

Photonic true time delay module for high frequency broad band phased array antenna

Yihong Chen, Ray T. Chen

Microelectronics Research Center, The University of Texas at Austin, Austin, TX 78758

ABSTRACT

A 2-D true-time delay (TTD) module for phased-array antennas (PAAs) is presented, which is based on substrate-guided wave elements. We use substrates of different thickness to get time delays as small as needed. We also use coated wedge to substitute input hologram element to decrease losses up to 60%. Also, a step is designed to obtain 0 degree steering which is impossible for packaging in the previous design. We designed special delay steps to avoid the side lobe caused by the limitation of the distance between adjacent antenna elements. The simulation results were given for the far-field radiation pattern of PAA controlled by this module. Experimental results of the TTD module are shown in both 2D and 3D images.

Keywords: Photonic analog true-time delay, phased-array antenna, substrate-guided wave elements, hologram optical element

1. INTRODUCTION

Many kinds of photonic phased-array antenna (PAA) techniques were proposed [1]-[5], which can provide feeding signals for the array elements with correct phase relationship at any RF frequency so that avoid the beam squint which is the main drawback of conventional phased-array antenna based on phase-shift control designed at a single RF frequency.

In previous paper [6], we demonstrated the compact optical true-time delay module based on substrate-guided wave structure. It is a fan out structure and the delay step is obtained by the holographic volume grating that was recorded on the top surface of the glass substrate. But the disadvantage is that the delay step is limited by the thickness of the substrate, so it cannot get very small delay steps, which is required by high RF frequency antenna.

In this paper, a new scheme of an optical true-time delay is proposed, which is not limited by RF frequency. The new module is based on our substrate-guided wave hologram-grating structure. We use substrates of different thickness to get time delays as small as needed. We also use coated wedge to substitute input hologram element to decrease losses up to 60%. Also, a step is designed to obtain 0 degree steering which is impossible for packaging in the previous design.

2. TTD THEORY

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

$$E(\theta, t) = \sum_{n=1}^N A_n \exp(i\omega_m t) \exp[i(\psi_n + nk_m d \sin \theta)] \quad (1)$$

where A_n is pattern of the individual element, ω_m is the microwave frequency, $k_m = \omega_m / c$ is the wave vector, ψ_n 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 an angle θ_0 , ψ_n is set to the following value:

$$\psi_n = -nk_m d \sin \theta_0. \quad (2)$$

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 (TTD) 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

$$t_n(\theta_0) = -(nd \sin \theta_0) / c \quad (3)$$

3. 2-D TRUE TIME DELAY MODULE

In this module (fig.1), we design guiding-wave substrate with a set of thickness from h_1 to h_i . On the top-surface of the substrate, there is a transparent grating film made by the hologram recording. All of the substrates have wedges of same degree and a step of same height. The wedges are coated with total reflect material to ensure that all light power is coupled into the substrate, which in turn increase efficiency by 60% (4.4dB). The first output, which is induced by the step, has the same time delay for all substrates, corresponding to 0 degree steering which is hard to achieve for some kinds of modules.

