A 32-Element 8-Bit Photonic True-Time-Delay System Based on a 288 × 288 3-D MEMS Optical Switch

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***Abstract*—A large-scale three-dimensional microelectromechanical-system optical switch is used for the first time to realize a true-time-delay (TTD) beamformer for phased-array radar applications, with a capacity of 32 antenna elements and eight bits of delay. The 288 × 288 optical switch has a median loss of 1.4 dB and all measured 82 944 paths exhibit less than 2.3 dB loss at 1310 nm. The TTD beamformer exhibits a loss variation of 1.5 dB, which is equalized using a mirror-offset technique.**

***Index Terms*—Array signal processing, microelectromechanical devices, microelectromechanical system (MEMS), optical fiber delay lines, optical switches, phased-array radar.**

I. INTRODUCTION

AN IMPORTANT element of wide-band phased-array radar is the ability to obtain large-element number and high bit accuracy true-time delays (TTDs) in a low-cost, small, and light volume with minimal signal degradation. Current all-electronic TTD systems based on microwave components suffer from high signal loss and dispersion as well as large size and weight. On the other hand, due to their low loss and low dispersion, optical fibers are ideal photonic delay lines. In the past decade, several photonic TTD beamformers have been demonstrated with some of the more popular techniques being based on tunable lasers with dispersive fiber delay lines [1], [2] or fiber grating prisms [3], [4], integrated optical switches [5]–[7], or a white cell [8]. The performance of optically switched TTD units based on integrated waveguides has traditionally been limited by the high fiber-to-waveguide coupling losses, high polarization-dependent losses (PDLs), and a broad loss variation for different paths. Furthermore, the relatively small switching size (up to 8 × 8) of waveguide-based switches requires a cascaded-switch TTD system architecture for achieving high bit accuracy per element of delay, which not only augments the optical loss limitations, but also increases the number of switches and overall cost, size, and control of the TTD system.

In order to realize a large and compact TTD system with a capacity for 32 antenna elements and eight bits of delay, it is desirable to increase the optical switch size without introducing excess loss. The recent development of two-dimensional microelectromechanical-system (2-D MEMS) switches has resulted in lower optical losses (maximum 3.1 dB) with switch sizes up to 16 × 16 [9]. However, since the number of switching elements and electrical drivers scale as N^2, there is a practical limit in the achievable switch size with 2-D MEMS-based switches. On the other hand, the developments in 3-D MEMS (with a superior scaling of only $2N$ switching elements) have allowed the demonstration of much larger switches, with recent switch sizes beyond 200 ports [10], [11]. In this letter, we present and demonstrate, for the first time, variable TTD beamforming for wide-band phased-array radar applications using a low-loss 288 × 288 3-D MEMS based optical switch.

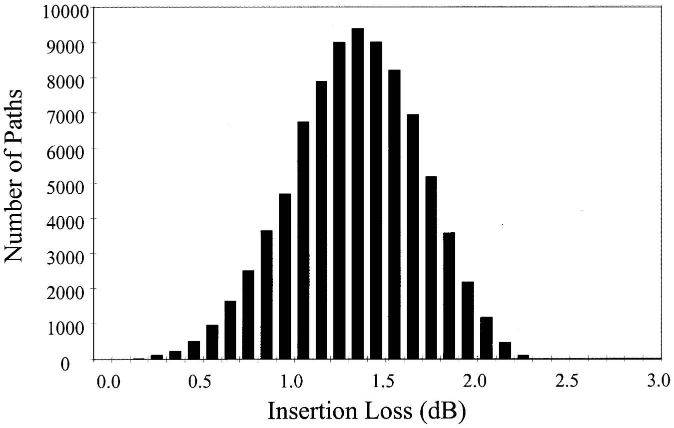

Fig. 1. Measured loss distribution (including connector losses) of the 288 × 288 3-D MEMS optical switch. The median loss is 1.4 dB at 1310 nm.

