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## Photonic delay lines using polarization-selective holograms for optical signal routing

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# Photonic Delay Lines Using Polarization Selective Holograms for Optical Signal Routing

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## ABSTRACT

The use of polarization selective holograms for the implementation of photonic delay lines (PDLs) is proposed. A single bit PDL using FLC devices as active polarization switches and polymer dispersed liquid crystal (PDLC) devices as polarization selective optical path routing components is experimentally demonstrated and characterized. Different within-channel leakage noise filters are discussed and experimentally demonstrated, and high signal-to-leakage noise ratios (>45 dB) are obtained for both PDL settings.

**Keywords:** Phased array antennas, polarization-selective holograms, polymer dispersed liquid crystal (PDLC), ferroelectric liquid crystal (FLC), photonic beamformer, delay lines, microwave radar.

## 1. INTRODUCTION

In the recent years, several photonic delay lines (PDLs) based on various optoelectronic technologies have been proposed<sup>1</sup>. PDL applications include phased array antennas, laser radars<sup>2</sup>, astronomy<sup>3</sup>, ultrasound<sup>4</sup> and two-photon memories<sup>5</sup>. During the last few years, we have concentrated our work on the implementation of N-bit PDL systems using electrically controlled polarization switching devices such as nematic liquid crystal (NLC)<sup>6</sup> and ferroelectric liquid crystal (FLC) devices<sup>7</sup>. These PDLs use passive polarization components such as cube polarization beam-splitters and beam-combiners for optical signal routing.

A new promising technology for optical signal routing is polarization-selective holograms (PSHs). PSHs are optical elements capable of acting with an arbitrary independent phase function depending on the state of polarization of the incident light. Fixed PSHs can be recorded on organic dyes<sup>8</sup>, dichromated gelatin<sup>9</sup>, and photorefractive crystals<sup>10</sup>. Birefringent computer generated holograms have also been reported<sup>11</sup>. Other polarization dependent beam routing elements can be implemented using nematic liquid crystal materials<sup>12</sup>.

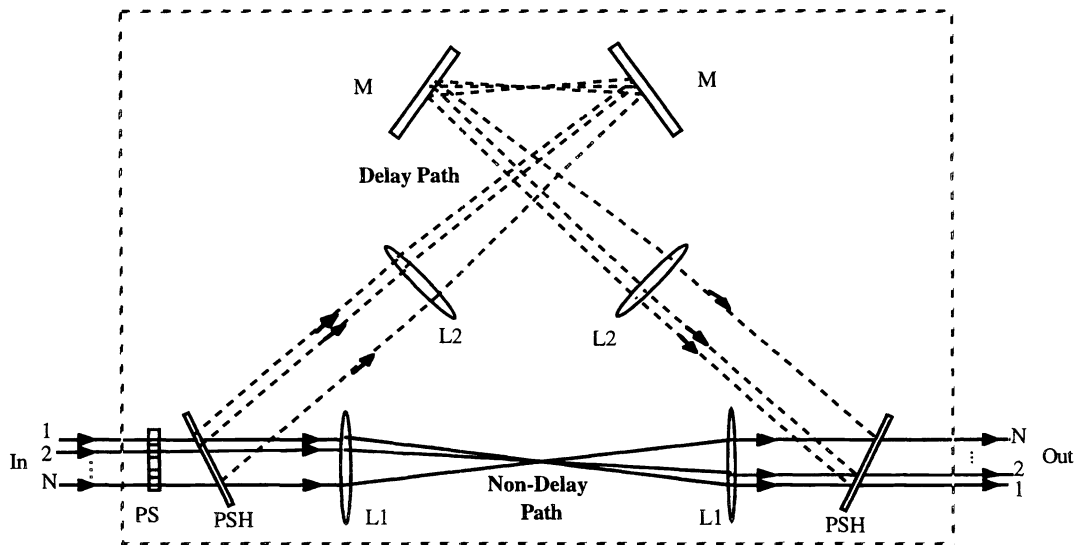
This paper describes the basic workings of a PSH-based switched PDL. A PSH device can be fabricated using any of the technologies mentioned in the previous paragraph. A proof of concept experiment for the characterization of such a PDL is also presented. The PSHs used in our experiment are based on polymer dispersed liquid crystals (PDLCs). The basic operation of a PDLC device is as an active holographic element whose diffractive power can be electrically modulated. Interest in PDLC devices for delay lines has been recent as proposed by us<sup>13, 14</sup> and others<sup>15</sup>. Previously, we have shown how PDLC devices can act as both active polarization switches and beam routers and combiners to form low component count PDLs<sup>14</sup>. In this paper, we do not electrically modulate the PDLC diffractive power to form a polarization switch. Instead, the PDLC devices are used as fixed PSHs to form beam routers and combiners. A feature of our proposed PDL is that it uses 2-D polarization switching arrays and single large area PSHs. This makes the PDL implementation an easier task because of the current mature liquid crystal technology that can give high pixel count, low cost 2-D flat panel switching arrays.

