# A THz-TDS-based Measurement Technique for Characterizing Picosecond Pulses Radiated from Silicon Chips

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***Abstract*—This paper presents a time-domain optoelectronic picosecond pulse measurement technique, where radiated pulses from a silicon chip are sampled by a laser-gated photoconductive antenna (PCA). The PCA detector provides a measurement bandwidth up to 4.5THz. In this scheme, the radiated picosecond pulses from a silicon chip are synchronized with a femtosecond laser source in an optical sampling system. In this technique, waveform sampling is performed directly at the PCA, mitigating measurement complexities associated with loss and distortion calibrations of waveguides, coaxial cables, and connectors. The reported custom measurement technique is used to sample pulses as short as 5.4ps.**

***Index Terms*—picosecond pulse measurements, optical sampling, silicon RFIC, terahertz optoelectronics, THz-TDS, time-domain measurements.**

## I. Introduction

DURING the past decade, mm-wave and THz waves have been used in a variety of applications, such as biology and medical sciences [1], high-resolution 3D imaging [2], non-destructive evaluation [3], and environmental monitoring [4]. The increasing current gain cutoff frequency ($f_T$) and maximum oscillation frequency ($f_T$) of transistors in BiCMOS and CMOS processes, have resulted in silicon-based sources operating in the THz regime. The majority of these sources are based on narrowband Continuous Wave (CW) signal generation. Since these sources are narrowband, they can be characterized by waveguide probes or horn antennas coupled to rectangular waveguides. These methods are not suitable for broadband picosecond pulses that span a frequency range from 30GHz to beyond 1THz. Recently, silicon-based digital-to-impulse architectures have been reported that generate and radiate picosecond pulses [5], [6], [7], [8], [9]. These radiators require a direct time-domain sampler with a measurement bandwidth exceeding 1THz.

Traditionally, picosecond pulse generation is done through Photoconductive Antennas (PCAs) triggered by femtosecond laser pulses. Unfortunately, PCA sources require a bulky and expensive laser source. They also have a low repetition rate (100MHz or below). Recently, fully-electronic silicon-based picosecond pulse radiators are reported that produce high-power broadband pulses in the THz regime without using any laser source [5], [6], [7], [8], [9]. These chips convert a low-frequency trigger signal to high-power picosecond pulses in the THz regime. They can also produce picosecond pulses with a high repetition rate of 5GHz.

Although these sources produce picosecond pulses, due to their broadband nature, their characterization remains extremely challenging. Conventionally, high-speed oscilloscopes are used to sample short pulses but their bandwidth is limited to 100GHz [10], which is not high enough to characterize pulses with several picosecond duration in the THz regime. To be more precise, rise time of oscilloscopes is an important performance metric for picosecond pulse measurements. In an oscilloscope, the rise time and the bandwidth are related by [11], [12],

$$BW = \frac{k}{Rise\ Time_{(10\%-90\%)}} \tag{1}$$

where $BW$ is the bandwidth of oscilloscopes. $k$ varies from 0.4 to 0.45 in oscilloscopes with a bandwidth of larger than 1GHz.

As reported in [12], oscilloscopes must have sufficiently small rise time to accurately capture the details of rapid transitions as shown below,

$$t_{rise,oscilloscope} \leq \frac{t_{rise,signal}}{5} \tag{2}$$

where $t_{rise,oscilloscope}$ is 10%-90% rise time of oscilloscopes and $t_{rise,signal}$ is that of the signal of interest. Therefore, to measure an impulse-like pulse with a 10ps Full-Width-at-Half-Maximum (FWHM), which has an approximate 5ps rise time, oscilloscopes should have a rise time less than 1ps. However, the highest bandwidth of off-the-shelf oscilloscopes is 100GHz, associated with 4.5ps rise time (10%-90%) [10], which fails to meet the requirement for measuring picosecond pulses.

In addition to the limited bandwidth, in the conventional oscilloscope-based techniques, the received pulse has to pass through an antenna, coaxial cables, and coaxial connectors before being sampled by the internal electronics of the

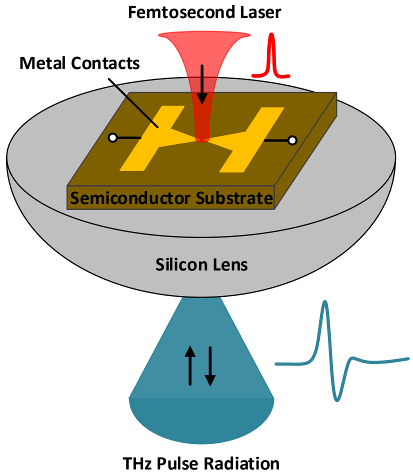


Fig. 1. Schematic of a photoconductive antenna (PCA).

