# High Packing Density 2.5 THz True-Time-Delay Lines Using Spatially Multiplexed Substrate Guided Waves in Conjunction with Volume Holograms on a Single Substrate

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***Abstract*—A 3-bit true-time-delay lines device having a packing density of 5 lines/cm$^2$ with a minimum delay step of ~100 ps is designed, fabricated and demonstrated. This device is based on substrate guided wave propagation combined with slanted photopolymer volume phase gratings. In this paper, we report the delay and bandwidth measurements for the 3-bit delay lines fabricated on BK-7 glass substrates with a substrate bouncing angle of 45°. The power fluctuation among the outputs due to the cascading fanout effect (a serious drawback for real system applications) is experimentally investigated as well. A power fluctuation controlled to within ±10% is achieved. A femtosecond laser pulse is sent through the device and a bandwidth measurement of up to 2.5 THz is obtained. The delay step is measured by employing an ultrafast photodetector together with a sampling scope. The true-time-delay device presented herein has the potential to be integrated with photodetector arrays due to its planar structure on a single substrate together with the surface normal fan-in and fan-out features.**

***Index Terms*—Phased array antenna, photopolymer holograms, substrate guided waves, true-time-delay.**

## I. INTRODUCTION

FOR a linear phased array with an individual phase control, the far field pattern is the combination of microwave signals from all radiating elements with the same frequency $(\omega_m)$ having different phase shifts ($\psi_n$'s). By electronically controlling the relative phase shifts among successive radiating elements of the array, the direction of the radiated beam can be precisely steered. However, for the phase-delay approach with a fixed set of phase shifts $\psi_n$'s, the radiated beam will drift by an amount of $\Delta\theta_0$ whenever the microwave frequency $\omega_m$ is changed by an amount of $\Delta\omega_m$ [1]. The drifting of the beam angle due to the change in frequency leads to a drop of the antenna gain in the $\theta_0$ direction. Such a phenomenon is undesirable. In order to satisfy the ultra-wide bandwidth operation of future phased-array antennas (PAA's), it is necessary to implement true-time-delay (TTD) steering techniques such that the far field patterns are independent of the frequency employed. If true-time shift is set according to a particular steering direction, the microwave phase shift at each antenna element, which is proportional to the microwave frequency $\omega_m$, follows the frequency scan without creating a $\Delta\theta_0$ in beam steering. In the TTD approach, the path difference between two radiating elements is compensated by lengthening the microwave feed to the radiating element with a shorter path to the microwave phase-front. A fixed set of delay lines compensates for the path differences corresponding to a particular steering angle at all frequencies. These are usually accomplished by lossy and bulky metallic waveguide feeds, resulting in high cost and heavy weight. The progress in photonics technology in recent years has raised great interests in providing true-time-delays using optical means [2], [3]. Compared to electronic phase-shifters, photonic TTD's offer a wider bandwidth while keeping a compact size, a reduced weight with very low RF interference. This requires the photonic system employed to offer true-time-delay transmission paths for the microwave signals that are distributed to array elements.

For real system implementations of photonic TTD beam steering, it is usually impractical trying to realize a continuously tuned TTD due to the level of complexity in size and high costs. Almost all practical TTD beam steering systems adopt the following two approximations. First, the array elements are grouped into subarrays, each subarray shares a common time delay network. Second, each time-delay unit is built to provide a discrete set of delay lines [4]. 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 $\Delta t$, requiring more bits of resolution. The antenna can thus 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. A TTD delay unit made from fiber delay lines has been demonstrated by other research groups [4]. The lengths of the fibers in these links were

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Manuscript received December 2, 1996; revised May 21, 1997. 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 0733-8724(97)08888-9.

