Research on the properties of the periodic surface structures which arise during the laser annealing of various materials has shown that these structures are manifestations of a stimulated scattering of the laser beams by the surfaces. It has been shown\(^{1-3}\) that the scattering by a surface roughness, the interference of the scattered light with refraction in the interior of an absorbing medium, and the consequent nonuniform energy evolution at the surface can intensify one or several particular spatial harmonics from the surface roughness spectrum. According to this mechanism, that orientation of a corrugation for which the growth rate is highest is the one on which the lines of the corrugation are oriented perpendicular to the electric field (\(\vec{E}\)) of the incident light, although a longitudinal corrugation (whose lines run parallel to \(\vec{E}\)) may also be intensified. Figure 1 shows the difference between the energy evolution in the valleys of the corrugation and at its hills, \(\Delta Q\), versus the quantity \(\lambda / \Lambda\) (\(\lambda\) is the wavelength of the incident light, and \(\Lambda\) is the period of the corrugation) for transverse and longitudinal corrugations and for TM-polarized light incident on liquid germanium at an angle \(\theta = 60^\circ\). It follows from Fig. 1 that as the surface is bombarded a transverse corrugation with a relatively small period should arise first, then a transverse corrugation with a relatively large period, and last a longitudinal corrugation. Experimentally, however, the transverse corrugation with the relatively small period is followed by the formation of a longitudinal corrugation, and only after this step does a transverse corrugation with a relatively large period form. It follows that in order to reach an understanding of the reasons for the formation of the longitudinal corrugation we must look beyond the diffraction of light by the corrugation itself. We have accordingly taken up the problem of the diffraction of light by a grating consisting of a modulation of the dielectric constant (\(\varepsilon\)) of the medium and the self-intensification of this grating under the influence of the incident light, by analogy with studies\(^{34}\) which have been carried out for a corrugation. A similar problem was studied in Refs. 1 and 5 for the case of normal incidence.

We write the dielectric constant of the medium as

\[
\varepsilon(y, z) = \varepsilon_1 + \Delta \varepsilon \varepsilon^{\text{ref}} \cos (K_y y + K_z z),
\]

where the \(z\) axis runs normal to the surface, into the nonabsorbing medium, \(\Delta \varepsilon\) is the modulation of the dielectric constant of the medium at its surface, \(\varepsilon_1\) is the dielectric constant of the absorbing medium, and \(\alpha\) is the parameter describing the weakening of the grating with depth. The energy absorbed in the medium is given by

\[
Q = \frac{\omega}{2\pi} \vec{E} \cdot \vec{E}^* \text{Im}(\varepsilon),
\]

where \(\omega\) is the frequency of the incident light, \(\vec{E} = \sum_{\vec{q}} \vec{E}_q\), and \(\vec{E}_q\) is the electric field of diffraction order \(q\). We restrict the calculations to diffraction orders 0 and \(\pm 1\), and we use the approximation of small \(\frac{\Delta \varepsilon}{\varepsilon_1} \ll 1\). The energy which evolves at the surface can be written

\[
Q_{\text{surf}} = \frac{\omega}{2\pi} \text{Im}(\varepsilon) \left[ Q_0 + \text{Im}(\alpha \varepsilon) Q_0 \cos(K_y y) + \sum_{\vec{q} \neq \vec{q}_1} \left( 2k_0 \varepsilon_0 (\varepsilon_0 + 1) \cos(K_y y) - 2 \sum_{\vec{q}} \text{Re}(\varepsilon_0) \sin(K_y y) \right) \right],
\]

where \(Q_0\) is the intensity of the refracted light, and \(\alpha \varepsilon_0\) is the scalar product of the complex amplitudes of the refracted wave and the wave of diffraction order \(q\) for \(q = \pm 1\). The term

\[
P = \frac{\omega}{2\pi} \text{Im}(\varepsilon) \left[ \text{Im}(\alpha \varepsilon) Q_0 + 2 \sum_{\vec{q} \neq \vec{q}_1} \text{Re}(\varepsilon_0) \right]
\]

in (3) corresponds to an intensification or weakening of the original grating. The other terms in (3) correspond to a general heating of the surface and to a displacement of the original grating along the surface. As models for calculation we use solid and liquid germanium (with \(\varepsilon_0 = 16 + 0.81\) and \(\varepsilon_0 = -32 + 721\), respectively), and we calculate

\[
\Delta Q = P' / (\Omega^2 F_1) \quad \text{for the case in which the imaginary and real parts of } \Delta \varepsilon \text{ are identical (Fig. 2) and for the case in which they are equal in magnitude but opposite in sign (Fig. 3).}
\]

