Total reflection of light from a corrugated surface of a dielectric waveguide

G. A. Golubenko, A. S. Svakhin, V. A. Sychugov, and A. V. Tishchenko

Institute of General Physics, Academy of Sciences of the USSR, Moscow

(Submitted February 28, 1985)
Kvantovaya Elektron. (Moscow) **12**, 1334–1336 (July 1985)

It is shown that reflection of a plane monochromatic wave by the surface of a corrugated waveguide structure may excite a guided mode in one of the diffraction orders and thus alter greatly the reflection and transmission coefficients of the incident wave until total reflection or total transmission are achieved.

Interaction of laser radiation with surfaces of condensed media is attracting special attention because the formation of a periodic microrelief on the surface of a medium under the action of one laser beam is a universal effect.[1] A similar relief was found to form on the surface of a dielectric waveguide illuminated by one laser beam.[2] Since the initial stage of formation of a microrelief can be described in terms of the diffraction of light by a specific spatial harmonic of the surface irregularities,[1] it has seemed natural to apply the diffraction approach also to a waveguide. The problem of the diffraction of light by a corrugated boundary of a layer medius was considered earlier,[3] but the case of diffraction of light on excitation of guided modes was not discussed. The diffraction of light under these conditions was observed experimentally[4] and it was found that there were abrupt changes in the behavior of the intensity of the first-order wave when a waveguide was excited. We shall report the results of a detailed investigation of the diffraction of light on the boundary of a corrugated waveguide and we shall allow for the excitation processes.

The diffraction is shown schematically in Fig. 1. A waveguide is assumed to be infinite along the X axis and a plane monochromatic wave is incident on the waveguide from air ($n_2 = 1$) at an angle close to

$$\theta_2 = \sin^{-1}(n^* - \lambda/\Lambda), \tag{1}$$

where n^* is the effective refractive index of the waveguide, λ is the wavelength of light in vacuum, and Λ is the corrugation period. The problem was solved in the approximation of

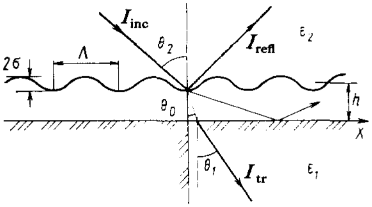

FIG. 1. Schematic representation of the process of diffraction by a corrugated surface of a waveguide.

0049-1748/85/070886-02$04.10

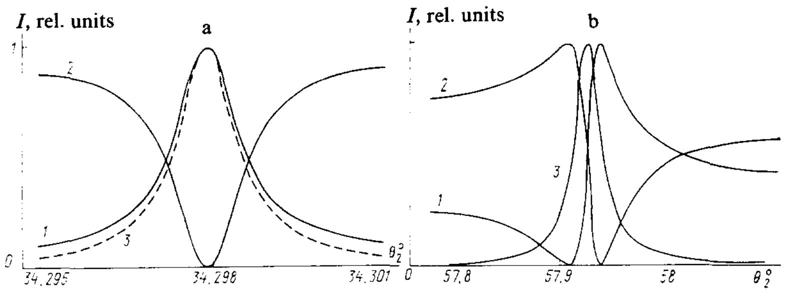

FIG. 2. Dependences of the relative intensities of waves of 0 and + 1 diffraction orders on the angle θ_2 in the case of excitation of modes in diffused (a) and thin-film waveguides with corrugations on the substrate side (b). Waveguide parameters: a) $n_{\text{sub}} = 1.512$, $\Delta n = 0.01$, parabolic profile, $\sigma_2 = 0.02$ μ; b) $n_0 = 1.98$, $n_{\text{sub}} = 1.512$, $h = 0.4\,\mu$, $\sigma_1 = 0.02\,\mu$. The parameters applicable to both cases are $\Lambda = 0.6\,\mu$ and $\lambda = 0.63\,\mu$; 1) $R = I_{\text{refl}}/I_{\text{inc}}$; 2) $T = I_{\text{tr}} \cos\theta_1 / I_{\text{inc}} \cos\theta_2$; 3) $I_{\text{mode}} = I/I_{\text{max}}$.