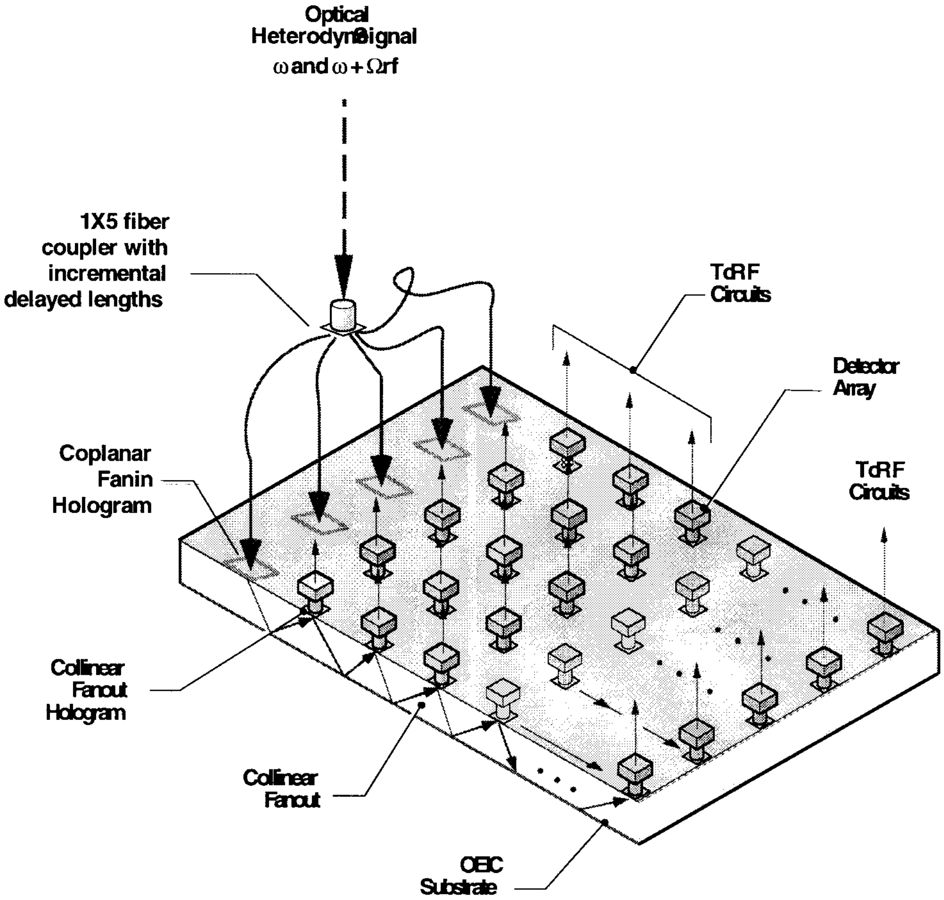


Fig. 1. Optical delay lines based on substrate guided mode together with holographic grating couplers.

cut to provide a prespecified set of differential time delays determined by the antenna aperture and its maximum steering angle. During steering of the phased array, one delay line, as specified by the steering angle, is selected to provide the required time delay for the antenna subarray fed by the module. However, the switching in and out of varying lengths of optical fibers has serious problems associated with the system insertion loss due to the large fanout required for a practical system. More recently, a guided wave version of a 2-bit true-time-delay on GaAs substrate for phased array antenna is demonstrated [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. This approach does have the advantage of monolithic integration with detectors, however, it suffers from large consumption of GaAs real estate and hence few delay lines per unit area.

In this paper, the distribution of true-time-delay broadband microwave signals for phased array antenna is accomplished through multiplexed substrate guided wave optical fanouts. The conversion of light wave propagation from free space to a 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 radiation elements. The TTD architecture reported herein offers compactness, cost-effectiveness, wide instantaneous bandwidth and the potential advantage of the surface-normal integration with detectors to eliminate the vulnerable edge coupling among the optical delay-lines and the RF switching circuits. Due to the collinear spatial multiplexibility of the delay lines, a packing density of 5 delay lines/cm$^2$ is achieved. The fanout power fluctuation issue is discussed next. The delay intervals and bandwidth measurements are presented at last.

## II. DEVICE STRUCTURE AND FABRICATION

Fig. 1 illustrates the basic system architecture [6] of a TTD unit with delay paths provided by substrate guided optical fanouts. The input holographic grating coupler is designed to couple the surface normal incoming light into a substrate guided mode having a fixed bouncing angle of 45°. This angle ensures that the condition for total internal reflection (TIR) is satisfied. The output holographic grating couplers extract an array of substrate guided beams into a free space one-dimensional (1-D) array of surface normal fanout beams having a 1-to-$n$ fanout with accurately separated delay path intervals. Different optical delays are obtained at subsequent fanouts due to the extra distance the optical signal propagating within the waveguiding substrate. The gratings are created by successively exposing holographic patterns within the selectively defined regions shown in Fig. 1. These input and output holographic couplers can be made from silver halide, dichromated gelatin (DCG) films [7], [8] or from other

