The experimental results are shown in Fig. 2. The photographs are oscilloscope traces of a square signal at its first derivative (b), and its second derivative (c). The first two of these signals were obtained directly at the output of the photodetector; the last was obtained at the output from the circuit.

These results demonstrate the promising outlook for the use of charge-coupled photodetectors in hybrid optoelectronic circuits, since the ability to perform certain parts of a preliminary image processing directly in the photodetector itself or by means of simple electronic circuits frequently makes it possible to substantially simplify the information-processing system.

Translated by Dave Parsons

Light reflection from the surface of a corrugated waveguide

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Submitted May 2, 1985

Pisma Zh. Tekh. Fiz. 11, 971–976 (August 26, 1985)

Analysis of the diffraction of light by a corrugated surface of a dielectric waveguide shows that when a mode of this waveguide is excited the intensity of the zero-order waves undergoes pronounced changes, to the point that the intensity of the reflected wave becomes comparable to that of the incident wave. The physical interpretation of this phenomenon is that a mode propagating along the corrugated waveguide radiates waves whose phase changes with the mode excitation conditions. In particular, it is possible to arrange conditions such that there is a destructive interference of the transmitted wave, i.e., a total reflection of the incident wave.

In the present letter we report some results of a study of this phenomenon as a function of the parameters of the corrugated waveguide. We offer a theoretical analysis based on the results of Refs. 2 and 3 for waveguides with a shallow sinusoidal corrugation. We note at the outset that we are interested primarily in single-mode waveguides with corrugation periods \( \Lambda \) which make it possible to excite the waveguides when light is incident from air, and such that we can ignore the effect of the higher diffraction orders on the excitation efficiency:

\[
\frac{\lambda}{n^*} + 1 < \Lambda < \frac{\lambda}{n^*},
\]

(1)

where \( n^* \) is the effective refractive index for a mode in the waveguide.

Figure 1 shows spectra of the optical reflection coefficient \( R \) of the surface of a single-mode corrugated waveguide formed from a ZnO film \((n_0 = 1.98, h = 0.15 \mu m)\) on a glass substrate \((n_1 = 1.51)\).

The waveguide is corrugated on the side of the substrate, with \( \Lambda = 0.364 \mu m \) and \( \sigma = 0.02 \mu m \); the adjustable parameter is the loss in the waveguide. It follows from

![Fig. 1. Optical reflection spectra of the surface of a corrugated waveguide. 1) \( n_0 = 6.5 \); 2) \( n_0 = 1 \ cm^{-1} \); 3) \( n_0 = 10 \ cm^{-1} \); 4) \( n_0 = 10^6 \ cm^{-1} \).](https://example.com/fig1.png)

![Fig. 2. Angular dependence of the optical reflection of the surface of a ZnO-glass thin-film waveguide. 1) s polarization; 2) p polarization of the incident light.](https://example.com/fig2.png)
Fig. 1 that as this loss in the waveguide increases, the spectral width of the reflection increases, while the reflection amplitude decreases. This decrease in amplitude can be described by

$$R = 1 - \left( \frac{\alpha_{\text{ef}}}{\alpha_{\text{e}} + \alpha_{\text{r}}} \right)^2 \left( 1 - R_0 \right),$$

(2)

where $R_0$ is the Fresnel reflection coefficient, $\alpha_{\text{ef}}$ is the loss in the waveguide, and $\alpha_{\text{r}}$ is the radiative loss. The use of waveguides with a large difference between the refractive indices of the film and the substrate makes it possible to achieve large values of the radiative loss $\alpha_{\text{r}}$ and to observe the reflection of light beams of small diameter ($d \approx 1 \text{ mm}$) from the surface of a waveguide having a significant loss. For example, Fig. 2 shows the angular dependence of $R$ for the surface of a waveguide of a ZnO film on a glass substrate ($h = 0.36$, $\lambda = 0.5 \mu m$, $\sigma = 0.02 \mu m$, $\lambda = 0.53 \mu m$). Since the thickness of the waveguide is greater than the critical thickness for the TM mode of this waveguide, increased reflection can also be observed for an incident $p$-polarized wave. The amplitude of this reflection, however, is lower because of the lower value of $\alpha_{\text{r}}$ for the TM mode.4

The permissible loss in a waveguide in integrated optics would be on the order of 1 dB/cm, so that the angular and spectral width of the reflection of light from a surface of such a waveguide will be determined primarily by the radiative loss. On the other hand, it is obvious that if we are to achieve a significant effect, the diameter of the beam incident on the corrugation must be much greater than the coupling length $l = \alpha_{\text{r}}^{-1}$. The diffused waveguide is the most common type used in integrated optics. The simplicity and flexibility of the fabrication of waveguides of this type make them especially interesting. We have accordingly calculated the angular dependence of the reflection of $s$-polarized light from the surface of a diffused waveguide with a parabolic index profile and a grating of small depth ($\sigma = 0.02 \mu m$) on its surface. The calculations show that the corresponding spectral width of the reflection by this waveguide is only $\Delta \lambda \approx 0.1 \text{ Å}$. At a given grating depth, this is the minimum value of the width, since the calculations have assumed $d = \infty$. To evaluate the various possibilities for the use of corrugated diffused waveguides as selectively reflecting mirrors, we fabricated a single-mode waveguide by the diffusion of Ag ions into a corrugated glass substrate ($\lambda = 0.5 \mu m$, $\sigma = 0.2 \mu m$) from molten AgNO$_3$ + NaNO$_3$ (150) at $T = 330 \text{ °C}$ and $t = 1 \text{ min}$. In measuring the angular dependence of the reflection we used an LG-38 He-Ne laser with $\lambda = 0.63 \mu m$ and a beam width $d = 3 \text{ mm}$. Figure 3 shows the experimental results for various polarizations of the incident light. The angular width of the reflection achieved for $s$ polarization, 2°30′, corresponds to $\Delta \lambda = 2 \text{ Å}$. As we mentioned earlier, in order to achieve smaller widths it would be necessary to use larger gratings and larger beam diameters.

The most promising application of these reflectors is as dispersive elements in tunable lasers. To demonstrate this possibility, we have carried out experiments on the spectral characteristics of the output of a laser using the dye rhodamine 6G, shown schematically in Fig. 4a. To pump the laser we use the second harmonic ($\lambda = 0.53 \mu m$) from a Nd:YAG laser. Figure 4b shows the output spectrum of a dye laser with a dispersive element made from a corrugated diffused waveguide. The output wavelength is tuned in this case by varying the angle at which the light is incident on the surface of the waveguide.

We wish to thank T. B. Tulalkov and A. S. Svakhin for fabricating the diffraction gratings.

Translated by Dave Parsons


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