A Two-Dimensional Optical True Time-Delay Beamformer Consisting of a Fiber Bragg Grating Prism and Switch-Based Fiber-Optic Delay Lines

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***Abstract*—A two-dimensional optical true time-delay (TTD) beamforming system for a planar phased array antenna (PAA) is proposed and demonstrated. The optical beamforming system consists of a fiber-Bragg-grating-prism-based wavelength-dependent TTD (WD-TTD) unit for azimuth beam steering and a microelectromechanical-system-switch-based wavelength-independent TTD (WI-TTD) unit for elevation beam steering. The time delays generated by the WD-TTD and WI-TTD are measured. The results show that the proposed system can achieve the required time delays with the time-delay errors for the WD-TTD and the WI-TTD at 1 GHz less than 11.8 and 3.6 ps, which correspond to radiation direction errors of less than 1.5° and 0.4° for a planar PAA with the adjacent array elements spaced by a half radio-frequency wavelength.**

***Index Terms*—Fiber Bragg grating (FBG), optical fiber delay lines, phased array antennas (PAAs), true time-delay (TTD).**

I. Introduction

OPTICAL true time-delay (TTD) beamforming for phased array antennas (PAAs) has been an active research topic for the last few years thanks to the advantageous features such as small size, low loss, no electro-magnetic interference, large instantaneous bandwidth, high flexibility, squint-free beam scanning over a broad frequency range, and multibeam capability. Numerous schemes have been proposed for the implementation of optical TTD beamforming for a PAA, with most of the work focused on the realization of tunable time-delays for one-dimensional (1-D) beam steering [1]–[5]. For practical applications, however, it is required that the beamforming network can support two-dimensional (2-D) beam steering. Compared with a 1-D linear PAA, a 2-D planar PAA has a pencil-shape radiation pattern which is able to scan the main beam toward any point in space. Therefore, it is necessary to study a 2-D optical TTD beamforming network for a planar PAA. Several schemes have been recently proposed to implement a 2-D optical TTD beamforming system. In [6] and [7], binary fiber-optic delay lines were used, in which the delay-line lengths were controlled to follow geometric progression, leading to very long delay lines, especially for a TTD unit with a large number of delay lines. To solve the problem, recently we proposed a 2-D optical TTD beamforming network consisting of a wavelength-dependent fiber-optic delay-line matrix and a wavelength-independent delay-line matrix for a 10-GHz planar PAA [8]. Both delay-line matrices are implemented using microelectromechanical system switches. An optical TTD beamformer incorporating switch-based fiber-optic delay-line matrices offers the advantages of low complexity and stable operation, realized based on a scheme to simultaneously adjust the switches on a column-by-column basis by an electronic switch controller. More importantly, the problem of long fiber length is solved since the beamforming direction is a function of the time-delay differences and the absolute delay line lengths can be controlled short. The major limitation of the scheme in [8] is the large size of the system due to the use of a large number of optical switches. For an $n-$bit $\times$ $m-$bit beamforming system to support a $p \times q$ PAA, a total number of $n \times p + m \times q$ optical switches are needed.

In this letter, we propose and demonstrate a novel 2-D optical TTD beamforming system that uses only a single switch-based fiber-optic delay-line matrix. The 2-D beamforming is realized by using a fiber Bragg grating (FBG) prism that serves as a wavelength-dependent TTD (WD-TTD) for azimuth beam steering, and a switch-based fiber-optic delay-line matrix as a wavelength-independent TTD (WI-TTD) for elevation beam steering. The total number of switches is thus significantly reduced. Based on the proposed scheme, a 2-bit $\times$ 2-bit TTD beamforming system for a 1-GHz PAA is experimentally demonstrated.