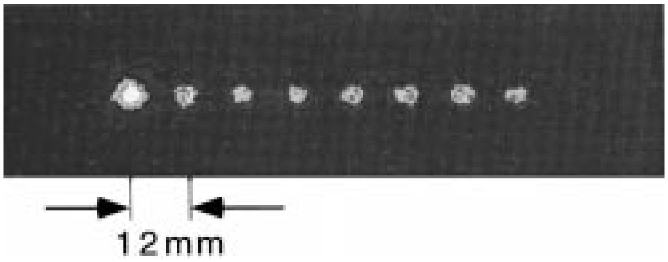


Fig. 2. CCD image of eight delay fanout lines with a fanout intensity fluctuation within 10% (excluding the first fanout).

photopolymer holographic recording films. The holographic optical elements reported herein are fabricated using DuPont photopolymer HRF-600 films. These films exhibit properties such as a high diffraction efficiency, dry-processing after exposure and environmental stability. The two beam interference method is used to define individual holographic gratings [9], each at a different recording angle resulting in a sinusoidal phase modulation profile.

Hologram recording procedures on a DuPont HRF-600 film consists of exposure, UV cure, and post-bake processing. The 514 nm line from an Argon ion laser is used as the recording wavelength. The laser output is first split into two separate beams, which are spatially filtered and collimated accordingly. Then they are designed to intersect on the photopolymer film with specific angles. These angles determine the grating periodicity and the slanted angle with respect to the surface normal of the film. The substrate bouncing angle depends critically on these two angles. To form a slanted grating coupler that converts a vertical incident wave to a TIR beam with a bouncing angle $\alpha$ in the substrate, the two incident angles of the recording beams with respect to the surface normal of the film are described in [9].

## III. Fanout Power Issue

One common problem related to massive substrate guided optical fanouts is that the fanout light intensities drop progressively along the light propagation direction due to cascaded fanout depicted in Fig. 1. Substrate absorption also contributes to the problem. For a practical device, it is desirable that the collinear multiplexed beams with true-time-delay paths are uniformly coupled out surface normally. A uniform light intensity relaxes the responsivity requirements for wideband fast detectors [6], hence achieving a more balanced signal-to-noise ratio (SNR) at the microwave end. This is critical since signal integrity at tens of GHz range is stringently restricted by the SNR requirement, wideband amplifier dynamic range and limited detector responsivities. To meet these requirements, the coupling efficiencies of the output couplers have to be individually tuned [6], which is often a challenge. Fig. 2 shows the CCD image of the one-dimensional fanouts with a three-bit ($2^3$) TTD lines on a BK-7 glass substrate at 786 nm.

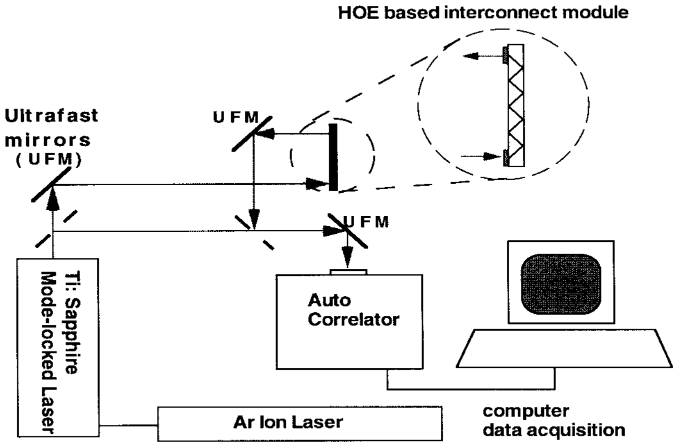
A fanout separation of 12.0 mm for adjacent beams is obtained with a substrate thickness of 6.0 mm and a bouncing angle of 45°. The above result was achieved by making use of the fact that the collimated laser beam has a Gaussian intensity distribution during hologram recording. As shown in Fig. 2, the first fanout (undiffracted light) intensity is stronger than the rest, which means that the input coupling efficiency is low. Experimentally, this fanout intensity can be adjusted to match the rest of the fanout by fine tuning the coupling-in efficiency. The fanout power fluctuations are controlled to within ±10% in this demonstration. From the measured coupling efficiency, the system insertion loss is measured to be 15 dB, including 9 dB fanout loss, 1 dB propagation loss, 3 dB coupling-in loss, and 2 dB coupling-out loss.

