Title	Adaptable delay balanced loss switched photonic time delay modules for antenna arrays
Authors	Madamopoulos, Nicholas;Riza, Nabeel A.
Publication date	1997-10-23
Original Citation	Madamopoulos, N. and Riza, N. A. (1997) 'Adaptable delay balanced loss switched photonic time delay modules for antenna arrays', Proceedings of SPIE, 3160, Optical Technology for Microwave Applications VIII, Optical Science, Engineering and Instrumentation '97 San Diego, USA. doi: 10.1117/12.283946
Type of publication	Conference item
Link to publisher's version	10.1117/12.283946
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Adaptable delay balanced switched photonic control modules for antenna arrays

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Adaptable Delay Balanced Switched Photonic Control Modules for Antenna Arrays

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ABSTRACT

A binary photonic delay line (PDL) module is proposed that gives balanced or equal gain/loss switched states. The module is based on a reflective and symmetric geometry and is adjustable to a wide range of time delays. Theoretical analysis as well as experimental demonstration of the proposed PDL architecture is performed. Issues such as electrical signal-to-noise ratio and relative output signal power between the two PDL settings are discussed.

Keywords: Photonic beam-forming, photonic delay lines, phased array antennas.

1. INTRODUCTION

Photonic delay lines (PDLs) can be used for the control of phased array antennas and are currently being studied to develop a future, wide bandwidth, compact, lightweight and small size array antenna controller. A wide range of optical technologies have been proposed for forming PDLs and these are described in ref.1. More recent methods include serial feeding and optical gating [2, 3], arrayed optical waveguides [4], and coherent detection methods [5]. We have proposed and demonstrated several polarization switching array (SA) based PDLs for wideband array antenna control [6, 7]. We have used both nematic liquid crystal (NLC) and ferroelectric liquid crystal (FLC) devices as SAs in our PDLs. The NLC PDLs maintained high on/off isolations (> 35 dB) for both states of the PDL with 1.5 ms switching times [8, 9]. The FLC PDLs also maintained high on/off isolations (> 40 dB) for both states of the PDL with the use of active noise reduction methods, but with a fast 35 microsec switching time [10].

So far, no PDL architecture has been described that can be adapted to provide the wide range of time delays that are required in a variety of phased array antenna applications ranging from large military radars to base station antennas for cellular communications. A combination of different PDL modules based on a variety of design geometries and polarization components have been proposed to obtain the required long, moderate and short time delays [7]. The variable N-bit PDL control system is formed by cascading N independent binary PDL modules. Thus, from an assembly and packaging point of view, it would be beneficial to use the same PDL for a wide range of time delays with minimum changes in hardware. For multichannel or array type applications, it is also important to maintain balanced optical signal gain or loss between the two settings of each single bit PDL module. Generally, the different performance (loss) of the optical components as well as the different number of optical components in the two possible paths of a PDL module can lead to different optical losses between the two settings. In general, for large phased array applications, large variations in the signal amplitude across the array channels is not desirable as it leads to wastage of excess optical power in the channels that suffer less optical losses. Hence, a PDL that maintains a balanced loss between the two settings of each PDL module would be beneficial from optical power budget point of view.

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In this paper, for the first time, we propose a balanced loss PDL design that can give a wide range of time delays, e.g., several picoseconds to tens of nanoseconds, desirable for the phased array application. Theoretical analysis and experimental results obtained for this PDL architecture are presented.

