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DIFFRACTION FROM PLANAR CORRUGATED WAVEGUIDES AT NORMAL INCIDENCE

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The effect of normal incidence mode excitation in a corrugated waveguide is studied theoretically. The behaviour of the reflectance is explained by a phenomenological approach.

1. Introduction

In our previous paper [1] we have shown that the resonance anomaly of a dielectric coated grating due to excitation of a waveguide mode induces strong wavelength and angular selectivity in the zeroth reflected order efficiency. In particular, a tunable narrow-band reflection filter with spectral halfwidth of 3 Å has been demonstrated. The theoretical minimum and maximum values of the reflectivity depend only on the symmetry of the system [2]. However, the considerations in ref. [2] are valid only away from the domain of anomaly interactions when in the waveguide two different modes are excited simultaneously.

On the other hand very often filter and tuning devices are used in a regime when the light is incident perpendicularly to the surface (for example Fabry-Perot interferometers, dielectric multilayered mirrors and wavelength filters, etc.) If the grating period is chosen properly a normally incident on the corrugated waveguide wave excites modes propagating in two directions, since the phase-matching conditions are satisfied simultaneously for both of them. The purpose of this work is to study the basic features of the anomaly in the zero-order efficiency caused by mode excitation at normal incidence. Although the problem can be treated using rigorous electromagnetic theories [3], the utilization of the phenomenological approach [4] enables to establish some simple rules, very useful for the optimization of the device operation.

2. Symmetry and phenomenological approach

Let us consider a corrugated waveguide shown schematically in fig. 1. From air ($n_1 = 1$) a linearly polarized plane wave with an amplitude a_1 illuminates the structure. We suppose that the grating period is such that in air and in substrate only the zeroth reflected and transmitted orders with amplitudes b_1 and b_2, respectively, are diffracted. At a certain set of the system parameters it is possible to excite two modes in the waveguide simultaneously (for example by two different diffraction orders). In the vicinity of the anomaly interaction the amplitudes of the diffracted wave can be represented by the following phenomenological formulae [5]:

$$b_j = \Gamma_{j1} \frac{\alpha - \alpha_1^z}{\alpha - \alpha_1^p} \frac{\alpha - \alpha_2^z}{\alpha - \alpha_2^p} a_1 , \quad j = 1,2 , \tag{1}$$

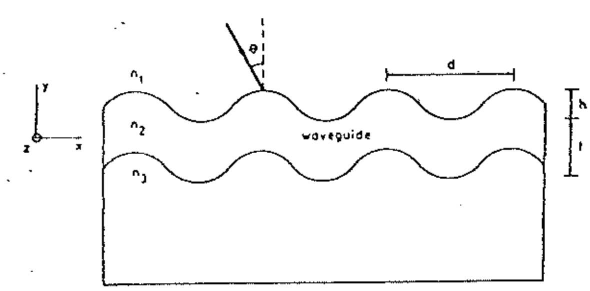


Fig. 1. Schematical representation of waveguide with double-side corrugation.

where $\alpha = \sin\theta$, θ is the angle of incidence, $\alpha_{1,2}^{z}$ and $\alpha_{1,2}^{p}$ are the zeroes and the poles corresponding to the two excited modes and Γ are slowly varying with α functions, which without corrugation coincide with Airy reflectance and transmittance coefficients of the plane layer.

The structure in fig. 1 has a symmetry with respect to a vertical Oyz plane and the zeroth reflected order efficiency must be independent of the sign of α, thus

$$\alpha_2^{z} = -\alpha_1^{z} = \alpha_{r,t}^{z} , \quad \alpha_2^{p} = -\alpha_1^{p} \equiv \alpha^{p} . \tag{2}$$

Therefore (1) can be expressed in the form:

$$b_1 = \Gamma_{11} \frac{\alpha^2 - (\alpha_r^z)^2}{\alpha^2 - (\alpha^p)^2} a_1 ,$$

$$b_2 = \Gamma_{21} \frac{\alpha^2 - (\alpha_t^z)^2}{\alpha^2 - (\alpha^p)^2} a_1 . \tag{3}$$

To check the validity of (3) in fig. 2 a comparison between rigorous numerical [6] and phenomenological results is made. For a single mode excitation in the case of a symmetry with respect to the Oyz plane the transmission zero α_t^z is real [2], therefore a 100% reflectivity is achieved, independent of grating and waveguide parameters. If the system is symmetrical with respect to the z-axis, too (fig. 1 with $n_1 = n_3$),

