All-optical BEAMTAP beamforming system

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ABSTRACT

We present a new approach to the all-optical implementation of time-delay-and-sum array processing for large, wideband adaptive-beamforming and nulling phased-arrays that utilizes two coherent-fiber tapped-delay-lines.

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1. Introduction

In this paper we present a new all-optical implementation of the BEAMTAP adaptive array processing system that is equivalent to the conventional time-delay-and-sum beamformer using least-mean-square (LMS) adaptation. The Broadband and Efficient Adaptive Method for Time-delay Array Processing (BEAMTAP) algorithm decreases the number of tapped delay lines required to process an N-element phased array antenna from N to only 2.[1] The implementation presented here utilizes adaptively cohered fiber tapped delay lines in order to avoid any bandwidth limitations associated with our previously discussed implementations based on acousto-optic devices or time-delay-and-integrate CCD detector arrays. This system can fully and optimally adapt to an arbitrarily complex spatio-temporal signal environment that can contain broadband signals, narrowband and broadband jammers – all of which can arrive from arbitrary ranges and angles onto an arbitrarily shaped array – thus enabling a variety of applications in radar, sonar, and communication. This algorithm is an excellent match with the capabilities of RF photonic systems using gratings in photorefractive crystals as adaptive weights, wideband EO modulators, a single coherent detector and the fiber tapped delay line assemblies. Because the number of available adaptive coefficients in a photorefractive crystal is practically unlimited, these photonic systems can adaptively control very large 1-D or 2-D phased arrays operating at ultra-wide instantaneous bandwidths that are well beyond the capabilities of conventional RF, real-time digital signal processing techniques, or alternative photonic techniques.

2. Adaptive Array Processing

Conventional broadband time-domain beamformers for phased array processing of radar signals require one tapped delay line (TDL) for each antenna element to avoid beam squint. Often these TDLs are implemented with digital delay lines at low frequencies for narrowband systems (up to a few MHz). To process frequencies or bandwidths up to about a GHz, TDLs can be implemented with ultrasonic delay lines, which can be conveniently tapped by acoustooptic diffraction.[2]At very high frequencies (perhaps even up to 100GHz) fiber optic TDLs have been proposed,[3–5] and in this paper we show how to efficiently utilize such fiber-optic tapped delay lines in fully adaptive beamforming and jammer nulling systems.

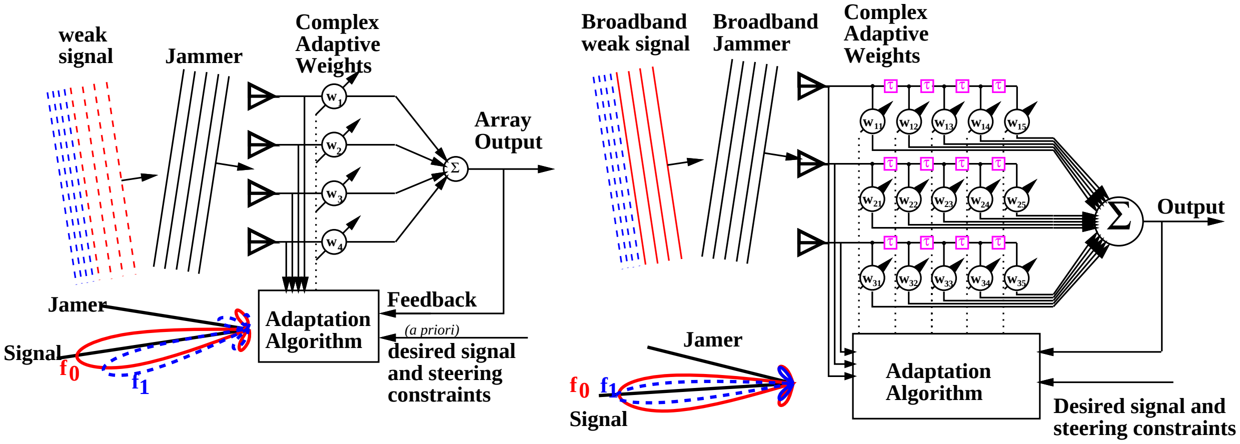

Figure 1: a) Narrowband phased array that suffers from frequency-dependent beam squint, b) conventional broadband true time delay beamforming algorithm illustrating the requirement for one tapped delay line at each antenna element in order to eliminate beam squint.