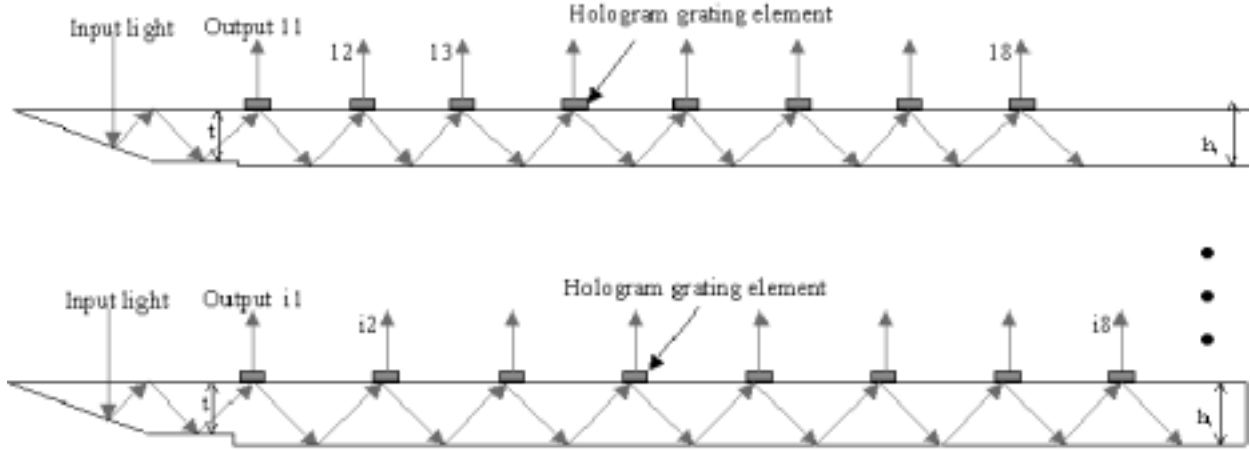


Figure1. Optical TTD module

Assuming the wedge angle is θ , the introduced time delay by the module between output (i, n) and (m, n) is:

$$\tau = \frac{2n(h_i - h_m)}{\cos(2\theta) \cdot c} \quad (4)$$

After we fix the required τ in the PAA system, the thickness difference can be calculated using the above formula.

For a PAA shown in figure 2, we designed the TTD module. The wedge angle is fixed as 21.5 degree, introducing the bouncing angle as 43 degree, which is larger than total internal reflection angle. The step thickness is 2.6mm. The smallest delay step τ is calculated to be 2.0108ps. The design results are shown in table 1.

Table.1 Thickness and steering angle

Thickness(mm)	3.6	3.747	3.894	4.041	4.188	4.335	4.482	4.629
Tuning angle(degree)	0	7.18	14.48	22.02	30	38.68	48.59	61.04

We use the output to control the first four elements of the first row and the second row. The simulated antenna far field pattern has neither squint nor side lobe. The simulation antenna field pattern in x-Y plane and y-z plane are shown in figure 3. Also because $dy=dx/2$, y-z plane is also TTD control.

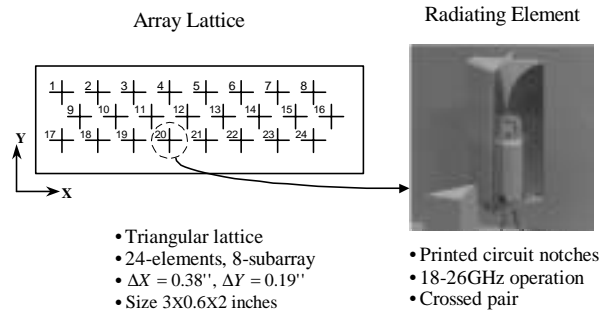


Figure2. High frequency phased array antenna

Figure 3.

In Fig.4 shown the 2-D TTD module package design. The input signals are from modulator array coupling from GRIN lens. Output beam from hologram element is also coupled from GRIN lens. RF signals are fed to antenna element after photodetectors.

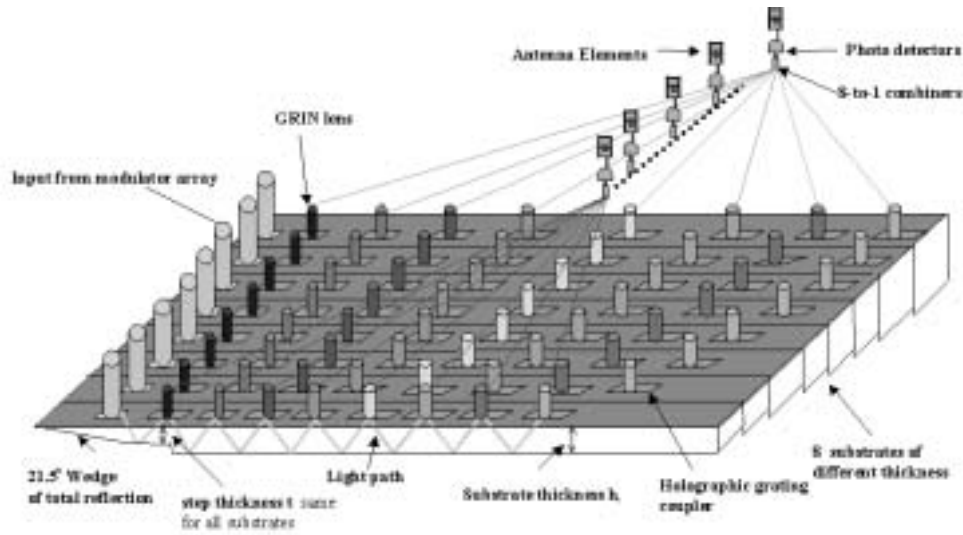


Figure 4. 2-D TTD module package design

4. EXPERIMENTAL RESULTS

The recorded output beam spot (2-D and 3-D) from one substrate is shown in figure 5. Before we recorded the module, we designed the efficiency for each hologram optical element to make the output uniform. From the images we can see that the output beams are uniform within 10%. The delay between adjacent outputs is the same as design.

