Photonic True Time-Delay Beam Steering for Radars

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***Abstract*—In this paper, a photonic true time-delay technique for phased-array beam steering is proposed and analyzed for radar systems. It uses a High-Dispersion Compensation Fiber (HDCF) and a phased array antenna, which can provide a continuous radio-frequency squint-free beam scanning. When the dispersion of the fabricated HDCF is as high as -1020±31 ps/nm/km, the laser wavelength can be tuned from 1549.95 to 1550.2 nm. The experimental results confirmed that the scanning angle of far field radiation patterns for the proposed technique can be tuned from -22^0 to +29^0 at frequencies 5.9, 12.7 and 17 GHz.**

Keywords-optical true time delay;high-dispersive compensation fiber; phased array antenna.

I. INTRODUCTION

Microwave photonics is the research of the mixing between microwave and optical waves for applications, like radars, communications, sensor networks, warfare systems and instrumentation [1]. Optical beam formation for phased array antennas has been intensely studied during the last decade. The development of beam-forming systems with high performance, low weight, high efficiency and low cost is essential. Passive optical devices, such as Photonic Crystal Fibers (PCF) prism, coupled micro-ring resonators, Dispersion Compensating Fibers (DCF) and PCFs, are used in the Optical True Time-Delay (OTTD) techniques [2-5]. Many applications of fiber optics in phased array radars are visualized. Optical control systems [6] allow the use of desirable array functions. The most important of these is true time-delay beam-formation, which is required for wide instantaneous bandwidth and squint-free operation.

The use of optical TTD (True Time –Delay) to control the radiation angle for Phased Array Antennas (PAA) allows frequency independent beam steering, compact size and light weight, large instantaneous bandwidth, low loss and Electro-Magnetic Interference (EMI), which make it a promising choice for broadband PAA [7][8]. PAA's also allow high directional control and rapid beam steering, without the need for physical movement. This antenna allows flexible electronic beam scanning over a wide range of angles, without the need for mechanical rotation of the antenna, and gives convenient spatial characteristics to the beam shaping, by independent control of the transmitting elements.

This study proposes an optical TTD system for a 1×2-element PAA that uses a HDCF module and a wavelength tunable laser. The time delay and the radiation pattern for the proposed system are verified by simulation and experimental measurement.

II. THEORY AND DESIGN

A. *Antenna Design*

The patch antenna design of microstrip transmission line (W and L) has length of approximately one-half wavelength of the center frequency resonant. The geometry of the 1×2-element array antenna and its size is shown in Fig. 1.

All of the designs are simulated using the software package Ansoft High Frequency Structure Simulator (HFSS), based on a three-dimensional finite element method (3-D FEM). The substrates are a FR4 printed circuit board (PCB) and a RT/duroid 6010 with dielectric constant of 4.4 and 10.2 and height of 1.6 and 0.635 mm, respectively. The length of the single patch antenna is 0.5 λ_g. The distance between the antenna and the antenna is 0.7 λ_{eff}. The λ_{eff} is the effective wavelength, calculated by assuming effective dielectric constant for the substrate of ε_{eff} = $(\varepsilon_r+1)/2$ [9]. From Fig. 1, it is seen that the sizes of the array antenna are, W_1 = 13.61, 4.43 and 3.2 mm, W_2 = 2.97, 0.59 and 0.59 mm, L_1 = 12.76, 2.48 and 3.46 mm and L_2 = 3.47, 1.26 and 0.84 mm, at 5.9, 12.7 and 17 GHz, respectively.

B. *Phase Array Aantenn*

An N-element linear array has a uniform amplitude and spacing. In order to operate the overall radiation pattern of the connection elements, we need to control several parameters. These parameters include the N array elements in the array, the distance between two adjacent antenna elements, the orientation of each element for the feed amplitude or phase shift. The array factor is expressed as:

$$AF(\varphi) = \frac{\sin(N_\varphi / 2)}{N \sin(\varphi / 2)} \tag{1}$$

with

$$\varphi = kd\cos\theta + \beta \tag{2}$$

where N is the number of elements, k is the wave number of the radiated signal (k =2π/λ_RF), d is the spacing between two antenna elements, θ is the spatial angle around the axis of orientation of the array and β is the phase shift of the electrical signals that feed the antenna elements.

