WAVE PROPAGATION IN INHOMOGENEOUS ANISOTROPIC RECTANGULAR WAVEGUIDES BY THE EFFECTIVE INDEX METHOD

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ABSTRACT

Hybrid mode dispersion and mapping of multilayer rectangular diffused birifrangent waveguides are studied by the effective index method for two orientations, horizontal and vertical, of the crystal optic axis. At first the structure is examined in the approximate lossless approach, then the perturbation technique allows us to evaluate the extinction coefficient value to employ as starting point in the direct search optimization strategy for determining the complex propagation constant for the exact solution. The guided E^x_{11} and E^y_{11} modes exhibit almost the same cutoff wavelength and their dispersion curves little differ from the ones of corresponding TM_o, up to 1 μm for vertical optic axis because of the surface plasma waves, and TE_o modes of the slab waveguide without and with the metal film respectively.

Introduction

Anisotropic indiffused waveguides are very interesting in the realization of multilayer structures for the fabrication of integrated optics devices and systems. A multilayer guide, including a thin film overlay and an embedded metal film, presents the advantage of a fine tuning of the propagation constant, by varying the overlay thickness or the refractive index[1] and a reduction of the ohmic losses[2]. Therefore, by these guiding structures, it is possible to realize complex and multifunctional devices.

Several authors[3,4,5] investigated the mode properties of slab multilayered dielectric waveguides but, till now, the optical anisotropic rectangular guides have not been examined in the proper way.

In this paper we determine the dispersion relations and the field distribution of anisotropic optical guides (see Fig. 1) whose rectangular cross section consists of a Ti diffused $LiNbO_3$ ferroelectric subtrate overlayed by an appropriate oxide buffer having a refractive index n_{ov} and a thickness b with two embedded Ag electrodes modeled by an ε_m complex dielectric constant and thickness h. The structure is investigated in the approximate lossless formulation and, then, the exact lossy solution is obtained by a direct search optimization strategy where the extinction coefficient k starting values are estimated by the perturbation technique.

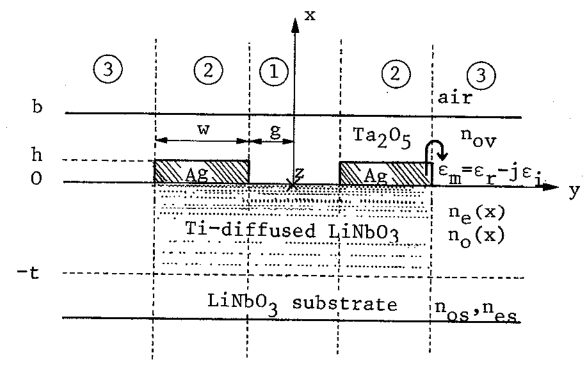

FIGURE 1: CHANNEL MULTILAYER WAVEGUIDE FOR ELECTROOPTICAL MODULATOR REALIZATION.

Moreover in order to assess the influence of the c optic axis orientation on the electromagnetic field and, therefore, the best configuration for the design of integrated optics devices, we investigate the waveguide both for c horizontal (∥) and vertical (⊥) under the hypothesis of a diagonal permettivity tensor.

This waveguiding system supports[6,7] the E^x_{pq} and E^y_{pq} hybrid modes that are TE or TM in respect to one transverse coordinate. More precisely, for uniaxial materials with optic axis horizontal or vertical, the guided waves are derivable from a c-directed hertzian potential. Since the rigorous solution of the two-dimensional wave equation is considerably complicated even for a not diffused and isotropic guide, the geometry analysis is carried-out by the effective index method[9] that is easy to use and gives a noticeable precision together with a short C.P.U. computer time after determining the slab guide characteristics by the transfortion matrix method[5,10,11].

Among the other results, it is worth while to notice that, for a silver film 0.02 μm thick, the guide configuration (∥) does not support surface plasma waves that are excited in the configuration (⊥) at the wavelengths less than 1 μm.

