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Photonic Time Delay Beamforming Architectures Using Polarization Switching Arrays

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Abstract

Photonic time delay line (PTDL) architectures have been proposed for transmit/receive mode antenna applications. These architectures are based on two dimensional pixelated optical arrays that act as optical polarization switching elements. Such elements can be nematic liquid crystal (NLC) arrays, ferroelectric liquid crystal (FLC) arrays, and magnetooptic arrays. Optical delay lines can be formed using either free space or solid optics propagation, as well as non-polarization maintaining fiber propagation for the case of long time delays. In this paper, various optical array based optical beamformer architectures are presented and compared. These different architectures are based on Thompson polarization beamsplitters, and polarizing cube beamsplitters, for both transmissive and reflective geometries. A novel ternary time delay architecture is also introduced that can give 3^N different time delay settings. In additions, a novel wavelength multiplexing architecture using a single channel dispersive fiber PTDL in cascade with multichannel PTDL is proposed for further hardware size and weight reduction.

Keywords: Optical Beamforming, Phased Array Antennas, Photonic Time Delay Lines, Wavelength Multiplexing

2. Introduction

Phased array antennas (PAAs) have features that are desirable for many emerging commercial applications such as cellular communications, satellite communications, air traffic control radars, and other mobile platform antenna systems. Recently there has been an increased interest in photonic control of PAAs. Advantages of photonic over electrical PAA control, such as compact and lightweight modules, large instantaneous and tunable signal processing bandwidths, and protection from electromagnetic interference (EMI) and electromagnetic pulses (EMP), highlight the importance of the development of photonic time delay beamforming architectures.

Over the past few years we have proposed various PTDL architectures for transmit-receive mode PAA control using two-dimensional (2-D) pixelated optical arrays that act as compact polarization switches [1-5]. We have demonstrated moderately fast (e.g., 1 ms), high on/off optical isolation (>35 dB) nematic liquid crystal (NLC) optical switches for our proposed PTDL architecture that uses a time-multiplexed antenna scanning mode to provide moderately fast (<1000 beams/s) antenna beam switching [6]. Low channel-to-channel electrical crosstalk (e.g., -42 dB) values have also been demonstrated by us for a 25-channel NLC PTDL [7].

In this paper we will describe different PTDL architectures that are based on 2-D pixelated optical arrays that act as optical polarization switching elements. We will categorize the different architectures based on the polarization optical components they use, and their geometry. We introduce for first time the ternary architecture, which can give higher number of time delay settings. A wavelength multiplexing technique for system size reduction is also presented.

3. Transmissive Architectures

3.1. Polarization Beamsplitting Prism Transmissive PTDL

As transmissive architectures we define those architectures that have both delay and no-delay path propagation once through each component of the delay and no-delay path, respectively. Fig. 1 depicts a PTDL architecture (architecture 1) based on

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polarization beamsplitting prisms (PBS). Even though the figures of the various PTDL architectures presented in this paper are self-explanatory we find it more appropriate to describe the first architecture in more details. The system of Fig. 1 forms a PTDL bit, which consists of a no-delay (solid line), and a delay (dashed line) path. Horizontal or p-polarized light coming from a microlens array hits the switching array (SA1). SA1 can be set either "on" or "off", to either rotate the incident polarization by 90°, or leave it unaffected. When the polarization changes to vertical or s-polarization, the light follows the delay path, while when it remains horizontal follows the no-delay path. Since PBSs as well as SAs can have polarization leakage, noise can built up, especially in a cascade architecture of PTDLs. Such an effect can be deleterious for the performance of the PAA controller. Noise is defined as the unwanted polarization propagating through the system. For a certain delay setting the light coming from the unwanted path is the noise, and the light coming from the desired path is the signal. Improvement of the PTDL performance is possible with the use of a noise reduction technique [8]. At the output of each PTDL bit, a noise filter can be used. It consists of a SA and a p-polarizer (or a s-polarizer, depending on the desired input polarization of the next bit). We will call this filter, the active noise filter, since the SA is an active optical component. Signal and noise come from different paths, and thus, they have orthogonal polarizations to each other. Using the active noise filter, the noise can be rejected, and only the signal propagates towards the second bit. For example, assume that the desired path is the no-delay path and due to noise leakage we have some light coming from the delay path. The polarization of the no-delay path is p-polarization, while that from the delay path is s-polarization. Setting the SA "off" the desired p-polarization remains unchanged and passes through the p output polarizer, while the unwanted s-polarization remains unchanged and is blocked by the output polarizer. The PTDL performance can be further improved by introducing a polarizer after the deflected output port of the first PBS. This polarizer is aligned with its polarization axis parallel to the s-polarization. The deflected output port of the PBS has poor polarization extinction ratio (ER) performance (ER < 50:1) due to the high p-polarization leakage from this port [5]. The s-polarizer restrains the p-polarization leakage of the PBS from propagating through the delay path. We will refer to the s-polarizer as the passive noise filter, in contrary with the active noise filter, because a polarizer is a passive optical component.

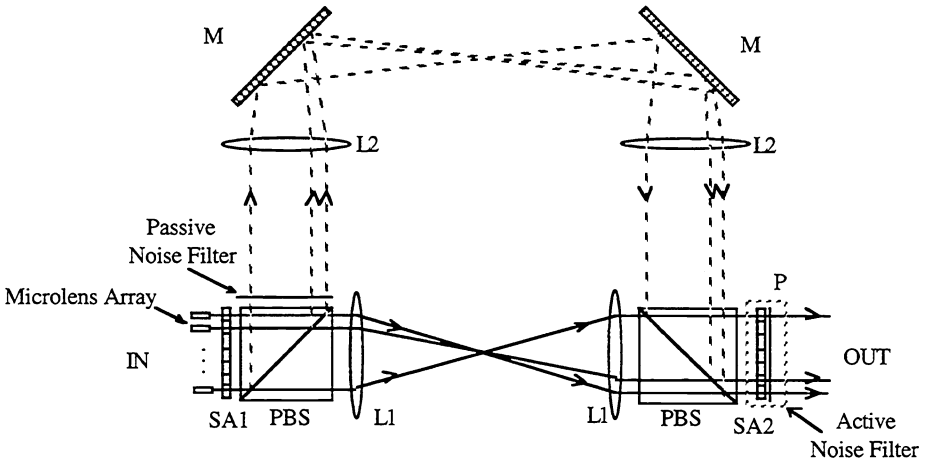


Figure 1: The PBS transmissive PTDL architecture (architecture 1)

