High-Speed Dynamic Polarization Controllers/Scramblers and Rotators Using EEO crystals

1. INTRODUCTION

In fiber optic communication, sensing systems, optical imaging and security, many devices, such as 100 Gb/s coherent detection systems, interferometers, and electro-optic modulators, are sensitive to polarization-related impairments. These impairments result from high internal birefringence, such as core asymmetry and built-in stresses, and from externally induced birefringence such as from, twists, pressure, mechanical stress and thermal stress applied to optical fiber links. The distortion in signals due to birefringence is known as polarization mode dispersion (PMD). The externally induced birefringence changes make PMD related impairments time dependent[1].

A high-speed dynamic and adaptive polarization controller is needed to overcome random variations. A dynamic polarization controller can convert any given polarization state to any desired polarization state[2].

Uninterruptible transmission is also critical for dynamic polarization controllers in optical networks. It is necessary that the polarization controller track continuously all changes in polarization without needing to be reset (endless tracking)[2].

High speed is essential for tracking fast polarization variations such as those caused by locomotives passing fibers laid alongside railway tracks or by ocean waves flowing over undersea fiber trunk lines. The response time of the dynamic polarization controller for PMD mitigation must be less than 1 ms. In practice, a response time less than 100 μs is required[3].

OZ Optics has implemented an innovative electro-optical crystal, EEO crystal, which provides a new platform to develop polarization controllers that are fast in response speed, endless in tracking, seamless in dynamic and adaptive control. This will form a significant milestone to overcome the polarization related impairments in optical fiber links and to meet the stringent requirements of modern applications, such as resolving high-speed optical signals to produce high-resolution images in Optical coherence tomography (OCT) systems.

2. Advantages

The main advantages of EEO crystals over other electro-optical materials for polarization control can be summarized as follows:

2.1- High electro-optic coefficient

One of the biggest advantages of utilizing EEO crystal for polarization control is the super high electro-optical coefficient. The electro-optical coefficient of EEO crystal working in transverse mode is 300~600 pm/V. In the polarization control devices, the size of each dynamic waveplate is dramatically reduced and the half-wave voltage needed can be designed to be less than 36 V.

2.2- Linear electro-optic effect

EEO crystal is non-centrosymmetric material and exhibits the *linear* electro-optic effect, where the refractive index change is proportional to the electric field strength. This linear electro-optic effect of EEO crystal can greatly simplify the polarization control algorithm.

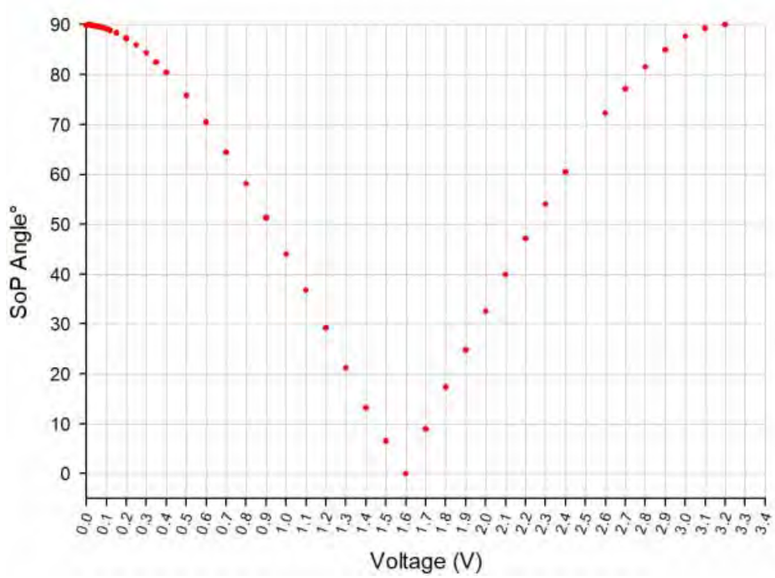


Figure 1. Single EEO crystal showing the SoP angle with respect to a fixed linear polarizer as a function of the input DC (pre-amplified) voltage.

2.3- Fast Response

The polarization control devices utilizing EEO crystal are offering fast response in microsecond level as shown in Fig. 2. The dramatic increase in speed enables a significant improvement of polarization sensitive devices and systems and helps saving time and money.

