A Fully Packaged True Time Delay Module for a K-band Phased Array Antenna System Demonstration

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***Abstract*—A 1-to-64 [6-bit(2^6)] optical true-time delay module is designed, fabricated, and packaged for squint-free beam steering in phased array antennas, providing linear time delays ranging from 0 to 443.03 ps. The phases versus RF frequencies are measured to verify that the time delay is independent of RF frequencies. The optical true-time delay module is integrated into a K-band (18–26.5 GHz) phased-array antenna system. Far-field patterns at different frequencies over the entire K-band are measured and compared with simulated results to verify the system's wide instantaneous RF bandwidth. The Q factor is measured to be 10.20 of the true-time delay optical link transmitting 2.5-Gb/s random digital signal.**

***Index Terms*—Far-field pattern, holographic-grating coupler, phased-array antenna, Q factor, true-time delay.**

I. Introduction

PHASED ARRAY ANTENNAS (PAAs) have the advantages of low visibility, high directivity, and quick steering. Each antenna element of a PAA must have the correct phase condition to accomplish the desired beam scanning. However, the conventional electrical phase trimmer technique is an intrinsically narrow-band technique that introduces beam squint. Recently, there has been growing interest in optical true-time delay (TTD) modules. Optical true-time delay (TTD) techniques are promising for squint-free beam steering of PAAs with features of wide bandwidth, compact size, reduced weights, and low electromagnetic interference. Many kinds of optical TTD techniques have been proposed, including the acousticoptic technique [1], Fourier optical technique [2], wavelength-multiplexing technique [3], planar waveguide technique [4], and *etc*. However, these modules are for applications with low RF frequencies, having higher insertion loss, and complicated structures for steering control. A TTD module based on a substrate-guided wave structure has been demonstrated in [5]. However, the time delay interval is limited by the thickness of the substrate and ultimately the diameter of the optical beam spot. This design is not suitable for PAAs operating at RF frequency above 1 GHz. For instance, a K-band array antenna requires several picosecond delay control. Furthermore, the scheme in [5] can not provide zero degree steering of PAAs. Chirped fiber grating (CFG) delay lines have been used to control a millimeter-wave PAA [6]. The drawback of this technique is that the module produced $\pm$1-ps time-delay ripple due to the CFG dispersion, which is critical for accurate steering of millimeter-wave PAAs.

In this letter, we implement a novel optical TTD module. The TTD module is fabricated, packaged, and evaluated. This is the first time to employ the photonic TTD module to control a K-band PAA system to evaluate the feasibility of the photonic TTD module. The phases versus RF frequencies are measured to verify that the time delay is independent of RF frequencies. The wide instantaneous bandwidth of the TTD module is confirmed by measurements of far-field patterns of the K-band PAA at different frequencies. A Q factor of 10.20 of the optical TTD link is obtained when a 2.5-Gb/s digital signal is transmitted.

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II. TTD Module Design, Fabrication and Characteristics

The schematic of the TTD module is shown in Fig. 1. This module is composed of eight subunits. The optical signal, carrying an encoded microwave signal, is distributed among the eight subunits using a one-to-eight splitter. On top of each BK-7 glass substrate, there is a photopolymer film on which holographic-grating couplers are recorded. The wedge angle is designed at 21.5°, introducing a bouncing angle of 43°, and the bouncing angle is larger than the critical angle (41.8°) at the interface of glass and air. The wedges are coated with total reflection material to ensure that all the optical power is coupled into the substrate. Adjacent to each wedge, the height of each subunit is maintained at the same value at 2.6 mm. The height of each subunit varies after one zig-zag bouncing and maintains at a fixed value for the rest of the subunit. Heights of the eight subunits after the first zig-zag bouncing are from 3.600 to 4.629 mm, with a difference of 0.147 mm between adjacent subunits. The input signals are coupled vertically into the module using graded-index (GRIN) lenses. A portion of the substrate guided wave is extracted out each time the wave encounters the output holographic-grating coupler. The extracted optical waves are focused back into optical fibers using pigtailed GRIN lenses. The 8×8 output optical signals from pigtailed GRIN lenses are used to control PAAs. The produced 8×8 two-dimensional delay matrix is shown in Table I. The K-band PAA used in the experiment has eight elements with a spacing interval of 0.3 in. By using the TTD requirement for beam-squint-free steering, we are able to calculate possible degrees of the steering of the K-band PAA to be $-33.6°$ to $33.6°$ as long as the columns of the matrix are used to provide delay steps.

