SURFACE WAVES

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Nonlinear surface waves on the boundary of a photorefractive crystal

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***Abstract*. Excitation of nonlinear surface waves is studied at the SBN-75 crystal – air interface. The SBN-75 crystal is characterised by the diffusion-type photorefractive nonlinearity, the surface wave being excited in the surface layer and the depth of its penetration into the crystal being determined by the nonlinear crystal parameters. Because of a large refraction coefficient in SBN-75, the penetration depth of the surface wave into the air is small; therefore, the nonlinear surface wave is localised in the surface crystal layer several micrometers in thickness. The oscillating intensity distribution of the surface wave at the output end of the crystal is measured. The oscillation period is determined by the angle of incidence of the exciting beam. The nonlinear wave is excited not only at the crystal – air interface but also in the case when the active surface of the crystal is covered by an electrode, for example, an aquadag layer. This circumstance opens up a possibility of studying new properties of the surface waves when an external electric field is applied to the crystal.**

Keywords: *photorefractive crystal, nonlinear surface waves.*

1. Introduction

By now most papers have studied the nonlinear propagation of light in media with the Kerr nonlinearity. This nonlinearity affects directly the light beam phase, which allows one to compensate for the phase diffraction effect. However, the nonlinear susceptibility χ_3 responsible for the Kerr effect is relatively small and that is why light intensities of no less than 1 MW cm^{-2} are required to produce non-diverging beams. In this case, photorefractive crystals, in which the nonlinear regimes of wave interactions manifest themselves already at the intensities smaller than 1 W cm^{-2}, have a significant advantage.

The photorefractive effect has many stages: light energy absorption, formation of free electrons and holes, their transfer and trapping followed by the production of bulk charge regions. After this charge, the electrooptical effect forms a spatial refractive index distribution of light, which in turn, interacts with the wave front of propagated radiation and changes it. Photorefraction was discovered by Ashkin and his colleagues in 1966 [1]. Two years later Chen used this phenomenon to write phase holograms and nowadays it is widely used for data processing [2].

In 1995 Mexican scientists performed an analysis of the nonlinear surface waves in photorefractive crystals with the diffusion mechanism of nonlinearity [3]. These guided and transform-limited waves can propagate along the photorefractive crystal – air (metal) interface. In this paper, we study self-channelling of a light wave along the surface of the photorefractive crystal without an initially prepared waveguide layer.

2. Surface waves

Consider propagation of extraordinary TM-polarised light along the z axis directed along the photorefractive crystal – air interface (Fig. 1) [4]. Because we study the grazing propagation of light, the anisotropy of the refractive index will be neglected. The magnetic field component of the surface wave, $H(x,z)$, along the y axis satisfies the equation

$$\nabla^2 H(x,z) + k^2 H(x,z) = 0, \tag{1}$$

where $k = k_0[n_2 + \Delta n(x)]$; $k_0 = 2\pi/\lambda_0$; λ_0 is the light wavelength in vacuum; n_2 is the unperturbed refractive index of the crystal; $\Delta n(x)$ is the nonlinear addition to the refractive

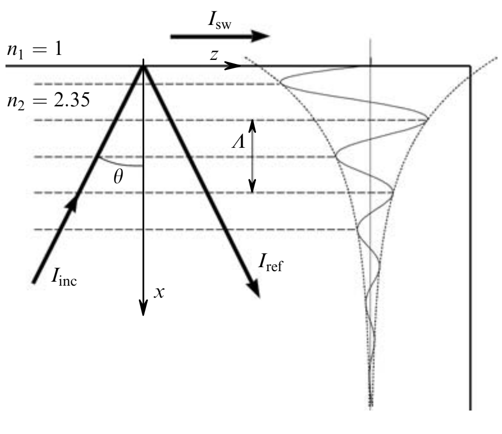

Figure 1. Scheme of surface-wave excitation and propagation: I_{inc}, I_{ref} and I_{sw} are the incident, reflected, and surface waves, respectively.

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index n_2. The stationary solution for the field distribution in the crystal is sought for in the form $H(x,z) = A(x)\exp(i\beta z)$, where β is the surface-wave propagation constant.

