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Composite waveguide on a photorefractive crystal

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Abstract. **A new waveguiding structure (composite waveguide) has been proposed, which has the form of a linear dielectric layer on the surface of a photorefractive crystal and supports spatially confined modes propagating along its surface. We demonstrate that the modal properties of the composite waveguide are determined by those of a Bragg waveguide and the properties of nonlinear surface waves and the leaky modes of the thin-film waveguide. Various schemes of mode excitation in the composite waveguide are examined.**

Keywords: *photorefractive crystal, nonlinear surface waves.*

1. Introduction

It is well known that, when light propagates through a photorefractive (PR) crystal in a dynamic self-diffraction mode, a refractive-index grating is generated in the beam-overlap region [1]. Energy exchange between the beams on the index grating near the crystal surface may result in nonlinear surface waves, which have attracted researchers' particular attention in the last two decades [2–4] owing to the potential of observing nonlinear effects at intensities below 1 W cm^{-2} and the possibility to concentrate energy near the crystal surface. This can be used in sensing applications and second harmonic generation experiments.

Consider different types of structures in which light propagates near their surface. In a conventional thin-film waveguide, the transverse field confinement is due to total internal reflection because the refractive index of the film exceeds that of the adjacent media, and the guided-mode field decays exponentially in these media. The guided modes in a conventional waveguide are discrete because only certain values of the effective refractive index, n^*, meet the transverse resonance condition at a given wavelength.

Bragg waveguides take advantage of the resonance reflection from a periodic structure on one or both sides of the waveguide, instead of total internal reflection. The decay of the mode field in the periodic structure is sign-alternating, with an exponential envelope. Such waveguides also have discrete guided modes because the transverse resonance condition should also be satisfied.

A surface electromagnetic wave on a metal–dielectric interface (surface plasmon polariton) has essentially no waveguiding layer: there are only two media adjacent to the surface. The mode field of such a structure is confined owing to exponential field decay in the two adjacent media. The effective mode refractive index can be found from the dispersion equation derived using the constraint of field continuity across the interface. Thus, we have one mode at a given wavelength, i.e. a discrete n^* spectrum.

A surface photorefractive (SPR) wave is electromagnetic radiation propagating along the interface between a PR crystal and adjacent medium. The SPR wave penetrates the adjacent medium to only a small depth and decays exponentially in the crystal to form an index grating, which reflects the wave coming from the surface. As a result, the energy of the wave is localised near the surface of the crystal [5].

Localisation of a surface wave near the surface of a PR crystal means that the wave propagates like in a waveguide. The waveguide is of the Bragg type: there is total internal reflection from the interface, and the other (Bragg) reflection is ensured by an index grating whose layers in the PR crystal are parallel to the interface. The periodic index variation in the crystal arises from the photorefractive effect: photoinduced refractive index changes. In electro-optical crystals, this effect is due to linear modulation of the refractive index by an external electric field (Pockels effect) through the photoexcitation and spatial redistribution of charge carriers under nonuniform illumination. One important distinction of the structure under consideration from the Bragg waveguide considered by Yariv [6] is that a periodic index profile is produced by the propagating electromagnetic wave itself.

Like in the case of Bragg reflection, the mode field is sign-alternating, with an exponential envelope. A fundamental distinction of the waveguide we propose from those considered above is that its modes are not discrete. At a given wavelength, the relevant boundary conditions can be met at any n^*, and field decay in the PR crystal is ensured by a nonlinear effect, with the decay rate being independent of n^*. The study of the advantages of nonlinear photorefractive waves opens up new possibilities for designing PR crystal based composite structures for integrated optical applications and for investigating various nonlinear phenomena in such crystals.

The purpose of this work is to study a structure combining a linear dielectric layer and nonlinear PR crystal.

2. Theoretical model

The proposed waveguide has the form of a film (of thickness h) on the surface of a PR crystal (Fig. 1) [7]. The refractive index of the film, n_1, is lower than that of the PR crystal, n_2, and higher than that of the ambient medium (air), n_m.