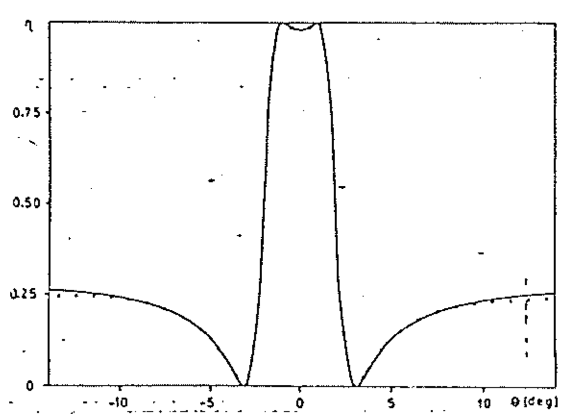


Fig. 2. The numerical (solid curve) and phenomenological (black circles) reflectance for a waveguide with $n_1 = n_3 = 1$, $n_2 = 2.3$, $d = 0.37$ μm, $h = 0.04$ μm, $t = 0.102$ μm, TE polarized light with wavelength $\lambda = 0.6328$ μm. The following phenomenological parameters are used: $|\Gamma_{11}|^2 = 0.262$, $\alpha_r^z = 0.05298$ and $\alpha^p = 0.03427 + i0.01654$.

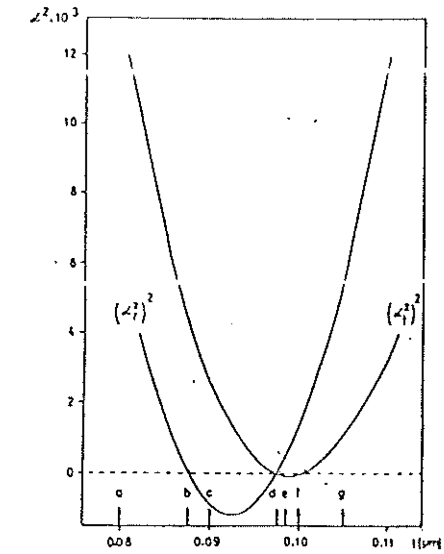
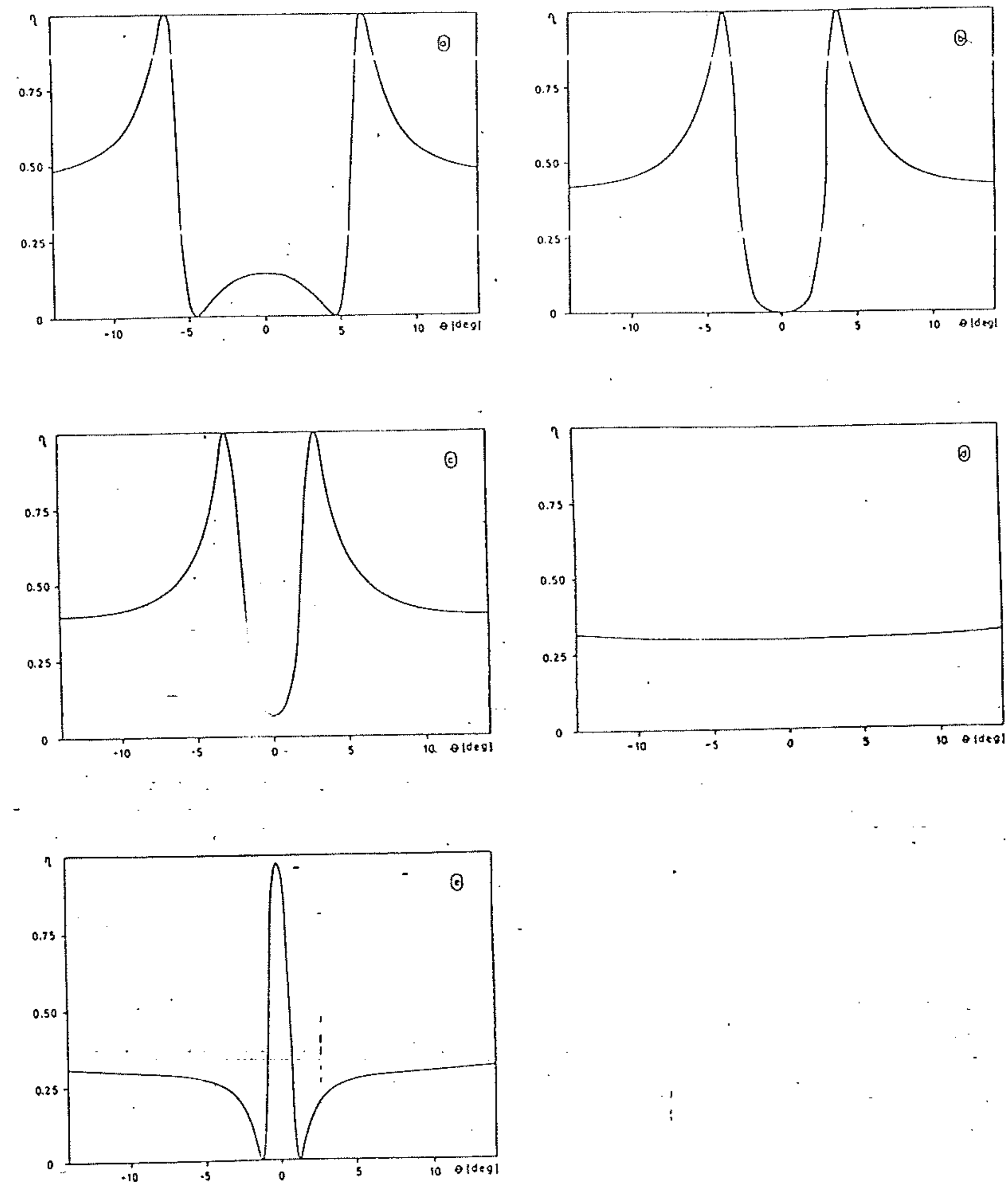