2. The Proposed Adaptable Reflective-Symmetric Architecture

The proposed adaptable reflective-symmetric architecture borrows elements from the previously proposed reflective architecture [9, 11]. In this PDL the light travels twice through the delay path. This leads to a reduction of the physical size of the system. Using this reflective design with a special polarization scheme and a birefringence compensation technique, it becomes possible to use free-space, solid-optics, and non-polarization maintaining (PM) fiber-based optical delay paths, that are smaller, lighter and more compressed than other transmissive PDL designs. When non-PM fibers are utilized to obtain the long time delays a novel birefringence compensation technique is used which consists of a Faraday rotator-mirror (FR-M) module. The propagation of the light twice through the fiber delay path and the Faraday rotator leads to the compensation of any random induced birefringence effects that the fiber may have suffered due to the changing environmental conditions or the changes in the optical wavelength [9, 11]. Nevertheless, this reflective PDL design is limited to moderate and long time delays mainly because of limitations set by the size of the polarizing beamsplitter cube (PBS).
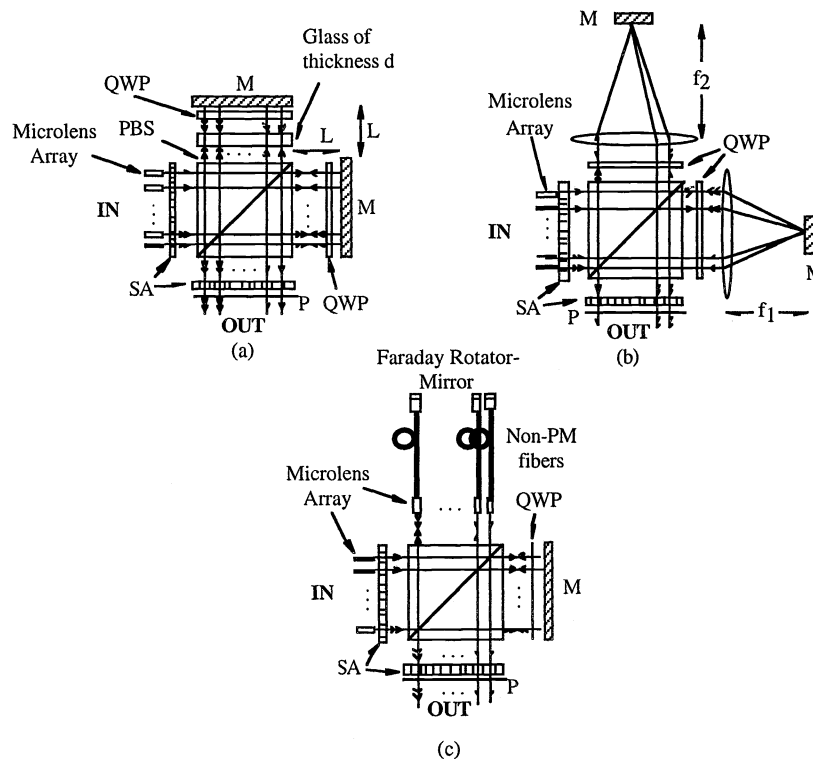

Figure 1: Three options of the proposed PDL, using (a) solid optics, (b) free space, and (c) fiber delay paths for ultra short, moderate, and long time delays, respectively. P: Polarizer, QWP: Quarter wave plate , M: Mirror, SA: Switching Array.

The basic reflective-symmetric architecture design of the proposed adaptable delay PDL single bit module is depicted in Fig 1. Fig. 1(a) shows the solid optics option for ultra-short time delays. Fig. 1(b) shows the moderate time delay option, where free-space imaging optics are used for low interchannel crosstalk. The design of Fig. 1(b) can also give ultra-short time delays if the relative difference of the focal lengths f_1, and f_2 is small enough. Fig. 1(c) shows the non-PM fiber version for long time delays.

Linearly polarized (i.e., vertical or s-polarized) light enters the system in the form of a two-dimensional (2-D) optical beam array. The switching array independently controls the state of polarization of each of these incident beams. When the SA is set "on", it rotates the

incident polarization by 90°, and when the SA is set "off", the incident polarization is essentially unaffected. Specifically, when the SA is set in its "on" state, light changes to horizontal or p-polarization and travels straight through the PBS towards the non delay path. Light travels through the quarter wave plate (QWP), which has its optical axis at 45° with the incident p-polarization. After reflection from the mirror (M) the light passes one more time through the QWP and changes to s-polarization. Then it is deflected by 90° from the PBS towards the output port of the PDL. On the other hand, when the SA is set "off", the s-polarized light is deflected by the PBS towards the delay path. Light travels twice through the QWP (for the solid optics and free space case), changes to p-polarized light and travels through the PBS towards the output of the PDL bit. At the output of the PDL an additional SA and polarizer form an active noise filter to suppress any leakage noise coming from the first SA or the PBS [9, 11]. For the fiber delay PDL the light follows a similar path, in this case a Faraday-rotator with a power of 45° is used instead of a QWP.