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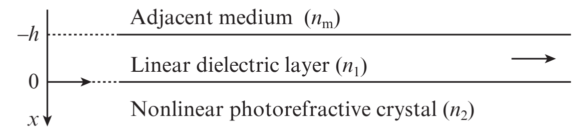

Figure 1. Schematic of the composite waveguide.

Consider the possibility of obtaining, in this composite structure, modes whose field is concentrated in the film and is confined on the side of the adjacent medium owing to total internal reflection and on the side of the crystal owing to the same mechanism as is responsible for surface waves on the interface between a PR crystal and air.

When extraordinarily (ordinarily) polarised light propagates along the z axis parallel to the surface of a PR crystal, the magnetic field component parallel to the y axis, $H(x, z)$, meets the wave equation

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

[as does $E(x, z)$], where $k(x) = k_0 n_m$ for $x < -h$, $k(x) = k_0 n_1$ for $-h < x < 0$ and $k(x) = k_0[n_2 + \Delta n(x)]$ for $x > 0$; $k_0 = 2\pi/\lambda_0$; λ_0 is the wavelength of the light in vacuum; n_2 is the unperturbed refractive index of the PR crystal; and $\Delta n(x)$ is a nonlinear contribution to the refractive index n_2. We seek the eigensolution of Eqn (1) in the form of a mode propagating along the crystal surface: $H(x, z) = A(x)\exp(-i\beta z)$, where $\beta = k_0 n^*$ is the mode propagation constant.

Like in the case of a conventional thin-film planar waveguide, the inequality $n_m < n^* < n_1$ should be satisfied. Otherwise, the mode will leak out to the adjacent medium (for $n^* < n_m$) or its field will decay exponentially in the film (for $n^* > n_1$), and it will differ not much from earlier studied surface waves on the surface of PR crystals. This limits the ranges of angles, θ_1 and θ_2, at which the waves that form the mode field distribution in the linear dielectric layer (film) and the sign-alternating tail of the mode in the PR crystal can propagate and at which such a mode can be excited from the film and crystal:

$$n^* = n_1 \sin\theta_1 = n_2 \sin\theta_2, \quad (2)$$

$$\arcsin\left(\frac{n_m}{n_1}\right) < \theta_1 < \frac{\pi}{2}, \quad \arcsin\left(\frac{n_m}{n_2}\right) < \theta_2 < \arcsin\left(\frac{n_1}{n_2}\right).$$

For example, for $n_2 = 2.36$, $n_1 = 1.46$ and $n_m = 1$ we have $43.2° < \theta_1 < 90°$ and $25.1° < \theta_2 < 38.2°$. The field then decays exponentially in the adjacent medium.

A mode with this structure in the film and crystal can be represented as a combination of two waves propagating along and against the x axis. These waves decay exponentially in the PR crystal because they are reflected from periodic disturbances of the refractive index, $\Delta n(x, z)$, due to a diffusion mechanism of nonlinearity [8]:

$$\Delta n(x) = \frac{1}{2} n_2^3 r_{\text{eff}} \frac{k_B T}{q} \frac{1}{I(x) + I_d} \frac{d}{dx}[I(x) + I_d], \quad (3)$$

where q is the elementary charge; r_{eff} is the effective electro-optical coefficient; k_B is the Boltzmann constant; T is the absolute temperature, $I(x) \propto |A(x)|^2$ is the mode intensity; and I_d is the dark intensity.

Thus, we deal with a waveguide similar to a Bragg waveguide, with the difference that the index modulation period is set by the mode itself. In this structure, like in earlier examined periodic guiding structures with a capping layer [9, 10], the mode field amplitude may peak in a thin film grown on the surface of the structure. Neglecting the dark intensity, I_d, compared to the mode intensity, we can represent the steady-state field amplitude distribution in the structure for $\beta < (k_0^2 n_2^2 - \gamma^2/4)^{1/2}$ ($\gamma = 2 k_0^2 n_2^4 r_{\text{eff}} k_B T/q$ is a coefficient characterising the PR effect) in the form