II. 3-D MEMS OPTICAL SWITCH CHARACTERISTICS

The 288-port optical switch is based on 3-D MEMS technology for large port counts and compact size. The light from an input fiber is collimated and incident on a MEMS mirror which can deflect light onto any of the output MEMS mirrors. The output mirror then aligns the optical beam onto a particular output collimator. For low-loss coupling, the position and angle of the beam must be aligned with the collimator, which requires $2N$-switching elements for an N-port switch. The single crystal structure and the flatness of the bulk MEMS allow for excellent mechanical properties and very low optical loss over a wide wavelength range. The 288 × 288 optical switch has a median loss of 1.4 dB at 1310 nm and the measured loss is shown in Fig. 1. All 82 944 paths exhibit less than 2.3-dB loss, which also includes connector losses. The switch also has

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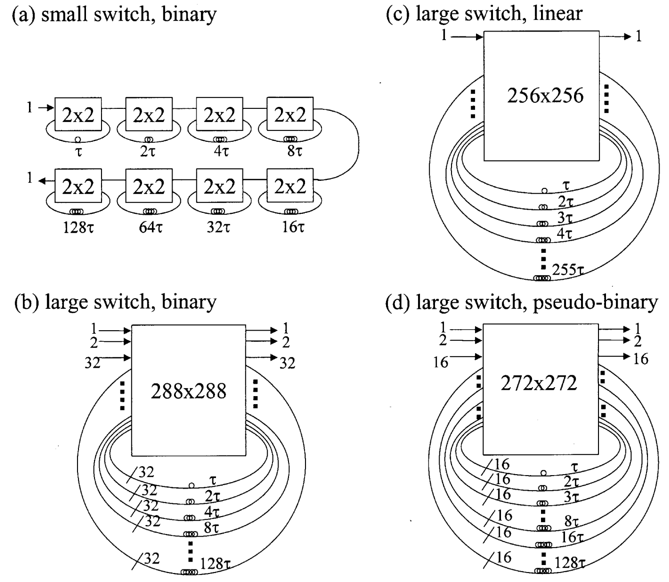

Fig. 2. (a) Single-element 8-bit resolution TTD unit based on 2×2 switches and a binary delay architecture with a typical maximum loss of 12.6 dB. The delays are τ, 2τ, 4τ, 8τ, 16τ, 32τ, 64τ, and 128τ. (b) A 32-element 8-bit resolution TTD unit based on a 288×288 switch and a binary delay architecture with a typical maximum loss of 12.6 dB. The delays are τ, 2τ, 4τ, 8τ, 16τ, 32τ, 64τ, and 128τ. (c) Single-element 8-bit resolution TTD unit based on a 288×288 switch and a linear delay architecture with a typical maximum loss of 2.8 dB. The delays are τ, 2τ, 3τ, 4τ, $\ldots$, 253τ, 254τ, and 255τ. (d) An eight-element 8-bit resolution TTD unit based on a 288×288 switch and a pseudobinary delay architecture with a typical maximum loss of 5.6 dB. The delays are τ, 2τ, 3τ, $\ldots$, 8τ, 16τ, 24τ, $\ldots$, 56τ, 64τ, and 128τ.

a wide transparent optical bandwidth from 1260 to 1625 nm with a loss variation of less than 1 dB. The measured median PDL is 0.07 dB with a maximum of 0.3 dB. Due to the design of the switch, chromatic dispersion (<0.1 ps/nm) and polarization-mode dispersion (<10 fs) are negligible and degradation of the radar signal would not be expected for frequencies well beyond 40 GHz. The switch is also capable of handling optical input powers beyond +13 dBm as well as providing stable loss over a wide range of environmental conditions. The excellent optical properties of the 288-port switch ensure minimal signal degradation and a high signal-to-noise ratio. Typical measured mirror switching times are less than 10 ms.