In order to discard the beam squint and to allow a wide range of frequencies, the beam-forming, with OTTD is used.

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Rather than producing a phase shift in the electrical signals that influence the antenna elements, time delay phase shift allows all frequencies to be steered in the same direction [5]. Therefore, the phase shift of the electrical signals must be counted on frequency and can be expressed as:

$$\beta = 2\pi f \Delta t \tag{3}$$

f is the frequency of the electrical signal and Δt is time delay phase shift.

III. EXPERIMENTAL ARCHITECTURE

The chamber is used for antenna pattern measurement. Fig. 2 shows the system level diagram for a TTD beam-former that uses a HDCF (DC-C-N-1020-UW-SC/APC/P) and also shows the major modules of the system. The input radio frequency signal (5.9, 12.7 and 17 GHz) is generated by a Signal Generator (SG) and is proposed to Horn Antenna (HA). The PAA receives signal from the HA and transmit signal through port 2 to the Power Amplifier (PA) and the distance between PAA and HA is from 120 cm to 150 cm. The wavelength of output laser from Tunable Laser Source (TLS) is set from 1549.95 nm to 1550.2 nm. The enhanced signal from the output for PA is injected into the Mach-Zehnder Modulators (MZM) which modulates the output of TLS. The PA is used to ensure enough input RF power to drive MZM in order to overcome the dynamic range and inherently high RF loss in the microwave cables line and receiving RF signal that feed the system.

The modulated optical carrier is then fed into the Erbium-Doped Fiber Amplifier (EDFA), which amplifies the optical signal to avoid optical attenuation through devices. Normally, when the wavelength of TLS increases, the time delay decreases in the HDCF that compensates for the dispersion in the standard Single Mode Fiber (SMF). The optical signals are converted into electrical signals by using 70 GHz pin Photo-Detectors (PD, XPDV3120R). A signal from port 1 of PAA output with -35 dBm to 38 dBm is injected into a power splitter which combine the signal from the PD with -35 dBm to 38 dBm for analysis by a spectrum analyzer and vector network analyzer HP 8510C.

Fig. 3 shows the system level diagram for a comparison between the optical phase group delay and the electrical signals and shows the major modules of the system by using a digital communication analyzer. Fig. 4 shows the PAA system for measurement of main lobe beam forming. Signal from port 1 and port 2 of PAA output with -35 dBm to 38 dBm are injected into a power splitter and measured by a spectrum analyzer and vector network analyzer HP 8510C.

IV. RSULTS AND DISCUSSION

The 1×2-element PAA for simulation and the measurement results for the reflection coefficient characteristic, S11, are shown in Fig. 5. The measured -10 dB return loss bandwidths are from 5.8 to 6, 12.22 to 12.42 and 16.1 to 16.4 GHz (0.2, 0.2 and 0.3 GHz), and there is a 3.4, 1.5 and 1.8 percent bandwidth for the center frequency of 5.9, 12.7 and 17 GHz, respectively. The S-parameter performance is somewhat different to the simulation and measurement results because of the fabrication undercut and improper soldering of connectors. The fabricated antenna was measured in an anechoic chamber and was analyzed using an Agilent E5071C network analyzer.

The simulated and measured radiation patterns for the relative phase are shown in Fig. 6, which shows a main lobe at 0 degrees beam forming at 5.9, 12.7 and 17 GHz. In order to better understand the phase properties of the beam steering, the feed network for the 1× 2-element array is used. The measured phases for the optical turn time delay at 5.9, 12.7 and 17 GHz are shown in Figs. 7(a) and 7(b). The phase from the output of power splitter and the group delay of optical and electric signal are measured as shown in Fig. 7(a). The optical true time delays are approximately 20°, 35° and 40° per 0.1 nm at 5.9, 12.7 and 17 GHz, respectively. As is seen, the optical true time can change from -180° to 180° by purely tuning the wavelength of the TLS to about 0.25 nm as shown in Fig. 7(b). The TLS is the optical carrier with a tunable wavelength of 1549.95 to 1550.02 nm and serves as the optical source for the system.

