Optically Controlled Generation and True-Time-Delay Phase-Shifts of Broad-Band 60-GHz Signals

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Abstract—**A new technique of generating true-time-delay phase shifts of broad-band microwave and millimeter-wave signals through optical control has been demonstrated. Continuous and precise phase shift with a range of 360° has been achieved without millimeter-wave signal loss. The microwave/millimeter-wave circuit and the optic-electronic intermixing structure can be monolithically integrated. Optical fiber distribution of the picosecond triggering pulses could be applied. The potential applications of this optical control technique are in phased-array radar and satellite-borne communication systems.**

I. Introduction

One important requirement in system operation of millimeter-wave devices is the ability to control phase variation of propagating wave along a transmission line [1],[2]. Semiconductor phase shifters using field-effect transistor, Schottky diode, and PIN diode technologies suffer from considerable RF insertion loss, and are limited in operation at millimeter-wave frequencies. The application of optical techniques to obtain phase-shift was first demonstrated by optically illuminating a semiconductor dielectric waveguide [3]. Similar approaches have been applied to integrated transmission lines [4]. Recently, injection locking of oscillation have been demonstrated for phase-shift up to 18 GHz [5]. Using microwave modulated optical signals and microwaves generated by beating two lasers of slightly different in frequencies have demonstrated true-time-delay phase shift up to 50 GHz [6]. Ultrafast optics can also be used to control the phase of millimeter waves by synchronizing millimeter waves to mode-locked laser pulse trains. This letter demonstrates the true-time-delay phase shift of broad-band 60-GHz signals using this new scheme. Such true time-delay is necessary in a phased-array radar, whereby broad-band signals are generated, in order to achieve the required antenna pointing accuracy [7].

II. Experiment

A block diagram of the optically controlled broad-band signal generator and phase shifter is shown in Fig. 1. A 5-ps electrical signal with a 76-MHz repetition rate is generated by focusing a 3-ps mode-locked laser pulse train on a gallium arsenide (GaAs) photoconductive (PC) switch. The PC switch has a length of 10 μm, and a substrate thickness of 4 mil [8]. The present switch was proton implanted at a dose of 10^{14} cm^{-2} and multiple sequence of energies to achieve an uniform damage from the surface to a sufficient depth for fast optical response.

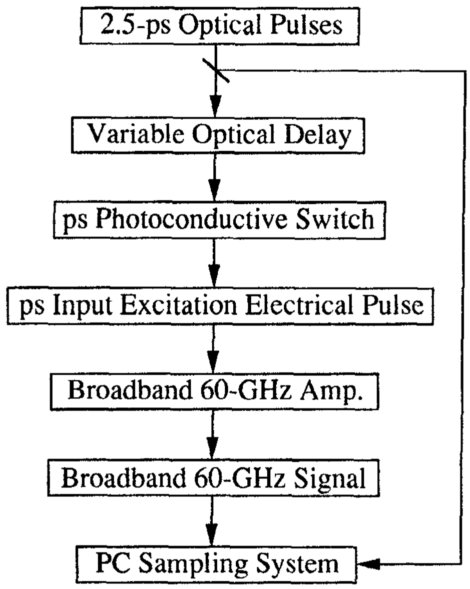

Fig. 1. Block diagram of the experimental set up.

The PC switches are connected to the input and output of a multistage V-band monolithic integrated low-noise amplifier (LNA) through wire bonds. The amplifier is fabricated using InGaAs–GaAs pseudomorphic high electron mobility transistor (HEMT) technology. It has a power gain of 20 dB (or 30 dB at high-gain bias), and a bandwidth of 8 GHz. The electrical pulses, which cover a frequency spectrum from dc up to about 150 GHz, are input to the amplifier. Only signals of frequencies within the gain bandwidth of the LNA are amplified. This optical/millimeter-wave scheme results in coherent, broad-band 60-GHz signals at the output of the LNA in response to the input electrical pulses generated by the optical excitation at the PC switch. The broad-band 60-GHz signal at the output of the amplifier is then mapped out using the PC sampling techniques [9]. By time-delaying the triggering optical pulse trains, the generated broad-band 60-GHz signal can be phase-shifted.

