Optical and Quantum Electronics 18 (1986) 123–128

Diffraction characteristics of planar corrugated waveguides

G. A. GOLUBENKO, A. S. SVAKHIN, V. A. SYCHUGOV, A. V. TISCHENKO
Institute of General Physics, Academy of Sciences of USSR, Vavilov St. 38, Moscow, USSR

E. POPOV, L. MASHEV
Institute of Solid State Physics, Bulgarian Academy of Sciences, Lenin Boul. 72, Sofia 1184, Bulgaria

Received 12 August; revised 10 October 1985

The diffraction efficiency curves are calculated as a function of the angle of incidence for planar waveguides with corrugation on the waveguide–air boundary or on the waveguide–substrate boundary, respectively. It is shown that the reflectance of the system is increased up to 100% because of the excitation of the waveguide mode. A detailed phenomenological study is carried out taking into account the influence of the waveguide thickness and the corrugation depth. Possible applications of these waveguides as a narrow band reflection filter and selective mirror are discussed.

1. Introduction

Corrugated planar waveguides are widely used in integrated optics as input–output couplers, filters, demultiplexers, in DFB and DBR lasers, etc. These numerous investigations of such waveguides (see, e.g. [1, 2]) can be classified mainly in three ways: (i) coupling of the incident volume wave into waveguide modes; (ii) conversion between different modes in the case of Bragg diffraction (including both the co-planar and oblique incidence of modes on the grating); and (iii) searching for eigenvalues and eigenfunctions.

The purpose of this paper is to present a study of the diffraction efficiency behaviour of a planar waveguide with sinusoidally modulated waveguide–air or waveguide–substrate boundaries. If a plane monochromatic wave illuminates the structure at an angle close to the angle of excitation of a waveguide mode, some surprising effects are observed. First, the reflectance of the system is changing rapidly with a peak up to 100%. Secondly, the zeroth order becomes angular and/or wavelength selective and thirdly, contrary to the well-known grating anomalies which are usually accompanied by a sharp failure of the efficiency, the -1 orders both in air and in substrate have maxima.

2. Formulation of the problem

Fig. 1 is a schematic drawing of the structure and the diffraction process under consideration. The planar waveguide is infinite along the x-axis and one of its boundaries is corrugated. For simplicity, we assume that the grating with a period d and a groove depth $2h$ is sinusoidal. A plane monochromatic wave (TE polarization) excites a waveguide mode at an angle θ_i from the air side, near to

$$\theta_i = \sin^{-1}[(\beta/k)_n - \lambda/d] \qquad (1)$$

where $(\beta/k)_n$ is the effective index of the nth waveguide mode and λ is the wavelength in vacuum.

0306–8919/86 $03.00 + .12

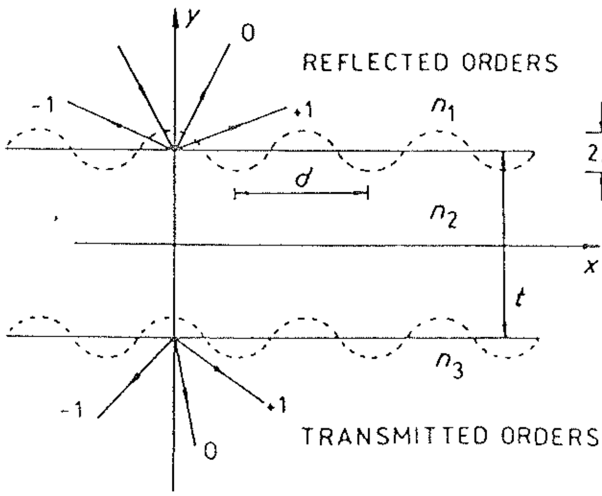

Figure 1 Schematic representation of a waveguide with corrugated surfaces.

Two approaches have been used for calculating the diffraction efficiency curves: (i) numerical treatment based on the Rayleigh–Fourier theory [3] and (ii) theoretical analysis based on the resul of [4, 5]. The theoretical analysis is valid in the assumption of small corrugation, i.e. $(2\pi h/d) \ll 1$, whereas the numerical results show good convergence up to the ratio $h/d \approx 0.35$ [3]. In fact the two approaches give identical results for shallow gratings.

