Optically-Controlled Serially-Fed Phased Array Sensor

David A. Cohen*, Yian Chang†
A. F. J. Levi*, Harold Fetterman†
Irwin Newberg‡

Abstract

A new type of RF-photonic sensor design which uses an optical serially-fed phased array is proposed for applications in radar and communication systems. This sensor has the advantages of true time delay and yet only requires one tunable laser and one fiber optic grating delay for beam steering. In addition to discussing the system operation in transmit and receive modes, we also present initial experiments establishing the viability of the basic serial-feed design approach.

* Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089-1111
† Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095
‡ Radar and Communication Systems, Hughes Aircraft Company, Los Angeles, CA 90009-2426

I. Introduction

We propose a new photonic system suitable for RF phased array sensors. This system uses a serial-feed concept that represents a major simplification in both optical and microwave components compared with conventional parallel systems[[1]]-[[6]]. Our system provides both phase delay and true time delay (TTD) for beam steering and requires only a single tunable laser, optical modulator, and time delay element[[7]]. In this paper we present descriptions of transmit (XMIT) and receive modes as well as initial experimental data establishing the viability of this approach. In our design, the use of fiber optic techniques, such as long and low-loss delay lines, is intrinsic to the operation of the system. It is predicated upon using the pulsed nature of most microwave sensors in a manner similar to clocked systems used in digital configurations. Precise timing control of photonic signals is used to distribute RF pulses with time/phase delay information to each element in a radiating/receiving array.

II. Transmit Mode

To describe the proposed mechanism of operation, we divide the XMIT function into two parts: the timing unit and the tapped optical delay line feed. The timing unit is shown in Fig. 1a. The most technologically intensive component, the fast and broad-band tunable laser shown on the left, can rapidly change its wavelength by at least 20 nanometers using proper current adjustment.[[8]] A typical laser of this type can be electronically tuned in less than a nanosecond. Using an optical modulator, light from the laser is amplitude modulated at the desired microwave operating frequency and is gated at the radiated pulse width. After leaving the modulator lasing light passes through an optical circulator and then into a fiber grating. Reflected light from the grating returns to the circulator and is directed onto a tapped optical delay line as shown in Fig. 1b.

The timing information is obtained via the fiber grating which yields a wavelength-selective propagation delay for each gated pulse. Although our initial efforts use a grating with discrete wavelength selectivity, the system may alternately incorporate a continuously chirped grating or multiple gratings in parallel to enhance the time resolution. A laser which can be tuned continuously over a 20 nm range and fiber grating reflectors with a 0.3 nm FWHM linewidth (corresponding to an 53 GHz bandwidth) allow access to at least 60 different time delays with time delay accuracy around 1 ps. Each serially-fed optical pulse has a unique time delay relative to the RF pulse gate timing. It is these TTDs that control the pointing direction of our phased array. The number of pulses in the fully loaded line corresponds to the number of radiating elements in the array (or subarray). The wavelength stability needed in the system can be readily achieved by maintaining the temperature fluctuations to within 1 °C[[5]]. Note that this task is much easier in our system than in others because fewer active elements and passive delay elements are used.

The tapped delay line consists of a fiber having equally spaced taps; each tap is connected to an optical detector. The optical propagation time between these taps corresponds to the length of the longest radiated pulse. It is important to note that the RF pulse gate period in this approach must be equal to (or an integral multiple of) the inter-tap delay time. From the circulator, each gated pulse will arrive, with the additional delay for beam steering imposed by the fiber grating, simultaneously at the intended tap on the delay line. Essentially the delay line "stores" the pulses until it is fully loaded with the correct pulse adjacent to each tap. At this moment the microwave signal from the optical detector, located at each tap in the fiber manifold feed, is switched to the antenna element and all pulses on the line are radiated simultaneously. Each antenna element's microwave pulse has the correct time delay, as set by the fiber's Bragg grating reflector, to form a radiating beam in a desired direction. There is complete freedom in choosing this direction constrained only by the number of available laser wavelengths and associated Bragg grating reflectors. After the signal is radiated, the detector outputs are simultaneously switched away from the antenna elements and the fiber manifold feed can be reloaded. Due to the power splitting along the tapped delay line, each photodetector receives $1/n$ of the useful optical power, where n is the number of radiating elements. This corresponds to a $-10\,\mathrm{Log}\,n\,\mathrm{dB}$ of optical power loss for each element. For a practical size ($n \approx 100$) of subarray or array, this loss can be compensated by a single optical amplifier ($+20\,\mathrm{dB}$ or more) if necessary. For quasi CW transmit or receive mode systems, a modification of the basic system permits each optical pulse to be accessed in turn by each element and each element takes $1/n$ of the optical power. No optical power is lost in these cases.

