files \( n(z) \) obtained from the dependences \( n(T_g) \) determined by us (dashed lines in Figs. 4a and 4d).

Films 1 and 2 exhibited a range of compensation temperatures \( \Delta T_c \) so that we could compare the refractive index profiles \( n(z) \) with the profiles of the compensation "surface" \( T_c(z) \) shown in Figs. 4b and 4e. The position of \( T_c \) depended on the concentrations of the same \( \text{Bi}^{3+} \) and \( \text{Al}^{3+} \) ions which determined the refractive index \( n \), namely \( T_c \) fell on increase in \( x \) (because of a reduction in the \( \text{Gd}^{3+} \) concentration) and on lowering of \( y \) (Ref. 11). Therefore, the position of the minimum of the dependence \( T_c(z) \) should correspond to the maximum of \( n(z) \). This condition was satisfied for film No. 2 when the mode spectrum was calculated selecting the asymmetry parameter to be \( S = 0.2 \) (Ref. 8) and this parameter corresponded to \( z(n_{\text{max}}) = z(T_{\text{min}}) \). Figures 4c and 4f give the distributions \( x(z) \) and \( y(z) \) for films Nos. 1 and 2 using the dependences \( x(T_c) \) and \( y(T_c) \), which were correlated reasonably with the distributions \( n(T_g) \) and \( T_g(z) \).

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Anomalous reflection of light from the surface of an amplifying corrugated waveguide

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The problem of reflection of light from the surface of an amplifying corrugated waveguide is solved. An increase in the waveguide gain increases considerably the reflection coefficient and reduces the spectral width of the reflection peak.

Excitation of a corrugated waveguide by a plane electromagnetic wave results in anomalous reflection of light.\(^1,2\) The reflection coefficient reaches high values (\( R \sim 1 \)) in a narrow range of angles of incidence and wavelengths. Therefore, such narrow-band reflection of light from the surface of a corrugated waveguide is used to select the emission frequency of a semiconductor laser.\(^3\) The resonant nature of the anomalous reflection in combination with nonlinear optical phenomena has made it possible to build a bistable reflecting device based on a corrugated waveguide.\(^4\)

We shall consider theoretically such anomalous reflection of light from the surface of an amplifying corrugated waveguide layer. We shall show that a considerable (by several orders of magnitude) enhancement of the reflection coefficient is possible. This would be of interest in, for example, lasing as a result of amplification on reflection. (The phenomenon of the anomalous reflection of light from the surface of an amplifying corrugated waveguide is possibly responsible for the enhancement of the reflection coefficient of light incident on the surface of an optically excited semiconductor.\(^5\))

We shall consider a corrugated waveguide (Fig. 1). We shall solve the problem of diffraction of a plane wave by this

![FIG. 1. Corrugated thin-film waveguide. Here, \( n_1, n_2, \) and \( n_3 \) are the refractive indices of the ambient medium, waveguide layer, and substrate, respectively; \( h_0 \) is the thickness of the waveguide layer; \( \Delta \) and \( \sigma \) are the period and half-width of the grating (corrugations).](image-url)
waveguide in the approximation that the corrugations are not very large \((k \sigma \ll 1, \lambda = 2\pi /\lambda\) where \(\lambda\) is the wavelength of light in vacuum) and we shall consider three diffraction orders \((m = 0, +1, +2)\) employing the Rayleigh–Fourier method.\(^6\) We shall derive some relationships on the assumption that the incident light has the TE polarization and that the waveguide excitation geometry is collinear (when the projection of the wave vector of the incident wave on the waveguide plane is parallel to the wave vector of the diffraction grating).

