Polymer Waveguides and Thermo-Optic Switches for an Optical True Time Delay Phased Array Antenna

Brie Howley[*a], Xiaolong Wang[a], Qingjun Zhou[a], Yihong Chen[b], Ray T. Chen[a]
[a]Microelectronics Research Center University of Texas at Austin, Austin, Texas 78758
[b]Omega Optics, Austin, Texas, 78758

ABSTRACT

The design and fabrication of a polymer optical waveguide based true time delay (TTD) device is described. Optimization of the fabrication process decreased the waveguide propagation loss from more than 1.55 dB/cm to 0.38 dB/cm at a wavelength of 1.55um. Waveguide bend loss structures were fabricated and measurement results were compared to simulations. A bend radius of 3 mm provides low insertion loss and small device size. 2x2 thermo-optic TIR switches were fabricated with insertion losses of 2.8 dB. A 4-bit TTD device for use with a 4x4 sub-array of a 10GHz phased array antenna was calculated to have an insertion loss of 23.88 dB.

Keywords: Optical Waveguide, Phased Array Antenna, Thermo-Optic Switch, Polymer Waveguide, True Time Delay, Planar Lightwave Circuit

1. INTRODUCTION

Waveguide transmission lines are excellent candidates for the transmission and control of RF signals in wide bandwidth phased array antenna (PAA) systems. Optical waveguides provide low RF and microwave signal propagation loss, immunity to electromagnetic interference and reduced system size and weight. Waveguide optical delay lines, patterned by photolithographic methods, are able to deliver precise delays with sub-picosecond resolution for phased array antenna systems. Additionally, optical delay lines can be integrated with lasers, modulators, switches, and detectors to form compact planar lightwave circuits (PLC's) that are ideal for PAA applications.

Several material systems have been used to fabricate waveguide optical delay lines, notably silica[1], silicon on insulator (SOI)[2], and polymers[3]. In contrast with alternative material systems, polymer waveguides are easier to fabricate on almost any substrate of interest. The refractive indices of polymer waveguide materials can be adjusted across a broad range to address the compromise between coupling losses and bending losses. Additionally, the thermo-optical coefficient, $\Delta n/\Delta T$, of polymer materials can be in excess of an order of magnitude greater than that of SiO_2,[4] making polymers ideal candidates for low power, thermo-optic switches.

This paper reports on the fabrication and optimization of basic channel waveguide structures used in an n-bit true time delay device composed of polymer waveguide delay lines and polymer thermo-optic switches. The propagation loss of the channel waveguides is reduced to the polymer absorption loss limits in order to minimize the total device insertion loss. Using these optimized channel waveguides, bend losses and 2x2 optical switch losses are evaluated. A calculation is presented for an integrated n-bit delay device.

2. DESIGN

For a square array of antenna elements, the time delay required for each element of a PAA is given by

$$t = (p-1)\cdot\frac{d\sin\theta\sin\Phi}{c} + (q-1)\cdot\frac{d\sin\theta\cos\Phi}{c} \qquad (1)$$

[*] brie@ece.utexas.edu; phone 512-232-2586; fax 512-471-8575

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where (p,q) is the index of each element, d is the distance between elements, c is the speed of light in vacuum, and θ and Φ are the beam steering angles in the elevation and rotational directions, respectively. Fig. 1 shows the maximum time delay requirements for a 4x4 sub-array of a PAA with a maximum ±45° scanning coverage in the elevation and rotational directions over the frequency range from 8-26.5 GHz (X, Ku, and K-bands). It is assumed that the antenna element spacing is fixed at one half the RF wavelength.

