POLARIZATION-ROTATED RADIATION CONVERSION IN ELECTROOPTIC WAVEGUIDES

S. Yamamoto
Faculty of Engineering Science, Osaka University
1-1 Machikaneyama, Toyonaka, Osaka, 560 JAPAN

ABSTRACT

We report several experimental results on the fundamental characteristics of guided-radiation mode coupling in optical waveguides. Three types of polarization-rotated (TE⟶ TM or vice versa) radiation conversion are examined, which utilize electrooptic effect of $LiNbO_3$ and $LiTaO_3$.

Introduction

Mode coupling phenomena are important in the field of guided-wave optics and therefore a number of works were reported on their active and passive device applications. Most of them utilized guided-guided mode coupling.

Recently the application of guided-radiation mode coupling has attracted an increasing attention. Proposed examples include an acoustooptic deflector,[1,2] an electrooptic or magnetooptic modulator[3,4] and a nonreciprocal isolator.[5] Introduction of radiation modes into the coupling process leads to several attractive features. For instance, it is possible to realize direct intensity modulation in simple device configurations. Also the phase matching condition is met with noncritical control of the waveguide parameters. However, relatively few works have so far been presented on the experimental demonstration of the proposed operations.[6,7]

We have investigated the fundamental properties of guided-radiation mode coupling from various points of view. Here we present experimental results on three types of electrooptically controlled radiation mode conversion in diffused $LiNbO_3$ and $LiTaO_3$ waveguides. The experimental arrangements are summarized in TABLE I.

Interaction-Length and Applied Voltage Dependences of Mode Conversion

The first structure in TABLE I uses an out-diffused $LiNbO_3$ Z-plate as a basic waveguide [Fig.1(a)]. Here the phase matching is automatically met between TM guided and TE radiation(substrate) modes due to the negative anisotropy of $LiNbO_3$. This mode pair can then be coupled via the electrooptic effect by applying a voltage to the coplanar electrodes.

We were interested in the dependence of the mode conversion on the interaction(electrode) length L and on the applied voltage V. In the guided-to-radiation mode conversion via the linear electrooptic effect, the normalized output of an incident guided mode is expressed as

$$P_{out}/P_{in} = \exp[-AV^2L] \cong 1 - AV^2L, \qquad (1)$$

where A is a constant. The second expression is a small-argument approximation that applies to our case. The above characteristic should be compared with the characteristic of guided-to-guided mode conversion

$$P_{out}/P_{in} = 1 - B'\sin^2[B''VL] \cong 1 - BV^2L^2, \qquad (2)$$

where B's are constants. Comparison of Eqs.(1) and (2) shows that the difference is in the L-dependences of the two conversions.

We used the longitudinally divided electrode configuration in Fig.1(a), which consists of three tandem sections of unequal lengths. With this arrangement we were able to change the interaction length L in six different values from 1.6 to 8.0mm. In Fig.1(b) are plotted the measured guided mode (TM_0) outputs as functions of L for fixed V's. The linear variation confirms the characteristic of guided-radiation mode coupling predicted by Eq.(1) as compared with a square-law (L^2) dependence of guided-guided mode coupling in Eq.(2). Next Fig.1(c) shows TM_0 outputs in varying V keeping L constant. The square-law (V^2) behavior is consistent with the characteristic of Eq.(1). As far as the small conversion region is concerned, the two operations in Eqs.(1) and (2) are indistinguishable in the V-dependence.

Effect of Periodic Coupling

The configuration of the second mode converter in TABLE I is shown in Fig.2(a). The waveguide was fabricated by Cu-electrodiffusion into a $LiTaO_3$ Z-plate. Our concern here was to show the usefulness of periodic electrodes for improving the efficiency of guided-radiation mode coupling.

In the $LiTaO_3$ waveguide the phase matching is met between TE guided and TM radiation modes. Naturally they can be coupled via the electrooptic effect by using longitudinally uniform electrodes. However, such a simple electrode configuration does not always provide an optimum operation. Due to the anisotropy of the crystal, the transverse field overlap of coupled modes leading to a large coupling coefficient is generally met between certain phase-mismatched modes rather than between the phase-matched ones. Coupling of such initially phase-mismatched modes is possible with the use of longitudinally periodic electrodes.

We measured TE_1-to-TM radiation mode conversion. An examination of the effective index of TE_1 mode offered the use of electrodes with the period Λ of about 300μm. In order to measure the dependence of the mode conversion efficiency on Λ, we fabricated, one by one, four pairs of periodic electrodes with alternating polarity along the propagation axis as shown in Fig. 2(a), where Λ varied from 278μm to 308μm with 10μm increments. In Fig.2(b) are plotted the measured conversion efficiencies as functions of Λ for three different values of the applied voltage. The solid lines are the theoretical curves based on a simplified waveguide model. Since the radiation modes form a continuum, mode conversion occurs continuously in varying Λ. We note the maximum conversion is achieved at $\Lambda \sim 300$μm as expected.

Quasi-Linear Operation in Off-Axial Propagation

The third structure in TABLE I utilizes an off-axial propagation on a Cu-diffused $LiTaO_3$ X-plate [Fig.3(a)]. The angle θ between the propagation axis z and the optic axis Z is called the propagation angle. The operation of this mode converter is different from

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the operation of the converters in Figs.1(a) and 2(a) using on-axial propagation. Because of the anisotropy of the crystal, TM guided mode suffers a loss due to conversion into TE radiation modes when θ exceeds a critical value. This "passive" radiation conversion can then be controlled electrooptically by applying a voltage to the electrodes set along the propagation axis as shown in Fig.3(a).[8] A specific feature of the off-axial converter is that with an appropriate setting of θ a quasi-linear intensity modulation is possible with no dc bias as compared with the converters in Figs.1(a) and 2(a) with nonlinear modulation characteristics that requires a dc bias for linear operation.