Large arrays can have up to 1000 elements for 1-dimensional arrays and up to 100×100 elements for 2-dimensional arrays, requiring $N = 10^3 - 10^4$ broadband TDLs which is both expensive and technologically challenging. These TDLs are necessary to avoid beam squint, which is the undesired rotation of the antenna pattern with frequency, and is especially troublesome in large arrays for large fractional bandwidth applications. In order to obtain squint-free octave-bandwidth beamforming over a half-space for a half-wavelength spaced array, each TDL needs approximately as many complex taps as there are elements in a 1-D phased array or elements along the longest diagonal for a 2-D array. To avoid the necessity for a large number of TDLs, many phased arrays are operated in a narrowband mode in which each antenna output is simply multiplied by a single complex coefficient for beamforming, as shown in Figure 1a. However, when the fractional bandwidth $F = B/f_0$, (where B is the bandwidth and f_0 is the center frequency), exceeds the spatial array resolvability $Q = \lambda_0/L \sin\theta_{max}$ (where L is the maximum array aperture which equals $L = Na$ for an N-element 1-D array of element spacing a, and $\lambda_0 = c/f_0$, and θ_{max} is the maximum angle from boresight over which the array must steer), then a plane wave pulse arriving at a large angle θ from boresight takes a time $T = \frac{L}{c}\sin\theta$ to propagate across the array aperture, and this delay is resolvable within the bandwidth of the system. In this case, when $F > Q$, the antenna array function is significantly altered as the frequency changes across the bandwidth B, resulting in an undesired angular rotation of the main beam and an additional undesired rotation of the adaptive nulls. When broadband operation is required (eg when $F > Q$), a weighted TDL with at least $M = \sin\theta_{max}BL/c$ taps is required at every antenna element as shown in Figure 1b.

In this paper we present the wideband all-optical implementation of a new, more efficient algorithm for broadband time domain beamforming that requires only one output tapped delay line detector and one input tapped delay line modulator for weight programming for arbitrarily large arrays. This BEAMTAP system makes broadband beamforming viable for large arrays and appears amenable to implement using RF photonic hardware. The BEAMTAP algorithm is compatible with real-time calculation of the required $MN = 2F/Q^2$ adaptive weights that encompass the necessary degrees of freedom to optimally beamsteer and null rotate without squint in an arbitrarily complex spatio-temporal signal environment. We present a proposed all-optical RF photonic implementation of the BEAMTAP algorithm utilizing a fiber-remoted coherent phased array, photorefractive crystal, and two adaptively cohered fiber optic tapped delay lines. Simulations are presented that demonstrate the operations of BEAMTAP main-beam forming and jammer nulling. Finally, we summarize our technical highlights and the benefits of the proposed all-optical BEAMTAP array processing system.

3. Optical Adaptive Phased Array Processing

There have been numerous approaches to optically implementing adaptive phased-array phase-only beam steering, which unfortunately suffer from beam squint for broadband signals.[6, 7] Previous optical implementations of broadband adaptive beamforming avoided beam squint by using multi-channel acoustooptic delay lines to implement a TDL for every antenna element input, and are thus limited to 32 channels because of the limits of AO technology.[8–12] Fiber-optic true-time-delay (TTD) beamforming networks have been employed to bring the main beam onto the apparent array boresight where there is no frequency dependent beam squint,[4, 13, 14] though squint is still present in the sidelobes and nulls. Elegant wavelength-tuned fiber true-time-delay systems have been developed based on fiber prism,[4] dispersive,[15] or grating-reflective approaches.[16] Although they have the potential to be scanned rapidly, these systems are not adaptive and are only able to process linear or planar arrays and not conformal, irregular, or dynamically flexing arrays. Traditionally, these fiber-based systems do not provide for a mechanism of adaptively weighting the array function to optimally null out multiple jammers. Recently however, these approaches have been extended to multiple beams[5] and simultaneous beam steering and jammer nulling by building two such systems - one pointed towards the desired signal, another towards the jammer, and then subtracting the two outputs.[17] Such an approach allows for a very wide bandwidth of operation but requires duplication of the hardware of the entire system every time one additional jammer must be nulled. Further, it is not adaptive in the sense that the angle-of-arrival of the signal and the jammers must be known *a priori*, and more complex scenarios requiring space-time Wiener filtering for optimal signal-to-interference plus noise (SINR) can not be accommodated.