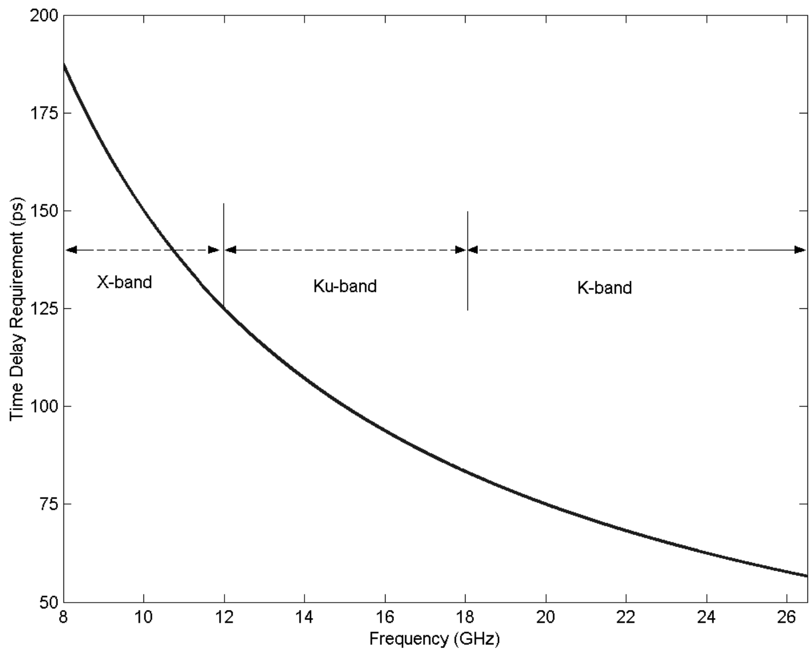

Fig. 1. Time delay needed as a function of RF frequency for a 4x4 element sub-array.

An optical TTD device structure is described which provides the required time delays to each element of a PAA sub-array. The TTD device structure is based on thermo-optic polymer switches and fixed delay polymer waveguides. The structure for the waveguide delay module is shown in Fig. 2. A single mode input fiber is butt coupled to a 2x2 optical switch (n=1). A planar lightwave circuit (PLC) comprised of two different lengths of polymer waveguides is positioned at the output ports of the n=1 switch. Depending on whether the bar state or cross state of the switch is chosen, light is delivered to the waveguide with length of l or Δl. These waveguide delay lines are again connected to another 2x2 optical switch (n=2) and the output ports are coupled to two more waveguides of lengths l and $2\Delta l$. This sequence is continued with lengths of the short waveguides remaining at a length of l and the long waveguide sections increasing in length according to $\Delta l \cdot 2^{(n-1)}$. The time delay, t, provided by these fixed delay waveguides is given by

$$t = \frac{L \cdot n_{eff}}{c} \qquad (2)$$

where *L* is the sum of the waveguide lengths through which the light travels, c is the speed of light in vacuum, and n_{eff} is the effective index of the waveguide. The last switch (n+1) of the n-bit delay device is controlled to deliver the optical signal to the output optical fiber.

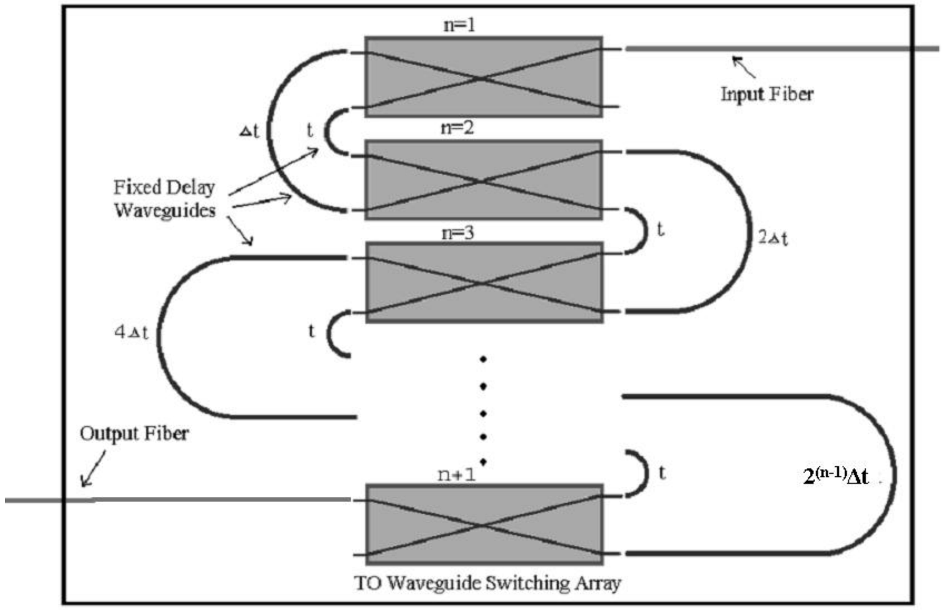

Fig. 2. TTD device structure employing waveguide optical switches and delay lines.

