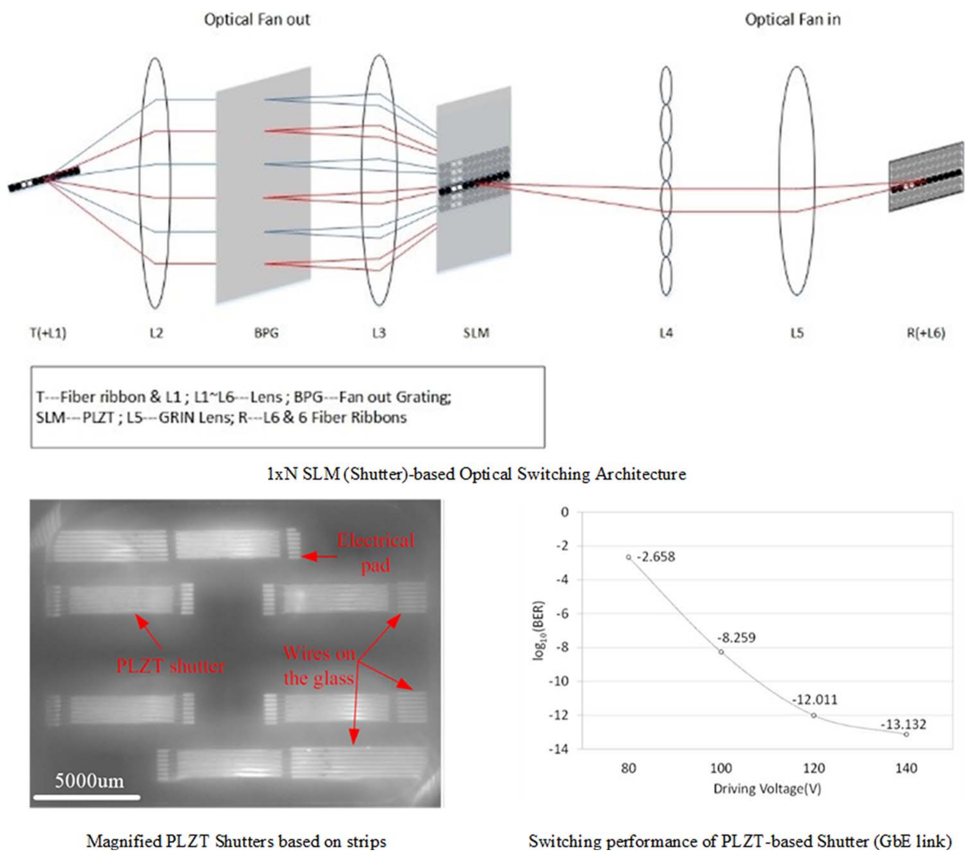
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

PLZT-Based Shutters for Free-Space Optical Fiber Switching

Volume 8, Number 1, February 2016

Fan Zhang
Hsi-Hsir Chou
W. A. Crossland



DOI: 10.1109/JPHOT.2015.2511090

IEEE photonics SOCIETY

IEEE

PLZT-Based Shutters for Free-Space Optical Fiber Switching

Fan Zhang,[1] Hsi-Hsir Chou,[1,2] and W. A. Crossland[1]

[1]Department of Engineering, University of Cambridge, Cambridge CB3 0FA, U.K.
[2]Department of Electronic and Computer Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan

DOI: 10.1109/JPHOT.2015.2511090

Manuscript received September 3, 2015; revised December 12, 2015; accepted December 16, 2015. Date of publication December 22, 2015; date of current version January 7, 2016. This work was supported in part by the U.K. Engineering and Physical Sciences Research Council (EPSRC) DTI LINK Project and in part by the Taiwan Ministry of Science and Technology under Grant MOST 104-2221-E-011-046. Corresponding author: H.-H. Chou (e-mail: hsi-hsir.chou@trinity.cantab.net).

Abstract: With the increasing demand for optical fiber switching technologies from data center networks, shutter-based free-space optical fiber switching technology is promising for such network applications as the major advantages of this switching technology are that multicast switching, which is a vital functionality required in data center networks, can be easily achieved through its optical fan-out mechanism and that the switching performance can also be significantly strengthened while new materials with a faster response time are used as a spatial light modulator (SLM) to act as shutters. In this paper, the characteristics of ferroelectric liquid crystals and lead lanthanum zirconate titanate EO ceramic (PLZT) materials used as an SLM to act as shutters based on a type of strips for free-space optical fiber switching technology have been investigated. Although the PLZT-based shutters have a fundamental characteristic that a higher driving voltage might be required in order to provide a fast switching time less than a subnanosecond, with the use of a simple push–pull amplifier circuit design that can make a small input signal ride on a large dc voltage, the driving of a PLZT device in an optical switch can easily be achieved. Although the power consumption problem of this PLZT device resulting from a high driving voltage was not investigated in this paper, it can be effectively improved through a general boost converter that can be used to raise a small input dc voltage to a required higher driving voltage for the PLZT device. A proof of concept $1 \times N$, i.e., a 1×6 free-space optical fiber ribbon switching architecture capable of scaling to an $N \times N$ switching architecture for data center network application, was experimentally implemented to investigate the fiber array switching properties of PLZT-based shutters based on a type of strip. The experimental results show that the bit error rates estimated from the Q-factor were all less than 10^{-9} and that the jitters were all less than 7.35% under a variety of shutter driving voltages at a link speed of 1 Gb/s and above.

Index Terms: Shutter, lead lanthanum zirconate titanate electro optical (EO) ceramic (PLZT), ferroelectric liquid crystal (FLC), free-space optical switch.

1. Introduction

With the increasing applications of optical fiber transmission technologies in data center networks, optical switching technologies are emergence as a direct approach to improve the performance of data center networks. Recent analysis in [1] and [2], however, has almost led to the conclusion that all-optical packet switching nodes will not take place in the near future since optical buffering technologies are still immature and that the high cost of current optical switch fabrics have made them uncompetitive with current optical packet switching nodes.

