3-Bit Substrate-Guided-Mode Optical True-Time-Delay Lines Operating at 25 GHz

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***Abstract*— We report a high packing density true-time-delay lines based on substrate guided wave propagation combined with slanted volume phase grating fanout couplers. Three-bit delay lines with delay step of 42 ps are fabricated on quartz substrates with a substrate bouncing angle of 45°. A fanout power fluctuation of around 10% is experimentally achieved. A 25-GHz optical heterodyned signal has been detected through the device with a S/N ratio of 20 dB. Compared with similar devices, the true-time-delay lines reported herein achieves both high packing density per unit substrate area (~5 delay lines/cm^2) and ultrawide microwave bandwidth.**

***Index Terms*— Phased-array antennae, true-time delay, holographic grating, heterodyne detection.**

FUTURE phased-array antennas (PAA's) satisfying the wide bandwidth requirements must implement true-time-delay (TTD) steering techniques such that the far field pattern is independent of frequency. In the TTD approach, the path difference between two radiators is compensated by lengthening the microwave feed to the radiating element with a shorter path to the microwave phase-front. These are usually accomplished by lossy and bulky metallic waveguide feeds, inducing high cost and heavy weight. There have been great interests in photonic true-time-delays for PAA applications in recent years [1]–[3]. This requires the photonic system to offer true-time-delay transmission paths for the microwave signals that are distributed to array elements. Compared to electronic phase-shifters, photonic TTD's offers wide bandwidth, compact size, reduced weight and very low RF interference.

Continuously tuned TTD beam steering system is hard to realize and impractical because of size and cost concerns. To build a practical TTD beam steering system, two approximations are usually necessary. First, the array elements are grouped into subarrays, each subarray share a common time delay network. 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 that dictates delay times of $0, \Delta t, 2\Delta t, \cdots, N\Delta t$ across the array. A higher degree of accuracy can be achieved with a smaller Δt, i.e., with more bits of resolution, then the antenna can be scanned at correspondingly smaller angular increments. In this way, the system provides some, but not all, of the benefits of true-time-delay steering. One research group [4] has demonstrated a time-delay unit consists of eight fiber delay lines that form 2^3 discrete delay increments for achieving three bits of resolution in setting the microwave phase front. The radiating elements are grouped into four subarrays and the total number of TTD modules is four. During steering of the phased array, one delay line, as specified by the steering angle, is selected from each of four such modules to provide time delay for the antenna subarray fed by the module. However, the switching in and out of varying lengths of optical fibers has serious loss problems associated with the large fanout required for a practical system. More recently, a guided wave version of a 2-b true-time-delay on GaAs substrate for phased array antenna is demonstrated by the same research group [5]. It contains only two bits of delay lines with four ridge waveguides due to limitations of wafer size and device technology. As a result, the selection of steering angle is fairly broad. Although this approach does have the advantage of monolithic integration with detectors, it suffers from large consumption of GaAs real estate and hence few delay lines per unit area, ~4 delay lines/10 cm^2.

In this letter, the distribution of true-time-delay broad-band microwave signals for phased array antenna is accomplished through multiplexed substrate guided optical fanouts. The conversion of light wave propagation from free space to substrate guided mode is accomplished through holographic grating couplers. This substrate guided wave is used as a carrier for distributing and for delaying the microwave signals that drive the antenna radiating elements. The TTD architecture reported herein offers compactness, low cost, wide instantaneous bandwidth and the potential advantage of integration with detectors to eliminate the delicate interface between the optical delay-lines and the RF switching circuits. Due to the collinear multiplexibility of the delay lines, the packing density is determined to be ~5 delay lines/cm^2 with a Δt of 42 ps. This architecture results in more than an order of magnitude increase in packing density than the result reported by Hughes Research Lab. [5] for a 2-b TTD module. Furthermore, the broad-band microwave signal is generated by optical heterodyne techniques that provides hundreds of GHz base bandwidth while maintaining 100% modulation depth, compared with only about 10 GHz in [5]. The physical aspect of the photonic TTD architecture is first introduced. The design and fabrication issues on the planar holographic gratings are

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Manuscript received August 26, 1996; revised October 9, 1996. This work was supported by the Office of Naval Research, the DARPA's Center for Optoelectronics Science and Technology, and the ATP program of the State of Texas.

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Publisher Item Identifier S 1041-1135(97)00567-3.

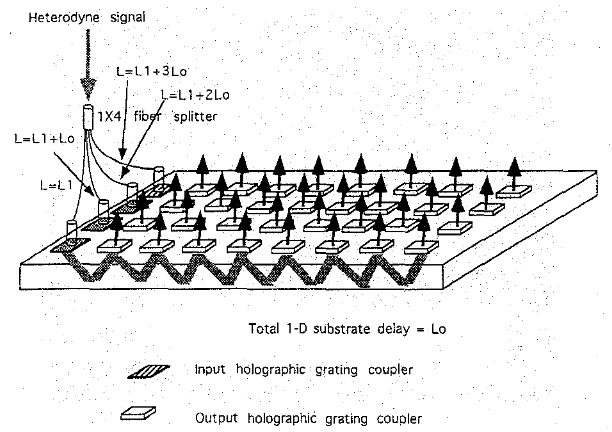

Fig. 1. True-time-delay architecture with substrate mode optical fanouts.

discussed. The generation and detection of high frequency microwave signals of 25 GHz by optical heterodyne techniques are demonstrated as well.

