μm (and is even lower for λ = 10.6 μm) because of the thermal characteristics of quartz. The scattered radiation can be measured reliably by covering the inner surface of the cell made of chalcogenide glass with a thin film of an adhesive which is a good absorber in the 5–10-μm range.\(^{(14)}\)

On the basis of the experimental results and of the signal-to-noise ratio, one can estimate the ultimate possibilities of the present apparatus. The minimum measurable absorption coefficients are \(\beta_0 \approx (1-2) \times 10^{-9}\) cm\(^{-1}\), for a radiation power of 1 W in the fiber-optic waveguide, i.e., the sensitivity is sufficient for measuring the lowest expected losses in fiber-optic waveguides for the middle infrared range. A piece of fiber-optic waveguide having a length of a few centimeters is sufficient for making measurements with this sensitivity. This sensitivity is almost an order of magnitude lower than the ultimate sensitivity determined by thermal fluctuations of the gas pressure in the cell.\(^{(2)}\)

It may be mentioned that the discovered substantial influence on the absorption losses on the lateral surface of the fiber-optic waveguides is possibly of a more general nature for fiber-optic waveguides without an optically reflecting cladding in the middle infrared region. Thus, similar measurements performed on fiber-optic waveguides made of KRS-5 also showed a strong contribution of the absorption on the lateral surface of the waveguides in the transparency region.

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**Optimization of the characteristics of a dispersive element based on a corrugated waveguide**

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A selectively reflecting mirror based on a corrugated waveguide was used in semiconductor lasers with an external resonator. Two-layer thin-film waveguides provided extensive opportunities for optimization of the characteristics of such lasers.

**INTRODUCTION**

Excitation of waveguide modes by a plane wave incident on the surface of a corrugated waveguide results in anomalous reflection of light. Interference between the waves emitted by the waveguide and those reflected by the boundaries of the waveguide layer results in major changes in the intensity of zeroth diffraction orders. The reflection and transmission coefficients of a corrugated waveguide structure may vary from zero to 100% (Refs. 1 and 2). In view of the resonant nature of the excitation of such a waveguide, these anomalies are localized in a fairly narrow spectral interval \(\Delta \lambda /\lambda = \alpha \lambda /2\pi n^*\), where \(\alpha = \alpha_r + \alpha_d\) are the total losses in the waveguide (\(\alpha_r\) and \(\alpha_d\) represent radiative and dissipative losses, respectively). The dissipative losses are always present in real waveguides. A considerable increase in the reflection coefficient\(^{(3)}\) is observed for \(\alpha_r /\alpha_d \gg 1\), so that the spectral width \(\Delta \lambda\) of a reflection peak cannot be infinitesimally small.\(^{(1)}\)
Another factor which limits the selectivity of a corrugated waveguide regarded as a dispersive element is that the light beams used in practice always have finite dimensions or are not fully collimated. A beam of transverse size $d$ and characterized by a plane wavefront is reflected strongly (total external reflection) if the condition $2d > l$ is satisfied. Detailed investigations of the reflection of bounded beams by surfaces of periodically perturbed waveguides are reported in Refs. 4 and 5.

Our aim was to determine the capabilities of combined waveguides used as frequency selectors based on the anomalous reflection of light on the surface of a corrugated waveguide and also to demonstrate that such a selector can be used as an external resonator mirror in a semiconductor laser.

1. PRACTICAL UTILIZATION OF THE ANOMALOUS REFLECTION OF LIGHT BY THE SURFACE OF A CORRUGATED WAVEGUIDE

The anomalous reflection of light can be used in various spectral devices such as monochromators, optical filters, and dispersive elements of laser resonators. The last application seems to us to be the most promising. The first experiments demonstrating that selective mirrors can be constructed from corrugated waveguides were carried out on lasers in which the active medium was the dye rhodamine 6G (Refs. 3 and 6). It was established that the use of corrugated waveguides not only reduced the width of the emission spectrum, but also improved the spatial coherence of the radiation. The latter was due to the fact that reflection from a corrugated waveguide under the anomalous reflection conditions broadened the beam because the waveguide mode carried part of the energy outside the illumination spot.6

