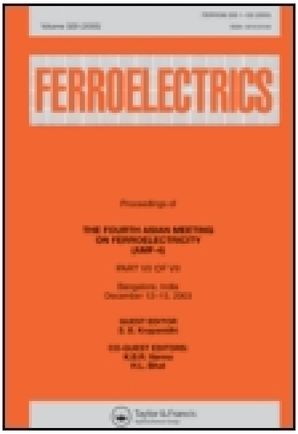

Ferroelectrics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gfer20

TE-TM mode converter based on PPLN waveguide

Yuanxin Xi [a], Quan Wang [a], Zhiliang Wan [a], Xuejin Zhang [a], Yanqing Lu [a] & Naiben Ming [a]

[a] National Laboratory of Solid State Microstructures, Nanjing University, Nanjing, 210093, P. R. China

Available online: 26 Oct 2011

To cite this article: Yuanxin Xi, Quan Wang, Zhiliang Wan, Xuejin Zhang, Yanqing Lu & Naiben Ming (2001): TE-TM mode converter based on PPLN waveguide, Ferroelectrics, 253:1, 201-208

To link to this article: http://dx.doi.org/10.1080/00150190108008459

Ferroelectrics, 2001, Vol. 253, pp. 201-208
Reprints available directly from the publisher
Photocopying permitted by license only

TE-TM Mode Converter Based on PPLN Waveguide

YUANXIN XI, QUAN WANG, ZHILIANG WAN, XUEJIN ZHANG, YANQING LU and NAIBEN MING

National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, P. R. China

(Received June 2, 2000)

Electro-optic effect of periodically poled optical superlattice $LiNbO_3$ (OSLLN) was studied. A novel design of TE-TM mode converter based on PPLN waveguide is proposed. Conversion efficient is theoretically calculated, and the distribution of external electric field in the waveguide is analyzed. Full TE-TM conversion occurs when phase matching requirement is satisfied.

Keywords: PPLN; Mode coupling; Quasi-phase-matching

INTRODUCTION

PPLN (periodical polarized lithium niobate) is a kind of optical supper-lattice, whose non-linear optical properties have been widely studied. Because the spontaneous polarization was periodically reversed, some important properties also changed periodically, such as the electro-optic coefficient, nonlinear coefficient, and the piezoelectric coefficient. There were many applications of such material, like frequency doublor and optical parametric oscillator. In this paper, we focused on the periodic electro-optic property of PPLN, which can be utilized in integrated optical devices, such as the TE-TM mode converter[5].

Traditional designs of TE-TM converter is to fabricate periodic electrodes on homogeneous LN[4], and such periodic electrodes will produce periodic disturbance of refractive indices, which will induce the coupling between TE and TM mode. In our design, we implement such conversion between TE and TM modes through quasi-phase-matching (QPM), that is to say, the periodic micro-structure of the material will make the original wave and coupling wave interfere in phase, so that the phase match requirements is satisfied.

The schematic demonstration of this design is shown in Fig. 1.

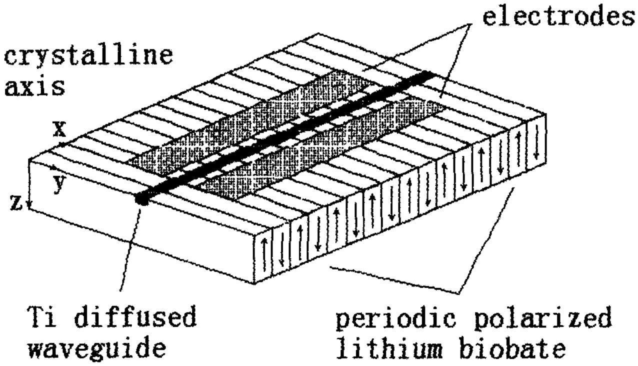

Fig. 1 Schematic representation of TE-TM mode Converter based on PPLN waveguide

The waveguide is along the x-axis of the crystal, and there are two electrodes parallel to it. As we can see, the two electrodes are not directly covered on the waveguide zone, so no buffer layer is needed. The incident light propagates along the x-axis of the crystal, the electric field is applied mainly along y-axis, and the spontaneous polarization of the crystal was along the z-axis.