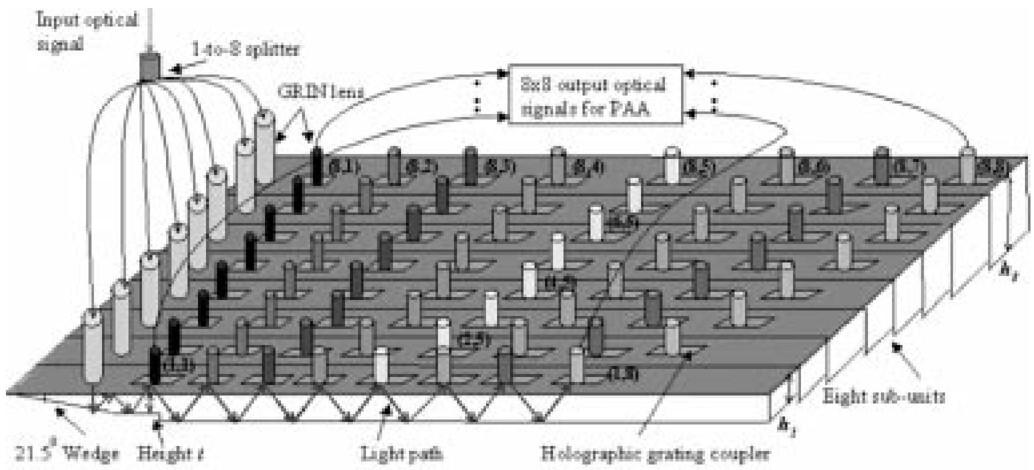

Fig. 1. Schematic of the TTD module. The TTD module is composed of eight subunits with holographic-grating couplers on top of the substrates. The input signals are coupled vertically into the module using graded index (GRIN) lenses. A portion of the substrate guided wave is extracted out each time the wave encounters the output holographic-grating coupler and focused back into optical fibers using GRIN lenses.

TABLE I
THE TIME DELAY MATRIX AND CORRESPONDING SCANNING ANGLES OF THE TTD MODULE.

Row \ Column	1	2	3	4	5	6	7	8
1	0	49.22	98.44	147.66	196.88	246.10	295.32	344.54
2	0	51.23	102.46	153.69	204.92	256.15	307.38	358.61
3	0	53.24	106.48	159.72	212.96	266.20	319.44	372.68
4	0	55.25	110.50	165.75	221.00	276.25	331.50	386.75
5	0	57.26	114.52	171.78	229.04	286.30	343.56	400.82
6	0	59.27	118.54	177.81	237.08	296.35	355.62	414.89
7	0	61.28	122.56	183.84	245.12	306.40	367.68	428.96
8	0	63.29	126.58	189.87	253.16	316.45	379.74	443.03
Delay intervals	0	2.01	4.02	6.03	8.04	10.05	12.06	14.07
Scan angles	0^0	$\pm4.5^0$	$\pm9.1^0$	$\pm13.7^0$	$\pm18.5^0$	$\pm23.3^0$	$\pm28.3^0$	$\pm33.6^0$

Unit of time delay: Picosecond

The column and row numbers are corresponding to Fig 1. Time delays are calculated using the first column as reference. Delay intervals in the table are the differences between adjacent rows for a certain column.

Dupont photopolymer film HRF600* 14–20 is utilized to form the holographic gratings in the TTD module. To achieve uniform fan-out beams from each subunit and notice that the achievable maximum efficiency of the photopolymer at 1550 nm is 40%, the efficiencies of the eight holographic-grating couplers on each sub unit are designed as 10.5%, 11.7%, 13.3%, 15.4%, 18.2%, 22.2%, 28.6%, and 40% sequentially.

The phases versus RF frequencies are measured to verify the primary feature of the TTD approach — the delay independency of the RF frequencies. Frequency-phase measurements of the fifth column fan-outs are performed and the measured data are shown in Fig. 2. For each measurement the phase of the delayed signal is measured with respect to the (1,5) fan-out (1 is the row number, 5 the column number), so that the data reflect the time delay intervals. Time delays can be obtained from the slope of the phase versus RF frequency, and the time delays of (2,5), (4,5), (6,5), (8,5) are calculated to be 8.04, 24.12, 40.20, and 56.28 ps, respectively. The results demonstrated that the TTD module has the ability to provide various time delays as designed. Moreover, from the phase-frequency curve, it can be easily seen that the time delay has the desired property of being independent of RF frequencies.

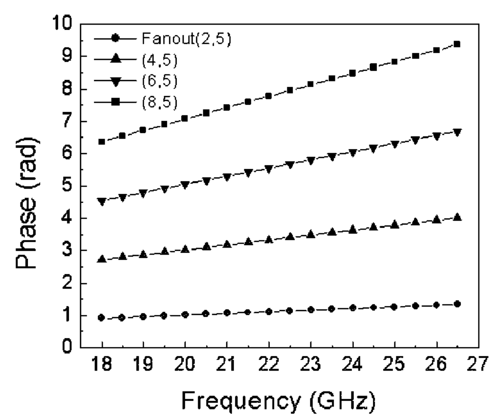

Fig. 2. Measured phase as a function of frequency of the fifth column fan-outs. The delayed signal is measured with respect to the (1,5) fan-out. The time delays of (2,5), (4,5), (6,5), (8,5) are calculated to be 8.04, 24.12, 40.20, and 56.28 ps from the slope of the phase versus RF frequency.

