Reconfigurable True-Time Delay for Wideband Phased-Array Antennas*

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ABSTRACT

A novel reconfigurable true-time delay feed for phased-array antennas working from X to Q (8-50GHz) frequency bands is presented. The reconfigurable optical true-time delay feed, employing monolithic integration of polymer waveguide delay lines and polymeric optical switches, has great advantages in providing power efficient, lightweight, and small size features. Optical switch technique provides large delay selections enabling the module to operate in ultra-broad radar bands. Polymer waveguides with optical propagation loss of less than 0.9dB/cm were achieved at 1550nm. 2X2 thermo-optic switchs as fast as 1ms were fabricated with an excess insertion loss of 0.5 dB in the "switching state" and 1.5dB in the "non-switching state". Reconfigurability of the true-time delay line was demonstrated through accurate time delay measurement.

Keywords: Phased-array antenna, true-time delay, polymer waveguide, polymeric optical switch

1. INTRODUCTION

Microwave phased-array antennas are important in both military and civilian applications. However, wide bandwidth is not available employing traditional electrical feeding networks due to their intrinsic narrow band nature. Ultra-wide bandwidth operation would be made viable only with a wideband true-time delay (TTD) antenna feed. Many optical schemes have been proposed to take advantages of an optical feed for true-time delay, including acousto-optic (AO) integrated circuit technique [1-3], Fourier optical technique [4-6], bulky optics techniques [7-12], dispersive fiber technique [13-17], fiber grating technique [18-19], and substrate guided wave techniques [20-22]. Time delay modules utilizing the AO technique are considerably compact and integrated. However, this approach has a relatively limited bandwidth. Fourier optical technique is capable of rapid and high-resolution beam steering with only azimuth and elevation commands and no digital processing. However, this method is not a broadband true-time delay technology, because the optical frequency needs to change with the RF frequency of the antenna to maintain the correct phase ramp period for a certain steering angle. The drawbacks of the bulk optics approach are large space requirement and alignment maintenance. Increased maximum time delay will require more space, so the total size of the TTD control unit will be massive. Dispersive fiber technique is quite effective in power consumption and space consumption. However, it is relatively difficult for this technique to produce large enough time delays, since it requires excessively long dispersive delay lines. Bragg fiber grating technique can be used only for microwave signals of less than 1 GHz. The waveguide loss is a limiting factor of substrate guided wave techniques.

Each of the above methods possesses some, but not all, the desirable advantages. Furthermore, none of the available approaches is able to achieve long delay in a small and low-cost monolithic integrated circuit. We demonstrated a monolithic TTD module based on polymer platform in this paper.

2. TRUE-TIME DELAY THEOTY

For linear phased array antenna, radiating elements with individual phase control, the far field pattern along the direction of θ can be expressed as

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$$E(\theta,t)=\sum_{m=1}^{M}A_m\exp(i\omega t)\exp[i(\psi_m+nkd\sin\theta)] \qquad (1)$$

where A_m is pattern of the individual element, ω is the microwave frequency, $k=\omega/c$ is the wave vector, ψ_m is the phase shift, and d is the distance between radiating elements. By varying the progressive phase excitation, the beam can be oriented in any direction to give a scanning array. For example, to point the beam at angle θ_0, ψ_m is set to the following value:

$$\psi_m=-nkd\sin\theta_0\,. \qquad (2)$$

The problem is that conventional phase shift pre-determined for a specific steering angle is de-coupled from scanning frequency, resulting in beam squinting when the frequency changes.

In order to ensure the ultra wide bandwidth operation of future phased array antennas, true-time delay steering techniques are necessary to make the far field pattern independent of the microwave frequency. If time shift is set according to a particular steering direction, the microwave phase shift can follow the frequency scan to avoid beam squinting, which means time shift of

$$t_m(\theta_0)=-(md\sin\theta_0)/c \qquad (3)$$

The delay line pitch (length difference of delay lines for adjacent antenna elements) of an equal space interval linear array or the one-dimensional time delay interval of an equal space interval two-dimensional array can be calculated using the following equation

$$\Delta l=d\sin\theta_0/n, \qquad (4)$$

where n is the refractive index of the waveguide core material.

