Invited Paper

PRACTICAL PHOTONIC BEAMFORMING

Paul J. Matthews

Naval Research Laboratory
Code 5651, Optical Sciences Division
Washington, DC 20375-5338

I. INTRODUCTION

Phase-array antennas are seeing increased acceptance due to the many advantages they possess over more traditional fixed or mechanically steered antennas. The more advanced uses of array antennas also permits the possibility of multiple, simultaneous, independent beams performing different functions and sharing a common antenna aperture leading to an increased system affordability.

Despite these advantages, array antennas have not seen universal acceptance due to various system limitations of all-electronic control of the array elements. The major drawbacks of current phased array antenna systems have been cost, complexity, size, weight, loss, EMI susceptibility and narrow instantaneous bandwidths of the signal distribution and beamforming networks. Many research efforts have sought to alleviate these problems through either traditional electronic means or by the use of photonics. Due to the interest in this area, optical control of array antennas has served as a primary motivating factor in the field of microwave photonics.

Early photonic efforts for array antennas simply sought to attain some of the benefits touted for array antennas while reducing the considerable hardware complexity, weight and size associated with these systems. Despite many novel and excellent research efforts, photonics failed to have much impact at the system level for array antennas. This was due in part to a natural resistance by systems designers to new technologies, the advancement of solid-state and packaging technologies to overcome many of the early size/weight/cost/complexity issues and the lateness of the photonics community in understanding and addressing the important systems issues involved in transitioning to a real-world application.

The impetus for future array antenna systems has revolved around the demands for increased capabilities in array antennas including larger arrays for higher power and better angular resolution, wide bandwidths, reconfigurability and higher operating frequencies. In order to move microwave photonics technology for array antennas beyond the proof-of-concept phase and to compete with alternate approaches, the community must be quicker to grasp the systems issues involved. This talk will survey some of the photonics techniques for optical control of array antennas, address the

system-level issues for technology insertion and discuss some of the competing technologies.

II. PHOTONIC APPROACHES

In general, photonic beamforming implementations may be categorized according to the intended instantaneous bandwidth of the application. Phase-steered techniques, similar to traditional electronic techniques are intended for narrow instantaneous bandwidths. True time-delay (TTD) techniques provide the wide instantaneous bandwidths required by many future applications such as imaging radar systems. A large variety of optical phase-only and true time-delay beamforming techniques have been proposed. A collection of original papers, reprinted in [1], summarizes the state of the art circa 1996.

A number of photonic techniques use either externally-modulated or directly modulated optical links, with various methods for implementing the phase-shift function [1]. However, the associated RF insertion losses, non-linearities, reduced dynamic range, increased system costs and the requirement for high-power electronic signal sources to drive the links negates many of the advantages offered by photonics. Coherent optical techniques have also been proposed which generate the microwave carrier signals directly from two optical waves [1, 2] or from a single source using optical frequency shifters [3, 4]. The relative phase shifts between adjacent elements are introduced in the optical domain where wavelength is considerably shorter, thus reducing beamformer size requirements. Phase shifts may be introduced via angular spatial offset of two optical beams [2, 5, 6, 7], using a lens as a spatial Fourier transform element, with the far-field pattern corresponding to another Fourier transform.

Much of the recent focus in optical control of array antennas has centered on the use of photonic techniques for true time-delay beamforming. This is due to the fact that most traditional microwave implementations of TTD beamformers suffer from severe drawbacks and are currently impractical for a variety of reasons. The numerous approaches to photonic TTD beamforming may be grouped into two main categories – switched-path delay lines (either free-space or integrated optic) and modulated propagation velocity time-delays. A third, smaller category may include optical implementations of a Rotman lens [8].

Figure 1. The average sidelobe levels of an N element array as a function of random amplitude and phase errors.

Switched-path optical delay lines seek to mimic the traditional microwave solution to TTD beamforming. Some of the methods proposed and demonstrated include [1] integrated optical [9], acousto-optic, free-space and polarization-based switching to name a few. One of the more well-developed demonstrations is the switched optical source and detector approach which was capable of steering a 96 element, conformal, L-band array over $\pm 60^\circ$ with a 50% bandwidth [10]. Another impressive demonstration is the hybrid microwave/photonic approach in [11] which uses wavelength-division multiplexing (WDM) to reduce system complexity.