Fig. 8 shows the simulated and measured array factors for a 1×2-element PAA, using the proposed optical TTD. A comparison of the measured results and the simulation results is shown in Table 1. The range of scanning angles for the far field radiation patterns can be tuned at least from -22° to +29° at fixed frequencies of 5.9, 12.7 and 17 GHz, using proposed OTTD technique. The simulated and measured results are in close agreement. The difference in the measured beam-steering and the simulated angle may be due to optical attenuation through the multiple devices and to RF losses in the microwave cables that feed the array system.

V. CONCLUSIONS AND FUTURE WORKS

The proposed OTTD phased array antenna with wide angle beam-steering is designed for a 1 × 2 array. Without the OTTD system in the feed line, as shown in Fig. 4 , the main lobe is directed along the 0° axis. However, in Fig. 8, when the OTTD system is used in the feed lines, the main lobe will be steering. The beam-peak is steered from 33° to -22°, 30° to -27° and 29° to -25° at PAA frequency of 5.9, 12.7 and 17 GHz, respectively, where the wavelength of TLS is tuned from 1549.95 to 1550.2 nm. It can be seen that the beam-steering angle can be tuned by changing the phase shift of the OTTD.

In the future work, the PAA will be increased the number of elements scaling up 4 in the front-end system. It can be used to reduce the phase adjustment scale and therefore a much more accurate beam steering angle is expected.

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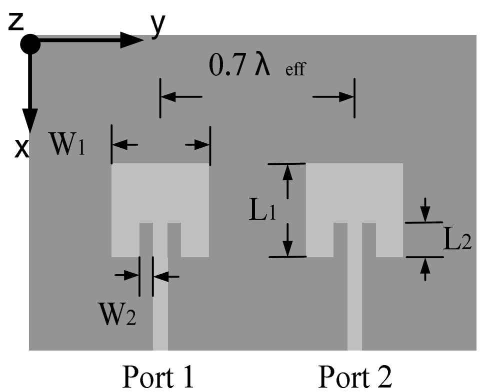


Fig. 1 The geometry of the top view of the planar 1 × 2-element array antenna.

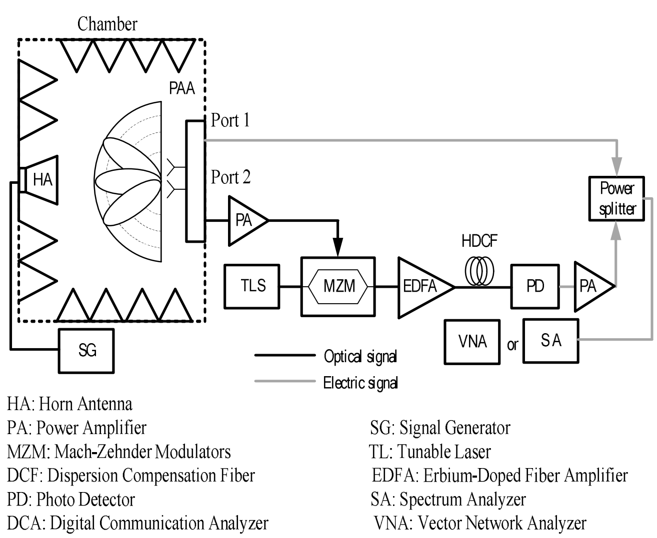


Fig. 2 The proposed OTTD system structure for uniformly spaced 1 × 2-element PAA that use HDCF.

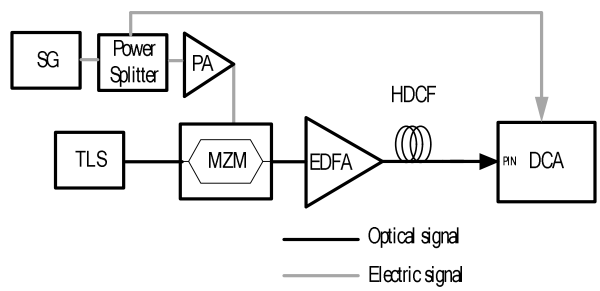


Fig. 3 A comparison of the system level diagrams for the optical phase group delay and the electrical signals.