A tunable laser with a dispersive element based on a corrugated waveguide is generally larger than one with a metal diffraction grating operating in the autocollimation regime. However, if a corrugated waveguide acts directly as the exit mirror of a laser resonator, a very compact laser with a stabilized emission frequency can be constructed.6

The reduction in size of semiconductor lasers is one of the most important requirements in the case of optical communication systems. Therefore, information of practical importance can be obtained by investigating the operation of semiconductor lasers which are frequency-stabilized by a selective mirror made of a corrugated waveguide. In our investigations the active medium was an element taken from a commercial LPN-206 laser emitting at the wavelength of 1.3 $\mu$m. The end of this element facing a corrugated-waveguide mirror was antireflection-coated, so that the transmission coefficient became $r \approx 0.99$. The radiation emitted from this end of the laser was collimated by an objective with an aperture of 0.85 and a magnification of 60 x. The selective mirror was perpendicular to the collimated light beam and the corrugation ridges were parallel to the $p-n$ junction of the laser diode. The mirror was formed by depositing a diffraction grating with a period $A = 0.842 \mu m$ and a total depth of $2d = 0.25 \mu m$ on the surface of a polished glass plate. Then, a waveguide was formed by the diffusion of Ag in the surface layer of the glass substrate. The diffusion took place when the substrate was immersed for 2.5 min in a melt containing silver nitrate (mass fraction 2%) kept at a temperature of $T = 320^\circ C$. The efficiency of the interaction of waveguides with three-dimensional radiation (representing the incident and reflected waves) was improved by evaporating a thin (20 nm) silicon film on the waveguide surface. This film did not form a waveguide layer, but distorted the mode field distribution in the waveguide by increasing the field at the surface. The refractive index of the dominant waveguide mode was $\eta = 1.542$ and the reflection coefficient at $\lambda = 1.29 \mu m$ was $R \approx 40\%$. Evaporation of the Si film generated also a second mode with $\eta = 1.51$. The effective refractive indices of the modes were quite different, so that the anomalies in the reflection spectrum were separated by a considerable interval ($\approx 50 \text{ nm}$) and the presence of the second mode had practically no effect on the emission spectrum of the laser.

We employed a fairly simple optical system with a rotatable diffraction grating, which made it possible to record instantaneously the emission spectrum of the laser. The spectral resolution of the recording system was $\Delta \lambda \approx 0.2 \text{ nm}$.

Our investigation indicated that inclusion of an external resonator based on such a selective corrugated-waveguide mirror had the following effects: firstly, it approximately halved the lasing threshold (from 50 to 25 mA); secondly, in the range of pump currents where lasing action was not observed in the absence of the external resonator (25–50 mA) only one main longitudinal mode was generated, because the intensities of the other longitudinal modes were 30–35 dB less than the intensity of the main mode; thirdly, in the range of currents 50–80 mA this external resonator suppressed the wide emission spectrum of the laser selecting just one longitudinal mode of intensity 15–20 dB higher than the intensities of the other modes; fourthly, at even higher pump currents ($\approx 90 \text{ mA}$) the radiation became of multimode nature because the selection performed by the external resonator was no longer effective. Oscillograms of

FIG. 1. Emission spectra of a semiconductor laser observed in the range of $\lambda \approx 1.3 \mu m$ using an external mirror based on a corrugated waveguide. Pump current (mA): a) 40; b) 70; c) 70 (without the external mirror); d) 90.
the emission spectra obtained under different operating conditions are shown in Fig. 1.

We thus established that the use of a corrugated waveguide as one of the mirrors of the external resonator provided an effective means for ensuring single-mode emission from a semiconductor laser. We could now deal with the task of stabilization of operation of this laser in a wide range of pump currents, temperatures, etc., and we could tackle the problem of reducing the width of the emission line. Undoubtedly, an increase in the selective reflection coefficient of such a corrugated-waveguide mirror would provide one of the methods for performing these tasks. Another method would be to increase the selectivity of the reflection of light by the mirror, which—as in the case of echelle gratings—should increase on increase in the number of lines in the grating.

