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ACOUSTOOPTIC CONVERSION OF TE AND TM MODES IN A DIFFUSIVE PLANAR WAVEGUIDE

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This paper gives the results of calculations of the accoustooptic effect in a planar graded index waveguide obtained from the diffusion of titanium to a Y-cut $LiNbO_3$. The effect of TE and TM modes are considered. The effectiveness of diffraction ($TE_m \to TE_m$, $TM_m \to TM_m$) and conversion ($TE_m \to TE_n$, $TM_m \to TM_n$, $TE_m \to TM_m$) of modes, depending on the acoustic power, is investigated. Calculations are carried out for acoustic wave of 360 MHz frequency.

1. Introduction

Papers [1-5], published recently on the earliest developments of acousto-optic elements in integrated optics, show wide applications of these elements possible in integrated systems of information transmission and processing. In these elements the acoustooptic effect occurs through surface acoustic waves (SAW) acting on a light beam conducted by a waveguide. In view of the complex character of this effect (modal character of light propagation, anisotropic medium), different functions can be implemented in these elements, giving a large family of acoustooptical elements of integrated optics, such as modulators, deflectors, mode convertors, spectrum analysers etc.

The present work contains the results of calculations of acoustooptical diffraction and conversion of modes in a planar modulator with a variable profile of the diffraction coefficient $n(y)$. These calculations took into account three phenomena occurring in the acoustooptical effect in anisotropic crystals:

— photoelastic effect,

— electrooptical effect,

— corrugation of waveguide surface.

The process of conducting a light beam by a waveguide has a modal character, i.e. the light beam conducted has a relevant field distribution in waveguide cross-section.

In view of this, the acoustooptical effect in waveguides can be divided into:

1. mode diffraction (e.g. $TE_0 \rightarrow TE_0$, $TM_0 \rightarrow TM_0$),
2. mode conversion (e.g. $TE_0 \rightarrow TE_1$, $TE_0 \rightarrow TM_0$).

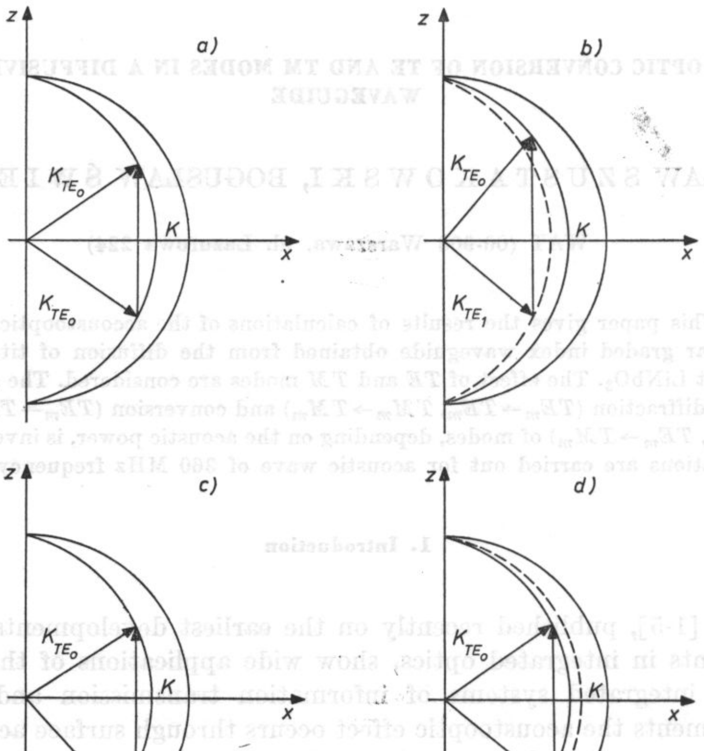

Fig. 1. Relations between wave vectors: a) diffraction of modes, b) conversion of modes (change in mode number), c) conversion of modes (change in polarisation), d) conversion of modes (change in polarisation and mode number)

Fig. 1 shows a relation between the vave vectors of the acting modes and the wave vectors of acoustic waves K in the cases mentioned above. It is necessary to note that in the case of conversion it is possible to distinguish between change in mode number (e.g. $TE_0 \rightarrow TE_1$, Fig. 1b), change in polarisation (e.g. $TE_0 \rightarrow TM_0$, Fig. 1c) and change in polarisation related to change in mode number (e.g. $TE_0 \rightarrow TM_1$, Fig. 1d).

2. Theoretical basis of calculations

Fig. 2 shows the geometry of the system.