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## 2. THE POLARIZATION SELECTIVE HOLOGRAM-BASED SWITCHED PDL

The proposed PSH-based PDL is shown in Fig. 1. An array of linearly polarized collimated laser beams enters the PDL system. The polarization switch (PS) array controls the state of polarization (SOP) of the individual beams. When the switch is set in its “on” state it rotates the incident polarization by 90°. On the other hand, when the PS is set in its “off” state it leaves the incident polarization unaffected.



**Figure 1:** A single bit of the proposed photonic delay line based on polarization switching devices and polarization selective holograms. Dashed lines: delay path; Solid lines: non-delay path; PS: polarization switch; PSH: polarization selective hologram; M: mirror; L: lens.

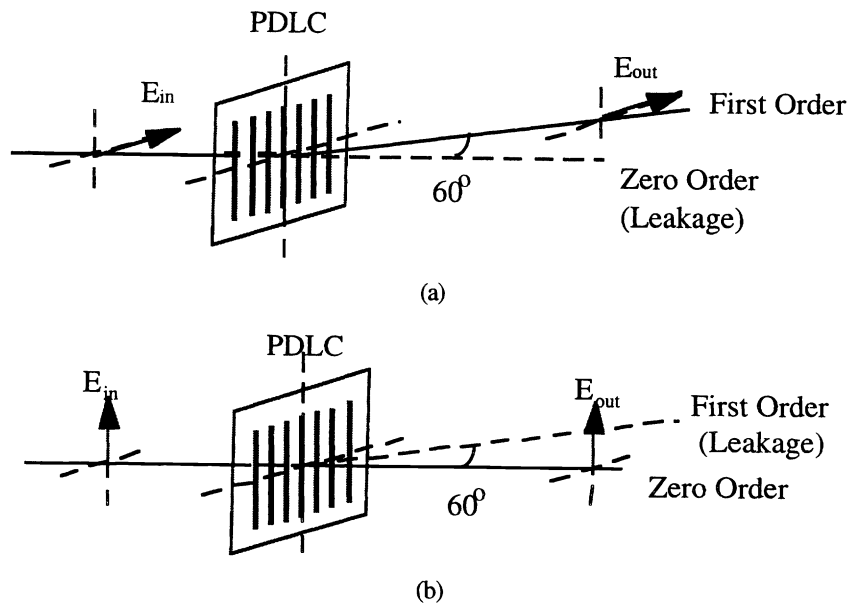
Depending on the SOP of the beams, the PSH either deflects the beam at a specific and predefined angle or leaves the incident beam to pass straight through. Hence, in the first case, the optical signal follows the delay path, and after reflection from the two mirrors (M) it passes through the second PSH. Note that in any single bit PDL module, the two paths have to be combined before the beam exits the module. This is because single bit modules are cascaded to form the N-bit PDL. As seen in Fig. 1, we use a PSH device for this important 2:1 recombination operation. In the second case, the light travels unaffected through the two PSHs towards the output of the PDL bit. Imaging lenses can be used in the PDL system to minimize the interchannel crosstalk<sup>16</sup>.