## IV. Delay and Bandwidth Measurements

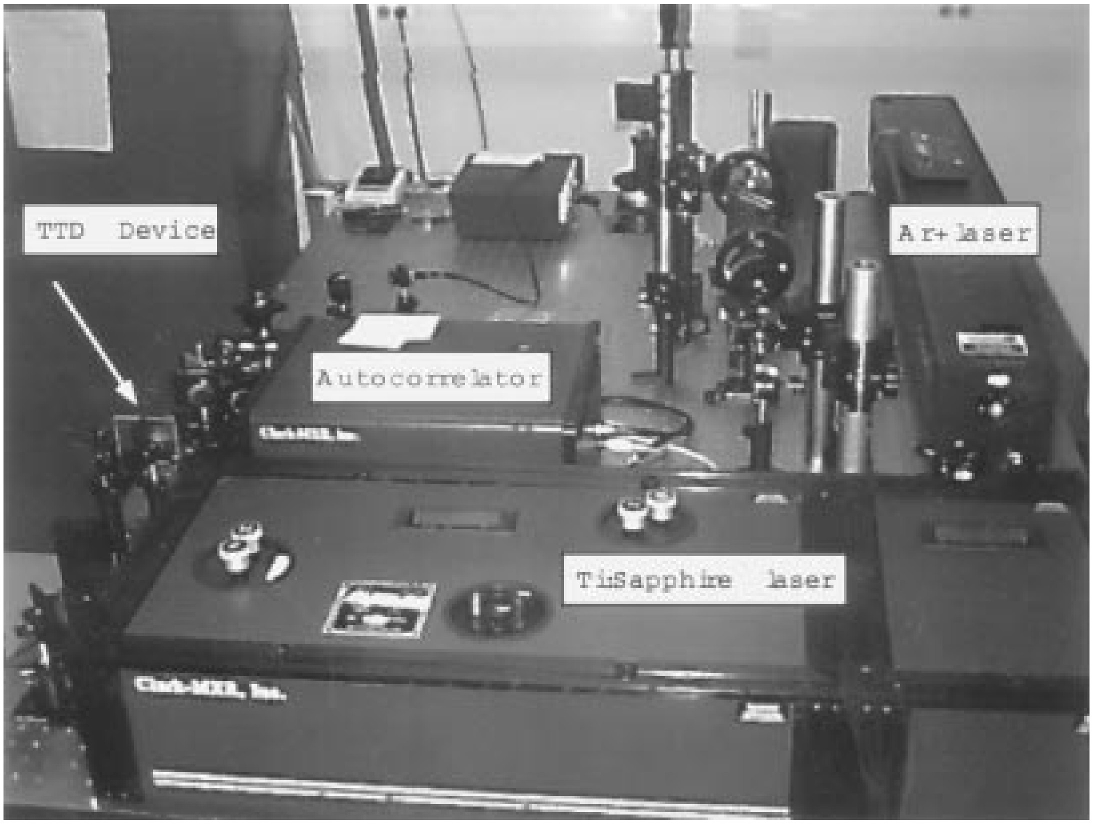
The dispersion of this device is mainly due to two factors. One is the dispersion caused by holographic grating coupler. Diffraction angles of different incident wavelengths are different. Consquently, the propagation lengths of different wavelength after many zig-zag bouncings are different. Therefore, there is a group time delay between different wavelengths. The second factor is material dispersion caused by different propagating velocities of different wavelengths. Since a signal with a longer optical wavelength has a higher speed and a longer propagating distance, these two factors' contribution to dispersion can cancel out in some degree. The phase delay at total reflection surface is negligible because for different wavelengths, the delays are almost the same. Based on these considerations, we can calculate the dispersion as follows. The group delay is

$$\tau = \frac{2hm * n_1}{\cos\theta_1 * c} - \frac{2hm * n_2}{\cos\theta_2 * c} = \frac{2hm}{c}\left(\frac{n_1}{\cos\theta_1} - \frac{n_2}{\cos\theta_2}\right)$$