The calculation of the effectiveness of the acoustooptical effect in a waveguide with a variable profile $n(y)$ requires the determination of the spatial distributions of the electric field of the light beam $E_m(y)$ and the fields related to SAW propagation, i.e. the displacement field $S(y)$ and the electric field in the piezoelectric material $E^a(y)$.

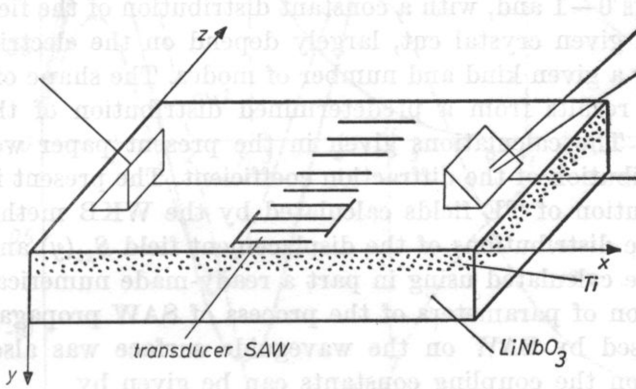

Fig. 2. A schematic diagram of the acoustooptical planar light modulator

The effectiveness of the acoustooptical effect in a waveguide with a variable profile $n(y)$ is given by the expression (6)

$$\eta = \Gamma_{nm}^2 L^2 \sin^2 TL/(TL)^2, \tag{1}$$

where L is the length of the path of the effect, Γ_{nm} is the coupling coefficient, $T^2 = \Gamma_{mn}\Gamma_{nm}$, m, n are mode numbers.

The coupling coefficients Γ_{mn} and Γ_{nm} are given in the following form

$$\Gamma_{mn} = \frac{\pi}{\lambda_0 n_m \cos\theta_m} \frac{\int E_m(y)\Delta\varepsilon(y)E_n(y)\,dy}{\int E_m^2(y)\,dy},$$

$$\Gamma_{nm} = \frac{\pi}{\lambda_0 n_n \cos\theta_n} \frac{\int E_n(y)\Delta\varepsilon(y)E_m(y)\,dy}{\int E_n^2(y)\,dy}, \tag{2}$$

where $\Delta\varepsilon(y)$ is change in the tensor of dielectric permittivity; n_m and n_n are the diffraction coefficients for the modes of the orders m and n; θ_m and θ_n are the angles of anisotropic Bragg diffraction.

The change in the dielectric permittivity $\Delta\varepsilon$ of a crystal caused by the acoustic wave field has the form [7]

$$\Delta\varepsilon_{rs} = -\varepsilon_{ri}(p_{ijkl}S_{kl} - r_{ijk}E_k^{(a)}\varepsilon_{js}, \tag{3}$$

where p_{ijkl} and r_{ijk} are, respectively, components of the tensor of photoelastic and electrooptical constants; S_{kl} are components of the displacement tensor; $E_k^{(a)}$ are components of the vector of the intensity of the electric field in piezoelectric material. In expression (3), the first term describes the photoelastic effect, while the second defines the electrooptical effect.

The integrals occurring in formulae (2) for the coefficients Γ_{mn} and Γ_{nm}, called the integrals of field overlap, have direct influence on the effectiveness of the interaction of surface acoustic and optical waves. Their numerical values vary in the limits $0-1$ and, with a constant distribution of the field of acoustic wave $S(y)$ for a given crystal cut, largely depend on the electric field distribution $E_m(y)$ for a given kind and number of modes. The shape of the function $E_m(y)$, in turn, results from a predetermined distribution of the diffraction coefficient $n(y)$. The calculations given in the present paper were taken for a Gaussian distribution of the diffraction coefficient. The present investigations used the distribution of TE fields calculated by the WKB method and given in paper [8]. The distributions of the displacement field $S_{kl}(y)$ and the electric field $E_k^{(a)}(y)$ were calculated using in part a ready-made numerical programme for the calculation of parameters of the process of SAW propagation [9]. The corrugation caused by SAW on the waveguide surface was also considered.

Its impact on the coupling constants can be given by

$$\Gamma_{mn}^{(c)} = \frac{\pi}{\lambda_0 n_m \cos\theta_m} U_2(0) \frac{E_m(0)(\varepsilon - I)E_n(0)}{\int E_m^2(y)\,dy},$$
$$\Gamma_{nm}^{(c)} = \frac{\pi}{\lambda_0 n_n \cos\theta_n} U_2(0) \frac{E_n(0)(\varepsilon - I)E_m(0)}{\int E_n^2(y)\,dy}, \tag{4}$$

where $U_2(0)$ is the value of the component U_2 of the displacement on the surface $y = 0$ and I is a unity matrix.