A key feature of this device structure is the layout of the delay lines, which are each composed of two straight segments of the appropriate length connected by a single 180 degree bend. This design minimizes the total length of curved waveguides thereby minimizing the total amount of device bending loss.

The insertion loss is a critical parameter for such a TTD device. For a fully integrated device, there will only be optical coupling and reflection losses between the input and output fibers and the planar lightwave circuit. For an n-bit TTD device, the total insertion loss will be the sum of the fiber to waveguide coupling losses (CL), the input and output reflection losses (RL), the loss from the n+1 optical switches (SL), the bending loss (BL) from the n waveguide delay lines, and the total path loss (PL) of the appropriate delay line length, L. The resulting equation for the insertion loss of an n-bit channel waveguide based TTD device is

$$IL = 2(CL + RL) + (n+1)SL + n \cdot BL + PL \qquad (3)$$

where

$$PL = \frac{c \cdot t \cdot \mathrm{Pr}\,opagationLoss}{n_{eff}} \quad . \qquad (4)$$

The polymer waveguide is the basic building block of the TTD device. A poorly fabricated waveguide will significantly increase of the propagation loss, thus increasing both the overall path loss (PL) as well as the switch loss (SL). Additionally, the bending loss (BL) may also be increased due to scattering effects if the waveguide edges are too rough. Because of the critical need to minimize the total insertion loss of the TTD device, it is important that the waveguide efficiency be maximized.

3. RESULTS

3.1 Waveguide fabrication procedure

The fabrication process for the polymer waveguides used in the optical switches and delay lines is shown in Fig. 3. A polymer bottom cladding material is spin coated onto a clean substrate. The thickness of the layer is determined by the spin speed. After UV and thermal curing, a second layer of polymer is spun which serves as the core layer. This core layer has a slightly higher refractive index which is needed for guiding the light by total internal reflection. A suitable thickness of a hard masking material is then deposited followed by photoresist which is defined by photolithography. The hard mask is then patterned by either a wet or dry etching method depending on the hard mask material. Once the hard mask is properly defined, reactive ion etching (RIE) is used to form the channel waveguides in the core material. The remaining hard mask is then removed and a polymer top cladding layer is spin coated and cured.

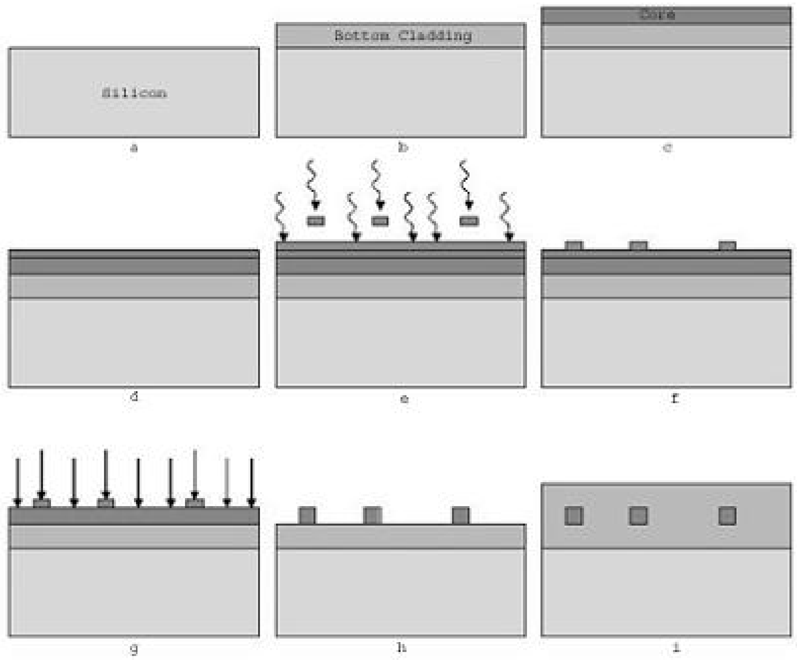

Fig. 3. The polymer waveguide fabrication process.

