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A Novel Optical Polarization Splitter Using a Dimensionally Tapered Velocity Coupler

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SUMMARY   A new polarization splitter at optical frequencies is proposed. The basic structure of the device is a tapered velocity coupler which is composed of a straight and a dimensionally tapered slab waveguide on a $LiNbO_3$ substrate. The numerical results obtained with the finite difference method indicate that extinction ratios of polarization less than 2% for both TE and TM modes are possible of realization under moderate control voltages and that the splitting characteristics are stable over a wide range of frequencies.
key words: polarization splitter, tapered velocity coupler, electro-optic effects, $LiNbO_3$, finite difference method

1. Introduction

Polarization splitters or converters are essential devices to optical signal processing systems which are sensitive to polarization. Various types of such devices have been achieved by making good use of the electro-optic effects in $Ti:LiNbO_3$ waveguides. Some devices are based on the mode sorting effect in a branching waveguide with branches having different effective refractive indices[1],[2]. However, the fabrication technology of this type is somewhat complex. Other devices are based on synchronous coupling in a uniformly distributed directional coupler or on periodic coupling in a single waveguide with a periodic index change induced by an interdigital or finger electrode[3],[4]. Another type is a fiber-optic polarization splitter which is also based on synchronous coupling in a dual-core optical fiber with identical cores[5],[6] or with different cores[7]. These devices are very sensitive to operating frequencies because of the interferometric exchange of optical power.

Tapered velocity couplers of which concept was first proposed by Cook for applications at microwave frequencies[8] are now attracting great attention of researchers working in the field of integrated optics. Complete power transition between the waveguides under the adiabatic condition would seem to be applied in a wide variety of optical signal processing devices[9],[10]. Once the adiabatic condition is satisfied, the tapered velocity couplers maintain the complete power transition over a wide range of frequencies, which fact suggests that we can always be indifferent to strict fabrication

tolerances as is not the case with interferometric couplers.

Recently, Ramaswamy et al. have proposed and demonstrated a digital optical switch using a tapered, both in dimension and in index, velocity coupler in a $Ti:LiNbO_3$ waveguide with a small voltage length product[11],[12]. Shani et al. have demonstrated an adiabatic device for polarization splitting on a silicon substrate[13]. Baran et al. have reported a study on another type of adiabatic polarization splitter on a $LiNbO_3$ substrate[14]. Each one of these polarization splitters consists of two different kinds of waveguides, which means that two distinct processes are required for fabricating devices.

In the present paper, we propose a new type of polarization splitter at optical frequencies. The basic structure of the device is a tapered velocity coupler which consists of a straight and a dimensionally tapered slab waveguide on a $LiNbO_3$ substrate[15]. This device is composed of waveguides of one type and would be fabricated much easier than the polarization splitters mentioned above. The device performance is confirmed by means of numerical results obtained with the finite difference method[16]. In practical applications, guided-wave devices have been achieved in three dimensional structures. However, most of them can be reduced to equivalent two-dimensional structures mathematically in good approximation by means of the method of effective refractive index. Therefore, the slab-waveguide model is studied in the present paper.

2. Basic Principles

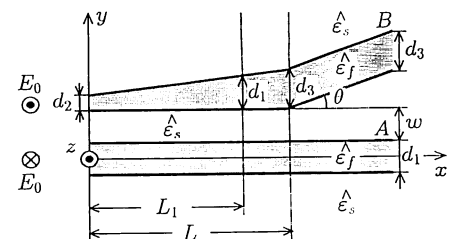The polarization splitter proposed in this paper is shown in Fig. 1, together with the coordinate system

Fig. 1   Structure of the polarization splitter and the coordinate system for the analysis.

used for the analysis. The tapered waveguide B changes its film thickness linearly from d_2 to d_3 in the region of $0 < x < L$ and keeps it constant through the region of $x > L$. The film thickness of the straight waveguide A is d_1 which is thicker at the input end and thinner at the output end than that of the tapered waveguide; hence the thickness of the tapered waveguide becomes equal to d_1 at some place $x = L_1$ where $L_1 < L$. The local normal modes of both waveguides A and B are supposed to have the same effective refractive index at $x = L_1$. The coupler has a constant gap w between the waveguides in the region of $0 < x < L$ and a increasing gap $w + (x - L)\tan\theta$ in the region of $x > L$. The increasing gap is introduced in order to reduce the device length.

Suppose that the optical axis of LiNbO$_3$ is directed to the positive z axis. Then the permittivity tensor of the material is given by

$$\hat{\varepsilon}_p = \varepsilon_0 \begin{pmatrix} n_{op}^2 & 0 & 0 \\ 0 & n_{op}^2 & 0 \\ 0 & 0 & n_{ep}^2 \end{pmatrix} \qquad (1)$$

where ε_0, n_o and n_e are the permittivity of a vacuum and the refractive indices for the ordinary and extraordinary waves and the subscript p represents s(substrate) or f(film). In this coordinate orientation, TE modes sense n_e as the refractive index of the material, while TM modes sense n_o. It is possible to find the structural parameters of the coupler which maintains the adiabatic process for both of the TE and TM modes simultaneously. When the complete power transition occurs in the coupler under the adiabatic condition, the effective refractive index of the local normal mode changes qualitatively as the solid lines in Fig. 2. Each set of lines representing the TE or TM modes has an intersection.