THEORETICAL ANALYSIS

According to the electro-optic effects, the refractive tensor will changed when external electric field applied. We can express them in the following equations.

$$\Delta\beta_{ij} = \gamma_{ijk} E_k \tag{1}$$

$$\beta_{ij} x_i x_j = 1, \qquad \beta = 1/n^2 \tag{2}$$

$$\gamma = \begin{bmatrix} 0 & -\gamma_{22} & \gamma_{13} \\ 0 & \gamma_{22} & \gamma_{13} \\ 0 & 0 & \gamma_{33} \\ 0 & \gamma_{51} & 0 \\ \gamma_{51} & 0 & 0 \\ -\gamma_{22} & 0 & 0 \end{bmatrix}. \tag{3}$$

In this case, external field is along y-axis, so the electro-optic effect will cause refractive index ellipse rotate a tiny angle θ in the yz-plane.

$$\theta \approx \frac{\gamma_{51} E n_s^4}{n_o^2 - n_e^2}, \qquad n_s^2 = n_o n_e \tag{4}$$

As γ changes its sign periodically, the azimuth angle rocks right and left from $+\theta$ to $-\theta$ successively. When the incident light travel through the waveguide, the polarization direction of the light will rotate. This is because the periodic rotation of optic axis will cause the polarization of incident light also rocks left and right respect to the optic axis[5]. So there is power exchange between orthodoxy guiding modes. And in order to obtain maximum conversion, the incident wavelength must satisfy phase matching requirements.[1][5]

$$m\lambda = \Lambda(n_o - n_e) \tag{5}$$

Λ is the length of one period, which is thickness of one negative domain and one positive domain. Each time the incident light travel through one period, the polarization of the light will rotate 4θ. In typical, we suppose the incident light is only in TE mode. If we want to implement full conversion between TE and TM modes, we must rotate the polarization at least by $\pi/2$, that is to say, the minimal total number of periods $n = L/\Lambda = \pi/8\theta$, so the output light is in TM mode.

We can also describe such process in the coupled mode theory. When external field applied, there will be disturbance of dielectric tensor. Such disturbance will induce mode coupling between TE and TM modes, thus there will be power exchange between them. Phase matching is still required, the coupled waves must interfere in phase. The reciprocal vector of the periodic micro structures is used to compensate the phase mismatch. This principle is the same as those of traditional designs[4], which use periodic electrodes on homogeneous material to obtain periodic disturbance.

The dielectric tensor can be written as $\varepsilon = \varepsilon(0) + \Delta\varepsilon$, where $\varepsilon(0) = \varepsilon_0 \begin{bmatrix} n_o^2 & 0 & 0 \\ 0 & n_o^2 & 0 \\ 0 & 0 & n_e^2 \end{bmatrix}$ and $\Delta\varepsilon = -\varepsilon_0 \gamma_{51} E_2 n_s^4 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \cdot f(x)$. Here $f(x)$ is a periodic function to represent the periodic sign change of γ_{51}, $f(x) = \begin{cases} +1 & \mathit{if\ x\ is\ in\ the\ positive\ domains} \\ -1 & \mathit{if\ x\ is\ in\ the\ negative\ domains} \end{cases}$. The coupled mode equations are[1][5]

$$dA_{TE}/dz = -iKA_{TM}e^{i\Delta\beta z} \tag{6}$$

$$dA_{TM}/dz = -iKA_{TE}e^{i\Delta\beta z} \tag{7}$$

$$K = -\frac{1}{2} n_s^3 k_0 \gamma_{51} E \frac{i(1-\cos m\pi)}{m\pi}, \quad m = 1,3,5\cdots \tag{8}$$

