# Analog Vector Modulation-Based Widely Tunable Frequency Photonic Beamformer for Phased-Array Antennas

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***Abstract*—A compact free-space/solid optics photonic controller for phased-array antennas/transducers is introduced which uses the principle of in-phase (I) and quadrature (Q) vector modulation via two-dimensional (2-D) spatial light modulators (SLM's). The SLM's are used as distributed optical-gain control devices to implement the required vector modulation operation required to generate the desired RF signals with the correct phase and amplitude values.**

***Index Terms*— IQ vector modulation, phased-array antennas, phased-based beamforming, photonic beamforming, amplitude-modulated spatial-light modulators.**

## I. Introduction

OVER the last ten years, several photonic control systems for phased-array antennas have been proposed for both time-delay and modulo-$2\pi$ phase-based control [1]. Most phased-array antenna systems used in communications and radar applications use phase-based array control, which implies that the system operates in a narrow-band mode, i.e., a few percent of the system-carrier frequency. Most previous phase-based photonic beamformers have directly relied on optical phase shifts introduced via spatial light modulators (SLM's) in optical interferometers, or via integrated-optic (IO) waveguide electro-optic phase shifts in IO Mach–Zehnder (MZ) interferometers to generate the required RF phase shifts. Depending on the application environment, these systems can be quite sensitive to mechanical vibrations as interference on a sub-micron scale forms the basis of these systems. In this paper, we propose a novel phase-based photonic-control system for phased arrays which does not directly rely on the optical phase shifts to obtain the equivalent RF phase shifts for array beamforming and beamsteering, thus forming a more stable and robust array controller [2]. The principle behind the operation of this photonic controller is analog vector modulation, a method which dates back to the 1930's, when Armstrong, a pioneer in electronic radios, proposed various signal modulation methods including a basic in-phase/quadrature (I–Q) signal-phase modulator [3].

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Recently, an IO analog of the RF I–Q phase shifter has been proposed using the intrinsic modulation and biasing properties of IO MZ amplitude modulators (MZAM's) [4]. In one design of this IO photonic I–Q device, two independent variable-gain controlled lasers (controlled via two amplifiers) feed two MZAM's which are further coupled to a 2:1 IO coupler that couples to a fiber and detector. The MZAM's are electrically driven via an RF 90° hybrid coupler. Thus, for each antenna element in the array, a separate IO photonic I–Q device is required which contains eight separate components (not including the fiber and detector). This means that for an $N$-element phased array, $N$ IO photonic I–Q devices are required with a total of $8N$ components. For a typical microwave radar with 1000 elements, this means 8000 components; a possible cost and interconnection challenge, let alone the varied nonlinear effects specifically from the MZAM's, along with the varying path lengths caused by the use of the many element level hybrid couplers. Thus, there is the possibility of a calibration nightmare for the entire system. The purpose of this paper is to introduce a photonic controller which also relies on the I–Q vector modulation principle, but does away with the thousands of IO components, and instead uses a few bulk optical components to implement the required phased-array control operations.

## II. The I–Q Vector Modulation Principles and the Photonic Beamformer

Fig. 1 shows the four cases on how an I–Q vector modulator architecture can generate 0°–360° phase shifts for an input RF carrier, in addition to providing amplitude control. The key principle behind the I–Q technique is the weighted summation of two phase-shifted signal replicas where the relative weight of the adding signals controls the phase and amplitude of the resultant vector sum signal. For 0°–360° phase control, we need two pairs of amplitude trimmer sets. In other words, for a 1000-element array, we need 4000 amplitude-control grey-scale devices. In our controller, this amplitude-control operation can be done in three nematic liquid-crystal (NLC) SLM's. Previously, we have experimentally shown that NLC's can give over 7 b of grey-scale control [5], with a potential of over 12 b of optical dynamic range, i.e., 5000:1 or 36-dB optical on/off attenuation, or 72 dB of RF attenuation [6].

