Reflection of a bounded light beam from the surface of a periodically perturbed waveguide

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The study of the interaction of bulk light waves with guided modes of periodically perturbed waveguides opens up the possibility for new and unconventional applications of planar waveguides in quantum electronic devices. In particular, the use of rippled waveguides of the diffused and thin-film types as narrow-band frequency filters and selective reflectors in laser resonators was discussed in Refs. 1 and 2. These applications are based on the anomalous reflection of light from the surface of a periodically perturbed waveguide upon excitation of a waveguide mode. The waveguide mode is radiated by periodic inhomogeneities in the direction of the reflected and transmitted beams. As a result, the field of this radiation interferes coherently with the field of the reflected wave, and, depending on the phase of the radiated waves, the reflected wave can be enhanced or diminished by the interference. Similar arguments hold for the transmitted wave.

In this paper we consider one of the possible structures of this type: a thin-film waveguide with a modulated refractive index in the waveguide layer. The calculated method is set forth in detail elsewhere. Here we present the main results of the solution of the problem of reflection of light from a structure with material constants

\[
\begin{align*}
\epsilon_1 &> 0, \\
\epsilon_2 &+ \Delta \epsilon \cos Kx, \\
\epsilon_3 &< 0, \\
\end{align*}
\]

with allowance for the nonzero dissipative losses in the waveguide and the finite dimensions of the incident beam. The family of curves in Fig. 1 illustrates the influence of dissipation on the anomaly in the angular dependence of the reflectance of a plane wave of TE polarization. In the calculations we used the following parameters of the waveguide structure: \( \epsilon_2 = 1, \epsilon_3 = 3.92 \) (ZnO), \( \epsilon_3 = 2.286 \) (glass), waveguide thickness \( d = 0.0847 \mu m \), modulation factor \( \Delta \epsilon / \epsilon_2 = 0.0125 \), incident wavelength \( \lambda = 0.6328 \mu m \), grating period \( \Lambda = 2\pi / K = 0.44 \mu m \). The radiative loss was \( \sigma_{\text{rad}} = 1.85 \text{ cm}^{-1} \). It should be noted that the total reflection is possible in the absence of dissipation (curve 1). Increasing the dissipation loss coefficient \( \sigma_{\text{dis}} \) causes a leveling of the extreme in the angular dependence of the reflectance \( R(\theta) \). For the structure considered, the maximum value of \( R \) is around 50% for \( \sigma_{\text{dis}} \approx 3 \text{ cm}^{-1} \) is around 50%.

The dependence of the shape of the curve on the thickness of the waveguide is due to the following circumstance. The effect under discussion is a typical interference effect and is sensitive to the phase relationship between the waves propagating in the direction of the reflected beam. In the absence of a grating the phase of the reflected wave depends on the thickness of the waveguide, and in the presence of a

\[
\sigma_{\text{dis}} = \sigma_2 \quad \text{(see Eq. (6))}
\]

The quantity \( \sigma_{\text{dis}}(1, h) \) is taken to be

\[
\sigma_1(h, h) = \frac{1}{4} \sigma_2 (1 + (1 + 8h_1)^{1/2}),
\]

which has the meaning of the effective electrical conductivity of a polycrystal with layered crystallites.

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FIG. 2. Possible shapes of the angular dependence of the reflectance for various thicknesses of the waveguide layer $d(\mu m)$: 1) 0.107, 2) 0.188, 3) 0.237.

Grating this dependence leads to the indicated diversity in the shapes of the anomalies.

We note that for a fixed modulation factor the angular and spectral widths of the reflection peak depend on the thickness of the waveguide layer. As the thickness of the waveguide decreases toward the critical thickness, the fraction of the energy of the waveguide mode that is localized within the waveguide layer decreases, leading to a decrease in the radiative loss and, hence, in the width of the reflection peak.

Up till now we have assumed an infinite plane wave ($\mathbf{E} \sim e^{i(k \cdot x - \omega t)}$). In practice, however, one deals with beams of finite dimensions. We have therefore considered the problem of the reflection of a bounded light beam from the surface of a waveguide having a modulated refractive index in the waveguide layer. In the calculations we used a completely conventional algorithm. The field of the incident wave,

$$E_t(z) = A(z) e^{i\omega z},$$

where

$$\theta = -\frac{2\pi}{\lambda} \sin \theta$$

($\theta$ is the angle of incidence), was represented as a sum of plane waves with projections $q$ of the wave vector onto the plane of the waveguide:

$$E_t(z) = \int B(q) e^{iqz} dq,$$

$$B(q) = \frac{1}{2\pi} \int A(z) e^{i\omega z - iqz} dz.$$

The amplitude reflection factor $r(q)$ was calculated according to Ref. 3. The field of the reflected wave is

$$E_r(z) = \int B(q) r(q) e^{iqz} dq.$$

The results of the calculation are given in Fig. 3. The distribution of the intensity in the incident beam was assumed Gaussian:

$$I_i(z) = |A(z)|^2 = \exp \left(-2 \left(z/d\right)^2\right).$$

FIG. 3. Reflection of a Gaussian beam for various diameters of the beam. $a_{rad}$: 1) 18.5, 2) 3.7, 3) 1.4, 4) 0.2.

For large dimensions of the incident beam the shape is reproduced on reflection with negligible distortion. The beam as a whole is displaced a propagation of the waveguide mode by $\sim \lambda_c a_{rad}^{-1}$. For $a_{rad} = 20$ (curve 1) the distortion is at most 9%. In the other extreme case $a_{rad} \ll 1$, the value of the dielectric constant of the waveguide layer is substantially affect the reflectance of the wave. For $a_{rad} \approx 1$ there is a significant increase in reflectance (up to 50%) and a broadening of the beam (curve 3).

We can thus formulate the conditions for a substantial reflection of light from the surface of a perturbed waveguide. First, the angle of incidence should be small compared to the radius of curvature of the grating; second, the beam must correspond to excitation of a waveguide mode that is not the most efficiently excited; third, the dimension of the incident beam should be large compared to the coupling length: $d/\lambda_c = a_{rad}$.

In conclusion we note that according to the present analysis one can obtain a spectral width of the reflection peak $\Delta \lambda = 0.1 \, \lambda$ at a quite small value of the dissipative loss level for planar waveguide $\alpha_{dis} \sim 1 \, dB/cm$. A multilayer mirror with these characteristics should contain only a few layers. Since the technology of fabricating narrow frequency filters using periodically perturbed waveguide is rather simple, such filters can be of great practical interest.

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