II. Principle

The schematic diagram of the proposed 2-D optical TTD beamforming system for a $p \times q$ PAA is shown in Fig. 1. The system consists of a multiwavelength source with p-wavelengths, a wavelength-dvision-multiplexing (WDM) multiplexer (Mux), an electrooptic modulator (EOM), an erbium-doped fiber amplifier (EDFA), a 2-D TTD consisting of a WD-TTD and a WI-TTD, q WDM demultiplexers (Demuxs), and $p \times q$ photodetectors. The p wavelengths from the multiwavelength source are multiplexed at the Mux, and modulated by the radio-frequency (RF) signal at the EOM. The modulated optical signal carried by the p wavelengths is amplified by the EDFA and then applied to the 2-D optical

Manuscript received October 28, 2008; revised January 21, 2009. First published February 24, 2009; current version published April 29, 2009. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC). The work of B.-M. Jung was supported in part by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) KRF-2007-357-D00179.

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Digital Object Identifier 10.1109/LPT.2009.2015275

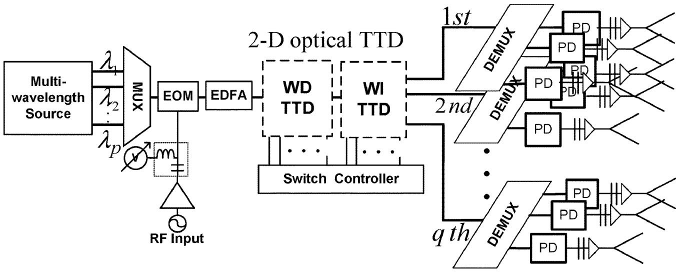

Fig. 1. Schematic diagram of the proposed 2-D optical TTD beamforming system.

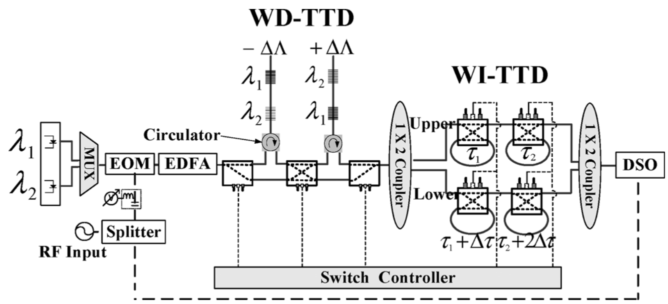

Fig. 2. Experimental setup for the time-delay difference measurement.

TTD to obtain wavelength-dependent and wavelength-independent time-delays. Specifically, in the WD-TTD the RF signals carried by p wavelengths are reflected by the FBGs at different locations, generating time-delays for azimuth beam steering [9]. The time-delays for elevation beam steering are generated by the WI-TTD [8]. The q delay lines at the output of the WI-TTD are connected to q WDM Demuxs, with the optical signal from each delay line being split into p-wavelength channels and then fed to a PAA with $p \times q$ antenna elements.

III. Experiment

To prove the concept, a 2-bit $\times$ 2-bit optical TTD for a 1-GHz planar PAA is experimentally investigated. Fig. 2 shows the setup for the measurement of the time-delays. The two wavelengths from the light source are $\lambda_1 = 1542.52$ and $\lambda_2 = 1544.76$ nm, which are multiplexed and modulated by the 1-GHz RF signal at the EOM. The output from the EOM is amplified by the EDFA which has a gain of 18 dB, and then launched into the WD-TTD. In order to scan $\pm$ beam directions, the WD-TTD in Fig. 1 is realized by a grating prism consisting of two FBG delay-lines with the grating spacing of $-\Delta\Lambda$ and $\Delta\Lambda$. In general, for an n-bit antenna array, the grating spacing is from $-2^{n-1} \cdot \Delta\Lambda$ to $2^{n-1} \cdot \Delta\Lambda$, where $\Delta\Lambda$ is a unit grating spacing in an FBG delay line and the number of azimuth beam steering directions is 2^n. In the experiment, a 2-bit ($\boldsymbol{n} = 2$) grating prism, as shown in Fig. 2, is implemented. For a 2-bit grating prism, four time-delay differences are generated. The unit time-delay difference, ΔT, of the WD-TTD can be expressed as