III. EXPERIMENTAL DATA

Instead of using a tunable laser, it is possible to use arrays of lasers, including VCSELs, that are switched on and off to obtain a large set of precise optical wavelengths.[[9]]-[[10]] To evaluate the basic concept of wavelength controlled time delays in our serially-fed system, we have performed a prototype experiment using two 1.3 μm DFB lasers and a ten grating reflector fiber. These lasers are tuned to different grating reflectors on a single-mode fiber separated by 1.7 mm corresponding to 17.5 psec round-trip delay. The lasers are alternately switched on and off as shown in Fig. 2a. In this example, pulse widths are approximately 6 ns with the complete switching time occupying less than 1 ns. There is no fundamental limit to the length of the pulses used in this experiment; 6 ns was only chosen for convenience. In Fig. 2b we show the time averaged optical spectrum after 10 GHz microwave modulation and reflection from the grating. The typical -35 dB side-mode suppression in the DFB laser is enhanced by a few dB after passing through the fiber grating. This is due to the fact that the reflection wavelength of the neighboring line does not overlap with the DFB's natural subsidiary maxima. Therefore we obtain about -40 dB (-80 dB electrical) optical purity which can contribute to the signal to noise performance of the system. No other significant reflections have been noted from the terminated fiber grating.

Measurements have been made at 3, 10 and 18 GHz to examine the precision and switching dynamics of the fiber-optic TTD timing unit. Fig. 3a shows the output of a digital sampling oscilloscope with a 3 GHz RF signal which was analyzed, by best-fitting sine functions, to have a TTD of 17.5 ps. The figure shows that the system can be effectively switched in less than 1 ns. The oscilloscope is triggered with the same synthesizer driving the modulator. The results at 10 GHz (Fig. 3b) have a TTD = 17.5 ps. This experiment was also repeated at 18 GHz and yielded a phase shift of 110° as shown in Fig. 3c. Finally, by switching to another grating reflector on the fiber corresponding to a TTD = 54.9 ps, a phase shift of 200° at 10 GHz was obtained as shown in Fig. 3d.

These measurements demonstrate that wavelength switching speeds and the reproducibility required for the laser can be obtained using commercially available components. These results also establish that existing fiber grating delay lines offer sufficiently high contrast ratios to limit the background scattered light level in the system. Note that an electrical phase noise ratio of better than 80 dB is outstanding for such a system.

IV. Receive Mode

In the receive mode only the RF phase is required at each antenna element for a given direction of observation, there is no optical or microwave pulse gating. Using the same timing unit and tapped delay line as in XMIT mode, local oscillator (LO) signals, in exact reverse phase as used to transmit the beam, are supplied to mixers located at each antenna element. The received signal at each antenna is the other input to each mixer.

Essentially, the receiver we propose utilizes the conjugate phase delays to yield the equivalent of a configurable matched filter. Thus, in our system the signals from the XMIT photodiodes are fed to a mixer which homodynes this optically generated microwave LO signal with the received microwave signal. The signals, mixed to baseband, from each antenna element are then added coherently in a simple summer signal processor to form the received antenna beam signal. For a combined XMIT and receive system, an electronic switch could be used between XMIT and receive functions to allow the same timing unit and optical feed to be used to generate RF signals with steering phases for XMIT and receive. A laser may also be used to transmit the composite summed baseband signal to a remote site for further processing and display.

It is important to note that these delayed RF signals, generated by laser tuning and grating delay, have a RF phase characteristic of a true time delay system. This yields a wide tuning frequency bandwidth capability for constant pointing. The technique is relatively simple and capable of steering the receive beam through all angles as in the XMIT mode. The proposed system can meet the RF performance specifications of a large subset of potential users. By using two parallel delay lines the duty cycle can be increased to essentially 100% as in the XMIT mode.

