Transformations of a light beam on reflection from the surface of a corrugated waveguide

I.A. Avrutskii, A.S. Svakhin, and V.A. Sychugov

(Received 8 December 1986)

The reflection from the surface of a corrugated waveguide of a light beam bounded along one coordinate is examined. It is shown that in the case of anomalous reflection of light (on excitation of a waveguide mode), a Gaussian light beam can be transformed into a first-order Gaussian-Hermitian mode. On the basis of the experimental data, it is shown that the energy coefficient of transformation can reach a value of the order of \( (1-2) \times 10^{-2} \) in this case.

The excitation of waveguide modes when a plane wave is incident on the surface of a corrugated waveguide is accompanied by anomalous light reflection. Since the excitation of a waveguide is a resonance process, the anomalies are observed in a fairly narrow range of angles of incidence

\[
\Delta \theta \sim \frac{\lambda}{2 \pi \cos \theta},
\]

where \( \alpha \) is the total loss in the waveguide (mainly the radiation loss on the grating). The amplitude of the reflected wave may change from 0 to 1 as the angle of incidence changes by \( \Delta \theta \), and the phase changes continuously by \( 2\pi \).

The dependence of the reflection coefficient \( r \) and phase \( \varphi \) of the reflected wave on the angle of incidence results in singularities in the reflection of bounded beams. A typical example of this type of phenomenon is the Goos-Hänchen shift during total internal reflection.

In the case of anomalous reflection of light from the surface of a corrugated waveguide, these phenomena can be particularly pronounced because of large values of \( \Delta r / \Delta \theta \) and \( \Delta \varphi / \Delta \theta \). In a theoretical analysis, it is convenient to take as the independent variable not the angle of incidence \( \theta \), but the projection \( q \) of the wave vector of the incident wave on the waveguide plane

\[
q = \frac{2\pi}{\lambda} \sin \theta.
\]

Let us consider the reflection of a beam bounded in one coordinate in the case of anomalous light reflection. The distribution of the electric field (for TE-polarized wave) and magnetic field (for a TM-polarized wave) in the incident wave in the plane \( z = 0 \) is (Fig. 1)

\[
E_i(z) = F(x) e^{i\varphi z},
\]

where \( q_0 = \frac{2\pi}{\lambda} \sin \theta_0 \), \( \theta_0 \) is the angle of incidence, and \( |F(x)|^2 \) is the distribution of energy in the beam in the plane \( z = 0 \). We will represent the incident beam as a superposition of plane waves

\[
E_i(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} E_i(q) e^{iqx} dq,
\]

\[
E_i(q) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} F(x) e^{i(q-\gamma)x} dx.
\]

Then the electric field of the reflected wave is

\[
E_r(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} R(q) F(q) e^{i\varphi x} dq,
\]

where \( R(q) = r(q) \exp[i\varphi(q)] \) is the reflection function for plane wave. The dependence \( R(q) \) is fairly complex, but in the case of sufficiently wide beams, the diffraction divergence which is much smaller than \( \Delta \theta \), use may be made of the linear approximation

\[
R(q) = [r_0 + \beta (q - q_0) \exp [i \{ q_0 + \beta (q - q_0) \}]].
\]

Then the distribution of the electric field in the reflected wave will be

\[
E_r(x) = \left[ r_0 e^{i\varphi_0} F(x') + b e^{i(q_0 + \beta)q} \frac{d}{dq} F(x') \right] e^{i\varphi z},
\]

\[
z' = z + \beta.
\]

Thus, the displacement of the beam on reflection is given by the derivative \( \beta = dp/dq \), and the dependence of reflection coefficient \( r \) on the angle of incidence leads to a change in beam shape (Fig. 2). In particular, if \( F(x) = H_n(x/a) \times \exp \left[ - \left( x/a \right)^2 \right] \), where \( H_n(x/a) \) is a Hermitian polynomial of order \( n \), then \( (d/dx') F(x') = -(1/a) H_{n+1}(x'/a) \exp \left[ - \left( x'/a \right)^2 \right] \), i.e., when Gaussian-Hermitian modes of order \( n \) are incident on a structure, modes of order \( n + 1 \) are present in the reflected beam. A detailed analysis of such a transformation in the case of reflection from an interface of dielectrics is given in Ref. 4. For a zero-order Gaussian beam

\[
F(x) = \exp \left[ - \left( \frac{x}{a} \right)^2 \right]
\]
the energy coefficient $\gamma$ of reflection of the incident wave into a first-order mode is

$$\gamma = \frac{\int_{-\infty}^{+\infty} b \frac{d}{dx} F(x) dx}{\int_{-\infty}^{+\infty} F(x) dx} = \left(\frac{b}{a}\right)^2. \tag{11}$$

Considering that the quantity $b$ represents the slope of the curve $r(q)$, and $1/a$ is the diffraction divergence in units of $q$, one can state that the size and slope of the linear segment on the $r(q)$ curve will determine the attainable values of $\gamma$.

In order to estimate the attainable values of $\gamma$, we studied the dependence $r(q)$ for a corrugated waveguide made from the structure SiO$_2$-Nb$_2$O$_5$/CaF$_2$. The waveguide was obtained as follows. Magnetron evaporation was used to deposit an SiO$_2$ layer ($n = 1.4625$) 1 $\mu$m thick on a CaF$_2$ substrate with refractive index $n_1 = 1.4328$ ($\lambda = 0.633 \mu$m). Then a standard method$^{5,6}$ was used to prepare a lattice with period $\Lambda = 0.38 \mu$m on the SiO$_2$ surface. After the photoresistive mask was removed, the thickness of the SiO$_2$ layer with the lattice on the surface was reduced to 0.44 $\mu$m, so that the waveguide became almost critical. The depth of the lattice also decreased to 20 min. This operation eliminated most of the stray scattering of light in the lattice. Finally, in order to improve the waveguide properties of the structure and increase the efficiency of interaction of light with the lattice, a thin layer of Nb$_2$O$_5$ ($n = 2.3$) was evaporated onto the corrugated SiO$_2$ layer.