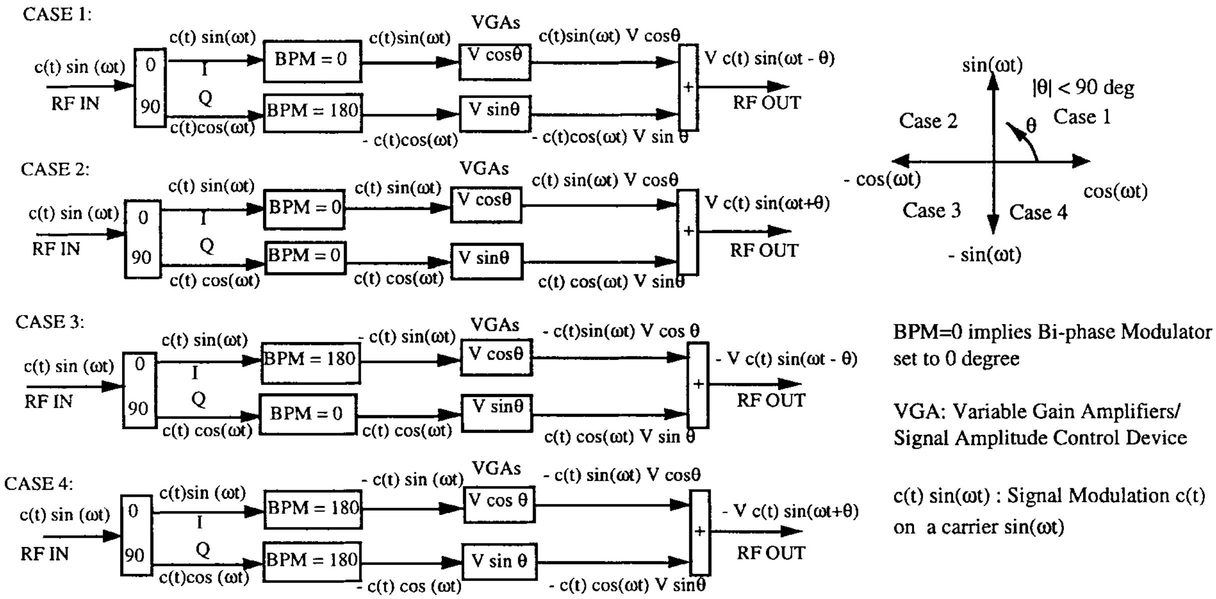



Fig. 1. The key principles of the I–Q vector modulator which are used in our photonic controller.

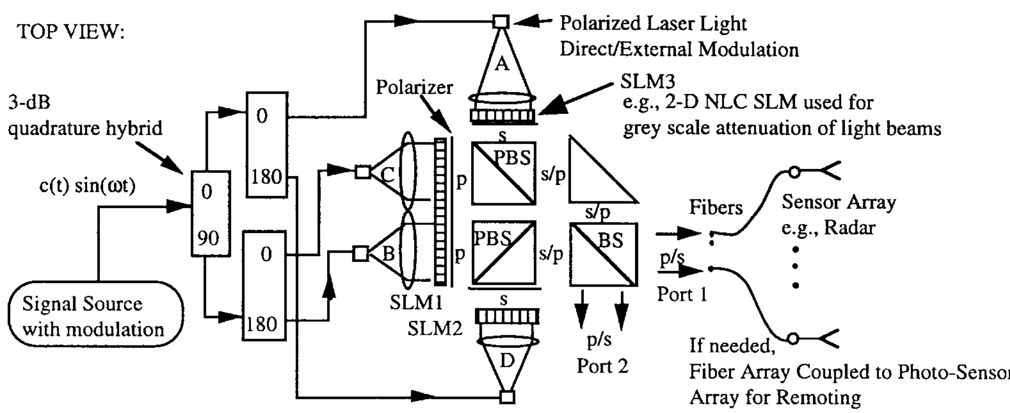



Fig. 2. One typical design of the proposed compact photonic controller which uses three SLM's for the optical attenuation operation required for controlling phased-array systems.