3. ADAPTABLE PDL TIME DELAY RANGE

As mentioned earlier, the proposed PDL architecture can generate a wide range of time delays ranging from the ultra-short (< 0.1 ns) time delay to extra long (> 10 ns) time delay. The delay range depends on which option of those shown in Fig. 1 is implemented.
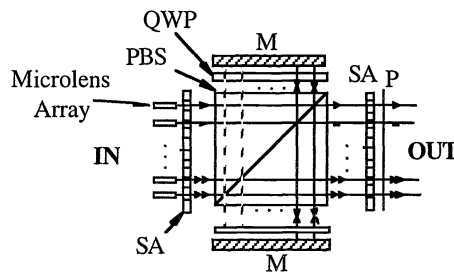

Figure 2: The previously proposed reflective architecture.

Using the previously proposed reflective PDL architecture (Fig. 2), the possible time delays are limited by the dimensions of the PBS. Note that in the delay path the light travels thrice through the PBS, while in the non-delay path the light travels through the PBS only once. Thus, the minimum possible relative path difference between the two paths is equal to two PBS lengths. For a typical 25.4 mm cube PBS and for a zero distance between the PBS, the QWP and the mirrors, the minimum obtainable time delay is

$$t = \frac{d}{U} = \frac{n \times d}{c} = \frac{1.5 \times (2 \times 25.4 \times 10^{-3} \,m)}{3 \times 10^8 \,m/s} = 0.254 ns, \tag{1}$$

where n=1.5 is the index of refraction of the PBS, d is the path difference between the delay and the non-delay path (two PBS lengths), and c is the speed of light in air.

Using our new reflective-symmetric PDL architecture (Fig. 1) where the delay and non-delay paths are independent of each other, the relative path length difference can near the zero mark. Thus, by having a very small optical path length difference between the two paths, ultra short time delays (< 0.1 ns) can be obtained using either the solid-optics or free-space option. Millimeter wave antenna applications require time delays as short as a tenth of a picosecond. These time delays can be realized by placing one of the mirrors (e.g., the delay path mirror) on a micrometer resolution translation stage and then adjusting the relative optical path length difference between the two paths to sub-millimeter resolution (Fig. 3(a)). A different approach is to use two glass plates of different thickness; one in each of the paths of the PDL, where the delay and non-delay path lengths in free space are equal (Fig. 3(b)). The small difference between the thickness of the two glasses will give the desired time delay. It is also possible to use a birefringent mode NLC device in the delay path with its NLC molecular director aligned with the vertical (or horizontal) polarization (Fig. 3(c)). The refractive index of the NLC device can be controlled using a low voltage electrical signal, and thus the effective optical path length of the delay path can be set to the desired magnitude [12]. In addition to the sub-picosecond time delays, extra long time delays (>10 ns) are also possible using fiber optic cables in the delay path. Thus, the adaptable reflective-symmetric PDL architecture is capable of giving the required wide range of time delays.
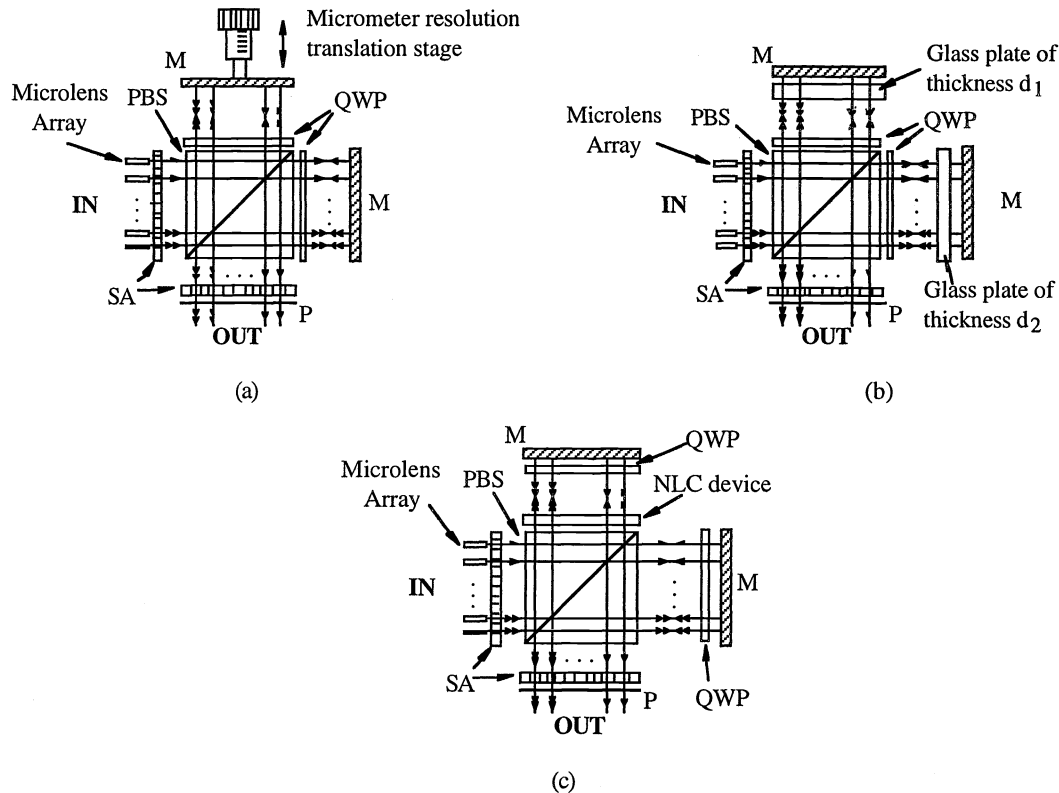
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(a)