3. TRUE TIME DELAY LINE DESIGN

The optical-switch-based reconfigurable true-time delay line is detailed in figure 1. Reconfigurability is built into the structure by combining the polymer waveguides and optical switches. Using optical switches, various time delay values are achieved with a minimum number of hardware devices. For example, we can achieve $2^N=1024$ time delay values with $N=10$ segment waveguides. The differential delay time through one TTD line is

$$T_l=\sum_{j=1}^{N}S_{l,j}\Delta t_j=\sum_{j=1}^{N}S_{l,j}2^{j-1}\tau;\quad S_{l,j}=0,1, \qquad (5)$$

where $S_{l,j}$ is the state of the j-th optical switch in the l-th TTD unit.

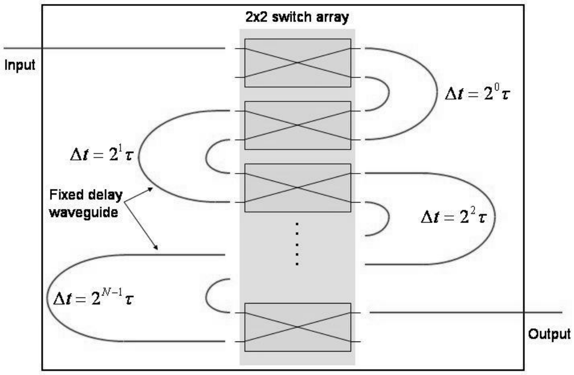


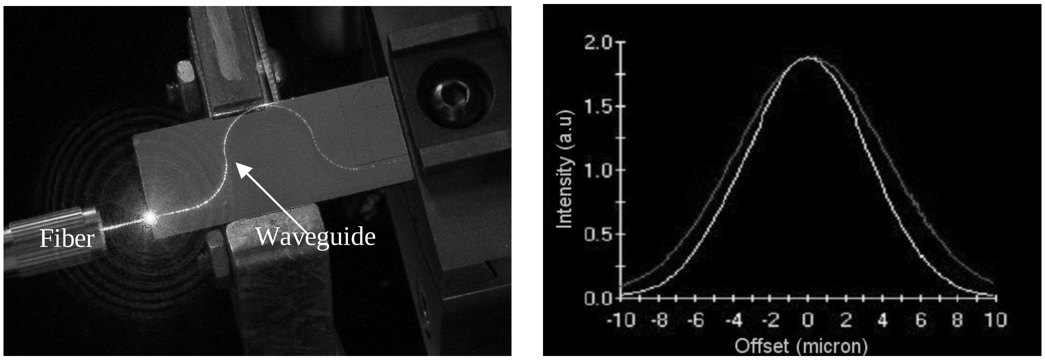
Figure 1. Schematic diagram of a reconfigurable true-time delay line.

Polymer is adopted as the platform of waveguide delay line and optical switches. Considering the optical propagation loss, material availability and fabrication process compatibility, Hitachi Chemical's OPI series polymer was selected to fabricate the TTD unit. The core material has a refractive index of 1.534, while the cladding material has a refractive index of 1.525. The size of the single mode waveguide is $6\,\mu m \times 6\,\mu m$. The minimum radius not to introduce notable loss ($<10^{-7}$dB/degree) is 4.5mm. And the coupling between standard single mode fiber and waveguide is estimated to be 0.56dB.

Assume an X-band PAA has an array pitch *d* of 0.01875m (half of the wavelength of 8GHz signals to avoid grating lobes) and 45° steering angle, the delay line pitch is calculated to be $8694\,\mu m$ from Equation (4). For a Q band microwave signal, if the minimum steering angle is 2°, the delay line pitch will be $74\,\mu m$. The delay interval from $74\,\mu m$ to $8694\,\mu m$ is easily achievable due to the photolighography accuracy down to sub-micron, and the reconfigurable TTD architecture.

4. EXPEIMENTAL RESULTS

The red He-Ne laser beam (633 nm) was coupled into the polymer waveguide to show the optical propagation, Figure 2(a) shows red He-Ne laser beam propagation in a 4.28cm-long waveguide. It can be seen that the scattering loss is decreased along the waveguide, which means most of the light propagates along the waveguide. Furthermore, the output light has a symmetric near field mode profile as measured in Figure 2(b). The measured propagation loss of the waveguide at 1550nm is 0.9dB/cm.



(a) (b)

Figure 2. (a) 633nm red light propagation in a 4.28cm-long waveguide (b) Measured near field mode profile.