3. Calculated results

The calculations were taken for several fundamental modes of TE and TM modes. The distributions of the fields $E_m(y)$ for the TE modes were taken from paper [8] in order to make easier the interpretation of the results (Fig. 3).

In the case of the interaction of modes $TE_m \to TE_n$, the description of the effect only requires the determination of the distribution of one component $\Delta\varepsilon_{33}$ of the tensor of dielectric permittivity. This distribution is shown in Fig. 3b. The electrooptical effect $\Delta\varepsilon_{33}^{(e)}$ dominates as a result of a large value of the constant r_{33} compared to that of the photoelastic p_{33} ($r_{33} = 0.308$; $p_{33} = 0.088$ [10]) for this orientation of $LiNbO_3$ (Fig. 2).

Fig. 4 shows the distribution of the field $E_m(y)$ and the distributions of the components $\Delta\varepsilon(y)$ which describe the interaction of modes $TM \to TM$.

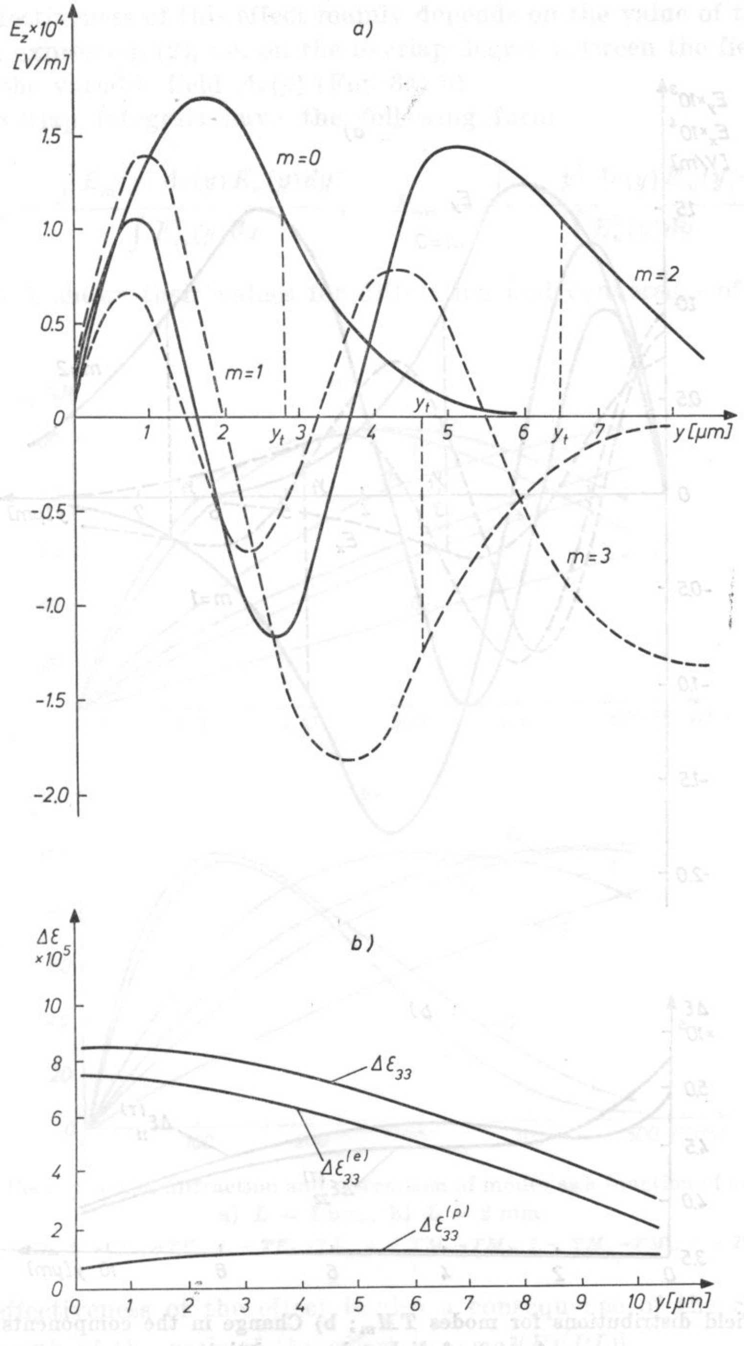

Fig. 3. a) Field distributions for modes TE_m in an $LiNbO_3$: T_i waveguide. The index m represents the number of a mode; b) Change in the component $\Delta\varepsilon_{33}(y)$ of dielectric permittivity: $\Delta\varepsilon^{(p)}$ – change caused by the photoelastic effect, $\Delta\varepsilon^{(e)}$ – change caused by the electrooptical effect