$$\Delta T = \frac{2 \cdot \Delta\Lambda \cdot n_{\text{eff}}}{c} \tag{1}$$

where n_{eff} is the effective refractive index of the fiber, and c is the speed of lightwave in free space. The time-delayed RF signal carried by each wavelength with the required time-delay for azimuth beam steering is divided into two identical signals by the 1×2 coupler, and fed to the 2-bit WI-TTD with a unit time-delay difference of $\Delta\tau$. The time-delay difference between the upper and lower lines shown in Fig. 2 can be obtained as one of 0, $\Delta\tau$, $2\Delta\tau$, $3\Delta\tau$ since the 2×2 optical switches in the WI-TTD with the time-delay increments of $\Delta\tau$ and $2\Delta\tau$ for the first and second columns are simultaneously adjusted on a column-by-column basis. Finally, the time-delayed signals with the time-delays introduced by the WI-TTD and the WD-TTD are converted to electrical signals and are monitored using a digital sampling oscilloscope.

In a planar PAA system, the maximum time-delay difference $\Delta t_{\max}$ between adjacent antenna elements for $\theta_{\max} = \pm 90°$ should be

$$|\Delta t_{\max}| < \frac{\sin\theta_{\max}}{2 f_{\text{RF}} \cdot N} \tag{2}$$

where f_{RF} is the frequency of the RF signal and N is the number of antenna elements along one line in a planar PAA, which can be p or q. Therefore, we have chosen the time-delay $\pm\Delta T$ as $\pm$200 ps in the WD-TTD and the unit time-delay increment $\Delta\tau$ as 120 ps in the WI-TTD for a 1-GHz planar PAA.

IV. Experimental Results and Discussion

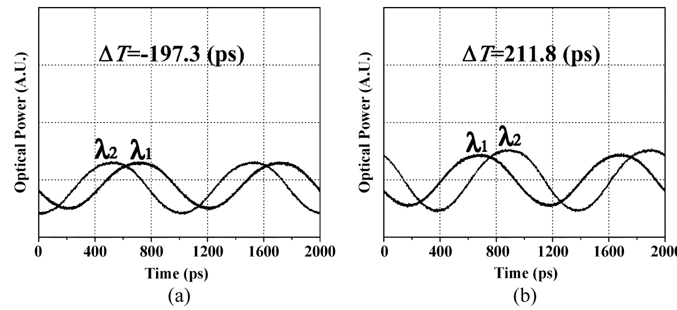

Fig. 3. Measured waveforms of the RF signals carried by λ_1 and λ_2 with time-delay difference generated by (a) the first and (b) the second FBG delay lines in the WD-TTD when the optical switches in the WI-TTD are in the BAR-BAR states.

The time delays generated by the proposed TTD beamforming system are measured. Fig. 3 shows the waveforms with time-delay difference generated by the FBG delay lines in the WD-TTD. As can be seen from Fig. 3(a), a time-delay difference is generated between the two microwave signals carried by λ_1 and λ_2, which corresponds to the gratings spaced by $-\Delta\Lambda$ in the first FBG delay line when the switches in the WD-TTD and WI-TTD are in the BAR-CROSS-CROSS and BAR-BAR states, respectively. Fig. 3(b) shows the two RF signals with a time-delay difference generated by the second FBG delay line, in which the two gratings are spaced by $\Delta\Lambda$. The measured time-delay differences between the two signals in Fig. 3(a) and (b) are $-$197.3 and 211.8 ps, respectively, with time-delay errors of 2.7 and 11.8 ps. The time-delay errors are caused by the grating spacing errors in the FBG delay lines and the measurement errors in the experiment.

Table I summarizes the time-delay difference measurement for the FBG delay lines operating at 1 GHz when the switches

TABLE I
TIME-DELAY DIFFERENCE MEASUREMENT OF THE WD-TTD. B: BAR; C: CROSS

Azi. angle [deg]	Switch states	Time-delay difference Calc. [*ps*]	Meas. [*ps*]	Error [*ps*]	Angle error [deg]
-23.6	BCC	-200	-197.3	2.7	**0.3**
0	CBC	0	1.5	1.5	0.2
23.6	CCB	200	211.8	11.8	**1.5**