3. Results

The diffraction efficiency of the zeroth reflected and transmitted orders as a function of the angle of incidence θ_i for the case of waveguide–air boundary corrugation are presented in Fig. 2. At optimal angle of excitation of the mode the intensity of the transmitted wave in the lossless waveguide is equal to zero, the reflectance of the system reaching almost 100%. However, for the same waveguide parameters when the corrugation is at the waveguide–substrate boundary the result is different: zero intensity of the zeroth order wave can be attained not only in the substrate but in the air too (see Fig. 3). Another interesting feature is that in the vicinity of the excitation of the waveguide mode the efficiency of the -1 order has a maximum both in the air and in the substrate (Fig. 4). The value of the reflection maximum depends on the losses of the waveguide. The results of calculations of the reflection spectral characteristics for waveguides with different attenuation constants ($\gamma = 1, 10, 100\,\mathrm{cm}^{-1}$) are presented in Fig. 5. The calculations show that in real waveguides with losses less than $50\,\mathrm{dB\,cm}^{-1}$ the described effects can be observed. For experimental verification of that phenomenon we made a ZnO waveguide with thickness $t = 0.36\,\mu\mathrm{m}$ on a corrugated glass substrate ($d = 0.6\,\mu\mathrm{m}$, $h = 0.02\,\mu\mathrm{m}$). The real waveguide turned out to be

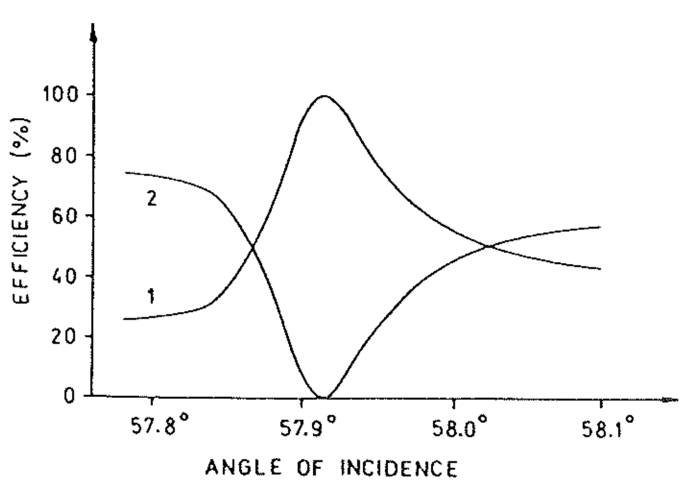

Figure 2 Intensity of the zeroth diffraction reflected, Curve 1, and transmitted, Curve 2, orders as a function of the angle of incidence in the vicinity of a waveguide mode excitation. The parameters of the system are: $n_1 = 1$, $n_2 = 1.98$, $n_3 = 1.512$, $\lambda = 0.6328\,\mu\mathrm{m}$, $t = 0.4\,\mu\mathrm{m}$, $h = 0.02\,\mu\mathrm{m}$ and $d = 0.6062\,\mu\mathrm{m}$.

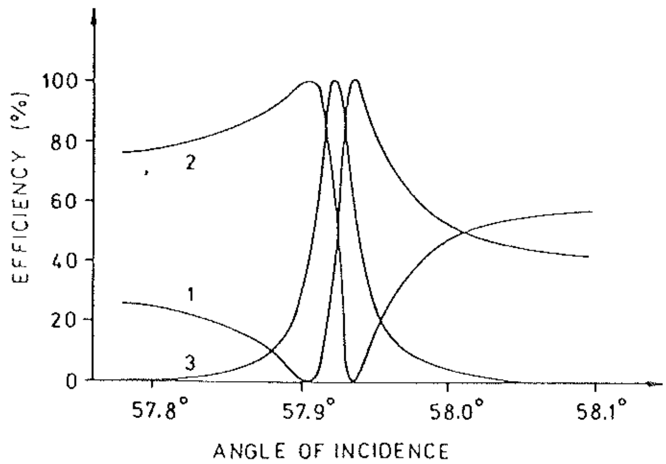

Figure 3 As for Fig. 2 except that the substrate is corrugated. Curve 3 is the normalized amplitude of the waveguide mode, $I_{mode} = I/I_{max}$.

corrugated from both the air and substrate sides. To attain zero intensity of the reflected wave, it is necessary to provide a proper ratio of the depths of the upper and lower corrugation. Because in the experiment this condition could not be satisfied, we observed only an increase of the intensity of the reflected wave and the corresponding reduction of the intensity of the transmitted wave under optimal excitation conditions of the waveguide mode (Fig. 6).