The nonlinear addition $\Delta n(x)$ can be represented as a result of action of the diffusion mechanism of nonlinearity [5]:

$$\Delta n(x) = \frac{1}{2} n_2^3 r_{\rm eff} \frac{k_{\rm B}T}{q} \frac{1}{I(x) + I_{\rm d}} \frac{\rm d}{{\rm d}x}[I(x) + I_{\rm d}], \quad (2)$$

where q is the electron charge; $r_{\rm eff}$ is the effective electrooptical coefficient; $k_{\rm B}$ is the Boltzmann constant; T is the temperature; $I(x) \propto |A(x)|^2$ is the surface-wave intensity; $I_{\rm d}$ is the dark intensity.

Note that expression (2) demonstrates the disparity of two directions of the x axis appearing due to the fact that the crystal is polarised in the direction of the x axis (coinciding with the crystallographic axis c).

When the dark intensity $I_{\rm d}$ is small compared to the surface-wave intensity, it can be neglected and equation (1) can be written in the form

$$\left[\frac{{\rm d}^2A(x)}{{\rm d}x^2} + 2k_0^2n_2^4 r_{\rm eff}\frac{k_{\rm B}T}{q}\frac{{\rm d}A(x)}{{\rm d}x} + \left(k_0^2n_2^2 - \beta^2\right)A(x)\right] \times \exp({\rm i}\beta z) = 0, \quad (3)$$

where $\exp({\rm i}\beta z)$ describes the established surface-wave propagation in the direction of the z axis. In this case, equation (3) can be simplified:

$$\frac{{\rm d}^2A(x)}{{\rm d}x^2} + \gamma\frac{{\rm d}A(x)}{{\rm d}x} + \left(k_0^2n_2^2 - \beta^2\right)A(x) = 0, \quad (4)$$

where $\gamma = 2k_0^2n_2^4 r_{\rm eff}k_{\rm B}T/q$. The eigenvalues of equation (4) have the form $\lambda_{1,2} = -\gamma/2 \pm (\gamma^2/4 + \beta^2 - k_0^2n_2^2)^{1/2}$.

When $\beta < (k_0^2n_2^2 - \gamma^2/4)^{1/2}$, the surface-wave amplitude is

$$A(x) = \exp(-\gamma x/2)\cos\left[\left(k_0^2n_2^2 - \beta^2 - \gamma^2/4\right)^{1/2}x + \varphi\right], \quad (5)$$

where 2φ is the phase difference of incident and reflected light beams producing an interference pattern. The surface-wave amplitude decreases exponentially, experiencing oscillations.

When $\beta > (k_0^2n_2^2 - \gamma^2/4)^{1/2}$, the field amplitude is

$$A(x) = c_1\exp\left\{\left[-\gamma/2 + \left(\beta^2 - k_0^2n_2^2 + \gamma^2/4\right)^{1/2}\right]x\right\} + c_2\exp\left\{\left[-\gamma/2 - \left(\beta^2 - k_0^2n_2^2 + \gamma^2/4\right)^{1/2}\right]x\right\}. \quad (6)$$

This case corresponds to the nonoscillating profile of the surface-wave amplitude and can be observed only at small grazing angles of the beam forming the surface wave.

In air the surface-wave amplitude is

$$U(x) = U_0\exp\left[\left(\beta^2 - k_0^2n_1^2\right)^{1/2}x\right], \quad (7)$$

where n_1 is the refractive index of air. When $\beta > kn_1$, the field amplitude decreases exponentially while moving away from the crystal boundary. The continuity conditions for tangential field components at the photorefractive crystal – air interface yield the equalities

$$U(x)|_{x=0} = A(x)|_{x=0}, \quad \frac{1}{\varepsilon_1}\frac{\partial U(x)}{\partial x}\bigg|_{x=0} = \frac{1}{\varepsilon_2}\frac{\partial A(x)}{\partial x}\bigg|_{x=0}, \quad (8)$$

where ε_1 is the dielectric constant of air; ε_2 is the dielectric constant of the photorefractive crystal.

