Photonic Technologies for Antenna Beamforming

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Abstract: Among the many photonic technologies available for antenna beamforming, those which provide flat RF response over a very wideband RF bandwidth, high signal to noise ratio, multiple-beam capabilities and minimum complexity are to be preferred.

OCIS codes: (280.5110) Phased-array radar, (060.2330) Fiber optics communications, (060.5625) Radio frequency photonics, (230.2090) Electro-optical devices

1. Introduction

Over the last fifty years, the engineering community recognized the need for true time delay in phased array antennas. However, the subject has become increasingly important in the last decade, as radar systems were required to achieve higher resolution, farther distances and wider scan angles. A classic phased array uses a Transmit/Receive module on each of its antenna elements to control the phase (as well as the amplitude) of the transmitted/received elemental wave. This works well for a system with a narrow RF bandwidth. However, when wide bandwidths (short pulses) are involved, a phased-steered array has a frequency dependent beam shape, resulting in wider beams, temporally distorted pulses and loss of gain, as well as spatial and temporal resolutions[1]. This 'squint' phenomenon, which makes phased-steered antennas unacceptable for many modern and future applications, can be eliminated by replacing the phase delays in the system with true time delays. One of the preferred RF solutions is the Rotman lens [2], which uses RF guided waves in a specially designed geometrical structure to produce these delays for a number of discrete beams. Rotman lenses have been and are still being employed in many radar systems. However, the need for smaller volume and lower weight, as well as for still wider bandwidth, has made this option less attractive. Alternatively, true time delay may be implemented digitally, using fast (many Giga-Samples/sec) Analog to Digital converters on every element. This power-hungry technology, though, has not yet reached maturity but may become a viable solution in the future. This leaves photonic technology as a mid-term feasible option.

In photonic beamformers the far field pattern of the antenna array is spatially shaped by optically introducing an appropriate True Time Delay (TTD) between adjacent array elements. Optical tunable delays have been demonstrated through a variety of techniques including: (a) optical path switching [3]-[7]; (b) wavelength switching and/or conversion in conjunction with the use of dispersive elements [7]-[12]; (c) optical control of the delay, commonly referred to in the literature as "slow light" [13]-[17]. This paper briefly discusses the need for TTD in wideband systems. It then proceeds to analyze some of the published photonic beamformers along with their optical TTD (OTTD) implementations, in terms of performance criteria, such as: quality of the overall RF transfer function, available signal to noise, angle switching speed, multiple-beam capabilities, and complexity.

2. The need for TTD in broadband phased array antennas

In traditional phased array antennas, RF phase shifters are used to control the viewing angle of the array, Fig .1. A CW RF signal of frequency f [Hz] will be steered by the array to the angular direction θ_s, provided the phase difference between neighboring elements obeys:

$$\varphi = 2\pi f d \sin\theta_s / c \qquad (1)$$

where d is the element spacing and c is the velocity of the electromagnetic wave. For a broadband waveform, Eq. (1) implies that for a given setting of the phase shifters, each frequency in the wide bandwidth will aim at a slightly different angle, θ_s, resulting in the broadening of the integrated antenna pattern [1]. Consider a one dimensional X-band radar, Fig. 1, operating with a 1GHz bandwidth around f_c =10GHz carrier, with N antenna elements spaced $d=\lambda_c/2$ apart and $\theta_s=60^\circ$ at f_c. Under these conditions, squint-induced broadening is given by [1]:

$$\Delta\theta_{\text{squint}} \cong (180B)/(\pi f_c \tan\theta_s) = 10[\deg]. \qquad (2)$$

For practical values of N (100 or more), $\Delta\theta_{\text{squint}}$ may become significantly larger than the natural beam width of the array ($\sim 2\lambda/(N\cdot d\cos\theta_s)$), and, therefore, totally unacceptable, Fig.2. Beam width performance is restored once the phase shifters are replaced by TTDs, with an inter-element delay, in our example, of $\tau = d\cdot\sin\theta_s/c$=43ps.

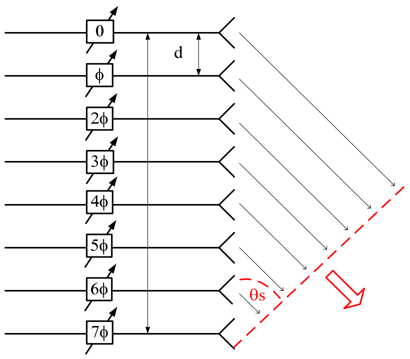

Fig. 1. Phased-array radar with RF phase shifters.

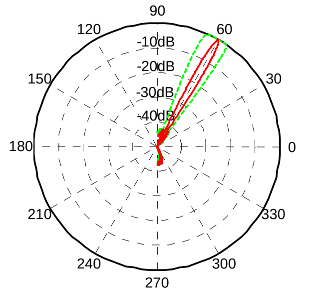

Fig. 2. Envelope of the radiation patterns for a simulated 128-elements array, pointing at θ_s=60°, as the RF frequency covers 1GHz around 10GHz. Dashed line: when the array is scanned by phase shifters; Solid line: a TTD driven array.