$$A(x) =$$

$$\begin{cases} A_m \exp[\gamma_m (x + h)], & \gamma_m = (\beta^2 - k_0^2 n_m^2)^{1/2}, \quad x < -h, \\ A_1 \cos[\kappa_1 (x + h - h_0)], & \kappa_1 = (k_0^2 n_1^2 - \beta^2)^{1/2}, \quad -h < x < 0, \\ \exp(-\gamma x/2)\cos(\kappa_2 x + \varphi), & \kappa_2 = (k_0^2 n_2^2 - \beta^2 - \gamma^2/4)^{1/2}, \quad x > 0, \end{cases} \quad (4)$$

where A_m is the field amplitude at the boundary of the adjacent medium; A_1 and h_0 are the maximum field amplitude and the corresponding depth in the film; and 2φ is the phase difference between the incident and reflected beams, which generate an interference pattern in the crystal.

The field configuration in the film is similar to that in a conventional thin-film waveguide. For the characteristic length scale of the field distribution in the film to exceed the wavelength (in order to more easily assess the field distribution in the film), the effective mode refractive index should differ little from the refractive index of the film, and θ_2 should approach the critical angle. In this respect, the waveguide under consideration also resembles a Bragg waveguide with a reduced refractive index of the core. Like in the case of Bragg reflection, the mode field is sign-alternating and decays exponentially in the crystal, so no boundary condition should be satisfied on this side. The mode penetration depth in the crystal is governed by its nonlinear properties ($d = 2/\gamma$).

The relationship between the mode field amplitudes in the film and PR crystal depends on the phase accumulation in the film and can be tuned by varying the parameters of the film and the angle of incidence, θ_1. Using representation (4), from the constraint of the continuity of the tangential field components across the $x = -h$ and $x = 0$ boundaries we easily obtain

$$A_m = A_1 \cos(\kappa_1 h_0), \quad A_m \gamma_m n_m^{-p} = A_1 \kappa_1 n_1^{-p} \sin(\kappa_1 h_0),$$

$$A_1 \cos[\kappa_1 (h - h_0)] = \cos\varphi, \quad (5)$$

$$A_1 \kappa_1 n_1^{-p} \sin[\kappa_1 (h - h_0)] = \tfrac{1}{2}\gamma n_2^{-p} \cos\varphi_2 + \kappa_2 n_2^{-p} \sin\varphi,$$

where $p = 0(2)$ for the TM (TE) polarisation. Relations (4) and (5) for a given value of $n^* = \beta/k_0$ allow φ, A_m and A, which determine the mode amplitude distribution in a composite waveguide, to be represented in the form

$$\varphi = \arctan\left(\frac{n_2^p \kappa_1}{n_1^p \kappa_2} \frac{n_m^p \kappa_1 \sin(\kappa_1 h) - n_1^p \gamma_m \cos(\kappa_1 h)}{n_m^p \kappa_1 \cos(\kappa_1 h) + n_1^p \gamma_m \sin(\kappa_1 h)} - \frac{\gamma}{2\kappa_2}\right), \quad (6)$$

$$A_m^2 = \frac{n_m^p \kappa_1^2 \cos^2\varphi_2}{[n_m^p \kappa_1 \cos(\kappa_1 h) + n_1^p \gamma_m \sin(\kappa_1 h)]^2}, \quad A_1^2 = A_m^2\left(1 + \frac{n_1^p \gamma_m^2}{n_m^p \kappa_1^2}\right).$$

Using (4) and (6), it is easy to derive expressions for P_m, P_1 and P_2, related to the power of the light propagating in the air, film and crystal,

$$P_{\rm m} = \frac{A_{\rm m}^2}{2\gamma_{\rm m} n_{\rm m}^p}, \quad P_1 = \frac{A_1^2}{n_1^p}\left[\frac{h}{2} + \frac{\sin(2\kappa_1 h_0) + \sin(2\kappa_1(h-h_0))}{4\kappa_1}\right],$$
$$P_2 = \frac{1}{2\gamma n_2^p} + \frac{\gamma\cos(2\varphi) - 2\kappa_2\sin(2\varphi)}{2(\gamma^2 + 4\kappa_2^2)n_2^p}, \qquad (7)$$

and to find the fraction of power (relative to the total power of the mode) propagating in the dielectric layer:

$$P_{\rm w} = \frac{P_1}{P_{\rm m} + P_1 + P_2}.$$

3. Modes of the composite waveguide

Consider light propagation in a composite (compound) structure in the form of a linear dielectric layer (n_1 = 1.46, h = 1.2 μm) on the surface of single-crystal SBN-75 (solid solution between barium and strontium niobates, $Sr_xBa_{1-x}Nb_2O_6$), with electro-optical coefficients $r_{\rm eff}$ = 750 and 67 pm V^{-1} for the extraordinary and ordinary polarisations, respectively. Formally, a mode may exist at any given n^* ($n_{\rm m} < n^* < n_1$), but the fraction of power propagating in the dielectric layer, $P_{\rm w}$, strongly depends on n^* (Fig. 2). $P_{\rm w}(n^*)$ curves obtained using Eqns (7) have maxima, where a substantial fraction of the total power propagates in the linear dielectric layer, and these solutions can be termed modes of the composite waveguide. They result from the coupling between the leaky modes of the thin-film waveguide and nonlinear surface waves of the PR crystal. It is worth noting in this context that the modal properties of the composite waveguide are determined by those of a Bragg waveguide and the properties of SPR waves and the leaky modes of the thin-film waveguide. Analysis of Eqns (4)–(6) indicates that, when the condition

$$\kappa_1 h = \frac{\pi}{2}(2m+1) + \arctan\left(\frac{n_1^p \gamma_{\rm m}}{n_{\rm m}^p \kappa_1}\right), \quad m = 0, 1, \ldots \qquad (8)$$

is satisfied, the phase shift, φ, is $\pi/2$ and the field at the crystal–film interface is zero. The field distribution in the linear dielectric layer is then similar to that of a leaky mode of a planar waveguide formed by a low-index film on the surface of a high-index substrate. Condition (8) is the well-known dispersion equation for such waveguides. The integer parameter m specifies the mode number. The phase shift at the film–air interface is determined by the Goos–Hänchen shift, and that at the crystal–film interface is π, so that the field amplitude at this interface is zero. The maximum in the field amplitude in the linear dielectric layer,

$$A_1 = \frac{\kappa_2}{\kappa_1}\left(\frac{n_1}{n_2}\right)^p, \qquad (9)$$

is a distance

$$h_0 = \frac{1}{\kappa_1}\arctan\left[\frac{\gamma_{\rm m}}{\kappa_1}\left(\frac{n_1}{n_{\rm m}}\right)^p\right] \qquad (10)$$

from the film–air interface.

It follows from Eqns (8) and (9) that the zeroth-order mode has the largest amplitude A_1. Figure 3 shows the field distribution in the composite waveguide for the fundamental mode (m = 0), which ensures the highest power density in the linear dielectric layer. According to (8) and (9), the maximum field amplitude is substantially greater for the TE polarisation (Fig. 3a). At the same time, the coefficient γ, which character-

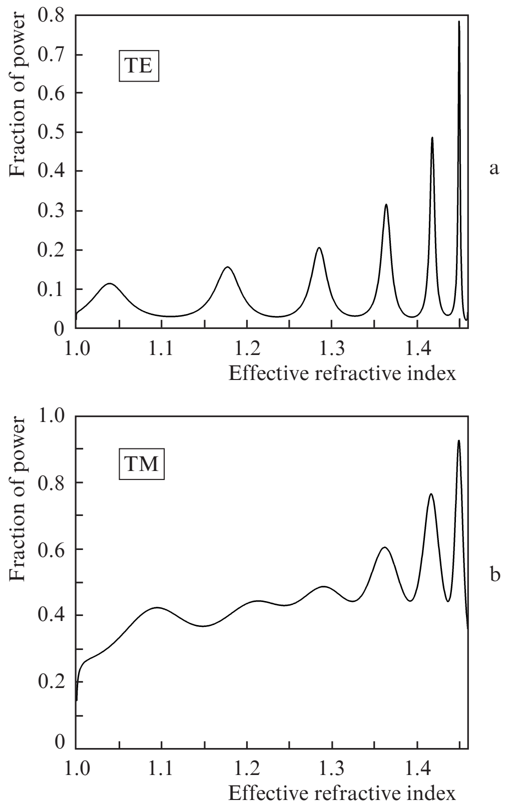

Figure 2. Fraction of power, $P_{\rm w}$, propagating in the linear dielectric layer as a function of n^* for (a) TE and (b) TM polarisations.