By applying continuity condition (8) to equations (5) and (7), we obtain

$$\varphi = \arctan\left\{\frac{\varepsilon_2}{\left(k_0^2n_2^2 - \beta^2 - \gamma^2/4\right)^{1/2}} \times\left[\frac{\left(\beta^2 - k_0^2n_1 2\right)^{1/2}}{\varepsilon_1} + \frac{\gamma}{2\varepsilon_2}\right]\right\}. \quad (9)$$

The surface-wave propagation constant β is related to the angle of incidence of the exciting light onto the interface, β, by the expression

$$\beta = k_0n_2\sin\theta \quad (10)$$

(note that the c axis of the crystal is directed along the normal to the interface).

By using the above expressions, we can determine, for the given angle of incidence θ, the surface-wave amplitude distribution. This wave has a characteristic field oscillation period

$$\Lambda = \frac{2\pi}{\left(k_0^2n_2^2\cos^2\theta - \gamma^2/4\right)^{1/2}} \quad (11)$$

and penetrates into the photorefractive crystal to the depth

$$d = 2/\gamma. \quad (12)$$

It is known that the light propagates in a conventional waveguide in the form of discrete modes characterised by their propagation constants, the field distribution across the waveguide and the angle of incidence of exciting radiation on the waveguide. The mentioned characteristics of the radiation modes are determined by the fulfillment of the transverse resonance condition required to realise the waveguide propagation of light. However, for such a waveguide structure as the photorefractive crystal – air interface, the transverse resonance condition is not necessary for the wave propagation.

Photorefractive surface waves as well as waveguide modes are characterised by the propagation constant, the wave field distribution across the direction of the wave propagation and the angle of incidence θ. However, the surface modes of the photorefractive crystal significantly differ from the modes of ordinary waveguides. Because the attenuation of the mode field inside the photorefractive crystal is determined by the photorefractive effect and is independent of the wave phase, the necessity to satisfy the boundary condition stands no longer and the mode spectrum becomes continuous, i.e. this mode can exist at any propagation constant β and, hence, at any angle of incidence of exciting radiation.

Surface electromagnetic waves can propagate along the interface of isotropic media whose dielectric constants have different signs. Thus, the propagation of the field deep inside the media is related to the purely imaginary value of the wave number in a medium with a negative dielectric constant and to the fulfillment of the condition for total internal reflection (TIR) in a medium with a positive dielectric constant. The requirement to change the sign of the dielectric constant with passing through the interface appears due to the necessity of matching the continuity condition of the tangential field components at the medium interface and the exponential decrease in the field amplitudes on either side of the interface.

For the surface wave to exist at the photorefractive crystal – isotropic dielectric (air) interface, the change of the sign of the dielectric constant is not required.

3. Experimental setup for studying surface waves in photorefractive crystals

The aim of our investigations was to excite and record the surface waves at the linear medium – photorefractive crystal interface and to check the mode concept for the nonlinear surface waves. As a photorefractive medium we used optical elements made of single crystal SBN-75 solid solution of barium strontium niobate ($Sr_xBa_{1-x}Nb_2O_6$) characterised by the electrooptical coefficient for extraordinary polarisation $r_{\rm eff} = 750$ pm V^{-1}.

The problem of excitation of the surface waves at the linear medium – photorefractive crystal interface requires the solution of a number of problems. The first of them consists in the fact that first of all it is necessary to find that photorefractive crystal surface where the surface wave can be excited most efficiently. In papers [6, 7], where the surface wave was obtained, this surface is ambiguously; therefore, it is needed to find the criterion for determining this surface. Such a criterion, in our opinion, is the direction of the fanning effect, which was first described in paper [8]. This effect consists in photoinduced scattering of extraordinary polarised light propagating in the direction perpendicular to the c axis of the photorefractive crystal. The surface on which the nonlinear surface wave can be excited should have a normal directed opposite to the spontaneous polarisation vector $\boldsymbol{P}_{\rm s}$ (or the direction of the c axis).