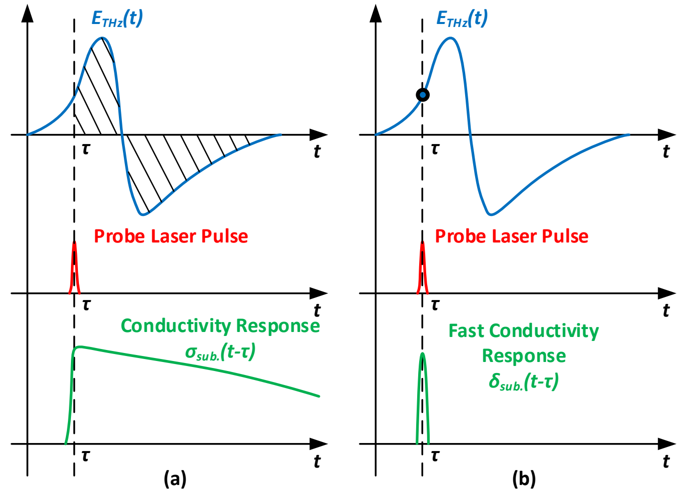


Fig. 2. Sampling mechanism of a PCA detector with (a) slow substrate conductivity response and (b) fast substrate conductivity response.

oscilloscope. The loss and phase response of these components need to be calibrated in a broad frequency range so that the distortion effects on the picosecond pulses are de-embedded correctly. Therefore, the measurement complexity is significantly increased due to the broadband calibrations of numerous passive components between the antenna and the internal sampler of the oscilloscope.

This paper presents a novel time-domain optoelectronic picosecond pulse measurement technique based on Terahertz Time-Domain Spectroscopy (THz-TDS). The proposed method has a rise time of about 100fs [13], [14], associated with 4.5THz measurement bandwidth. This intrinsic ultra-fast transient response allows to accurately measure picosecond pulses radiated from a silicon chip. In the proposed measurement technique, received picosecond pulses are directly sampled at a PCA detector, mitigating measurement complexities associated with broadband calibrations of passive components as in the conventional methods based on high-speed oscilloscopes.

This paper is outlined as follows. Section II describes conventional photoconductive-based THz-TDS systems, focusing on the measurement principle and physical mechanism. Section III reports the details of the measurement technique and Section IV discusses the measurement results. Finally, Section V concludes the paper.

## II. THz-TDS System

In a THz-TDS system, photoconductive antennas are commonly used as THz sources and detectors. In this section, first, physical mechanisms of a PCA are described. Second, details of the THz-TDS system used in this work, which is based on an Asynchronous Optical Sampling (ASOPS) scheme [15], are discussed.

### *A. Photoconductive Antennas (PCAs)*

PCAs are the first devices used to measure transient electric field of a THz pulse [16], [17]. In contrast to bolometric detectors, PCAs record both phase and amplitude information of a THz pulse. Fig. 1 demonstrates a simple PCA, consisting of two metal contacts evaporated onto a semiconductor substrate. When a PCA is used as a THz emitter, the electrodes are biased with a constant DC voltage. Then, a femtosecond laser pulse shines at the gap between the electrodes and produces carriers in the semiconductor substrate. This event generates an ultra-fast transient photocurrent, excites the antenna, and results in THz radiation. A silicon lens is usually mounted on a PCA to increase the antenna gain.

When a PCA is used as a THz detector, two electrodes are connected to the input of detection and data-acquisition electronics. In contrast to a PCA THz emitter, no DC bias is applied between the electrodes. In absence of a THz wave, when a femtosecond laser pulse is shined at the gap between the electrodes, only photo-carriers are produced and no current is generated. In presence of a THz wave, the electric field of the THz wave drives the photo-carriers and results in a non-zero current. This current is amplified and digitized by data acquisition units following the PCA detector.

According to Ohm's law, in a semiconductor material, the generated transient current density $\vec{J}(t)$ is the multiplication of transient conductivity response $\sigma_{sub.}(t)$ and transient driving electric field $\overrightarrow{E_{THz}}(t)$. The relation can be expressed as

$$\vec{J}(t) = \sigma_{sub.}(t)\overrightarrow{E_{THz}}(t) \quad (3)$$

The conductivity response of the semiconductor, $\sigma_{sub.}(t)$, depends on the concentration of photo-carriers generated by the femtosecond pulse. As illustrated in Fig. 2, when the timing delay between the received THz pulse and the femtosecond laser pulse is $\tau$, the generated transient current, $I(t)$, will be expressed as

$$\vec{I}(t) = A\sigma_{sub.}(t-\tau)\overrightarrow{E_{THz}}(t) \quad (4)$$

where $A$ is the cross-section area of the conducting region in the semiconductor substrate.