For multichannel PTDLs, zero channel-to-channel crosstalk is desirable, since crosstalk between adjacent channels will decrease the signal-to-noise ratio and dynamic range of the system. Low channel-to-channel crosstalk requires imaging optics [7]. The 1:1 imaging optics set-up is a 4f two lens set-up, where f is the focal length (FL) of the lenses. SA1 is placed at the front focal plane of the first lens, and SA2 is placed at the rear focal plane of the second lens. The separation between the two lenses is two FL. The use of imaging optics dictates the use of mirrors for deflecting the light, instead of the other alternative, i.e., total internal reflection (TIR) prisms. Fig. 2 shows a ray tracing diagram for a set of beams deflected by a TIR prism. The principle of TIR is based on the angle of incidence of the light on the hypotenuse of the prism. There will be an angle of acceptance of incident beams that can be totally internally reflected. For a typical TIR prism with an index of refraction of n=1.5, the critical angle is $\varphi_c = 41.8°$. Ray 1 in Fig. 2 is incident on the hypotenuse of the prism with an angle of incidence always greater than 41.8° and it is totally reflected. On the other hand, ray 2 has to satisfy the condition $\varphi_2 \geq 41.8°$, and thus, $\varphi_2' \geq 90° - \varphi_2 = 48.2°$, and in effect $\psi_2' \geq 180° - (45° + \varphi_2') = 86.8°$. This leads to $\psi_2 \leq 90° - \psi_2' = 3.2°$. Thus, the angle of incidence of ray 2

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onto the TIR prism face has to be $\theta_{inc} \leq \arcsin(1.5 \sin\psi_2) = 4.8°$. Such an angle can be obtained for R/D ratios of at least 5.95, where R is the distance of the front face of the TIR prism from the lens and D is the distance between the two outermost beams incident on the lens. For D≈2 cm, the required length R will be at least 12 cm. This in effect sets a limit on the use of TIR prisms for only long enough delay paths that can satisfy the above condition.

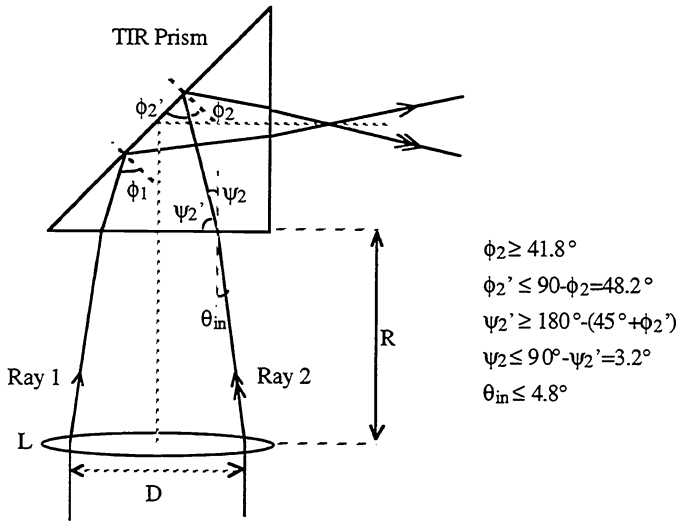


Figure 2: Ray tracing diagram for total internal reflection from a prism of a pair of beams focused by a lens.

In Fig. 3 and 4 we show two different configurations of the PBS PTDL systems. The first consists of a sequence of PTDL bits in cascade, while the second one has the bits interchangeable at the two sides of a "sandwiched" design of two SAs and a polarizer, which is the active noise filter of one bit and the input SA of the following bit. The advantage of the second architecture over the first design is the use of only a pair of single-substrate SAs, that are possible because of the mature large scale liquid crystal (LC) display fabrication techniques. In addition, the optical alignment and assembly of this PTDS becomes simpler and the overall cost can be lower because the SAs are on the same single substrate, and no cutting and mounting of each individual array is required.

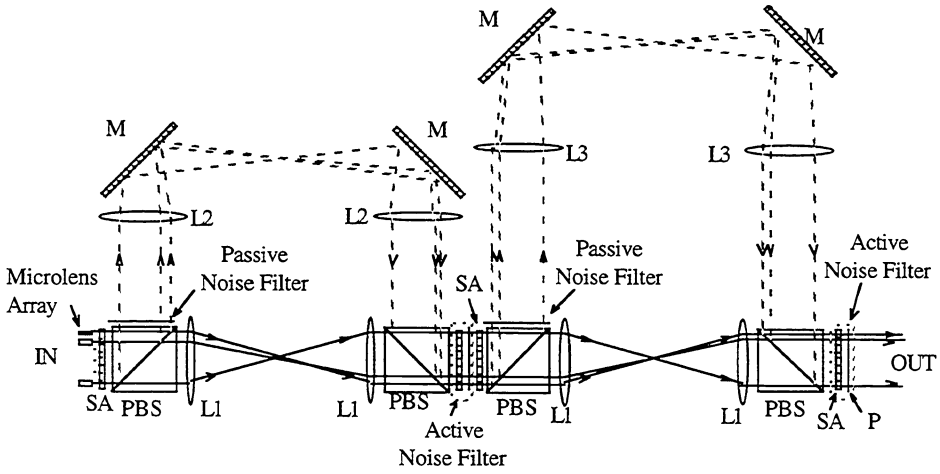


Figure 3: PBS based transmissive PTDS cascade architecture.

