Highly efficient broadband waveguide based adiabatic polarization converter with apodization

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Abstract- **We report the design of a highly efficient broadband electro optic waveguide polarization converter using the rapid adiabatic passage mechanism, a well-known technique in the field of quantum optics. We also introduce a novel design for apodization of electrode pattern to get a ripple free bandwidth spectrum.**

I. INTRODUCTION

Many waveguide devices require control of polarization state of the propagating mode and one of the important polarization devices is the polarization converter based on the electro optic effect in quasi phase matching (QPM) configuration [1]. For increasing the bandwidth, linearly chirped QPM techniques have been used but with the associated disadvantage of reduced efficiency. However, recent analogy between two level atomic systems in quantum mechanics and coupled mode equations in wave optics [2] has helped in providing a novel solution to this problem in several nonlinear frequency conversion devices and bulk polarization conversion devices [3,4].

In this paper we show that it is possible to address the problem of efficiency-bandwidth tradeoff in polarization converters using the process of rapid adiabatic passage (RAP), and we have shown that almost complete conversion from one polarization state to another can be achieved over a broad bandwidth. Since this process leads to large ripples in the bandwidth curve, we propose a novel design for apodization of the electrode arrangement used for electro-optic coupling to solve this problem and have shown that using this design, the ripples can be reduced significantly without any notable change in either the bandwidth or the efficiency.

II. THEORY

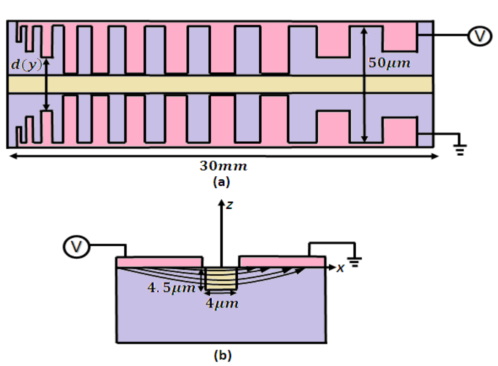

Fig. 1. Schematic diagram: (a) top view (b) cross-sectional view of z-cut LiNbO3 polarization converter.

We consider a titanium indiffused *z*-cut lithium niobate (LN) waveguide with light propagation along *y*-direction. For the waveguide structure considered in our problem, we have electrodes placed on either side of the waveguide (Fig.1) so that the generated electric field points in the *x*-direction, hence inducing a coupling between *x* and *z* polarizations through the r_{51} electro-optic coefficient.

Coupling between the two orthogonal modes under quasi phase matched condition are described by the following standard coupled mode equations [5]:

$$\frac{\partial A}{\partial y} = i\kappa B\, e^{i\Delta\beta y} \tag{1}$$

$$\frac{\partial B}{\partial y} = i\kappa A\, e^{-i\Delta\beta y} \tag{2}$$

Here A and B correspond to *y*-dependent amplitudes of the field distribution of x and z polarized modes, $\Delta\beta = \beta_x - \beta_z - K(y)$ where β_x and β_z are the propagation constants of x and z polarized modes respectively and $K(y)$ is the *y*-dependent spatial frequency of the applied aperiodic field given as $K(y) = K_0 + \alpha(y - L/2)$, α is the chirp constant and κ is the coupling coefficient given by [5]

$$\kappa = \frac{k_0{}^2 n_o^2 n_e^2 r_{51} \iint \left(F_1(x,z) - F_2(x,z)\right) E_x E_z dxdz}{2\beta_x \iint E_x^2 dxdz} \tag{3}$$

Here n_o and n_e are the ordinary and extraordinary refractive indices, $F_1(x,y)$ and $F_2(x,y)$ being the maximum and minimum electric field intensity applied along the x-direction corresponding to the small electrode spacing and large electrode spacing respectively for a given period, E_x and E_z are the transverse modal field distribution corresponding to the x and z polarized modes respectively. K_0 is the spatial frequency corresponding to the aperiodic electrode pattern at $y = L/2$ and L is the length of the device.