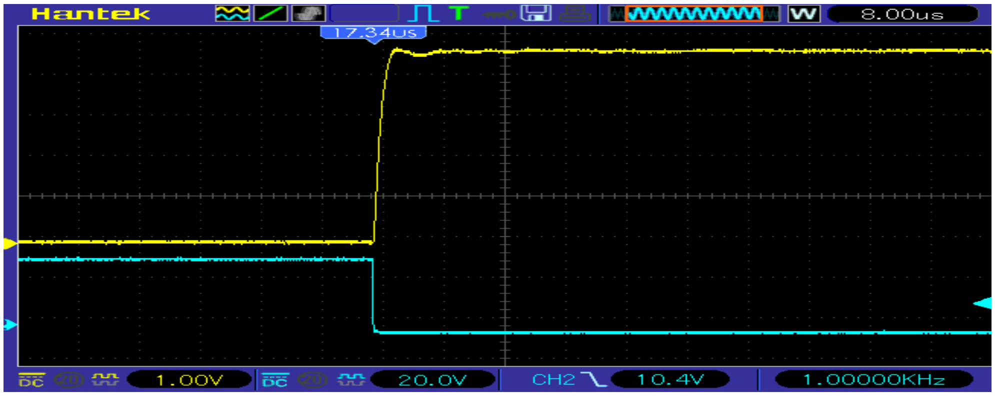


Figure 2. Demonstration of high speed, rising and falling time <1.5µs.

2.4- High repetition rate

EEO crystal provides high repetition rate, shown in Fig. 3, which is required in polarization scrambling devices against rapid SoP (state of polarization) variations in modern fiber optic transceivers, and other systems that deploying coherent detection techniques.

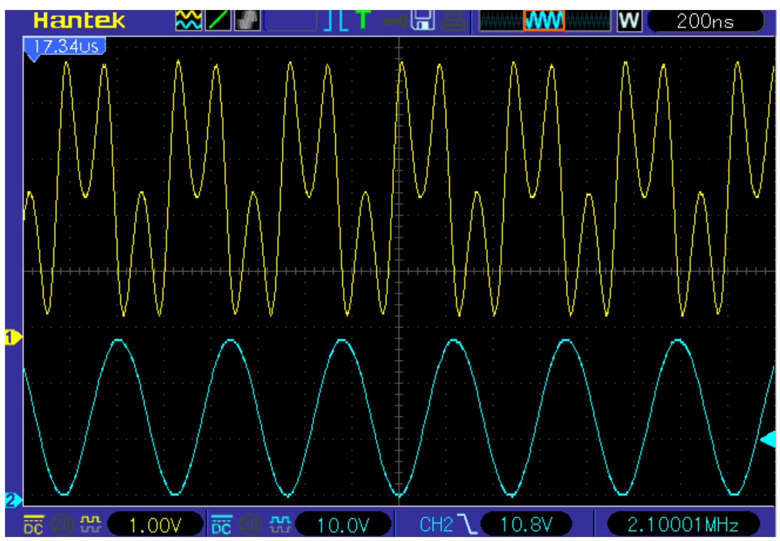
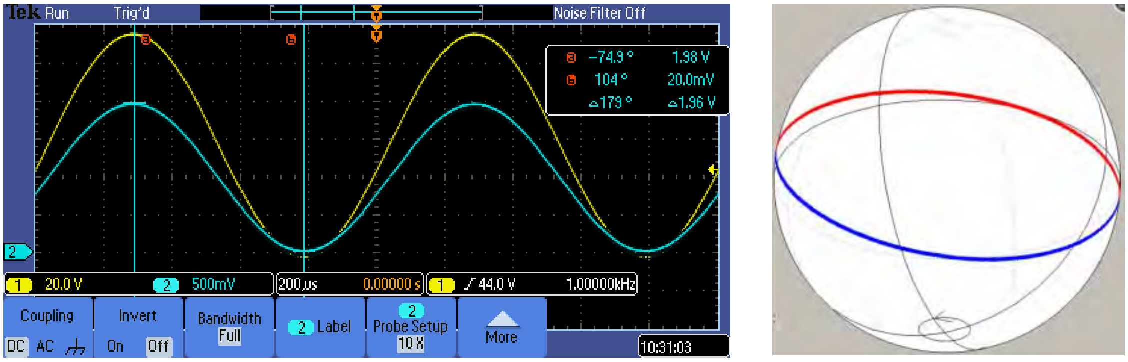


Figure 3. Up to 2.1 MHz modulation rate in 0~2π phase shift range.

Complete polarization circle on Poincare sphere is scanned using a polarimeter at a kHz frequency and a voltage of 1.55 V ($V_{2\pi}$) as shown in Fig. 4.



(a) (b)

Figure 4. SoP of a single EEO crystal, driven by a wave-function generator at 1kHz frequency (a), captured on Poincare sphere (b).

