Compact broadband 5-bit photonic true-time-delay module for phased-array antennas

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Photonic true-time-delay (TTD) lines offer many advantages over their electronic counterparts and are attracting more and more research effort. We demonstrate a device with 32 TTD lines (5-bit) based on substrate guided-wave propagation combined with slanted photopolymer volume phase gratings on a quartz substrate. System design, device fabrication, optimization of fan-out intensity uniformity, and device performance evaluation are addressed as well. The device has a measured bandwidth of up to 2.4 THz and a measured fan-out delay step of 50 ps. The fan-out beam intensity uniformity is within $\pm 10\%$. The packing density is 2.5 delay lines/cm^2, which is to our knowledge the highest demonstrated thus far. © 1998 Optical Society of America

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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. PAA's offer many advantages, including steering without physical movement, accurate beam pointing, agile beam scanning, precise elemental phase and amplitude control, low spatial sidelobes, and reduced weight and power consumption.[1]

The far-field pattern of a linear phased array is a combination of microwave signals radiated from all array elements with the same frequency that have different phase shifts. The direction of the radiated beam is precisely steered by control of the relative phase shifts among successive radiating elements of the array. To overcome the problem of the scanning angle's changing with microwave frequency, one uses a true-time-delay (TTD) line so that greater bandwidth and hence higher-resolution phased-array radar operation is possible.[2] Photonic TTD's offer a wide bandwidth, compact size, reduced weight, and low rf interference.[3,4]

We can achieve squint-free beam pointing in one specific direction only by setting the TDD's. For real system implementations of TTD beam steering, to scan the beam into another angle, one has to establish a completely different configuration of the delays. Many practical TTD beam-steering systems adopt two approximations.[5,6] First, the array elements are grouped into subarrays, where all the elements in the subarray share a common time delay. Second, each time-delay unit is built to provide a discrete set of delay lines. The set of discrete time-delay increments selected for each steering angle represents a quantized approximation to a linear phase taper. A higher degree of scanning accuracy requires a smaller time-delay increment and more bits of resolution. TTD units made from fiber delay lines were demonstrated by other research groups.[6,7] However, switching in and out of varying lengths of optical fibers has serious loss problems associated with the large fan-out required for a practical system. A guided-wave TTD on a GaAs substrate for phased-array antennas was also demonstrated.[8,9] This approach has the advantage of monolithic integration with detectors; however, it suffers from large consumption of GaAs real estate and hence results in fewer delay lines per unit area.

In this Letter a collinear fan-out scheme is proposed and then developed. A 5-bit TTD unit with 2.5 delay lines/cm^2 that distributes up to 2.4-THz TTD microwave signals with delay steps of 50 ps for a phased-array antenna is achieved through the combination of a fiber bundle and substrate guided optical fan-outs.

Figure 1 illustrates the basic system architecture of our 5-bit TTD device.[10,11] The two-dimensional substrate guided-wave optical elements are used for successive optical delays of 0, $\Delta\tau$, $2\Delta\tau$, $3\Delta\tau, \ldots, 31\Delta\tau$. A 1-to-4 fiber beam splitter with different fiber lengths is used to provide four delay signals with an $8\Delta\tau$ delay increment. Each of the delay signals from the

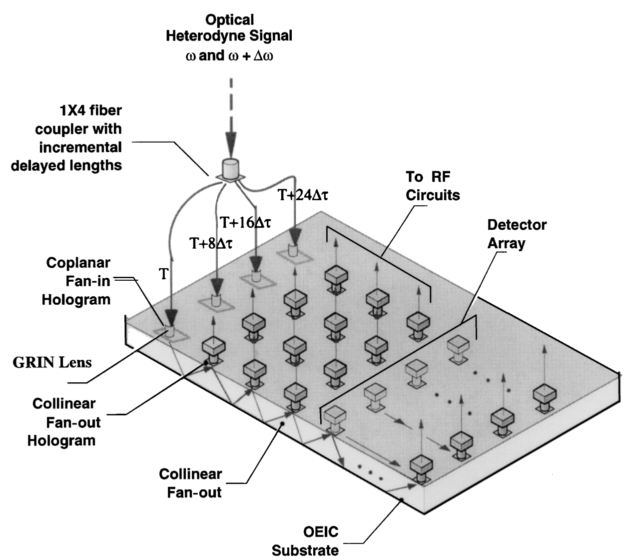

Fig. 1. 5-bit optical delay lines based on a substrate guided mode with holographic grating couplers. RF, radio-frequency; GRIN, graded-index; OEIC, optoelectronic integrated circuit.