weak corrugations, i.e., $(2\pi\sigma/\lambda)^2 \ll 1$ (σ is the corrugation amplitude), and allowance was made only for waves of the 0, ± 1, ± 2 diffraction orders. We were interested particularly in the waves of the 0 and ± 1 orders. A theoretical analysis was made on the basis of the results of Ref. 5. Figure 2a shows the calculated intensities of the waves of the 0 and ± 1 orders obtained for a corrugated diffused waveguide as a function of the angle θ_2. It is clear from these calculations that in the case of optimal excitation of a loss-free waveguide the intensity of the transmitted wave (i.e., of the wave in the waveguide substrate) vanishes, whereas the intensity of the reflection wave reaches the intensity of the incident wave. A similar result is obtained also in the case of a thin-film waveguide corrugated on the air side ($\sigma_2 \neq 0, \sigma_1 = 0$). However, if a thin-film waveguide is corrugated on the substrate side ($\sigma_1 \neq 0, \sigma_2 = 0$), the result is somewhat different: the initial intensity of the zeroth-order wave can be obtained not only in the substrate, but also in air (Fig. 2b). The condition for zero intensity of the reflected wave is as follows:

$$h = \frac{\lambda}{2\pi n_0 \cos\theta_0} \left\{ \pi m \pm \tan^{-1} \left(n_0 \cos\theta_0 \times \sqrt{\frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_2 \cos\theta_2 \left(n_0^2 \cos^2\theta_0 - n_1 n_2 \cos\theta_1 \cos\theta_2\right)}} \right) \right\}, \tag{2}$$

where

$m = 0,\ 1,\ 2, \ldots;$

h is the film thickness; n_0, θ_0, n_1 θ_1, n_2, and θ_2 are the refractive indices and the angles at which light travels in the film, substrate, and air, respectively.

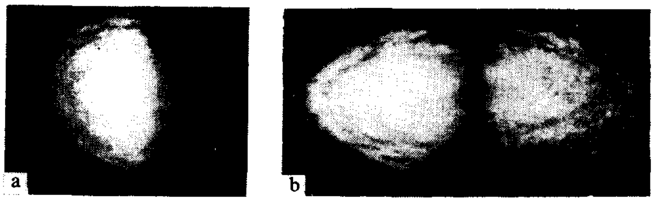

FIG. 3. Far-zone field patterns obtained for the reflected (a) and transmitted (b) waves. The elongation of the transmitted beam spot is due to the wedge shape of the substrate.

Physical interpretation of these results, for example, those obtained for a corrugated diffused waveguide, is quite obvious: the incident light beam excites a guided mode which then propagates along the corrugated waveguide and is emitted into air and into the substrate. The directions of the emitted waves coincide exactly with the directions of the reflected and transmitted waves, whereas the phases of the investigated waves (dependent on the mode excitation conditions) may change. Since the phase of the reflected wave differs by 180° from the phase of the transmitted wave, it follows that by altering the mode excitation conditions (for example, by altering the angle θ_2), we can achieve interference suppression of the transmitted wave, i.e., we can attain total reflection of the incident wave.

We checked experimentally these results by preparing a waveguide from a ZnO film ($h = 0.36\,\mu$) deposited on a corrugated ($\Lambda = 0.6\,\mu$, $\sigma_1 = 0.02\,\mu$) glass substrate. The waveguide was then corrugated both on the air and substrate sides. Therefore, we carried out calculations which showed that in order to attain zero intensity of the reflected wave it was necessary to ensure, for a given film thickness, a specific ratio of the amplitudes of the upper (σ_2) and lower (σ_1) corrugations. Since this condition was not satisfied in our experiments, we observed only an enhancement (or weakening) of the intensity of the reflected (transmitted) wave for the optimal excitation of the guided mode (Fig. 3).

We thus found that when light is reflected by a corrugated waveguide structure and a guided mode is excited in one of the diffraction orders, it is possible to alter drastically the reflection and transmission coefficients of the incident wave right up to a situation when total reflection or total transmission is achieved. This effect is of resonant nature and, consequently, it can be used to construct narrow-band frequency filters and mirrors reflecting selectively along a given direction. The results of an investigation of the influence of losses in the waveguide on the properties of such devices will be reported later.

[1] P. V. Bazakutsa, V. L. Maslennikov, A. M. Prokhorov, V. A. Sychugov, and A. V. Tishchenko, Kvantovaya Elektron. (Moscow) **11**, 1447 (1984) [Sov. J. Quantum Electron. **14**, 976 (1984).

[2] L. A. Ageev and V. K. Miloslavskiĭ, Zh. Tekh. Fiz. **54**, 888 (1984) [Sov. Phys. Tech. Phys. **29**, 530 (1984)].

[3] Yu. P. Udoev, Opt. Spektrosk. **56**, 140 (1984) [Opt. Spectrosc. (USSR) **56**, 85 (1984)].

[4] L. Mashev and E. Popov, Opt. Commun. **51**, 131 (1984).

[5] V. A. Sychugov and A. V. Tishchenko, Kvantovaya Elektron. (Moscow) **9**, 1451 (1982) [Sov. J. Quantum Electron. **12**, 923 (1982)].

Translated by A. Tybulewicz