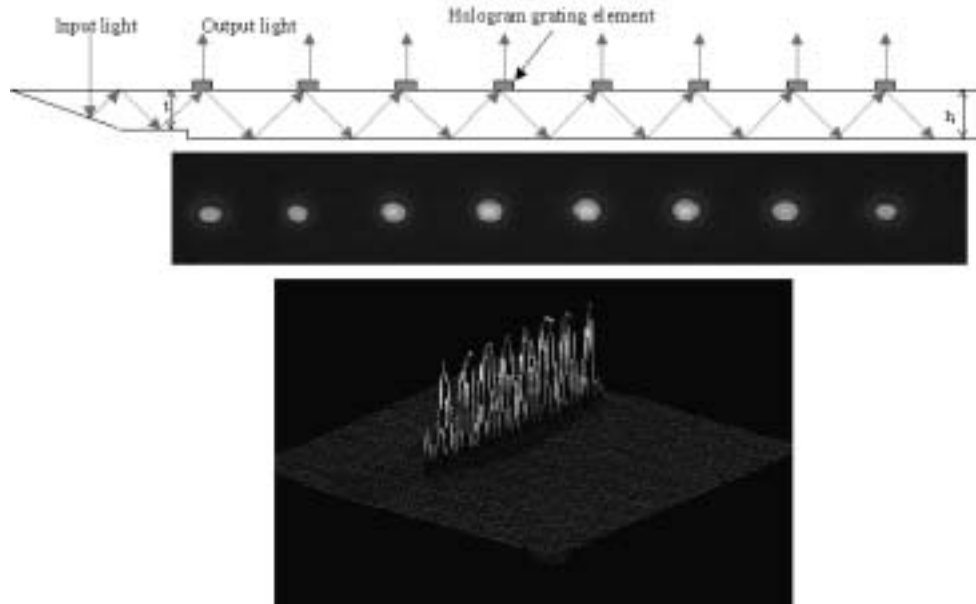


Figure 5. Output beam spot from one substrate

5. SUMMARY

We use substrates of different thickness to get time delays as small as needed. In theory, it is not limited by frequency band. We also use coated wedge to substitute input hologram element to decrease losses up to 60%. Also, a step is designed to obtain 0 degree steering which is impossible for packaging in the previous design. We designed special delay steps to avoid the side lobe caused by the limitation of the distance between adjacent antenna elements. It's compact and economical. Also this module has good efficiency uniformity around 1550nm.

REFERENCE

1. Yoshihiko Konishi, etc., "Carrier-to-Noise Ratio and Sidelobe Level in a Two-Laser Mode Optically Controlled Array Antenna Using Fourier Optics", *IEEE Transactions on Antennas and Propagation*, Vol. 40(12), pp. 1459-1465, 1992.
2. D. Dolfi, etc., "Experimental demonstration of a phased-array antenna optically controlled with phase and time delays," *Applied Optics*, Vol. 35(26), pp. 5293-5300, 1996
3. Dennis T. K. Tong and Ming C. Wu, "A Novel Multiwavelength Optically Controlled Phased Array Antenna with a Programmable Dispersion Matrix," *IEEE photonics Technology Letters*, Vol. 8(6), pp. 812-814, 1996.
4. Akis Goutzoulis, Ken Davies, etc., "Development and field demonstration of a hardware-compressive fiber-optic true-time-delay steering system for phased-array antennas," *Applied Optics*, Vol. 33(35), pp. 8173-8185, 1994.
5. C. T. Sullivan, etc., "Switched time delay elements based on AlGaAs/GaAs optical waveguide technology at 1.32 μ m for optically controlled phased array antennas," *Optical Technology for Microwave Applications VI and Optoelectronic Signal Processing for Phased-Array Antennas III, Proc. SPIE* Vol. 1703, pp. 264-271, 1992.
6. Zhenhai Fu, Ray T. Chen, "Compact broadband 5-bit photonic true-time-delay module for phased-array antennas," *Optics Letters*, Vol.23(7), pp. 522-524, 1998.