Wideband phased array antenna controlled by a single substrate guided wave true-time-delay module

Zhenhai Fu and Ray T. Chen
Microelectronics Research Center
The University of Texas at Austin, Austin, Texas 78758
Tel: 512-4717035; Fax: 512-4718575; E-mail:raychen@uts.cc.utexas.edu

Abstract

A 5-bit true-time-delay lines device having a packing density of 2.5 lines/cm² with a minimum delay step of 50 ps which can controls antenna array with 9 subarrays simultaneously is designed, fabricated and demonstrated in this paper. The power fluctuation among 32 delay lines is controlled to within ±10%. A bandwidth of 2.4 THz is experimentally confirmed. To verify the bandwidth of the device, up to 50GHz optically heterodyned microwave signal is generated, sent through the device, and then detected at the output end.

Phased array antenna (PAA) systems combine the signals from as many as thousands of antenna elements to point a directive beam at a certain angle in space. They offer many advantages, including steering without physical movement, accurate beam pointing, and reduced weight and power consumption. In order to overcome the problem of scanning angle changing with microwave frequency, true-time-delay (TTD) line is used so that greater bandwidth and higher resolution phased array radar operation is possible. Two methods have been used to produce time-corrected steering in practical phased arrays[1,2] as shown in Fgiure 1. The first method is to group the array into subarrays, use time-delay device behind each subarray, and use phase shift behind each element. Second, each time-delay unit is built to provide a discrete set of delay lines rather than continuous delay lines. In this way, the system provides some, but not all, of the benefits of true-time-delay steering. Photonics TTDs offer a wider bandwidth, a compact size, a reduced weight and low RF interference[3,4]. Many photonic TTD structures have been proposed, but most of these devices can only provide delay signals to one antenna element each.

A 5-bit true-time-delay unit with 2.5 delay lines/cm^2 which distributes up to 2.4 THz true-time-delay microwave signals with delay step of 50 ps to a phased array antenna with 9 subarrays is accomplished through the combination of a fiber bundle and substrate guided optical fanouts. Figure 2 illustrates the basic system architecture of the TTD device[5,6,7]. A 1-to-4 fiber beam splitter with different fiber lengths is used to provide 4 delay signals with 8 $\Delta\tau$ delay increment. Each of the delay signal from the 1-to-4 beam splitter is coupled into the substrate surface normally with a 53.5° substrate bouncing angle by a holographic grating coupler. During bouncing, portions of the light are sequentially extracted surface-normally through a holographic grating coupler array[8,9]. Different optical delays are

Part of the SPIE Conference on Photopolymer Device Physics, Chemistry, and Applications IV • Québec, Canada • July 1998
SPIE Vol. 3417 • 0277-786X/98/$10.00

obtained at subsequent fanouts within the substrate. The time delay between two successive collinear fanouts is $\Delta\tau$. The delayed optical fanouts are then detected by high speed detector array. Thus, 32 (2^5) delay lines can be achieved. The detected RF signals are later amplified and sent to antenna element by programmed switching.