Fig. 3. Variation of $(\alpha_r^z)^2$ and $(\alpha_t^z)^2$ with the waveguide thickness. The other parameters are the same as in fig. 2.

both the reflection and the transmission zeroes are real [2]. Repeating the treatment in ref. [2] with α^2 instead of α (see the Appendix), it directly follows that in our case $(\alpha_r^z)^2$ and $(\alpha_t^z)^2$ must be real. Numerical calculations confirm this. The dependence of $(\alpha_r^z)^2$ and $(\alpha_t^z)^2$ on the waveguide thickness for the system with both kinds of symmetry is given in fig. 3. In the next section it is shown that the zeroth reflection order efficiency $\eta = |b_1/a_1|^2$ is quite different for each one of the seven thicknesses indicated with arrows in fig. 3.

3. Reflectance peculiarities

The realness of the zeroes squares means that the zeroes are either real or purely imaginary. This is quite important for the reflectance behaviour since it depends on α and not on α^2. In the regions where α_t^z or α_r^z are imaginary, total reflection or transmission cannot be achieved. This is illustrated in fig. 4 where the dependence of the reflected energy on the incident angle is shown for the seven waveguide thicknesses of fig. 3. It is worth noting that the system response as a function of wavelength has a similar form.


η
0.75
0.50
0.25
0
-10
-5
0
5
10
θ [deg]
a
b
c
d
e

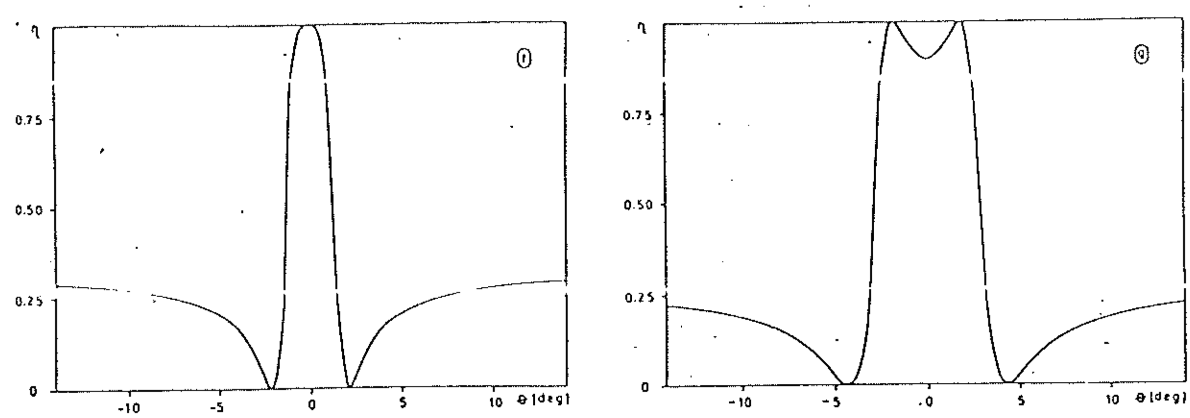


Fig. 4. Reflected zero-order efficiency as a function of the angle of incidence. Different cases correspond to various layer thicknesses indicated with arrows in fig. 3.