We believe that the first of these cases is a qualitative model of the change in \(\varepsilon\) of a semiconductor as it is heated, while the second case simulates the increase in the density of free charge carriers upon the absorption of photons with an energy greater than the band gap. Figures 2 and 3 show curves of \(\Delta Q(\vec{q})\) for a longitudinal corrugation and for TM-polarized light incident at various angles. We see that the shape of the \(\Delta Q(\vec{q})\) curve changes greatly with...
Increasing angle of incidence, developing extrema near 
\( \frac{\lambda}{A} \cos \theta \). With increasing angle of incidence, the extrema become progressively better defined. This result agrees with the experimental fact that a longitudinal corrugation forms at large angles (\( > 30° - 40° \)) in the case of TM-polarized light. To determine which of these extrema lead to the formation of the corrugation, we carried out some experiments in which germanium was illuminated with TM-polarized light (\( \lambda = 1.06 \mu m \)) at an intensity near the threshold for the formation of a corrugation. Figure 4 shows a reflection pattern of a longitudinal corrugation produced under these conditions. There is a sharp edge on the long-period side, while on the low-period side there is a smooth decrease. Comparison of the reflection pattern with the calculations reveals that the formation of the corrugation apparently begins as a result of an intensification of a modulation \( \Delta \varepsilon \) of the dielectric constant in solid germanium. A simple comparison of the values of \( \Delta Q \) for a corrugation on liquid germanium and for a longitudinal (grating) modulation of \( \varepsilon \) on solid germanium shows that a necessary condition for the appearance of a longitudinal corrugation due to the modulation of \( \varepsilon \) before a transverse corrugation with a large period is \( \text{Im} (\Delta \varepsilon) > 0.12 \) [comparison of Figs. 2a and 3a shows that a change in the real part of \( \varepsilon \) has little effect on \( \Delta Q \), although it causes a significant change in the shape of the \( \Delta Q(\lambda/\Lambda) \) curve]. For semiconductors at high temperatures, a modulation \( \Delta \varepsilon \) of this sort corresponds to a small temperature modulation \( \Delta T \). For silicon at \( T = 600^\circ C \), for example, the value \( \text{Im} (\Delta \varepsilon) = 0.12 \) corresponds to \( \Delta T \sim 25^\circ C \). As the temperature is raised further, the value of \( \Delta T \) decreases.

It is difficult to make a direct comparison of the values of \( \Delta Q \) or of other characteristics of the intensification of a corrugation for mechanisms involving the corrugation itself and mechanisms involving a modulation of the dielectric constant \( \varepsilon \), because the development and intensification of the dielectric-constant grating begin as soon as the laser pulse reaches the surface, i.e., while the surface has not yet warmed to the melting point. By the time melting begins, the amplitude of the dielectric-constant grating may be large, while the amplitude of the corrugation is still small, and the latter may begin to increase only after melting has begun. A systematic comparison of the corrugation growth mechanisms involving the corrugation itself and a modulation of the dielectric constant requires reliable information on the optical properties of germanium during intense laser bombardment. In addition, the increase in \( \Delta \varepsilon \) before the beginning of melting must be taken into account. Nevertheless, we believe that the results and arguments presented in the present letter already show that at large angles of incidence of intense TM-polarized light the formation of a longitudinal corrugation on germanium should be attributed to an increase in the modulation of \( \varepsilon \).
photoinduced piezoelectric phase modulation of light by crystals

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The $\text{Bi}_2\text{SiO}_5$ (BSO) crystal is being studied widely as a reversible medium for optically controlled space–time light modulators and for writing holograms. In either case, optical information is written in the crystal by means of a photorefractive effect involving the formation of a photoinduced charge by the writing light in the interior of the crystal. The electric field of this charge works through an electrooptic effect to change the refractive properties, so that the polarization state of a readout light beam can be modulated.