In the study of the dependence $|r^2(\theta)|$, use was made of a telescope which broadened the beam of an He–Ne laser to 10 mm, and of a theodolite that made it possible to determine the angles of incidence of light on the lattice to within $5^\circ$.

Figure 3 shows curves of the intensities of the reflected and transmitted beams, as well as their sums, as a function of the angle of incidence of the laser beam on the lattice. On excitation of the waveguide mode, the summation signal decreases, owing to the losses of light in the waveguide and to its scattering by the lattice imperfections. The maximum reflectance of light for the structure considered was 70%. This in itself is a fairly highly value of reflectance, but in our view, more perfect lattices must be used in order to reach the theoretical limit. Conversion of the data shown in Fig. 3 into the dependence $r(q)$ shows that for the investigated waveguide structure, the maximum value of $\gamma$ is $(1-2) \times 10^{-2}$ if one remains within the framework of condition (7).

In devices where the effect of selective reflection of the light from the surface of a corrugated waveguide can be used, a regime of maximum reflection of a bounded light beam is desired. Such a regime, however, is possible because of the boundedness of the beam, and the maximum attainable value of the reflectance will be lower. For example, on the structure considered, for a 3° diffraction divergence of the beam, this value was 65%. It should be noted that in this regime, the transformation of the reflected wave into higher-order modes is minimal, since the value of $\gamma$ changes sign as it goes through the maximum of $r(q)$.

Thus the results obtained demonstrate the possibility of using corrugated waveguide structures as effectively reflecting mirrors and narrow-band optical filters.

---

Parametric processes in the field of an ultrashort pulse in noncentrosymmetric media

A. S. Kindyak and O. Kh. Khasanov

(Received 5 June 1986)

The vector model of coherent two-photon effects is extended to the case of maximum influence of the intrinsic dipole moment of particles. Numerical and analytical studies are made on the propagation characteristics of an ultrashort pulse of coherent radiation in a resonant noncentrosymmetric medium, as well as on second-harmonic generation in the field of a pump pulse during single-photon absorption of the latter. The interaction of the intrinsic dipole moment with the field of the pump pulse is equivalent to the presence in the sample of a multifrequency field with an infinite set of multiple harmonics. The soliton mode of pulse propagation does not take place under these conditions. Generation of multiple harmonics takes place during the passage of the pump pulse. The duration of second-harmonic pulses is one-fifth to one-third that of the pump pulse, and the conversion efficiency is 35% or higher. The Stark shift of the resonance levels decreases the conversion efficiency by a factor of ~3–2. In all cases, a significant phase modulation of the pump and harmonic pulses was observed.

Considerable progress has been made in the area of harmonic generation and frequency mixing in both the continuous and pulsed modes under resonance as well as nonresonance conditions. Interest in this area is due, on the one hand, to the great potentials of nonlinear coherent spectroscopy, and on the other hand, to the prospects of creating tunable sources of powerful coherent radiation in a wide spectral region including the VUV range, as well as in the far IR and microwave spectral regions.

Most advanced is the quasistationary theory of parametric resonance processes, in which the pulse duration \( \tau_p \) considerably exceeds the relaxation time of populations and polarization. As was shown in Ref. 6, when first- and second-order processes take place simultaneously under phase-matching conditions, phase capture of the generated harmonics takes place. Intensive energy exchange between the radiation components occurs, resulting in parametric bleaching of the substance. The maximum efficiency of second-harmonic generation (SHG) at resonance can be 43%, in contrast to nonresonance conditions, where the conversion efficiency can be 100%.

Of late, considerable attention has been focused on the dynamics of frequency conversion in a nonstationary mode, when the influence of dissipative processes may be neglected. As was shown in Ref. 8, the process of third-harmonic generation in the two-quantum mode is closely related to the phenomenon of two-photon self-induced transparency and is of threshold character. The influence of the Stark shift of the levels and of phase modulation causing a complex temporal structure of the generated harmonics becomes significant.

References 11 and 12 dealt with the propagation effects of ultrashort resonance pulses (USP) of light in noncentrosymmetric crystals. It was shown that the intrinsic dipole moment (IDP) of particles in a field of even circularly polarized light leads to anharmonicity of the oscillations of induced dipoles, this being equivalent to taking into consideration a multifrequency field with an infinite set of multiple harmonics. The probability of multiphoton transitions increases, and the medium becomes optically anisotropic. As a result of interaction of the light pulse with the IDP of the particles, the soliton mode of passage does not occur; only quasisoliton solutions apply, when the influence of second-harmonic resonance is slight.

This paper examines the parametric processes taking place in the field of an ultrashort pulse of electromagnetic radiation propagating in a noncentrosymmetric medium under single-photon resonance absorption conditions.

Let us consider a system of atoms located in a strong constant electric field \( E_0 \) directed along the [010] axis. In such a system, in a direction perpendicular to \( E_0 \), there is propagated an ultrashort light pulse whose shape, account being taken of the influence of the IDP, will be chosen in the form