2. METHODS FOR IMPROVING THE CHARACTERISTICS OF SELECTIVE MIRRORS BASED ON CORRUGATED WAVEGUIDES

As pointed out above, the anomalous reflection of light became significant when the radiative losses in the waveguide $\alpha_r$ exceeded the dissipative losses $\alpha_d$. When the dissipative losses in a waveguide cannot be reduced, the only way of increasing the reflection coefficient of a selective mirror is to increase the coefficient $\kappa$ representing the coupling between the waveguide mode and the incident radiation. It is known that among the waveguides of different types (thin-film, diffused, etc.) with the same parameters (refractive index on the waveguide surface, effective refractive index of a mode, effective thickness of the waveguide, and corrugation depth) the largest coupling coefficient $\kappa$ is obtained for a thin-film waveguide.

Thin film waveguides transparent in the near infrared range are usually formed by the evaporation of oxide films on substrates with a relatively low refractive index or by epitaxial growth of semiconductor layers on substrates of the GaAs, Si, InP, etc. type.\footnote{For example, magnetron sputtering of a silicon target in an oxygen and argon atmosphere provides an effective method for the fabrication of low-loss waveguides on CaF$_2$ substrates. Significant losses appear in these waveguides as a result of their corrugation, i.e., they appear after ion etching via a resistive mask. In the main these are losses due to the scattering of light by the irregularities of the grating. The influence of these losses on the reflection coefficient of a selective mirror can be reduced by evaporating a thin film with a higher refractive index (for example, silicon, niobium oxide, etc.) on the corrugated surface of a waveguide. This is illustrated in Fig. 2, which gives the results of a calculation of the reflection spectra of the corrugated surface of a CaF$_2$/SiO$_2$/Si structure. These calculations apply to the structure shown as an inset in Fig. 2a. A characteristic feature of this structure is the presence of two corrugated interfaces, which distinguishes it from similar structures with one corrugated boundary discussed earlier. It should be pointed out that the evaporation of an Si film of thickness 15 nm naturally broadens the reflection spectrum. However, in the case of structures with finite dissipative losses ($\alpha_d = 2.5 \text{ cm}^{-1}$ in the present case) a film of Si on the waveguide surface makes it possible to achieve a reflection coefficient of $\approx 76\%$, whereas in the absence of Si the anomalous reflection does not exceed 30%. This can be explained by calculating the distribution of the mode fields in the investigated waveguides. It is clear from Fig. 2b that the evaporation of an Si film increases greatly the field on the corrugated surface of the waveguide and this increases the ratio $\alpha_r/\alpha_d$ for a real (lossy) waveguide. We carried out an experimental study of the reflection of He–Ne laser radiation by a corrugated surface of a CaF$_2$–SiO$_2$–Nb$_2$O$_5$ waveguide structure and found that the reflection coefficient reached 70%, demonstrating the usefulness of such waveguide structures in stabilization of single-mode emission from semiconductor lasers.

The resolving power of a dispersive element based on a corrugated waveguide is governed by the number of grating lines participating in the reflection of light, i.e., in the final analysis it is governed by the dimensions of a collimated laser beam. In the development of compact semiconductor lasers with a stabilized emission frequency the opportunities for increasing the beam dimensions are limited. Moreover, in contrast to lasers with echelle gratings, when an increase in the number of lines can be achieved by rotating the grating.

FIG. 2. Reflection spectra of the surface of a corrugated waveguide obtained for $\Lambda = 0.91 \mu m$, $2\sigma = 0.04 \mu m$, $n_0 = 1.4328$ (CaF$_2$), $n_1 = 1.46$ (SiO$_2$), $n_2 = 3.5$ (Si), $n_3 = 1$, waveguide layer thickness $h_1 = 1.71 \mu m$, film thickness $h_2 = 0 \mu m$ (1, 2) or 0.015 $\mu m$ (3, 4), $\sigma_d = 0$ (1, 3) and 2.5 cm$^{-1}$ (2, 4) a) and profiles of the TE modes in the waveguide for $h_2 = 0$ (1) and 0.015 $\mu m$ (2) b).