If the semiconductor substrate is grown at low temperature or is ion-damaged, exhibiting very short photocarrier lifetimes [4],

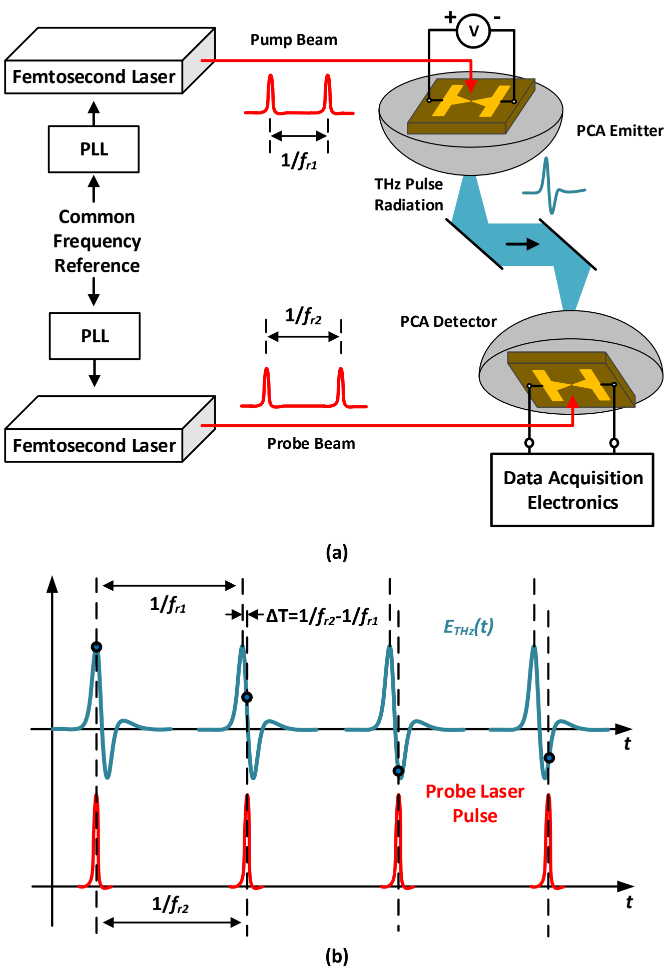


Fig. 3. (a) Schematic of a THz-TDS system with ASOPS scheme. (b) Sampling mechanism of ASOPS scheme.

the detection circuit will be only closed as long as the PCA detector is illuminated by the femtosecond laser pulse. As shown in Fig. 2(b), because the duration of a femtosecond laser pulse, e.g. ~50fs, is usually much shorter than that of a THz pulse, Equation (4) can be further simplified using a Dirac delta function,

$$\vec{I}(t) = K\delta_{sub.}(t-\tau)\overrightarrow{E_{THz}}(t) \quad (5)$$

where $K$ is a constant number related with the conductivity response strength and the cross-section area $A$.

Therefore, when the timing delay between the received THz pulse and the femtosecond laser pulse is $\tau$, at each sampling, the collected electric charge $Q(\tau)$ is

$$Q(\tau) = \int_{\tau^-}^{\tau^+} I(t)dt = \int_{\tau^-}^{\tau^+} K\delta_{sub.}(t-\tau)E_{THz}(t)dt = KE_{THz}(\tau) \quad (6)$$

The sampled output, $V_{out}(\tau)$, is proportional to the collected electric charge $Q(\tau)$, which can be expressed as

$$V_{out}(\tau) \propto Q(\tau) \propto E_{THz}(\tau) \quad (7)$$

Therefore, the shape of received transient THz pulse can be obtained by directly plotting the sampled outputs with different timing delays $\tau$. This condition is valid in this work for measuring picosecond pulses. Even though the above condition is not valid for measuring <100fs THz pulses, the actual time-domain waveform of THz pulses can still be recovered if substrate conductivity response $\sigma_{sub.}(t)$ is characterized [18].

As shown in Equation (3), $\sigma_{sub.}(t)$, the conductivity response of a PCA's semiconductor substrate, determines the bandwidth of the PCA detector and how rapid transitions can be captured accurately. With a femtosecond laser pulse excitation, which can be considered as an instantaneous excitation, $\sigma_{sub.}(t)$ rises exponentially towards the steady-state value with a time constant given by the carrier scattering time [14]. A typical value of the carrier scattering time for a semiconductor is less than 100fs [13], which is much shorter than the state-of-the-art rise time of off-the-shelf electronic oscilloscopes (4.5ps). According to Equation (1), the bandwidth of a typical PCA THz detector can be estimated to be around 4.5THz.

Apart from detection mechanism, Signal-to-Noise Ratio (SNR) is another concern for a PCA THz detector. The intrinsic noise of a PCA mainly comes from the Johnson-Nyquist noise, which is related to the average resistance of the PCA. Substrate materials with shorter photocarrier lifetimes result in PCAs with a lower noise current level. However, shorter lifetime substrate materials have lower photocurrent responsivity, which reduces signal level as an expense. As a result, to maximize PCA's SNR, it is important to optimize the substrate material [19].

