2-bit Reconfigurable True Time Delay Lines Using 2×2 Polymer Waveguide Switches

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***Abstract*—A 2-bit (four delays) polymer waveguide delay device is demonstrated and characterized. The device is composed of polymer waveguide delay lines, optical fiber delay lines, and polymer thermooptical 2×2 switches. The insertion loss for the fully integrated device ranges between 8.12 and 9.81 dB depending on the delay path chosen. The polarization-dependant loss is 0.04 dB. Measured delays are 0, 37.8, 160.4, and 199.2 ps. The switching speed is less than 4 ms. The designed polymer waveguide delays match well with the measured values.**

***Index Terms*—Antennas, delay effects, optical fiber, optical switch, phased arrays, planar waveguide circuit, polymer optical waveguides, thermooptic effects.**

I. Introduction

OPTICAL fiber and waveguide transmission lines are excellent candidates for the transmission and control of radio-frequency (RF) signals in future wide bandwidth phased array antenna (PAA) systems. Optical waveguides and fiber provide low propagation loss of RF and microwave signals, immunity to electromagnetic interference, and reduced system size and weight. They also remove the beam squint effect caused by highly dispersive electrical delay lines [1].

In contrast to fiber delay lines, waveguide optical delay lines, defined by photolithographic methods, are able to deliver precise delays with subpicosecond resolution for PAA systems. Additionally, optical waveguide delay lines can be formed in a compact planar lightwave circuit with waveguide-based optical switches. This technique has the potential for occupying less space than systems using optical fibers, such as microelectromechanical systems and acoustooptic-based delay systems.

Several material systems have been used to fabricate waveguide optical delay lines, the most notable being silica [2], silicon-on-insulator [3], and polymers [4]. In comparison with the alternative material systems, polymer waveguides are easy to fabricate on almost any substrate of interest which reduces manufacturing costs and opens the possibility of single-chip integration with active PAA components, such as lasers, modulators, and detectors. The refractive indexes of polymer waveguide materials can be adjusted widely to address the compromise between coupling losses and bending losses. Additionally, the thermooptical coefficient $\Delta n/\Delta T$ of polymer materials can be more than an order of magnitude greater than that of SiO_2 [5], while polymers' thermal conductivities are a fraction of SiO_2 and silicon's. Because of these properties, polymers can be used to make thermooptic switches with power consumptions less than silicon or oxide based devices. [6] .

A previously reported 2-bit integrated polymer delay unit with delays up to 94 ps had an insertion loss greater than 34 dB, despite having glass optical fibers for two of the delay lines [7]. The delay unit architecture was similar to the one discussed in this letter. Such a high loss is impractical for actual antenna applications. In order to reduce the insertion loss, smaller waveguide propagation losses must be obtained by using passive polymer materials. Additionally, optimized waveguide bending radii must be used in order to minimize the propagation distance while maintaining the correct time delays.

This letter reports on the demonstration of a 2-bit true time delay device composed of polymer waveguide delay lines and polymer thermooptic switches. The insertion loss and device size of the reported delay device are reduced by using passive polymer materials and by reducing the bending radii, and thus the propagation length, of the waveguide delay lines. Using a rectangular channel waveguide structure rather than rib or strip loaded waveguide structures enables the mode profiles of the waveguides and fibers to be similar in shape and size, thus reducing the coupling losses. The single-mode polymer channel waveguides have a numerical aperture (NA) of 0.17, which matches well with the telecommunication fiber employed ($\mathrm{NA} = 0.14$). Full characterization results of the delay device are presented.

II. Procedure and Results

Polymer waveguides were fabricated using an ultraviolet curable perfluorinated acrylate material. The refractive index of the core and cladding materials after curing was 1.46 and 1.45, respectively. The channel waveguide cores, 7 μm wide by 6.5 μm tall, were formed by reactive ion etching. The waveguides exhibited single-mode behavior with a measured propagation loss of 0.64 dB/cm at the wavelength of 1.55 μm. These polymer channel waveguides were used to form passive delay lines and 2×2 digital optical switch (DOS) structures.

Fig. 1 shows a schematic of the 2-bit reconfigurable device including the 2×2 DOS. Light enters one input port of the first switch and is adiabatically split by a Y-branch. The large thermooptic effect ($-1.7 \cdot 10^{-4}$/K) of the polymer material is employed to lower the refractive index of one of the arms of the Y-branch, causing the light to propagate in the opposite arm.