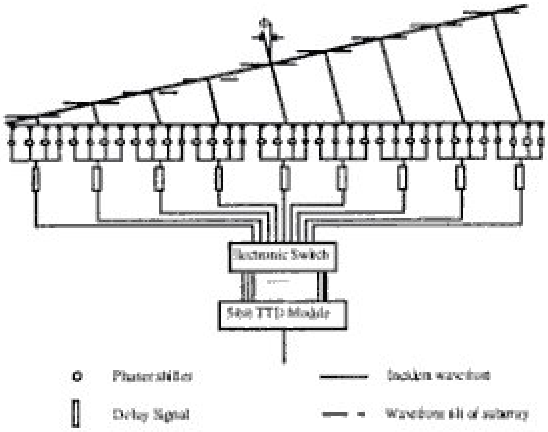

Figure 1. Wideband scanning array feeds: each unit control 9 subarrays

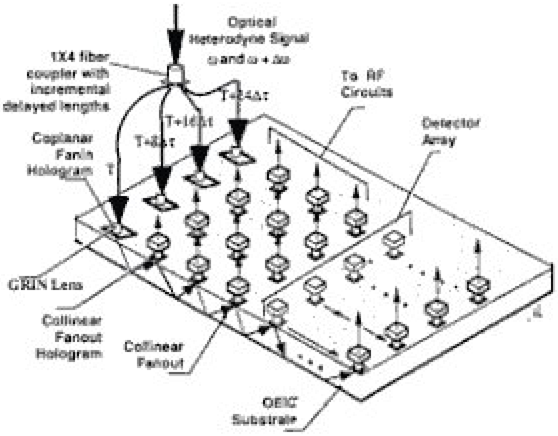

Figure 2. 5-bit optical delay lines based on substrate guided mode with holographic couplers

Each of such true-time-delay unit can be used not only to provide true-time-delay signals to one antenna element but also to provide delay signals to several antenna elements simultaneously. In the first case, let's suppose that the PAA is programmed to steer from +45° to -45° angular range. For the 5-bit TTD unit, the smallest differential delay increment is given by

$$\Delta\tau = L\sin\Phi_{\max} / 31c, \tag{1}$$

where L is the linear dimension of the linear PAA. Assume L =65cm, then $\Delta\tau = 50$ ps.

In the second case, as shown in Figure 1, 36 antenna elements are divided into 9 groups. Each subarray is controlled by one delay signal. A phase shifter is behind each antenna element. Similarly, suppose the PAA is programmed to steer from +45° to -45° angular range and L = 67 cm. The scanning angle and the corresponding delay of each subarray are shown in Table 1, where $\Delta\tau$ is set as 50 ps.

With a substrate total internal bouncing angle of θ, the optical delay between successive output couplers is given by

$$\Delta\tau = \frac{\Delta L'}{c/n} = \frac{2d/\cos\theta}{c/n} \tag{2}$$

where $\Delta L'$ is the difference in propagation length between two successive fanouts, d is the substrate thickness, c is the speed of light, and n is the refractive index of the substrate material. For a 50ps delay, one possible thickness d of the quartz substrate is 3 mm, the corresponding θ is 53.5° and the distance between two successive fanouts is 8 mm.

Table 1 Scanning angles and the corresponding delays of each subarray

Scanning angle	Sub-array 1	Sub-array 2	Sub-array 3	Sub-array 4	Sub-array 5	Sub-array 6	Sub-array 7	Sub-array 8	Sub-array 9
-45°	0	4 Δτ	8 Δτ	12 Δτ	16 Δτ	20 Δτ	24 Δτ	28 Δτ	32 Δτ
-32°	0	3 Δτ	6 Δτ	9 Δτ	12 Δτ	15 Δτ	18 Δτ	21 Δτ	24 Δτ
-21°	0	2 Δτ	4 Δτ	6 Δτ	8 Δτ	10 Δτ	12 Δτ	14 Δτ	16 Δτ
-10°	0	Δτ	2 Δτ	3 Δτ	4 Δτ	5 Δτ	6 Δτ	7 Δτ	8 Δτ
0°	0	0	0	0	0	0	0	0	0
10°	8 Δτ	7 Δτ	6 Δτ	5 Δτ	4 Δτ	3 Δτ	2 Δτ	Δτ	0
21°	16 Δτ	14 Δτ	12 Δτ	10 Δτ	8 Δτ	6 Δτ	4 Δτ	2 Δτ	0
32°	24 Δτ	21 Δτ	18 Δτ	15 Δτ	12 Δτ	9 Δτ	6 Δτ	3 Δτ	0
45°	32 Δτ	28 Δτ	24 Δτ	20 Δτ	16 Δτ	12 Δτ	8 Δτ	4 Δτ	0