2.5- Low activation loss

The low activation-induced loss makes the EEO crystal-based polarization devices ideal for applications in high precision PDL measurement instruments, and in feedback loops for compensating for polarization induced penalties.

2.6- All solid-state configuration

The Solid-state structure of EEO crystal-based polarization control devices provide flexibility on arranging and designing the orientation of dynamic waveplates and the number of channels. More components, such as tap, and photodiode (PD), polarizers, and passive waveplates can be integrated in one mechanical package.

2.7- Long life time/ High reliability

High reliability of EEO crystal-based polarization controllers come from to the nature of the crystal and special designs of the packaging with no moving parts.

3. EEO CRYSTALS (ELECTRO-ELASTO-OPTICAL CRYSTAL)[4]

EEO crystals are the first practically useful PMN-PT based ferroelectric crystal. The unique features are well identified from the combination of inverse Piezoelectric effect, Elasto-Optic effect and pure Electro-Optic effect. The EEO crystal is structurally stable and crystal-clear. It shows very low V_π and great effective E-O coefficient.

EEO crystals have excellent transparency over a wide range of wavelength band, from visible to middle IR as shown in Fig.5.

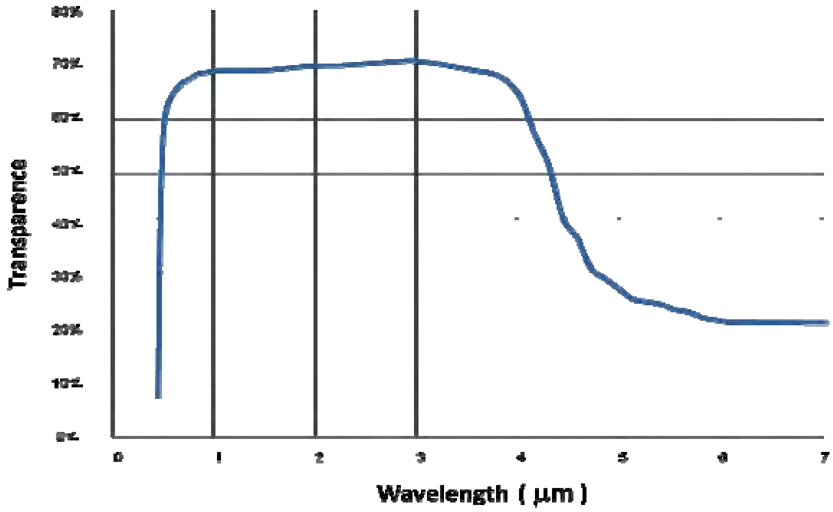


Figure 5. Optical transmission spectrum of EEO crystal wafer with a thickness of 2 mm from 300~7000 nm.

EEO Crystals exhibit the *linear* electro-optic effect, or ***Pockels effect***, where the refractive index change is proportional to the electric field strength. One important property of EEO crystal is the large EO coefficient, which is approximately 10 to20 times higher than single LiNbO3 crystals.
Table 1 shows the comparison of EO coefficient of EEO crystals to traditional EO crystals.

Table 1. Physical Property Comparison of EEO Crystals to Traditional E-O Crystals

E-O Crystal	Apparent γ_c (pm/V)	$V_\pi^T{}_{(l=d)}$ (V)	V_π^l (V)
$LiNbO_3$	31	3,030	5,300
EEO Crystal	300~600	80~165	100~150

where:

- γ_c is Effective (Apparent) E-O coefficient, pm/V
- $V_\pi^T{}_{(l=d)}$ is Transverse half-wave voltage (normalized to $l = d$)
- V_π^l is Longitudinal half-wave voltage

4. APPLICATIONS

Controlling the polarization state of light by polarization rotation techniques is important not only in intensity/phase optics but also in several fields of optoelectronics, including display technology, fiber optics, optical communication and optical measurements[5]. Polarization

Rotators can continuously rotate the polarization state of a input beam through more than 180°. On the Poincare sphere the rotation by a rotator causes that the initial SoP moves to a new SOP along the same latitude line. In recent decades for controlling the polarization orientation, intensive developments, including prism rotators, Faraday rotators, and Liquid Crystal rotators[6,7], are all focus on linear polarized (LP) lights input.

With free-space micro-optic design, additional active and passive optical components can be easily added along the optical path and integrated into compact mechanical package, where some applications require six distinctive SoPs for better calibration accuracy. Also, quarter wave-plates, polarizers, a tap mirror, photodetectors can be added as built-in components depending on a system control algorithms.