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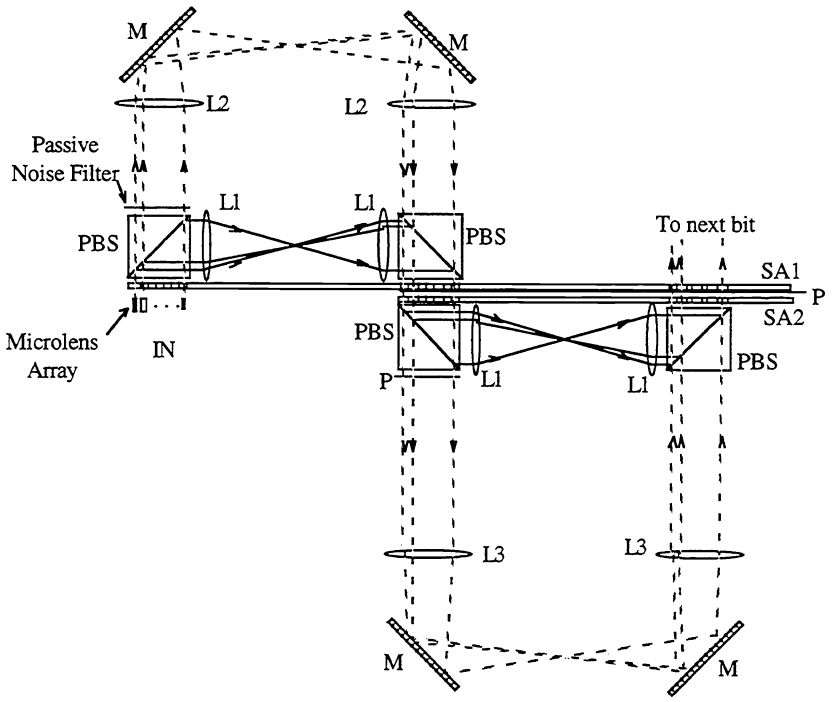


Figure 4: PBS based transmissive PTDS "sandwiched" architecture.

A second PBS transmissive PTDL architecture is shown in Fig. 5 (architecture 2). The principles of operation are similar to the architecture discussed earlier. In this design we introduce a second set of mirrors and imaging system in the delay path, but only one PBS is used. The cost of this architecture is almost the same as that for the previous architecture 1, since the cost of two high reflectivity mirrors and two anti-reflection coated lenses is almost the same as that of a commercially available PBS. The advantage of this architecture is the smaller size of the module for the same time delays. In architecture 1, the time delay is given by the propagation time difference between the delay and no-delay path. In architecture 2 the no-delay path is common in the delay path too, so the time delay is obtained by the actual time it takes for the light to propagate through the delay loop (dashed line). Furthermore, since in architecture 2 the no-delay path is not involved in the time delay, it can be very small, thus minimizing the overall size of the system. This can not be done in architecture 1, since time delay is dependent on the no delay path length.

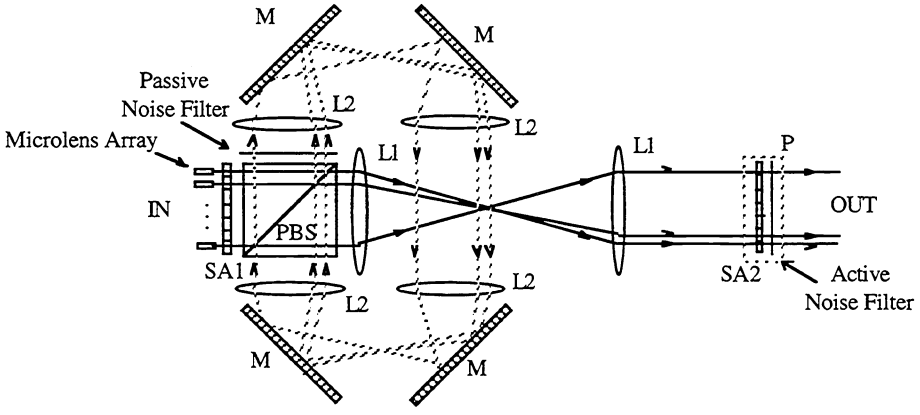


Figure 5: The single PBS transmissive PTDS architecture (architecture 2).

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Architecture 2 can be modified and used as a re-circulating architecture. In this case, a SA is introduced in the delay path, before the PBS. Then light remains in the delay path, until the SA is switched to direct the light out of the delay path. In the re-circulating architecture, pulsed light has to be used. The pulse duration and separation should be such that there is no overlapping between different settings of the PTDL. This means that all the channels should first be clear of the propagating light before the PTDL setting is changed.

3.2. Thompson Polarization Prism Transmissive PTDL Architecture

A Thompson polarization prism based PTDL architecture is shown in Fig. 6. The much better performance of the TBSs (ER > 10,000:1) for both ports, compared to that of cube PBSs (ER ~ 1,000:1 for the straight port, ER<50:1 for the deflected port) improves the polarization ER of the delay path, and results in a high signal-to-noise for the PTDL. Thus, in this architecture, a passive noise filter is not necessary. On the other hand, the TBS cost today, which is four times higher than the PBS cost, can increase the price of the system significantly, thus limiting the use of TBSs in non-cost sensitive PTDL applications.

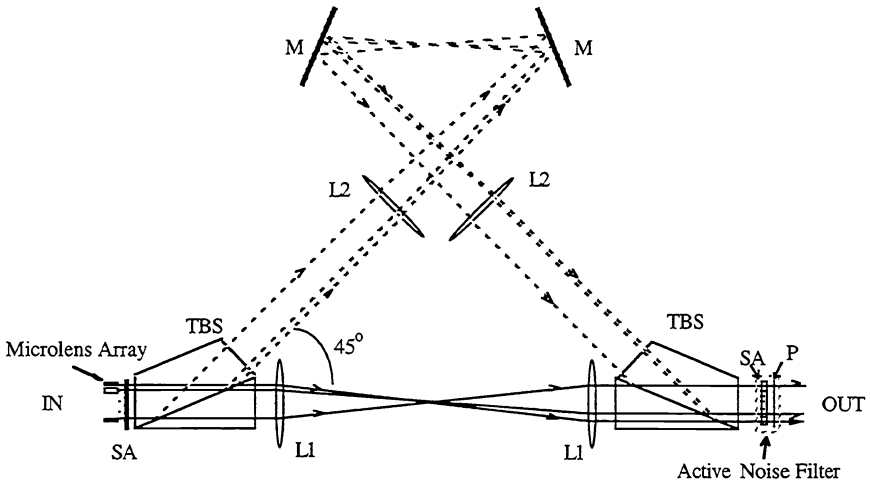


Figure 6: The TBS based transmissive PTDL architecture.