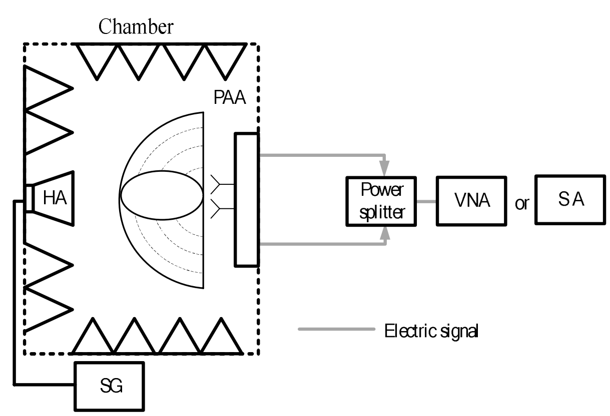
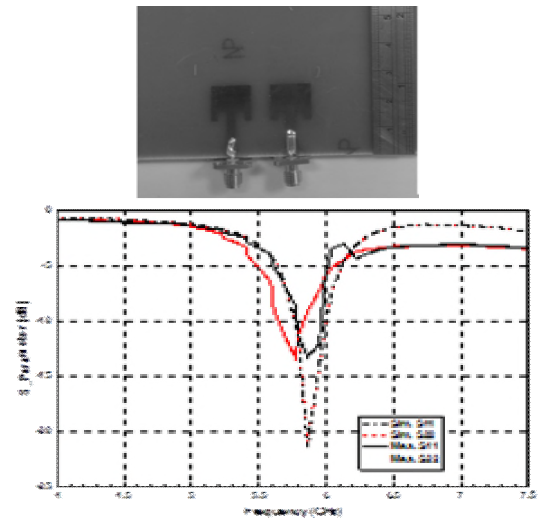


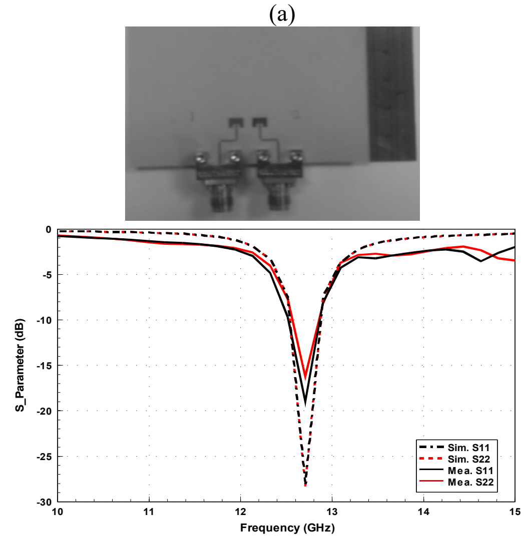
Fig. 4 Measurement of main lobe beam forming.

TABLE I. SIMULATED AND MEASURED RESULTS FOR THE OPTICAL TTD STEERING ARRAYS.

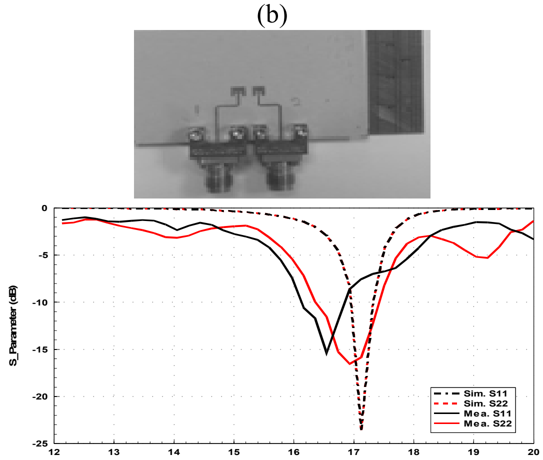
Optical TTD Steered Array	at 5.9 GHz provided 140° and -100°		at 12.7 GHz provided 120° and -90°		at 17 GHz provided 120° and -90°	
	Mea.	Sim.	Mea.	Sim.	Mea.	Sim.
Beam-Steer Angle	33° to -22°	33° to -25°	30° to -27°	32° to -28°	29° to -25°	33° to -29°



(a)



(b)



(c)

Fig. 5 A photograph of the fabricated 1 × 2 phased array antenna (Above) and the simulated and measured S-parameters for the antenna (Below) at (a) 5.9, (b) 12.7 and (c) 17 GHz.