Figure 2 shows the photograph of the fanning beam from a 0.44-μm He – Cd laser obtained on the screen placed behind the SBN-75 crystal, whose c axis is perpendicular to the direction of incidence of the He – Cd-laser beam with extraordinary polarisation. The fanning region has a pear-like shape elongated in the negative direction of the c axis from the spot of the incident laser beam.

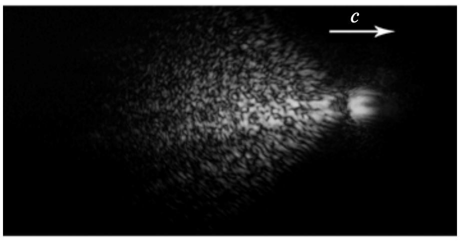

Figure 2. Photograph of the fanning effect on the screen after propagation of the laser beam through the SBN-75 crystal.

Figure 3a shows the scheme of the experimental setup we used to study the peculiarities of the surface-wave exciation at the air – SBN-75 crystal interface. The angle of incidence of the exciting light beam onto the crystal, α, is related to the angle of incidence onto the internal crystal surface, θ, by the expression

$$\sin\alpha = n_2 \cos\theta. \quad (13)$$

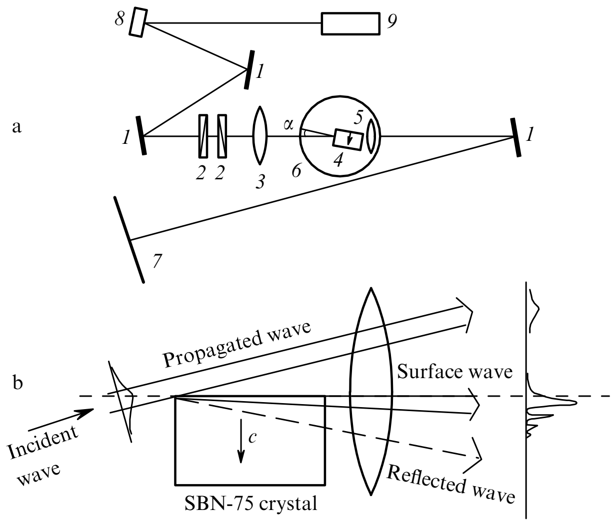

Figure 3. Optical scheme of the experiment (a) and scheme of surface-wave excitation in the SBN-75 crystal (b): (*1*) mirror; (*2*) polarisers; (*3*) long-focus lens; (*4*) sample; (*5*) microobjective; (*6*) goniometer; (*7*) screen; (*8*) polarisation rotation unit; (*9*) He – Cd laser.

Nonlinear surface waves were previously excited by two ways. The first method [6] is excitation through the sample end face, exciting radiation propagating along the same face as the surface wave. At the end of this face there appears the problem of separation of two waves for detection. The authors of paper [6] used a near-field microscope to detect the wave field intensity distribution at the output end face of the crystal.

In the second excitation method [7] (see Fig. 3b), the surface and excitation waves are separated initially because the surface wave appears due to the TIR of the excited light incident onto the crystal surface. In this case, the surface wave propagates along the crystal surface, while the exciting reflected wave propagates deep inside the photorefractive crystal at the TIR angle. In the output plane these waves are spatially separated and can be detected apart. Figure 4 presents the photograph of the radiation spot of the surface wave obtained at the SBN-75 sample output with the help of the $330^{\times}$ optical system. This allowed us to detect clearly on the screen the field distribution and to measure the period of spatial surface-wave oscillations. However, detection of the waves can cause some difficulties if the images of the output waves are overlapped. Images can be overlapped due to the fanning effect inherent in the exciting and reflected waves.

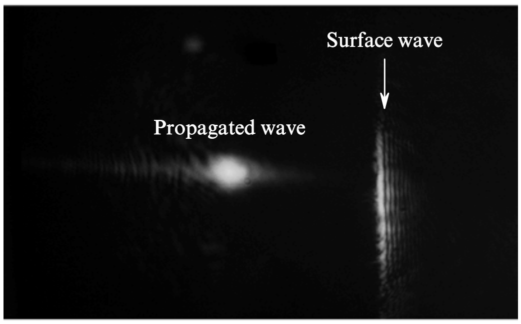

Figure 4. Light intensity distribution at the output crystal end face in the case of the surface-wave excitation.