where $h$ is the height of substrate, $m$ is bouncing times, $c$ is velocity of light in free space, and $\theta$ is the bouncing angle in the substrate. The calculated bandwidth of the demonstrated 3-bit device is about 2 THz. The real-time bandwidth of the TTD delay unit is experimentally tested by evaluating the Fourier transforms of the measured pulse widths. For this purpose, a femtosecond laser pulse is sent through the device. The pulse width of the last fanout beam is measured and then compared with that of the incoming pulse. Fourier transforms of both pulses, i.e., dispersed and reference pulses, from time domain to frequency domain are performed to deduce the bandwidth of the device. Fig. 3(a) shows the set-up for the bandwidth measurement and Fig. 3(b) illustrates the corresponding equipment employed for the measurement. An argon ion laser (INNOVA-90-PLUS) is used to pump a Ti:Sapphire mode-locked laser (Clark-MXR-model NJA-4) which provides pulses around ∼150 fs at the vicinity of 850 nm and the pulses repeat every 10 ns. An autocorrelator (Clark-MXR-model AC-150) is employed to measure the pulse widths both before and after the TTD device. When the TTD device is in place, the optical signal has to be re-routed (aligned) [see Fig. 3(a)] into the autocorrelator. To minimize any pulse broadening effect caused by the mirrors, two ultrafast mirrors (Newport 10B20UF.25) working at a wavelength range from 700 to 930 nm at 45° are used. The autocorrelator is driven by a computer-interfaced driver module (Clark-MXR-ODL-1E) for calibration and data collection. Fig. 4 illustrates the autocorrelation traces for the input (reference) and output (dispersed) pulses respectively. The Fourier transform of the two



(a)



(b)

Fig. 3. (a) Schematic for measuring the device bandwidth and (b) photograph showing the equipment used in the measurement.

pulses in frequency domain generates bandwidth information about the device, as shown in Fig. 5. Here it is seen that the 3-dB bandwidth of the TTD device is approximately 2.5 THz.

The delay intervals for the adjacent surface-normal fanout modes are measured using the same Ti:Sapphire femtosecond laser system. Fig. 6 illustrates the schematic of measuring the fanout delay interval. Two successively delayed pulses from the TTD unit are combined with a focusing lens and coupled into a multimode fiber cable. In this way, it is guaranteed that the two beams experience equal extra delays after being combined. The output of the fiber is fed into an ultrafast metal-semiconductor-metal(MSM) photodetector (Picometrix Model PX-D7-FC) which has a rise time of ~7 ps. The output of the electrical response from the MSM detector is amplified through a 20 GHz 18 dB amplifier (NewFocus Model 1422). This amplified signal is connected to a sampling scope (7704 A main frame with a S-6 sampling head). The sampling scope is synchronously triggered by a reference pulse string from a monitoring photodiode of the mode-locked femtosecond laser. A 100 ps delay interval is experimentally confirmed using this set-up and the result is illustrated in Fig. 7. The distortion of the pulse shape near the rise-edge of the second pulse (delayed signal) is caused by the added oscillating rings from the tail of the first pulse, which can be seen clearly from the second

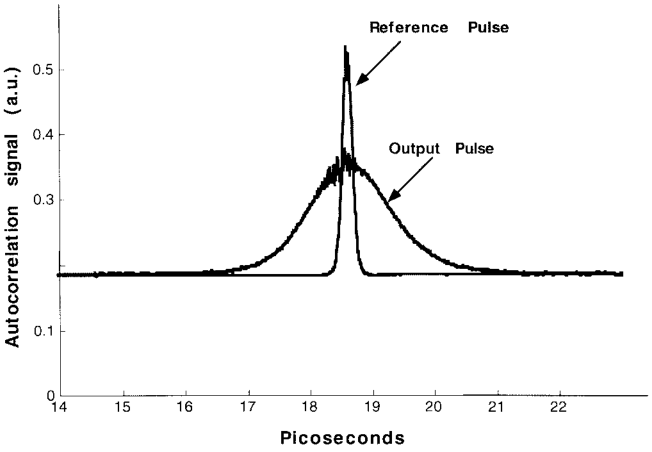


Fig. 4. Pulse width measurements before and after the TTD delay unit.