The progress in the development of new optical switch fabrics have recently emphasized on the design of cost-effective optical switching core capable of scaling in size to over one hundred ports, and simultaneously provide a faster switching time beyond the nanosecond scale. Although a sub-nanosecond switching time can be achieved by $LiNbO_3$ coupler-based switches [3], only few of such couplers can be integrated on a single substrate to form a large switch fabric resulted from the large size of each directional coupler and the large bending radii required in the integrated waveguides. Similarly, the high cost of semiconductor optical amplifiers (SOAs) or array waveguide gratings (AWGs) are also too expensive and impractical [4], [5] to build a large switching architecture. Although the 3-D microelectromechanical systems switch has the potential of constructing a large switch fabric with hundreds of port numbers [6], its switching speed is limited to the order of milliseconds [7] and the practical use also faces a big challenge due to its complex control electronics [3]. For the application in data center network, shutter based free-space optical switch has a better advantages at providing good scalability and reliability compared with other free-space optical switches [8].

In shutter-based free-space optical switch, a low-cost computer generated binary phase grating component is used to duplicate the optical input beams onto a shutter (optical fan-out) and a spatial light modulator (SLM) acts as a shutter to select one or a sub-set of the beams through optical fan-in for propagation to the output fiber ports. The multicast transmission through optical fan-out, a vital functionality required in data center network is possible when several shutters are opened simultaneously. The shutter in this switching architecture is typically a pixelated device, similar to a display, in which each pixel can be controlled to perform the amplitude or phase modulation for the light passing through it. The switching performance can be significantly improved while new materials are used as shutters to raise the switching speed.

The progress in the development of SLMs has been fast and a wide variety of designs for SLMs have been proposed [9], [10]. Using electro-optical (EO) effects, SLMs demonstrated have included the use of Lead Lanthanum Zirconate Titanate EO Ceramic (PLZT), and liquid crystal (LC) materials. However the switching properties of these SLMs used as shutters in a free-space optical fiber switching architecture has not investigated and examined thoughtfully especially when a greater pixel dimension over several hundred micrometers is used to switch fiber array simultaneously. Our research works reported in this paper is distinguished with conventional PLZT shutters and PLZT based switches that have been presented in the past, since the pixel sizes that they have used were all in the scale of few micrometers i.e., 8 μm [11] and several pixels were used to switch only one single fiber/channel in a low dimension switching architecture. In our research, each pixel of PLZT shutters based on a strip type can be used to switch fiber array simultaneously.

In this paper, the investigation of material property of ferroelectric liquid crystal (FLC) and PLZT materials for SLM used as shutters based on a type of strips is reported in Section 2. A driving approach based on a simple and effective circuit to make a small input signal ride on a large DC voltage for the application of PLZT-based shutters in a free-space optical fiber ribbon switching architecture is presented in Section 3. In Section 4, a proof of concept 1×6 shutter-based free-space optical fiber ribbon switch which was experimental implemented to investigate the fiber array switching properties of the proposed PLZT-based shutter device in a link speed of 1 Gb/s and above is demonstrated. Finally, some conclusions are made in Section 5.

2. Material Investigation for Shutter

There are many materials that can potentially be used as shutters have been studied. Typical examples include electro-optic (EO) materials, Liquid Crystals (LCs), magneto-optic materials, acoustic-optic and photo-refractive materials. Among these materials, the FLCs, which allow easy reorientation of the polarization direction, make them an attractive device for applications in free-space optical switching [12]. Lead Lanthanum Zirconate Titanate EO Ceramic (PLZT), as

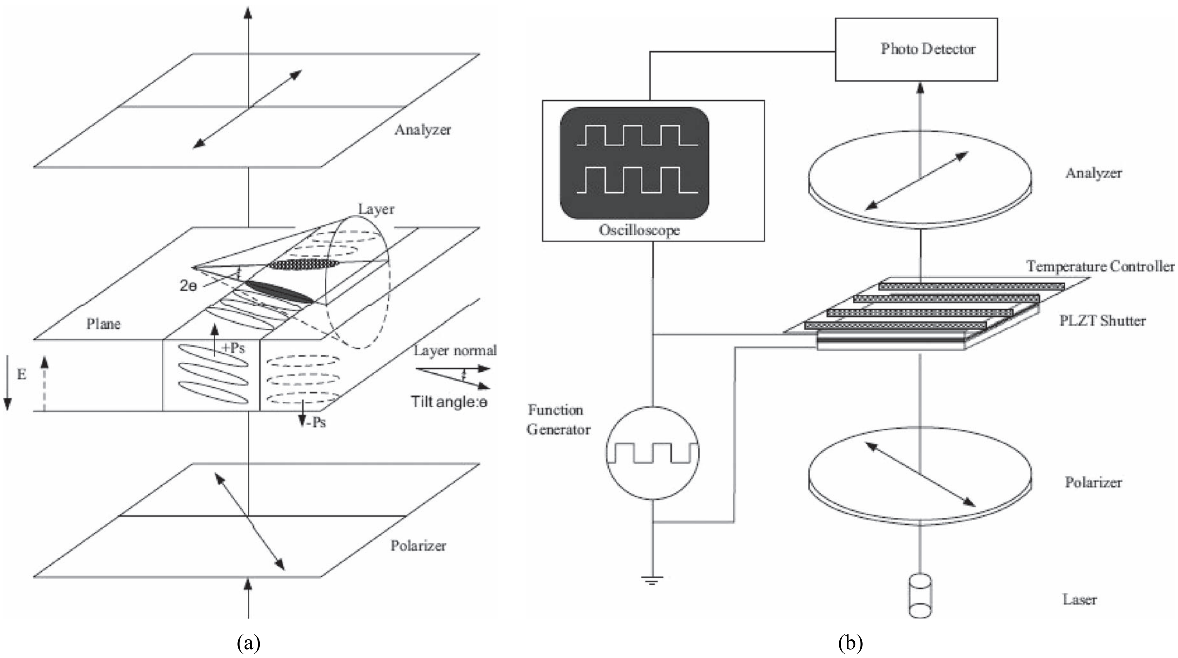


Fig. 1. Experimental setup for SLM characteristic measurement. (a) Bistable LC cell used between two polarizers. (b) Experimental setup for PLZT shutter.

the first transparent ferroelectric ceramic, has been widely used in the areas of shutters, filters and displays. The fast response, high resolution and wide operating temperature range make PLZT a viable candidate for shutters [13]. In this research, both FLC and PLZT materials for SLM used as shutters have been investigated.