4. The Reflective Architecture

The PTDL architectures discussed earlier can provide moderate time delays (e.g., < 5 ns). When the required time delays are long (e.g., > 5 ns), issues related to large free-space/solid optics systems such as degree of mechanical stability and size problems of the PTDL arise. These problems can be overcome with the use of a reflective geometry PTDL architecture. Reflective geometry is defined as the PTDU geometry where the delay and/or no-delay path light can propagate more than once through the optical components that make the path. A reflective geometry PTDL architecture is depicted in Fig. 7, where two bits are shown; one free-space bit and one fiber delay bit. The advantage of this reflective configuration is that the light travels twice through the same path (delay path) acquiring time delays that with a transmissive architecture would require longer delay paths. Moreover the use of low loss fibers can easily give time delays > 5 ns, that, with a transmissive design are rather bulky. Since the system is based on polarization switching, polarization maintaining (PM) fibers are required to maintain the high state of polarization (SOP) of the propagating light. In fact, any unwanted change in polarization in the propagating light beam will negatively affect the performance of the PTDL. Recently, we have shown that in the reflective architecture, non-PM fibers can be used with a Faraday rotator-mirror (FR-M) configuration, where the retracing of the beam through the fiber compensates for 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]. The lower cost of the non-PM fibers is a major advantage of this reflective architecture when compared to architectures that require the use of PM fibers. Note that total PTDL cost mainly depends on the price of the

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FR-M set-up, and not on the non-PM fiber cost, which is relatively lower. Moreover, a single, large FR-M can be used with a bundle of fibers, instead of coupling every fiber to an independent FR-M assembly, thus reducing the cost and assembly time.

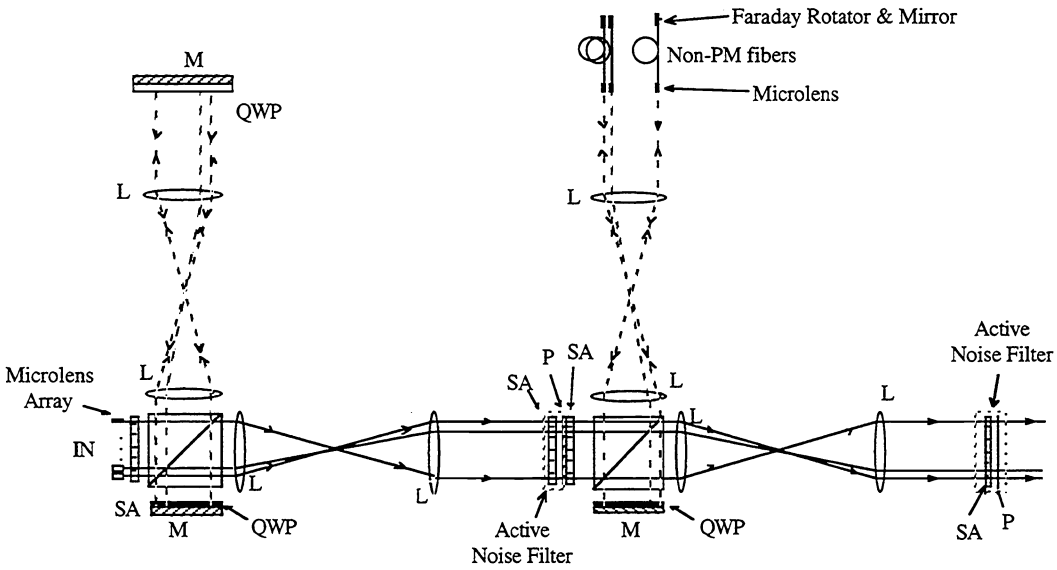


Figure 7: The reflective PTDL architecture.

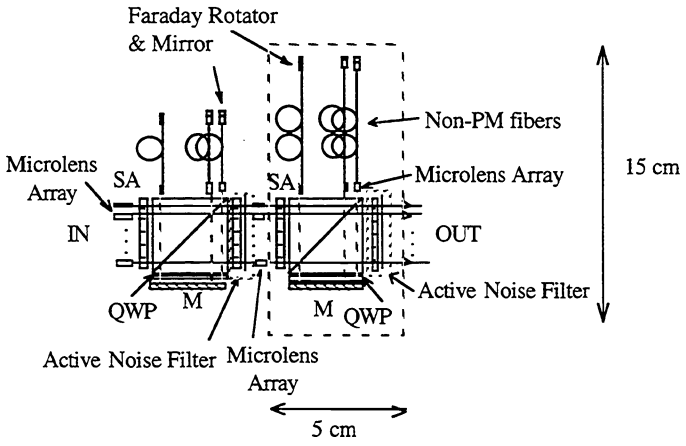


Figure 8: The compact fiber PTDL architecture. Microlens arrays are used between the bits to maintain the high degree of interchannel isolation.

The reflective PTDL design is useful not only when long time delays are required, but also when small PTDL system size is desired. A modified version of the reflective architecture is depicted in Fig. 8, where microlens (e.g., GRIN lens) fiber collimators are used for coupling light in and out of the system. Here, bulk imaging optics is not used as the microlens optical divergence is not high and light remains collimated for distances of ≤ 5 cm [10]. Note that when light propagates in the fibers, it is guided. Thus, the longest free space and solid optics propagation in the PTDL system is of the order of ~ 5 cm. In this case, microlens arrays can be placed between adjacent PTDL bits to keep the light collimated. Furthermore, to ensure minimum non-

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fiber propagation, the quarter wave plate (QWP) and mirror (M) can be deposited on the PBS surface. Typical size of such a PTDL bit design can be 5 cm × 15 cm, as shown in Fig. 8.