We have previously developed adaptive phased array processing systems using photorefractive crystals as the adaptive weights that achieved 45dB narrowband jammer nulling, and had the potential capability for TTD processing, but in a rather complex frequency domain implementation.[18] This photorefractive adaptive array processing system was simplified by the use of the BEAMTAP algorithm which could be implemented through the use of a traveling wave detector such as a 1-dimensional time-delay-and-integrate charge-coupled device (TDI CCD)[19] or a photo-conductive traveling fringes detector[20] to allow for the generation of the necessary time delays in the electrical domain rather than the optical domain. Programming of the photorefractive adaptive weights can be accomplished using a traveling wave modulator such as an acousto-optic device. However the bandwidth limitations of these components can be circumvented using an all-optical approach based on self-cohered optical delay lines[21, 22] that replace the acoustooptic brags cells and the TDI CCD. All of the adaptive timing, phasing, and weighting is done in the optical domain, with

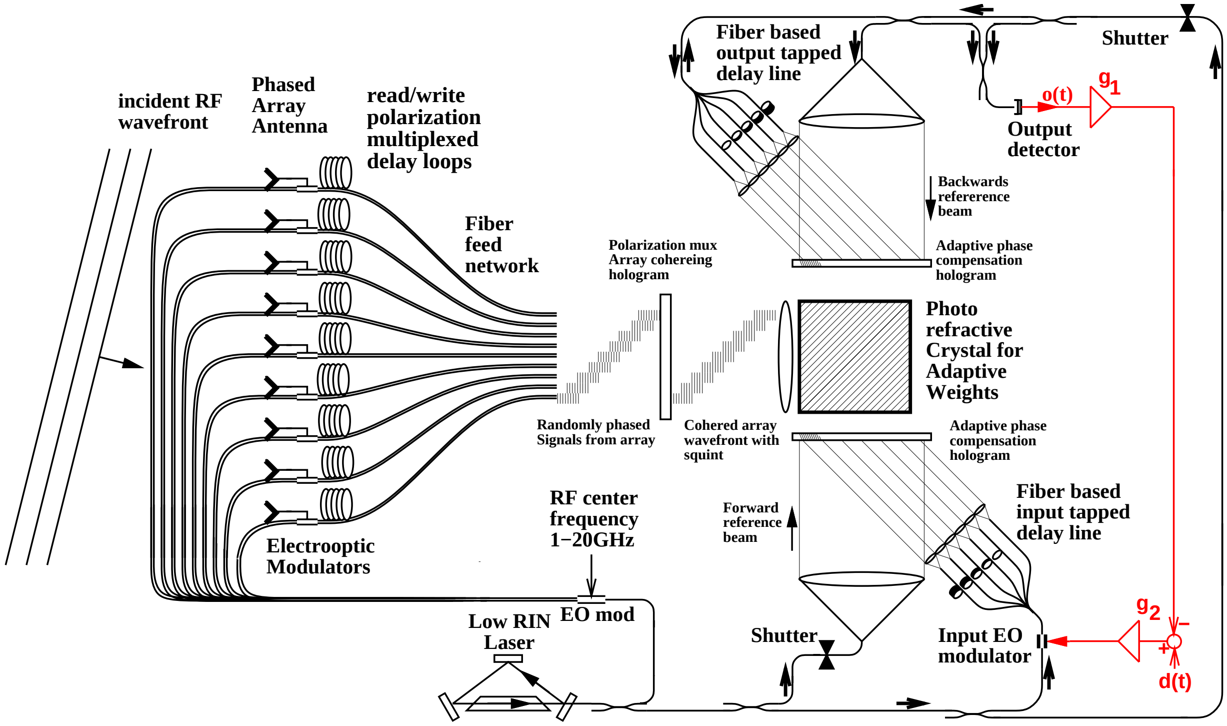

Figure 2: All optical BEAMTAP system utilizing cohered fiber tapped delay lines.

the speed limitations of the EO modulators and high speed photodetectors presenting the only bandwidth limitation on the system performance.