(b)

(c)

Figure 3: Sub-picosecond time delay option of our proposed adaptable PDL architecture using (a) a micrometer resolution translation stage, (b) two glass plates of different thickness, and (c) a birefringent-mode electrically controlled NLC device, whose index of refraction can be precisely controlled.

4. BALANCED GAIN/LOSS PERFORMANCE OF THE PROPOSED PDL

Another very important attribute of the proposed PDL is that light travels the same number of times through the polarizing beamsplitter (PBS) for both the delay and the no-delay path. Thus, light suffers the same loss through either path. This results in a balanced loss for both states of the module. For most high power phased array applications, the signals driving the antenna elements are required to be of equivalent amplitudes, providing maximum transmit power efficiency. Thus the balanced loss between the two settings of the PDL is an important advantage. Note that if variable gain control amplifiers (VGCAs) are used to equalize the amplitude of the signals, this can lead to power wastage for channels that have less losses compared to channels with higher losses. Thus, from optical power budget point of view, the proposed reflective-symmetric PDL offers the great advantage of efficient usage of optical power.
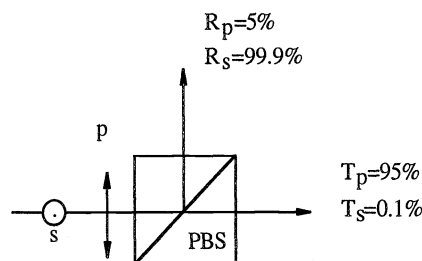

Figure 4: The transmission (T), and reflection (R) intensity coefficients of a typical commercial cube PBS. s: vertical polarization, p: horizontal polarization.

The balance loss for both of the PDL settings also gives a balanced signal-to-noise ratio (SNR) for both switched states. Optical SNR is defined as 10log(signal power/noise power). As signal, we define the optical power in the optical beam of the desired polarization that travels through the desired delay or non-delay path of the module; all other optical power measured at the output is regarded as noise optical power.
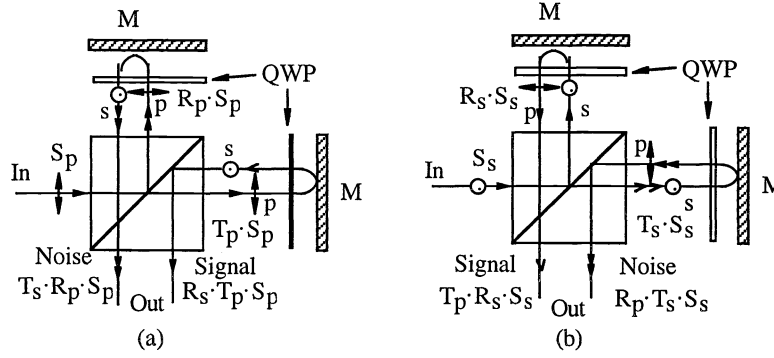

Figure 5: SNR analysis of the (a) non-delay mode and (b) delay mode of the proposed PDL.