### *B. Asynchronous Optical Sampling (ASOPS) Scheme*

Fig. 3(a) shows a schematic of a THz-TDS system, which is based on an Asynchronous Optical Sampling (ASOPS) scheme. In such a scheme, two femtosecond laser sources generate two beams. One is called the pump beam, the other is called the probe beam. These two laser beams have slightly different repetition frequencies, $f_{r1}$ and $f_{r2}$, respectively. The frequency detuning is denoted as $\Delta f_r$. The pump beam excites a PCA THz emitter, which produces synchronized THz pulse radiations. The probe pulse travels to gate a PCA THz detector in order to measure the THz pulse radiation. The output of the PCA THz detector is connected to data-acquisition electronics. The trigger signal required for data acquisition can be extracted from the pump and probe beams.

As shown in Fig. 3(b), the repetition frequency detuning between the pump and probe beam enables the PCA THz detector to sample the whole measurement window, which is defined by the pulse-to-pulse spacing of THz radiations. The scan rate is determined solely by the repetition frequency detuning $\Delta f_r$, when it is much smaller than $f_{r1}$ and $f_{r2}$. The upper limit of $\Delta f_r$ is determined by the bandwidth of detection and date acquisition circuits, as well as the required timing resolution [15]. Compared with a conventional THz-TDS system, which usually incorporates a mechanical translation stage with a retroreflector mirror to shift timing delays [4], the ASOPS scheme has superior scan rate and eliminates the noise

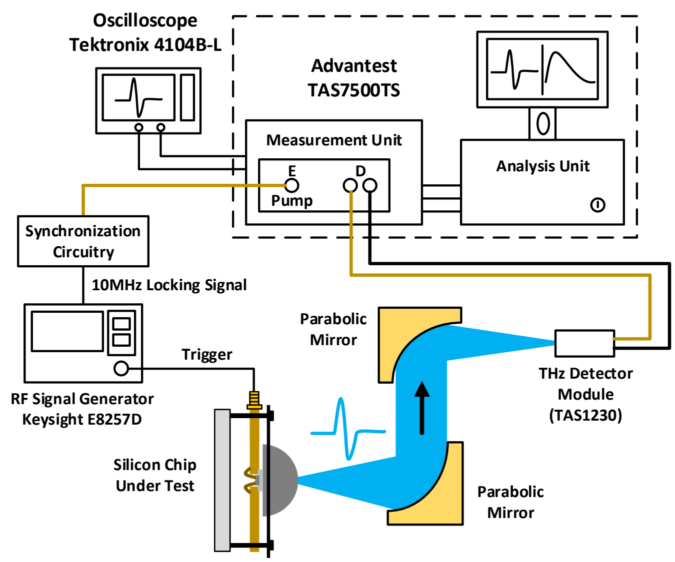


Fig. 4. Schematic of the proposed measurement technique.

induced by the mechanical movements during the long timing delay.

No matter which scheme is used, synchronization is the essence of time-resolved THz measurements. In the conventional THz-TDS schemes, a single femtosecond laser beam passes through a beam splitter, which results in two synchronized pump and probe beams. The probe pulse is used to detect the THz pulse excited by the synchronized pump pulse. In the ASOPS scheme, pump and probe pulses are generated by two individual femtosecond laser sources. Repetition frequency fluctuations of each laser source generate a deviation from the chosen scan rate $\Delta f_r$, resulting in a timing jitter and distortions in sampled waveforms, reducing SNR. Therefore, the repetition frequencies of the two femtosecond laser sources are stabilized by two PLLs that share a common frequency reference.

## III. An Optoelectronic Measurement Technique for Characterizing Picosecond Pulses

This section describes an optoelectronic measurement technique for characterizing picosecond pulses based on an ASOPS THz-TDS system. In this section, first, details of the reported measurement technique are described. Second, synchronization challenges between electrical and optical domains are discussed.

### *A. An Overview of the Measurement Technique*

As discussed in Section II, a PCA THz detector has superior bandwidth than current off-the-shelf electronic oscilloscopes. Therefore, a PCA detector is used to measure picosecond pulses radiated from a silicon chip. Since the PCA detector works based on a pump-and-probe scheme, the pulses radiated from the silicon chip under the test should be synchronized with the femtosecond laser associated with the PCA detector.