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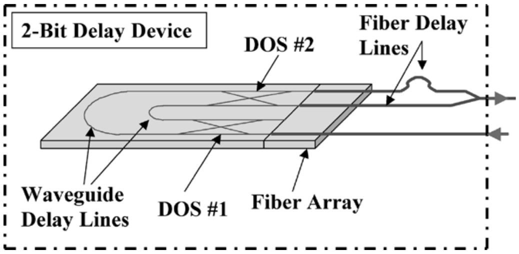

Fig. 1. Schematic of the 2-bit reconfigurable delay device.

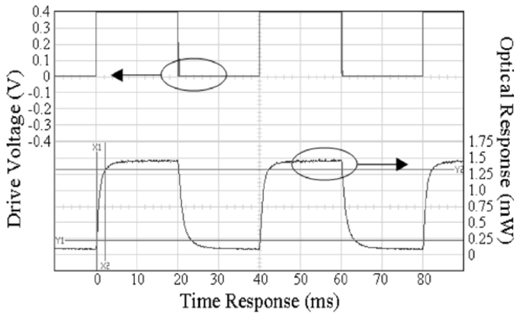

Fig. 2. Switching speed measurement results of the 2 × 2 DOS switch.

The 2×2 switch operates in the bar state when current is applied to the inner four heaters. By contrast, the switches operate in the cross state when the outer four heaters are activated [8], [9]. Depending on the state of the first 2×2 switch, light is guided through one of two polymer waveguide delay lines. A second 2×2 optical switch follows these polymer waveguides. A fiber array is then coupled to the opposite side of the chip that holds the 2×2 switches and the waveguide delay lines in order to complete the delay device. In this device, the first two delays are generated by the polymer waveguides and the second two delays are generated in the output fibers of the fiber array. The length difference of these output fibers is designed to yield a 40-ps delay while the difference in polymer waveguide lengths is intended to provide 160 ps of delay. These delays are chosen in order to provide steering angles of up to 45° for a 4×4 element subarray of an X-band (8–12 GHz) PAA [10]. The bend radii of the inner and outer waveguide delay lines are 3 and 3.75 mm, and total propagation lengths are 11.404 and 44.213 mm, respectively.

The switching speed of the DOSs were measured. A 25-Hz electrical signal with a 50% duty cycle was applied to the switches and the optical output fall and rise time responses were measured. Both the bar and cross state switching speeds were measured to be less than 4 ms. Fig. 2 shows the switching speed measurement results. The insertion loss of each DOS was 2.8 dB with less than 0.2-dB difference between cross and bar switching states. The extinction ratio of both switches was greater than 40 dB with 360 mW of applied power.

The total insertion losses, fiber-in to fiber-out, corresponding to each of the four delay combinations, are shown in Table I along with the switching state of each DOS. The insertion losses varied between 8.12 and 9.81 dB depending on the delay path chosen. The device's polarization-dependant loss (PDL) was also measured. The device insertion loss with transverse-magnetic (TM) polarized light was 0.04 dB greater than when using

TABLE I
DELAYS, LOSSES, AND SWITCH STATES FOR EACH DELAY PATH

Delay Path	Switching State #1	Switching State #2	Coupling Loss(dB)*	Insertion Loss(dB)	Measured Delay(ps)	Designed Delay(ps)
1	Cross	Bar	1.0	8.27	0	0
2	Cross	Cross	1.0	8.12	37.8	40
3	Bar	Cross	1.0	9.72	160.4	160
4	Bar	Bar	1.0	9.81	199.2	200

* Coupling losses were calculated from the mode mismatch between the delay lines, the DOSs and the fiber array.

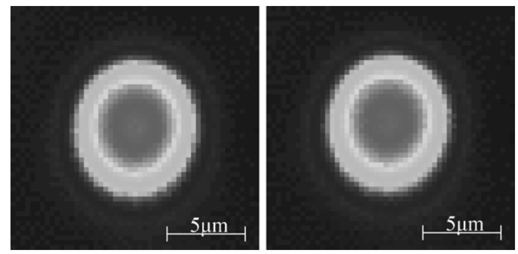

Fig. 3. Near-field images of TE (left) and TM (right) polarizations emanating from the 2-bit device.

transverse-electric (TE) polarized light. Fig. 3 shows near-field images of TE and TM modes emanating from the device. The mode patterns and intensities are nearly identical.

