True Time Delay w/3D MEMs

(Invited Paper)

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ABSTRACT: A Fiber Delay Integrated Switch (FIDELIS) photonic beamformer using a large optical switch allows compact implementation of true time delay for phased array radars. The use of a three-level subarray architecture enables very large beamformer arrays using only a small number of photonic time delays.

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Introduction

Electrical time delay with high bandwidth is an enabling technology for many high performance applications, most notably for large phased array radar beamformers. Figure 1(a) shows the use of time delay to steer a transmitted and reflected beam of a phased array radar. The variable time delay between elements causes the transmitted signal phase at each element to add constructively to form a beam propagating in the desired direction. The same beam steering can be achieved at a single frequency with phase shifters rather than with the time delay shown, but beam steering with phase shifters produces beam squint, where the angle of the transmitted beam changes with carrier frequency. The amount of time delay required for phased array beam steering depends on the diameter of the antenna array and on the maximum scan angle, typically 1-10ns, with some applications requiring >10ns of delay.

A very large phased array antenna might have a diameter of >100 elements across the array, with ~10,000 total antenna elements, so providing true time delays to subarrays is a cost-effective solution. There are only two independent variables (azimuth and elevation) that determine the required delays, resulting in a high degree of structure in the required delay as shown in example in Fig. 1(b). Delays required for closely spaced antenna

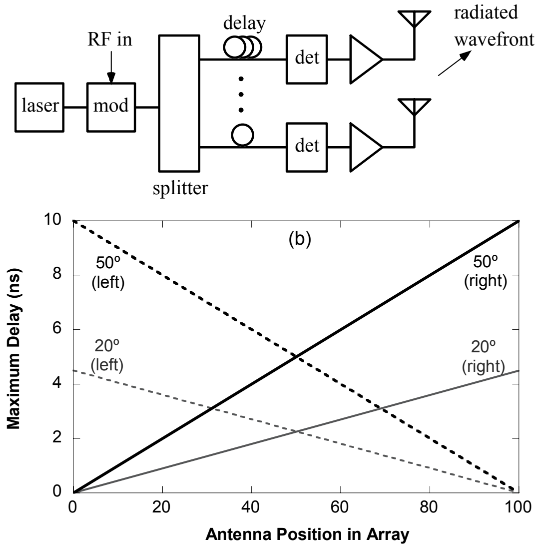

Fig. 1. (a) Photonic beamformer architecture
(b) required true time delay required for each antenna element.

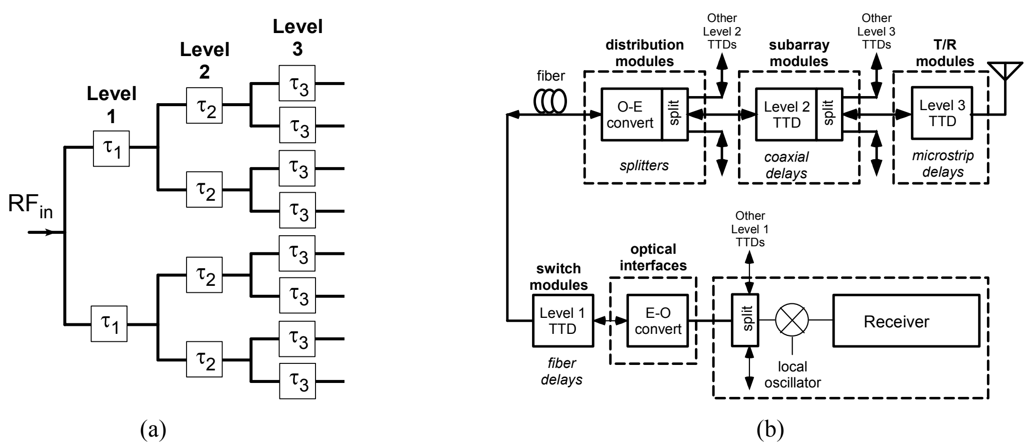

Fig. 2. (a) Illustration of a three-level cascade of delay elements. High degree of structure in time delay required to neighboring elements allows simplification to beamformer using cascaded delay stages. (b) Implementation of three-level architecture.