2.1. Ferroelectric Liquid Crystals (FLC)

Since the ferroelectricity of chiral smectic C phase (C*) LCs was recognized and demonstrated in 1975 by Meyer [14], [15], FLCs joined the already rich family of ferroelectric materials as the ones retaining the fluid properties of LCs [16]. Unlike most other LCs with high symmetry, FLCs allow spontaneous polarization (P_s), which is the main characteristic of a ferroelectric [16]. Because of the existence of P_s, FLCs exhibit different EO properties compared with other LCs, such as very fast response speeds. The response time τ shown by a FLC cell when an electric field E is applied is [16]

$$\tau = \frac{\gamma}{P_s \cdot E'} \tag{1}$$

where γ is the rotational viscosity of the LCs. Fast FLCs possess low γ and high P_s. Using surface stabilized FLC (SSFLC) geometry, the response time τ can be as short as between 1 μs and 10 μs [17] because of high P_s and small SSFLC geometry were discovered by Clark and Lagerwall in 1980. The helix that makes the total polarization of FLCs average to zero is suppressed by using a cell gap that is less than the helical pitch (normally 1 μm–5 μm) and planar alignment techniques [17], [18]. The helix is unwound and the director, i.e. average molecule direction, is inclined to lie in the plane of the bounding plates. Because of this condition and the fact that the director is constrained to be at a certain angle, there are only two stable states, as illustrated in Fig. 1. In Fig. 1, the upper one is named as analyzer. When the applied electric field sign changes, the molecule rotates. The director rotated angle from the normal to one stable state is defined as tilt angle, θ. It was discovered that such an SSFLC cell can be switched rapidly between optically distinct, stable states simply by alternating the sign of an applied electric field [17]. SSFLCs can be used to make either displays or relatively fast shutters. Increasing temperature can reduce the viscosity and thus reduce the response time. Similarly, increasing the applied electric field also improves the response speed (1).

For a cell between two crossed polarizers with light incident normally to the bounding plates, and optic axis along one polarizer direction, extinction is always obtained. Upon rotating the optic axis by applying the electric field to rotate the director through an angle θ, a cell of thickness d produces a transmission T at wavelength λ to be [16]

$$T = \sin^2 4\theta \sin^2(\pi \Delta n d/\lambda) \quad (2)$$

where Δn is the birefringence. Increasing temperature normally reduces the tilt angle θ, which affects the transmission of the FLC cell. Therefore, there is a tradeoff between the switching speed and the achievable transmission by increasing the temperature. Similarly, there is also a limitation on the applied electric field because of the existence of the dielectric breakdown in LCs. The dielectric breakdown voltage depends on the alignment material, the liquid crystal phase, the cell thickness, and the field frequency [19]. The applied voltage must be less than the breakdown voltage.

The response time of the material determines the reconfiguration time of the SLM used as shutters, which significantly affects the switching performance. According to the simulation results [8], longer reconfiguration time of shutters generates more data loss and longer delay. In order to get the best switching performance, the reconfiguration time needs to be as fast as possible.

By measuring and comparing nearly a hundred LC cells with different LC mixtures and various thicknesses, a FLC mixture DRA2 turned out to be promising. DRA2 was developed as part of the (DTI)/LINK project (GR/K05641). It uses the difluoroterphenyl as a host and uses a chiral dopant to induce a high P_s in the difluoroterphenyls. DRA2 has a spontaneous polarization of 26 nC/cm^2. A DRA2 cell with the thickness of 1.5 μm was tested. At the temperature of 50 °C and the applied voltage of 12 V, the response time was 2.4 μs and the tilt angle was 20°.

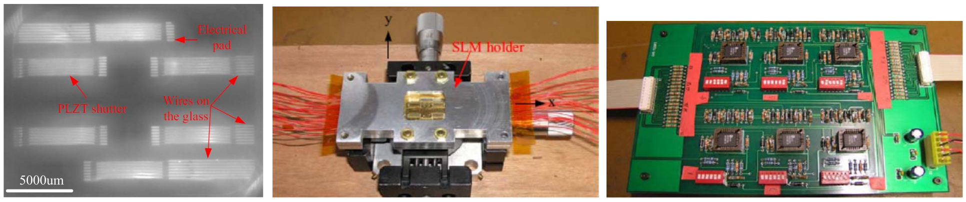
Electroclinic effect shown at the A*-C* transition of LCs is also attractive for applications in SLMs because its tilt angle is initially a linear function of the applied field and its response time can be as low as 100 ns [16]. The response time of the LCs in electroclinic mode is [16]

$$\tau = \frac{\gamma}{\alpha \cdot (T - T_C)'} \quad (3)$$

where T_C is the A*-C* transition temperature. α affects the restoring torque $(\alpha \cdot (T - T_C) \cdot \theta)$ required to restore the director back to the normal of the layer. A small α means a weak transition. By increasing the applied field, we can't reduce the switching time but we can continuously increase the induced tilt angle [16]. Felix-020, provided by Clariant in Japan, uses the FLC mixture in the electroclinic mode. It has a high P_s of 65 nC/cm^2 and exhibits sub-microsecond response time at a temperature of 50 °C with the applied voltage of 20 V/μm. Even though increasing the applied field can increase the tilt angle, it was still less than 6° at 40 V/μm. Another LC cell using R1305 electroclinic test mixture provided by Clariant has a P_s of 38 nC/cm^2. Its response time approaches half microsecond at a temperature of 55 °C with the applied electric field of 25 V/μm. Under this condition, the tilt angle was only 8°. The experimental phenomenon observed when the response times of these two LC cells approached 1 μs shows that the detected signal was extremely unstable and the amplitude of the detected signals became only 2% of the maximal value. Electroclinic LCs are therefore not appropriate for use in shutter-based switches, where the losses in the system (contributed by fan-out) are already significant.