The spectral dependence of the amplitude reflection coefficient \(r(\lambda)\) is described by the formula\(^7\)

\[
|r(\lambda)| = |r_F(\lambda)\lambda - \lambda_o)| / |(\lambda - \lambda_o)|,
\]

where

\[
\lambda_o = \lambda / [n^* - n_1 \sin \theta - T/2r_o + (i/2k) (\alpha_{\text{diss}} - \alpha_g)];
\]

\(n^*\) is the refractive index of the waveguide in the absence of the corrugations;

\[
\begin{align*}
\lambda_o &= \lambda / [n^* - n_1 \sin \theta - T/2r_o + (i/2k) (\alpha_{\text{diss}} - \alpha_g)]; \\
&= \lambda / [n^* - n_1 \sin \theta - T/2 + (i/2k) (\alpha_{\text{diss}} - \alpha_g)];
\end{align*}
\]

\(\theta\) is the angle of incidence;

\[
\begin{align*}
n^* &= n^* + n \{\kappa \sigma / 2\} \{g_{n1} + g_{n2} \} + 2 [g_{n1} / (n^* - n)]^{1/2}; \\
&= n^* + n \{\kappa \sigma / 2\} \{g_{n1} + g_{n2} \} + 2 [g_{n1} / (n^* - n)]^{1/2};
\end{align*}
\]

\(\beta^*\) is the effective thickness of the waveguide;

\[
\begin{align*}
g_{n1} &= \{n^2 - n_1 \sin \theta + m \lambda / \lambda\}^{1/2}; \\
&= \{n^2 - n_1 \sin \theta + m \lambda / \lambda\}^{1/2};
\end{align*}
\]

\(\beta^*\) are the normalized (relative to \(k\)) components of the wave vectors of the diffracted waves normal to the waveguide surface; \(j = 1, 2, 3\) is the index of the medium;

\[
r = \{g_{n1} + g_{n2} \} / [g_{n1} + g_{n2} + g_{n3} + g_{n3}];
\]

\(\beta^*\) is the coefficient of the Fresnel reflection from the waveguide structure (in the absence of a corrugation but allowing for the reflection at the boundaries of the waveguide layer);

\[
r_o = \{g_{n3} - g_{n3} \} / [g_{n3} + g_{n3} \exp (2i g_{n3} h_{n3})];
\]

\[
T = 2i(n^2 - n_1^2) \{\kappa \sigma / 2\} [g_{n1} / (g_{n1} + g_{n1})];
\]

\[
\alpha_{\text{diss}} \text{ and } \alpha_g \text{ represent the dissipative losses in the waveguide and the waveguide gain; the imaginary part of the parameter } T \text{ is related to the radiative losses in the waveguide}.
\]

The phase \(\lambda / 2\) is neglected because it is small compared to the wavelengths of interest.

\[
\text{Im}(T) = k^{-1} \alpha_{\text{rad}}.
\]

If the reflection at the interface between the waveguide layer and the substrate is weak \((|r_o| \ll 1)\), Eq. (1) becomes

\[
\begin{align*}
r(\lambda) &= \lambda / \{\kappa^* - n_1 \sin \theta + (i/2k) \} \times (\alpha_{\text{diss}} - \alpha_g - \alpha_{\text{rad}} / r_o) / \{\kappa^* - n_1 \sin \theta + (i/2k) (\alpha_{\text{diss}} + \alpha_{\text{rad}} - \alpha_g)\};
\end{align*}
\]

In the absence of amplification and dissipation the total reflection \((|r| = 1)\) is attained if the following waveguide excitation condition is obeyed:

\[
\lambda / \{\kappa^* - n_1 \sin \theta + (i/2k)\} = n_1, \sin \theta = \kappa^*.
\]

In the presence of amplification or dissipation the maximum reflection coefficient is also obtained when the condition (11) is obeyed and it amounts to

\[
R_{\text{max}} = \left| \left( \frac{\alpha_{\text{diss}} - \alpha_g}{\alpha_{\text{diss}} + \alpha_{\text{rad}} - \alpha_g} \right) \right|.
\]

It is clear from Eq. (12) that if \(\alpha_g \rightarrow \alpha_{\text{diss}} + \alpha_{\text{rad}}\) we have \(R_{\text{max}} \rightarrow \infty\). Physically this means that an undamped mode is propagated if the waveguide gain is sufficiently high. The dissipative and radiative losses are then compensated exactly by the amplification in the waveguide. The radiation does escpace from the waveguide and there is no incident wave, i.e., the reflection coefficient becomes infinite.