Consider that an external electric field E_0 is applied in parallel with the optical axis only in the film regions of both waveguides in the above situation. If E_0 is applied in the negative z direction in the waveguide A and in the positive z direction in the waveguide B, the
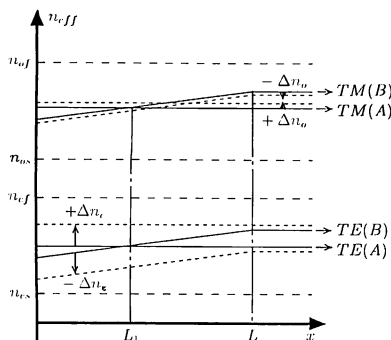
electro-optic effects modify the refractive indices into

$$n'_{of} = \begin{cases} n_{of} + \Delta n_o , & \text{in the waveguide A} \\ n_{of} - \Delta n_o , & \text{in the waveguide B} \end{cases} \qquad (2)$$

$$n'_{ef} = \begin{cases} n_{ef} + \Delta n_e , & \text{in the waveguide A} \\ n_{ef} - \Delta n_e , & \text{in the waveguide B} \end{cases} \qquad (3)$$

where $\Delta n_o = n_o^3 \gamma_{13} E_0 / 2$ and $\Delta n_e = n_e^3 \gamma_{33} E_0 / 2$. The constants γ_{13} and γ_{33} are the electro-optic coefficients. We assume in the numerical calculations that $\gamma_{13} = 8.6 \times 10^{-12}$ m/V and $\gamma_{33} = 30.8 \times 10^{-12}$ m/V. Because $\gamma_{13} \ll \gamma_{33}$, TE modes experience a much larger change in the refractive index than TM modes. Therefore, under the influence of some appropriate external electric field, the effective refractive index of the local normal mode changes along the coupler as the dotted lines in Fig. 2. The lines representing the TE modes have no intersections, while the lines representing the TM modes intersect each other. The adiabatic condition is still satisfied for both TE and TM modes. However, physical power transfer between the waveguides can never be observed for the TE modes. Consequently, when the straight waveguide A is excited with optical waves containing both polarizations, only the TM mode is transferred to the tapered waveguide completely. On the other hand the TE mode is shut off from coupling, staying in the straight waveguide.

3. Numerical Results

The structural parameters are chosen by trial and error to some extent as follows: $d_1 = 3\,\mu\text{m}$, $d_2 = 1\,\mu\text{m}$, $d_3 = 4\,\mu\text{m}$, $w = 2\,\mu\text{m}$, $L = 6500\,\mu\text{m}$ and $\theta = 0.05°$. The refractive indices are assumed as $n_{os} = 2.286$, $n_{of} = 2.2885$, $n_{es} = 2.200$, and $n_{ef} = 2.2025$; so the weakly guiding condition is satisfied for both TE and TM modes.

Figure 3 shows the coupling characteristics with the wavelength as a parameter (a) for the TE mode and (b) for the TM mode when a voltage of 9 V is applied between the waveguides. The ordinate is the power carried in each waveguide which is normalized relative to the input power and the abscissa is the propagation distance along the device. It is found from the figure that the extinction ratios of polarization for both TE and TM modes are less than 2% at the output end of the device. It is also found from these results that the frequency dependence of the characteristics are not recognized over the wavelength region of $0.623\,\mu\text{m} < \lambda < 0.643\,\mu\text{m}$.

In this paper, the optical power carried in each waveguide is evaluated with the following overlap integral [17]:

Fig. 2 Effective refractive index of each local normal mode versus propagation distance.

$$P_T = \frac{\left\{ \int E_1 \cdot E_2^* \, dy \right\}^2}{\int |E_1|^2 dy \cdot \int |E_2|^2 dy} \qquad (4)$$
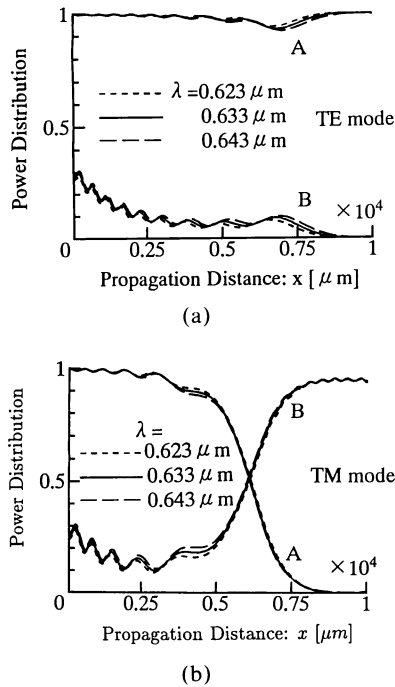
Fig. 3 Optical power distributed in the waveguides A and B versus propagation distance, with a voltage of 9V applied between the waveguides: (a) TE mode and (b) TM mode.