## 3. BASIC CHARACTERISTICS OF THE POLYMER DISPERSED LIQUID CRYSTAL DEVICES

Researchers have recently been studying the electro-optic characteristics and applications of PDLCs<sup>17-21</sup>. The basic operation of PDLC devices is as an active holographic element whose diffractive power can be electrically modulated. Hence, PDLC devices have been used as light valves for displays<sup>18</sup>, and as switchable diffractive elements for optical beam steering, holographic read only memories (ROMs), and switchable focus lens applications<sup>17, 20</sup>. The PDLC electrically switched gratings are based on a photopolymer holographic recording material whose microstructure after processing contains a distribution of sub-micron pores corresponding to a variation of refractive index<sup>22</sup>. The porosity permits birefringent liquid crystals to be infused into the material, filling the empty spaces. The index modulation creates a grating that strongly diffracts light into the first order. By reorienting the liquid crystal molecules in an electrical field, the pores gain an effective refractive index. This applied electrical field is of the order of ~200-400 V across a 8 μm thick material. This is a rather high voltage and it is currently limited due to the large surface interaction of liquid crystal molecules in the sub-micron pores<sup>22</sup>. If the electrically controlled pore refractive index matches the index of refraction of the host polymer, the index modulation vanishes and thus the grating also vanishes. Light then travels straight through the device without any deflection. When the applied voltage is removed, the liquid crystal molecules reorient back to their initial state, again creating an index modulation and

thus a grating. Hence, the PDLC device diffracts light to a predefined direction for one of its states and leaves the light unaffected for the other state.

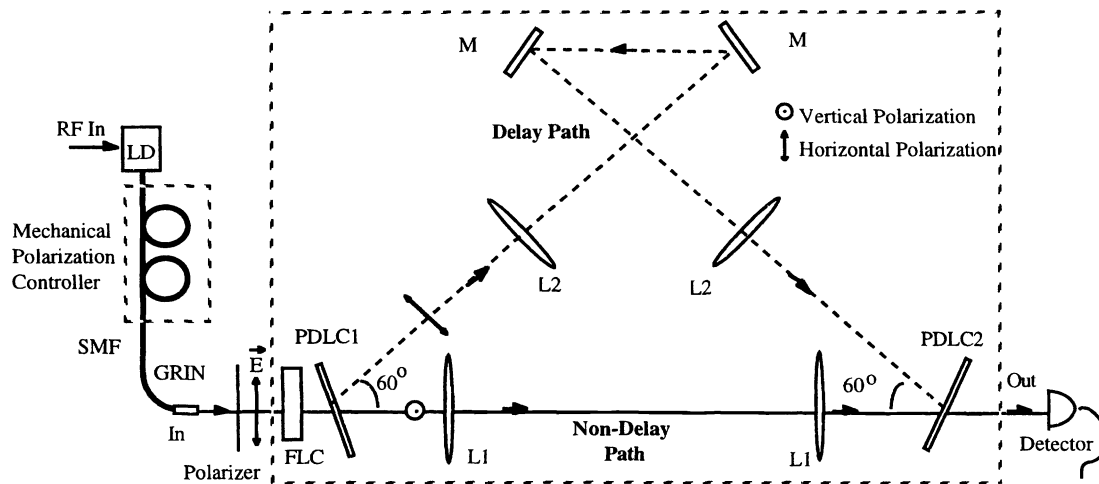
Note that because of the liquid crystal birefringence, the grating can be polarization sensitive. This is possible when the right combination of photopolymer and liquid crystal material is used and the LC is infused into the photopolymer pores has the molecules aligned such that with no electric field applied across the PDLC device, the PDLC acts as a grating for one polarization, and as a glass plate for the other orthogonal polarization. This happens because in the first case the light “sees” an index modulation formed by the index of refraction of the photopolymer and that of the liquid crystal. On the other hand, for the orthogonal polarization, the light does not “see” any index variation since the photopolymer and the liquid crystal refractive indices have the same value. In our experiments, we used two PDLC based gratings fabricated by Foster-Miller, Inc. When the incident polarization is along the grating fringe direction, the PDLC devices diffract the light at an angle of  $60^\circ$  with respect to the zero order beam (for our PDLC devices this happens for horizontal polarized light) (see Fig. 2). On the other hand, if the incident polarization is perpendicular to the grating fringe direction (i.e., vertical polarization), the light passes through the PDLC unaffected (Fig. 2).



**Figure 2:** The PDLC as a polarization selective hologram (a) horizontally polarized input “see” the grating and is deflected into the first order, (b) vertically polarized input does not “see” the grating and passes through unaffected.