5. The Symmetric PTDL Architecture

So far, we have discussed architectures that generally give large time delays, e.g., > 0.5 ns. There are applications that require very short time delays, e.g., < 0.5 ns. The symmetric PTDL architecture shown in Fig. 9 can give these short time delays. We call this architecture symmetric because the two arms of the PTDL have exactly the same physical length. A relative time delay difference between the two paths can be introduced by placing two high quality glass plates in the two arms. The relative optical path length difference between the two arms can be controlled by an appropriate choice of the thickness of the two glass plates. We choose to use a glass plate in each of the arms, instead of just one plate in one of the arms, mainly because of mechanical stability issues that arise for thin plates. As an example, for time delays of 0.01 ns, the required thickness is 2 mm for a material with an index of refraction of 1.5. A thin plate of 2 mm thickness, placed in one of the arms can be susceptible to thermally or mechanically induced material stresses, strains, and vibrations. This can alter the uniformity of the thickness or index of refraction of the plate, thus, affecting differently the time delays of the beams passing through the multichannel PTDL. On the other hand, two glass plates with a thickness difference of 2 mm will be less susceptible to such environmental and packaging related effects, giving a uniform time delay to all the beams in the multichannel PTDL. Moreover, controllable NLC array devices can also be used to give the small time delays, as the NLC index of refraction is voltage controllable. This architecture has basically the same characteristics as the double PBS transmissive architecture, as the same optical components are used. In effect, the cost of the symmetric architecture is the same as that of the PBS transmissive architecture 1.

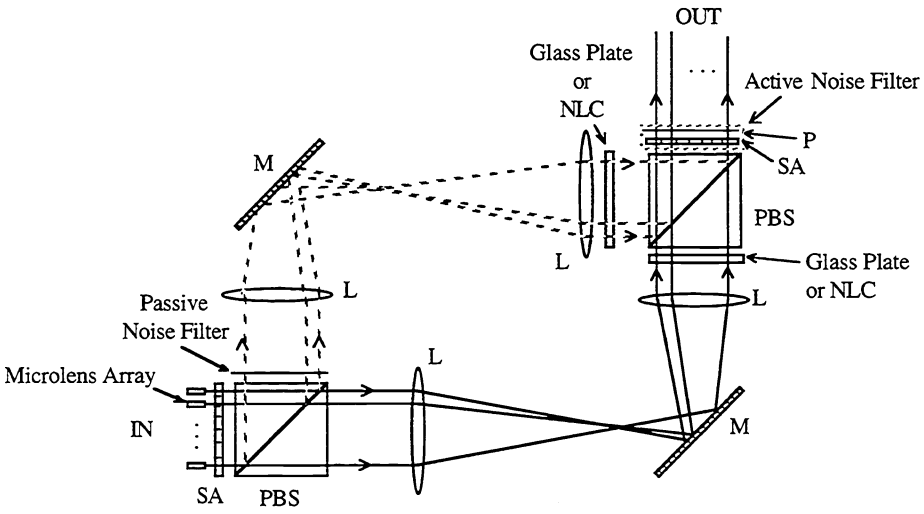


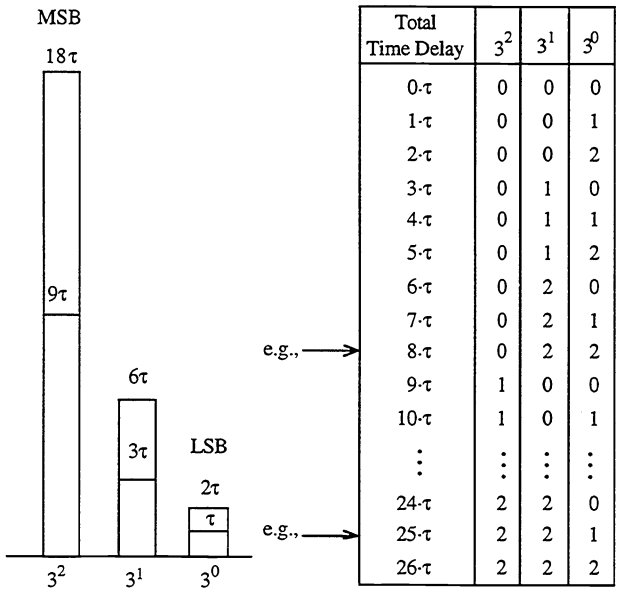
Figure 9: The symmetric PTDL architecture.

6. Ternary Architecture

So far, all the PTDL architectures discussed were binary architectures. N-bit binary architectures can provide 2^N different time delay settings. In this paper, we introduce a ternary PTDL architecture that can give 3^N different time delay settings. Fig. 9 shows a schematic diagram of this ternary architecture, and shows a table with the possible delay settings. In this ternary architecture, a certain bit can have values of 0, 1, or 2. Thus the ternary architecture must consist of bits that have two delay path settings. The time delays of the two delay paths of each bit have a time delay ratio of 1:2. The advantage of the ternary architecture is that a fewer number of bits are required than for a binary architecture, for the same number of PTDL settings. For example, a 3-bit ternary PTDL architecture can provide $3^3 = 27$ different time delay settings, while for a binary PTDL architecture, even a 4-bit delay line can provide only $2^4 = 16$ time delay settings. Note that ternary PTDL architectures can be

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obtained from the binary PTDL architectures presented earlier with some modifications. Fig. 11 and 12 show two possible designs for ternary architectures using PBSs and TBSs, respectively.



Total Time Delay	3^2	3^1	3^0
0·τ	0	0	0
1·τ	0	0	1
2·τ	0	0	2
3·τ	0	1	0
4·τ	0	1	1
5·τ	0	1	2
6·τ	0	2	0
7·τ	0	2	1
8·τ	0	2	2
9·τ	1	0	0
10·τ	1	0	1
⋮	⋮	⋮	⋮
24·τ	2	2	0
25·τ	2	2	1
26·τ	2	2	2

e.g., $8\tau = 0\tau \cdot 3^2 + 2\tau \cdot 3^1 + 2\tau 3^0 = 0 \cdot \tau + 6 \cdot \tau + 2 \cdot \tau$

$25\tau = 2\tau \cdot 3^2 + 2\tau \cdot 3^1 + 1\tau 3^0 = 18 \cdot \tau + 6 \cdot \tau + 1 \cdot \tau$

Figure 10: Schematic diagram of the 3-bit ternary architecture, and a table showing the possible delay settings.

