NEW ARRAY CAPABILITIES BY PHOTONIC BEAMFORMING (INVITED)

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ABSTRACT

A large number of organizations are currently developing concepts in photonic beamforming. We briefly review the growth and then present an updated and expanded motivation for photonic beamforming in terms of current system expectations. Fortunately, many experiments in the literature demonstrate the enormous potential for photonic techniques to meet the growing demands. Current photonic capabilities and limitations based on dispersion are presented.

SUMMARY

The serious interest in using optical processing for RF phased arrays began about the time that G.A. Koepf proposed the free-space heterodyne optical beamformer [1]. At that time, the motivation was toward generic phased arrays (of any kind) to attain the associated benefits of rapid, non-mechanical steering. The optical processor introduced simple two-command (i.e., azimuth and elevation) beamforming and helped address the problems of hardware complexity and weight and prime-power consumption of active phase shifters [1]. Other added capabilities were also provided including amplitude and phase weighting as well as general Fourier transformations of the optical beam into an RF beam. Since then, the research activity in optical beamforming has flourished as measured by the increase in publications (Fig. 1), which have been doubling about every 4 years. Since 1984, both the needs and advantages of optical control have also grown. Here, we present an updated version of the needs, advantages, and limitations of optically controlling a phased array.

The needs for optical beamforming continue, have grown, or new ones have appeared in the following ways. Phased arrays remain useful for compensating platform movement, generating randomly accessed beam directions, beam shaping (including sidelobe control and nulling), providing graceful degradation, and, with solid-state amplifiers, improving reliability. Additionally, demands have expanded due to practical frequencies of interest extending to the 35 GHz, 60 GHz, and 90 GHz ranges for various applications including radar systems, personal communication services, and automobile collision warning systems. Since antenna elements are typically spaced in inverse proportion to frequency, the increased frequency reduces available volume or "footprint" at the antenna interface. The number of elements of phased arrays has grown, in some applications, to a few thousand and, hence, component costs must be reduced or shared, specialized components are precluded, and even greater parallel processing is required.

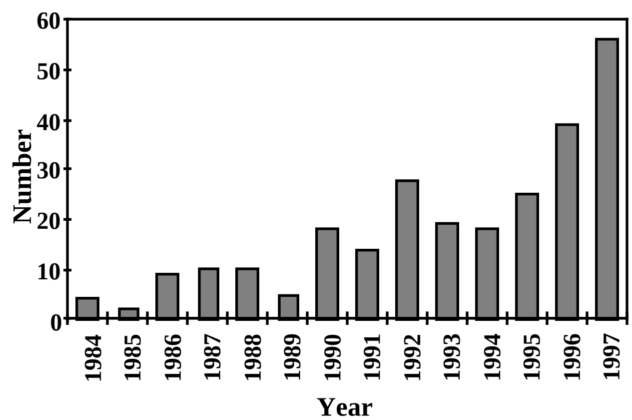

Figure 1. Approximate Number of Publications by Year

The combination of large phase-steered arrays (for spatially-combined high power or for high angular resolution) and wide bandwidths (for large communication channels, high range resolution, spread spectrum, multipath mitigation, etc.) necessarily implies beam squint. Hence, a true time-steered array is needed. Also, the need for wide bandwidth has been exacerbated by the increased interest in multifunction arrays, arrays that instantaneously and simultaneously combine several types of radar, electronic warfare, and communications channels. Although challenging, the multifunction aperture offers numerous benefits for various military platforms including a) radar cross section reduction, b) reduced total aperture cost, c) improved antenna siting, d) easier functional upgradeability, and e) increased performance [2]. In addition to bandwidth, a multiple channel system also demands continued and

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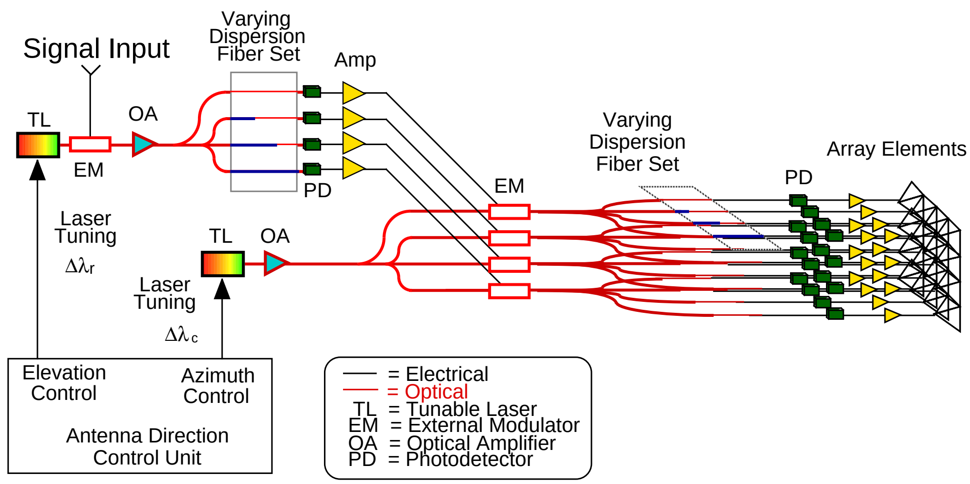

Figure 2. 4x4 Transmit Array Configuration

improved immunity to electromagnetic inteference. Other not-so-often appreciated demands include flexible feed harness, passive (amplifierless) harness, a rugged, fieldable design, immunity to lightning strikes, and long-distance delivery of high-fidelity, usable signal levels. Indeed, the list of specifications for the beamformer has grown and become more de-manding. In many ways, however, these demands help to highlight the numerous capabilities of the photonic approaches.