FIG. 3. Reflection spectra of the surface of a corrugated waveguide with an anti-reflection coating of its surface (1) and in the absence of such a coating (2) obtained for $\Lambda = 0.382 \mu m$, $2\sigma = 0.02 \mu m$, $n_0 = 3.4$, $n_1 = 3.5$, $n_2 = 1.84$, $n_3 = 1$, $h_1 = 0.51 \mu m$, $h_2 = 0$ (1) and 0.18 $\mu m$ (2).
ing, the geometry used in the present case (normal incidence of a light beam on a grating) excludes this possibility. However, the waveguide nature of the reflection of light provides a different opportunity for increasing the number of grating lines: we can use waveguides with a high refractive index \( n^* \). In this case the grating period \( \Lambda = \lambda / n^* \) decreases and, for given dimensions of the beam, a higher spectral resolution can be achieved. However, the use of materials with high refractive indices enhances the usual Fresnel reflection far from the anomalies due to the excitation of waveguide modes (for \( n_0 \sim 3.5 \) the reflection coefficient exceeds 30%). Mode selection in a semiconductor laser with such a mirror is not sufficiently strong and it is more difficult to achieve single-frequency emission. Clearly, this problem can be solved by depositing antireflection coatings on the waveguide surface. If the refractive index and thickness of an antireflection film are \( n_{ar} = \sqrt{n_0} \) and \( h_{ar} = \lambda / 4n_{ar} \), we can achieve practically complete suppression of the Fresnel reflection. Our calculations (Fig. 3) show that the anomalous reflection of light is still retained. It should be pointed out that these calculations apply to a waveguide structure with two corrugated interfaces (inset in Fig. 2), corresponding to a situation encountered in practice when an antireflection layer is evaporated.

CONCLUSIONS

The anomalous reflection of light from the surface of a corrugated waveguide makes it possible to construct a simple and compact laser with a stabilized emission frequency. The spectral characteristics of selectively reflecting mirrors of this type can be varied by the deposition of thin films on waveguide surfaces. Films with a high refractive index increase the radiative losses in a waveguide and, consequently, broaden the reflection spectrum and increase the maximum reflection coefficient. Deposition of antireflection films suppresses the Fresnel reflection with practically no change in the anomalous reflection due to excitation of waveguide modes.

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APPENDIX. ESTIMATE OF THE WIDTH OF AN ANOMALOUS REFLECTION PEAK

A phenomenological approach to the problem of the amplitudes of the diffracted waves (including zeroth-order waves) proposed in Ref. 9 demonstrates that the spectral dependence of the reflection coefficient can be described by the formula

\[
\mathcal{R}(\lambda) = \mathcal{R}(\lambda - \lambda_0) \left( \lambda - \lambda_0 \right)^2,
\]

(A1)

where \( \eta \) is the Fresnel reflection coefficient; \( \lambda_0 \) and \( \lambda_\star \) are the characteristic wavelengths governed by the waveguide parameters. This approximation is valid in a narrow range of wavelengths near \( \text{Re} \lambda_\star \), where \( \lambda_\star \) satisfies the condition of excitation of a waveguide mode

\[
\lambda_\star / \Lambda = n^* - \sin \theta_\star,
\]

(A2)

where \( n^* \) is the perturbed value of the effective refractive index of the waveguide (influenced by the presence of the corrugations) and \( \theta \) is the angle of incidence. Moreover, it is assumed that there is no resonant transformation of the modes in the waveguide, i.e., that the angles of incidence \( \theta \) are sufficiently large.

It follows from Eq. (A1) that the spectral width of a reflection peak is \( \Delta \lambda = \text{Im} \lambda_\star \). The total losses in the waveguide are \( \alpha = (4\pi / \lambda) \text{Im} \eta \), so that using the relationship \( \text{Im} \lambda_\star = \text{Im} \eta^* \) [see Eq. (A2)], we obtain

\[
\Delta \lambda = \lambda \alpha / 4\pi.
\]

(A3)

In the case of normal incidence of the beam we have \( \Lambda = \lambda / n^* \) and the spectral width of the reflection peak increases approximately twofold because of the interaction between the waveguide modes in the second diffraction order, so that in this case the best estimate of the width of the reflection peak is given by

\[
\Delta \lambda = \lambda \alpha / 2\pi n^*.
\]

(A4)

\[\text{References}\]

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