# Electro-optical polarization controller based on solc filter in periodically poled lithium niobate

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**Abstract**

Polarization controller (PC) for optical fiber is a major area of study in the general field of coherent-optical communication systems. In communication systems based on single-mode fiber, the states of polarization in fiber vary randomly due to temperature variations and mechanical perturbations along the fiber. These polarization changes can have a detrimental impact on polarization sensitive components. Recently, more and more research attentions have been paid to a new artificial nonlinear material: the periodically poled $LiNbO_3$ (PPLN) because of its outstanding nonlinear optical properties.

In this paper, we analytically proposed an electrical tuned polarization controller based on a single chip of Z-cut $LiNbO_3$ crystal. The first part is a Z-cut lithium niobate and the second part is periodically poled. The electric field is applied along the transverse and longitude directions for the separated part to implement the electro-optical polarization controller, respectively. With two electric fields applied by special control algorithms, the first part can transform an incident light with arbitrary ellipsoid polarization into a linearly polarized light and the second part will turn this linearly polarized light to a fixed linearly polarized light. Furthermore, if we use PPLN waveguide to fabricate such a device, only about 10V maximum driven voltage is needed for each stage, which is very attractive.

**Keywords:** polarization controller, periodically poled lithium niobate

## I. Introduction

Polarization controller (PC) for optical fiber is a major area of study in the general field of coherent-optical communication systems. In communication systems based on single-mode fiber, the states of polarization in the fiber vary randomly due to temperature variations and mechanical perturbations along the fiber. These polarization changes can have a detrimental impact on polarization sensitive components. Various methods have been used to form a polarization controller. Early, a kind of polarization controller consisted of three of four phase shifters connected in series with fast axes rotated by 45° relative to each other. [1-4] Another controller consisted of two devices, operating as a quarter-wave plate and a half-wave plate, polarization control is obtained by optimizing the angle of the two plates. [5-8] These two kinds of controllers have large size and control complexity. A polarization controller using electro-optic waveplate


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is proposed in [9], which used the quadratic electro-optic effect of PLZT. In recent years, new kinds of polarization controller have been reported, such as liquid-crystal polarization controller [10]; WDM polarization controller in PLC technology [11]; integrated electro-optic polarization controller based on $LiNbO_3$ [12][13].

Recently, more and more research attention has been paid to a new artificial nonlinear material: the periodically poled $LiNbO_3$ (PPLN) because of its outstanding nonlinear optical properties. In this paper, we propose an electrically tuned polarization controller based on a single chip of Z-cut $LiNbO_3$ crystal. The first part is a Z-cut lithium niobate and the second part is periodically poled. The electric field is applied along the transverse and longitudinal directions for the separated part to implement the electro-optical polarization controller, respectively.

## II. The model

The basic structure of the polarization controller is showed in Fig. 1. It is a single chip of Z-cut $LiNbO_3$ crystal and contains two parts. The first part has length $L_1$ with the electric field applied along the Z axis. The second part is periodically poled with the electric field applied along the Y axis. If an arbitrary polarized light is incident on the crystal, the first part of this device can transform it into a linearly polarized light and the second part of it will turn this linearly polarized light to a fixed linearly polarized light while the electric field is applied.

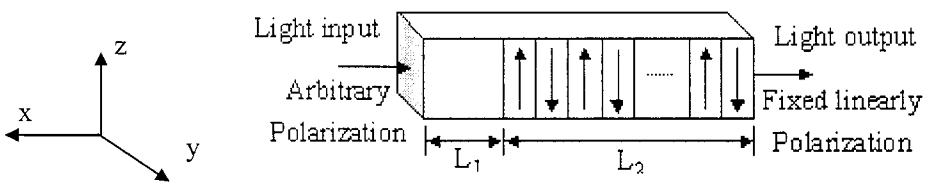


Fig 1. The basic structure of an electric polarization controller, X, Y, and Z represent the principal axes of the original index ellipsoid. The arrows inside the PPLN indicate the spontaneous polarization directions.