4. Cohered fiber time delay BEAMTAP processor

Optical convolvers based on fiber tapped delay lines can weight and sum wide bandwidth modulated optical signals emerging from an array of fibers with linearly increasing time delays.[23] These fiber tapped delay lines can be used for incoherent optical signal processing applications by cutting the fiber lengths to an accuracy given by a small fraction (typically 1/4 to 1/10) of the highest RF frequency times $c/n_g \approx 2 \times 10^{10}$cm/sec. Thus for a system with 10GHz bandwidth, the fiber lengths should be cut to an accuracy of a few mm and lengths of 1-10m, which can be readily accomplished. Such incoherent signal combination systems achieve a gain N proportional to the number of signals added, but substantially larger gain of N^2 can be achieved by coherently combining these signals (eg adding the field amplitudes and detecting the intensity instead of simply summing intensities). However, for coherent optical signal combination the length accuracy must be a tiny fraction of an optical wavelength (under 100nm) and this must be maintained even when the fiber flexes or its temperature varies. This represents a fractional length change of 10^{-5} or less and clearly can not be maintained without active correction and compensation. Although fiber stretchers can be servoed using closed loop feedback circuits,[24] when more than a few fibers are required this discrete component approach becomes impractical. For this reason, we instead utilize a dynamic hologram to sense the phase of each fiber and compensate for any errors in this phase by interfering the output of an array of fibers cut to approximately the correct array of lengths (within 1mm or so) with a plane wave reference beam; subsequent diffraction of the beams from the fiber array off of the gratings in this hologram then become phase uniform. Therefore, as long as the dynamic hologram responds at least as fast as the phases in the fiber drift then this cohered fiber tapped delay line can be used for coherent optical processing.

In the adaptive array processing system shown in Figure 2 two such fiber tapped delay lines are required – one to program the photorefractive adaptive weights as a time integrated correlation between a feedback signal and the array signals, and one to appropriately delay the diffracted outputs of the array by the hologram in order to produce squint free beams and nulls. Coherent optical processing requires that a single powerful laser be utilized and split into several paths: an array of beams which are then modulated by signals from the array, a signal for the feedback tapped delay line, and references for cohering the delay lines. Each of the modulated signals from the array is transmitted from the modulators at the phased array through the fiber feed network to an array of terminated fibers. The terminated fibers can be in any topological arrangement (1-D linear array, 2-D hexagonal array, random, etc) and with an arbitrary permutation with respect to the spatial topology of the phased array. The modulated signals from the fiber feed network are then imaged or focused into the photorefractive crystal.

The feedback signal given by the amplified difference between the desired signal and the processor output, $f(t) = g_2(d(t) - g_1 o(t))$, is applied to the reference EO modulator in order to control the adaptive weights. The modulated signal is distributed through the fiber tapped delay and launched as an array of beams with linearly increasing delays, which are corrupted by unavoidable random phases. However, the diffraction of this array of delayed beams off the cohering hologram produces a phase compensated and appropriately time delayed array of beams that can then be used to adapt the photorefractive weight hologram. The adaptive weights are recorded as the interference between this time delayed array of beams and the fiber remoted RF modulated signals from the phased array (corrupted by random phase and time delays). The diffraction of the phased array signals off this holographic weight matrix compensates for the random phase delays due to the array fiber feed, and produces the diffraction at respective spatial positions corresponding to the relative time delays between the array signals and feedback signals. These adaptively weighted diffracted beams are re-diffracted by the output delay line cohering hologram (which precompensates for the random phases of the output fiber tapped delay lines) towards the output fiber tapped delay lines (notice the complementarity of the delays in the two delay lines which sums to $M\tau$ at each position), so that at the M-port star coupler the weighted and delayed signals recombine coherently. Interferometric detection of this signal on a single high speed photodetector produces the heterodyne output signal $o(t)$. Closed loop adaptation drives the adaptive weights to the desired optimal beamforming and nulling solution. When the fiber tapped delay lines are perturbed the cohering holograms must be re-adapted by opening the shutters.