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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.[12,13] Different optical delays are obtained at subsequent fan-outs within the substrate. The time delay between any two of the eight successive collinear fan-outs is $\Delta\tau$. The delayed optical fan-outs are then detected by a high-speed detector array. Thus, 32 (2^5) delay lines can be achieved. The detected rf signals are later amplified and sent to transmitters by programmed switching.

Assume that the scanning angular range of the PAA is $\pm 45°$ and the dimensional size of the PAA is 65 cm; in this case a 50-ps delay between two successive fan-outs is required. The thickness of the substrate needed to provide such a delay interval is 3 mm, which means that the distance between two successive fan-outs is 8 mm.[10] Owing to the collinear multiplexibility of the delay lines, a packing density of 2.5 lines/cm^2 can be achieved, which is to our knowledge the highest demonstrated thus far.

The 5-bit TTD unit with a 50-ps delay increment is fabricated upon a 3-mm-thick quartz substrate. The input and output holographic couplers are created by means of holographic recording, with DuPont photopolymer and a two-beam interference method.[13–16] For a practical device, it is desired that collinear multiplexed beams with TTD paths be uniformly coupled out surface normally, because a uniform light intensity will relax the responsivity requirements for wideband fast detectors; hence, one will achieve a more-balanced signal/noise ratio at the range of tens of gigahertz.[10] However, the fan-out light intensity of substrate guided optical fan-outs drops toward the light propagation direction owing to a cascading fan-out effect. To ensure uniform beam fan-out, one must precisely tune the diffraction efficiency from each output coupler, using the following equation:

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

where η_k is the diffraction efficiency of the kth fan-out coupler. Depending on the value of N and the maximum diffraction efficiency achievable for each holographic grating, the diffraction efficiency of each element can be determined. In our case, $N = 8$, and assuming that $\eta_8 = 90\%$, diffraction efficiencies η_k for $k = 1, 2, \ldots 7$ are given by Eq. (1). To achieve the desired diffraction efficiencies, we first derive the relationship governing the diffraction efficiency as a function of the exposure dosage and then record holograms with different exposure dosages to achieve the desired diffraction efficiencies.

Figure 2 shows an image of 5-bit delay fan-outs (4 × 8) in the TE mode, with a fan-out intensity fluctuation within $\pm 10\%$, as indicated in Fig. 3, which shows the relative intensities of the 32 fan-outs. The packaging density of the device is 2.5 fan-outs/cm^2, which is to our knowledge the highest demonstrated thus far with $\Delta\tau = 50$ ps. From the measured coupling efficiency, the system's optical insertion loss is determined to be 18 dB, including an 8-dB 1 × 4 fiber beam-splitter insertion loss, a 9-dB substrate guided-wave fan-out loss, and 1-dB propagation and other losses. The same results can be achieved with TM-mode incidence.

The delay interval and the bandwidth of the TTD unit can be measured by use of a Ti:sapphire femtosecond laser system.[17] Two successive delay pulses from the TTD unit are combined with a focusing lens and coupled into a multimode fiber cable. The output of the fiber is fed into an ultrafast metal–semiconductor–metal photodetector. The output of the electrical response from the metal–semiconductor–metal detector is amplified through a 20-GHz, 18-dB amplifier that 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 Fig. 4, the delay between two successive fan-outs is nearly 50 ps.

Since the diffracted angles of different incident wavelengths are different, the propagation lengths of different wavelengths after N bounces are different. In addition, different wavelengths have different velocities in the substrate. Therefore there is a group time delay between different wavelengths. The resulting bandwidth of the TTD unit can be evaluated by measurement of the pulse widths before and after the device.[17] For this purpose, a femtosecond laser pulse

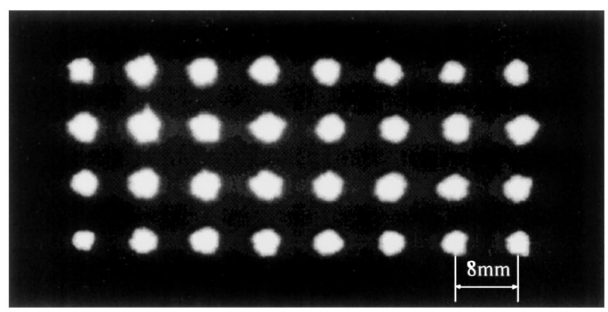

Fig. 2. CCD image of 5-bit delay fan-out lines (4 × 8) with a fan-out intensity fluctuation within $\pm 10\%$.