K is the coupling coefficient, m is the rank of K. As we only discuss co-direction coupling, so

$$\Delta\beta = \beta_{TE} - \beta_{TM} - 2m\pi/\Lambda \tag{9}$$

For well-confined modes in the waveguide, $\beta_{TE} \approx n_o k_0 = n_o \frac{2\pi}{\lambda}$ and $\beta_{TM} \approx n_e k_0 = n_e \frac{2\pi}{\lambda}$. The solutions of the mode coupling equations are[1][5]

$$A_{TE}(z) = e^{i\frac{\Delta\beta}{2}z}[(\cos sz - i\frac{\Delta\beta}{2s}\sin sz)A_{TE}(0) - i\frac{K}{s}\sin szA_{TM}(0)] \quad (10)$$

$$A_{TM}(z) = e^{i\frac{\Delta\beta}{2}z}[(\cos sz - i\frac{\Delta\beta}{2s}\sin sz)A_{TM}(0) - i\frac{K^*}{s}\sin szA_{TE}(0)] \quad (11)$$

$$s^2 = KK^* + (\frac{\Delta\beta}{2})^2 \quad (12)$$

According to these equations, there will be power exchange between TE and TM mode[1][5], as showed in Fig. 2.

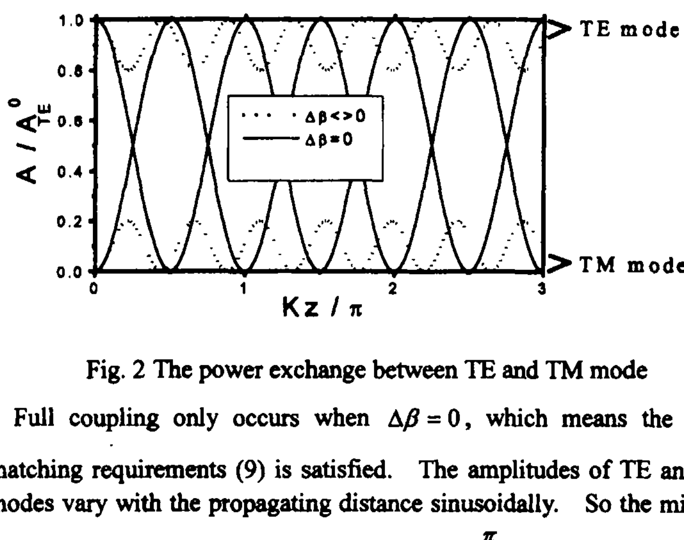

Fig. 2 The power exchange between TE and TM mode

Full coupling only occurs when $\Delta\beta = 0$, which means the phase matching requirements (9) is satisfied. The amplitudes of TE and TM modes vary with the propagating distance sinusoidally. So the minimal total coupling length L for full conversion is $\frac{\pi}{2K}$, which is the same as we acquired in previous paragraph.

In general, the external electric field is not uniformly distributed in the waveguide, so we need a coefficient α to denote the efficient of current electrical field, compared to ideal uniform field.[1][2]

$$\alpha = \frac{\int E_{TE}^*(y,z)\varepsilon_m(y,z)E_{TM}(y,z)dydz}{\varepsilon_m^0 \int E_{TE}^*(y,z)E_{TM}(y,z)dydz} \quad (13)$$

ε_m is the mth rank component of $\Delta\varepsilon$, and the effective coupling coefficient $K_{eff} = \alpha K$.

$$\Delta\varepsilon = \sum_{m\neq 0} \varepsilon_m \exp(-im\frac{2\pi}{\Lambda}z) \tag{14}$$

$$\varepsilon_m = -\varepsilon_0 \gamma_{51} E n_s^4 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \frac{i(1-\cos m\pi)}{m\pi} \tag{15}$$

So ε_m is proportional to the electric field, we can calculate α by analyzing the distribution of the external electric field. Because of the phase matching requirement (9), only one component ε_m contributes to the mode coupling, others will be neglected due to the phase mismatch. The cross section of the device is showed in Fig. 3.

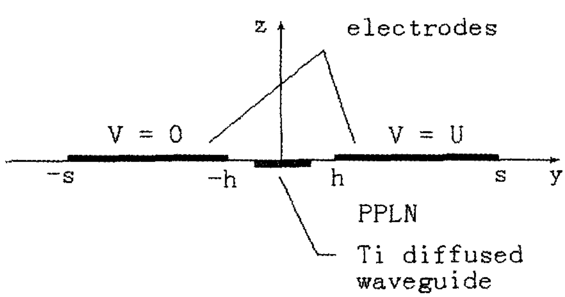

Fig. 3 Schematic representation of the cross section of the electrodes.