Exact time delay values generated by the 2-bit device were measured. A continuous-wave laser, operating at 1.55 μm, was modulated by a $LiNbO_3$ modulator fed by an HP8510C network analyzer. The output of the modulator was input to the delay device. The output fibers of the fiber array were connected to a 2×1 coupler and an erbium-doped fiber amplifier was used to amplify the signal. A photodetector covering the X-band frequency range was used to convert the modulated optical signal to an electrical signal that was fed back to the network analyzer.

Fig. 4(a) shows the measured microwave phase versus the frequency sampled from 2 to 14 GHz. The shortest delay path, delay path 1, served as the reference. The time delays for each delay path were calculated from the slope of the fitted lines. Table I lists the delays associated with each delay path. The measured time delays were 0, 37.8, 160.4, and 199.2 ps. The experimental uncertainty in the delay measurement is ± 1 ps due to jitter in the network analyzer's measurement of the phase. Fig. 4(b) shows the time response of a femtosecond laser pulse propagating through the device. The four delays are clearly seen.

III. DISCUSSION AND CONCLUSION

The 1.69-dB variation in insertion loss, depending on the delay path chosen, is smaller than the 2.11 dB that would be expected from the measured propagation loss and length differences of the polymer waveguides. The insertion loss measurements of the DOSs show that the switching state has less than 0.2 dB effect on insertion loss. The waveguide delay line design is such that the bend radiation loss of the inner waveguide delay line is large enough to partially compensate for the added loss of the longer waveguide delay line. This is a desirable effect for maintaining a constant radiated power from the PAA, irrespective of the steering angle chosen by the delay path.

The demonstrated 2-bit polymer waveguide delay unit has been shown to provide up to 199.2 ps of optical true time delay.

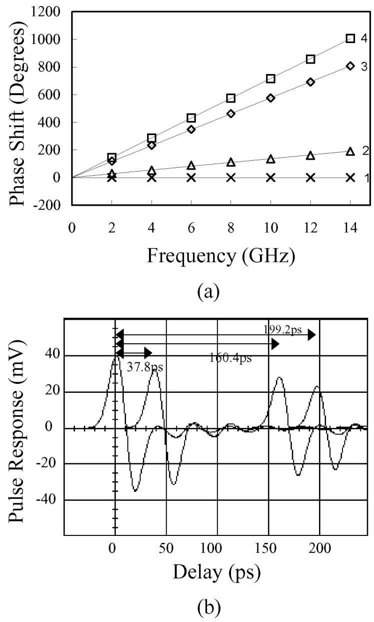

Fig. 4. (a). Phase versus RF frequency measurement results for each of the four delay states. (b) Time response of a femtosecond laser pulse through the device.

This delay is sufficient for two-dimensional steering of a wide bandwidth X-band 4×4 subarray up to 45° from broadside without any beam squinting effects. By using polymer thermooptic DOS switches, the steering angle response time of the PAA is less than 4 ms which is acceptable for the Navy's 10-ms requirements of PAAs onboard submarines [11]. The use of passive polymer channel waveguides and thermooptic polymer switches ensures that the PDL is minimal.

While the stable sub-10-dB insertion loss of the polymer delay device is currently larger than what is required for actual PAA systems, the fundamental loss of the 2-bit device is less than 3 dB with small incremental increases in the loss as the device scales to higher numbers of bits. These losses could be compensated with the potential integration of a polymer waveguide amplifier [12]. There are three contributors to the large majority of the loss in this device: propagation, bend, and switch loss. New highly fluorinated polymers have been reported with losses in the C-band of less than 0.1 dB/cm [13] and in fact the theoretical propagation loss limit of polymer has been calculated to be less than that of glass optical fiber in this wavelength range [14]. The bend loss can be managed by increasing the bend radius at the expense of the device size or alternatively introducing bend loss reduction methods as will be reported in a future publication. The long propagation length of the DOS is responsible for all but approximately 0.5 dB of the switch loss. By using low-loss polymers, the switch loss could be reduced to the excess loss introduced by the Y-junctions.

The use of polymer waveguides for PAA beam forming networks is highly attractive. Low-loss polymer waveguides and low power consumption polymer thermooptical switches can be combined to form compact delay switching networks with low insertion loss. Future work will include increasing the number of bits of the device while at the same time reducing the device size and insertion loss.

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