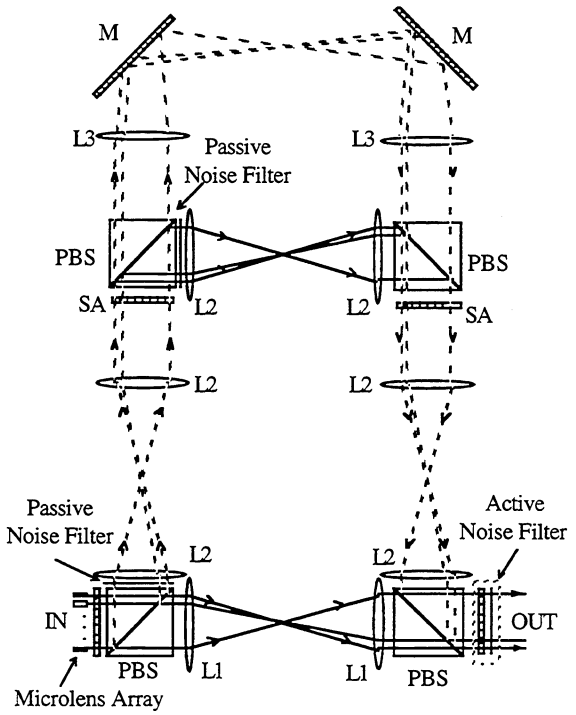


Figure 11: The PBS based PTDL bit ternary architecture.

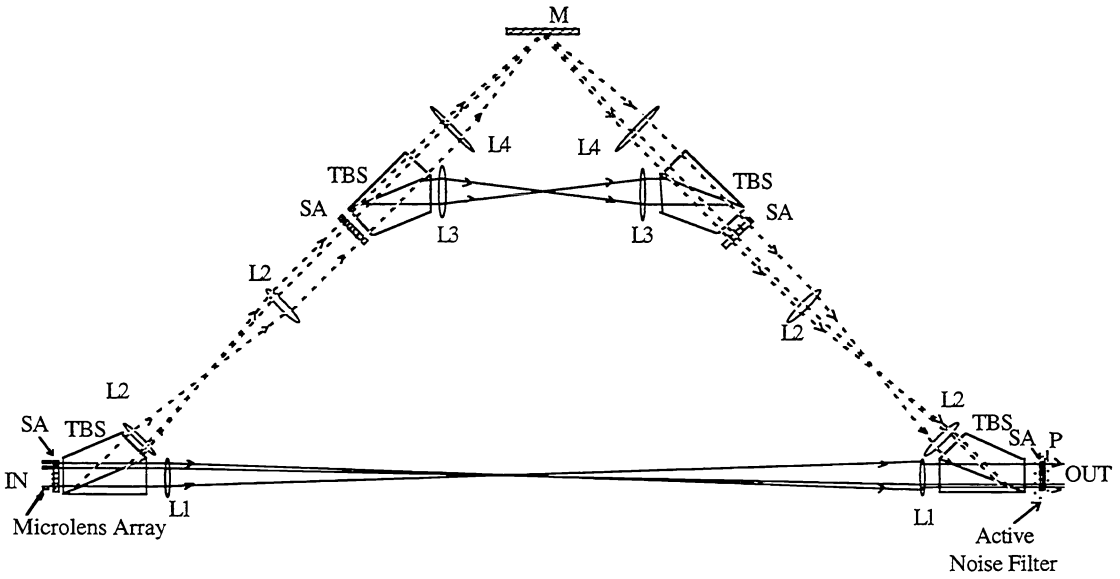


Figure 12: The TBS based PTDL bit ternary architecture.

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7. Wavelength Multiplexed Reversible Architecture using a Single Channel Switched Dispersive Fiber PTDL and a Switched Multichannel PTDL

The amount of hardware used in PTDL systems for the photonic control of PAAs can be reduced by using wavelength multiplexing [11]. Also, the use of independent (multichannel prism geometry) dispersive fibers with a single high power tunable laser source has been proposed for continuously variable photonic time delay lines [12, 13]. For the first time, we propose a photonic controller for phased array antennas that combines wavelength multiplexing with dispersive fiber delays to form a fully reversible array antenna controller that has the highest proposed hardware reduction.

The wavelength multiplexing technique is based on partitioning the PAA into sub-arrays, where there are a total of N sub-arrays, with M antenna elements per sub-array. The m-th element of the (n+1)-th sub-array requires a time delay that is equal to the time delay of the m-th element of the n-th sub-array plus a bias delay (Fig. 13). Thus, the photonic control system can be designed as a cascade of two photonic subsystems. The first switched PTDL sub-system will give the required time delays that control the M antenna elements in each sub-array. The second switched PTDL sub-system will give the additional required bias delays for controlling each of the N sub-arrays. Our novel system architecture based on wavelength multiplexing for both transmit and receive mode operation is shown in Fig. 13. In the transmit mode, for example, M high power diode lasers (H-LD) that operate at different wavelengths, λ_1, λ_2, ... λ_M, are modulated by the transmit signal. H-LDs are needed in the transmit operation because signals are split and distributed to the entire antenna array. A M:1 optical λ-multiplexer is used to couple the signals at different wavelengths into a single channel dispersive fiber based F-bit switched PTDL system. The different wavelengths "see" different indices of refraction in the dispersive fiber and thus travel with different velocities, obtaining small time delay differences with respect to each other. A 1:N optical splitter is used to split the M delayed signals into N sets of different wavelength signals. These N sets of λ_1, λ_2, ... λ_M signals then pass through the G-bit N-channel switched bias time delay system, obtaining the appropriate bias delays. Each channel of the bias PTDL can give, for example, 2^G delays, such as 0, T, 2·T, ..., k·T, ...(2^G-1)·T, where k is an integer, and $G \geq N$. For example, for $2^G = K$, the longest time delay will be $T_{NF} = \tau_F(\lambda_M) + (K-1)\cdot T$, where $\tau_F(\lambda_M)$ the longest time delay from the F-bit dispersion fiber delay line (Fig. 13). Finally, N 1:M optical λ-demultiplexers are used to separate the different M signals that drive the elements of each sub-array.