In fact, optical beamformers have already responded to many of the above needs as follows. The basic phased array beamforming function has been demonstrated in anechoic chambers and in the field [3-8]. These demonstrations have included time steering in both transmit and receive modes—well beyond the conceptual, laboratory-bench stage. Most optical designs can, in principle, be extended to millimeter-wave frequencies. Optical receive modules have been fabricated that measure less than $\Lambda/2$ on a side at 20 GHz. Utilizing wavelength division multiplexing, a unique feature of photonics, beam shaping and simultaneous multi-beam demonstrations have been reported for both transmit and receive modes. At the Naval Research Laboratory, the dispersion-based beamforming approach has proved to provide much of the needed functionality with few limitations and is illustrative of the capabilities of beamformers.

Our fiber-optic beamformer is based on a simple dispersive prism optical delay approach (Fig. 2), with separate azimuth and elevation control stages. The azimuth dispersive prism stage includes an amount of dispersion in each link proportional to the corresponding column position in the array. The microwave signals, properly time-delayed for azimuth steering, are amplified and serve as inputs to identical dispersive prisms feeding the elements in each column. The elevation dispersive prism stages include an amount of dispersion in each link proportional to the corresponding row position in the array. Each time-delayed microwave signal feeds a single element in a 4 x 4 array. Two-dimensional array pattern measurements in an anechoic chamber clearly demonstrate independent ±30˚ azimuth and ±30˚ elevation steering. There was no observed squint over the microwave-component determined bandwidth of 6-18 GHz [7].

Also, with a one-dimensional version of the same beamformer, we have demonstrated fully-independent, dual-beam, dual-frequency ultrawide-band antenna transmitter operation. The multiple beams at a single frequency could be viewed as beam shaping. Furthermore, the linear beamformer was shown to be capable of controlling the transmitter under pulsed operation with microwave pulse-widths as short as 75 ps, which has also recently been extended to receive mode. The receiver (Fig. 3) is based on the same dispersive-fiber prism configuration that properly time-delays the signals originating at receiving each element for (RF) coherent combining in the optical domain. The receive array showed an instantaneous bandwidth of 6 to 18 GHz, limited by the available matched microwave amplifiers. The array exhibited unprecedented squint-free steering over an azimuth scan of 120° over the full frequency range. Lastly, simultaneous multiple-beam capability was demonstrated; the receiver exhibited squint-free ±60° azimuthal steering of two simultaneous beams with no observable beam squint over the 6 to 18 GHz range [8].

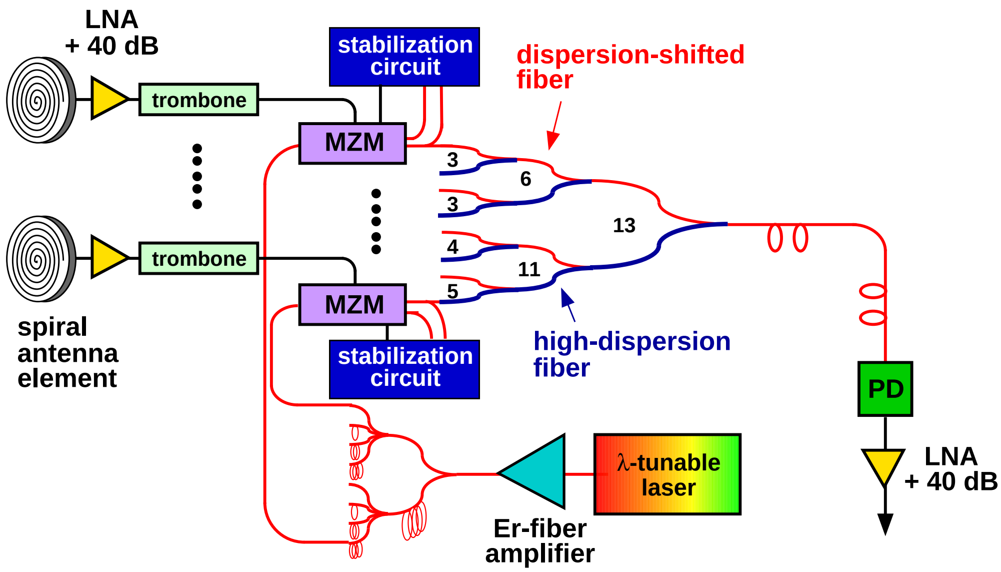

Figure 3. The fiber-optic true time-delay receiver schematic.