#### 4. EXPERIMENTAL DEMONSTRATION OF THE POLARIZATION SELECTIVE HOLOGRAM-BASED PHOTONIC DELAY LINE

Fig. 3 depicts the experimental set-up for our proposed PSH based PDL. A Lasertron model QLINK1-051 microwave fiber-optic transmitter ( $\lambda=1310\text{nm}$ ) is used as the laser source. The modulated light is coupled into the PDL via a single mode fiber (SMF) connectorized to a gradient index (GRIN) lens. A mechanical fiber-optic polarization controller is used to make the input polarization horizontal. A high extinction ratio (10,000:1) polarizer is also used to suppress any polarization leakage at the other orthogonal state. A FLC device is used as a polarization switch. This switch acts as an electrically controlled half wave plate. When the switch is set “off”, the SOP of the light does not change. As mentioned earlier, the PDLC device diffracts the light when the incident polarization is along the grating fringe direction. Hence, the horizontally polarized light “sees” the grating and is diffracted at  $60^\circ$  with respect to the zero order beam. After reflection from the mirrors, the light hits the second PDLC device with an angle of  $60^\circ$  with respect to the non-delay path. The light is then diffracted towards the output of the PDL. On the other hand, when the switch is set “on”, the polarization of the light rotates by  $90^\circ$ . Hence, the light does not “see” the grating in PDLC1 device and passes straight through towards the PDLC2 device that also acts as a flat glass plate for the vertically polarized light. Thus, the input light propagates towards the output port of the PDL.



**Figure 3:** The experimental set-up of the proposed PDL using a FLC device as a polarization switch and PDLC devices as polarization selective holograms. Dashed lines: delay path; Solid lines: non-delay path; SMF: Single mode fiber; RF: radio-frequency.

### 5. LEAKAGE NOISE MEASUREMENTS AND SYSTEM IMPROVEMENTS

An important issue of our PDL is the optical signal-to-leakage noise ratio (SNR). The optical SNR is defined as  $10\log(\text{signal power}/\text{leakage noise power})$ . As signal, we define the optical power in the optical beam that travels through the desired delay or non-delay path of the module; all other optical power measured at the output is regarded as leakage noise optical power. Note that the optical SNR is a measure of the leakage noise in the system due to the non-optimized PDLC diffraction efficiency as well as leakage from the FLC switch.

Optical SNR measurements were obtained by independently measuring the signal and leakage noise of each PDL setting at the output of the PDL bit. For example, for the delay setting, the noise was measured by physically blocking the signal traveling through the delay path, while the signal was measured by physically blocking the noise traveling through the non-delay path. The optical signal was detected at the output of the PDL bit using a large area detector (1 mm in diameter) and a power meter. Table 1 shows the optical SNR for the non-delay and delay setting of our PDL.

**Table 1:** Optical SNR measurements for the two PDL settings (without noise filter).

PDL Setting	Optical SNR without noise filter (dB)
Non-delay	22.0
Delay	16.7

These optical SNR numbers are rather limited. There are two reasons for this limited PDL performance. The first reason is that PDLC devices are not 100% efficient. For example, the PDLC1 device diffracts some part of the vertically polarized signal into the delay path, and some of the horizontally polarized light into the non-delay path. This ends up to be part of the leakage noise at the output of our PDL. We will be referring to this noise as PDLC-based leakage noise. The second source of noise in our system is the FLC device and its limited on/off performance. We have seen that today's FLC devices do not fully rotate the incident polarization by  $90^\circ$  when they are set "on"<sup>23</sup>. This means that unwanted horizontal polarization leakage propagates through the delay path and contributes to the output leakage noise. Moreover, when the FLC device is set "off" it does degrade the SOP of the incident polarization and thus a vertical component leaks through the non-delay path. We will be referring to this noise as FLC switch-based leakage noise. Optical SNR numbers of  $> 30$  dB are required for most PDL applications. Thus, a way of improving the system performance is necessary. Two different ways of improving the system performance were tested and are discussed in the following paragraphs.