In the transmit mode operation of the antenna array the microwave signal for transmission modulates the H-LDs of the controller optoelectronic transmit/receive module, and the required time delayed signals are detected by the photodetectors at the antenna element optoelectronic transmit/receive module (Fig. 14). The signals from the photodetectors pass through the T/R module electronic phase shifters that must be used to compensate for element level signal path/channel phase due to noise sources such as small variations in the length of optical and/or electrical paths. Fortunately, because electronic phase shifters already exist in the commonly used MMIC T/R modules for phased array antennas, it thus becomes simple to compensate for vital element level phase errors that exist in all practical deployed antenna systems.

As mentioned before, our control system is reversible, as essentially the same hardware is used for both the transmit and receive modes of the antenna. In the case of the receive mode, each antenna element is connected to a low noise laser diode (LD). The M outputs of each antenna sub-array modulates the M LDs which operate at the M different wavelengths. Note, that the wavelength of the LD used for the m-th element for each of the N sub-arrays is the same. Light propagates in the opposite direction in the system when compared to the transmit mode. For each sub-array, the wavelengths are multiplexed and pass through the bias PTDL. After the bias PTDL, the bias time delays have been canceled. A N:1 optical combiner is used to couple all the signals to the single channel dispersive fiber PTDL system, where now the shorter time delays corresponding to the individual elements of each sub-array are canceled. The received optical signals are directed to the detectors, of the controller optoelectronic transmit/receive modules, after which all the signals are electrically summed, and sent to the electronic receiver for post-processing.

Note that in the N-channel G-bit PTDL in the controller, the optical SAs have to be equally effective over the λ_1, λ_2, ... λ_M wavelength range of operation. Recall that polarization switching is based on retardation effects on the propagating light which is in fact wavelength dependent. Our interest is to obtain fast switching times, and ferroelectric liquid crystal (FLC) devices, can give switching times of 30 μs [14]. FLC SAs can be designed to act as a half-wave retarders at a certain designed center wavelength, with an external voltage signal used to change the retardation of the device between two states which either give a 90° rotation, or leave the incident light polarization unaffected. For our wavelength multiplexed system, we must examine the

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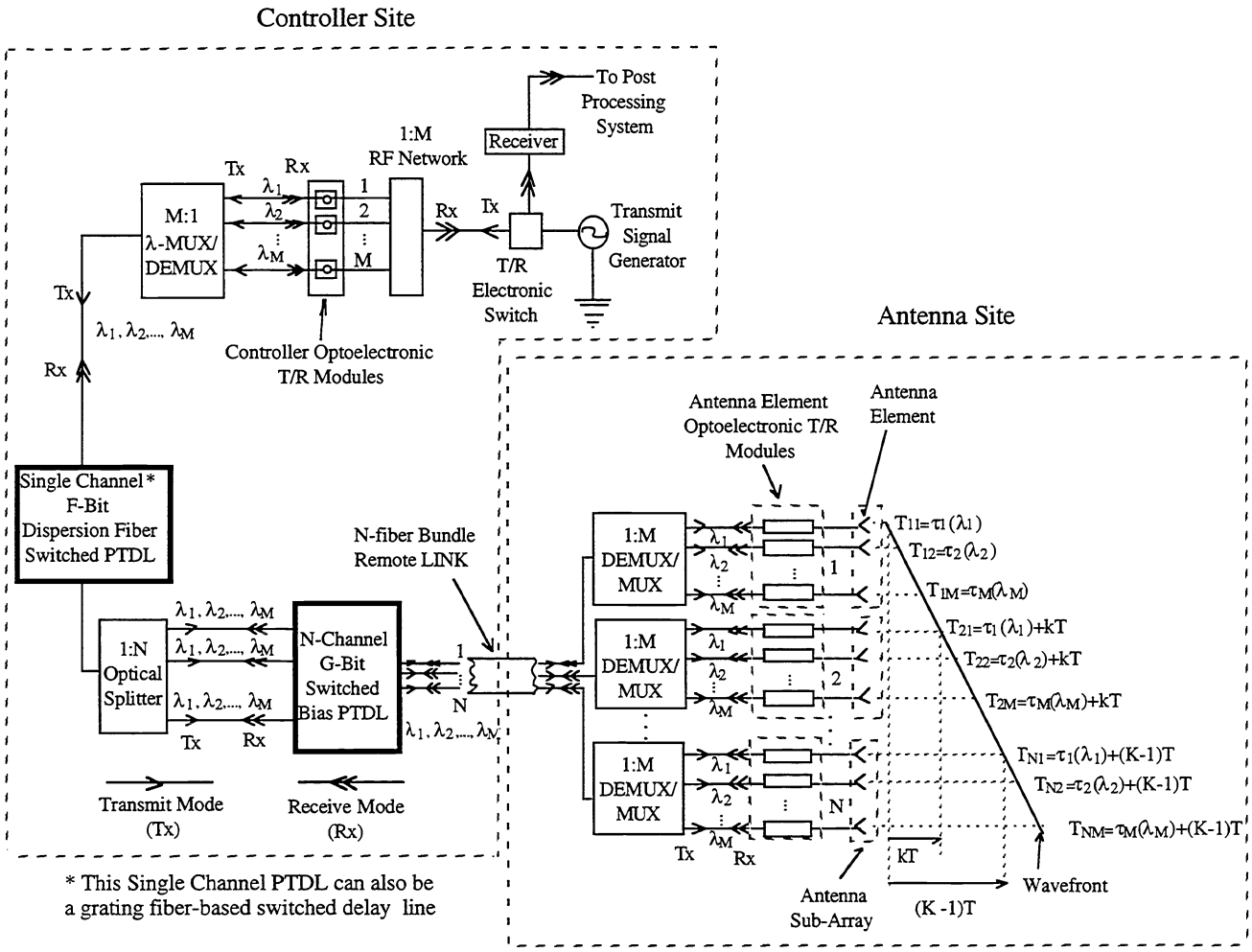


Figure 13: The novel CREOL wavelength multiplexed reversible photonic control system for phased array antennas using a single channel F-bit switched PTDL in cascade with a multichannel G-bit switched PTDL.

effects of wavelength diversity on the performance of a system using FLC SAs. For a FLC designed to act as a half wave retarder at 1310 nm, and for a set of wavelengths from 1290 nm to 1330 nm, the retardation obtained is between 1.014 π and 0.9859 π. This is a maximum deviation of ~ 1.4 % from the desired retardation of π obtained for the center wavelength [15]. This means that when the FLCs are set to rotate the polarization by 90°, the polarization does not fully rotate by 90° for all the wavelengths in the system. This, in effect, will give unwanted polarization components propagating through the system that can add to overall system noise. Fortunately, recently we have demonstrated the use of active noise filters in the PTDLs that efficiently reject these unwanted polarization components, thus improving the system performance in terms of signal-to-noise ratio [8,9]. Thus, these active noise filters will be used in our wavelength multiplexed based photonic antenna controllers.

