radiation. A Ag^+ -diffused corrugated waveguide mirror of period $\Lambda = 0.376 \mu\text{m}$ was used in this resonator. The line position of the selective mirror reflection resulting from the use of a corrugated waveguide did not coincide with the maximum position of the dye amplification. Thus, in the laser generation spectrum, along with the narrow radiation line (caused by selective mirror reflection and corresponding to the waveguide mode) there is a wide band available, which corresponds to the centre of the amplification band of the dye and is caused by the usual Fresnel mirror reflection. Figure 8 demonstrates irradiation in the far zone of this laser, the small spots result from laser radiation under the regime of selective mirror reflection while the large spots result from laser radiation under the regime of Fresnel mirror reflection. This irradiation pattern is due to the narrow-band and wide-band laser irradiation (figure 8(b)). Thus the irradiation caused by anomalous and Fresnel reflection can easily be separated by the absorbed optical filters.

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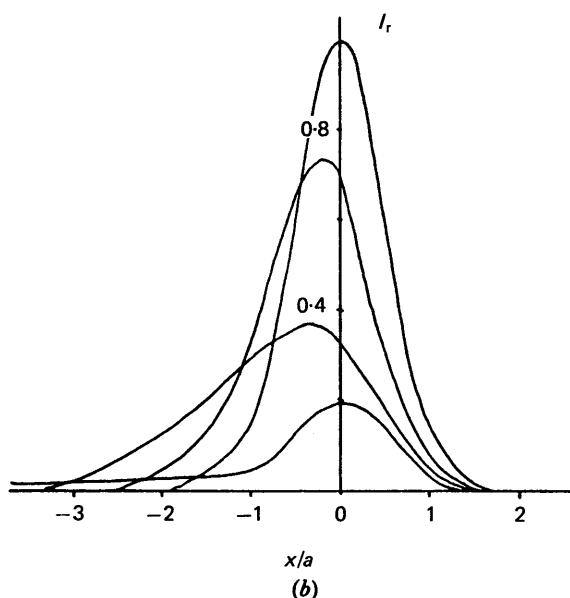
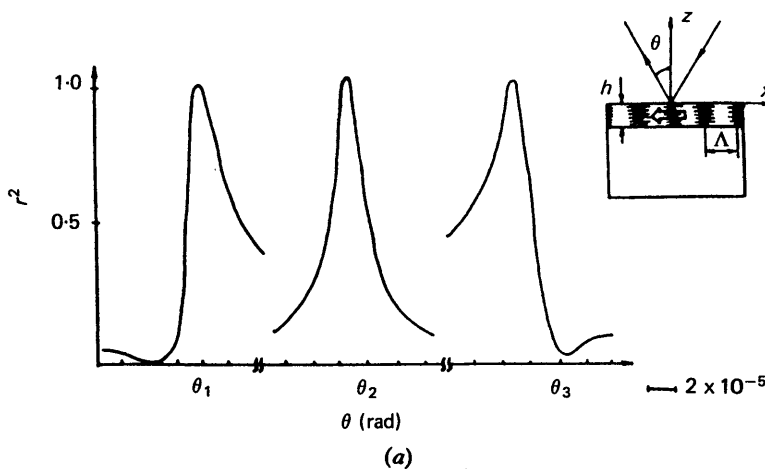


Figure 7. Characteristic shapes (a) of the $r^2(\theta)$ dependence for the bulk grating waveguide for: $h=0.107 \mu\text{m}$, $\theta_1=0.163$ radians; $h=0.158 \mu\text{m}$, $\theta_2=0.255$ radians; $h=0.237 \mu\text{m}$, $\theta_3=0.370$ radians (from left to right). Shift and change of the beam shape (b) upon anomalous reflection from the bulk dielectric grating waveguide for: $a = \infty$, 20 mm, 7.5 mm, 1 mm; $\alpha_r = 1.8 \text{ cm}^{-1}$ (from highest to lowest peaking).

Since the dye-pumping range is in itself a narrow line, stretched across the grating lines, the divergence of radiation along the lines is equally large under both regimes, whereas perpendicular to the lines it differs considerably. For irradiation under the usual Fresnel reflection regime it is sufficiently large. Several independent generation zones appeared to exist within the pumping range. For irradiation under the anomalous reflection regime the divergence is the same as in the diffraction regime, corresponding to the dimensions of the pumping range, that is the whole pumping range irradiated coherently.