4. Phenomenological study

A physical explanation of the above-stated results can be obtained using the well-known phenomenological approach [6]. Near the excitation of the surface wave in a grating surface layer (metallic or dielectric), in the case of no anomaly interactions, the amplitudes of the diffracted waves b_i can be expressed in the following form

$$b_i = \Gamma_i(\alpha)\,\frac{\alpha - \alpha_i^z}{\alpha - \alpha^p} \tag{2}$$

where $\alpha = \sin\theta_1$, $i =$ r, t for the reflected and the transmitted zeroth orders, respectively, α_r^z and

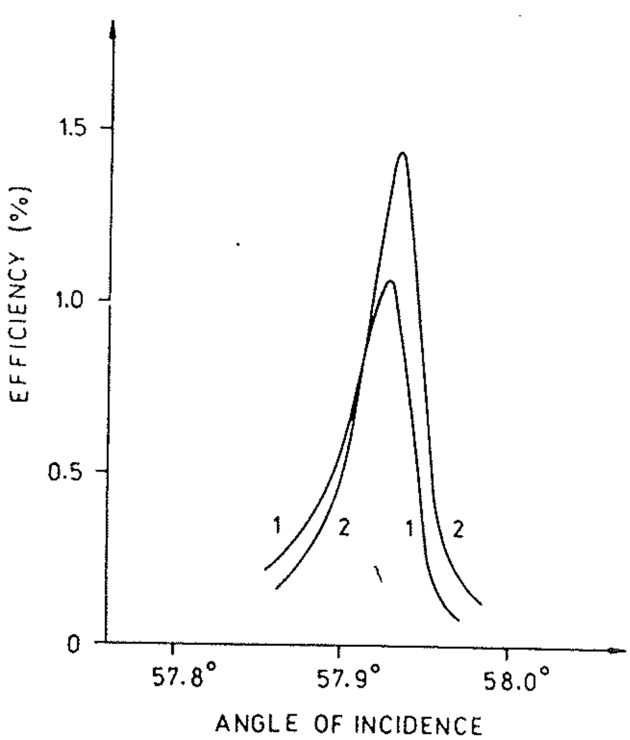

Figure 4 Angular dependence of the efficiency of the −1 reflected (Curve 1) and transmitted (Curve 2) orders, when the corrugation is at the waveguide–substrate boundary. The parameters of the system are the same as in Fig. 2.

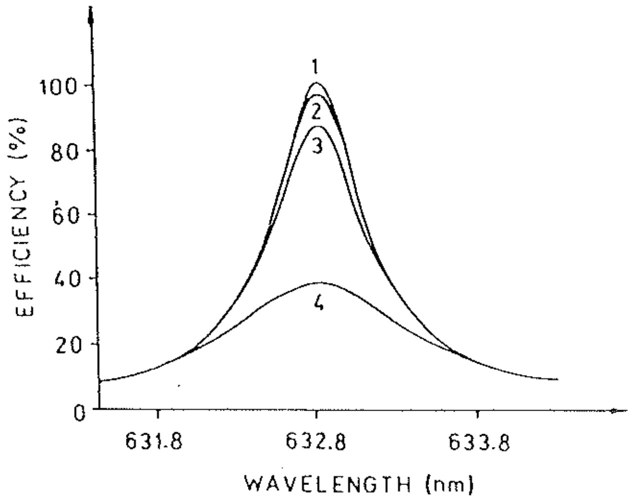

Figure 5 Spectral characteristics of the reflectance of a waveguide with corrugation of the waveguide–substrate boundary: $n_1 = 1$, $n_2 = 1.98$, $n_3 = 1.512$, $t = 0.158\,\mu m$, $d = 0.4\,\mu m$, $h = 0.02\,\mu m$. Curve 1, $\gamma = 0\,cm^{-1}$; Curve 2, $\gamma = 1\,cm^{-1}$; Curve 3, $\gamma = 10\,cm^{-1}$ and Curve 4, $\gamma = 100\,cm^{-1}$.

α_t^z are the zeroes of the reflectance and transmittance, α^p is a pole of the amplitudes (one and the same for all of them) and $\Gamma_r(\alpha)$ and $\Gamma_t(\alpha)$ are coefficients slowly varying with α, which for shallow gratings coincide with the Fresnel reflection and transmission coefficients. It can be shown that in the case of planar lossless waveguide

$$\alpha^p = \alpha_r^z = \alpha_t^z = (\beta/k) - \lambda/d \tag{3}$$

When the corrugation of the boundary is introduced Equation 3 is no longer satisfied. Both the pole and the zeroes move from the real axis of α into the complex plane. It must be pointed out that when the pole, the zeroes and $\Gamma(\alpha)$ are known, the efficiencies calculated using Equation 2 coincide (with a relative error less than 0.1%) with the curves in Figs 2 and 3.