The beam combination and coherent detection schemes utilized in this architecture raise some interesting issues. The cohering of the output fiber delay line allows the recombination of the different delayed fibers at the $1 : M$ coupler coherently, thereby avoiding the normal $1/M$ constant radiance fan-in loss. In addition it also provides a selective filtering which suppresses unwanted jammers diffracting off of a main beam sidelobe since they will not be correctly phased. Furthermore this coherent combination of desired signals occurs even for large angles of arrival for broadband signals because the propagation induced time delays are compensated for by the fiber feed network. The coherent signal summation produces a superposition of the modulated signals from each antenna and the unmodulated carriers. For beamforming an array of signals with linearly increasing delays $s_n(t) = d(t - t_n)$ this signal summation produces an output with compensated time delays which neglecting array apodization can be represented as

$$o(t) = \left| r + \sum_n (\eta s_n(t + t_n) + b) \right|^2 = (r + Nb)\eta N d(t) + \eta^2 N^2 |d(t)|^2 + \mathrm{cc} + \mathrm{bias}$$

where r is an optional additional reference, η is the EO modulation depth (typically very small), $b = \sqrt{1 - \eta^2}$ is the unmodulated carrier. The second term is an unwanted signal self mixing term that must be eliminated. In octave bandwidth limited scenarios it can be eliminated by bandpass filtering. For super-octave applications either the additional reference beam r must be very large or the modulation depth of the EO modulators in the array must be very small so that $b = \sqrt{1 - \eta^2} \gg \eta$, in which case the self mixing term can also be neglected. Thus the output signal can be seen to be proportional to $o(t) \propto N^2 d(t)$, which provides the full coherent array gain rather than the electronically combined signal processing gain of only N in conventional fiber remoted arrays.

5. BEAMTAP system simulations

Figure 3 characterizes the input signals used in a computer simulation of the optical implementation of the BEAMTAP algorithm, shown in spatio-temporal Fourier-space with transverse spatial frequency along the vertical axis and single sided temporal frequency along the horizontal axis. The desired signal is a broadband Gaussian chirp spanning the frequency range from 0.5 GHz to 2.5 GHz, but whose $1/e$ spectrum is limited by the Gaussian window to the frequency range from 1.1 GHz to 1.9 GHz. Its angle of arrival is 0.25 radians. Jammer 1 is a broadband filtered Gaussian white noise signal, spanning the frequency range from 0.5 GHz to 2.5 GHz, with an angle of arrival of -0.2 radians. Jammer 2 is a narrowband sine wave at a frequency of 0.8 GHz and with an angle of arrival of 0.5 radians. Jammer 2 lies on the maximum of the first sidelobe of the receptivity pattern of the chirp when beam-forming is performed without jammers. In the simulations presented here the power in each jammer is one thousand times stronger than the power in the desired signal. However, the power in each of the signals was normalized in Figure 3 for illustrative purposes in order to make them all visible.

The diagram shown in Figure 4 illustrates the operation of the BEAMTAP algorithm. The leftmost figure shows the spatio-temporal RF field amplitude detected by the 64 antenna array elements along the vertical spatial axis. Only the jammers are visible, since they are much stronger than the signal. The final weight values after adaptation for 1.02ms are shown in the center of this figure. Notice the tilted stripe, resulting from the correlation between the feedback signal $f(t)$ (the difference between the output and the desired chirp signal) and the input signals $s_n(t)$ (chirp and jammers) whose tilt is an indication of the angle-of-arrival of the desired signal. Weak sidelobes seen in the weight matrix are due to a cross-correlation between the signal and jammers and are responsible for the manipulation of the antenna nulls to point towards the undesired jammers. The instantaneous input signal vector from the array is multiplied by this weight matrix. The diffracted signal is deflected vertically into the fiber delay lines where the sums are time delayed in proportion to their position (thereby

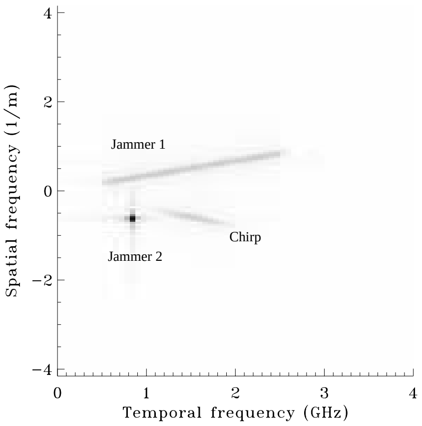

Figure 3: Fourier-space representation of the input signals used in the computer simulation of the BEAMTAP algorithm. The desired signal is a broadband Gaussian chirp. Jammer 1 is a broadband filtered Gaussian noise and jammer 2 is a single frequency sine wave. The tilt of the Fourier loci for off-axis signals is the phenomena that produces squint in phase-only beam steering systems.