Figure 3(b) shows the measured normalized outputs of TM_1 and TM_2 modes as functions of the applied voltage for θ=41° and 29°, respectively. The linearity of the characteristic curves are fairly good up to about ±50V, where the modulation depth is 27% for TM_1 and 22% for TM_2 mode.

The $LiTaO_3$ mode converter described here offers a complementary operation to the $LiNbO_3$ converter[7] that operates in TE guided modes.

References

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TABLE I EXPERIMENTAL ARRANGEMENTS*a

No.	Crystal*b	Cut	Waveguide Fabrication	Propagation Direction	Electrode Configuration	Mode Conversion*c
1	$LiNbO_3$	Z-cut	Out-Diffusion	On-Axis (// Y)	Divided	TM(G)→TE(R)
2	$LiTaO_3$	Z-cut	Cu-Electro-diffusion	On-Axis (// Y)	Periodic	TE(G)→TM(R)
3	$LiTaO_3$	X-cut	Cu-Electro-diffusion	Off-Axis (θ from Z)	Uniform	TM(G)→TE(R)

Notes: *a Experiments were performed at the wavelength 0.63μm.
*b Refractive indices: $LiNbO_3$ (n_o=2.286, n_e=2.200)
$LiTaO_3$ (n_o=2.176, n_e=2.180)
*c G and R denote guided and radiation modes, respectively.

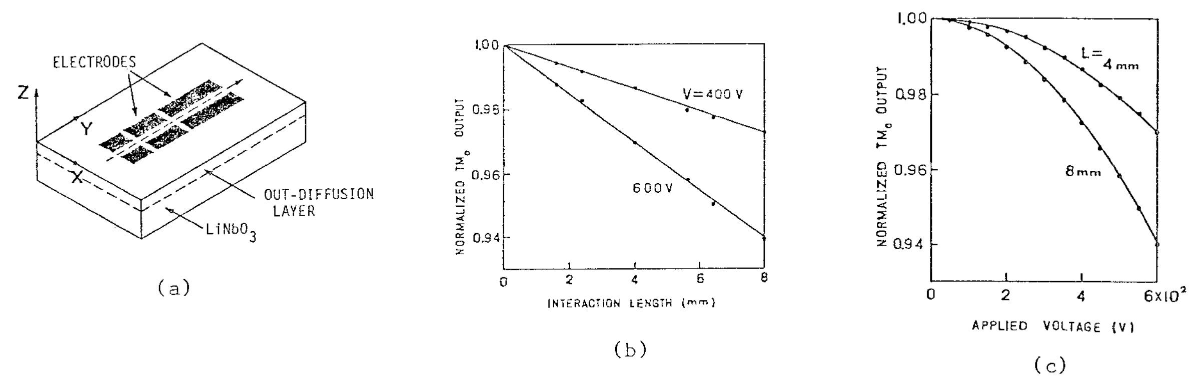
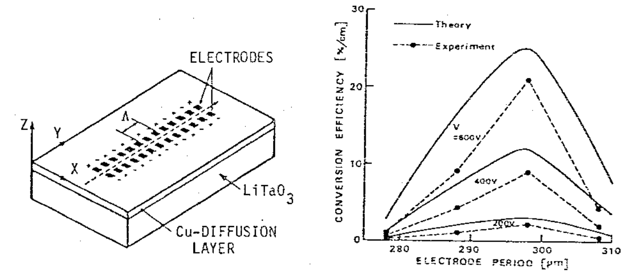
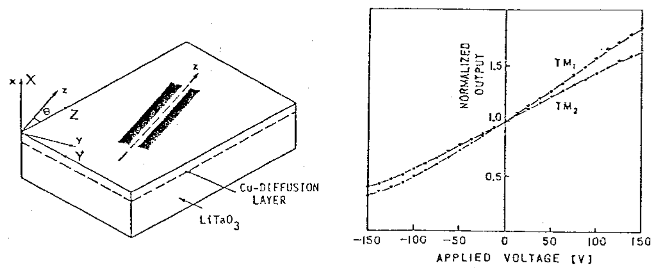


Fig.1 (a) $LiNbO_3$ TM(G)-to-TE(R) mode converter [Refractive-index increase by diffusion $\Delta n_e \sim 2\times10^{-3}$, Diffusion depth d∼7μm, Electrode length L=1.6, 2.4, 4mm, Electrode gap g∼50μm. X, Y and Z denote the crystalline axes.] (b) Normalized TM_0 output vs. interaction length L for constant applied voltage V. (Solid lines are the linear profiles 1 - A'L with A' adjusted.) (c) Normalized TM_0 output vs. applied voltage V for constant interaction length L. (Solid lines are the square-law profiles $1 - A''V^2$ with A'' adjusted.)



(a) (b)

Fig.2 (a) $LiTaO_3$ TE(G)-to-TM(R) mode converter [$\Delta n \sim 7.5\times10^{-3}$, $d\sim6\mu m$, L=7.0, 7.2, 7.4, 7.6mm for the electrode period Λ=278, 288, 298, 308μm, respectively, $g\sim45\mu m$.] (b) Efficiency of TE_1-to-TM(R) conversion vs. electrode period Λ for constant applied voltage V.



(a) (b)

Fig.3 (a) $LiTaO_3$ TM(G)-to-TE(R) mode converter [$\Delta n\sim5\times10^{-3}$, $d\sim8\mu m$, L=7.2mm, $g\sim52\mu m$. (X, Y, Z) and (x, y, z) denote the crystalline and the waveguide axes, respectively.] (b) Normalized TM_1 and TM_2 outputs vs. applied voltage V [θ=41° for TM_1, 29° for TM_2]