elements are similar, so beamformers typically use a subarray topology with a small number of true-time delay elements driving a number of phase shifters in the array, which simplifies the hardware compared to providing separate time delays to each antenna element. The optical switch architecture discussed here works with this conventional two-level subarray architecture as well. However, this two-level subarray architecture does not scale well to extremely large phased arrays regardless of the photonic time delay architecture that is used.

In the three-level architecture shown in Figure 2(a), a small number of Level-1 delay elements provide large coarse time delays to large subarrays, a larger number of Level-2 delay elements provide medium resolution time delays to smaller subarrays, and a Level-3 time delay element at each antenna provides fine resolution time delay. Sharing the long delays among many elements results in a substantial decrease in hardware usage, as long delays are the most costly and take up the most space. The three-level delay architecture of Figure 2(b) scales up to phased applications with even millions of antenna elements, while requiring only a modest amount of photonic hardware.

Time Delay Medium

The optimum time delay medium depends on the required delay. Small variable time delay, on the order of 0.1 ns, can be implemented using monolithic microwave integrated circuits (MMICs), some of which use switched electrical delays using lengths of microstrip. Longer time delays can be achieved using switched lengths of coaxial cable, although coaxial suffer from a number of problems with long time delays, including frequency dependant loss, dispersion, multiple reflections, and temperature dependent delays.

It is very difficult to build octave bandwidth radar beamformers without photonic time delay lines. The loss of an electrical coax is shown in Figure 3(a) as a function of carrier frequency. For electrical time delay <1 ns, frequency flatness is not a major issue. However, for electrical time delay >>1 ns, the difference in frequency response between elements of the array with long time delay and elements with short time delay becomes a major limitation in forming broadband steerable beams. Another limitation to using long electrical delays for radar beam formers is the temperature dependence of the time delay through the coax, shown in Figure 3(b). The temperature variation of even the best large coaxial cables has a maximum slope at some temperature that is ~4x worse than that of fiber, and compact solid PFTE coaxial cable has substantially worse temperature dependence than fiber.

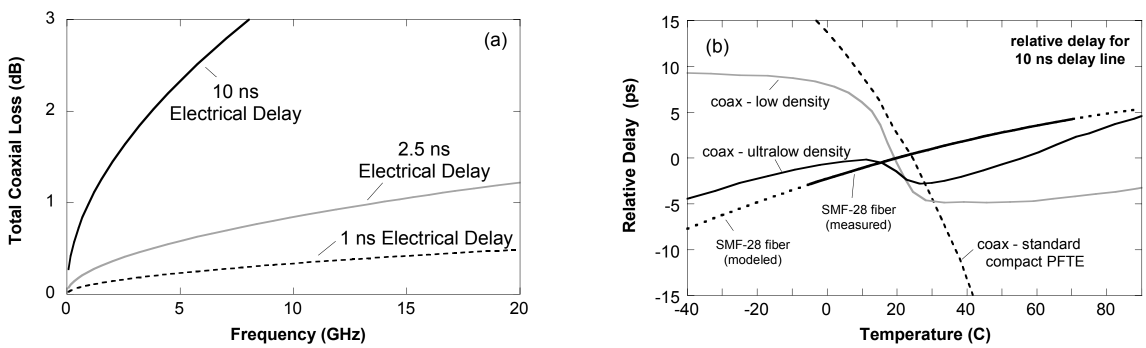

Fig. 3. Calculated (a) frequency dependence as a function of time delay in coaxial cable (b) temperature dependence of time delay in optical fiber and coaxial cable.