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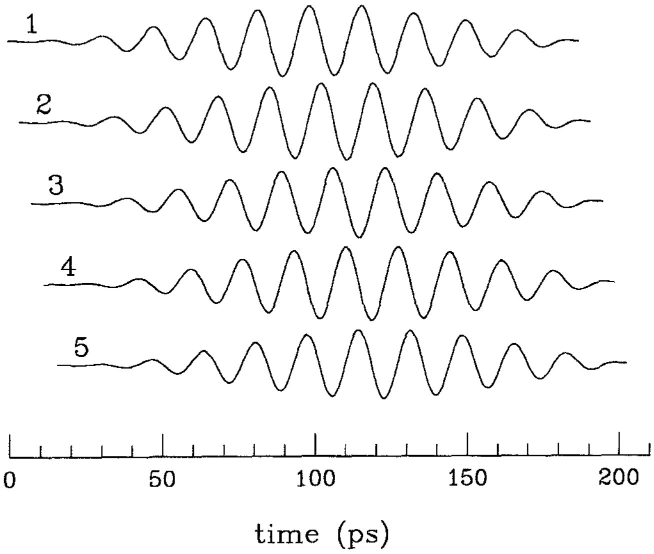

Fig. 2. True time delay of the broad-band 60-GHz signals, successive time delay on the onset of 60-GHz signal is achieved by delaying the arrival time of the optical pulses.

III. Results and Discussion

Fig. 2 shows the measured waveforms of the time-delayed broad-band 60-GHz signal. The timing jitter of the output waveform from the LNA is negligible as evident from the excellent signal to noise ratio of the time-domain waveform. With optical round-trip delay of only 2.4 mm, the 60-GHz signals can be continuously shifted by one complete cycle, 360°. The present feature of requiring only short optical delay is important for phased-array applications [10], since it allows very fast and accurate control of the phase shift of the millimeter-wave signal, which can be readily accomplished by properly designing of the optical system using piezoelectric devices.

The generation of the 60-GHz broad-band signals follows closely the delay of the optical triggering signal, with the corresponding phase-shift shown in Fig. 3. In order to demonstrate continuous phase shifting of the 60-GHz millimeter wave, nine equally spaced time-delay measurements were made. In general, the amount of phase shift, $\phi(f)$, is equal to

$$\phi(f) = \frac{-2\pi f}{c_0}\Delta L,$$

where c_0 is the velocity of millimeter-wave signal in the free space, f is the frequency, and ΔL is the single-pass optical delay length.

With the present setup, the accuracy of the phase control is better than 0.1°. By performing Fourier transform of the time-domain waveforms, the phase information can be obtained as shown in Fig. 4. The reference zero phase is set at the center frequency (58.5 GHz) of the first millimeter-wave wavepacket (label as trace 1 in Fig. 2). The phases of these millimeter-wave signals are fairly linear over the broad-band spectrum. It results in the linear relationship between the phase-shift per unit propagation distance and millimeter frequencies as depicted in Fig. 5. This characteristic implies that the entire beam of a broad-band signal will diffract with a single diffraction angle, θ_0, in a phased-array system

$$\theta_0 = \sin^{-1}\left(\frac{c_0}{2\pi d}\frac{\phi(f)}{f}\right),$$

where d is the spacing between the array elements. The linear relation is an important requirement for a broad-band phased-array radar because it permits the radar to operate on separate carrier frequencies, and to transmit broad-band signals, with high resolution. One additional advantage of this scheme is that there is minimum millimeter-wave loss in the phase-shifting process.

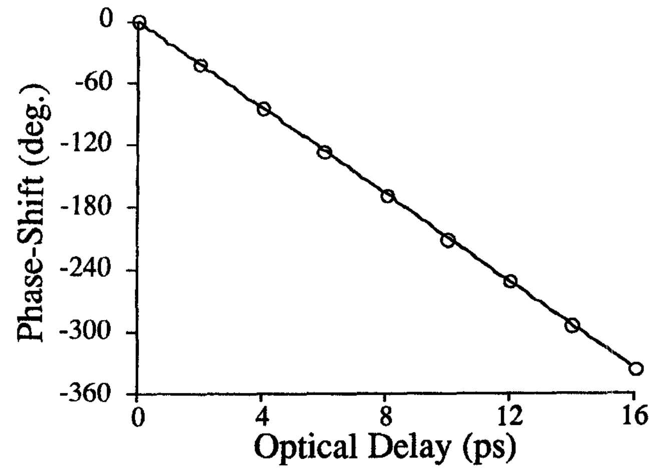

Fig. 3. Optically controlled phase shift of the millimeter-wave signals at the center frequency of 60 GHz.