### 5.1 Passive Leakage Noise Filter

As mentioned in section 5, one source of the leakage noise is the PDLC devices. This limitation is related with not getting high enough diffraction efficiencies from the PDLC devices. This is a fabrication process limitation and can be improved by careful fabrication techniques. For our PDLC1 device and for vertically polarized input incident light onto the device, all the light is expected to pass through the device with no diffraction in the first order beam. Nevertheless, a 3% diffraction is observed into the first order beam, which translates into PDLC-based leakage noise in our PDL. Note that this leakage noise is vertically polarized. Thus, the use of a horizontal polarizer can block the leakage traveling through the delay path. In a similar way, for horizontally polarized light incident onto PDLC1, a 100% diffraction efficiency is expected. In this case, 89% of the input light is diffracted and 11% stays in the zero order beam. This rather large leakage noise travels through the non-delay and significantly affects the PDL SNR performance. Note that the leakage noise is horizontal and thus a vertical polarizer would block the leakage. Note also that in both cases, the polarization of the signal traveling through the desired path is parallel to the axis of the polarizer placed in the path and thus will not be affected by the polarizers. Thus, a vertical and a horizontal polarizer were positioned along the non-delay and the delay paths, respectively. Table 2 shows the SNR measurements obtained using this passive noise filter. From Table 2 we can conclude that the use of the passive noise filter suppresses the noise leakage in the delay setting by  $> 10$  dB. In the non-delay setting we do not observe such an improvement basically because the SNR number is already  $> 20$  dB. Based on the measured PDLC diffraction efficiency on the first order and the bypass efficiency on the zero order beam, the theoretically expected SNR without taking into account the FLC switch-based leakage noise is 26 dB and 17 dB for the non-delay and the delay settings, respectively. The passive noise filter gives SNR numbers of 23 dB and 25 dB respectively. This is still not adequate for advanced phased array antenna applications or other PDL applications that require SNRs of  $> 30$  dB.

### 5.2 Active Noise Filter

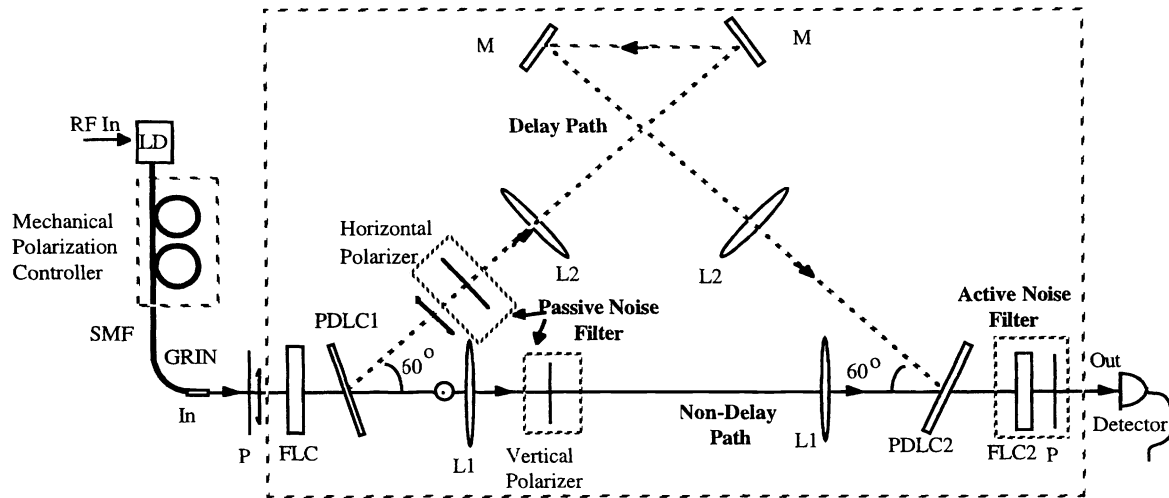
The other source of leakage noise in our PDL is the FLC polarization switch. The FLC switch does not fully rotate the polarization of the incident light when it is set “on”. This causes the horizontally polarized leakage noise to be deflected by the PDLC1 device in the delay path. Moreover, when the FLC switch is set “off”, the SOP of the light is not maintained at the high input polarization extinction ratio. This vertically polarized FLC-based leakage does not “see” the grating on the PDLC1 device and travels through the non-delay path unaffected. In both cases, signal and FLC switching leakage noise are of orthogonal polarizations at the output of the PDL. Thus, by using an additional FLC device and a vertical polarizer at the output of the PDL, we can suppress this FLC switch-based leakage noise. For example for the delay setting, horizontally polarized signal travels through the delay path, and vertically polarized FLC switch-based leakage noise travels through the non-delay path. The output FLC is set “on” and thus rotates the polarization of both the signal and the leakage noise. The vertical polarizer is then used to block the leakage noise and pass through the signal. In the non-delay setting, FLC2 is set “off” and thus the vertically polarized signal from the non-delay path remains unaffected and passes through the polarizer, while the horizontally polarized FLC switch-based leakage-noise is blocked. Note that the two FLC devices operate in opposite modes, i.e., when FLC1 is “on”, FLC2 is “off” and vice versa. This is because the two states of the FLC devices do not perform equally well<sup>23</sup>. The SNR measurements of the PDL system using the active noise filter are shown in Table 2. Using the active noise filter we improved the non-delay setting by  $>10$  dB, but the delay setting SNR remains at low levels (e.g.,  $< 20$  dB). This limited improvement for the delay setting is due to the vertically polarized PDLC-based leakage noise that eventually passes through the active noise filter and contributes to a low SNR. The FLC2 switch also contributes to this noise since it is set in its “on” state and there is some FLC switch-based leakage.