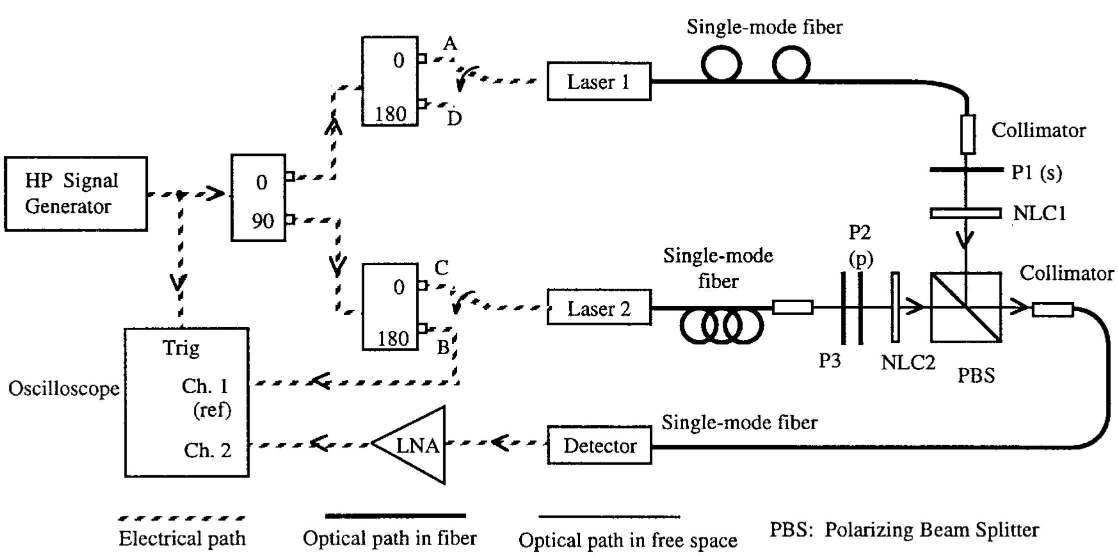



Fig. 3. The experimental setup used to demonstrate the principles of our photonic controller.

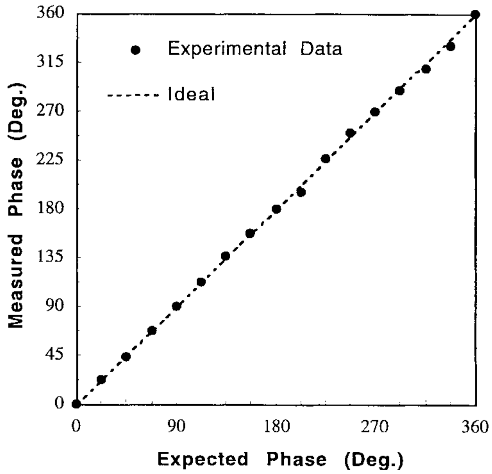
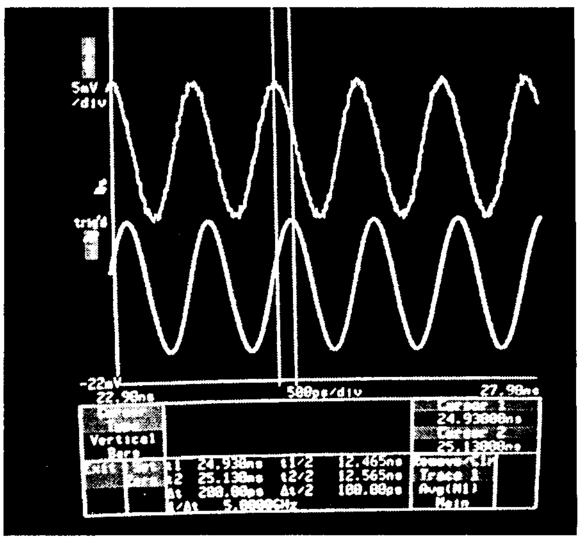
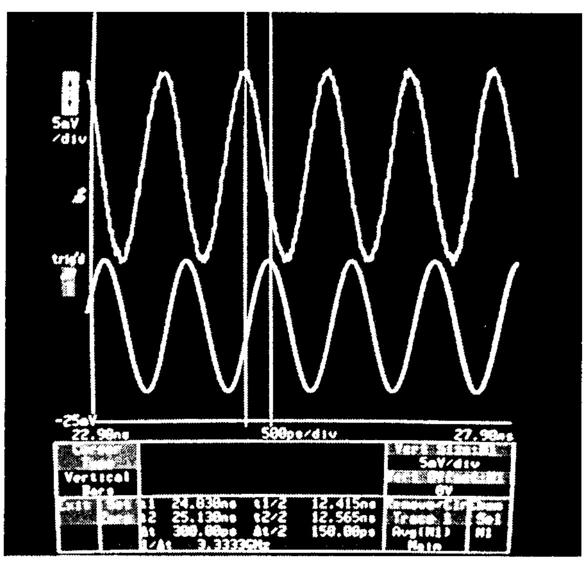