To ensure uniform beam fanout, it is necessary to precisely tune the diffraction efficiency from each output coupler using the following equation

$$\eta_k = \frac{\eta_1}{1-(k-1)\eta_1}, \qquad k=1,\ 2,\ 3,.....N, \tag{3}$$

where η_k is the diffraction efficiency of the kth fanout coupler. In our case, N=8, and assuming that $\eta_8=90\%$, diffraction efficiencies for k=1,2, ...7 are determined to be $\eta_1=12.3\%$, $\eta_2=14\%$, $\eta_3=16.3\%$, $\eta_4=19.5\%$, $\eta_5=24.2\%$, $\eta_6=32\%$, $\eta_7=47\%$. To achieve the desired diffraction efficiencies, we first derive the relationship governing the diffraction efficiency as a function of the exposure dosage, then record holograms with different exposure dosages to achieve the desired diffraction efficiencies. Figure 3 shows the packaged device with a packing density of 2.5 fanouts/cm^2. Figure 4 shows the image of 5-bit delay fanouts (4X8) at TE mode with a fanout intensity fluctuation within ±10%. From the measured coupling efficiency, the system insertion loss is determined to be 18 dB, including an 8 dB 1X4 fiber beam splitter insertion loss, a 9 dB substrate guided wave fanout loss, a 1 dB propagation and other loss. Same results can be achieved with TM mode incidence.

The delay interval and the bandwidth are measured by employing a Ti:Sapphire femtosecond laser system[7]. Two successive delays pulses from the TTD unit are combined with a focusing lens and coupled into a multimode fiber cable and then fed into an ultrafast MSM photodetector. The detector output is amplified through a amplifier which is connected to a sampling scope. The sampling scope is synchronously triggered by a reference pulse string from a monitoring photodiode output. As shown in Figure 5, the delay between two successive fanouts is nearly 50 ps. The bandwidth of the TTD delay unit can be evaluated by measuring the pulse widths before and after the device. For this purpose, a femtosecond laser pulse is sent through the device. The pulse width of one of the fanout beams from the TTD unit is measured and compared with that of the incoming pulse. Fourier transforms are performed on both to deduce the bandwidth of the device. As shown in Figure 6, the 3-dB bandwidth of the TTD device is thus experimentally confirmed to be 2.4 THz.

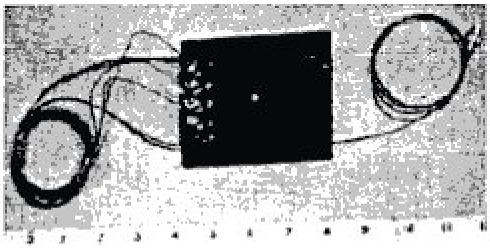

Figure 3 Photograph of the 5-bit TTD device

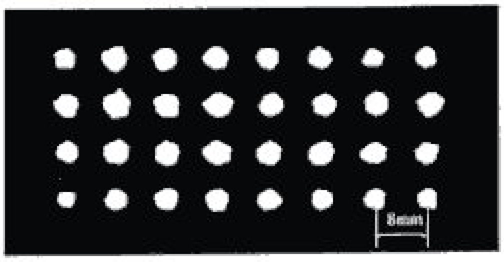

Figure 4 CCD picture of 5-bit delay fanout line(4X8) with a fanout intensity fluctuation within ±10%

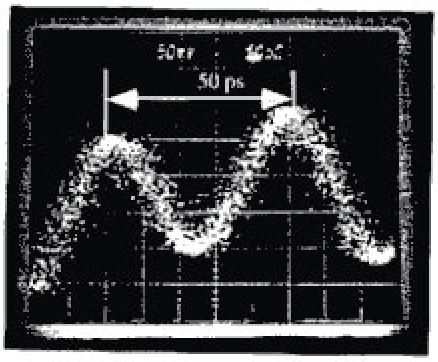

Figure 5 Photograph of the sampling scope screen showing the two pulses pulses coming from successive fanouts

