Reflection of light from the surface and propagation characteristics of a double-sided corrugated waveguide

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A theoretical investigation is made of the anomalies of the spectral and angular dependences of the reflection coefficient of light incident on the surface of a waveguide corrugated on both sides. The formulas for radiation losses in such a waveguide are given and analyzed. It is shown that for a certain ratio of the amplitudes and phases of the diffraction gratings the radiation is coupled out of the waveguide only into one of the adjoining media and there is no anomalous reflection of light from the waveguide surface.

Periodically perturbed waveguides occupy a special place in integrated optics because of the many functions they can perform. The interest in these waveguides has now been enhanced by a new unconventional application. It is based on the use of anomalies of the angular and spectral dependences of the coefficient of reflection of light by the surface of a periodically perturbed waveguide when a waveguide mode is excited. When the dimensions of the incident beam exceed the length of the region of coupling between a waveguide mode and the incident radiation and the dissipative losses are low compared with the radiative losses, the influence of a waveguide mode on the reflected wave is particularly strong. In this way it is possible to achieve total reflection or total transmission of light by a waveguide layer. The resonant nature of this effect makes it possible to construct narrow-band frequency filters and mirrors for various optical systems.

One of the possible technologies which can be used to fabricate periodically perturbed waveguides is the evaporation of thin films on corrugated substrates. The waveguide which is then formed is frequently corrugated on the air and sides, and the amplitudes and phases of the resultant diffraction gratings are generally different (Fig. 1). The difference between the phases $\varphi$ may be due to deviation from the normal of the angle of incidence of a molecular beam on a substrate during the process of film evaporation. Consequently, it is of practical importance to determine the influence of the phase shift $\varphi$ between the gratings on the amplitude of the anomalous reflection of light from the surface of a waveguide corrugated on both sides.

We shall solve the problem of the excitation of a waveguide corrugated on both sides by assuming a sinusoidal profile of the corrugations with the same period $\Lambda$ in both cases and with a small amplitude; the phase shift within the corrugations will not be restricted.

The solution of this problem, which includes waves up to the fifth diffraction order inclusive (from order $-2$ to order $+2$), involves tackling a system of 20 linear equations for the amplitudes of the diffraction waves. Such a cumbersome system of equations is difficult to analyze, so that the spectral dependences of the reflection coefficient of light $R(\lambda)$ will be obtained by us for different phases $\varphi$ using a numerical method. Figure 2 shows these dependences for TE-polarized light in the case of a waveguide corrugated on both sides and representing a layer of SiO$_2$ of thickness $h = 0.7 \mu$ deposited on a CaF$_2$ substrate. It should be pointed out that if $\varphi \neq 0$, the problem of the reflection of light from the surface of a waveguide corrugated on both sides becomes invariant under the coordinate transformation $x' = -x$. For a given intensity of the incident wave the amplitudes of the excited waveguide modes are different when the angles of incidence are $\theta = \theta$, and $\theta' = -\theta$. The general tendency is such that the greater this asymmetry in the excitation of waveguide modes, the smaller the maximum value of the coefficient of reflection of light by the waveguide.

We shall use this observation in order to understand the relationship between the amplitude of the reflected wave and the asymmetry of the waveguide excitation. We shall do this by considering the simpler problem of radiative losses in a waveguide corrugated on both sides.

We shall assume that the waveguide and grating parameters are such that in the first diffraction order the radiation is coupled out of the waveguide both into the substrate and into the covering layer, and the refractive indices obey

$$n_1 > |n^* - \lambda| \Lambda, \quad n_3 > |n^* - \lambda| \Lambda,$$

where $n_i$ ($i = 1, 2, 3, 4$) are the refractive indices of the covering layer, waveguide film, and substrate, respectively, $n_3 > n_1 > n_4$, $\lambda$ is the radiation wavelength in vacuum, $\Lambda$ is the grating period. The coefficient $\alpha$, representing radiative losses in the case of TE modes in such a waveguide considered in the approximation of a weak corrugation, i.e., when $k_0 \sigma_1, 2 \ll 1( k_0 = 2\pi/\lambda; \sigma_1, \sigma_2$ are the amplitudes of the gratings), is described by the formula