Early modulated propagation velocity techniques were based upon dispersive fiber delay lines. Array control may be carried out by using a multiple wavelength source and switching in different lengths of dispersive fiber [12] or by using a wavelength tunable laser and a single length of dispersive fiber [13]. Efficient array control may be accomplished using the latter approach by implementing a fiber-optic prism [14]. A variation of these techniques incorporates discrete or chirped fiber gratings as the dispersive elements in the system [15].

III. PRACTICAL ISSUES

All of the photonics approaches described above possess inherent advantages and drawbacks due to the particular details of the approach. The applicability of any of the techniques is very much a function of the intended system or application. Thus, it is imperative that the needs of the targeted application are well known and that the use of photonics is clearly advantageous. Due to the recent emphasis on wideband techniques, the issues discussed below will focus on TTD systems although much is applicable for phase-steered systems.

A key requirement in the system design for any array antenna is the amplitude and phase errors (tracking) of all of the sub-systems across the frequency range of interest. This specification directly impacts the radiated beam pattern effecting

Figure 2. A hybrid TTD architecture with phase shifters at each element and subarray level time-delay.

the average and peak sidelobe levels and the beam pointing accuracy. The effect of random amplitude and phase errors on the average sidelobe level are shown in Figure 1 [16]. It is readily apparent that very low sidelobe arrays require strict control of tracking errors. Also, the effects of random errors are reduced as the array size is increased. These parameters can be related to the time-delay requirements for wideband arrays where every element is fed. In order to achieve -40 dB average sidelobes in a 100 element, 10 GHz array, a time-delay error of ~ 1 ps is required if the amplitude tracking can be held to 0.5 dB.

Periodic amplitude and phase errors are generally more problematic. These errors arise from the use of quantized, n -bit amplitude or phase control. Implementing control at the sub-array level such as is typically done for TTD beamforming due to cost and other constraints leads to a more stringent set of requirements on phase and amplitude control. Additionally, a sub-array architecture will produce quantization lobes which are essentially grating lobes due to the periodic nature of the sub-arrays. Here we will concentrate on errors due to performing TTD at the sub-array level in a hybrid phase/time-steered system as is shown in Figure 2.

The number of TTD feeds is generally a trade-off between cost and performance. The system performance parameters of interest include the instantaneous bandwidth and the average and peak sidelobe levels. The instantaneous bandwidth of the system is given by the inverse of the physical size of the sub-array

$$\Delta f = \frac{0.886c}{2Nd\sin(\theta_o)} \quad (1)$$

where d is the array element spacing, N is the number of elements in the subarray, c is the speed of light and θ_o is the angle steered off broadside. This equation determines the maximum number of elements that may be grouped into a sub-array. Thus, an array consisting of n sub-arrays of N

Figure 3. Radiation pattern for a 64 element, 10 GHz array with 8 TTD feeds and a 1 GHz bandwidth.

elements each will result in n times the bandwidth of a purely phase-steered array. The use of TTD sub-arrays also leads to quantization lobes as a result of the phase squint of the sub-array pattern relative to the time-steered array pattern. This is illustrated in Figure 3. The power in the p^{th} lobe can be solved for analytically. The sidelobe requirements usually dictate a much smaller sub-array size.

The above analysis for hybrid TTD systems implies a perfect time delay beamformer. In reality, the beamformer has a finite resolution and accuracy. In general, the requirements on time-delay resolution are more stringent than the equivalent resolution in a phase-steered system due to the lack of 2π periodicity. One method of determining the required time delay resolution in a hybrid system is to determine the minimum delay required to steer the beam from broadside by one-half of a beamwidth. This leads to

$$\tau_{\text{MIN}} = \frac{0.886}{2f(n-1)} \quad (2)$$

for a uniformly illuminated array. Thus, a one-dimensional, 18 GHz array with 64 elements having eight time-delay feeds will require a time-delay resolution of ~ 3 ps. This leads to a minimum path-length difference for switched delay-line approaches.