Fig. 4. A plot showing a comparison of the expected versus measured phase-shift data from our laboratory system operating at 1.017 GHz.




(a)




(b)

Fig. 5. (a) Shows the reference time origin while (b) shows the 36.6° phase-shifted 1.017-GHz signal output from the photonic controller (time scale: 500 ps/div). The top traces (5 mV/div) are the photodiode outputs while the bottom traces are the reference signals coming from the appropriate (and unused) electronic 180° hybrid port.

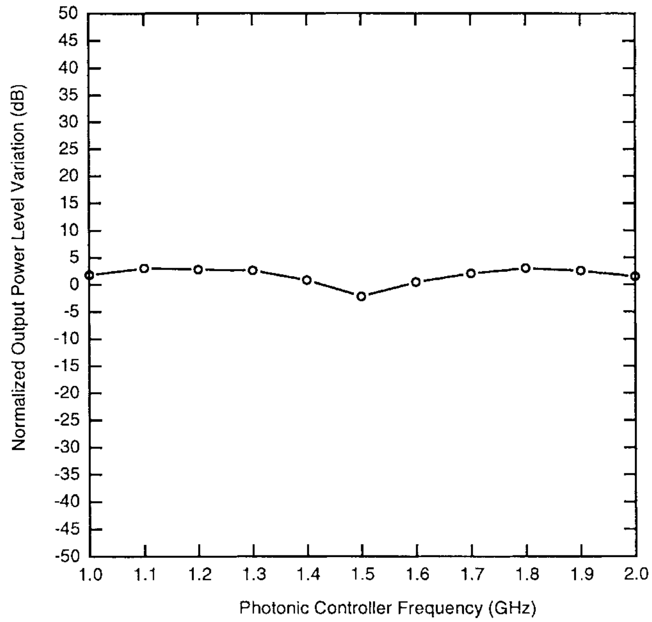



Fig. 6. Experimental photonic controller data showing a 1–2-GHz widely tunable frequency.

Fig. 2 shows one possible design of the photonic controller. Four different sets of intensity-modulated light beams labeled $A$, $B$, $C$, and $D$, are incident on their respective $N$ pixel areas on their SLM's. Here, the phased array has $N$ elements; thus SLM1 has $2N$ pixels, while SLM2 and SLM3 each have $N$ pixels, giving the required total of $4N$ optical-gain control sites. To generate a signal with the correct phase and amplitude for the $n$th element in the array, a combination of two light beams from only two of the sets is required, i.e., $A+B$ (case 1), $A+C$ (case 2), $D+C$ (case 3), or $D+B$ (case 4). Thus, if $A+C$ is required, then the light from the $n$th pixel in sets $B$ and $D$ should be fully attenuated. The system is designed such that any two beams per pixel which are optically combining at the photo-sensor have orthogonal polarizations. For example, the beams from set $A$ are $s$-polarized (vertical) while the beams from sets $B$ and $C$ with which $A$ can combine are $p$-polarized (horizontal). Because the polarizations are orthogonal, undesired coherent mixing effects are minimized. This is a vital feature of our controller as linear summation of light-beam intensities is required at the optical sensor to give a linear summation of electrical-signal components. This also means that it is preferable that the two light beams are mutually incoherent to minimize coherent mixing effects or their beat signal is out of the range of photo-sensor or feed-channel RF bandwidth. There are various ways to achieve this mutual incoherence. In our approach, only two laser sources have to be mutually incoherent. In other words, the same laser can feed the two independent optical modulators which generate light-beam sets $A$ and $D$. Similarly, one laser can generate the other sets $B$ and $C$. This is because on any $n$th photosensor, the operations $A+D$ and $B+C$ never happens. Our polarization-based design also allows us to replace the four independent lasers used in Fig. 2 with a single high-power laser that simultaneously feeds four high-speed optical modulators. Other spatial and temporal techniques can also be