### 5.3 Combination of the Active and Passive Noise Filter

From the PDL optical SNR results obtained from the passive and active noise filters, we see that each approach improves the SNR for only one of the two settings. If we were to use both of the filtering methods simultaneously, we would obtain higher SNR numbers for both PDL settings. The experimental set-up showing the combination of the two noise filters is depicted in Fig. 4. The passive noise filter suppresses the PDLC-based leakage noise, while the active noise filter suppresses the FLC switch-based leakage noise. SNR measurements of  $> 40$  dB were obtained for both PDL settings. These SNR numbers are highly desirable for PDL applications such as phased array antennas.

**Table 2:** Optical SNR for all the different leakage noise filtering approaches. The SNR without any noise filter is also shown for comparison.

PDL Setting	Optical SNR			
	Without Noise Filter	Passive Noise Filter	Active Noise Filter	With Passive and Active Noise Filter
Non-delay	22.0	23.3	33.8	44.0
Delay	16.7	25.1	17.0	48.0



**Figure 4:** The PDL experimental set-up showing the passive and active noise filters. P: polarizer, GRIN: gradient index lens; SMF: single mode fiber; L: lenses; LD: semiconductor laser.

#### 5.4 “Orthogonal Drive” PDLC Device Configuration

The current limitation in our PDL system is mainly the low diffraction efficiency of our PDLC devices in the first order (e.g., ~89%). Note also that in any of the two PDL settings, both of the PDLC devices either deflect the signal or bypass it. The difference between the bypass efficiency in the zero-order beam (~97%) and the diffraction efficiency (~89%) in the first-order beam also leads to an unbalanced SNR performance for the two PDL settings.

We propose an “orthogonal drive”<sup>24</sup> PDLC device configuration to compensate for that unbalanced performance. This “orthogonal drive” device configuration was first proposed and demonstrated in ref. 23 to compensate for the poorer performance of the FLC devices when they are set in their “on” state compared with when they are set in their “off” state. For our case, this “orthogonal drive” PDLC device configuration is obtained by setting one of the PDLC devices to diffract in the first order and the other device to bypass in the zero order for each of the PDL settings. This can be accomplished by fabricating the two PDLC devices such that one device diffracts the vertical polarization and the other device diffracts the horizontal polarization. Nevertheless, this approach will lead to increased expense and fabrication time, since two different sets of PDLC devices will have to be fabricated. We choose to use a simpler approach, where we place a half wave plate in each of the PDL paths. Thus, the polarization of the light in any of the paths is rotated before it reaches the PDLC2 device. In this case, a horizontal polarization signal coming from PDLC1 device through the delay path is rotated to vertically polarized light, and does not “see” the grating in the PDLC2 device. Thus, it passes through the PDLC2 device unaffected. Similarly, vertically polarized light coming from PDLC1 device through the non-delay path is rotated to horizontally polarized light, and is deflected by the PDLC2 device.

Optical SNR measurements were obtained for this PDL that makes use of the “orthogonal drive” configuration and are shown in Table 3. Note that we actually use this orthogonal drive configuration twice in our system; once for the PDLC devices and once for the FLC devices. From Table 3, we can conclude that the “orthogonal drive” configuration improves the overall SNR performance for our PDL especially when no noise filter technique is used. Note that the SNR numbers of our PDL are still



not high enough when only one of the noise filter techniques is used. This is mainly due to the low diffraction efficiency into the first order beam of the PDLC devices. Note that if the performance of the PDLC devices is improved such that they can give 99% diffraction in the first order for the horizontally polarized light and a 99% bypass efficiency in the zero order for the vertically polarized light, then the theoretical expected SNR would approach 40 dB with only one of the noise filters.

**Table 3:** Optical SNR for the PDL with the orthogonal drive configuration and for all the different leakage noise filter approaches. The SNR without any noise filter is also shown for comparison.