As we all know, the presence of an external electric field will cause a deformation of the index ellipsoid of a birefringent crystal. [14][15] For the first part of this device, an electric field is applied along the Z axis. While a light beam is propagating along the x axis, the birefringence seen by it is

$$\Delta n' = n_z - n_y = n_e - n_o - \frac{1}{2}(\gamma_{33} n_e^{\ 3} - \gamma_{13} n_o^{\ 3}) E_z \quad (1)$$

where $E_z$ is the field intensity; $\gamma_{33}$ and $\gamma_{13}$ are the EO coefficient; $n_o$ and $n_e$ represent the refractive indices of the ordinary and extraordinary wave, respectively.

We express the input light in terms of the normalized Jones vector

$$A_{in} = \begin{bmatrix} \cos\varphi \\ \sin\varphi e^{i\delta} \end{bmatrix} \quad (2)$$

with an electrical filed applied along the z direction，the Jones matrix is described as follows

$$J = \begin{bmatrix} e^{-i\pi(ne-no-\frac{1}{2}(r_{33}n_e^3-r_{13}n_o^3)E_z)L_1/\lambda} & 0 \\ 0 & e^{i\pi(n_e-n_o-\frac{1}{2}(r_{33}n_e^3-r_{13}n_o^3)E_z)L_1/\lambda} \end{bmatrix} \quad (3)$$

and the output light emitted from the first crystal with length $L_1$ is described as

$$A_{out1} = JA_{in} = \begin{bmatrix} e^{-i\pi(n_e-n_o-\frac{1}{2}(r_{33}n_e^3-r_{13}n_o^3)E_z)L_1/\lambda} & 0 \\ 0 & e^{i\pi(n_e-n_o-\frac{1}{2}(r_{33}n_e^3-r_{13}n_o^3)E_z)L_1/\lambda} \end{bmatrix} \begin{bmatrix} \cos\varphi \\ \sin\varphi e^{i\delta} \end{bmatrix}$$
$$= \begin{bmatrix} \cos\varphi e^{-i\pi(n_e-n_o-\frac{1}{2}(r_{33}n_e^3-r_{13}n_o^3)E_z)L_1/\lambda} \\ \sin\varphi e^{i\delta+i\pi(n_e-n_o-\frac{1}{2}(r_{33}n_e^3-r_{13}n_o^3)E_z)L_1/\lambda} \end{bmatrix} \quad (4)$$

with $2\pi(n_e - n_o - \frac{1}{2}(r_{33}n_e^3 - r_{13}n_o^3)E_z)L_1/\lambda + \delta = m\pi$ (m=±1,±2,...), the input light with arbitrary elliptic polarization will be transformed into a linearly polarized light. Fig.2 shows the relationship between the applied electric field and the phase delay of the extraordinary and ordinary wave. While the phase delay between extraordinary and ordinary wave of the input light is from $-\pi$ to $\pi$, an 0 kv/mm to 0.7kv/mm electric field is needed to transform an elliptic polarization into a linearly polarization with a crystal length of 1cm.

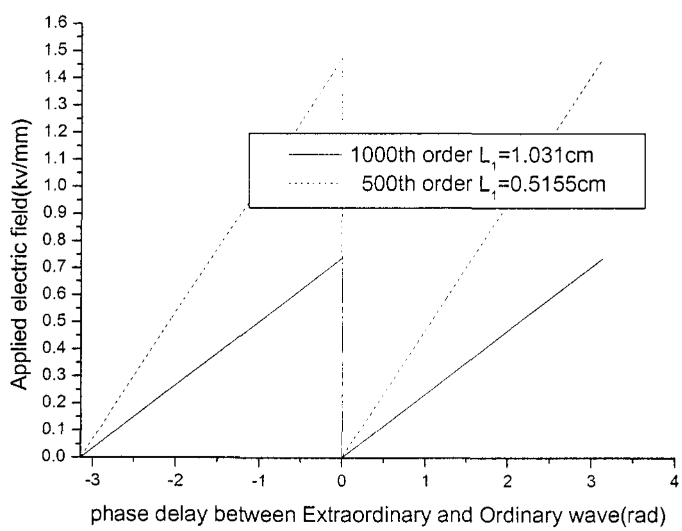


Fig.2 the relationship between the applied electric field and the phase delay of the extraordinary and ordinary wave