An optimization study was performed on the polymer RIE processing parameters: process temperature, pressure, and RF power. Table 1 shows the design of experiment (DOE) parameters that were used.

Table 1. DOE parameters for optimization of the polymer RIE process

Parameter	High Value	Low Value
Pressure (mTorr)	90	10
Temperature (°C)	25	0
Power(Watt)	200	100

The measured effects of the DOE were the etch rate, anisotropy, and sidewall edge roughness. Through experimentation and analysis it was determined that a combination of high temperature, low pressure, and high power resulted in channel waveguides with the smallest anisotropy and sidewall roughness. Fig. 4. shows a waveguide core produced with the optimized RIE parameters.

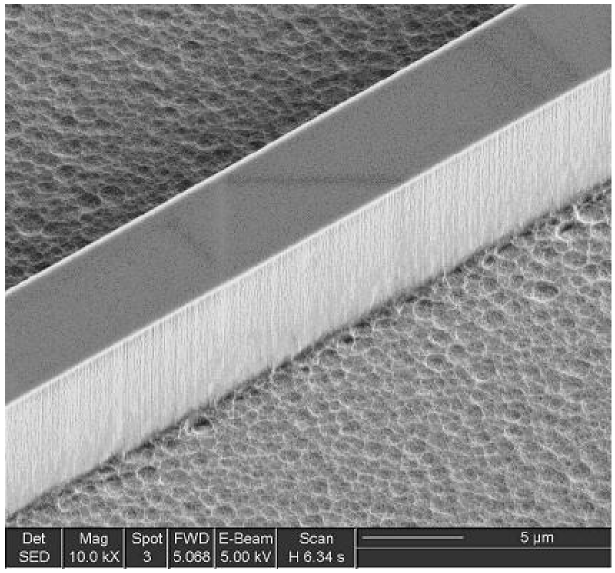

Fig. 4. SEM image of a channel waveguide core etched with the optimized RIE parameters.

In addition to the polymer RIE optimization, several hard mask material systems were examined to determine their effect on the overall propagation loss. Choices of hard mask materials included aluminum (Al), chromium/gold (Cr/Au), and silicon dioxide (SiO_2). Aluminum significantly degraded the performance of the polymer. Waveguides formed with aluminum hard masks exhibited extremely high polarization dependant loss (PDL). The exact mechanism of this degradation has yet to be determined but values for the propagation loss of the TE polarized light was 1.55 dB/cm while that for a TM polarization was in excess of 20 dB/cm. A combination of a thin layer of chromium and a thicker gold layer improved the results. The measured propagation loss with this material system was as low as 0.45 dB/cm with no measurable PDL. However, it was observed that the edges of the patterned Cr/Au mask were not smooth. The rough mask edge pattern was transferred to the polymer through the RIE process resulting in rough waveguide sidewalls. This roughness was possibly caused by the wet chemical etching of the metal hard mask. In order to combat this problem, silicon dioxide (SiO_2) was employed as the hard mask material. SiO_2 has the ability to be dry etched with a RIE plasma. The dry etch process yields smoother hard mask edges thereby reducing the roughness of the polymer waveguide sidewalls. Fig. 5a and 5b are SEM images of the patterned Cr/Au and SiO_2 hard masks, respectively.