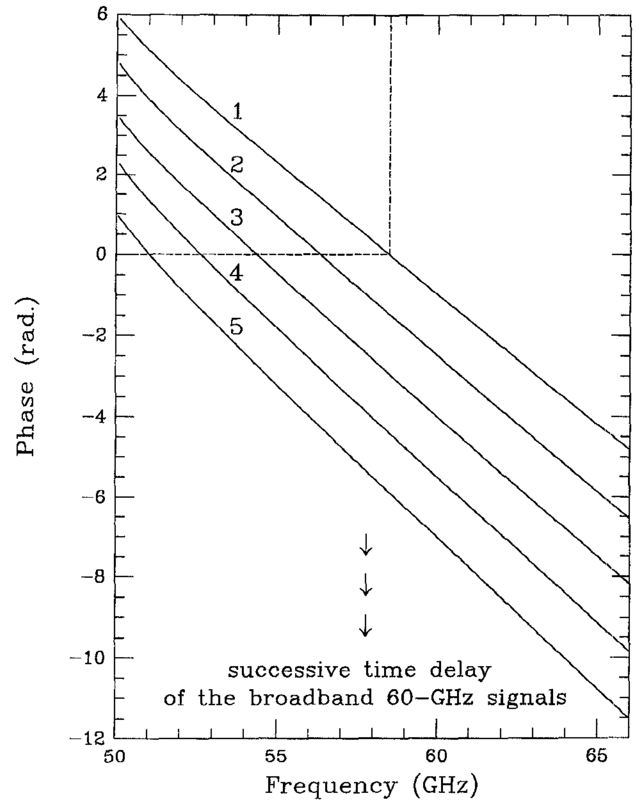

Fig. 4. Phases of the millimeter-wave signals vs. broad-band frequencies with successive propagation distances.

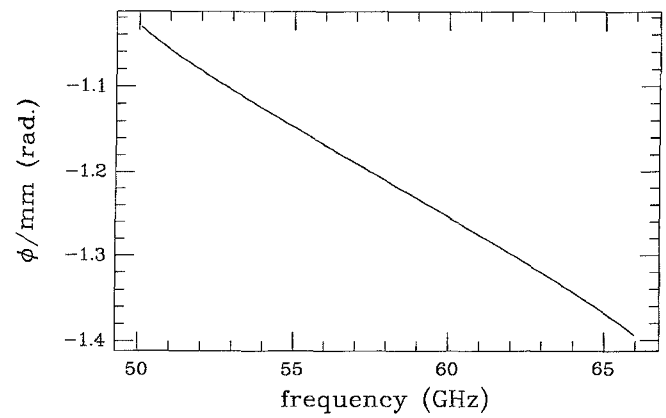

Fig. 5. Phase shift in unit optical delay vs. broad-band millimeter-wave frequencies.

IV. Conclusion

The incorporation of optical techniques into millimeter-wave technologies has created a new class of devices that can perform electrical functions that are not easily attainable by purely electronic means. Synchronization between the ultrafast optical pulse trains and millimeter wave makes it easy to control millimeter-wave devices. In this letter, the technique of optically controlled generation and phase shift of broad-band 60-GHz signals was presented. Potential applications of this technique are to control beam steering of satellite-borne communication system and phased-array radar. For satellite-borne communication, it is possible to modulate the broad-band carrier frequencies by digital or analog modulation on the bias for the PC switch [11]. We measured the timing jitter of the mode-locked laser pulse train to be about 1 ps that could match the critical demand for radar applications. In addition, improvements in the speed and accuracy of controlling the optical delay could lead to use of this true-time-delay technique in a smart antenna system.

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