Fig. 1 illustrates the architecture [6] of a TTD unit with delay paths provided by substrate guided optical fanouts. Two types of holographic grating couplers are employed. The first type is designed to couple the surface normal incoming light into a substrate guided mode having a fixed bouncing angle (45° in this design). The second type is designed to couple an array of substrate guided beams into an array of surface normal fanout beams. Different optical delays are extracted at subsequent fanouts due to the extra distance light propagated within the substrate. For demonstration purposes, a 3-b true-time-delay unit is constructed with successive delays of $0, \Delta\tau, 2\Delta\tau, \cdots$, and $7\Delta\tau$ ($\Delta\tau = 42$ ps). For such a device to be used as a TTD delay module within a subarray, the selection of a fixed delay among the eight different delays is accomplished through detector switching, which is also used in [5] to perform delay reconfiguration.

These input and output holographic couplers can be made from silver halide, dichromated gelatin (DCG) films [7], [8] or from other photopolymer holographic recording films [9]. In this letter, DuPont HRF-600 photopolymer films are used. Hologram recording consists of exposure, UV cure, and heat processing. The two-beam interference method [6] is used to define individual holographic gratings using the 514-nm line from an argon ion laser. The two recording angles, which are set by the substrate bouncing angle and the phase-matching condition, determine the grating periodicity and the slant angle with respect to the surface normal of the film [10]. Diffraction efficiency can be controlled by varying the photoexposure dosage or the ratio of the two interference beams. According to Kogelnik's coupled wave theory [11] for thick hologram gratings, the efficiency of a volume transmission grating is square of the sinusoidal function of the product of grating thickness and index modulation. By selecting the proper thickness for a holographic film with a given index modulation, large than 99% diffraction efficiency can be realized for a desired playback wavelength. Further increase in film thickness results in lower diffraction efficiency, a condition referred to as overmodulation [11].

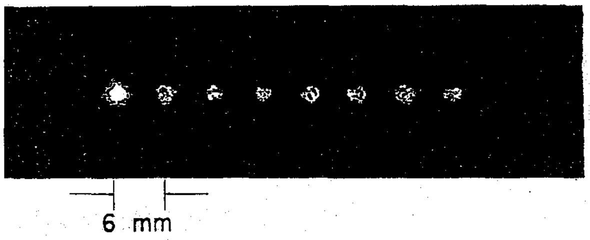

Fig. 2. CCD image of TTD fanouts at various substrate mode locations (wavelength = 786 nm).

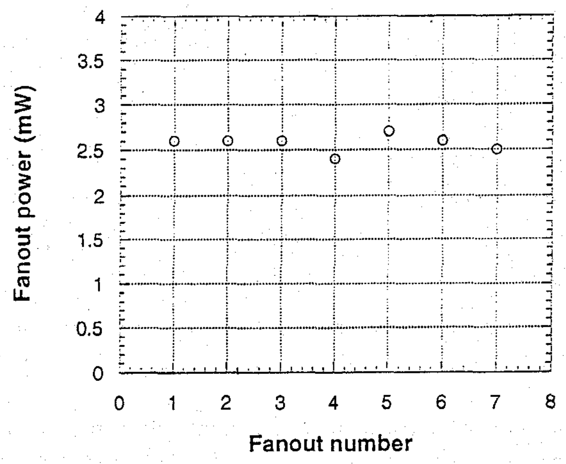

Fig. 3. 1-to-8 true-time-delay fanout intensity distribution (The undiffracted beam (0th fanout) is saturated in the plot with an intensity of 17 mW, while the rest of the fanouts are all around 2.6 mW).

One common problem related to massive substrate guided optical fanout is that the fanout light intensity drops along the direction of substrate wave propagation. This is caused by the cascading fanout effect if the output couplers have more or less the same efficiency. Substrate absorption also contributes to the problem. For a practical device, it is desired that the collinear multiplexed beams with true-time delay paths are uniformly coupled out surface normally. This is because that a small deviation of power to individual radiating elements can cause the quality of the radar beam deteriorate. Furthermore, an approximately uniform fanout intensity distribution will relax the responsivity requirements for wide-band fast detectors [6], hence achieving a more balanced signal-to-noise (S/N) ratio at the microwave end. This is critical since signal integrity at tens of GHz range is stringently restricted by the S/N ratio requirement, wide-band amplifier dynamic range and limited detector responsivities. To overcome this nonuniform fanout problem, the coupling efficiencies of the output couplers have to be individually tuned [6], which is often a challenge. By making use of the fact that the collimated laser beam has a Gaussian intensity distribution during hologram recording, we are able to fabricate a one-dimensional (1-D) device with relatively satisfying result. Fig. 2 shows the CCD image of the one-dimensional TTD fanouts on a quartz substrate at 786 nm. A fanout separation of 6.0 mm is obtained with a substrate thickness of 3.0 mm and a bouncing angle of 45°. Fig. 3 shows the light intensity distributions at the different fanout locations, demonstrating that the power fluctuations among the fanouts are within ±10%. One exception is the