III. SYSTEM INTEGRATION AND MEASUREMENTS

The integrated K-band PAA system is demonstrated in Fig. 3. A microwave signal is generated by the heterodyne technique using two external cavity tunable semiconductor lasers. The optical carriers are distributed into the eight sub-units of the TTD

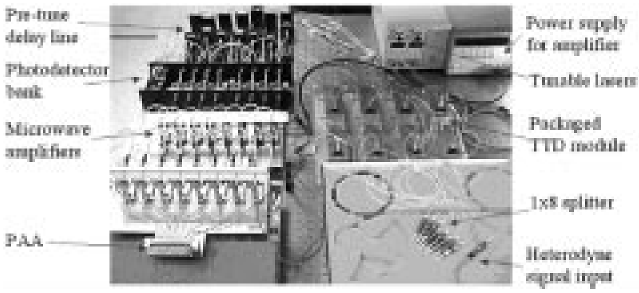

Fig. 3. Picture of the integrated K-band PAA system.

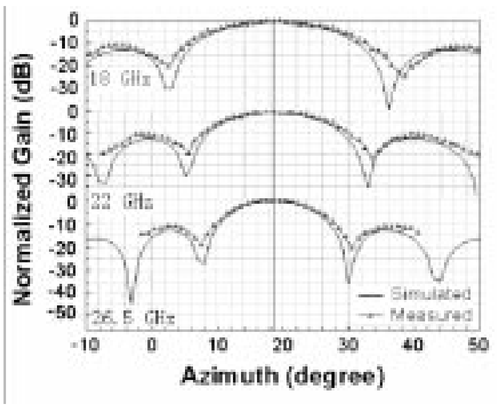

Fig. 4. Comparison of far-field patterns of the PAA at 18.5^0 scanning angle at three different frequencies: 18, 22, and 26.5 GHz. Solid curves show simulated results and curves with triangles show the measured data.

module by a one-to-eight splitter. After desired time delay, the microwave signals with correct phase relationship are detected by InGaAs high-speed photodetectors and fed into eight antenna elements individually after amplification. The ON/OFF states of photodetectors are determined by a computer controlled printed circuit board, so that the TTD module can be used in both of single angle scanning and full beamformer application, with the beam steering speed of the PAA determined by the computer speed and program running time ($\sim$ microsecond).

Far-field patterns of the PAA are measured to verify the instant broad RF band. Far-field patterns at 18.5° scanning angle corresponding to 18, 22, and 26.5 GHz are shown in Fig. 4. From Fig. 4, it can be seen that the simulation results and measured data agree very well. Furthermore, the PAA scanning angle is independent of the RF frequencies over the entire K-band, and this further prove the property of time delay being independent of RF frequencies.

In practice, information is transmitted in an encoded digital signal format. Therefore, a 2.5-Gb/s random digital signal from Agilent 8133A pulse generator is employed to evaluate the degradation of the TTD link. In order to exclude the effect of RF mixer and transimmsion, a 2.5-Gb/s digital signal is directly modulated onto the optical carrier. HP 83480A Digital Communications Analyzer is used to measure the Q factor and jitter in effective time, with the trigger coming from the pulse generator. Q factor is a measurement of signal noise ratio and

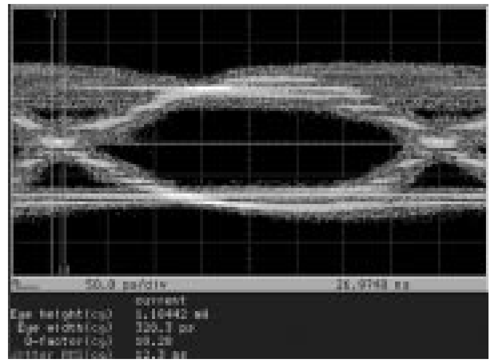

Fig. 5. Eye diagram of a 2.5-Gb/s random digital signal after the optical TTD link measured by HP 83480A Digital Communications Analyzer.

equal to $(S_1 - S_0)/(N_{1,\mathrm{rms}} + N_{0,\mathrm{rms}})$, and the signal is approximately Gaussian distribution. The back-to-back Q factor of the 2.5-Gb/s random digital signal is measured to be 50.42, while a Q factor of 10.20 and jitter of 12.3 ps is obtained after insertion of the TTD link with the eye diagram shown in Fig. 5. The main reasons for the degradation of Q factor and jitter are the noise coming from modulators, lasers, photodetectors, and amplifiers. The Q factor does not change with scan angle due to the passive nature of the TTD module.

IV. CONCLUSION

A novel optical TTD module has been fabricated, packaged, evaluated, and integrated into a K-band PAA system. This module is compact, low loss, and easy to fabricate while providing a wide instantaneous bandwidth. Furthermore, this module is promising in the transmitting/receiving mode and in beamformer applications. Moreover, this module can easily scale up for large arrays due to its compressive structure.

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