Fig. 4 Field distribution along the polarization splitter, with a voltage 9V applied between the waveguides: (a) TE mode and (b) TM mode.

Fig. 5 Optical power distributed in the waveguides A and B versus propagation distance when the external electric field is removed.

where E_1 is the modal profile of the local normal mode in the waveguide A or B and E_2 the field distribution obtained with the finite difference method. The asterisk indicates the complex conjugate. The optical power distributed in the waveguide B is estimated considerably larger in the region of $x < 6000\,\mu m$ than it should be. This error has been caused by the weak guidance and the narrow gap between the waveguides. The overlap integral (4) is, however, expected to offer accurate results around the output end of the device because of an enough separation between the waveguides. Inexactitude around the input end would not mislead the readers because it is the distribution of optical power at the output end that we are interested in. Figure 4 shows the field distribution along the device (a) for the TE mode and (b) for the TM mode. It is understood that the power distributed in each waveguide in Fig. 3 is accurately evaluated around the output end. It is also understood that the present polarization splitter would perform well.

Figure 5 shows the coupling characteristics for both TE and TM modes in the same polarization splitter when the external electric field is removed. The ordinate and abscissa are the same as Fig. 3. Figure 6 shows the field distribution of the TE mode along the device. Almost the same result has been obtained for the TM mode. As shown in these figures, more than 90% of the incident power in the waveguide A is transferred to the waveguide B.
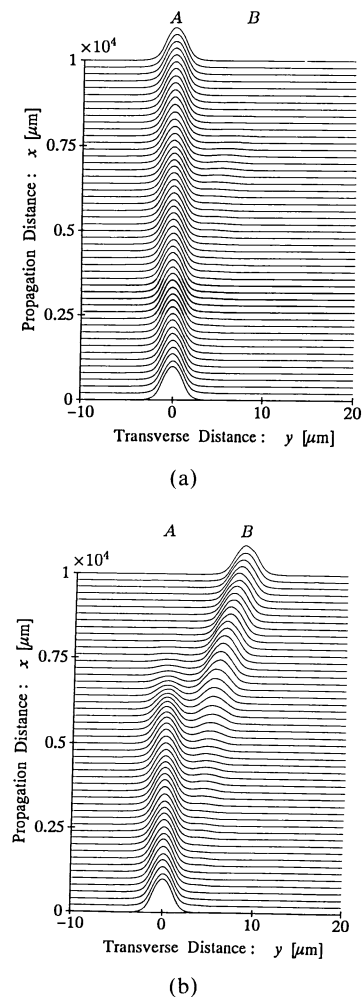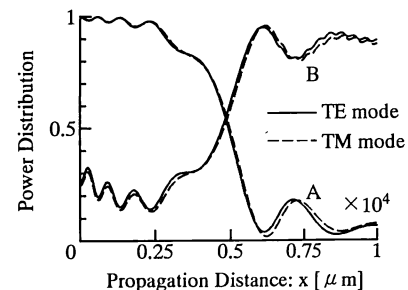
4. Conclusions

A new optical polarization splitter is proposed. The basic structure of the device is a dimensionally tapered velocity coupler which is fabricated on a $LiNbO_3$ substrate. It is verified numerically that the extinction ratios
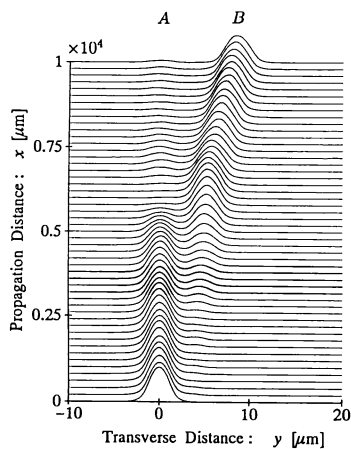
Fig. 6 Field distribution along the polarization splitter for the TE mode when the external electric field is removed.

of polarization are less than 2% for both TE and TM modes with a relatively low control voltage applied. It is also verified that the splitting characteristics of polarization are stable over a wide range of frequencies.
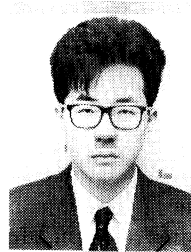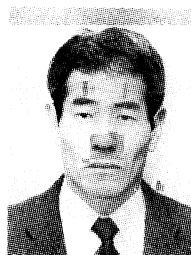
Acknowledgments

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