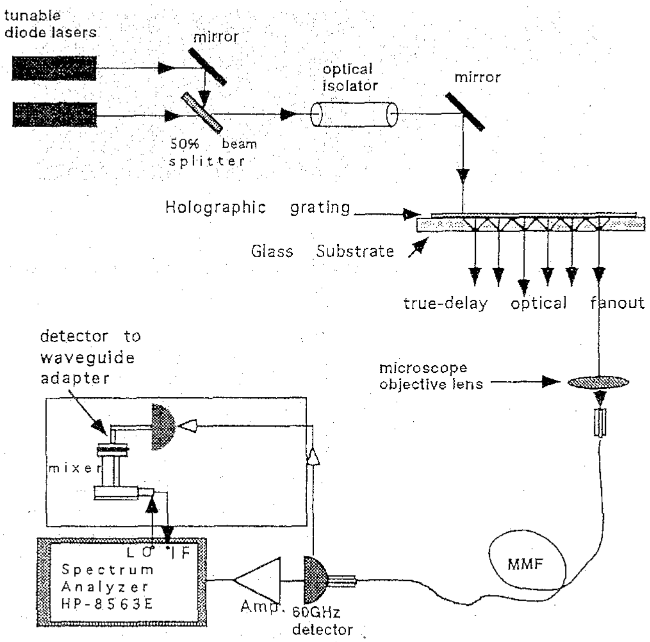

Fig. 4. The generation and detection of microwave signals by optical heterodyne technique.

first fanout, which represents the light not diffracted by the grating. Experimentally, this fanout intensity can be adjusted to match the rest of the fanouts by fine tuning the coupling-in efficiency. From the coupling efficiency measurement, the system insertion loss is estimated to be 15 dB, including 9-dB fanout loss.

With the coherent mixing of two CW lasers oscillating at single longitudinal frequencies, microwave frequency RF signals can be generated by the optical heterodyne technique [12]. We employed two tunable diode lasers with a lasing wavelength around 786 nm and a line width of 100 kHz. Both lasers are stabilized with current and temperature controllers. As indicated in Fig. 4, the outputs of the lasers are combined by a 50:50 beam splitter, passing an optical isolator and then coupled into the TTD unit at normal incidence. One of the weak fanouts is coupled to an ultrafast photodetector with 60-GHz bandwidth through a single-mode fiber cable with an FC connector. The PD output is amplified through a broad-band amplifier and connected to a spectrum analyzer for display.

With the set-up of Fig. 4, we have successfully produced and detected microwave frequency signals up to 25.6 GHz. Fig. 5 shows the detected 25 GHz RF signal of one of the fanouts by a spectrum analyzer. A signal-to-noise (S/N) ratio of ~20 dB is obtained. Presently, 25 GHz is limited only by the frequency response of the amplifier and the spectrum analyzer used. By employing external mixers and wide-band amplifier, much higher upper frequency [13] is expected. Our future goal is the important 60-GHz range and beyond.

We propose a drastically new approach using collinear spatially multiplexed substrate guided waves to provide highly compact true-time-delay lines with ultrawide bandwidth. Compared with other integrated optics version of TTD lines, this scheme significantly increases the number of bits per unit area and therefore a much more accurate beam steering angle is expected. The uneven fanout issue commonly related to substrate guided waves is addressed and a 1-D fanout uniformity of 10% is achieved. Also employment of the optical heterodyne provides an easy way of generating ultra-wide bandwidth microwave signals that are not achievable using the direct modulation technique.

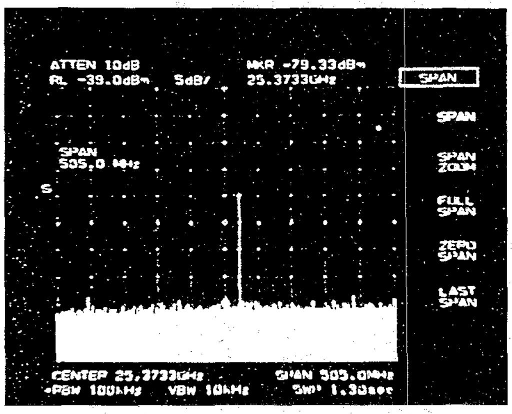

Fig. 5. 25-GHz optical heterodyne signal detected by a spectrum analyzer.

ACKNOWLEDGMENT

The authors would like to thank Dr. W. Ng of HRL for his help in this project.

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