Mode analysis by the effective index method

The multi-dielectric structure is depicted in Fig.1. The lithium niobate perovskite crystal is Ti-diffused according to the complementary error function in the x direction with maximum index changes Δn_e and Δn_o of ex traordinary $n_e(x)$ and ordinary $n_o(x)$ indices in respect to the bulk substrate n_{es}, n_{os} ones: $n_{e,o}(x)=n_{es,os}+\Delta n_{e,o}\,\mathrm{erfc}|x/d|$, (d=diffusion depth).

For uniaxial crystals if the optic axis is horizontal, the E^x_{pq} and E^y_{pq} modes supported by the optical guide are respectively transverse electric or magnetic to y coordinate while for vertical c-axis the z traveling hybrid modes are TE_x or TM_x.

In fact, in the last case, the E^x_{pq} mode are obtained by putting H_x=0 and solving the Maxwell's equations in respect to the H_y component that, in the diffused core, must satisfy the equation:

$$\frac{n_e^2}{n_o^2}\frac{\partial^2 H_y}{\partial x^2}+\frac{\partial^2 H_y}{\partial y^2}+n_e^2\frac{\partial}{\partial x}\left(\frac{1}{n_o^2}\right)\frac{\partial H_y}{\partial x}+k_o^2(n_e^2-\bar{n}_{eq}^2)H_y=0 \qquad (1)$$

where it was supposed a time harmonic variation and a normal mode one exp $(-jk_o n_{eq} z)$ along the propagation direction;$\bar{n}_{eq}$=n-jk is the complex equivalent index and $k_o=2\pi/\lambda_o$ is the free space wavenumber.

Let H_y (x,y)= $\varphi(x)\ \psi(y)$ be separable the equation (1) becomes

$$\frac{1}{\varphi}\frac{n_e^2}{n_o^2}\frac{d^2\varphi}{dx^2}+n_e^2\frac{d}{dx}\left(\frac{1}{n_o^2}\right)\frac{1}{\varphi}\frac{d\varphi}{dx}+k_o^2(n_e^2-\bar{n}_{eq}^2)=-\frac{1}{\psi}\frac{d^2\psi}{dy^2} \qquad (2)$$

The left side with $\partial/\partial y$=0, by imposing the boundary conditions at the interfaces x=b; x=h; x=0 and x= -t, gives rice to the TM_z modes whose equivalent indices $\bar{n}_{eq.s}$ depend on both n_o and n_e but chiefly on n_e because the real part n_s of $\bar{n}_{eq.s}$ ranges between n_{es} and $(n_{es}+\Delta n_e)$. Afterwards the result

$$\frac{1}{\varphi}\frac{n_e^2}{n_o^2}\frac{d^2\varphi}{dx^2}+n_e^2\frac{d}{dx}\left(\frac{1}{n_o^2}\right)\frac{1}{\varphi}\frac{d\varphi}{dx}=-k_o^2(n_e^2-\bar{n}_{eq}^2) \qquad (3)$$

is back substituted into (2) to get

$$\frac{d^2\psi}{dy^2}+k_o^2(\bar{n}_{eq.s}^2-\bar{n}_{eq}^2)\psi=0 \qquad (4)$$

that is the wave equation for the trapped TE_z modes when $\partial/\partial x$=0, $\bar{n}_{eq}$ being the desired index of the original rectangular structure obtained by imposing the continuity conditions of the interfaces y= g and y= (w+g).

Likewise, to obtain the E^y_{pq} waves we must put in the Maxwell's equation E_x=0 and couple the $\bar{n}_{eq.s}$ relative to the TE_z modes of the component ($\partial/\partial y$=0) planar waveguides to the TM_z polarization with $\partial/\partial x$=0.

The equation (3) relative to the three different guides indefinite along the y axis of Fig. 1 was solved as in [5,10] by the method of the transformation matrix relating the two continuous field components at the interfaces x=0 and x=-t where the diffusion process may be thought exhausted. The equation (3) splits in a system of two first-order differential equations that is integrated by employing the Gear's[12] praedictor-corrector technique that allows to reach the required numerical precision for arbitrary index profile also for wide integration range with a not excessive C.P.U. computer time. The zeros of the real eigenvalue equation are found by the secant method while the minima in the lossy approach are reached by the razor technique[13].