The second part of the crystal is periodically poled. With an external electric field applied along the Y axis, the index ellipsoid deforms to make the Y and Z axes rotate a small angle about the X axis. [15]

$$\theta \approx \frac{\gamma_{51} E_y}{(1/n_e^2) - (1/n_o^2)} \quad (5)$$

where $E_y$ is the field intensity; $\gamma_{51}$ is the EO coefficient; $n_o$ and $n_e$ represent the refractive indices of the ordinary and extraordinary wave, respectively.

In PPLN, all elements of the electro-optic tensor have different signs in different domains. After applying the field, the azimuth angle of the new Z axis rotates right and left from $+\theta$ to $-\theta$ successively due to the periodic EO coefficient in PPLN. While the domain thickness satisfy the phase matching condition, each domain acts as a half-plate. Thus, we can take this structure as a folded solc type filter.

We can use the coupled-mode theory to study such a structure. In PPLN, the coupled wave equations of the ordinary and extraordinary waves may be obtained as:

$$\begin{cases} dA_1 / dx = -i\kappa A_2 e^{i\Delta\beta x} \\ dA_2 / dx = -i\kappa^* A_1 e^{-i\Delta\beta x} \end{cases} \quad (6)$$

with $\Delta\beta = (\beta_2 - \beta_1) - G_m, G_m = \dfrac{2\pi m}{\Lambda}$,

$$\kappa = -\frac{\omega}{2c} \frac{n_o^2 n_e^2 \gamma_{51} E_y}{\sqrt{n_o n_e}} \frac{i(1-\cos m\pi)}{m\pi}, \text{ (m=1,3,5,....)}$$

where $A_1$ and $A_2$ are the normalized amplitudes of the ordinary wave and the extraordinary wave respectively; $\beta_1$ and $\beta_2$ are the corresponding wave vectors. $G_m$ is the *m*th reciprocal vector, $\Lambda$ is the modulation that is equal to twice the domain thickness $L_2$ if the duty cycle is 50%. The boundary condition of the equation is given by

$$A_{in2} = A_{out1} = \begin{pmatrix} \cos\varphi \\ e^{-im\pi}\sin\varphi \end{pmatrix} = \begin{pmatrix} \cos\varphi_1 \\ \sin\varphi_1 \end{pmatrix} \quad (7)$$

where $\varphi_1 = \begin{cases} \varphi & m = 0, \pm 2, ... \\ -\varphi & m = \pm 1, \pm 3, ... \end{cases}, (-\pi < \varphi_1 < \pi)$

The solution of the coupled-mode equations (6) is

$$A_1(x) = e^{i(\Delta\beta/2)x} \left\{ [\cos sx - i\frac{\Delta\beta}{2s}\sin sx]\cos\varphi_1 - i\frac{\kappa}{s}\sin sx \sin\varphi_1 \right\} \quad (8)$$

$$A_2(x) = e^{-i(\Delta\beta/2)x} \left\{ -i\frac{\kappa^*}{s}\sin sx \cos\varphi_1 + [\cos sx + i\frac{\Delta\beta}{2s}\sin sx]\sin\varphi_1 \right\} \quad (9)$$

where s is given by

$$s^2 = \kappa^* \kappa + (\frac{\Delta\beta}{2})^2$$

At the output of the PPLN, while the Phase matching condition is satisfied, i.e. $\Delta\beta = 0$ and