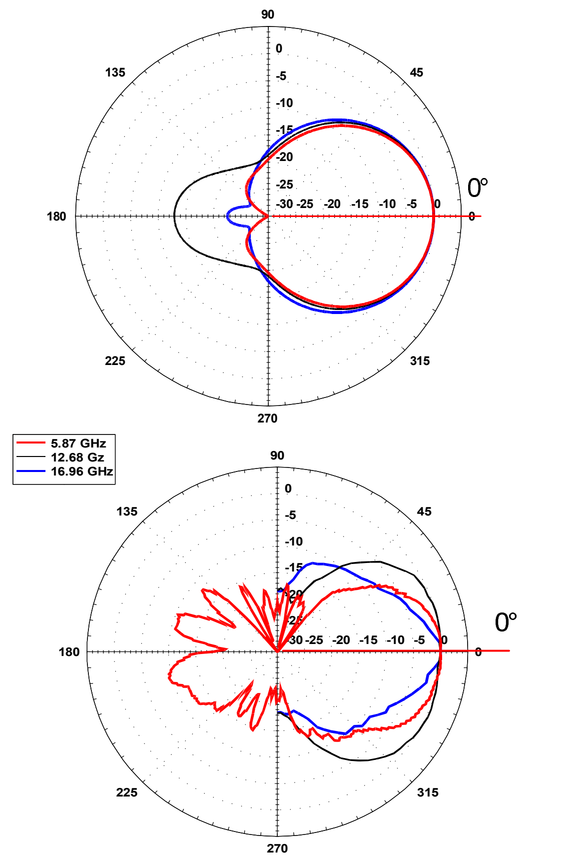
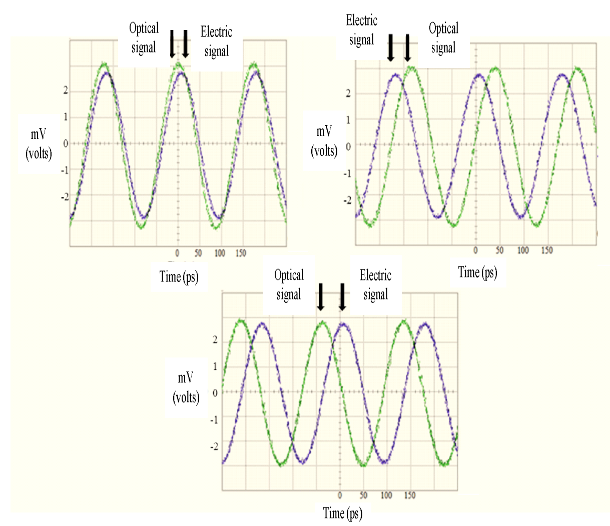
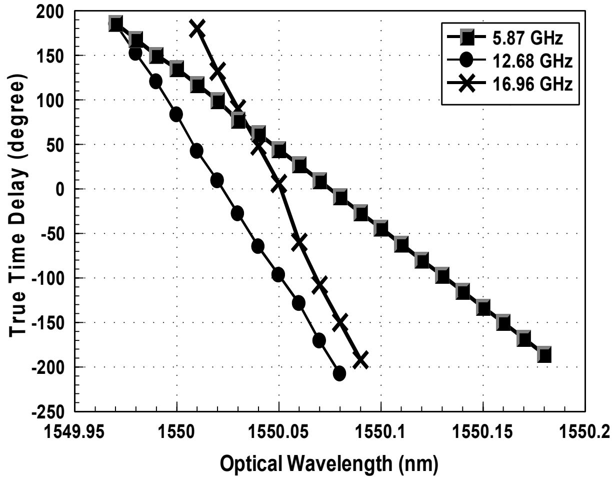


Fig. 6 The normalized gain simulation (Above) and the measured (Below) radiation pattern for the 1×2-element PAA at 5.9, 12.7 and 17 GHz.