$$\alpha = \frac{\left( n_2^2 - n_1^2 \right)}{2n_1^2 k_0^2} \left| s_1 \left( g_1 g_2^2 \cos^2 \chi + g_1 g_3^2 \sin^2 \chi \right) + g_3 g_4^2 \right|$$

$$+ s_2 \left( g_1 g_2^2 + g_1 g_3^2 \cos^2 \chi + g_1 g_4^2 \sin^2 \chi \right)$$

$$- (1-i)^m 2s_1 s_2 g_1^2 (g_1 + g_3) \cos \chi \cos \varphi, \quad (1)$$

FIG. 1. Waveguide corrugated on both sides ($K = 2\pi/\Lambda$).
where the following notation is used:

\[ g_0 = \left[ n_t^2 - (\nu - \lambda L)^2 \right]^{1/4} = n_t \cos \theta; \]
\[ s_1 = k_0 \sigma_1 (n_t^2 - n_0^2)^{1/4}; \quad \text{and} \quad s_2 = k_0 \sigma_2 (n_2^2 - n_0^2)^{1/4} \]

are the normalized depths of the gratings;

\[ h^* = h + (2 \lambda / 2\pi) \left[ (n^2 - n_0^2)^{-1/4} + (n^2 - n_1^2)^{-1/4} \right] \]

\[ \beta = \frac{\frac{g_0}{s_1} \left[ g_2^2 \sin^2 \chi + g_2^2 \sin^2 \xi \right] + s_2 g_2^2 - 2 (-1)^m s_1 s_2 g_2 \left[ g_2 \cos \chi \cos \psi + g_3 \sin \chi \sin \psi \right]}{g_2^4 s_1^2 + s_2^2 \left[ g_2^2 \sin^2 \chi + g_2^2 \sin^2 \xi \right] - 2 (-1)^m s_1 s_2 g_2 \left[ g_2 \cos \chi \cos \psi - g_3 \sin \chi \sin \psi \right]} \quad (3) \]

These formulas provide full information on the emission of light from a waveguide with two corrugated sides. In particular, when a waveguide is corrugated only on one side, Eq. (1) becomes identical with the formulas (2)–(4) in Ref. 3. Equations (1) and (3) are fairly cumbersome, so that it is interesting to consider some important special cases. In practical applications it is convenient to use the relationships between the waveguide and grating parameters for which the angles \( \theta_1 \) and \( \theta_2 \) are close to the normal. Therefore, in estimating the maximum values of \( \alpha \) and \( \beta \) we shall assume that \( g_0 \) depend weakly on the waveguide thickness and grating period, but are governed only by the refractive index \( n_t \). In this case the parameters \( \alpha \) and \( \beta \) for a waveguide made of materials with given values of \( n_t \) can be altered by varying the depth of the gratings \( s_1 \) and \( s_2 \), the phase advance \( \chi \) of the emitted wave in a distance equal to the waveguide thickness, and the relative phase of the gratings \( \varphi \) (Fig. 3).

The maximum value of the radiative losses \( \alpha \) corresponds to the condition

\[ (-1)^m \cos \chi \cos \varphi = -1. \]

The maximum losses are described by

\[ \alpha_{\text{max}} = \left( \frac{(n_2^2 - n_1^2)}{2n_0^4 h^*} \right) \left( \frac{(s_1 - s_2) g_2^2 (g_1 + g_3)}{|g_2^2 + g_1 g_3|^2 - (n_2^2 - n_1^2)(n_2^2 - n_3^2)} \right). \]

(5)

The distribution of the emitted energy between the media 1 and 3 is then given by \( \beta = g_0 / g_2 \).

In practical applications it is frequently important to ensure that the radiation is emitted into only one of the adjoining media, but it should be noted that it is very difficult to couple out all the radiation into a medium with a lower refractive index if a grating is used. Gratings with an asymmetric line profile are used for this purpose, but it would be a very laborious task to form such a grating on the surface of a given waveguide. We shall therefore consider how the phase shift between the corrugations of a waveguide affects the redistribution of the energy emitted into the adjoining media. An analysis of Eq. (3) shows that when the ratio of the amplitudes and phases of the gratings is given by

\[ s_1 g_2 = s_2 A, \quad (-1)^m \cos \varphi = -1, \]

where

\[ A = \sqrt{g_2^2 \cos^2 \chi + g_3^2 \sin^2 \chi}, \]

(7)

then the ratio \( \beta \) becomes infinite, i.e., the whole energy is emitted into the medium 1.