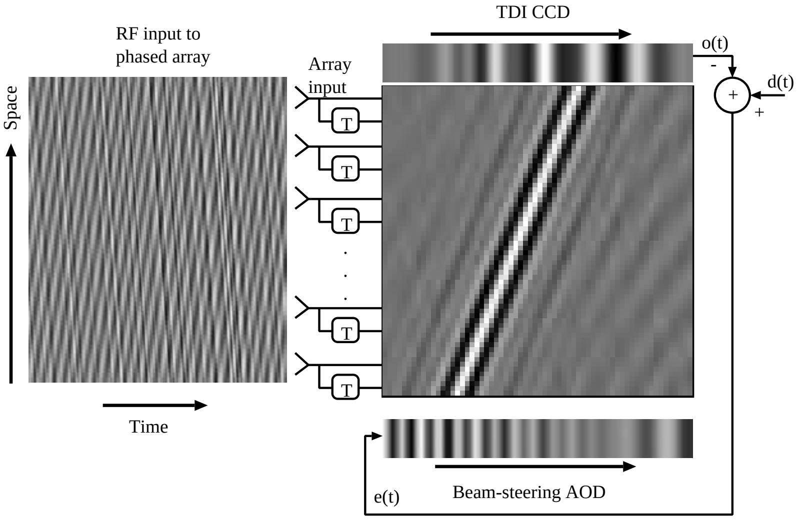

Figure 4: BEAMTAP simulation. The input signal is represented by the spatiotemporal signal at the left. At every time-step an instantaneous slice of the input is detected by the antenna arrays and is propagated through the adaptive weight matrix (center of figure). The product of the input vector with the weight matrix is diffracted vertically, delayed, and detected (top of figure). The output is then subtracted from the desired signal, generating the feedback signal which is delayed by a linearly increasing array of delays (bottom of figure). An outer-product between the feedback signal and a delayed version of the input is used to adapt the weights, producing the resulting tilted cross-correlation slice seen in the weight matrix.

compensating for the RF propagation induced time delay) and summed and detected to give the output $o(t)$. The upper part of the figure shows the contents of the fiber delay lines, and the lower part of the figure shows the output of the feedback fiber TDL at this instant in time. An outer-product between this signal and a delayed version of the input signal is used in order to adapt the weights. This simulation used 64 taps in the delay line, providing us with an array of 64×64 adaptive weights.

Figures 5 and 6 show the receptivity pattern of the system for two different cases. In figure 5 beam-forming is performed only with the desired repetitive chirp in the input, without the jammers. Notice the strong response in the direction of the desired signal (0.25 radians), over almost the entire chirp bandwidth (0.5 GHz to 2.5 GHz). Notice that the receptivity maximum is a straight line at a constant angle. This is a characteristic of a true time-delay system which has no beam-squint, but the main-lobe width does vary with frequency as do the positions of the sidelobes and nulls. This is to be expected, since adaptation optimized the response of the main lobe only.

In Figure 6 both the signals and jammers are present in the signal environment, so beam forming and jammer nulling are performed simultaneously. Notice the changes compared