V. CONCLUSIONS

A novel serially-fed TTD system has been proposed and the basic concept has been experimentally verified. The system we have presented is a RF sensor implementation based upon a serial-feed. It uses only one tunable laser, modulator and delay element to achieve completely addressable beam steering. The system is scaleable and additional lasers and fibers can be used in a parallel configuration to increase the number of available bits and time resolution. The system is also versatile and can be used to control both one and two dimensional arrays as well as multibeam systems. Because the amplitude and time delay for each radiating element is completely programmable, arbitrary beam forming is possible. Thus, by using the natural timing of pulsed RF systems we are able to greatly simplify, to reduce the cost, and to increase the flexibility of optically controlled radar, communication and electronic warfare applications.

ACKNOWLEDGMENT

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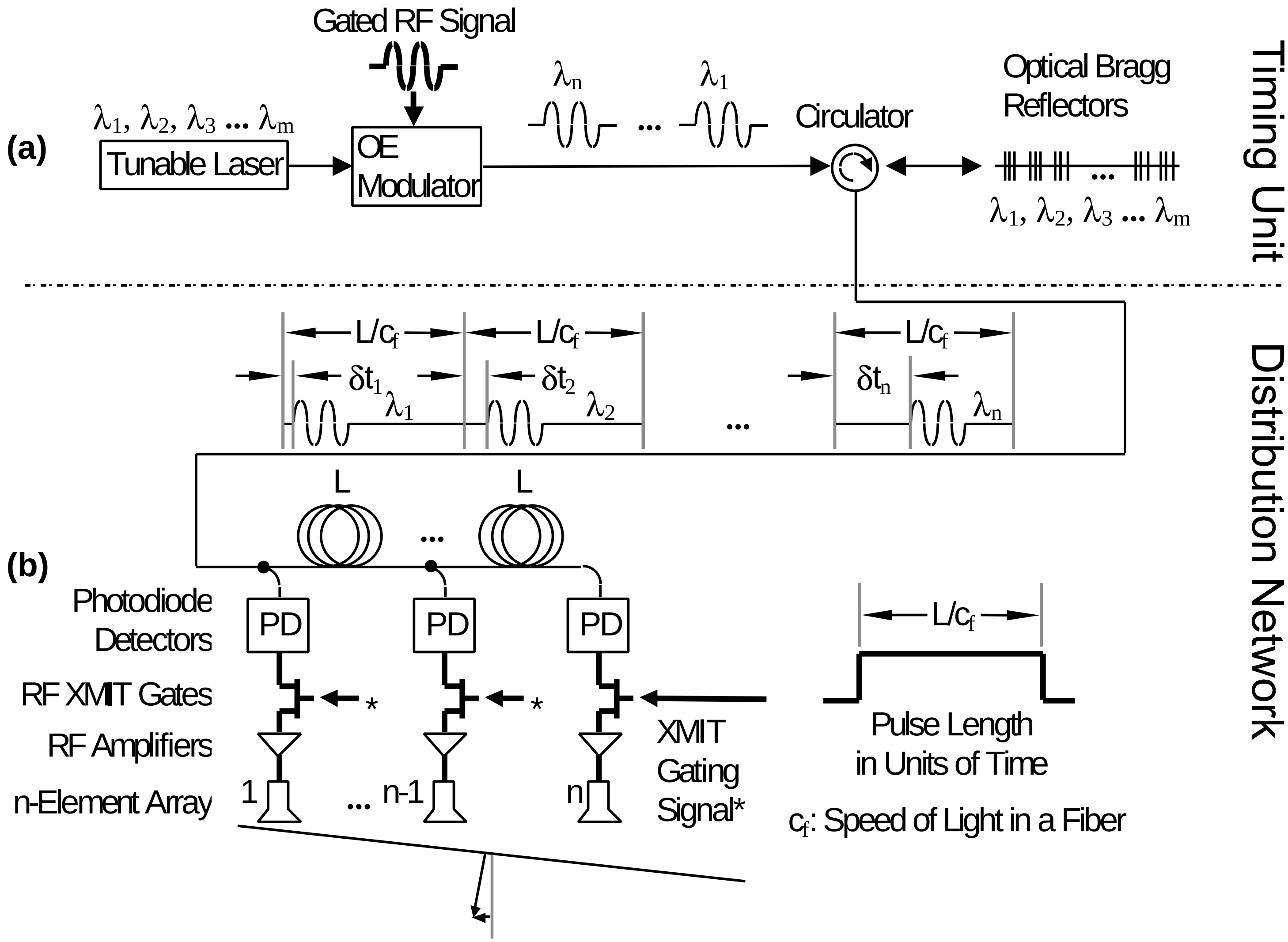
ILLUSTRATION CAPTIONS