Photonic Beamforming

A number of phonic beam forming architectures have been demonstrated for achieving variable optical delay [1-5]. Optical beams traveling in free space can be used to generate optical delays with very fine resolution, but it is not practical in a fielded system to generate the longest of the optical delays in free space, and it may be more cost effective to implement shorter delays electrically rather than generate short delays optically.

Optical fiber is the most convenience medium for generating long optical delays, although other waveguide media can be used. A binary fiber-optic delay line (BIFODEL) architecture using 2x2 optical switches can be used to vary the time delay [3,4]. Lengths of fiber with delays in binary increments are switched into the optical path. Using the three-level delay architecture shown in Figure 2(b), only a small number of bits of optical delay are needed, typically 4-6 bits of delay, depending on the application.

A Fiber Delay Integrated Switch (FIDELIS) implementation [5] where the switching is integrated into a large optical switch [6,7] is shown in Figure 4(a). This configuration can provide a compact implementation of the BIFODEL functionality, while offering valuable additional flexibility due to the greater flexibility of large optical switches. In this example, each of 45 subarray inputs is switched through at most two of six delay fibers. The six delay values are arranged in a linear-binary sequence of 1 ns, 2 ns, 3 ns, 6 ns, 10 ns, and 14 ns, which allows the delay to be changed from 0-17 ns in 1 ns increments.

The most demanding performance parameter of radar beamformers using fiberoptic delay is the dynamic range of the optical link. Achieving high dynamic range using external modulation requires low optical loss, and typically uses high optical power [8]. Therefore the FIDELIS architecture is ideal for optical time delay, as it provides low optical loss, and allows large optical power. Typical loss of these switches can be as low as 1.3 dB [6], with power handling capability as high as 100 mW per optical port.

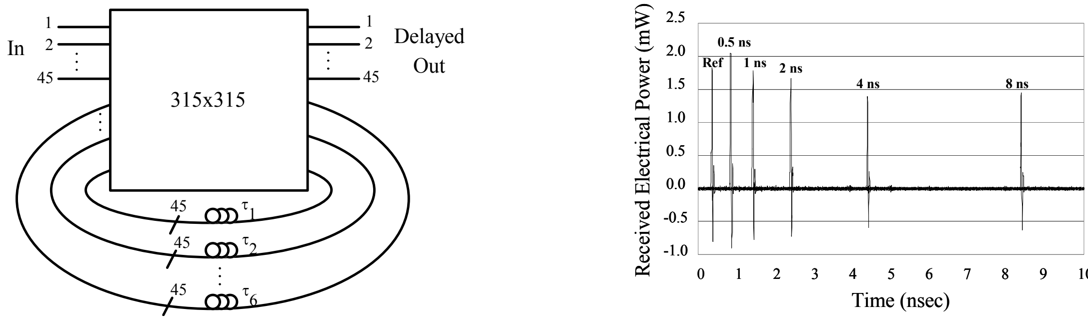

Fig. 4. (a) A 45-element 0-17 ns time delay unit based on a 315x315 optical switch with a typical optical loss of 3.9 dB. (b) Measured optical true-time delays. The loss variation is 1.5 dB.

Summary

A FIDELIS beamformer architecture using large MEMS-based optical switches can be used to switch fiber delays and generate true-time delay for broadband phased array radars. The low loss and high optical power handling capability of these large optical switches is ideal for generating time delay with the required high dynamic range, particularly for time delays >>1 ns which are difficult to generate electrically.

This FIDELIS optical time delay configuration combined with a three-level subarray architecture provides the benefit of broadband radar operation using optical delays, where the cost of the photonic elements can be amortized over a larger number of antenna array elements. For large phased arrays, a three-level subarray architecture allows an optimum balance between long photonic time delays, medium length coaxial delays, and shorter monolithically integrated microstrip delays, in order to provide the maximum radar performance at the minimum cost. This phased array architecture can scale up to large beamformers, even with millions of antenna elements.

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