In the subsequent analysis we shall assume that \(|r_F| \ll 1\).

Then, the maximum reflection coefficient becomes (Fig. 2)

\[
R_{\text{max}} = \left| \left( \frac{\alpha_{\text{rad}}}{\alpha_{\text{rad}} + \alpha_{\text{diss}} - \alpha_g} \right) \right|^2.
\]

Detuning by \(\delta \lambda\) from the condition (11) modifies the reflection coefficient to

\[
R(\delta \lambda) = \left( \frac{\alpha_{\text{rad}}}{\alpha_{\text{rad}} + \alpha_{\text{diss}} - \alpha_g} \right)^2.
\]

The width of the reflection peak at the \(1^{st} R_{\text{max}}\) level is

\[
\Delta \lambda = (\lambda / 2k) (\alpha_{\text{rad}} + \alpha_{\text{diss}} - \alpha_g).
\]

It therefore follows that an increase in the waveguide gain causes the small-signal maximum reflection coefficient to rise without limit in the anomalous reflection case and it reduces the width of the reflection peak. In the limit when \(\alpha_g = \alpha_{\text{rad}} - \alpha_{\text{diss}}\) we encounter the traveling-wave (guided mode) regime.

We discussed above an amplifying corrugated waveguide and the reflection of light from its surface. Similar results are obtained also in the case of a waveguide with periodic modulation of the refractive index along the waveguide layer.\(^8\)

No direct experiments on the anomalous reflection of light by an amplifying waveguide have yet been made. However,
ever, the effect described above may possibly explain the reflection of light from the surface of an optically excited semiconductor. For example, it is reported in Ref. 5 that excitation of a CdS crystal with a normally incident "pump" light beam of wavelength $\lambda_p = 0.35 \, \mu m$ results in an increase of the reflection of relatively low power radiation of wavelength $\lambda = 0.53 \, \mu m$ incident at $\theta = 70^\circ$. This increase in the reflection coefficient (by a factor of 2–6 compared with the reflection in the absence of pumping) is localized in a narrow range of angles of incidence (10°–30°) and wavelengths of the incident radiation (~5 nm).

It is known that high-power laser radiation of wavelength $\lambda_r < c h / E_g$ ($E_g$ is the width of the band gap, $c$ is the velocity of light, and $h$ is the Planck constant) on the surface of a semiconductor creates a periodic variation of the permittivity $\varepsilon$ in the surface layer. The spatial period $\Lambda$ of a change in $\varepsilon$ is approximately equal to $\lambda_p$. At $\lambda_p = 0.35 \, \mu m$ we have to assume that $\Lambda = 0.32 \, \mu m$ and in any case the estimate $\lambda_p / \Lambda = 1.1$ (Ref. 10) is valid also when relief gratings are formed as a result of interaction of powerful radiation with materials characterized by parameters corresponding to CdS ($n = 2.66$, $k = 0.3$).

Moreover, interaction of high-power radiation with a semiconductor may form an optical waveguide in its surface layer. Using the data of Ref. 8, we can estimate the effective refractive index of such a waveguide, $n^* = \lambda / \Lambda + \sin \theta \approx 2.5$, which is quite close to the refractive index of CdS at $\lambda = 0.53 \, \mu m$.

If this mechanism of enhancement of the reflection coefficient as a result of optical excitation of a semiconductor is correct, the angle of incidence and the wavelength corresponding to the maximum enhancement of the reflection coefficient should be related by Eq. (11). Moreover, irradiation of a semiconductor with an obliquely incident light beam should alter the period of the induced grating (as the angle of incidence of the pump beam is varied) and, consequently, it should alter the relationship between the wavelength and angle of incidence corresponding to the maximum reflection. Experiments of this kind can solve the problem of validity of the proposed mechanism of increase in the reflection of light.

7. A. Avrutskii and V. A. Sychugov, Preprint No. 56 [in Russian], Institute of General Physics, Academy of Sciences of the USSR, Moscow (1988).

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