The polymeric optical switch is based on the principle of Total Internal Reflection (TIR). The top-view of a fabricated switch is shown in Figure 3. The light coupled into Input 1 will propagate to Output 2 if there is no current flow through the electrode. The light will be reflected to Output 1 if enough index gradients can be established when there is current flow through the electrode. The switching time was measured to be 1ms. The measured cross talk is less than –28dB, for both "on" and "off" state. The total reflection takes place at a driving power of about 132mW (3V×44mA). Because the accessing parts (from wire bonding pad to the switch) of the heater electrode were too long in this initial design, electrical driving is not efficient. The heater electrode can be further optimized to enable efficient electrical driving. Compared the insertion loss of the dummy straight waveguides on the same chip, the average excess loss is only 0.5 dB in the "on state" and 1.5 dB in the "off state".

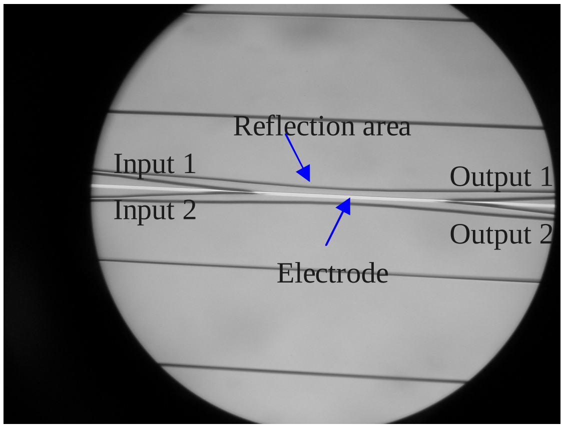


Figure 3. Photographs of optical switch top-view.

Figure 4 is the diagram of the experimental setup for demonstrating the reconfigurable TTD line. One bit TTD line was employed to demonstrate the TTD line. When the electrode temperature is increased by 60°C, nearly half of the optical power is reflected into Output 1, and the switch works as a splitter. A time delay interval of 88.9 ps is measured in Figure 5, which is the same as the designed delay value. When either output port is on, the pulse signal from the other channel will disappear. In this way, two delay times were generated. 2^N delay times will be generated employing two 1x2 switches, (N-1) 2x2 switches and *N*-segment delay lines.

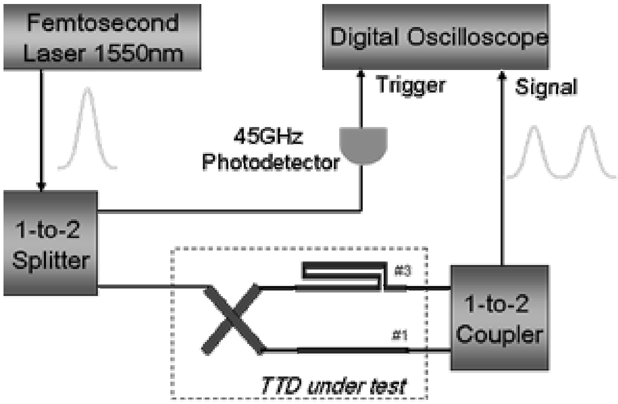
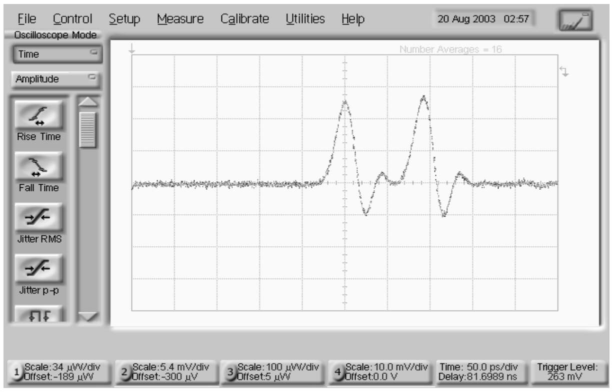


Figure 4. Diagram of the experimental setup for TTD demonstration.



1 Scale:34 µW/div Offset:-189 µW
2 Scale:5.4 mV/div Offset:-300 µV
3 Scale:100 µW/div Offset:5 µW
4 Scale:10.0 mV/div Offset:0.0 V
Time: 50.0 ps/div Delay:81.6989 ns
Trigger Level: 263 mV

Figure 5. Measured time delay interval of one bit TTD.

5. SUMMARY

A novel reconfigurable true-time delay line has been designed, fabricated and evaluated. This true-time delay line is compact, accurate, and easy to fabricate while providing a wide instantaneous bandwidth.

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