2.2. Lead Lanthanum Zirconate Titanate EO Ceramic (PLZT)

The first transparent ferroelectric ceramics were developed in the form of the PLZT materials since 35 years ago [20] and up to the present day, a broad category of compositions ranging from those best suited for piezoelectric applications to those specifically designed for



(a) (b) (c)

Fig. 2. PLZT-based shutter device. (a) Magnified PLZT shutters. (b) PLZT-based shutter on its holder. (c) Driving board for PLZT-based shutters.

pyroelectric devices has been constituted by the PLZT ceramics. The high transparency and desirable EO properties have made them a well candidate for many applications such as "light shutters, coherent modulators, color filters, segmented displays, linear gate arrays and image storage devices" [13].

The PLZTs were first produced in transparent form as a result of efforts to increase the optical translucency of the conventional lead zirconate titanate (PZT) ceramics through the addition of chemical modifiers such as Barium (Ba), Stannum (Sn), Bismuth (Bi), and Lanthanum (La). Of these, La was found to be significantly better than all of the others in reducing light scattering, thus promoting transparency. The PLZT materials are composed of a wide range of homogeneous compositions existing within the basic lead zirconate (Zr)-lead titanate (Ti) solid solution system. The general formula describing the compositions La/Zr/Ti (x, y, 1-y) in the PLZT system is given by [21], [22]

$$\mathrm{Pb}_{1-x}\mathrm{La}_x(\mathrm{Zr}_y\mathrm{Ti}_{1-y})_{1-x/4}\mathrm{O}_3. \tag{4}$$

Normally, the compositions of PLZT are represented by the ratio of La/$PbZrO_3$/$PbTiO_3$. In the La range from 8~16 atom percent, the composition ratio of $PbZrO_3$/$PbTiO_3$ equals to 65/35 are most transparent [13]. The compositions equal to 8.8–9.5/65/35 in PLZT-based device have widely employed in a variety of optoelectronic applications such as high-speed scanning, dynamic lenses, eye-protection devices [23], optical switches [24], and optical shutters [25].

PLZT's large EO effect, fast operation capabilities [25], [26], high contrast, high resolution, good temperature stability and availability of high quality material [13] make it an attractive material to act as shutters in EO switching devices. In such devices, PLZT is used in the same way as FLCs, set between two crossed polarizers, and, if external voltage is applied properly, it can rotate the incoming wave polarization so that it propagates through both polarizers. Thus, by turning the external voltage on and off, one can create the phenomenon of optical switching. Many PLZT based switches and shutters have been presented in the past [22], [24], [25], [27], [28] but have mainly been composed of small pixels in the scale of few micrometers in a low switching dimension. Since the material has a naturally isotropic structure, the electrode pair may be placed at any orientation on the plate surfaces. The orientation of the polarizer vibration directions are critical and must be 45° to the induced polarization direction in order to achieve maximum effect [13].

In our design, the La/Zr/Ti composition of the PLZT equal to (9/65/35) was chosen. The reason that PLZT (9/65/35) for shutters was chosen is due to its large quadratic EO coefficient and broadband optical transmission range [13]. Fig. 2(a) shows six magnified PLZT shutters and each shutter consists of six strips (pixels). Each strip (pixel) is 200 μm wide and 5000 μm long with a gap of 250 μm between them. The gaps contain electrodes which drive the electric fields across each PLZT strip (pixel) independently. This PLZT device has a depth of 300 μm which provides a phase retardation of π at an appropriate applied voltage.

For the application of PLZT shutters in optical switch, the PLZT shutter was set between two crossed polarizers to perform amplitude modulation. The PLZT-based shutters on a custom designed holder is illustrated in Fig. 2(b) as well as its driving board that will be discussed in next section is illustrated in Fig. 2(c). The polarization of the input light was at an angle of 45° with respect to the long or short axis of the PLZT pixel. The external voltage was applied to rotate the

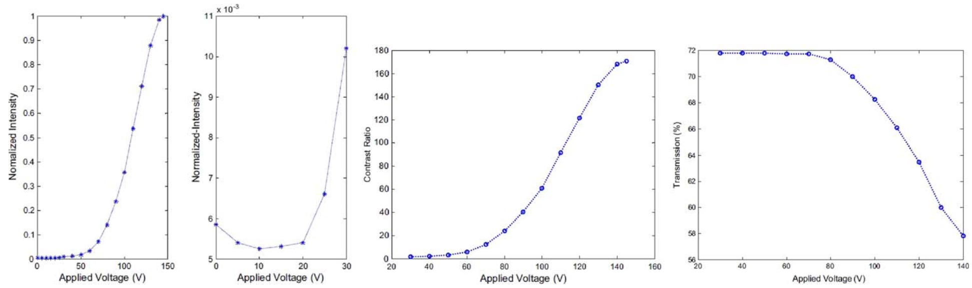


Fig. 3. Optical characteristics of PLZT at room temperature. (a) Normalized light intensity versus applied electric field. (b) Contrast ratio versus applied electric field. (c) Optical transmission versus the applied electric field.

incoming light polarization so that the light can pass through the analyzer. The experimental setup for the characteristic measurement of PLZT-based shutters is the typical configuration for using EO devices as illustrated in Fig. 1(b). The following measurements were carried out using this setup except the transmission measurement, in which the polarizers were not used.

The measurement results are shown in Fig. 3. Fig. 3(a) shows that the output light intensity of the PLZT increases linearly with the amplitude of the applied electric field [26]. However, under zero voltage there is no total darkening in crossed polarizers since there is some optical noise and optical non-uniformity of the pixels. Under low voltage of approximately 10 V, darkening is improved, and optical non-uniformity disappeared.