Fig. 1. (a) Basic XMIT mode implementation for array of n elements. It shows only one laser, one optical modulator and one delay element are needed. (b) Tapped optical delay line used as the distribution network to demultiplex serial pulses into parallel ones.

Fig. 2. (a) Laser #1 (solid line) with emission wavelength λ_1 and Laser #2 (dotted line) with emission wavelength λ_2 are alternately switched on and off with pulse widths about 6 ns and switching time less than 1 ns. (b) The optical spectrum of λ_1 after reflection from the fiber grating for the case of 10 GHz modulation. This shows the spontaneous emission background level resulting from reflection of the other grating reflectors is 40 dB below the desired signal.

Fig. 3. Solid lines: detected signals showing wavelength switching. Dotted lines: Sine-fit to the λ_1 RF signals. (a) 3 GHz RF signal with switched true time delay (TTD) equal to 17.5 ps, obtained by best-fitting of sine functions on a smaller time scale setting. This TTD corresponds to 18° phase change at 3 GHz. Switching time is less than 1 ns. The signal is inverted due to the RF amplifier. (b) 10 GHz RF signal with switched TTD = 17.5 ps. This TTD corresponds to 63° phase change at 10 GHz. (c) 18 GHz RF signal with switched TTD = 17.5 ps. This TTD corresponds to 110° phase change at 18 GHz. (d) 10 GHz RF signal with switched TTD = 54.9 ps. This TTD corresponds to 200° phase change at 10 GHz.



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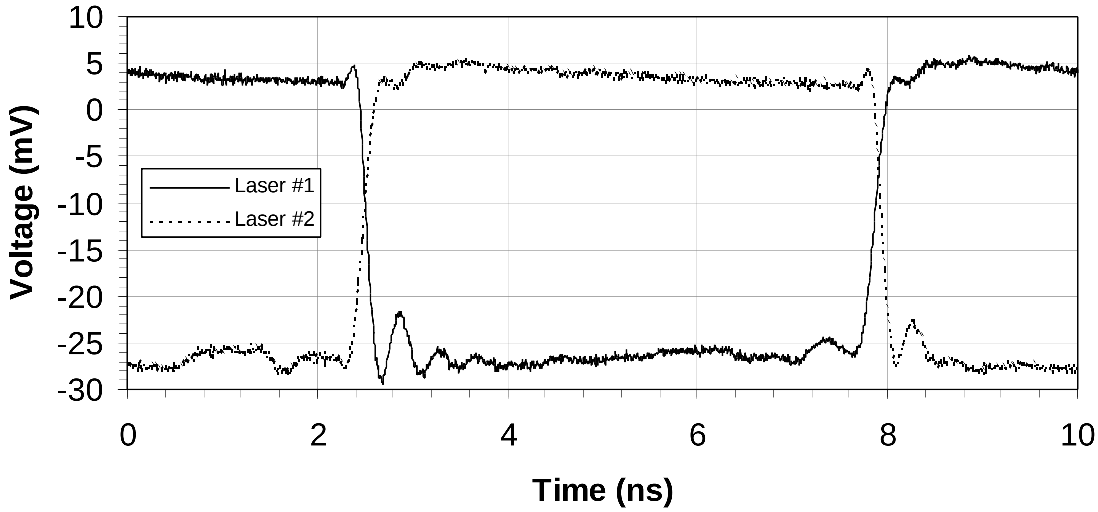