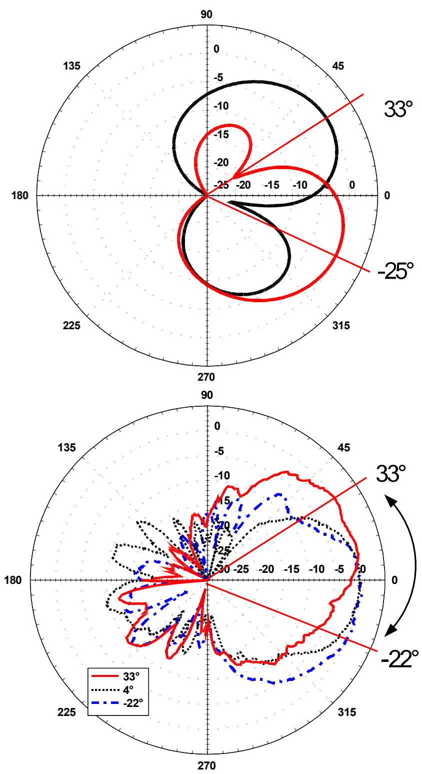


(a)

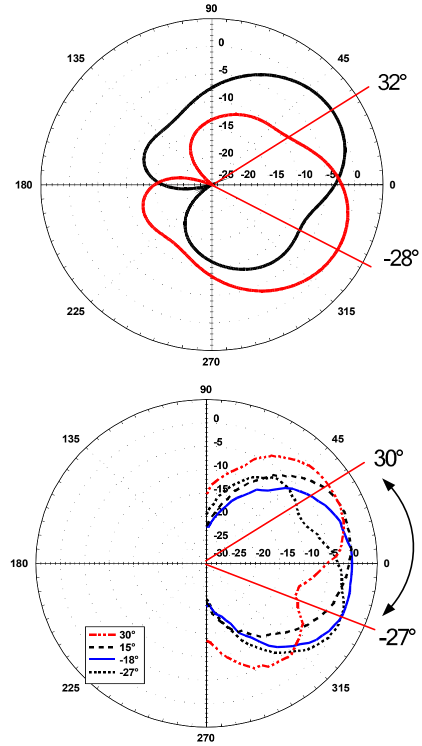


(b)

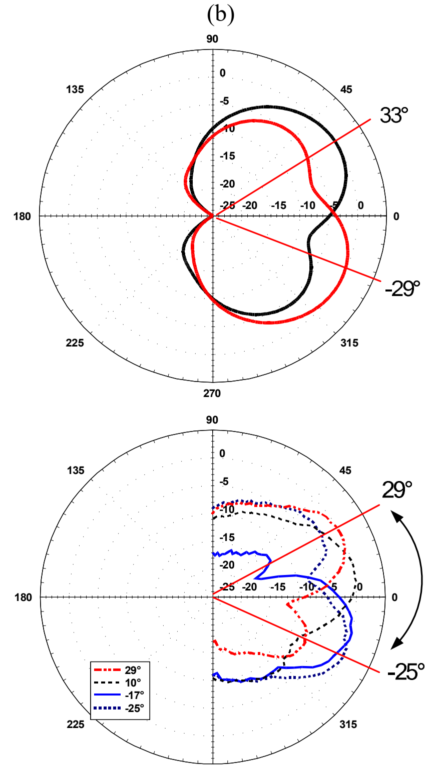
Fig. 7 The measured phase of the optical true time delay: (a) a comparison of the optical phase group delay and the electrical signals and (b) the optical true time delay per 0.1 nm at 5.9, 12.7 and 17 GHz.



(a)



(b)



(c)

Fig. 8 The optical TTD normalized gain simulation (Above) and the measured radiation pattern (Below) at (a) 5.9, (b) 12.7 and (c) 17 GHz under a tunable wavelength of TLS from 1549.95 to 1550.02 nm.

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