To find the pole and the zeroes the computer code based on the Rayleigh–Fourier method was generalized to work in the complex α plane. A Newton iterative method for two variables was used in searching for the pole and the zeroes and, usually, 4 to 5 steps were enough.

The dependences of the zeroes on the waveguide thickness are presented in Fig. 7 for the two cases investigated — with corrugation on the air–waveguide boundary ($\alpha_r^{z'}$ and α_t^{z}) and on the waveguide–substrate boundary ($\alpha_r^{z''}$ and $\alpha_t^{z''}$). In [7] where the case of a three-layer dielectric grating with only the zeroth propagating order is considered, it is shown that for the system with a symmetry with respect to the vertical y–z plane α_t^z and $\alpha_t^{z''}$ are real, i.e. zero transmission can be achieved

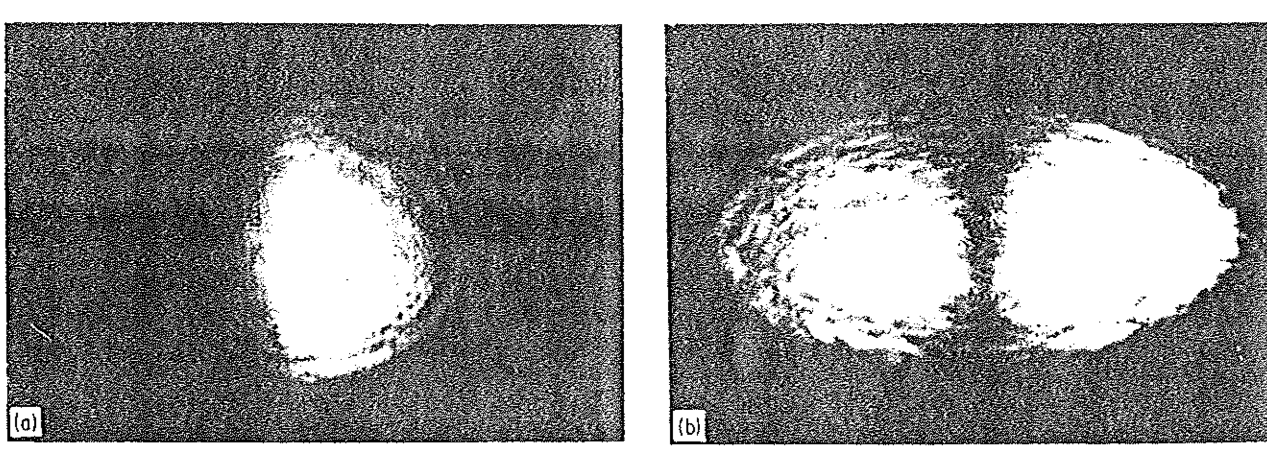

Figure 6 Far-field picture for (a) reflected and (b) transmitted waves. The prolongation of the transmitted beam sp is due to the wedge of the substrate. (Spot size on grating surface is ~100 μm.)