Using the commercially available PBS transmission and reflection characteristics (Fig. 4), we can calculate the optical SNR for the two settings of the proposed PDL. Fig. 5 shows the two settings of the proposed adaptable PDL where the optical SNR for the non-delay and the delay setting for all of our adaptable PDLs is

$$SNR = 10\log\left(\frac{T_s \cdot R_p \cdot S_p}{R_s \cdot T_p \cdot S_p}\right) = 42.78 \text{ dB},\qquad(4)$$

and

$$SNR = 10\log\left(\frac{T_p \cdot R_s \cdot S_s}{R_p \cdot T_s \cdot S_s}\right) = 42.78 \text{ dB}\qquad(5)$$

respectively. Hence, the PDL design proposed in this paper gives a balanced SNR performance for the two settings of the module, leading to an overall system performance improvement.

5. EXPERIMENTAL DEMONSTRATION OF THE PROPOSED PDL ARCHITECTURE

The experimental set-up for the proposed adaptable PDL architecture is shown in Fig. 6. In this experiment we are interested in characterizing the PDL in terms of losses and SNR. Thus, continuous wave (CW) unmodulated light is used as input to the PDL. CW light from a diode pumped Nd:YAG laser (λ=1319 nm) is fed into the PDL bit using a GRIN lens connectorized PM fiber. A high extinction vertical (or s) polarizer is used to clean the beam from any horizontal (or p) polarization component. The polarization switches used in the experiment are FLC devices that act as programmable half wave plates. When FLC 1 is "on" it rotates the polarization to p and the light goes through the non-delay path. FLC2 is set "off" and leaves the polarization unaffected to go through the s-polarizer. On the other hand, when FLC1 is set "off", the light is deflected by 90° from the PBS and follows the delay path. In this case FLC2 is set "on" and rotates the p-polarization to s-polarization, and the light exits the PDL module.
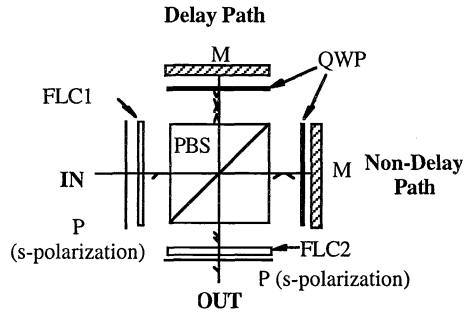
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Figure 6: The experimental set-up for the proposed adaptable PDL architecture. Delay paths are shown with double arrows, and non-delay paths with single arrows.

Optical SNR measurements were obtained using a power meter at the output of the PDL module. For each of the two settings, the signal propagates through the desired delay or non-delay path, and noise propagates through the non-desired non-delay or delay path, respectively. Signal and noise optical power measurements are easily obtained by just blocking the light traveling through the signal (or noise) path and measuring the optical power at the output of the module that corresponds to the noise (or signal) respectively. Table 2 shows the experimentally measured optical and electrical SNRs for both settings of the proposed laboratory proof of concept adaptable PDL.

Table 2: Experimentally measured optical and Electrical Signal-to-Noise Ratio for both settings of the new reflective-symmetric architecture.

PDL Setting	Optical Signal-to-Noise Ratio	Electrical Signal-to-Noise Ratio
Delay	41.32	82.64
Non-Delay	41.82	82.64

The experimental results in Table 2 show that the proposed adaptable reflective-symmetric PDL architecture gives a balanced SNR performance for both settings of the PDL.

6. CONCLUSION

We have proposed and experimentally demonstrated a new adaptable PDL architecture that allows a wide range of time delays as well as provides a balanced loss performance between the two settings of the PDL. The propagation of the optical signal through the same number of optical components leads to equivalent optical losses that are beneficial from an optical power budget point of view. Furthermore, the proposed experimentally demonstrated adaptable PDL architecture gives optical SNRs > 40 dB, which leads to electrical SNRs > 80 dB, a number that is highly desirable for advanced phased array antenna applications. Experiments conducted with the proposed adaptable PDL indeed showed the versatility and improved performance of this new PDL.

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