Results and discussion

In Fig. 2 are reported the lossy TM_z and TE_z normalized equivalent indices

$$N=\frac{n_{TM,TE}^2-n_{es,os}^2}{(n_{es,os}+\Delta n_{e,o})-n_{es,os}^2} \qquad (5)$$

vs.k_o for the ($\perp$) configuration with n_{ov}=2.10;b=0.4μm;

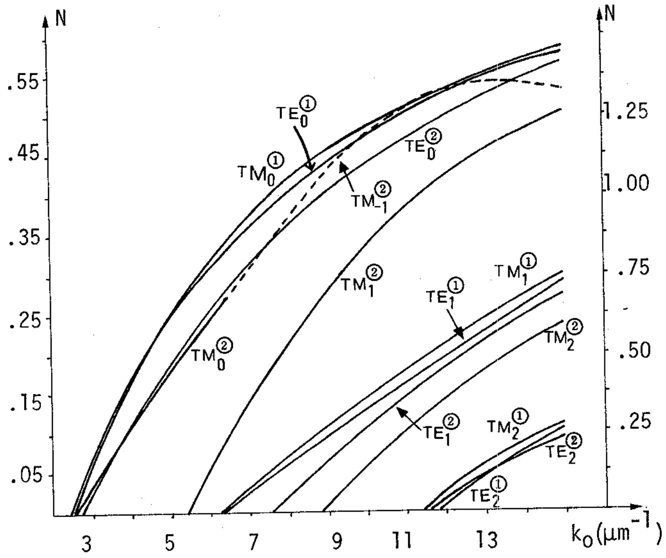

FIGURE 2: TE and TM DISPERSION CURVES RELATIVE TO ① AND ② GUIDES FOR C VERTICAL.

ε_m=-16.3- j0.522; h=0.02μm. The dispersion curves ① superscript refer to the slab guide ① whithout metal film and the ones with ② to the guide ② with silver layer. It is worth to notice that the $TE_z(\parallel)$ equivalent index values of the slab ① with horizontal optic axis differ from the $TM_z(\perp)$ ones relative to the vertical c configuration only on the fifth significant figure. The same applies to the $TM_z(\parallel)$ and $TE_z(\perp)$. This correspondence only in part occurs in the slab with me-

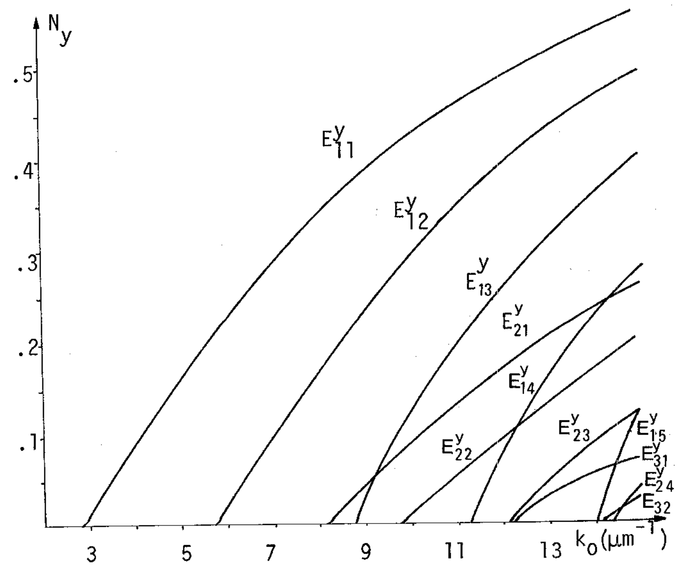

FIGURE 3: E^y_{pq} DISPERSION CURVES FOR C HORIZONTAL CONFIGURATION. THE PARAMETERS ARE AS IN THE FIG.2.

tal layer because the differences concern the third significant figure. Moreover, the TM polarization behaviour is rather different for the two configurations since the (∥) configuration does not support surface plasma waves (SPW) while for c vertical the TM_o wave suffers a transformation in TM_1 for wavelengths less than 1μm and tilts in its upper part because of the $LiNbO_3$ intrinsic dispersion. The extinction coefficients of the TE modes are two magnitude orders lower than the TM ones and there are absorbtion peaks near to 1μm.