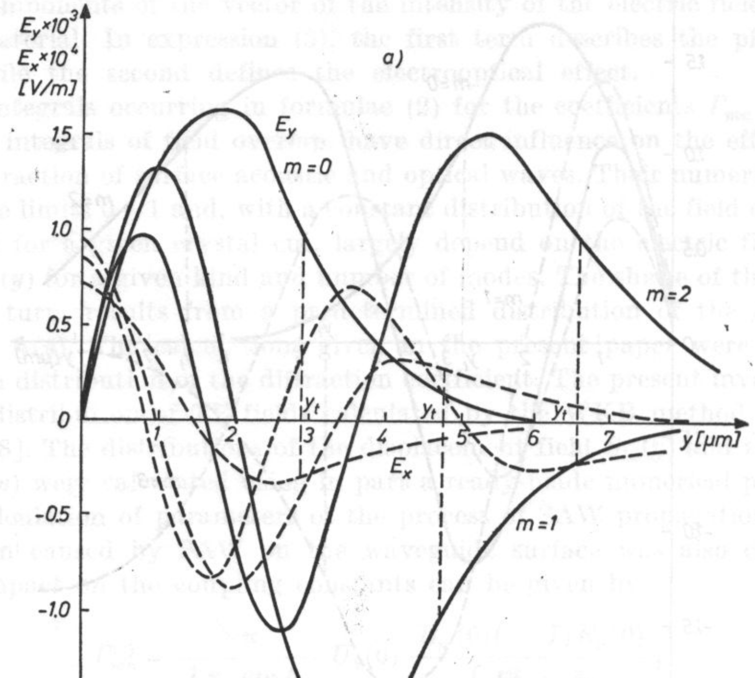

Fig. 4. a) Field distributions for modes TM_m; b) Change in the components $\Delta\varepsilon_{11}(y)$ and $\Delta\varepsilon_{22}(y)$ of dielectric permittivity

The effectiveness of this effect mainly depends on the value of the overlap integrals in expression (2), i.e. on the overlap degree between the fields $E_m(y)$, $E_n(y)$ and the variable field $\Delta\varepsilon(y)$ (Fig. 3a, b).

The overlap integrals have the following form

$$F_{mn} = \frac{\int E_m(y)\,\Delta\varepsilon(y)\,E_n(y)\,dy}{\int E_m^2(y)\,dy}, \quad F_{nm} = \frac{\int E_n(y)\,\Delta\varepsilon(y)\,E_m(y)\,dy}{\int E_n^2(y)\,dy}, \tag{5}$$

while Table 1 shows their values for diffraction and conversion of particular modes.

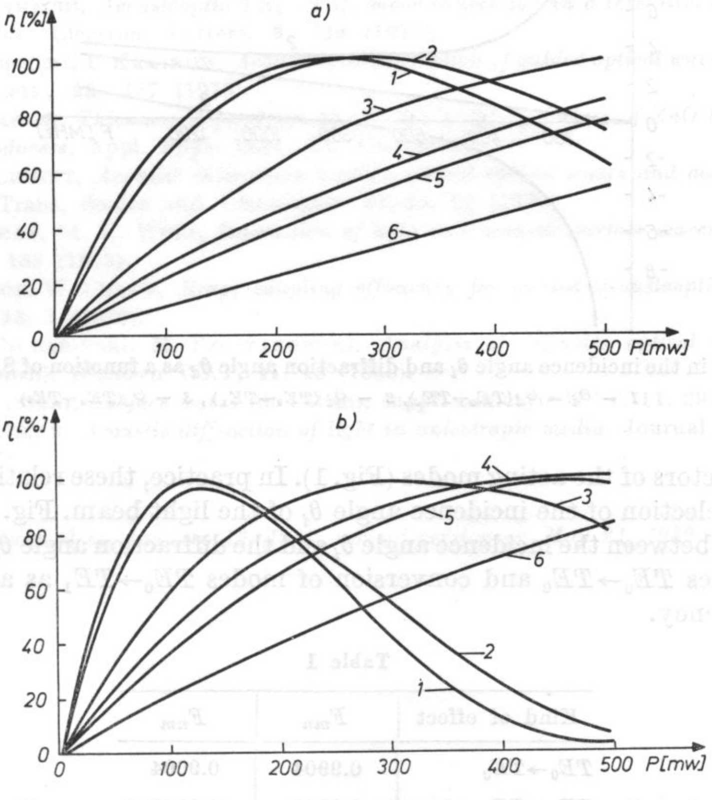

Fig. 5. The effectiveness of diffraction and conversion of modes as a function of acoustic power a) $L = 1$ mm, b) $L = 2$ mm