Typical design parameters of an advanced wideband phased array radar could be M = 49 or 7 × 7 element subarray, with N = 169 subarrays in the antenna aperture. This gives a total of 8,281 individual antenna elements in radar. This design implies that we would need 49 separate wavelengths for lasers used in the system. Distributed feedback (DFB) LDs have narrow spectral widths (FWHM < 0.1 nm) and LD-to-LD wavelength separation of 1 nm, and thus, DFB LDs can be used in the proposed wavelength multiplexed photonic reversible time delay control system to provide the 49 different wavelengths [16]. The above LD specifications also meet the resolution of commercially available wavelength multiplexers and demultiplexers [17].

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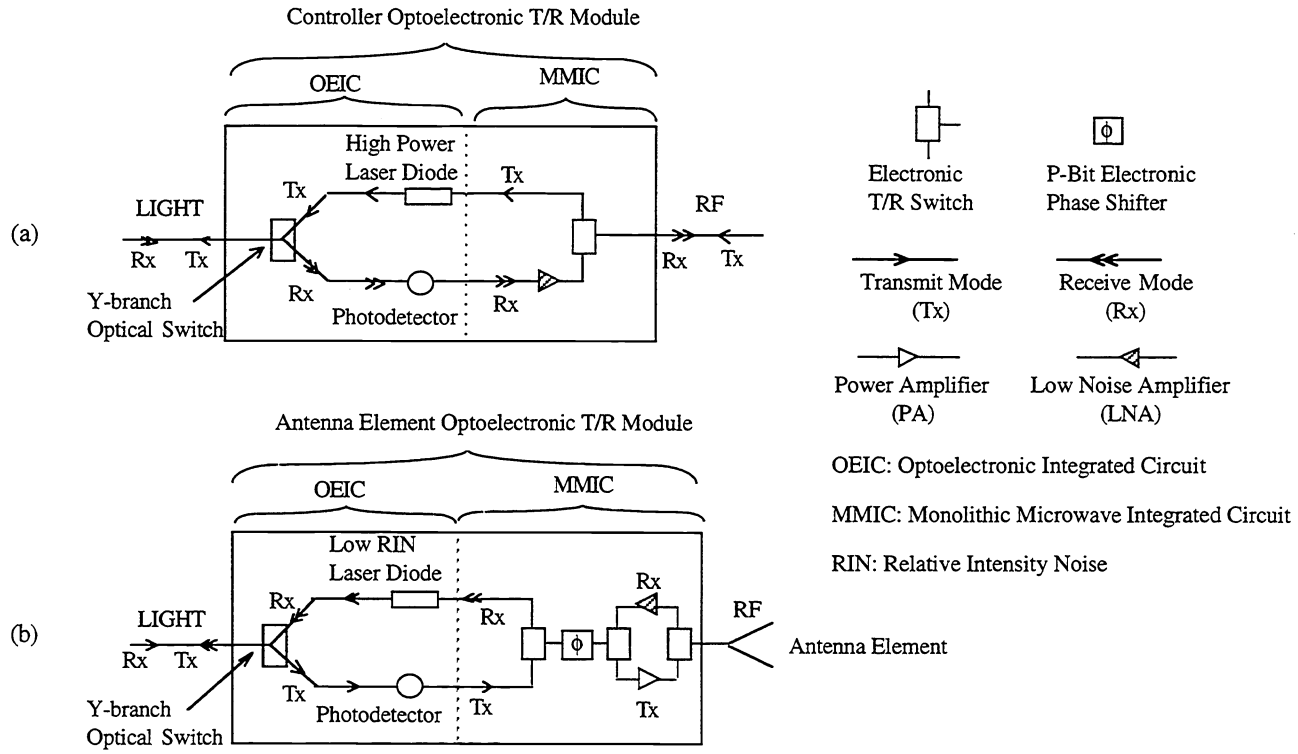


Figure 14: (a) Controller Optoelectronic Transmit/Receive Module, and (b) Antenna Element Optoelectronic Transmit/Receive Module used in our wavelength multiplexing photonic control system.

8. Conclusion

We have presented various novel PTDL architectures based on different optical polarization components and different design geometries. Each architecture has its advantages and limitations. The choice of which architecture is the most appropriate will depend on a trade-off between the various system design constraints and the specific application requirements. A combination of PDTL architectures can be utilized in a time delay system to cover different system requirements. For example, a symmetric PTDL can be used to provide the short time delays for the least significant bit (LSB) and the reflective architecture fiber delay line can be used to provide the longer time delays for the most significant bit (MSB) in a N-bit delay line. We also introduce a novel ternary PTDL architecture that can give a larger number of time delay settings than a binary architecture with the same number of bits. Finally, a unique wavelength multiplexed photonic reversible time delay control system combined with a single channel dispersive fiber switched PTDL for wideband phased arrays is introduced that can greatly reduce the number of control modules used for beam steering and control. Note that it is also possible to use a fiber with gratings to form a discretely variable non-switched optical delay element using a single tunable laser source [18, 19]. Therefore, we also propose, for the first time, a single channel switched fiber-grating-based optical delay line with a wavelength multiplexed optical input/outpu forming the required "Single channel F-bit switched PTDL" needed for our CREOL system in Fig. 13. Recent experimental results presented in reference 10 show that the use of imaging lenses is critical for low loss fiber-to-fiber coupling when implementing long time delays in PTDL systems. Presently, we are looking into systems that can monitor and control, in real time, the polarization of the input light to the PTDLs. This issue is important in our polarization switching-based PTDLs, especially in the case when we use optical fibers to couple light from the remotely located lasers into our system. Future work relates to the experimental demonstrations of these novel photonic control systems using imaging lenses.

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