In Fig. 3 are drawn the lossless E^y_{pq} indices N_y normalized by (5) to the n_{es} substrate index with the geometrical and physical parameters of Fig. 2 and g=w=0.75μm and relative to the configuration with horizontal optic axis.

The lossy n values differ from the lossless ones only on the tenth significant figure and no changes were found on the extintion coefficients in respect to the ones calculated via the perturbation approach.

Besides we point-out the fundamental mode whithout metal is the TE_o wave while the TM_o mode is the lower order field in the slab with metal. This result leads to cutoff wavelenghts almost equal for the E^x_{11} and E^y_{11} guided modes since the realpart of their refractive indices little differ from the TM_o fundamental mode of the slab without metal layer and the TE_o wave of the slab with metal layer respectively. At last we see that the E^x_{pq} and E^y_{pq} waves are alternatively even and odd modes in respect to the plane y=0 that behaves as an electric or magnetic wall. In Fig. 4 are drawn the extinc-

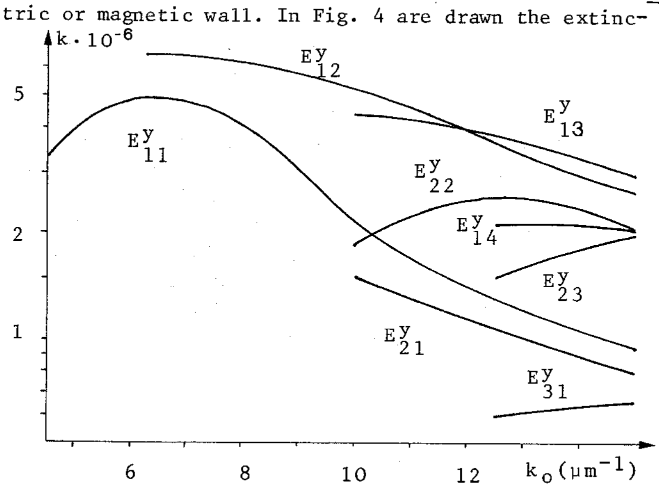

FIGURE 4: E^y_{pq} EXTINCTION COEFFICIENTS FOR C-HORIZONTAL.

tion coefficients of the E^y_{pq} modes. Also these curves show peak values at λ_o=1 μm.

The Fig. 5 shows the lossy (⊥) indices N_x of the E^x_{pq} modes as a function of k_o. The E^x_{pq} curves are considerably different for the two orientations of the optic axis. For the (⊥) case we find the fundamental mode E^x_{11} only for $\lambda_o \leq$1μm. For λ_o=1μm we find also the E^x_{21} mode lacking in the (∥) structure. Also in this case the differences between complex perturbated index values and the lossy exact ones are insignificant and the attenuations range between 1 dB/cm and the peak value of 169 dB/cm.

In this case the lossy fundamental TM_o indices are rather different from the E^x_{11} ones. Moreover, the lossy TM_z n values for the slab ② differ on the third significant figure from the lossless ones.

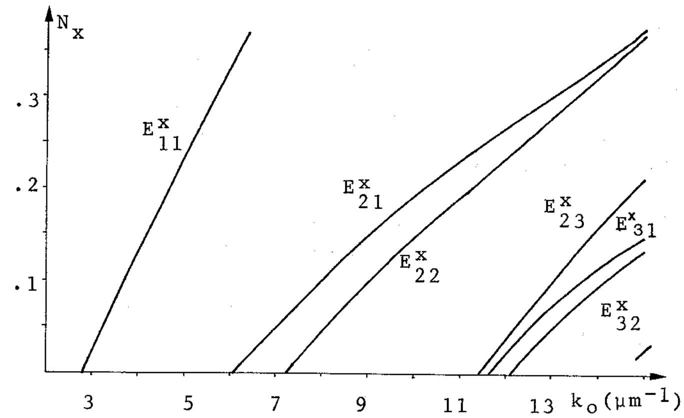

FIGURE 5: E^x_{pq} NORMALIZED INDICES vs. K_o FOR C-VERTICAL.

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