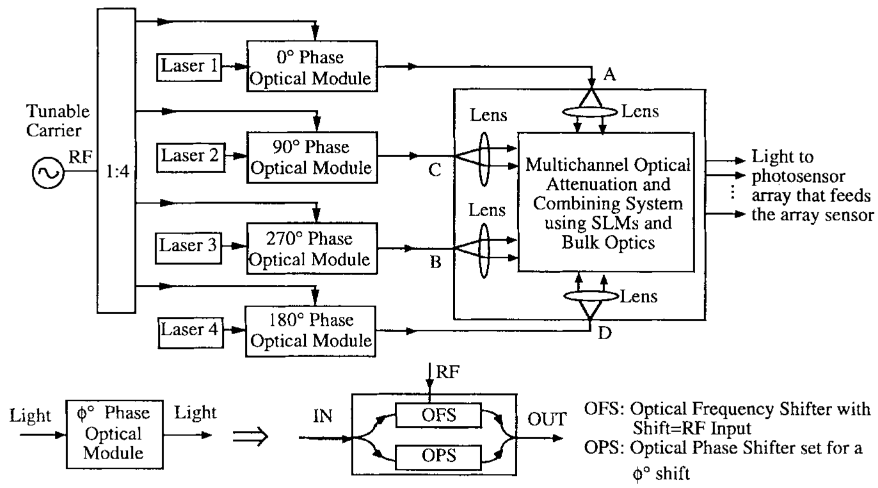



Fig. 7. The all-optical photonic beamformer with an extremely wide operational frequency.

used to reduce coherent mixing effects in the system. These include the use of moving diffusers to randomize the phase of the combining light beams, introducing relative time delays greater than the coherence length of the single source laser which feeds the four optical modulators that generate the four light sets, and the use of two mutually incoherent (wide linewidth) broad-band high-power lasers.

Note that when the controller RF carrier frequencies get high into the millimeter-wave regime, the slight electrical- and optical-path differences in the optical sets (e.g., $A$ and $C$) can cause relatively large RF output-signal phase errors. Ideally, in order to avoid this problem over a very high RF band, the photonic controller should be designed for zero path differences. In the Fig. 2 design, the combinations $A+C$ and $B+D$ have zero optical-path differences, while the other two cases have an optical-path difference which is equal to a cube side or approximately 0.1 ns for a 3-cm side cube. It is possible to use appropriate signal-flow layouts to minimize or compensate for any optical- and electrical-path differences. Note that the system has two output ports, where one port can be used for the transmit mode while the other set is used for received array processing via local-oscillator (LO) mixing [5]. Note that the photosensors can be used to act as down-converters, if used as three-terminal devices [7], thus causing the received signal to be mixed with the replica of the transmit LO which is generated by the optical system.