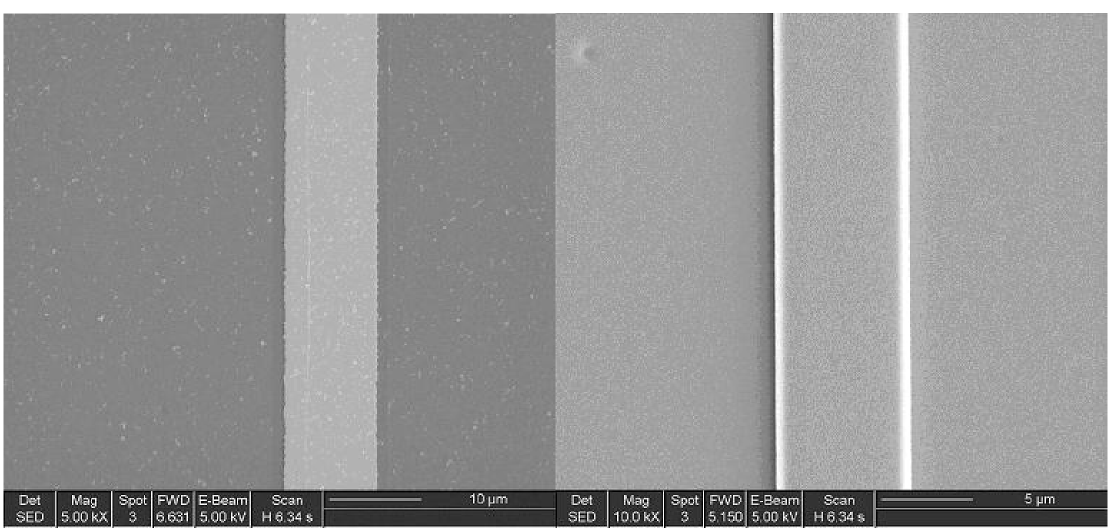

Fig. 5a.(left) Patterned hard mask of Cr/Au material and 5b(right) Patterned SiO_2 hard mask.

3.2 Device structures

Following fabrication of the optimized channel waveguide, the propagation loss was measured to be 0.38 dB/cm at a 1.55 um wavelength. This is near the lower limit set by the material absorption, measured from the planar waveguide propagation loss to be 0.35dB/cm. The coupling loss from this optimized waveguide to a single mode glass optical was measured to be 0.31 dB. Additionally, the reflection loss, between the 1.46 index of the waveguide core and the 1.0 air index, was calculated to be 0.15 dB. Using BeamProp software, the effective index of the 7x7 um waveguide was simulated to be 1.455.

In order to obtain an approximation of the overall device insertion loss, bending loss structures were fabricated to determine the minimum acceptable bending radius and the associated bending loss (BL). Additionally, 2x2 total internal reflection (TIR) thermo-optic polymer switches were fabricated to obtain a switch loss (SL) value.

3.2.1 Bending loss structures

Using BeamProp software simulation tools, the bending loss as a function of bend radius was simulated for the 7x7 um waveguides. As seen in Fig. 6 the simulation results for waveguides with 180 degree bends show an exponential increase in the bend loss as the bend radius decreases. Radii values of 3.5 mm or smaller have bend loss values less than 1dB. It should be noted that the simulations do not take into account the waveguide sidewall roughness which contributes to higher bend losses.

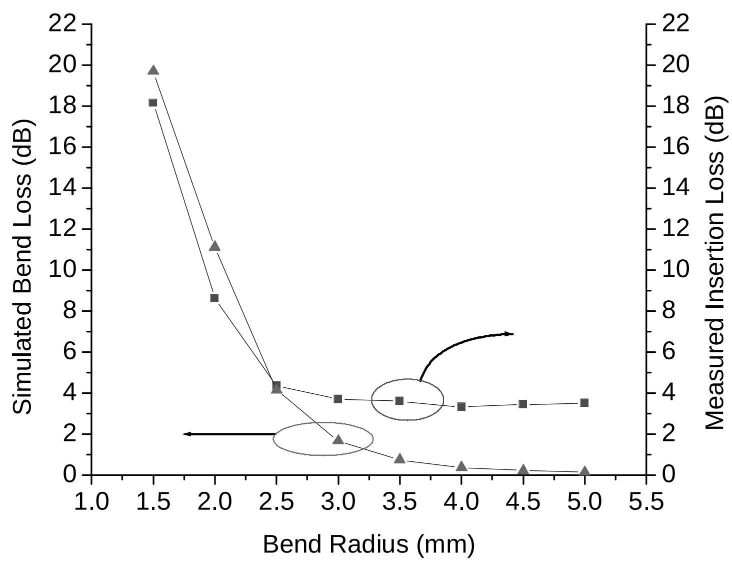

Fig. 6. Simulated bend losses and measured insertion losses for 180 degree bend.

In order to verify the simulation results, 180 degree bend waveguides were fabricated and the insertion losses were measured. The insertion loss values for the fabricated waveguides are also shown in Fig. 6. For bending radii between 3 and 5 mm the measured insertion loss is relatively flat with values ranging from 3.7 to 3.5 dB, respectively. These insertion loss values are considerably greater than the simulated bend loss. The increase in the loss between the simulated and measured sets of data at these relatively large bending radii is attributable to the simulations which do not account for the coupling or reflection losses nor the waveguide propagation losses. Additionally, as mentioned previously, the simulations do not account for scattering in the bends caused by the waveguide edge roughness.