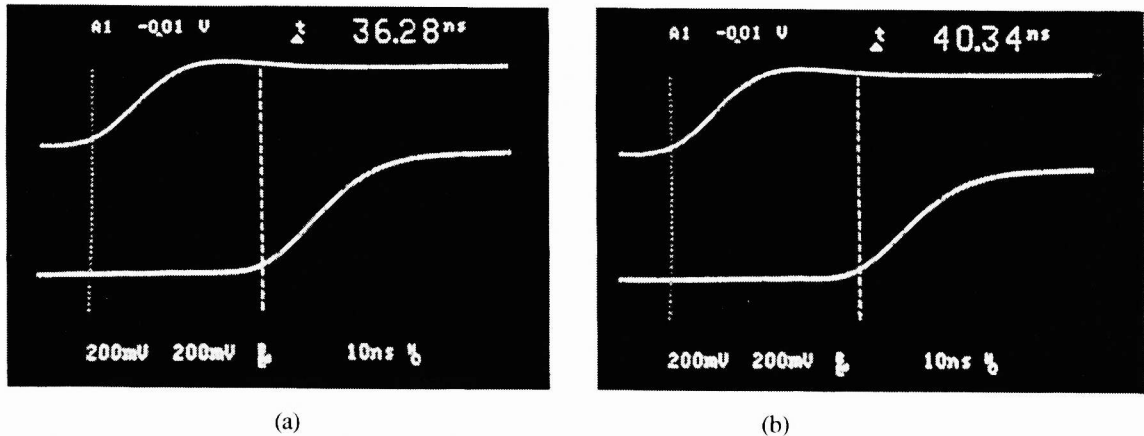
PDL Setting	Optical SNR			
	Without Noise Filter	Passive Noise Filter	Active Noise Filter	With Passive and Active Noise Filter
Non-delay	21.3	22.7	26.0	46.3
Delay	22.7	26.4	24.9	48.0

## 6. TIME DELAY MEASUREMENTS

Time delay measurements were also obtained for the single bit PSH-based PDL. Fig. 5 shows oscilloscope traces of the non-delayed and the delayed signal (bottom traces). The top trace represents the reference signal from the signal generator. A fiber pigtailed fast photodetector (New Focus, Model: 1414-50) was used to detect the modulated optical signal. The fiber used was a multi-mode fiber (50  $\mu\text{m}$  core diameter) connectorized to a GRIN lens. Fig. 5(a) shows the non-delayed signal, with a relative delay from the reference signal of 36.28 ns. The time markers have been positioned at the on-set of the traces. As on-set time we define the time when the pulse gets to 10% of its maximum value. Fig. 5(b) shows the delayed signal, with a relative delay from the reference signal of 40.34 ns. The relative time delay between the two photodetected signals is the time delay obtained from our PDL bit and is calculated to be 40.34 ns - 36.28 ns = 4.08 ns. The expected time delay can be estimated from the optical path length difference between the two paths. The PDLC-to-PDLC distance for the non-delay path is 29 cm. The PDLC-to-PDLC distance for the delay path is 152 cm. Thus the expected time delay can be found from the following equation

$$\Delta\tau = \frac{(\text{Delay Path}) - (\text{Non-delay Path})}{c} = \frac{153 \times 10^{-2} - 29 \times 10^{-2}}{3 \times 10^8} = 4.10 \text{ ns} . \quad (1)$$

The 0.02 ns difference between the expected and the measured time delay is due to measurement errors in the path lengths as well as the tolerance in the position of the time markers on the oscilloscope screen.



**Figure 5:** Oscilloscope traces showing (a) the non-delayed photodetected signal and (b) the delayed photodetected signal. Top traces: reference signal from the oscilloscope; Bottom traces: the photodetected output signal.

## 7. CONCLUSION

We have proposed and experimentally demonstrated a photonic delay line based on FLC devices for polarization switching and PDLC devices as polarization selective optical path routing components. Extensive investigation of the leakage noise in the system was performed, and two different leakage noise filters were investigated for improving the SNR numbers. Improved SNR performance ( $> 45$  dB) was obtained by combining both noise filters. Time delay measurements were also performed for our single bit single channel PDL. Future work relates with experiments using improved diffraction efficiency PDLC devices. PDL architectures based on alternative polarization selective holograms, such as computer generated holograms, or NLC-based routing elements will also be investigated.

## 8. ACKNOWLEDGMENTS

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