In the point d of fig. 3, $(\alpha_r^z)^2 = (\alpha_t^z)^2 = (\alpha^p)^2$, so the annihilation of the zeroes and the pole takes place [7]. Each zero is destructed by the pole thus the curve in fig. 4d is not influenced by the anomaly.

For the filtering and/or tuning, the device of fig. 1 is desired to operate in the regime shown in fig. 4f. However, the waveguide thickness and the symmetry of the system have to be chosen most carefully.

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Appendix

Let us introduce another wave with an amplitude a_2 incident from the lower medium at the same angle θ having the same wavelength and polarization as the first incident wave. Due to the linearity of the Maxwell's equations and boundary conditions there exists a linear connection through a scattering matrix S

$$b = Sa \qquad (5)$$

between the incident $a = \binom{a_1}{a_2}$ and the diffracted $b = \binom{b_1}{b_2}$ wave amplitudes. At fixed system parameters the components of S are functions of α: $S_{ij}(\alpha)$, $i,j = 1,2$.

As it is shown in ref. [2] the energy balance criterion, time reversal symmetry and the symmetry with respect to the vertical Oyz plane and to the horizontal z-axis results in the following connections between the components of the S matrix

$$S_{11}(\alpha) = S_{22}(\alpha), \qquad S_{12}(\alpha) = S_{21}(\alpha). \qquad (6)$$

The unitarity of S on the segment of the real α-axis $\alpha \in (-1, 1)$, determined by the energy balance criterion can be continued in the complex α-plane in the form [2,5]

$$\overline{S^{\mathrm{T}}}(\bar{\alpha}) S(\alpha) = I, \qquad (7)$$

where the overbar means complex conjugation, index T stays for matrix transposition and I is a unit matrix. Let us recall now that near the investigated anomaly the components of the S matrix are functions of α^2, having the form of eq. (3):

$$S_{11}(\alpha) = \Gamma_{11} \frac{\alpha^2 - (\alpha_r^z)^2}{\alpha^2 - (\alpha^p)^2},$$

$$S_{12}(\alpha) = \Gamma_{12} \frac{\alpha^2 - (\alpha_t^z)^2}{\alpha^2 - (\alpha^p)^2}. \qquad (8)$$

Substitution of (8) into (7) taking into account (6) results in

$$\bar{\Gamma}_{11}\,\frac{\alpha^2-(\bar{\alpha}_r^z)^2}{\alpha^2-(\bar{\alpha}^p)^2}\,\Gamma_{11}\,\frac{\alpha^2-(\alpha_r^z)^2}{\alpha^2-(\alpha^p)^2}$$

$$+\,\bar{\Gamma}_{12}\,\frac{\alpha^2-(\bar{\alpha}_t^z)^2}{\alpha^2-(\bar{\alpha}^p)^2}\,\Gamma_{12}\,\frac{\alpha^2-(\alpha_t^z)^2}{\alpha^2-(\alpha^p)^2}=1\,, \qquad (9)$$

$$\bar{\Gamma}_{11}\,\frac{\alpha^2-(\bar{\alpha}_r^z)^2}{\alpha^2-(\bar{\alpha}^p)^2}\,\Gamma_{12}\,\frac{\alpha^2-(\alpha_t^z)^2}{\alpha^2-(\alpha^p)^2}$$

$$=-\,\bar{\Gamma}_{12}\,\frac{\alpha^2-(\bar{\alpha}_t^z)^2}{\alpha^2-(\bar{\alpha}^p)^2}\,\Gamma_{11}\,\frac{\alpha^2-(\alpha_r^z)^2}{\alpha^2-(\alpha^p)^2}\,. \qquad (10)$$

Since the left hand side of (10) is zero for $\alpha^2 = (\alpha_t^z)^2$ it follows that either $(\alpha_t^z)^2 = (\alpha_r^z)^2$ or $(\alpha_t^z)^2 = (\bar{\alpha}_t^z)^2$. But if $(\alpha_t^z)^2 = (\alpha_r^z)^2 \neq (\alpha^p)^2$ then the left hand side of (9) will be zero. As the case $(\alpha_t^z)^2 = (\alpha_r^z)^2 = (\alpha^p)^2$ corresponds to the case of fig. 4d and is discussed in the text separately, so $(\bar{\alpha}_t^z)^2 = (\alpha_t^z)^2$ is real. Substitution $\alpha^2 = (\alpha_r^z)^2$ in the right hand side of (10) repeating the same considerations provides for the realness of $(\alpha_r^z)^2$.

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