1 – $TE_0 \to TE_0$, *2* – $TE_1 \to TE_1$, *3* – $TE_0 \to TE_1$, *4* – $TM_0 \to TM_0$, *5* – $TM_1 \to TM_1$, *6* – $TM_0 \to TM_1$;

The effectiveness of the effect is also a consequence of the SAW power and the length of the path of the effect $\left(\eta \sim \sin^2(\Gamma\sqrt{P}L)\right)$.

Fig. 5 shows the results of calculations of the effectiveness as a function of the acoustic power P for the length of the path $L = 1$ mm (Fig. 5a) and $L = 2$ mm (Fig. 5b). Comparison of Figs. 5a and 5b shows that a change of

1 mm in the length of the effect path L, which is equivalent to a 1 mm widening of the acoustic beam, leads to a change in the acoustic power required for a hundred percent effectiveness from 250 mW ($L = 1$ mm) to 125 mW ($L = 2$ mm). The corrugation of the waveguide surface is so slight ($\Gamma^{(c)} \approx 10^{-2}\Gamma$) that it can be neglected in the present case. The implementation of particular kinds of effects shown in Fig. 5 requires the satisfaction of respective relations among

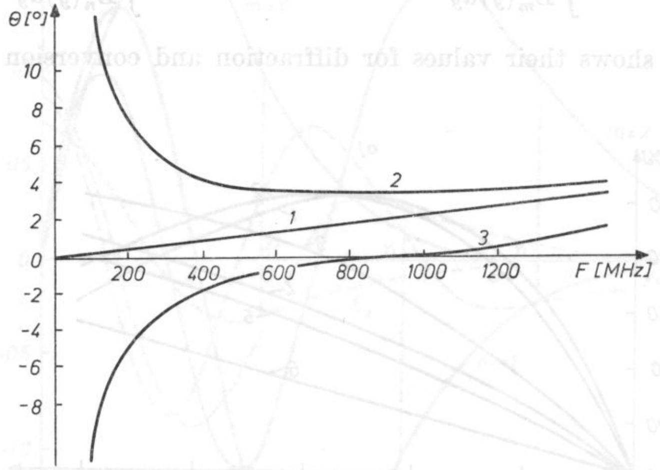

Fig. 6. Change in the incidence angle θ_i and diffraction angle θ_d as a function of SAW frequency
$1 - \Theta_i = \Theta_d(TE_0 \to TE_0)$, $2 - \Theta_i\,(TE_0 \to TE_1)$, $3 - \Theta_d(TE_0 \to TE_1)$

the wave vectors of the acting modes (Fig. 1). In practice, these relations are satisfied by a selection of the incidence angle θ_i of the light beam. Fig. 6 shows the relationship between the incidence angle θ_i and the diffraction angle θ_d for diffraction of modes $TE_0 \to TE_0$ and conversion of modes $TE_0 \to TE_1$ as a function of SAW frequency.

Table 1

Kind of effect	F_{mn}	F_{nm}
$TE_0 \to TE_0$	0.9904	0.9904
$TE_1 \to TE_1$	0.9145	0.9145
$TE_0 \to TE_1$	0.600	0.648
$TM_0 \to TM_0$	0.439	0.439
$TM_1 \to TM_1$	0.403	0.403
$TM_0 \to TM_1$	0.141	0.176

It follows from the behaviour of the relations $\theta_i = f(F)$ and $\theta_d = f(F)$ (Fig. 6) that, in the frequency range $F = 400\text{-}1300$ MHz, with a practically constant incidence angle θ_i, the diffraction angle θ_d varies from -2 to $+2°$.

This is an essential practical conclusion which can be used in the implementation of an acoustooptical planar deflector.

All the calculation whose results are given above were taken for a chosen SAW frequency, $F = 360$ MHz, and the light wavelength $\lambda_0 = 0.6328$ μm.

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