In this work, the laser sources and the PCA detector (TAS1230) in an Advantest TAS7500TS THz-TDS system are used to sample the pulses radiated from silicon chips. This measurement setup has a bandwidth (SNR=1) of more than 4THz. The schematic of the measurement technique is presented in Fig. 4. Advantest TAS7500TS utilizes an ASOPS scheme and is equipped with a measurement unit. The measurement unit provides an additional femtosecond laser output port, which is used for synchronizing the silicon chips under the test. The synchronization method will be discussed in section III B. The measurement unit transfers the sampled waveform at the output of the PCA to an analysis unit, which performs post-processing. These results can be displayed on the system monitor. Since the analysis unit has a limited memory, the displayed time-domain waveforms have a limited time duration. To solve this problem, a digital oscilloscope (Tektronix 4104B-L) is connected to the measurement unit to read the real-time sampled output of the received picosecond pulses.

To characterize picosecond pulses radiated from a silicon chip, a PCA THz detector can be placed in the far-field region of the silicon chip, without utilizing parabolic mirrors. In this case, broadband radiation patterns can be obtained. If the overall gain of the PCA detector and its following receiver path is known, broadband EIRP can also be measured. However, to increase the SNR of the received signal, off-axis parabolic metal mirrors are used to focus picosecond pulses on the PCA detector. Due to frequency-independent reflectivity of the parabolic mirrors, the pulse shape is not distorted. In this measurement, two off-axis parabolic mirrors are used to guide the picosecond pulses radiated from a silicon chip to the PCA (Fig. 4).

In addition to the enhanced measurement bandwidth, the reported measurement technique offers a much simpler calibration compared to conventional solutions based on high-speed oscilloscopes. This is because picosecond pulses are directly sampled at the PCA. It eliminates the need for broadband calibrations of waveguides, coaxial cables, and coaxial connectors that connect antennas and oscilloscopes in the conventional solutions.

### *B. Synchronization between the Chip and the THz-TDS System*

In the proposed measurement technique, the technical challenge is to synchronize the silicon chip under the test with the pump femtosecond laser source in the ASOPS THz-TDS setup. To explain the synchronization method, it is necessary to briefly review the working principles of the silicon-based picosecond pulse radiators [5], [9] that are tested in this work. The pulse radiating chips convert an electrical input trigger signal to a radiated wave that is synchronized with the trigger signal. Therefore, if the input trigger signal is synchronized with the pump femtosecond laser source, the radiated picosecond pulses from the chips will be synchronized with the PCA THz detector of the THz-TDS system (Advantest TAS7500TS).

Fig. 5(a) shows the block diagram of the synchronization technique. The output port of the pump laser source is attenuated with an optical attenuator (Thorlabs OVA50-APC) before being converted to an electrical trigger by a

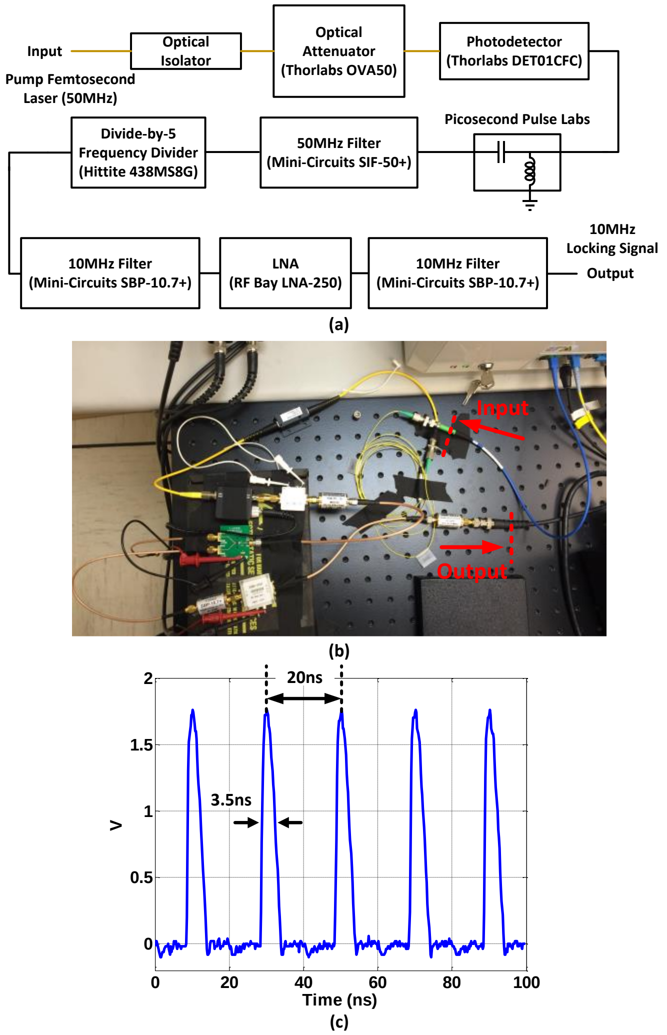


Fig. 5. (a) Block diagram of the proposed synchronization technique. (b) The actual circuit blocks for synchronization signal generation. (c) Converted electrical pulses from the pump femtosecond laser.