III. TTD CONCEPT

A TTD system with a capacity for 32 antenna input elements and 8-bit accuracy can be constructed with several different size optical switches. To simplify the comparisons of systems with different switch sizes, we assume a size-independent loss of 1.4 dB, which is reasonably accurate (1 dB for a 2×2 switch [9], 3.1 dB for a 16×16 switch [9], and 1.4 dB for a 288×288 switch). For a single input element and 8-bit resolution system constructed with 2×2 switches, as shown in Fig. 2(a), a binary delay architecture (with delays of τ, 2τ, 4τ, 8τ, 16τ, 32τ, 64τ, and 128τ) requires a cascade of eight switches with a maximum loss of 12.6 dB. On the other hand, the same bit accuracy and binary delay architecture can be implemented using a single 288×288 switch [Fig. 2(b)]. The minimum delay for the 288-port switch architecture is achieved with the input sending the optical signal straight to the output with a loss of 1.4 dB. For longer delays, additional passes through the switch are used for each extra bit of delay, which results in increased loss of 1.4 dB per pass (with a 12.6-dB typical loss for the worst case delay). In order to keep the loss the same for all delay values, the MEMS mirrors can be detuned from optimum alignment to increase the loss when using lower loss delay values, which is experimentally demonstrated in the next section. The TTD system based on a 288-port switch is able to support all 32 input elements using a single switch while a total of 288 2×2 switches would be required to realize the same capacity. Additionally, large-scale optical switches also allow for an architecture where the delays are in linear increments rather than binary increments, resulting in reduced losses per input element. As shown in Fig. 2(c), a 256×256 switch with linear delays of τ, 2τ, 3τ, $\ldots$, 253τ, 254τ, and 255τ would support a single input element for 8-bit resolution with a maximum loss of 2.8 dB. However, this low loss is achieved at the expense of 32 256-port switches in realizing a 32-element TTD system. It is also possible to trade off the number of large-scale switches and optical loss between the linear and binary delay limits by using a pseudobinary delay architecture. A 16-element switch with 8-bit resolution would require 16 delay lines (with delays of τ, 2τ, 3τ, $\ldots$, 8τ, 16τ, 24τ, $\ldots$, 56τ, 64τ, and 128τ) and a maximum loss of 5.6 dB per element [Fig. 2(d)].

TABLE I
THE NUMBER OF SWITCHING ELEMENTS AND OPTICAL LOSSES INCURRED FOR REALIZING A SINGLE-ELEMENT AND 8-BIT RESOLUTION TTD SYSTEM USING VARIOUS SIZE OPTICAL SWITCHES ARRANGED IN THE MINIMUM LOSS CONFIGURATION

Optical Switch Size	Fiber Delay Architecture	# of Switches per Element	# of Fiber Interconnects per Element	Typical Max. Loss per Element (dB)
2x2	Binary	8	15	12.6
4x4	Pseudo-binary	4	15	11.2
16x16	Pseudo-binary	2	31	5.6
256x256	Linear	1	255	2.8

TABLE II
THE MAXIMUM NUMBER OF INPUT ELEMENTS THAT CAN BE SUPPORTED WITH A SINGLE 288-PORT OPTICAL SWITCH WITH 8-BIT RESOLUTION

# of Input Elements per 288-port Switch	Fiber Delay Architecture	Total # of Switches for 32-Element TTD	# of Fiber Delays for 32-Element TTD	Typical Max. Loss per Element (dB)
1	Linear	32	8160	2.8
16	Pseudo-binary	2	512	5.6
32	Binary	1	256	12.6

The number of optical switches required in realizing a single-element TTD system based on various switch sizes is summarized in Table I, using a configuration to minimize optical loss for each switch size. Large optical switches can significantly reduce the optical loss, but require a substantial number of delay fibers for minimum loss. A large switch also allows a tradeoff between the loss and complexity to achieve a 32-element 8-bit TTD system, with linear delay for minimum loss, binary delay for minimum number of fiber delays, and a variety of pseudobinary delay sequences between these two limiting cases (Table II).