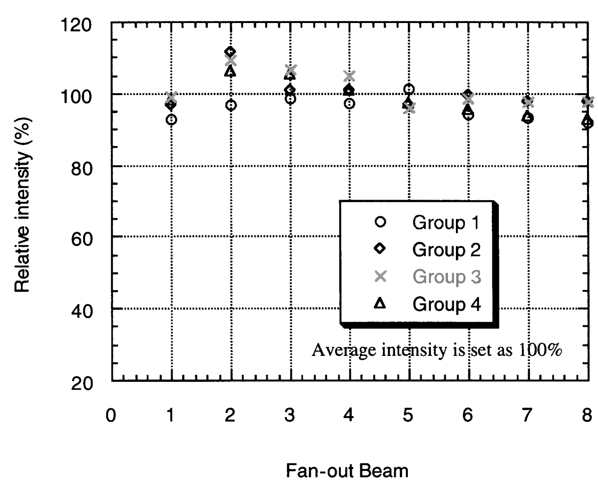

Fig. 3. Relative beam intensities of 32 fan-outs from the TTD unit.

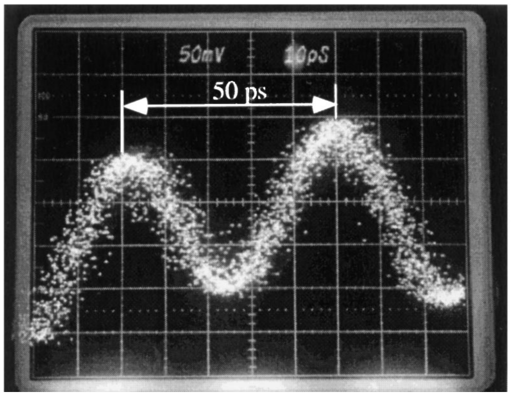

Fig. 4. Two pulses coming from successive fan-outs with a 50-ps delay between them.

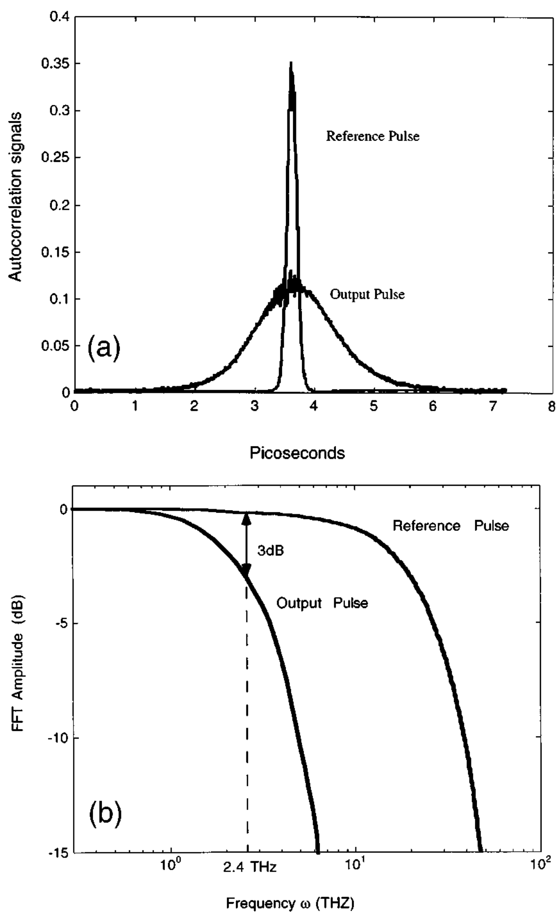

Fig. 5. (a) Pulse width measured before and after the TTD unit. (b) Fast Fourier transform (FFT) power spectrum for the input and output pulses.

is sent through the device. The pulse width of the later fan-out beam from the TTD unit that has the longest propagation distance is measured and compared with that of the incoming pulse, as shown in Fig. 5(a). We perform Fourier transforms on both pulses to deduce the bandwidth of the device. As shown in Fig. 5(b), the 3-dB bandwidth of the TTD device is thus experimentally confirmed to be 2.4 THz.

In summary, a device that has 5-bit true-time-delay lines, with a packing density of 2.5 lines/cm^2 with a minimum delay step of 50 ps, has been designed, fabricated, and demonstrated. This device is based on substrate guided-wave propagation combined with slanted photopolymer volume phase gratings. The power fluctuation among the outputs owing to the cascading fan-out effect was experimentally investigated and solved. A power fluctuation controlled to within $\pm 10\%$ was achieved. A delay step of 50 ps and a bandwidth of 2.4 THz were experimentally confirmed. The TTD device presented here has the potential to be integrated with photodetector arrays because of its planar structure on a single substrate and its surface-normal fan-in and fan-out features.

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