photodetector (Thorlabs DET01CFC). An optical isolator protects the laser by minimizing the power of the undesired reflections and a bias-tee (Picosecond Pulse Labs) is used to provide a proper biasing condition for the photodetector output. The generated electrical trigger is a 50MHz pulse train with a broadened pulse-width due to the limited bandwidth of the photodetector, as shown in the Fig. 5(c). A 50MHz filter (Mini-Circuits SIF-50+) extracts a 50MHz signal and feeds it to a broadband divide-by-5 frequency divider (Analog Devices 438MS8G). The undesired harmonic spurs are eliminated by a 10MHz narrowband filter (Mini-Circuits SBP-10.7+). After applying a low-noise amplifier (RF Bay LNA-250) and another 10MHz narrowband filter, a clean 10MHz signal is obtained with enough power to synchronize a RF signal generator (Keysight E8257D), which provides the input trigger for the silicon chips.

In the proposed measurement method, the PCA detector samples the received picosecond pulse radiation at the rate, $f_s$, which is given by that of the probe femtosecond laser. Here, $f_s$ is 50MHz+5Hz in the Advantest TAS7500TS, where the repetition rate of the THz pulse radiation is 50MHz. This means

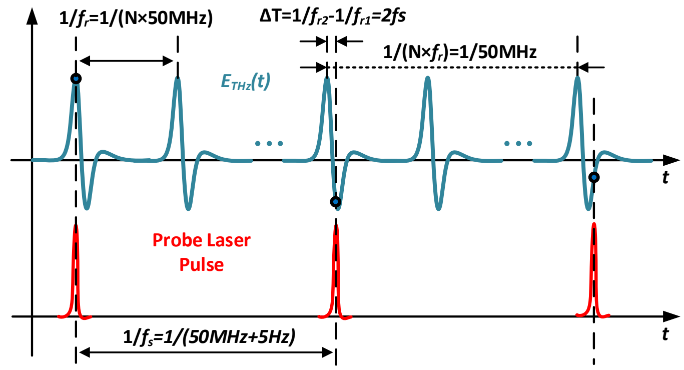


Fig. 6. Valid sampling conditions of the proposed picosecond pulse measurement technique.

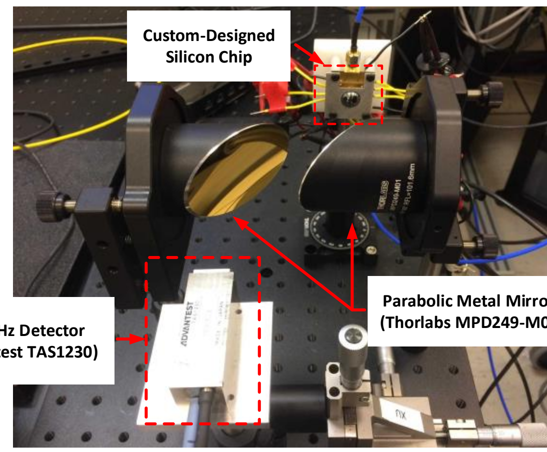


Fig. 7. Measurement setup for characterizing custom-designed silicon chips.

that the effective timing step of sampling is (1/50MHz-1/50.000005MHz)=2fs. It should be noted that although the repetition rate of the pump laser is 50MHz, the measurement technique allows us to trigger the chips with any repetition rate that is a harmonic of 50MHz. For example, as shown in Fig. 6, if the repetition rate of the radiated pulse train, $f_r$, is an $N_{th}$ harmonic of 50MHz, the PCA detector will sample one point for every $N$ received pulses, but the actual timing step of the sampled waveform is still 2fs. In fact, in our measurement, the repetition rate of the radiated picosecond pulses is larger than 1GHz.

## IV. Measurement Results

Fig. 7 presents the measurement setup used for characterizing the custom-designed silicon chips. As discussed in section III, two parabolic mirrors with gold coatings (Thorlabs MPD249-M01) are used to focus radiated picosecond pulses to the PCA detector (Advantest TAS1230). In this setup, the PCA detector is mounted on a 3D positioner for alignment purposes. A 10MHz synchronization signal is generated using the circuit shown in Fig. 5(a) and its time-domain waveform is shown in the Fig. 8(a). This waveform has a 7.7dBm peak power at 10MHz (Fig. 8(b)). In the proposed technique, the two laser pulses, which are used to provide the trigger signal to the chips as well as the sampling signal to the PCA, respectively, are generated almost at the