Therefore, our analysis shows that for a certain ratio of the depths of the gratings [see Eqs. (2) and (6)] and for a specific phase shift \( \varphi = -\varphi + m\pi \) [see Eqs. (6) and (7)] we can construct a coupling device ensuring that the radiation is transferred totally into one of the adjoining media.

Returning now to the problem of the reflection of light from the surface of a waveguide corrugated on both sides, we shall calculate the spectral dependence of the reflection coef-
Experimental observation of the self-switching of radiation in tunnel-coupled optical waveguides


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The phenomenon of self-switching of radiation in tunnel-coupled optical waveguides with two glass fiber waveguide cores was experimentally detected for the first time. The experiment was in agreement with theory. The results confirmed feasibility of constructing an optical transistor utilizing tunnel-coupled optical waveguides.

Self-switching of radiation in tunnel-coupled optical waveguides, predicted in Refs. 1 and 2 and theoretically investigated in Refs. 1–6, represents a discontinuous change in the ratio of the intensities \( I_{0f} / I_{0m} \) at the output of a device caused by a small change (\(-1\%\) or less) in the input intensity \( I_{00} \) close to a critical value \( I_M \). If the tunnel-coupled optical waveguides are identical and the radiation is coupled into one of them (which we shall call the zeroth fiber), then

\[
I_M = \frac{2cK\beta}{\theta\pi} (\text{Ref. 2}),
\]

where \( K \) is the tunnel coupling coefficient; \( \theta \) is the nonlinear waveguide coefficient; \( \beta \) is the effective refractive index of the waveguide. When \( I_{00} = I_M \approx I_M (1 - 8\exp(-L)) \), all the radiation emerges from the first waveguide \( (I_{01} = I_{00}) \), but when \( I_{00} = I_M \approx I_M (1 + 8\exp(-L)) \) it emerges from the zeroth fiber \( (I_{0f} = I_{00}) \). Here, \( L = 2\pi lK / \lambda \beta = \pi l / I_{LT} \); \( l \) is the length of the tunnel coupled optical waveguides; \( I_{LT} \) is the distance in which energy is transferred once in the linear regime (\( \theta = 0 \)); \( \lambda \) is the wavelength. In the region of the midpoint \( M \) (where \( I_{00} = I_M \)) of the self-switching curve (Fig. 1, see Ref. 2) there is a linear section of the characteristic whose slope is maximal and can be estimated from the formula

\[
\frac{\partial I_{01}}{\partial I_{00}} \sim -\frac{\partial I_{01}}{\partial I_{00}} \sim \exp(L) / 8 \text{ (Ref. 2).}
\]

This formula essentially describes the gain of an optical transistor, which can be very large. Thus, when \( L = 3\pi \), \( \partial I_{01} / \partial I_{00} \approx 1550 \).

The self-switching effect is best observed when radiation from a laser with phase-locked longitudinal modes is coupled into one of the tunnel-coupled waveguides, since this avoids stimulated Brillouin scattering which is parasitic concomitant of the self-switching effect, and since the threshold intensity for breakdown of the waveguide end is raised considerably (by one or two orders of magnitude).

We shall report an experiment in which a train of ultrashort second-harmonic radiation pulses \( (\tau_p \approx 50 \text{ psec}) \) from a YAG:Nd\(^{3+}\) laser \( (\lambda = 0.53 \mu) \) emitting a single zero-order transverse mode and passively mode-locked longitudinal modes was coupled into one tunnel-coupled optical waveguide by the method of Ref. 8, which was improved in the present study. The interpulse interval was \( \sim 7 \text{ nsec} \) and the

![FIG. 1. Self-switching curves for \( L = \pi \) (curve 1), \( 1.3\pi \) (curve 2), and \( 1.7\pi \) (curve 3).](attachment:image.png)