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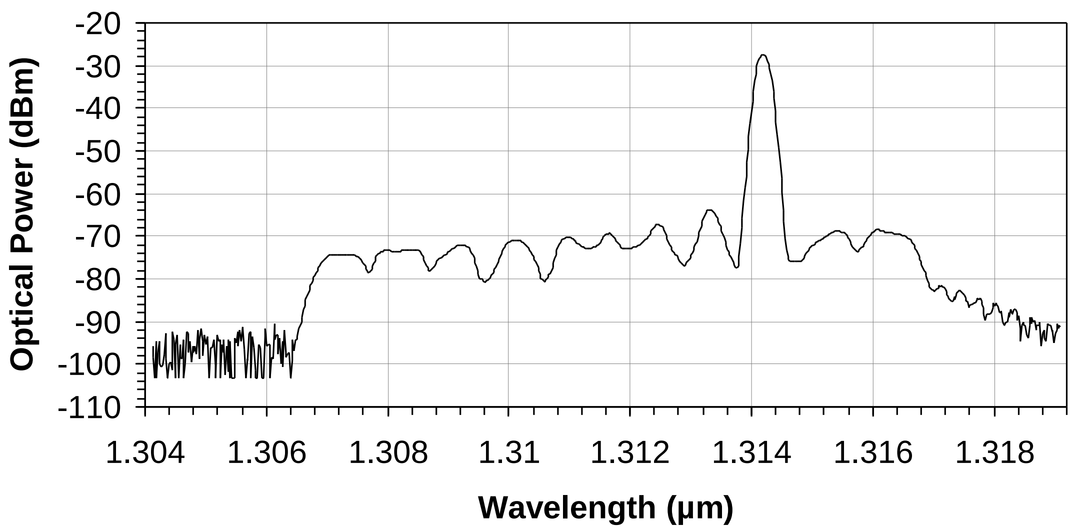

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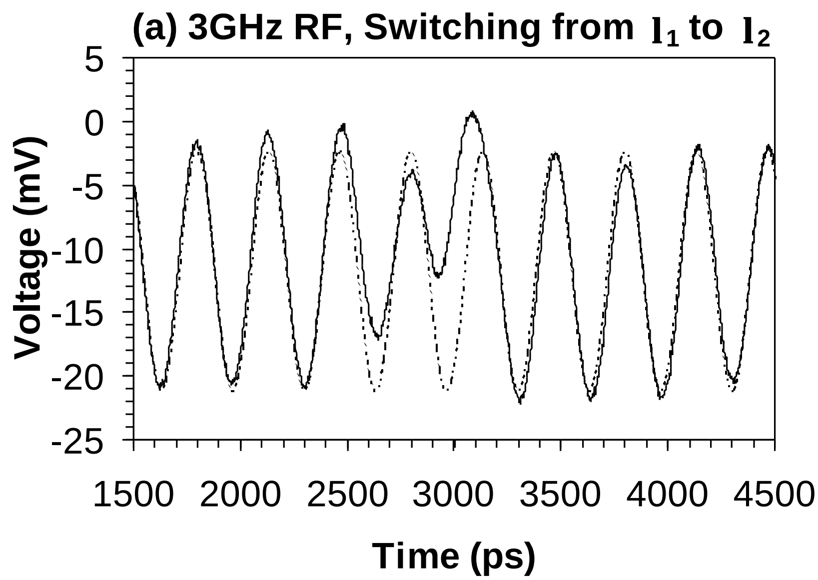

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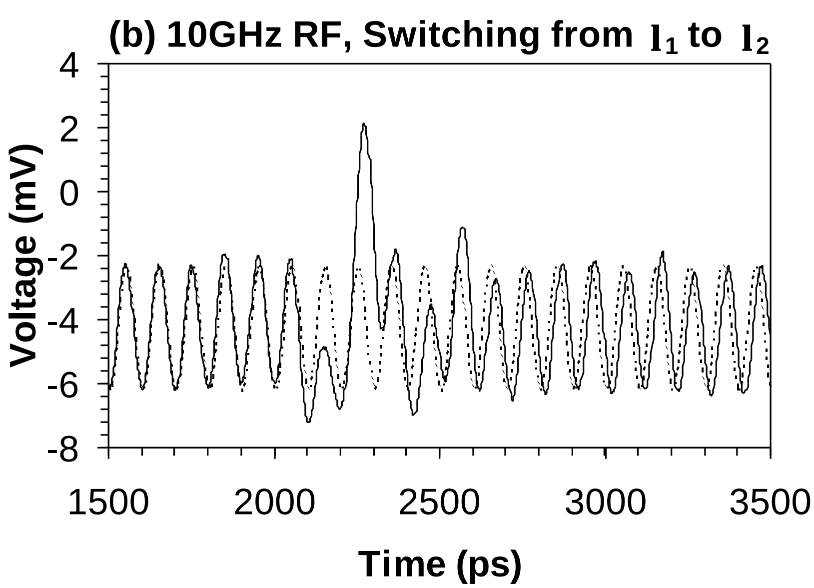