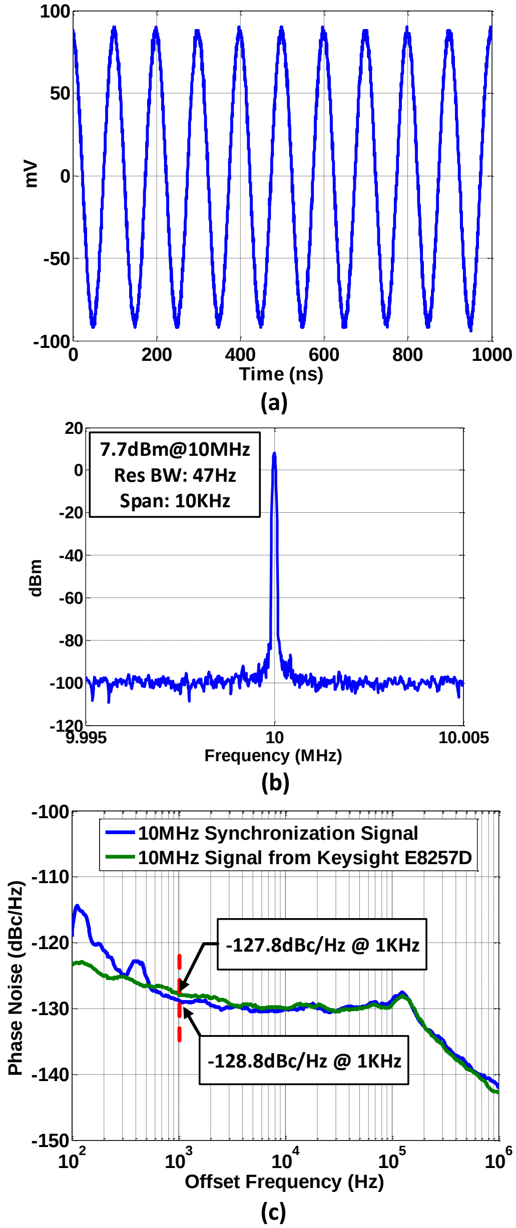


Fig. 8. (a) Measured time-domain waveform of the 10MHz synchronization signal. (b) Measured frequency spectrum of the 10MHz synchronization signal. (c) Measured phase noise of the 10MHz synchronization signal.

same time. Therefore, there is no need for long-term stability of the 10MHz synchronization signal. To measure the stability of the generated 10MHz signal, we have compared its phase noise with that of a state-of-the-art signal generator (Keysight 8257D) that uses an internal reference. This comparison is shown in Fig. 8(c).

In this work, two custom-designed silicon picosecond pulse radiators, [5], [9], are characterized using the measurement setup shown in Fig. 7. The RF signal generator (Keysight E8257D) provides a sinusoidal trigger signal to the silicon chips. The chips radiate picosecond pulses with the same repetition rate of the input trigger. Design details of chips are discussed in [5] and [9]. As discussed in section III B, the repetition rate of the picosecond pulses should be a harmonic of the sampling frequency (50MHz). In this work, the chips in [5] and [9] are tested using 1GHz and 5GHz sinusoidal trigger signals, respectively.

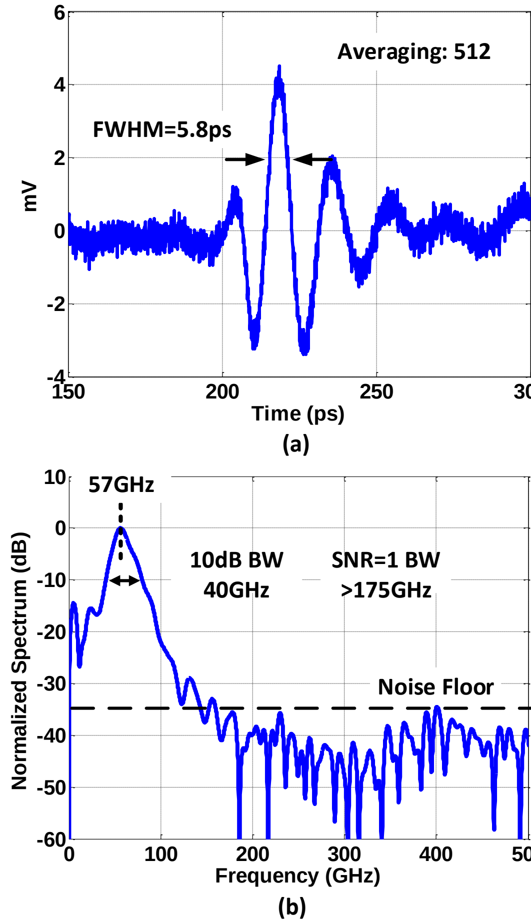


Fig. 9 (a) Measured time-domain waveform and (b) measured frequency spectrum of the picosecond pulse radiated from the chip [5].