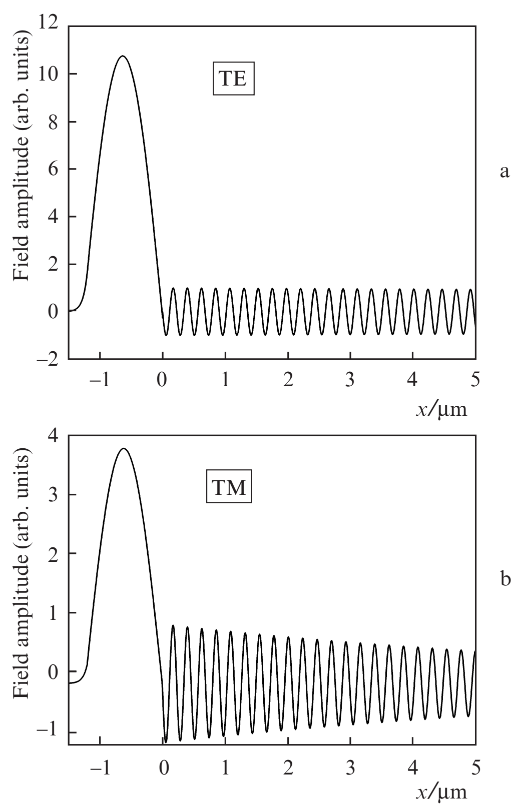

Figure 3. Fundamental mode field distribution in the composite waveguide for (a) TE and (b) TM polarisations.

ises the PR effect, is greater (by about a factor of 10) for the extraordinary polarisation, so the penetration depth (d) and the fraction of power (P_w) propagating in the crystal are smaller for this polarisation and, accordingly, the maxima in the fraction of power for the TM polarisation (Fig. 2b) are higher than those for the TE polarisation.

4. Possible schemes of mode excitation in the composite waveguide

Recent work [5, 11] has demonstrated highly efficient excitation of nonlinear surface waves on SBN-75 PR crystals by a focused Gaussian He–Cd laser beam at grazing incidence. Consider the possibility of mode excitation in the composite waveguide. SBN-75 crystals have large principal refractive indices ($n_o = 2.43$ and $n_e = 2.36$ at $\lambda = 0.44$ μm).

When light is launched from air ($n_m = 1$) through face A of the crystal (Fig. 4a), the effective refractive index of the excited nonlinear surface waves, n^*, can be varied (by changing the launch angle, α) from $n_2\cos[\arcsin(1/n_2^2)]$ to n_2 ($n_2 = n_o$ for the ordinary polarisation and $n_2 = n_o n_e/(n_o^2\sin^2\theta_2 + n_e^2\cos^2\theta_2)^{1/2}$ for the extraordinary polarisation; θ_2 is the angle of incidence of the excitation beam on the lateral face B of the crystal; and the optical axis $\boldsymbol{c}$ is normal to face B) and exceeds the refractive index of the film ($n_1 = 1.46$). When light is launched through face C, the n^* of the excited surface waves does not exceed unity. The presence of a waveguiding layer on face B does not alter the range of allowed n^* values. Thus, other ways of mode excitation in the composite waveguide should be found.

One possibility is to focus an incident beam onto the end face of the waveguiding film (Fig. 4b). A mode of the composite structure then may result from the coupling between the excited leaky mode of the thin-film waveguide and a nonlinear surface wave of the PR crystal. Index grating generation in the crystal is expected to be due to the interference between the wave that leaks out of the thin-film waveguide and scattered waves. In this configuration, high quality of the film end face is critical.