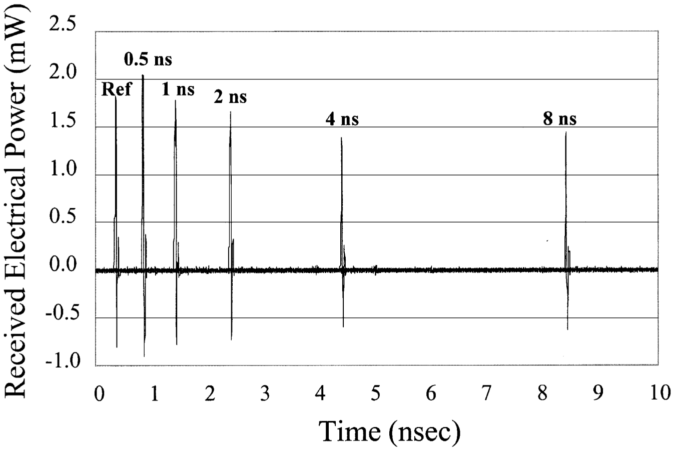

Fig. 3. Measured optical delays on a high-speed oscilloscope. The loss variation is 1.5 dB while the path delay accuracy is within 0.15 ns.

IV. Experimental Results

The 288 × 288 nonblocking 3-D MEMS switch (Fig. 1) was used to demonstrate the concept of a 32-antenna element, 8-bit TTD system, as shown in Fig. 2(a). The 1-ps output of a 20-MHz repetition rate 1550-nm short pulse source was split into 32 individual channels using two 1 : 16 optical splitters. These 32 channels at a peak pulse power of 3 mW were then fed into the input ports of the switch. For this demonstration, five different length optical fibers were connectorized and looped around the switch, with lengths equaling delays of 0.5, 1, 2, 4, and 8 ns. The switch outputs were then captured on a high-speed oscilloscope with respect to an attenuated reference point after a single bit of delay for each input (Fig. 3). The measured median delay error is less than 0.15 ns, which is due to varying internal switch fiber lengths and nonoptimal fiber splicing lengths. We estimate that a median delay error of less than 10 ps is possible.

As the optical paths within the switch have a loss distribution as shown in Fig. 1, the optical pulses for each delay line have different optical peak powers varying by 1.5 dB (Fig. 3). Additionally, the optical delay lines were connectorized, which added an extra loss to each path. This loss can be minimized once the delay lines are directly spliced to the internal switch fibers. In any case, the variability of the optical loss per path can be compensated by slightly misaligning the mirrors to introduce some additional loss. Hence, each path can be set to a specific optical loss at the output of the switch without requiring external variable optical attenuators. Fig. 4 shows the experimental results of offsetting the output mirror of a path to achieve different optical output powers. A dynamic range of 20 dB with 0.1-dB accuracy can be achieved with this technique and ensures constant output powers for the 32-element, 8-bit TTD system based on 3-D MEMS switch.

V. Conclusion

A compact and low-loss 288 × 288 3-D MEMS optical switch with negligible dispersion has been used for the first time to generate TTDs for phased-array radar applications. Large-scale optical switches have the advantage of lower loss and high switching density for reducing components and realizing high input element TTD systems with high bit accuracy. Additionally, employing 3-D MEMS for the switching technology allows for optical output equalization by misaligning the mirrors.

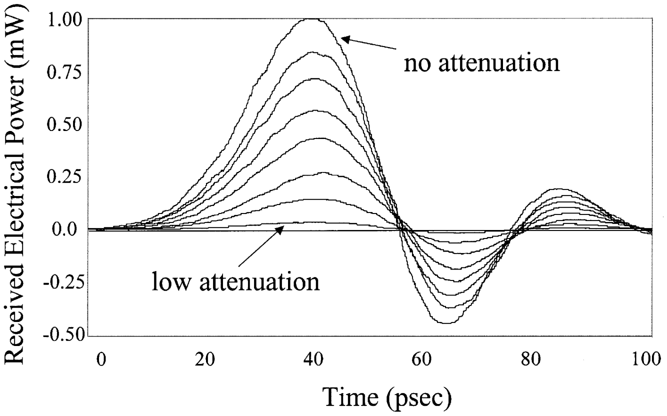

Fig. 4. Receiver response to an optical pulse demonstrating optical loss equalization in the optical switch by misaligning MEMS mirrors.

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