4.1 EEO POLARIZATION CONTROLLERS AND APPLICATIONS

One standard configuration that provides endless and seamless polarization control is shown in Fig. 6. Four EEO crystal plates are used to rotate the input SoP.They are oriented at 45º, 0º and 90º, and -45º, respectively, with respect to 0º orientation. By applying voltage to a plate, there is birefringence generated whose magnitude increases linearly with the applied voltage. Thus, the retardation angle in each plate is a linear function of the applied voltage.

Figure 6. Configurations of OZ Optics' high speed polarization controller.

Theoretically, two dynamic retarders placed 45º with respect to each other would be capable of changing the input SoP to any output polarization. In circumstances when one retardation-plate reaches π phase shift or its range limit, there are two options for subsequent operations: either further apply voltage beyond V_π to maintain system compensation or reduce the voltage to zero and start over again. Applying higher voltage than V_π voltage will increase activation losses, while reducing to zero voltage would leave the system an uncontrolled state for a short period, which is not acceptable. Therefore, a third dynamic retarder is added to help the rewinding process that is, when the voltage on the rewinding plate is reduced, the extra plate is biased up to realize a seamless and endless control. A fourth retardation plate is added to provide additional offset, increase error tolerance and improve system stability. Without any feedback control loop EEO polarization control can be used in polarization scrambling, by adjusting amplitude and frequency of each EEO elements. By connecting and integrating a feedback loop, EEO polarization controllers can be used in PMD compensation, polarization optimization, polarization-induced crosstalk reduction and PDL characterization and compensation.

4.2 Polarization Insensitive Polarization Rotator

OZ Optics' polarization insensitive polarization rotator, shown in Fig. 7, is configured with single-mode fibers on the input and output ports. One or two EEO elements function as dynamic retarders between two quarter wave-plates (QWPs). It can rotate the SoP from 0° to 180° quickly and repeatability.

Figure 7. Configurations of OZ Optics' insensitive polarization rotator with a single crystal sandwiched between two quarter-wave plates.

4.3 Linear Polarization Rotators

Linear Polarization Rotators, schemed in Fig. 8, can continuously rotate the polarization state of a linearly polarized input beam through more than 180° with no mechanical movement involved. A minimum extinction ratio of 1000:1 is guaranteed over the entire rotation range.

A linear polarization rotator consists of an EEO crystal variable retarder and a quarter-wave plate. The EEO element and wave plate have their fast axes (or slow axes) oriented at 45° with respect to each other. With linearly polarized light incident on the polarization rotator from the input, azimuth rotation of the output polarization can be achieved by adjusting the applied voltage to the EEO elements.

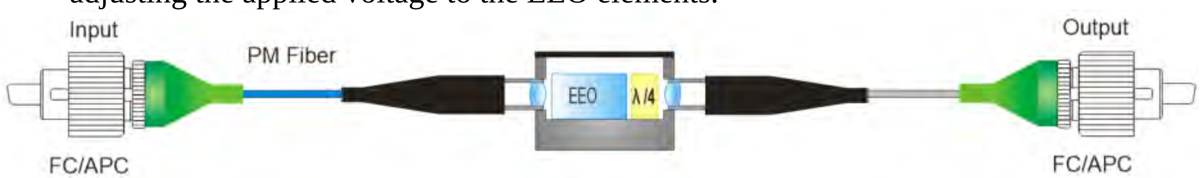


Figure 8. OZ Optics' linear polarization rotator with PM fiber on the input port and quarter wave-plate at the output.

4.4 Polarization Modulator

Compared to conventional mechanical modulators, EEO crystal based polarization modulators are electro-optical; they contain no moving parts, are completely vibration-free, and have a small footprint.

4.5 Polarization Switch

EEO polarization rotators can be configured for linear polarization output states switching between two orthogonal polarization states. Switching between other pre-defined polarization states is also possible. For example one can switch between linear and circular polarization, as well as between left-handed and right-handed circular polarizations.

4.6 Polarization State Generator

Two or more polarization rotators can be cascaded as a binary polarization state generator (PSG)[8], generating at least four distinctive polarization states on the Poincare sphere, such as 0°, ±45°, and 90°, or right-hand circular (RHC) and left-hand circular (LHC). PSGs are important tools for measuring and analyzing the polarization properties of light-wave components or systems by use of the Mueller matrix method[6]. The information obtained from such polarization state analysis can be used to measure other parameters, such as birefringence, polarization mode dispersion (PMD), polarization dependent loss (PDL), optical signal-to-noise ratio (OSNR), and state of polarization (SoP) of the optical components.

5. Reference

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