Fig. 3. (b) 10 GHz RF signal with switched TTD = 17.5 ps. This TTD corresponds to 63° phase change at 10 GHz

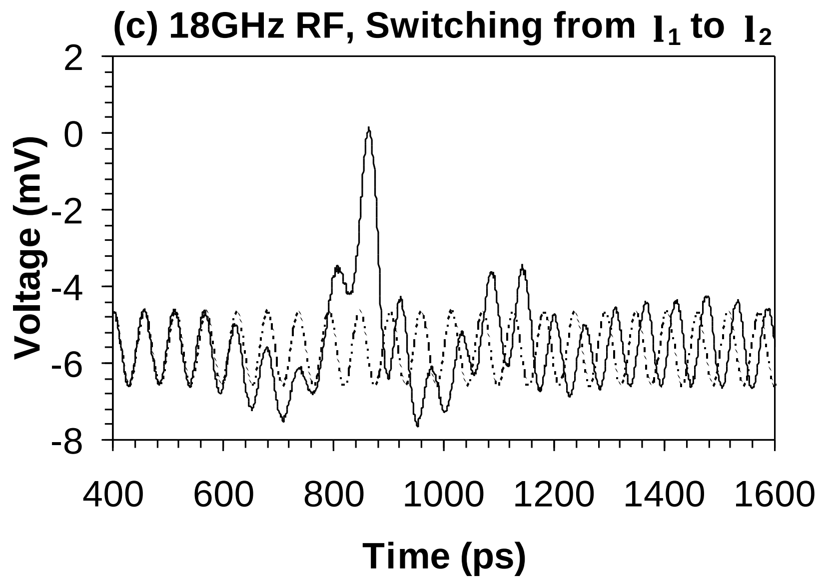

Fig. 3. (c) 18 GHz RF signal with switched TTD = 17.5 ps. This TTD corresponds to 110° phase change at 18 GHz.

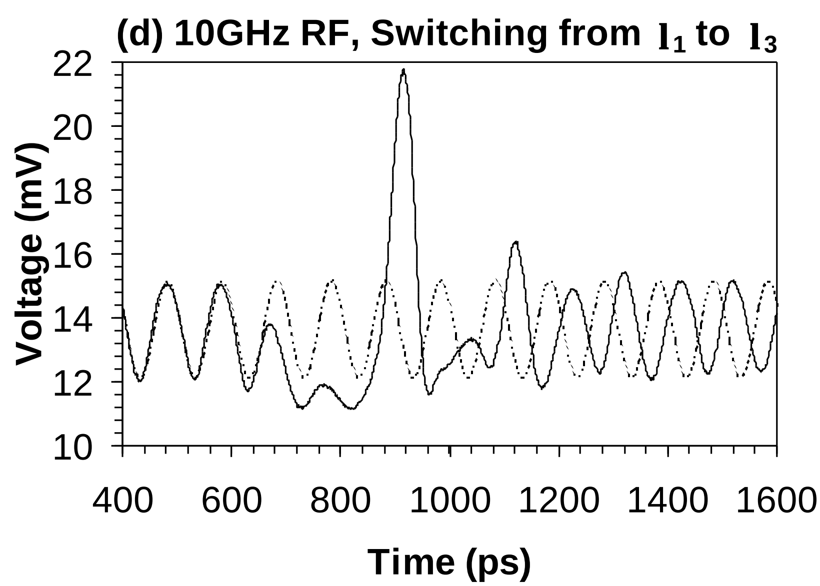

Fig. 3. (d) 10 GHz RF signal with switched TTD = 54.9 ps. This TTD corresponds to 200° phase change at 10 GHz.