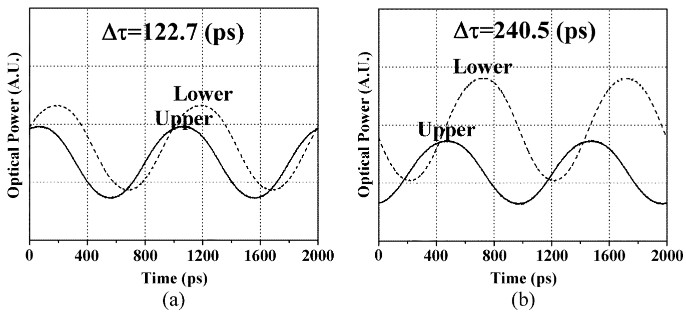

Fig. 4. Measured waveforms with time-delay difference generated by (a) the first column and (b) the second column of the fiber-optic delay-line matrix in the WI-TTD when all optical switches in the WD-TTD are set at the CROSS-BAR-CROSS states.

in the WI-TTD are in the BAR-BAR states. The result for BAR-BAR-BAR states is not included in Table I since the desired azimuth angle is identical to that when the switch states are in CROSS-BAR-CROSS. As can be seen when the switches are in CROSS-BAR-CROSS states, the measured time-delay difference is 1.5 ps. Theoretically, the value should be zero, and the nonzero value is caused by the errors of the delay-line lengths and the measurement errors. The beam steering direction error is calculated between the theoretical time-delay differences and the measured time-delay differences in Table I. The radiation angle error $d\theta$ due to time delay error $d(\Delta\tau)$ is given by $d\theta = [2f_{\rm RF}/\cos\theta]|_{\theta=\theta_0} d(\Delta\tau)$, where θ_0 is the main beam direction, and $f_{\rm RF}$ is the RF frequency. The spacing between adjacent antenna elements is assumed to be a half RF wavelength. The beam steering direction error is the highest when the intended angle is 23.6°. The calculated direction based on measured time-delay differences is 25.1° with a direction error of 1.5°.

Fig. 4 shows the waveforms with the time-delay difference generated by the switch-based fiber-optic delay-line matrix in the WI-TTD when the azimuth angle is 0°, namely, the switches in the WD-TTD are in the CROSS-BAR-CROSS states. Fig. 4(a) shows the time-delay difference between the upper line and lower line in the WI-TTD when the switches in the WD-TTD are in the CROSS-BAR-CROSS states and the first and the second columns in the WI-TTD are set in the CROSS-BAR states. The measured time-delay differences between the upper line and the lower line for Fig. 4(a) and (b) are 122.7 and 240.5 ps, respectively, with the time-delay difference errors of 2.7 and 0.5 ps.

Table II shows the experimental results measured for the time-delay differences of the switch-based fiber-optic delay-line

TABLE II
TIME-DELAY DIFFERENCE MEASUREMENT OF THE WI-TTD

Elev. angle [deg]	Switch states	Time-delay difference Calc. [*ps*]	Meas. [*ps*]	Error [*ps*]	Angle error [deg]
0	BB	0	3.6	3.6	**0.4**
13.9	CB	120	122.7	2.7	**0.3**
28.7	BC	240	240.5	0.5	**0.1**
46.1	CC	360	362.1	2.1	**0.3**

matrix for all of the desired directions when the switches in the WD-TTD are in the CROSS-BAR-CROSS states. In Table II, the angle error at the intended angle of 46.1° is the same as that at 13.9° although the error of the time-delay difference is smaller. This is because the gain and the side-lobe level decrease and the half-power beam width increases when the radiation angle of a PAA increases.

V. CONCLUSION

We have proposed and demonstrated a novel 2-D optical TTD beamforming system composed of a WD-TTD and a WI-TTD for a planar PAA. The WD-TTD was implemented using an FBG prism and the WI-TTD was realized using a switch-based fiber-optic delay-line matrix. The time delays generated by the WD-TTD and WD-TTD were measured. The time-delay errors at 1 GHz were less than 11.8 and 3.6 ps, which correspond to radiation direction errors of less than 1.5° and 0.4° for a planar PAA with adjacent array elements spaced by a half RF wavelength.

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