The overall time-delay accuracy, defined as the error from the ideal time delay for a given steering angle, is critical for hybrid architectures due to the gross effects of imperfections at the sub-array level. The time-delay accuracy is roughly equivalent to the minimum resolution but is normally more stringent. Switched delay-line techniques usually specify the time-delay in terms of the achievable number of bits of time-delay. The necessary number of bits can be shown to be

$$\# \text{ of bits} = 3.322 \log \left(\frac{2.257 L (n-1)}{\lambda} \right) \quad (3)$$

where L is the length of the array, and λ is the wavelength of the emitted radiation. From Equation 3 we can see that the number of bits required for switched delay-line techniques scales as the size of the array.

Figure 4. Measured time-delay error of a 40 nm bandwidth chirped grating ($D \sim 28$ ps/nm).

Another system related issue involves the beamsteering speed of the chosen architecture. Many applications such as a single beam, volume surveillance radar, may require beamsteering speeds on the order of a millisecond. More demanding applications or time-shared scenarios in multi-function apertures may require sub-microsecond beamsteering speeds. This implies that the proper time or phase gradient is generated and all switching transients have settled.

Issues that are often overlooked in most proof-of-concept demonstrations are the size, weight and especially the robustness or ruggedness of the beamformer. In many instances, the size and weight refer not the overall beamformer but to the hardware that are actually located at the array. Thus, architectures that minimize the number of components at the array by remoting are advantageous. The system must be stable to vibration and temperature and for space applications, radiation. Most arrays undergo an initial calibration, typically at an antenna test range, and are re-calibrated very infrequently. Thus, the beamformer must be stable and meet specifications for periods of time up to several years. As an example, in a receive array where the modulators must be at the array, the temperature drift in optical loss and modulator bias need to be considered. This, coupled with the DC drift phenomena of most commercially available modulators [17] leads to the need for active bias control of the modulators.

Environmental issues cannot be over-emphasized. The dispersive fiber techniques can involve the use of rather long lengths of fiber. In some cases, temperature fluctuations of a tens of millidegrees Celsius are problematic. In order to keep the time-delay error sufficiently low, care must be taken in the mechanical layout. For instance, winding all of the fibers on a common spool drastically reduces temperature problems. In most cases, some form of temperature control is necessary. The use of chirped grating minimizes this problem but does not eliminate it. A plot of the temperature dependence of a chirped fiber grating ($D \sim 28$ ps/nm) is shown in Figure 4. For most arrays using chirped gratings, a temperature control of $\sim 1^\circ \text{C}$ needs to be maintained.

In addition, the efficient use of optical power must be addressed in a systems environment. Until optical amplifier costs become negligible, architectures that are optically inefficient will be at a disadvantage. Also, in many cases where the available optical power is limited, inefficient architectures can lead to a performance degradation from insufficient optical power. Cost and reliability must also be addressed for the custom or specialized components used in architectures.

IV. COMPETING TECHNOLOGIES

In order to target insertion opportunities, knowledge of the competing technologies is essential. Most papers on photonic beamformers tend to discount switched microwave delay lines as a viable TTD technique. However, for many applications, especially at frequencies below 5 GHz, the performance of microstrip binary switched delay lines is comparable to or better than many photonic implementations at a significantly reduced cost [11]. Another approach that is currently being pursued is the use of a distributed waveform generator technique for transmit purposes. In this method, all waveforms are digitized at baseband, distributed to the subarrays via an electronic digital crosspoint switch where they are converted back to analog and then upconverted to the proper frequency individually at each subarray. Time-delay steering is implemented via a phase shifter on the clock input for the subarray DAC.

V. CONCLUSIONS

The use of photonic techniques for array antenna beamforming holds much promise for insertion into future systems. In order to realize this potential, the practical aspects of array antenna control and beamsteering need to be addressed. Also, careful consideration must be given to the systems and applications which would benefit most from the use of photonic techniques.

As an example, the dispersive prism TTD beamformer approach was recently transitioned to a 256 element transmit array covering the X and Ku bands [18]. The unit was extensively field tested at an outdoor antenna range and onboard a ship. Many of the issues discussed above had to be addressed in this transition effort illustrating their importance.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research.

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