$$|\kappa| L_2 + \varphi_1 = (2k+1)\pi / 2$$

$$A_1(L_2) = 0$$

$$A_2(L_2) = \pm 1$$

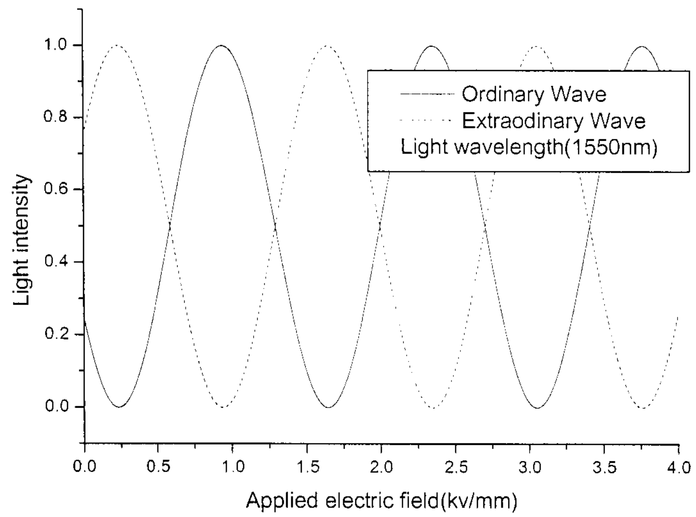


Fig.3 Power exchange relations between the extraordinary and the ordinary wave when the phase matching condition is satisfied ( $\Delta\beta = 0$ )

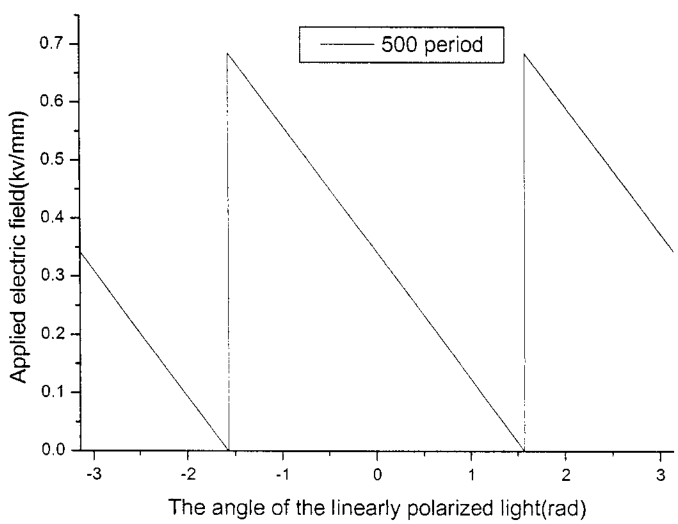


Fig. 4 Relations between applied electric field and the polarization angle of the light

Thus, the output light is linearly polarized along Y axis. Fig.3 shows the power exchange relations between the extraordinary and ordinary waves when the phase matching condition is satisfied. When the external field is absence, the light propagates through the PPLN with the polarization unchanged. Fig. 4 shows the relations between the applied electric field and the polarization angle of the linearly polarized light. While the polarization state of the input light is determined, the applied electric field of the first and the second stage can also be determined by Fig.2 and Fig. 4. Then the input light with arbitrary elliptic polarization will convert into a fixed linear polarization. Seen from Fig. 2 and Fig. 4, the maximum applied electric field is about 0.7 kv/mm. While we using PPLN waveguide to fabricate such a device, a low applied voltage is needed to control this system, which is very attractive.

## III. Conclusion

We proposed a single channel polarization controller based on a single chip of Z-cut $LiNbO_3$ crystal, which contains a periodically poled part. With two external fields applied on the two part of the crystal respectively, the input light with arbitrary ellipsoid polarization will transform to a fixed linearly polarized light.

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