In our design, the width of electrode is much larger than the interval between them, so $s >> h$. The electrical field distribution is showed in Fig. 4[2][3]. The parameter is z, the depth intothe material, and E_0 denotes the ideal uniform electric field $E_0 = \frac{U}{2h}$.

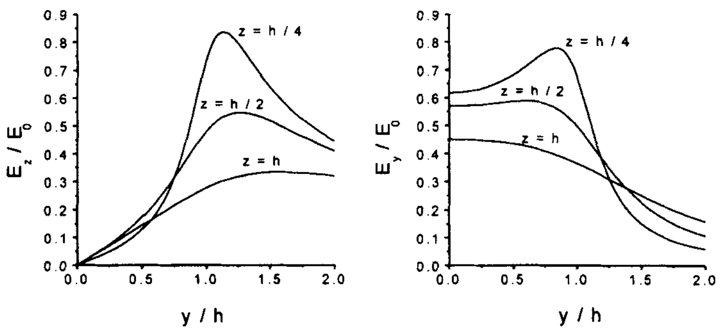

Fig. 4 Distribution of external electric field

This figure showed that the z-axis component is much smaller than the y-axis component in the waveguide zone. So the electro-optic effect of z-axis field can be neglected in this case.

For example, when the thickness and the width of the wave is $30\,nm$ and $2\,\mu m$, the space between two electrodes is $4\,\mu m$, and the incident wavelength is $632.8\,nm$. The period length is determined by the phase matching requirement, about $7.0\,\mu m$, and overlap factor $\alpha = 0.66$. When the driving voltage is $1V$, the coupling coefficient $K = 253m^{-1}$, from which we can derive the minimal coupling length $L = 6.20mm$.

When incident wavelength does not satisfy the phase matching requirements, phase mismatch will reduce the power exchange between TE and TM modes, as showed in Fig. 5[5].

The conversion efficient is strongly wavelength dependent, and the bandwidth $\Delta\lambda_{1/2} \approx 1.60 \dfrac{\lambda}{2mN}$. The bandwidth can be narrowed by increasing N, the total number of period.

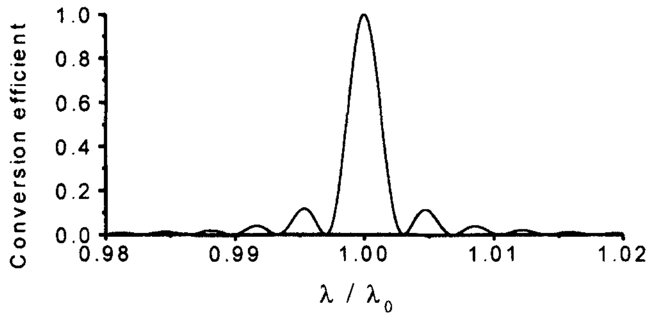

Fig. 5 Conversion efficiency versus wavelength ($\lambda_0 = 632.8nm$)

CONCLUSION

We designed a TE-TM mode converter based on PPLN waveguide. Because of the periodic electro-optic effects, full mode coupling will occur when electric field was applied along y-axis of the crystal if the phase matching requirement is satisfied. The driving voltage for obtaining the highest conversion efficiency is very low.

Acknowledgement

This work is supported by the State Key Program for Basic Research of China, the National Natural Science Foundation Project of China (Contract 69708007), and the National Advanced Materials Committee of China.

References

[1] A. Yariv, IEEE J. Quantum Electron. **QE-9**, 949 (1973).
[2] O.G. Ramer, IEEE J. Quantum Electron. **QE-18**, 386 (1982).
[3] R.C. Alferness and L.L. Buhl, Optics Letters. **5**, 473 (1980).
[4] R.C. Alferness, Appl. Phys. Lett. **36**, 513 (1980).
[5] A. Yariv, *Optical Waves in Crystal.*
[6] C.M.Kim, J. Lightwave Technol. **7**, 1063 (1989).