Since the contrast ratio is defined as I_v/I_{10}, total darkening is critical to get high contrast ratio. Fig. 3(b) shows that with increasing applied electric filed, the contrast ratio increases. However, the internal scattering and saturation of the EO effect are enhanced [23], resulting in the transmitted optical power to decrease as shown in Fig. 3(c). The OFF condition of the PLZT strips greatly determines the contrast ratio that is ultimately achieved. It is primarily dependent on two factors: the quality of the polarizers and the quality of the PLZT. Today's high efficiency polarizers are able to yield a contrast ratio of greater than 100 000 to 1. This value is, however, reduced to something less, depending on the quality of the PLZT. If there are defects in the PLZT (mottling, stars, and stress centers) which can cause light leakage due to scattering, depolarization or unintentionally-induced birefringence under polarized light, the OFF condition will be substantially degraded. This can be mitigated by having a high quality PLZT [13].

Although the PLZT shutters have a fundamental characteristic that a higher driving voltage might be required in order to reach the full ON state, a high contrast ratio in excess of 5000/1 can be achieved since a good OFF state (less than 0.0007 percent) can be produced with high efficiency polarizers [13]. In our measurements, the rise and fall time were defined as the time taken for the detected intensity changed from 10% to 90% and from 90% to 10%, respectively. Since the rise time decreased with increasing applied electric field [29], a rise time of 1 us was measured under an applied voltage of 120 V. Although a greater voltage can be used to shorten the rise time, the probability of electrical breakdown will be increased. In order to apply PLZT device in an optical switch, a driving approach composed by a simple and effective circuit to make a small input signal ride on a large DC voltage was designed and will be discussed in the next section.

3. Driving Circuit Design For PLZT-Based Shutters

Since Electroclinic LCs have been found that they are not appropriate to use as SLM to act as shutters in free-space optical switches from our research, PLZT material was selected for SLM to act as shutters. However the major problem of PLZT device is that a high driving voltage might be required in order to reach a full ON state. In this section, a driving circuit design based on a push-pull amplifier circuit which can make a small input signal ride on a large DC voltage for PLZT device to act as shutters in a free-space optical switch is reported.

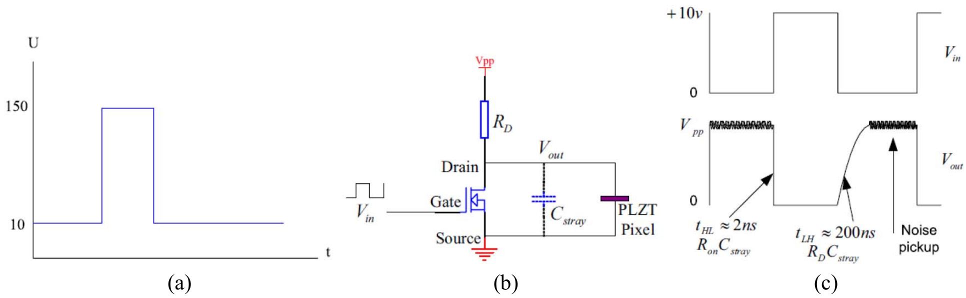


Fig. 4. PLZT driving voltage and a single MOSFET circuit. (a) PLZT shutter driving voltage. (b) Single MOSFET amplifier circuit. (c) Problems of single MOSFET circuit (R_{ON}: Resistance of the MOSFET in the ON state).

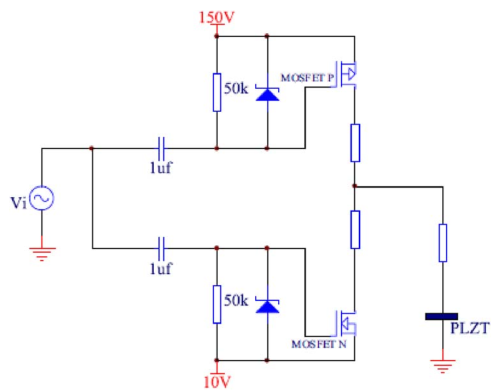


Fig. 5. PLZT pixel using push-pull configuration.

As discussed previously, darkening of PLZT-based shutters can be improved under a low voltage of 10 V. In order to realize the maximum contrast ratio, the driving voltage shown in Fig. 4(a) should be used. The simplest circuit to realize this driving voltage is to use one MOSFET as illustrated in Fig. 4(b) to construct an amplifier. However, this circuit has the disadvantage of drawing current in the ON state and having relatively high output impedance in the OFF state. The problem with high output impedance is capacitive noise pickup, and the reduced switching speeds [30] as illustrated in Fig. 4(c). In addition, if the Source end of the MOSFET is not connected to ground but to a positive voltage, a special signal source (V_{in}) must be designed to ensure $V_T < V_{\text{GS}_{\max}} < V_{\text{BK}}$, where $V_{\text{GS}_{\max}}$ is the maximum Gate-to-Source voltage, V_{BK} is the Gate-to-Source breakdown voltage, and V_T is the gate threshold voltage. If the source voltage is changed to another value, the signal source V_{in} should be re-designed accordingly.

The solution is to use a push-pull configuration and an AC coupling at the Gate as illustrated in Fig. 5. When a signal is coupled to an amplifier, an AC coupling, which acts as a high-pass filter as illustrated in Fig. 6, is often used since this is a simple and effective method to make a small signal ride on a large DC voltage [30]. The output impedance of the push-pull configuration is low in both ON state and OFF state, which means faster rise time, good noise rejection, and high driving ability. This configuration is the basic structure of all digital CMOS logic [30].

In a high-pass circuit, if the input signal V_{in} jumps from 0 to V_i, the voltage across the capacitor C is $V_c = V_i(1 - e^{-t/RC})$, and the voltage across the resistor is

$$V_{\text{out}}(t) = \begin{cases} \int_{0^-}^{t} \exp\left(\frac{x}{RC}\right) \times \frac{dV_{\text{in}}(x)}{dx} dx + A, & \text{if } 0^- \leq t \leq 0^+ \\ V_i \exp\left(-\frac{t}{RC}\right), & \text{if } t \geq 0^+ \end{cases} \quad (5)$$

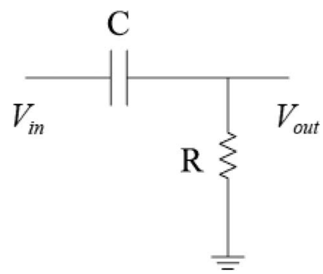


Fig. 6. High pass circuit.