First experiments on surface-wave excitation in the SBN-75 crystal showed that when the angle of incidence is $\theta \sim 89^{\circ}$ and the exciting beam intensity is chosen correctly, the problem of overlapping output radiation spots of separated waves does not appear because of the strong depletion of the reflected wave due to the fanning effect on the way to the output plane of the crystal after the TIR. The path length L of the light beam after exciting the surface wave is 9 mm so that the output beam intensity decreases by three times compared to the surface-wave intensity.

The authors of paper [9] pointed out that the fanning effect is most strongly pronounced in the blue region of the spectrum. Therefore, the decrease in the exciting radiation intensity at $\lambda = 0.44$ μm is quite expected. Besides, to reduce the influence of the fanning effect on the surface-wave excitation process, we deliberately chose the excitation region at the beginning of the photorefractive crystal.

Figure 5 presents the dependence of the oscillation period of the mode field intensity of the surface wave in the SBN-75 crystal on the angle of incidence of this mode, α. According to the above concept of the surface-wave modes [4] the oscillation period is described by relation (11). Comparison of our experimental dependence with the dependence calculated by expression (11) shows their satisfactory coincidence. Thus, verification of the concept of surface-wave modes can be considered as completed.

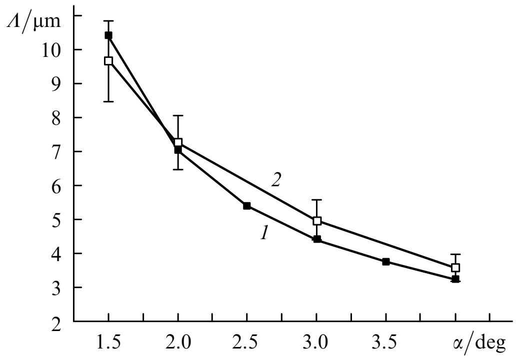

Figure 5. Theoretical (*1*) and experimental (*2*) dependences of the oscillation period of the surface-wave intensity on the angle of incidence of light onto the crystal end face.

4. Results and discussion

Photorefractive SBN-75 crystals have a high refractive index and, according to expression (8), a small field amplitude of the surface wave in air. This determines the losses when the surface wave propagates on the crystal surface due to the light scattering. Usually, the SBN-75 crystal is monodomenized by depositing aquadag electrodes on its surface and applying the voltage to these electrodes. One of the surfaces is used to excite nonlinear waves in the SBN-75 crystal. We obtained for the SBN-75 crystal a surface wave even when aquadag electrodes were deposited on its surface. This indicates that the scattering losses of the surface wave are indeed low, removal of the aquadag from the crystal surface having no effect on the wave propagation. Low light scattering losses indicated, first of all, the small field amplitude in air; therefore, the nonlinear surface waves in photorefractive crystals can be most likely called near-surface waves whose field is concentrated below the crystal surface. Ordinary linear surface waves in waveguides can be excited due to the tunnel coupling, for example, by using a prism for coupling light into the waveguide. In the case of photorefractive crystals whose n is large and the field in air is small, this coupling is complicated and the experiments similar to those in paper [10] are unlikely to be performed. However, a prism with a circular base [11] can be obviously used to detect the nonlinear surface waves.

5. Conclusions

Analysing the theory of nonlinear surface-wave modes and experiments on thier excitation at the SBN-75 photorefractive crystal – air interface, we have found the possibility of the surface-wave excitation at rather low radiation powers of the He – Cd laser (0.5 – 12 mW, $\lambda =$ 0.44 μm).

We have found in the experiments that depositing an electrode layer on the active crystal surface does not introduce any noticeable additional losses caused by propagation of surface waves in the SBN-75 crystal. Applying the external electric field to these electrodes will allow further investigation of it influence on the propagation of the surface waves in this crystal.

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