An apparent limitation of the dispersion-based beamformers may be dispersion itself. Namely dispersion of the modulated optical signal can distort the microwave signal at higher frequencies. However, large arrays (requiring large time delays and, hence, large dispersion) typically operate over lower frequencies. Consider the following: it can be shown that microwave power loss due to dispersion of an AM-modulated optical carrier is given by

$$\text{RF Throughput} \propto \cos^2\left[\frac{\pi LD}{c}\lambda^2 f^2\right]$$

or, the 3-dB frequency is given by

$$f_{3dB} = \frac{1}{2\lambda}\sqrt{\frac{c}{LD}} = \frac{1}{2\lambda}\sqrt{\frac{\Delta\lambda c}{\Delta\tau}}$$

where L is the length of dispersive fiber, f is the RF frequency, D is the fiber dispersion, λ is the optical wavelength, $\Delta\tau = LD\Delta\lambda$, $\Delta\tau$ and $\Delta\lambda$ are the minimum time delay and minimum wavelength (tuning) ranges, and c is the speed of light. We notice, however, that for a square aperture having a beamwidth given by $\Delta\theta_{3dB} \cong \Lambda / A$, where Λ is the RF wavelength and A is the aperture width, the maximum time delay $\Delta\tau$ needed is $\Delta\tau = A/c = 1/\Delta\theta_{3dB}\, f_{max}$. If we set, $f_{3dB} = f_{max}$, $\lambda = 1.55$ µm, and the laser wavelength tuning range $\Delta\lambda = 50$ nm, we find that

$$f_{3dB} \cong \frac{\Delta\theta_{3dB}\Delta\lambda c}{4\lambda^2} \cong \left(\frac{27\,\text{GHz}}{\text{deg}}\right)\cdot \Delta\theta_{3dB}$$

Hence, dispersion simply limits the frequency/beamwidth ratio, not the operating frequency.

Another drawback of a beamforming technique such as this one is the added complexity, cost, potential matching errors, etc., of the double RF-Optical-RF conversions. However a novel hardware-optimized approach has been proposed [9] to circumvent this problem. It can be summarized as follows: a one-dimensional time-gradient in N fibers is routed to M output fibers, independently using a programmable switch array (preferably a diffraction grating as shown in Fig. 4). Each time-delayed input is properly routed to one or many outputs corresponding to one or many arrays elements. Hence, only a one-dimensional beamformer is needed. This technique incorporates a number of significant advantages over existing approaches which include: minimized 2-D architecture complexity by requiring effective time-delay steering along a single dimension only, added flexibility in being able to select any of the many time-delay implementation options, and potentially reduced optical insertion loss. Furthermore, as with many previous photonic architectures, the critical technology required to implement the new design is leveraged off the rapid developments pursued by the telecommunications industry and is available today in commercial form.

Therefore, the few specific drawbacks of the dispersion-based beam- former have been addressed and may lead to some system trade-offs (as with all system designs), but the approach can meet specifications of many systems. Other more generic issues raised with wideband photonics for

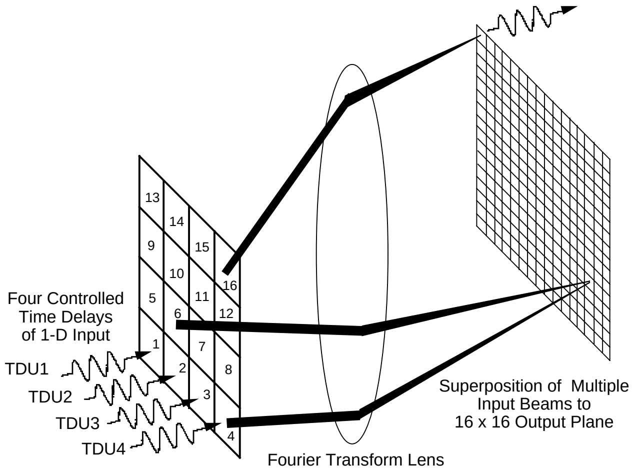

Figure 4. Holographic, dynamically-reconfigurable optical interconnection implementation.

beamforming systems include limited spur-free dynamic range (SFDR) (<100 dB·Hz$^{2/3}$), high noise figure (>30 dB), and low microwave output power (<10 μW). To quell these concerns, there have been two notable recent results. First, a broadband 3 GHz fiber optic link has been demonstrated with +5 dB gain, 16 dB noise figure, 119.5 dB·Hz$^{2/3}$ multi-octave SFDR, 168.4 dBHz 1-dB compression range, and >+10 dBm output power [10]. Additionally, two fiber optic links have been demonstrated to have minimal effects on a state-of-the-art AN/SPQ-9B pulsed-Doppler Advanced Development Model radar [11,12] exhibiting 87 dB SNR. Therefore, photonic beamforming remains a strong candidate for future systems. The challenge at this point seems to be obtaining state-of-the-art link performance (whose SFDR outperforms many microwave amplifiers) with a beamformer.

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