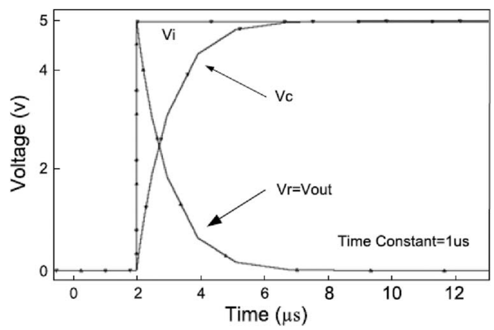


Fig. 7. PSPICE simulation of high-pass circuit.

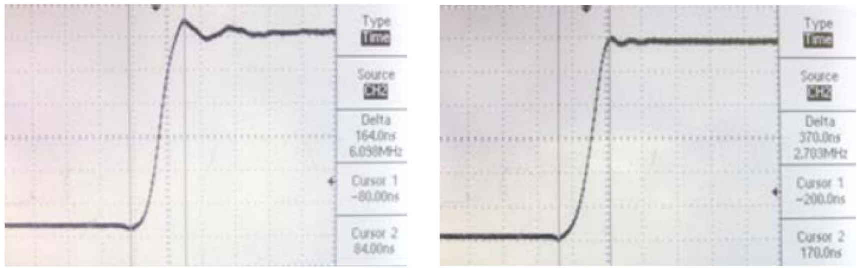
When V_{in} changes from 0 (at the time of 0^-) to V_i (at the time of 0^+), the voltage across the resistor jumps from 0 to V_i during the transition of V_{in} before the capacitor is charged. This is consistent with the theory that at the transition of V_{in}, the change in voltage across the capacitor should be zero [30]. Therefore, the rise time of the output voltage (across the resistor) is not controlled by the time constant but it follows the rise time of the input V_{in}. As long as the rise time of the input signal is fast enough, the output of this high-pass circuit is also fast. The PSPICE simulation result in Fig. 7 shows that the voltage across the resistor decreases exponentially and the voltage across the capacitor increases exponentially according to the time constant.

The rise time of this push-pull amplifier circuit is also affected by the rise time of the MOSFET itself. Therefore, a fast MOSFET supporting high voltage from Supertex Inc. was used in this driving circuit. The typical rise time of this type of MOSFET is 16 ns with drain current of 1 A, but if the drain current is reduced, the rise time becomes longer. Since the drain current is proportional to $V_{GS} - V_T$, V_{GS} will determine the rise time of the output. From the measurement results as shown in Fig. 8, with $V_{GS} = 5$ V, the full rise time was 340 ns and with $V_{GS} = 7.5$ V, the full rise time was reduced to 164 ns.

With the use of this simple push-pull amplifier circuit which can make a small signal ride on a large DC voltage, this PLZT device can be easily applied into an optical switch. Although the power consumption problem of this PLZT device resulted from a high driving voltage was not investigated in our research, it can be easily improved through a general boost converter which can be used to raise a small input DC voltage i.e., 10 V to a required higher driving voltage i.e., 150 V for PLZT device.

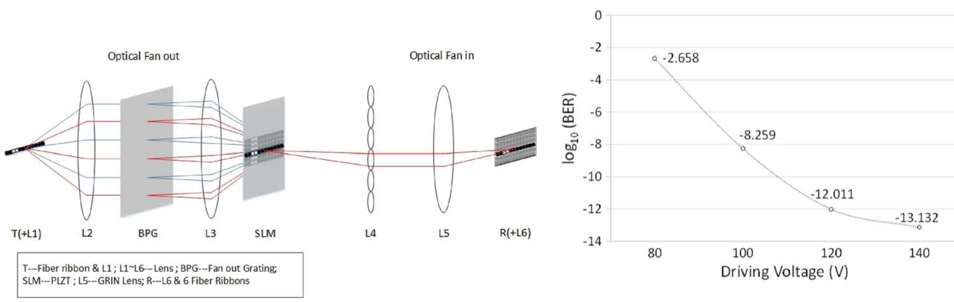
4. Fiber Array Switching Properties of PLZT-Based Shutters

In order to further investigate the fiber array switching properties of the PLZT shutters based on a type of strips in optical fiber switching architecture, a proof of concept 1 × 6 optical fiber ribbon switch as illustrated in Fig. 9(a) was experimentally implemented. In this switching architecture, data switching between one input and six output optical fiber ribbons which forwards



(a) (b)

Fig. 8. Driving speed with different gate-to-source voltage. (a) $V_{GS} = 7.5$ V and full rise time = 164 ns. (b) $V_{GS} = 5$ V and full rise time = 370 ns.



(a) (b)

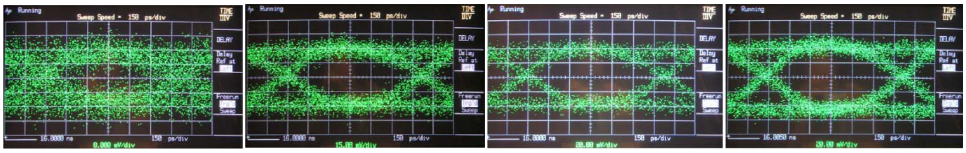
Fig. 9. Proof of concept 1 × 6 optical fiber ribbon switch and its switching properties at GbE link speed. (a) Switching architecture. (b) BER and driving voltage on PLZT-based SLM.

data arriving from one location to six destinations, as a group can be realized. Although this experimental demonstration was only based on a 1 × N switching architecture, it can be scaled up to a $N \times N$ switching architecture. By using 12 fibers per ribbon as a group of a switching unit, the switch capacity will be enhanced dramatically and the complex of the interconnection points within the switch will be simplified. This is a well switching core suitable for data center network application as the switching paths are a known number and the functionality of multicast transmission is required.

The 12 fibers of optical fiber ribbon used were multimode fibers (62.5 um core diameter) in a row with a fiber spacing of 250 μm between the centers of adjacent fibers and was mounted by a mechanically transferable (MT) connector style optical package.