In addition to the electrooptic effect, the BSO crystal has some pronounced piezoelectric properties. It can thus be expected that the internal field of the photoinduced charge will cause a deformation of a plate–shaped crystal. The displacements of the surface of the plate involved in this deformation may cause a significant phase modulation of a readout light beam reflected from the surface. In the present letter we report the first experimental data on a photoinduced piezoelectric phase modulation of light by BSO crystals.

The BSO samples are similar in structure to the $\text{PRZI}^1$ space–time light modulator. The sample is a circular plate of a (110)-cut crystal $\approx 20$ mm in diameter and $\approx 0.5$ mm thick. Transparent electrodes ($\text{In}_2\text{O}_3+\text{SnO}_2$) with a reflection coefficient $r^2 \approx 20\%$ are deposited directly on faces of the plate. A voltage of 2 kV is applied to the electrodes to produce a spatially nonuniform photoinduced charge in the crystal. In the crystal itself, the beam from a He–Cd laser ($\lambda_W = 441$ nm) writes a sinusoidal grating with a spatial frequency $\nu$. This grating is produced as the result of an interference of two light beams of equal intensity. As experiments carried out for the PRZ modulator have shown, a nonuniform field having both transverse and longitudinal components and a strength up to $10^5$ kV/cm is produced in the crystal under these conditions. The vector of the grating which is written, $\vec{K} (|\vec{K}| = 2\pi d)$, can be oriented in an arbitrary way with respect to the crystallographic axes of the plate. The spatial frequency is varied from 1 to 100 mm$^{-1}$. To detect the periodic surface relief on the sample, we illuminate the first electrode encountered by the writing beam by a uniform converging readout beam from a He–Ne laser ($\lambda_R = 633$ nm). The diffraction pattern of the light reflected from this electrode and modulated by the period relief is studied in the focal plane of the system which forms the readout beam. The small angle between the opposite faces of the plate about (20) makes it possible to separate the reflections from the front and rear electrodes. The first order of the diffracted light is sent to a photomultiplier, whose output signal is proportional to the diffraction efficiency $\eta$ of the photoinduced piezoelectric phase modulation.

Figure 1a shows some typical oscilloscope traces of $\eta$ versus the energy of the writing beam, $\varepsilon_W$, for various writing intensities $I_W$. The results show that up to a certain limit $\varepsilon_W = \varepsilon_L$, which varies with $\nu$, the proportionality $\eta \sim \varepsilon_W^2$ holds within the given accuracy. As the exposure is increased, $\eta(\varepsilon_W)$ goes through a maximum at $\varepsilon_W = \varepsilon_W^{\text{max}}$ and then falls to zero. The relative error of the measurements in this and all the other experiments was no worse than 10%. The photoinduced piezoelectric phase modulation was not detected when a positive potential was applied to the front electrode.

The value of $\eta$ for the phase modulation depends on both the spatial frequency of the grating and the orientation of its vector $\vec{K}$ with respect to the crystallographic axes. Different orientations correspond to different shapes of the space–time curves of $\eta(\nu)$; conversely, different values of $\nu$ correspond to different orientational dependences. Figure 1b shows the dependence of $\eta$ on $\nu$ for the case in which the vector $\vec{K}$ makes an angle $\phi = 45^\circ$ with the (110) axis. The direction of the (110) axis is determined from the maximum of the internal transverse electrooptic effect. The curves of $\eta(\nu)$ in Fig. 1b show a decrease in proportion to $\nu^{-2}$ at frequencies beyond the maximum. As $\nu$ tends toward zero, so does $\eta$, although the intensity of the undiffracted readout beam (in the zeroth order of diffraction) remains essentially constant because of the small value of $\eta \ll 1$.

Figure 1c shows curves of $\eta(\nu)$ for two orientations of the vector $\vec{K}$. The merging of curves 1 and 1' and of 2 and 2' reflects the experimentally observed tendency toward a reduction of the anisotropy of $\eta(\phi)$ in the interval $35^\circ < \phi < 145^\circ$ with increasing spatial frequency at comparably low values $\varepsilon_W < \varepsilon_L$.

We can use the experimental data to estimate the