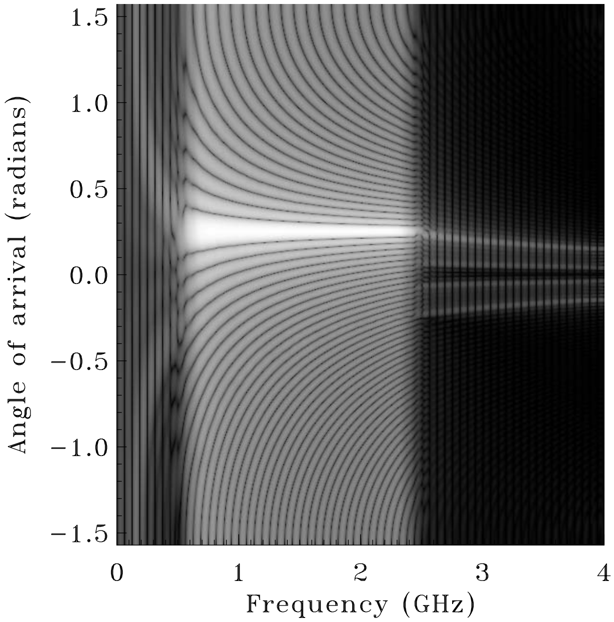

Figure 5: Beam-forming angle versus frequency receptivity pattern that develops after adaptation when only the desired signal is present at the input, demonstrating squint-free true time-delay beam-forming. Notice that the main lobe does not vary its position with frequency (although its width does change) and it spans the entire input signal bandwidth.

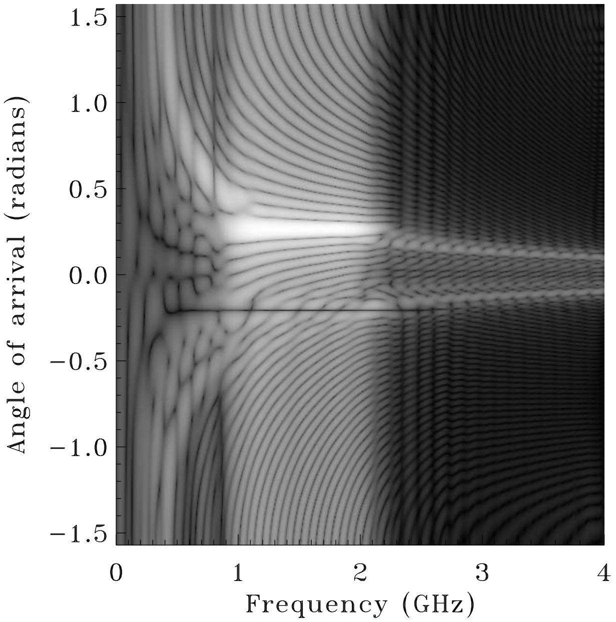

Figure 6: Simultaneous beamforming and jammer nulling angle versus frequency receptivity pattern after adaptation when the desired signal and strong jammers are both present at the input, demonstrating squint-free jammer suppression with deep nulls. Notice the constant angle squint free null at the angle of the broadband jammer over its full bandwidth, a narrowband null at .5 radians and 800MHz with deep sidelobe nulls and a reduction in the bandwidth of the system response to the desired signal.

to Figure 5. The wideband jammer 1 produced a broadband unsquinted null located at is angle of arrival (-0.2 radians) and spanning its complete bandwidth (from 0.5 GHz to 2.5 GHz). The narrowband jammer 2 produces a narrowband null whose sidelobes decrease the bandwidth of the main lobe.

6. Summary

We have presented a new approach to all-optical true-time-delay beamforming based on the BEAMTAP algorithm (Broadband and Efficient Adaptive Method for Time-delay Array Processing) that reduces the number of TDLs required for time-domain adaptive beamforming of a broadband N-element antenna from the conventional value of N to only 2, and we have showed how to implement these delay lines using cohered broadband fiber delay lines. The all-optical implementation of this BEAMTAP algorithm is ideally matched to the strengths of optical phased array processing systems. For large arrays the decreased number of delay lines represents a dramatic hardware savings that will allow the implementation of broadband adaptive phased arrays in sizes that were previously impractical.

We have presented an optical architecture based on this new hardware-efficient TTD algorithm that utilizes a fiber-remoted coherent phased array, a photorefractive crystal, and two holographically cohered fiber tapped delay lines, and a single high speed photodetector whose electronic output represents the adaptively beam-steered and jammer-nulled output. Simulations were presented that verified this operation for broadband desired signals in the presence of broadband jammers.

We wish to acknowledge the support by Dr. William Miceli of ONR and the Office of the Secretary of Defense through the ODDR&E MURI program grant no N00014-97-1-1006.

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