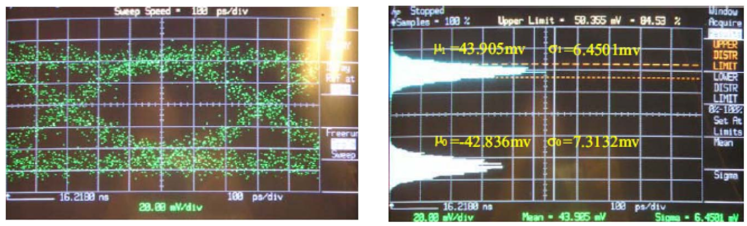
A 12 × 2.7 Gb/s parallel fiber optic link transmitter [31] was used to transmit a 12 parallel channel of optical signals for the switch. This transmitter has a 12 parallel channel of 850 nm VCSEL array interfaced with an industry standard multi-fiber push on (MPO) ribbon fiber connector. The most important subsystem of the switch is the optical fan-out system (multicast transmission) which includes a binary phase grating (BPG) component and a 4f-based optical system. The function of optical fan-out (multicast) within the switch was performed through a BPG element set between L2 and L3 in a 4f-based optical system to replicate input data from optical fiber ribbons onto the shutter. The PLZT-based shutter was set between a polarizer and an analyzer to perform amplitude modulation in this switch. Another 4f optical system composed of L4 and L5 was used to perform optical fan-in from PLZT-based shutter to any of six output fiber ribbons.

The fiber array switching property measurement of the PLZT shutters based on a type of strips in the implemented optical fiber ribbon switching system was performed at different driving voltage ranged from 80 V to 140 V at a link speed of 1 Gb/s and above i.e., 1.6 Gb/s, respectively. In this switching property measurement, a pulse pattern generator (Anritsu MP1650A) was used to generate input pseudo random coded data with an equal probability of a "1" and "0." These



(a) (b) (c) (d)

Fig. 10. Switching properties under different driving voltages on the SLM at a link speed of 1 Gb/s. (a) 80 V. (b) 100 V. (c) 120 V. (d) 140 V.



(a) (b)

Fig. 11. Switching properties of the SLM at a link speed of 1.6 Gb/s. (a) Eye diagram. (b) Histogram.

electrical signals were converted to optical signals through VCSEL module and were transmitted through optical fiber ribbon switch to the output fiber ribbons. Due to the weak power of the received optical signals from output fiber ribbons at a photo-receiver (Newfocus 1544B), an amplifier (HP 8447E) was used after the receiver and its output was connected to an HP 54120b oscilloscope through a low-pass filter. The BERs of this optical fiber ribbon switching system were estimated directly through the calculation of Q factors given by [32] according to the measurement results of eye diagrams

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}} \tag{6}$$

where the Q-factor is expressed as

$$Q = \frac{I_1 - I_0}{\sigma_0 + \sigma_1} \tag{7}$$

where I_1 and I_0 are the means of the amplitude histograms at logic one and logic zero levels, respectively. σ_0 and σ_1 are the standard deviations of the amplitude histograms at logic zero and logic one levels, respectively.

It has been discussed in Section 2 that the contrast ratio of the PLZT shutter will be improved (refer to Fig. 3), when the PLZT driving voltage increased. This phenomenon was reflected in the switching performance. Fig. 9(a) gives a direct relation between the BER and the driving voltage of shutters. When the driving voltage equals to 100 V and above, the BER estimated from the Q-factor were all less than 10^{-9} and the jitters were all less than 7.35%. Fig. 10 shows the eye diagrams measured under different driving voltages on the strips of PLZT shutter. It illustrates that with the decreasing applied voltage, the eye diagrams became smaller and blurred. That results in the increase of the BER and the jitter. The switching properties was also further investigated at a higher data link speed over GbE link i.e., 1.6 Gb/s and the measurement results (when a driving voltage of 140 V was applied on the strips of PLZT shutter) are illustrated in Fig. 11. According to the eye diagrams measured, the estimated BER from Q-factor was 1.47×10^{-10}, and the jitter was 7.07%.

5. Conclusion

Shutter-based free-space optical fiber switching technology is a promising optical fiber switching technology for data center network application since it is capable of multicast transmission and the switching performance can be significant improved while new materials are used as shutters to raise the switching speed. In this paper, Electroclinic LCs and PLZT materials used as SLM to act as shutters based on a type of strips for free-space optical fiber ribbon switch have investigated and the results shown that PLZT material are more appropriate than Electroclinic LCs as it has a faster response time less than sub-microsecond. Although the PLZT device has a fundamental characteristic that a higher driving voltage might be required, with the use of a simple push-pull amplifier circuit which can make a small signal ride on a large DC voltage, this PLZT device can be easily applied into an optical switch. Although the power consumption problem of this PLZT device resulted from a high driving voltage was not investigated in our research, it can be easily improved through a general boost converter which can be used to raise a small input DC voltage i.e., 10 Volts to a required higher driving voltage i.e., 150 Volts for PLZT device. A proof of concept 1×6 shutter-based free-space optical fiber ribbon switch has experimentally implemented to evaluate the fiber array switching performance of the PLZT shutters based on a type of strip. Our research work reported is distinguished with those of PLZT shutters and PLZT based switches that have been presented in the past, since each pixel of our PLZT shutters can be used to switch fiber array simultaneously rather than using several pixels to switch only one single fiber/channel. This dramatically provides an alternative approach to enhance the data center network performance and would be advantageous over the other currently available switches which are majority based on single fiber/channel to single fiber/channel switching. Our experimental results shown that the BERs estimated from the Q-factor were all less than 10^{-9} and that the jitters were all less than 7.35% under a variety of shutter driving voltages at a link speed of 1 Gb/s and above. Although our experimental demonstration was only based on a $1 \times N$ switching architecture, it can be further scaled up to a $N \times N$ switching architecture easily.

References

[1] R. Van Caenegem *et al.*, "From IP over WDM to all-optical packet switching: Economical view," *J. Lightw. Technol.*, vol. 24, no. 4, pp. 1638–1645, Apr. 2006.