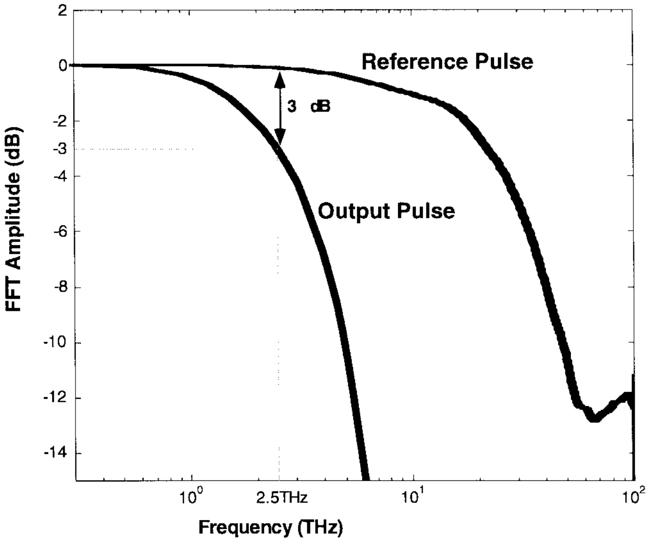


Fig. 5. FFT power spectrum for the input and output pulses.

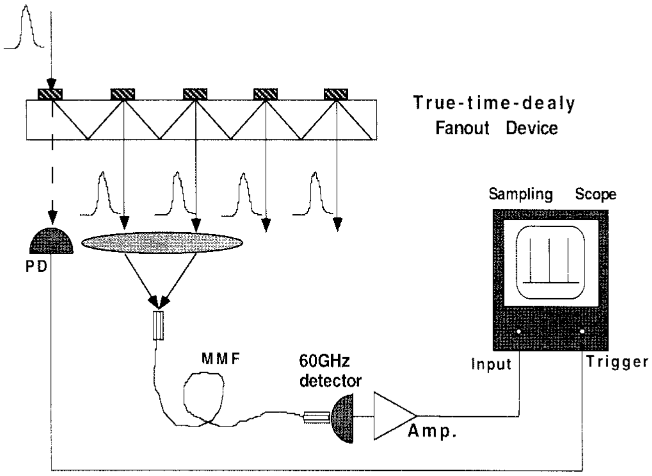


Fig. 6. Experimental set-up for measuring the minimum delay interval: MMF-multimode fiber; PD—photodetector; Amp.—broadband amplifier.

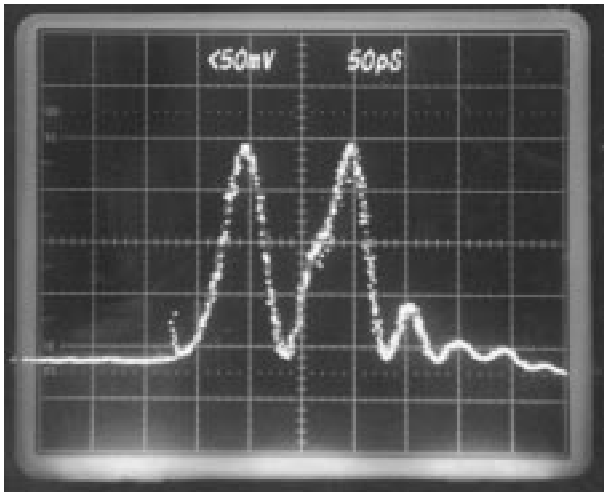


Fig. 7. Photograph of the sampling scope screen showing the two pulses coming from successive fan-outs are delayed with each other by ~100 ps.

pulse. This tail structure is attributed to reflections at cable connections of different bandwidth, such as SMA-to-Viltron K. The uncertainty due to jittering is estimated to be less than 2 ps. With this set-up, delay intervals down to 30 ps can be measured. Further decrease in delay can be resolved by a streak camera [10].

## V. CONCLUSION

A highly compact true-time-delay lines having a packing density of 5 delay lines/cm$^2$ with ultrawide bandwidth on a single substrate is proposed and fabricated. The TTD unit employs spatially multiplexed substrate guided waves to provide delay intervals of 100 ± 2 ps, which is measured experimentally. The uneven fanout intensity problem commonly related to substrate guided waves is addressed as well. Finally, we measured the bandwidth of the device by sending a femtosecond Ti:Sapphire laser pulse into the TTD delay unit. The measured 2.5 THz bandwidth is the most broad bandwidth ever reported for similar TTD delay devices. Compared with other integrated optic 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.

## ACKNOWLEDGMENT

The authors would like to thank Dr. Y.-S. Park for his encouragement and support in this project. The authors would also like to thank Dr. D. Deppe and L. Graham for helpful discussions on delay measurements.

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