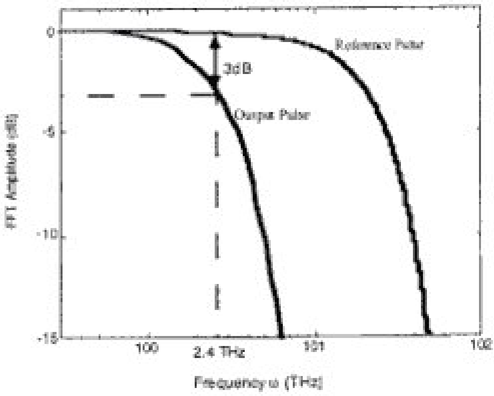

Figure 6 FFT power spectrum for the input and output

To testify the wide bandwidth of the device, a 50 GHz optically heterodyned microwave signal is generated, sent through the device, and then measured. Two tunable diode lasers oscillating at single longitudinal mode are employed to generate 50 GHz signal in our experiment. Due to the limitation of the bandwidths of the detector, amplifier, and the spectrum analyzer, this 50GHz signal can't be detected directly. A third tunable diode laser with wavelength between the above two lasers is used to down-convert this 50 GHz signal to two signals at about 25 GHz. We send this 50 GHz signal directly through the TTD device. The fanout from the device with $32\Delta\tau$ time delay is combined with the output of the third laser and is then sent to ultrafast photodetector with amplifier which is connected to the spectrum analyzer. From the measured signals on Figure 7, we get

$$\begin{aligned}\Delta f &= f_1 - f_2 \\ &= (f_1 - f_3) + (f_3 - f_2) \\ &= 24.85 + 25.90 = 50.75 \text{ GHz}.\end{aligned}$$

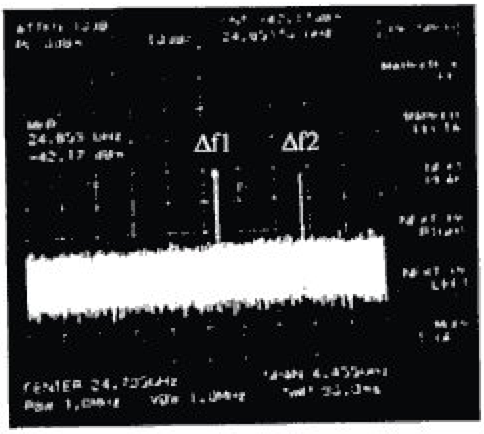

Figure 7 50 GHz optical heterodyne signal detected by spectrum analyzer

In summary, a 5-bit true-time-delay lines device having a packing density of 2.5 lines/cm^2 with a minimum delay step of 50 ps is designed, fabricated and demonstrated in this paper. This device is based on substrate guided wave propagation combined with slanted photo polymer volume phase gratings. The power fluctuation among the outputs due to the cascading fanout effect is experimentally investigated and solved. A power fluctuation controlled to within ±10% is achieved. A delay step of 50 ps and a bandwidth of 2.4 THz are experimentally confirmed. To verify the bandwidth of the device, up to 50GHz optically heterodyned microwave signal is generated, sent through the device, and then detected at the output end. The true-time-delay device presented herein has the potential to be integrated with photodetector arrays due to its planar structure on a single substrate together with the surface normal fan-in and fan-out features.

Reference

[1] Robert J. Mailloux, *Phased Array Antenna Handbook*, Artech House, 1994
[2] W. Ng et al., *IEEE J. of Lightwave Technology*, Vol. 9, no.9,pp.1124-1131, 1991
[3] H. Zmuda and E. N. Toughlian, *Photonic Aspect of Modern Radar*. Artech House, 1994
[4] E. Ackerman et al., *IEEE MTT-S Digest*, R-6, pp.681-684, 1992
[5] R. T. Chen and R. Lee, *SPIE Technical Digest*, vol. 2689, pp.176-187, 1996.
[6] Richard Li and Ray Chen, IEEE Photonics Technology Letters, Vol. 9, No. 1, pp. 100-102, 1997
[7] Richard Li et al., *SPIE* Vol. 3006, pp.256-263, 1997
[8] M.R. Wang et al., *Applied Optics*, vol. 31, no. 2, pp.236-249, 1992.
[9] R. T. Chen et al., *Appl. Phys. Lett.* , vol. 63, no.14, pp.1883-1885, 1993.