[2] J. P. Jue, W.-H. Yang, Y.-C. Kim, and Q. Zhang, "Optical packet and burst switched networks: A review," *IET Commun.*, vol. 3, no. 3, pp. 334–352, Mar. 2009.

[3] R. Ramaswami, K. N. Sivarajan, and G. Sasaki, *Optical Networks: A Practical Perspective*, 3rd ed. San Francisco, CA, USA: Morgan Kaufman, 2010.

[4] H. Q. Ngo, D. Pan, and C. Qiao, "Constructions and analyses of non-blocking WDM switches based on arrayed waveguide grating and limited wavelength conversion," *IEEE/ACM Trans. Netw.*, vol. 14, no. 1, pp. 205–217, Feb. 2006.

[5] V. A. Aksyuk *et al.*, "Beam-steering micromirrors for large optical cross-connects," *J. Lightw. Technol.*, vol. 21, no. 3, pp. 634–642, Mar. 2003.

[6] T. Yamamoto *et al.*, "A three-dimensional MEMS optical switching module having 100 input and 100 output ports," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1360–1362, Oct. 2003.

[7] W. A. Crossland *et al.*, "Holographic optical switching: The 'ROSES' demonstrator," *J. Lightw. Technol.*, vol. 18, no. 12, pp. 1845–1854, Dec. 2000.

[8] T. D. Wilkinson, W. A. Crossland, N. Collings, F. Zhang, and M. Fan, "Reconfigurable free-space optical cores for storage area networks," *IEEE Commun. Mag.*, vol. 43. no. 3, pp. 93–99, Mar. 2005.

[9] J. Goodman, *Introduction to Fourier Optics*. New York, NY, USA: McGraw-Hill, 1968.

[10] J. A. Neff, R. A. Athale, and S. H. Lee, "2-dimensional spatial light modulators—A tutorial," *Proc. IEEE*, vol. 78, no. 5, pp. 826–855, May 1990.

[11] [Online]. Available: http://holoeye.com/spatial-light-modulators/slm-pluto-phase-only/

[12] J. S. Patel and J. W. Goddby, "Properties and applications of ferroelectric liquid crystals," *Opt. Eng.*, vol. 26, no. 5, pp. 373–384, May 1987.

[13] G. H. Haertling, "PLZT electrooptic materials and applications—A review," *Ferroelectrics*, vol. 75, no. 1, pp. 25–55, Sep. 1987.

[14] R. B. Meyer, L. Liebert, L. Strzelecki, and P. Keller, "Ferroelectric liquid crystals," *J. Phys.-Lett.*, vol. 36, no. 3, pp. 69–71, 1975.

[15] R. B. Meyer, "Ferroelectric liquid crystals: A review," *Mol. Cryst. Liquid Cryst.*, vol. 40, no. 1, pp. 33–48, Jan. 1977.

[16] J. W. Goodby *et al.*, *Ferroelectric Liquid Crystals Principles, Properties and Applications*. New York, NY, USA: Gordon and Breach, 1992.

[17] N. A. Clark and S. T. Lagerwall, "Submicrosecond electro-optic switching in liquid crystals," *Appl. Phys. Lett.*, vol. 36, no. 11, pp. 899–901, Jun. 1980.
[18] N. A. Clark and S. T. Lagerwall, "Surface stabilized ferroelectric liquid crystal devices," U.S. Patent 4563059, Jan. 7, 1986.
[19] I. Dierking, "Dielectric breakdown in liquid crystals," *J. Phys. D, Appl. Phys.*, vol. 34, no. 5, pp. 806–813, Mar. 2001.
[20] G. Haertling and C. Land, "Hot-pressed (Pb, La)(Zr, Ti)O_3 ferroelectric ceramics for electrooptic applications," *J. Amer. Ceram. Soc.*, vol. 54, no. 1, pp. 1–10, Jan. 1971.
[21] D. Dimos, "Ferroelectric thin films for photonics: Properties and applications," *Annu. Rev. Mater. Sci.*, vol. 25, pp. 273–295, Aug. 1995.
[22] Y. Sampei, S. Naito, and Y. Kurita, "PLZT fiber-optic switch," *J. Lightw. Technol.*, vol. 5, no. 9, pp. 1203–1206, Sep. 1987.
[23] P. E. Shames *et al.*, "Modeling of scattering and depolarizing electro-optic devices I. Characterization of lanthanum-modified lead zirconate titanate," *Appl. Opt.*, vol. 37, no. 17, pp. 3726–3734, Jun. 1998.
[24] T. Utsunomiya, "Optical switch using PLZT ceramics," *Ferroelectrics*, vol. 109, no. 1, pp. 235–240, Sep. 1990.
[25] M. J. Landry and A. E. McCarthy, "Transmission switching characteristics of PLZT shutters," *Appl. Opt.*, vol. 12, no. 10, pp. 2312–2319, Oct. 1973.
[26] D. Goldring, Z. Zalevsky, E. Goldenberg, A. Shermer, and D. Mendlovic, "Optical characteristics of the compound PLZT," *Appl. Opt.*, vol. 42, no. 32, pp. 6536–6543, Nov. 2003.
[27] J. T. Cutchen, J. O. Harris, and G. R. Laguna, "PLZT electrooptic shutters: Applications," *Appl. Opt.*, vol. 14, no. 8, pp. 1866–1873, Aug. 1975.
[28] F. S. Chen, "Evaluation of PLZT ceramics for applications in optical communications," *Opt. Commun.*, vol. 6, no. 3, pp. 297–300, Nov. 1972.
[29] Y. Fogel, N. Bar-Chaim, and A. Seidman, "Longitudinal electrooptic effects in slim-loop and linear PLZT ceramics," *Appl. Opt.*, vol. 19, no. 10, pp. 1609–1617, May 1980.
[30] P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 1989.
[31] [Online]. Available: http://www.zarlink.com
[32] G. P. Agrawal, *Lightwave Technology Telecommunication System*. Hoboken, NJ, USA: Wiley, 2005.