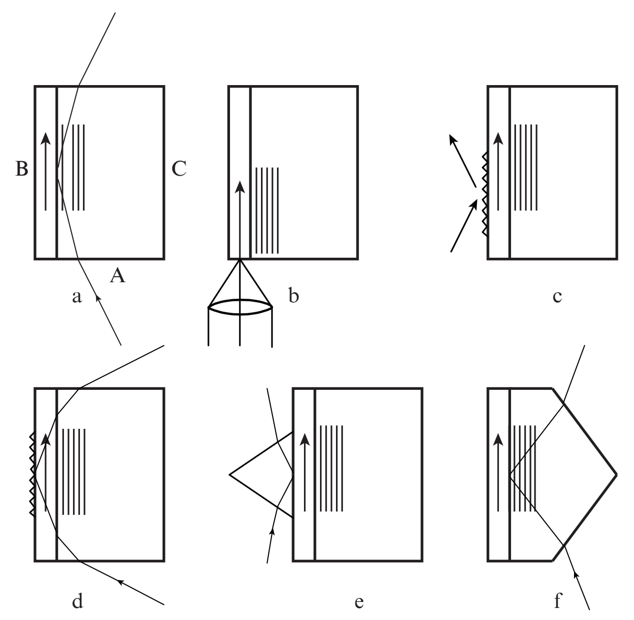

Figure 4. Different schemes of composite-waveguide excitation (see text).

A diffraction grating on the crystal surface (Figs 4c, 4d) may also ensure the excitation of surface waves with n^* in the required range ($1 < n^* < n_1$). The grating period ($\Lambda \sim \lambda$) and angle of incidence in this configuration should ensure resonance for mode excitation.

Yet another possibility is to launch light through a prism (Fig. 4e). This approach requires that the prism be pressed against the waveguiding film in a strictly controlled manner. A nonlinear crystal with cut angles can also be used as a prism (Fig. 4f). In our opinion, this configuration is optimal.

A mode of the composite waveguide is a combination of a leaky mode of the waveguide and a surface PR wave, which are coupled because of the partial transmission through the film–crystal interface. The proposed excitation methods rely on initial excitation of different parts of a mode of the composite waveguide.

In the case of initial excitation through the film, index grating generation in the crystal is expected to result from the interference between the wave that leaks out of the thin-film waveguide and scattered waves. Special mention should be given here to the following circumstance: since the index grating is generated by the propagating wave itself, a mode of the composite waveguide can be obtained with the refractive index of the adjacent medium varied in a wide range (from unity to values approaching the refractive index of the film, n_1). When this structure is used in an optical sensor, the wavelength range can be extended considerably because, in contrast to sensors based on static (preset) Bragg structures [9, 10], here the problem of matching the reflective Bragg grating period to the wavelength of the light is solved automatically. In this context, it is of some interest to study in detail the mode propagation and mode excitation efficiency in this composite waveguide configuration.

Mode excitation from the side of the crystal leads to index grating generation where the incident and reflected beams overlap. Energy exchange between the beams on the grating leads to the formation of a surface wave, which converts to a mode of the composite waveguide.

As follows from earlier results [12], the efficiency of nonlinear surface wave excitation at an angle of incidence $\theta_2 \sim 70°$ is relatively low. Therefore, to enhance the efficiency of nonlinear surface wave excitation by an obliquely incident beam ($\theta_2 \sim 50°$), it is desirable to increase the size of the region where the incident (I_{ins}) and reflected (I_{ref}) beams overlap to produce an index grating. The ability to increase the radius of the Gaussian excitation beam is determined by the mode penetration depth in the crystal, d, which is considerably greater for the TE polarisation. From this point of view, the use of TE-polarised light is preferable.

5. Conclusions

A new waveguiding structure (composite waveguide) has been proposed, which has the form of a linear dielectric layer on the surface of a photorefractive crystal. Theoretical analysis indicates that this structure may support spatially confined modes propagating along its surface. We demonstrate that the modal properties of the composite waveguide are determined by those of a Bragg waveguide and the properties of surface photorefractive waves and the leaky modes of the thin-film waveguide.

We have examined various schemes of mode excitation in the composite waveguide. The advantages of the proposed composite structure over conventional (linear) Bragg waveguide structures are the broader wavelength range and the possibility of widely varying the refractive index of the adjacent medium.

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