3. RF Performance

Modern radars use wideband, quite often coded, RF pulses, such as linear frequency modulated (LFM) waveforms, spanning a few GHz of bandwidth [1]. Clearly, in order to preserve the shape and contents of these RF signals, OTTD should act as a pure delay, with stringent tolerances on their RF magnitude and phase ripples (a frequency-independent loss, while a penalty, does not compromise the quality of the RF) [18]. The three main contributors to ripples in OTTDs are the electrical to optical converter (E/O), used to convert the RF input to optical modulation, the particular optical implementation employed, and finally, the optical to electrical converter (O/E), which recovers the delayed RF signal. It has been shown [6] that while off-the-shelf Mach-Zehnder E/O's can contribute a fraction of a dB to the loss ripples and a few degrees to the phase ripples, the contribution of the O/E's is much smaller, and can often be neglected. Indeed, a wavelength-controlled OTTD, employing a wavelength demultiplexer and different lengths of fibers to achieve the required delay [4],[6], has an RF transfer function (using double sideband modulation) that significantly outperforms a typical commercial Rotman lens [2].

Quite a few OTTD implementations use the chromatic dispersion of waveguides to achieve wavelength dependent delay [7]-[12]. Phased array antennas may employ 500 elements or more, spaced ~$\lambda_{RF}/2$ apart. A large array in the X-band, with the ability to scan up to ±60° degrees, using a tuning range of $\Delta\lambda_{opt}$ on the order of ~40nm, requires the chromatic dispersion, $\overline{D}$, to be as high as a few hundreds ps/nm. Since $\overline{D} = D \cdot L$, where D is the waveguide dispersion in ps/(nm·km) and L is its length in kilometers, high dispersion optical fibers, such as photonic crystal fibers [11] and high-order mode fibers [12] have been used to shorten L in order to reduce the thermal sensitivity of the rather long (hundreds of meters) fibers involved in this kind of implementation. The required high $\overline{D}$ also gives rise to magnitude fading and phase distortion when double sideband modulation is used [18],[19]. Single sideband does alleviate the magnitude fading at the expense of more complicated hardware [18],[19].

4. Dynamic range

Modern high-end microwave radar systems call for an ever increasing dynamic range. Limited from below by system noise, the available dynamic range is bounded from above by the appearance (at high input power) of power-dependent spurious signals, most often originating from nonlinearities in the RF transfer function of the system. OTTDs implementations, while offering very wide bandwidth, as well as other significant advantages, are not exempt from dynamic range limitations. In fact, the commonly used electro-optical modulators and to some extent also photodetectors, may add to the system nonlinear budget, and the implications of their nonlinear behavior to both single and multiple frequency signals have been studied in detail [20]-[21]. When linearly-chirped pulses are used, the contrast of imaging radars becomes severely limited by the nonlinear behavior of commonly used intensity modulators, imposing strict constraints on the allowable modulation index [22].

Noise must be minimized as well. To avoid being limited by the thermal noise of O/E and to overcome optical losses in the OTTD's, lasers of considerable power should be employed, along with optical amplifiers. Laser relative intensity noise and optical amplifiers signal-ASE beat noise then become the major noise contributors. Low loss optical splitting is quite common in photonic beamformers, but some architectures also use non-WDM optical addition of channels, possibly of the same wavelength [11],[15]. This addition can be used to great advantage if done coherently [15], requiring very careful, and quite often costly control of the optical phases of the different channels. However, when done incoherently [11], the addition is lossy and gives rise to sizable of phase-induced intensity noise [23].

5. An example

The architecture of a multiple beam photonic beamformer in Receive, Fig. 3, is based on fast tunable lasers, optical circulators and WDM demultiplexers with prescribed lengths of fiber attached to their output ports, each with a highly reflective (~100%) silver coated tip, which serves as a mirror. The laser output is double-sideband modulated by the RF source and then goes through the Demux, out to a specific length of fiber (for the generation of the necessary delay), then to the silver mirror and back. The length differences among the fibers coming out of the Demux determine the required time delays. Switching the optical carrier to a different wavelength routes the optical signal to a different port of the Demux, and consequently to a different fiber, changing the delay. Taking advantage of the commercial availability of fairly large port-count Demuxes, enough different wavelengths can now be allocated to different beams, so that multiple-beam operation can be achieved [7]. Implementation of this discrete scanning architecture has resulted in a very flat, low ripple RF response, high RF performance uniformity among the different channels, single point of control (i.e., the wavelength switching of the tunable lasers), submicrosecond angle switching, no splitting of the RF signal, no crosstalk among the different multiple beams and freedom of interferometric noise.

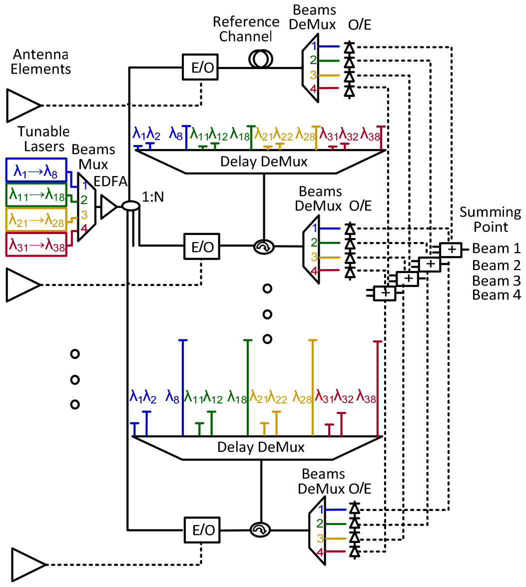

Fig. 3. Wavelength-controlled photonic beamforming receiver with 4 beams. The electronic path is denoted by dashed lines and the optical in full lines: black full lines for the 4 beams common paths, and colored lines for each beam unique optical path.

6. Conclusions

While modern photonic beamformers meet most functional performance criteria, their adoption by the radar community will also critically depends on their eventual size, weight and cost.

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