For bending radii less than or equal to 2.5 mm, the measured insertion loss increased significantly from that of the larger bend radii waveguides. However, the overall insertion loss values are nearly equal to or lower than the simulated bend loss values. This indicates that the BeamProp bend loss simulations are not accurate at these small bending radii.

In order to minimize the device size while also maintaining a low overall bending loss, a bend radius of 3 mm was chosen for the waveguide delay lines. This is a minimal concession to the overall insertion loss since there is only a 0.2 dB bending loss increase between the 5 mm and 3 mm bend radii. In order to calculate the overall bend loss (BL) for the device insertion loss calculation, the coupling losses and reflection losses must be subtracted from the 3 mm bend radius insertion loss of 3.7 dB. The total coupling loss (CL) between input and output single mode fibers and the 7x7 um waveguide is 0.62 dB. Additionally the reflection loss (RL) for both interfaces is 0.30 dB. The resulting 180 degree bend loss (BL) is therefore 2.78 dB.

3.2.2 Switch loss structures

A total internal reflection (TIR) based thermo-optical switch was designed, fabricated, and tested. The switch is composed of the basic optimized channel waveguide structure that has been described. The TIR switch structure has the merits of compact size, wavelength insensitivity and polarization independence. The TIR optical switch uses the negative thermo-optic effect of polymer materials, i.e., the refractive index of the polymer decreases as the temperature increases. An electrically driven heater was fabricated on the top cladding layer at the crossing point of a symmetric waveguide X junction as shown in Fig. 7. Since the crossing angle of the X junction is large enough, generally above 4°, the light launched into input 1 is transported to output 2 (defined as the ''cross'' state), when the heater is not powered. When sufficient driving power is applied to the heater, the refractive index of the polymer material below the heater is lowered and a TIR effect causes the light to reflect at the crossing point of the X junction and propagate to output 1(defined as the "bar" state) thus demonstrating a 2×2 switch.

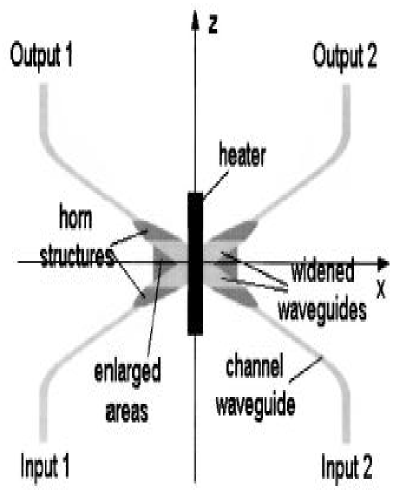

Fig. 7. A thermo-optic TIR switch design for use with polymer waveguides.

The total insertion loss (single mode fiber in, single mode fiber out) of the fabricated switch was measured to be 2.87dB. More details about the operating characteristics of this switch will be presented in a future publication. Using the same values for the coupling and reflection losses as was used in the previous section, the switch loss (SL) was calculated to be 1.95 dB.

3.3 Overall insertion loss

Given the above loss values, the overall insertion loss of the waveguide TTD device can be calculated. Using equations (1), (3) and (4), for a 4-bit TTD device designed for use in a 4x4 sub-array of a 10 GHz RF frequency antenna, the total insertion loss will be 23.88 dB when the optimized polymer waveguide with an effective index of 1.455 is used to construct the system.

4. CONCLUSION

The fabrication of an optical TTD device structure based on polymer optical waveguides has been presented. These polymer waveguides can be used to construct optical delay lines and 2x2 thermo-optic switches. By choosing the appropriate delay path, an optically delayed RF frequency can be delivered to each antenna element of a phased array antenna. The fabrication procedure of the waveguides has been optimized to reduce the total device insertion loss. Bend loss structures were fabricated and their measured losses were compared to simulation results. TIR thermo-optic switches were fabricated. Using the measured loss values, a 4-bit TTD device for 4x4 sub-array was calculated to have an insertion loss less than 24 dB.

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