Fig. 9 demonstrates the characterization results of the chip reported in [5]. The time-domain waveform of the captured pulse is shown in Fig. 9(a). This chip radiates pulses with a Full-Width-at-Half-Maximum (FWHM) of 5.8ps. In order to increase SNR, an averaging of 512 is used. The frequency spectrum of the picosecond pulse radiation is obtained by performing DFT on the recorded time-domain waveform (Fig. 9(b)). The 5.8ps pulse radiation has a peak frequency of 57GHz. Its 10dB bandwidth is 40GHz, and its SNR=1 bandwidth is more than 175GHz. Fig. 10 shows the characterization results of the chip reported in [9]. This chip consists of a 4×2 on-chip array of impulse radiators. In this experiment, the timing of radiation for each element is controlled using programmable delay generators to perform coherent spatial combining of impulses in space, by delaying the trigger of each radiating element. The measured combined time-domain signal is shown in Fig. 10(a), and an FWHM of 5.4ps is measured. In addition, by controlling the current switch bias node in the electronic chip [9], the amplitude of the radiation is modulated. Amplitude modulation results are plotted in Fig. 10(b).

Finally, a comparison between the proposed measurement technique and a conventional method that uses a

TABLE I
COMPARISON BETWEEN THE PROPOSED MEASUREMENT TECHNIQUE AND THE CONVENTIONAL METHOD BASED ON AN STATE-OF-THE-ART OSCILLOSCOPE

| | **Proposed Measurement Technique** | Conventional Methods |
|---|---|---|
| Sampling Method | **Optoelectronic sampling using a PCA detector** | Ultra-fast sampling using a real-time oscilloscope |
| Measurement Bandwidth | **4.5THz** | 100GHz [1] |
| Rise Time | **100fs [2]** | 3.5ps (20%-80%) [1] |
| Broadband Calibration Requirement | **PCA detectors** | Coaxial cables, connectors, sampler |
| Real-Time Sampling Rate | **50MS/s** | 240GS/s [1] |
| Effective Timing Step of Sampling | **2fs [3]** | 4ps |

[1] Based on the fastest commercial oscilloscope, Teledyne Technologies LabMaster 10 Zi-A High Bandwidth Modular Oscilloscopes 20GHz-100GHz [10].
[2] This is a typical number of a PCA detector, as discussed in section II A.
[3] This is estimated by calculating the difference between 1/50MHz and 1/50.000005MHz. In practice, this number is limited by the jitter of the measurement setup and the number of averaging used.

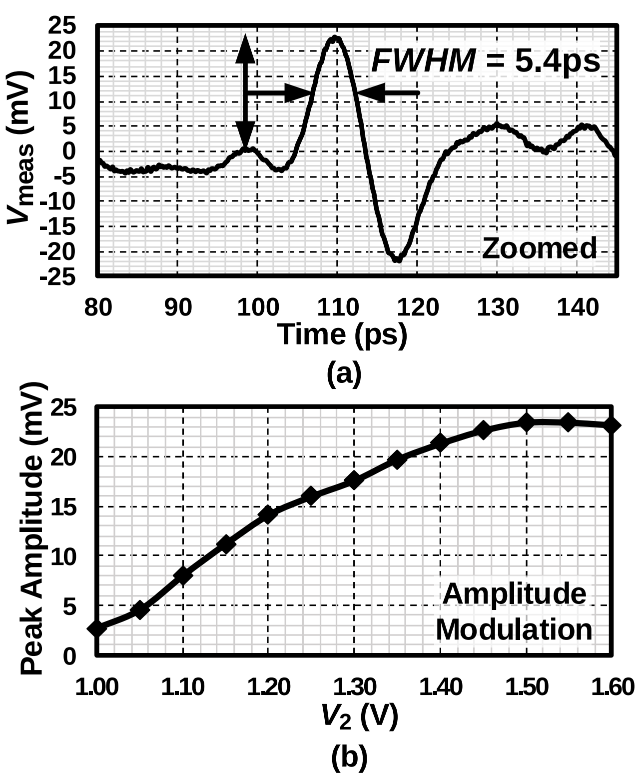


Fig. 10 (a) Measured time-domain waveform of the picosecond pulse radiated from the chip [9]. (b) Measured pulse amplitude modulation of the chip [9].

state-of-the-art off-the-shelf oscilloscope is summarized in Table 1.

## V. CONCLUSIONS

In this work, a novel optoelectronic measurement technique is demonstrated for characterizing picosecond pulses radiated from silicon chips. The method uses a PCA detector and is based on a pump-and-probe sampling scheme, which is provided by an Advantest THz-TDS system (TAS7500TS). The utilized PCA detector has an SNR=1 bandwidth up to 4THz, which is more than 40 times higher than that of the best off-the-shelf electronic oscilloscopes (100GHz). In addition, since the THz pulse is sampled at the PCA, there is no need for complex broadband calibrations of waveguides, coaxial cables and connectors used in conventional methods that are based on oscilloscopes. In the reported scheme, the radiated pulses from the silicon chips need to be synchronized with the pump laser of the THz-TDS system. Based on this scheme, two custom-designed silicon-based picosecond pulse radiators are characterized.

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