## III. Experimental Demonstration

Fig. 3 shows the experimental setup. We used two 2-mW directly modulated 1310-nm semiconductor lasers and one p-i-n photodiode receiver with a 7-GHz bandwidth. The 90° and 180° hybrids had a 1–2-GHz bandwidth. A 1.017-GHz 12-dBm signal from a synthesized sweeper feeds the 90° hybrid. The photodiode output is fed to a 20-dB-gain low-noise amplifier (LNA). The optical-beam gain-control devices used are two parallel-rub birefringent-mode single-pixel NLC devices which are driven by variable-gain 1-kHz square-wave signals. First, the RF- and optical-signal paths are adjusted for zero-path difference at a chosen frequency of 1.017 GHz. Next, output-signal phase-shift data is taken by varying the relative ac-level signal generated at the photodiode by the orthogonally polarized light from the two independent lasers. Fig. 4 shows that the measured phase shift is indeed the expected phase shift. This data is taken by using the two appropriate hybrid output ports for generating the phase shift in the desired quadrant. The measured carrier-to-noise ratio (C/N) of the photodiode output after the LNA was 85 dBc/Hz@+10-kHz offset using a 3-kHz analyzer resolution bandwidth (RBW). This C/N is the same as that measured for the fiber-optic link without the photonic controller; hence, the controller does not degrade signal quality and only acts as an attenuator. Fig. 5 shows the 1.017-GHz phase-shifted signal outputs from the photonic controller. Notice the expected change in the photodiode-output ac level when the phase is changed. Recall that we induce RF-signal phase change by controlling the relative optical power levels of the adding optical beams; hence, the change in the resultant vector magnitude.

## IV. System Features and the All-Optical Widely Tunable Frequency Beamformer

One advantage of our beamformer is that regardless of the number of antenna elements $N$ (within certain design constraints), the number of bulk components (in Fig. 2) remain the same, and only the pixel count in the SLM's changes. The hardware is largely frequency insensitive as only the three RF hybrids and perhaps the modulation electronics of the four lasers need to be changed when changing the frequency of operation. Other reflective, transmissive, and absorptive mechanism SLM's can be used in the controller such as deformable mirror devices, magneto-optic SLM's, multiple quantum-well device SLM's, and ferroelectric liquid-crystal SLM's. The bulk-optics nature of the controller allows us to use high-power lasers, unlike IO designs. An important feature of the photonic controller is its widely tunable carrier. Fig. 6 shows experimental data from the photonic controller indicating a wide 1–2-GHz tunable frequency. Note that this operational tunable bandwidth is mainly limited by the performance of our electronic 3-dB hybrids which were designed for a 1–2-GHz operational bandwidth.

One method to realize wider tunable frequencies is to replace the three electronic hybrids with three optical hybrids. Fig. 7 shows this all-optical photonic beamformer with an extremely wide operational carrier. This system shows how four mutually incoherent lasers, when combined with present-day externally fed integrated-optic lithum–niobate optical frequency and phase modulators, can lead to a controller tunable frequency of near dc to 18 GHz. Because the IO phase shifters are physically independent from the input RF, pure optical and, hence, RF phase shifts can be obtained for the 0, 90, 180, and 270° settings. Hence, each of the four input beams to the multichannel optical attenuation system are actually two beams; one beam has an optical frequency shift equal to the RF while the other beam has no frequency shift but has a predetermined optical phase shift. Hence, both colinear beams will pass through the multichannel optical attenuation system, receiving equal attenuations. Only on heterodyne detection at the photosensor is an RF signal with the correct hybrid phase and amplitude generated. Recall that only light from two of the four lasers is selected per pixel to fall on the photosensor. Hence, two variable-gain heterodyne detected RF signals (with different hybrid RF phase shifts) are generated at the photosensor. These two signals electrically add to give the required vector sum which leads to generation of the desired phase- and amplitude-controlled RF signal which is eventually used for beamsteering in a phased-array sensor. Alternate techniques for tunable control include phase-locking techniques with independent lasers.

## V. Conclusion

We have described a photonic beamformer which uses amplitude-modulated SLM's for RF signal phase and amplitude control. Full 360° phase control has been demonstrated for a 1-GHz RF carrier signal. Tunable operational frequency of 1–2 GHz has been observed for this system. An alternative wide-band all-optical system has been proposed to extend the tuning range of the system to 18 GHz. Applications for the photonic system can include wireless communications base-station antenna arrays, air-traffic radars, and broadcast satellite phased arrays.

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