The coupled equations given by (1) and (2) resemble those describing the dynamics of quantum mechanical two level systems. One principal approximation used in such dynamical systems is the adiabatic evolution approximation. For adiabatic approximation to be valid for our system, we need to satisfy the following condition

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$$\frac{d\Delta\beta}{dy} << \frac{\left(4\kappa^2 + \Delta\beta^2\right)}{2\kappa} \quad (4)$$

In addition, for an efficient and broadband conversion the phase mismatch parameter $\Delta\beta$ should be very large compared to the coupling coefficient κ and should also change adiabatically with the condition: $\Delta\beta(z=0)<0$ and $\Delta\beta(z=L)>0$ (or vice versa). In order to achieve these conditions we have chirped the electrode pattern as shown in Fig. 1 (a) [4].

Ripples in the output spectrum are reduced significantly by using apodized electrode pattern. It can be achieved by gradually varying the separation between the electrodes at both the ends with a constant separation in between (see Fig. 1).

III. Numerical Results

We have carried out simulations assuming that the incident light is in x-polarized state i.e. $A(y=0)=1$ and $B(y=0)=0$. The refractive indices for LiNbO3 substrate for different polarizations at different wavelengths are calculated using the Sellmeier equation given in Ref. [6]. The propagation constants for both the polarizations are calculated using the *standard perturbation technique* [7]. We have performed the analysis with the following waveguide specification: width = 4 µm, depth = 4.5 µm and L = 30 mm. To satisfy the adiabatic condition, the electrode pattern is chirped with following specification: $K_o = (\beta_x - \beta_z)$ at 1530 nm, $\Lambda_1 = 20.1\mu m$ and $\Lambda_2 = 20.7\mu m$ (Λ_1 and Λ_2 correspond to the period of electrode pattern at the input and at the output end respectively) and applied voltage = 20 V. For these parameters, $\Delta\beta$ varies from a large negative to a large positive value and also $\kappa/\Delta\beta \approx 0.001$, thus satisfying the required conditions.

In order to achieve apodization to get ripple free spectrum, we have proposed an electrode arrangement such that the separation between the electrodes varies along the propagation length which results in a super-Gaussian like variation in the coupling coefficient. Fig. 2 shows the variation of coupling coefficient along the length of propagation for an intermediate wavelength of 1530 nm.

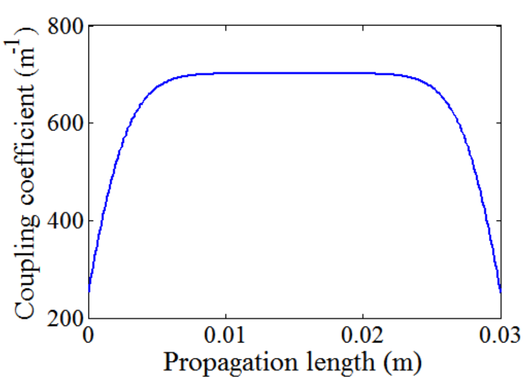

Fig. 2. Coupling coefficient variation along the length of the device due to apodization

We have solved the coupled equations given by (1) and (2) numerically using the Runge-Kutta method. The conversion efficiency is calculated as the ratio of intensity of *z*-polarized mode to that of input intensity in *x*-polarized mode. The input wavelength is varied from 1440 nm to 1600 nm. Fig. 3 depicts the conversion efficiency as a function of wavelength. It can be seen that with the proposed design it is possible to achieve a bandwidth of about 70 nm with an average efficiency of greater than 95% and with very low ripples in the spectral dependence.

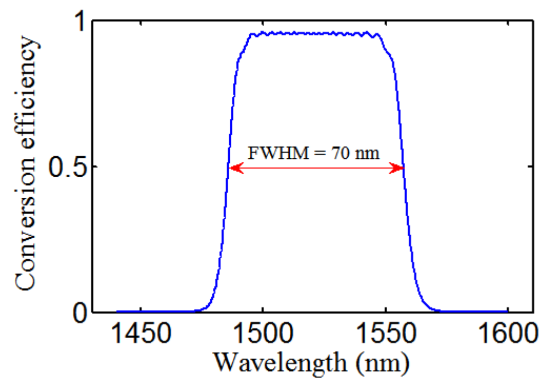

Fig. 3 Numerical results for conversion efficiency from x-polarized mode at the input to z-polarized mode at the output vs. input wavelength

IV. Conclusion

We have presented a novel design of a LiNbO3 waveguide based electro optic polarization converter under rapid adiabatic passage mechanism with apodization. We have shown that this design based on RAP provides us with a highly efficient broadband ripple free polarization conversion spectrum.

Acknowledgment

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