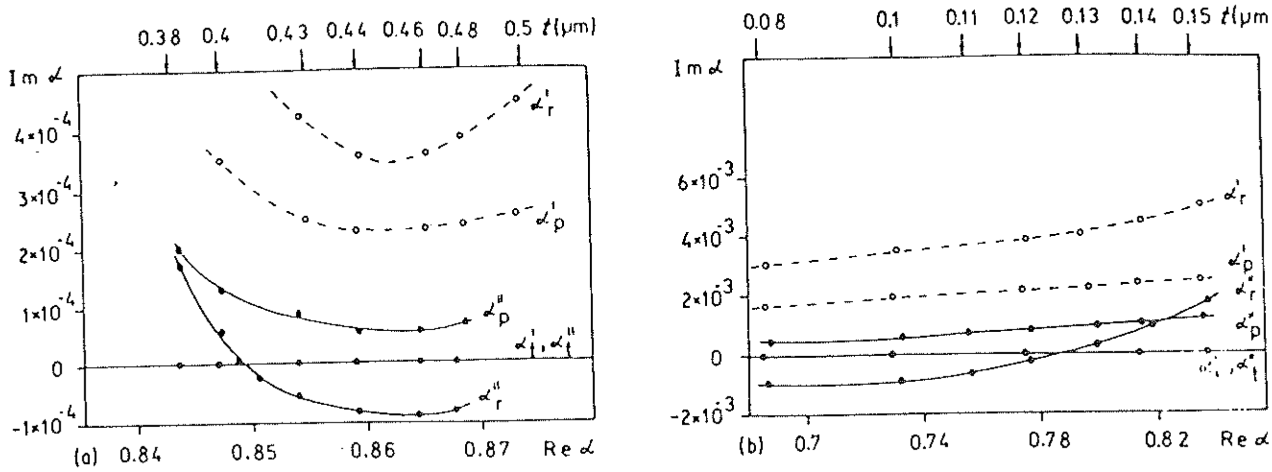

Figure 7 Trajectories of the poles and the zeroes in the complex α plane for different waveguide thicknesses. With o are indicated the positions for the case of the air–waveguide boundary corrugation, and with ● those for the waveguide–substrate boundary corrugation. With arrows are shown the values of the waveguide thickness. The other parameters are: $n_1 = 1$, $n_2 = 1.98$, $n_3 = 1.512$, $d = 0.6062\,\mu$m, $h = 0.02\,\mu$m; (a) $\lambda = 0.6328\,\mu$m, (b) $\lambda = 0.7438\,\mu$m.

real angles of incidence. Because the waveguide corrugation is shallow in the case investigated in this paper, it is expected that α_t^z will be real. This is confirmed by the behaviour of the imaginary part of the transmission zero which is negligible in comparison with the imaginary part of the pole (Fig. 7). However, if the grating groove depth is increased the transmission zero is moving away from the real α-axis. For example, the minimum of the intensity of the transmitted wave has a value of 6% for the same waveguide as in Fig. 2 but with $h = 0.12\,\mu$m ($h/d = 0.2$).

The different behaviour of the efficiencies in Figs 2 and 3 can be explained from the zero dependence of the reflection on the waveguide thickness (Fig. 7). In the case of air–waveguide boundary corrugation the reflection zero $\alpha_r^{\prime}$ does not cross the real α axis and, thus, the reflection minimum is always different from zero. On the contrary, in the case of waveguide–substrate boundary corrugation, $\alpha_r^{z\prime}$ crosses the real α axis at a certain waveguide thickness and, therefore, the zero-reflectance condition can be achieved. The condition for zero intensity of the reflected wave is given by

$$t = \frac{\lambda}{2\pi n_2 \cos\theta_2}\left\{m\pi + \tan^{-1}\left[n_2\cos\theta_2\left(\frac{n_3\cos\theta_3 - n_1\cos\theta_1}{n_1\cos\theta_1(n_2^2\cos^2\theta_2 - n_1 n_3\cos\theta_1\cos\theta_3)}\right)^{1/2}\right]\right\} \quad (4)$$

where $m = 0, \pm 1, \pm 2, \ldots$. Fig. 7a and b represents two solutions of Equation 4 for $m = 2$ and $m = 1$, respectively. To obtain the same angle range of mode excitation, the wavelength of the incident light in Fig. 7b is changed. The film thickness values at which the reflectance minimum is zero, calculated from Equation 4, correspond fairly well to the numerical results. The physical interpretation of the results obtained is quite obvious: the incident light beam excites a guided mode propagating in the corrugated waveguide and coupling out into air and substrate. The direction of the radiated wave coincides with the direction of the reflected or transmitted wave, whereas the phases of the radiated waves can vary depending on the excitation conditions. Because the phase shift between the reflected and the transmitted waves is approximately 180° (at least for shallow gratings), then by changing the excitation conditions of the mode one can achieve a destructive interference in the transmitted beam. For the reflected wave in the case of substrate-boundary corrugation this can happen at values of t given by Equation 4 (cross points of the trajectory of $\alpha_r^{z\prime}$ in the complex α plane with the real axis). For the air–waveguide interface grating the reflection zero remains complex and no total transmission occurs.

5. Conclusion

We have shown that in both the reflectance and the transmission of a corrugated waveguide structure an abrupt change is possible when an excitation of a waveguide mode takes place. This phenomenon has a resonant character; therefore, it allows the realization of narrow-band reflection optical filters and mirrors with selective reflection in a given direction.

References

1. T. TAMIR (ed.), 'Integrated Optics' (Springer, Berlin, Heidelberg, New York, 1975).
2. D. MARCUSE, 'Theory of Dielectric Optical Waveguides' (Academic, New York, 1974).
3. E. POPOV and L. MASHEV, *Opt. Acta* (submitted).
4. V. A. SYCHUGOV and I. CTIROKY, *Kvant. Elektr.* 9 (1982) 634.
5. V. A. SYCHUGOV and A. V. TISCHENKO, *ibid.* 9 (1982) 1451.
6. R. PETIT (ed.), 'Electromagnetic Theory of Gratings' (Springer, Berlin, Heidelberg, New York, 1980).
7. E. POPOV, L. MASHEV and D. MAYSTRE, *Opt. Acta* (submitted).