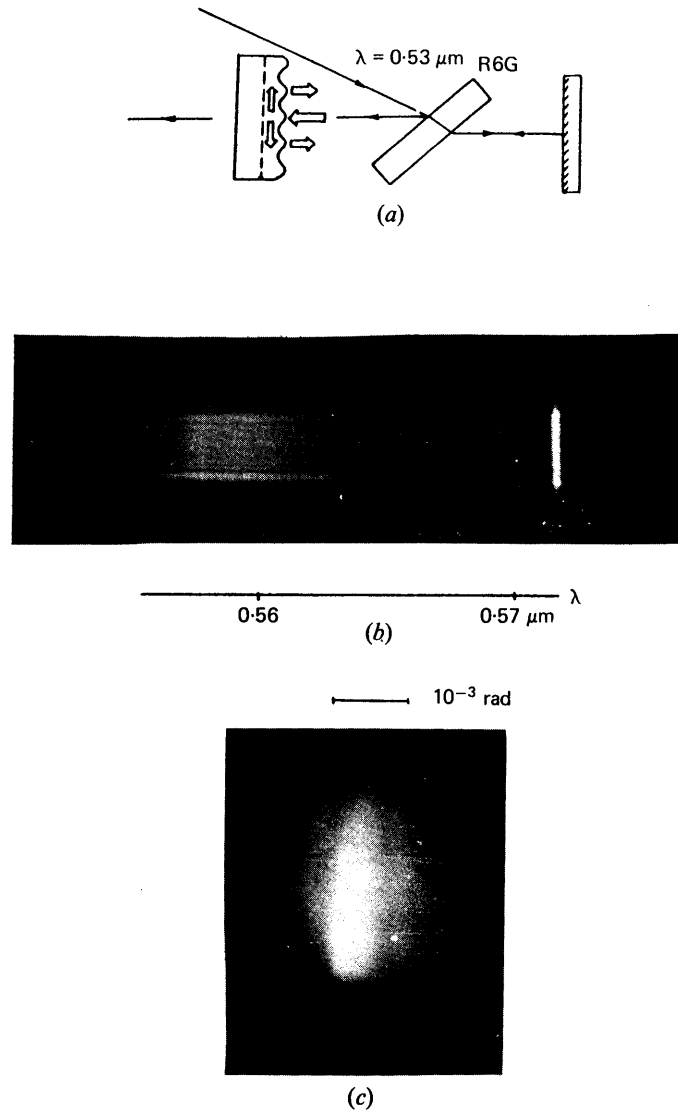


Figure 8. Schematic diagram (a) of a dye laser using a mirror as a corrugated dielectric waveguide; laser radiation spectrum (b); and energy distribution (c) in a laser beam in the far zone.

The maximum mirror reflection coefficient was ~ 0.5 .

We have stated using the empirical method that, for large reflection coefficients, waveguides with small gratings (small values α_r) are preferable and so consequently are large-size beams. This is due to specific features of our technology. In constructing deep gratings, non-periodic noise arises, which leads to increasing scattering (that is dissipative losses) in the waveguide, thereby making the waveguide slightly inhomogeneous with respect to thickness. We have succeeded in constructing a $\text{SiO}_2\text{-Nb}_2\text{O}_5/\text{CaF}_2$ waveguide mirror with maximum reflection coefficient ~ 0.7 and incident beam diameter $a = 10$ mm. He-Ne laser radiation

($\lambda = 0.6328 \mu\text{m}$) was used in the experiment. Decreasing the incident beam diameter to $a = 3 \text{ mm}$ reduces the reflection coefficient to ~ 0.65 .

It should be noted that maximum reflection (~ 0.7) has been achieved in the regime of anomalous light reflection from a corrugated waveguide by using a combined waveguide: a thin Nb_2O_5 film (thickness $d = 20 \text{ nm}$) on a SiO_2 thin-film waveguide (thickness $h = 0.44 \mu\text{m}$) on a CaF_2 substrate. The refractive indices in the spectrum range of interest are respectively $n_{\text{Nb}_2\text{O}_5} = 2.3$, $n_{\text{SiO}_2} = 1.46$ and $n_{\text{CaF}_2} = 1.4328$. The evaporation of the Nb_2O_5 film with its larger refractive index leads to a deformation of the profile of the waveguide, which intensifies the field at the surface and thereby provides the higher interaction of the waveguide mode from the incident and reflected waves. Both the coefficient of the radiative losses and the maximum reflection coefficient are increased then over the spectral range in which anomalous reflection occurs.

8. Conclusion

We have considered the influence of the finite size of an incident beam upon the anomalous-reflection spectrum and the shape of the energy distribution in the reflected beam. We have demonstrated that significant changes in the reflected-wave amplitude due to anomalous reflection lead to a deformation of the energy distribution in the reflected beam, while significant changes of the phase lead to shifts of the reflected beam. If $\alpha\alpha_r \gg 1$, the beam remains unaltered and, in the case of oblique incidence, is shifted a distance $\sim l = \alpha_r^{-1}$. If $\alpha\alpha_r \ll 1$, no anomalous reflection is observed. If $\alpha\alpha_r \approx 1$, significantly large reflection ($R \sim 0.5$) and reflected-beam broadening (symmetric for normal incidence and asymmetric for oblique incidence) is observed.

We have proved experimentally that the use of corrugated waveguides as selective laser-resonator mirrors improves the spatial coherency of radiation.

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