A THz Pulse-Radiating Array for Long-Range High-Speed Wireless Communication and Hyper-Spectral Imaging

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***Abstract*—This project report summarizes a novel THz pulse generation technique, Direct Digital-to-Impulse (D2I), that is capable of radiating a high-power picosecond pulse train with ultra-stable frequency tones (2 Hz at 1.1 THz). Unlike conventional THz pulse generation techniques, this radiator does not need an optical femtosecond laser, which is bulky, expensive and has a low repetition rate. Based on this architecture, a silicon-based single-chip radiating array is presented that can radiate picosecond pulses with a peak pulse EIRP of up to 1 W by coherently combining radiated pulses in space with a high timing-control accuracy. The reported array has been used to demonstrate gas spectroscopy and hyper-spectral imaging. In addition, an on-going project is focused on high-speed wireless communication using highly directive, beam-steerable pulse radiating arrays with amplitude modulation capability.**

***Index Terms*—Terahertz, picosecond pulse, on-chip antenna, single-chip array, hyper-spectral imaging, spectroscopy, THz communication.**

I. Introduction

Terahertz pulse generation and detection has attracted significant attention for sensing and communication over the past few years. Picosecond pulses can be used in rotational gas spectroscopy, hyper-spectral imaging, and Tbit/sec wireless communication. A THz pulse train translates into a broadband spectrum in frequency domain across mm-wave and THz regions, providing spectral information that can be used to produce hyper-spectral images. In addition, THz impulse-radiating arrays with a pulse-width of 2 ps and a repetition rate of 10 GHz can use amplitude modulation and time-interleaving to form Tb/s wireless links.

Conventionally, THz pulse generation is based on the excitation of a III-V photoconductive antenna (PCA) with a femtosecond laser pulse. This method of THz pulse generation and detection is widely used in THz time-domain spectroscopy (THz-TDS). Although THz-TDS is a powerful technique, it suffers from several limitations. First, it requires a femtosecond laser, which is not only bulky and expensive, but also has a low repetition rate (<100MHz), limiting the average radiated power. Second, to produce an image, the object must be mechanically scanned, significantly reducing the acquisition time. Finally, a sub-sampling scheme is used to capture the waveform, wherein a mechanical delay line shifts the laser pulse; this significantly reduces the measurement speed. These limitations compromise the accessibility and scalability of THz-TDS systems.

Recently, we introduced a laser-free, oscillator-less Direct Digital-to-Impulse (D2I) architecture, which overcomes the aforementioned limitations. This method converts a digital trigger edge to a radiated THz pulse with a high timing accuracy. We demonstrated that this method is capable of generating pulses with full width at half-maximum (FWHM) of 1.9 ps and peak EIRP of 19 dBm, radiating from a single radiator in a 130-nm SiGe BiCMOS process [1]. The radiated pulse train has a repetition rate of up to 10GHz and a peak radiating power of 2.6mW. In the frequency domain, the pulse train has a frequency-comb shape that is characterized up to 1.1 THz, with a spectral line width of 2 Hz at the 1.1 THz tone. It was shown that the starting time of the radiated pulse is locked to the edge of the input digital trigger with a timing accuracy greater than 270 fsec, when the trigger source has a jitter of 150 fs. Based on this high timing accuracy, a novel trigger-based beam-forming architecture is introduced that enables broadband pulse beam-steering in which all frequency content is steered simultaneously.

The rest of the report is organized as follows: Section II describes the D2I architecture. Section III focuses on the measurement results of the array as well as hyper-spectral imaging results. Section IV describes future plans of this project as well as my career plans and the impact of the MTT-S fellowship program on my decisions. I will also discuss the experience of attending IMS to receive this fellowship.

II. On-Chip THz Pulse Generation Architecture

In the D2I architecture, magnetic energy is accumulated by flowing a DC current through a broadband, phase-linear antenna, which acts as an inductor in low frequencies. This antenna is placed in sequence with a fast-current switch. By opening the switch, the DC current on the antenna is interrupted, converting the stored magnetic energy to a radiated impulse in the THz regime. In addition, an intermediate impulse-shaping network is designed to maximize the amplitude of the pulse and minimize ringing. The deep nonlinear switching mechanism results in numerous harmonics from GHz to THz. Having a high-power, broadband frequency-comb source is critical in imaging and spectroscopy applications. Fig. 1 shows the time and frequency domain measurement results of a single D2I radiator fabricated in a 130nm SiGe BiCMOS [1].

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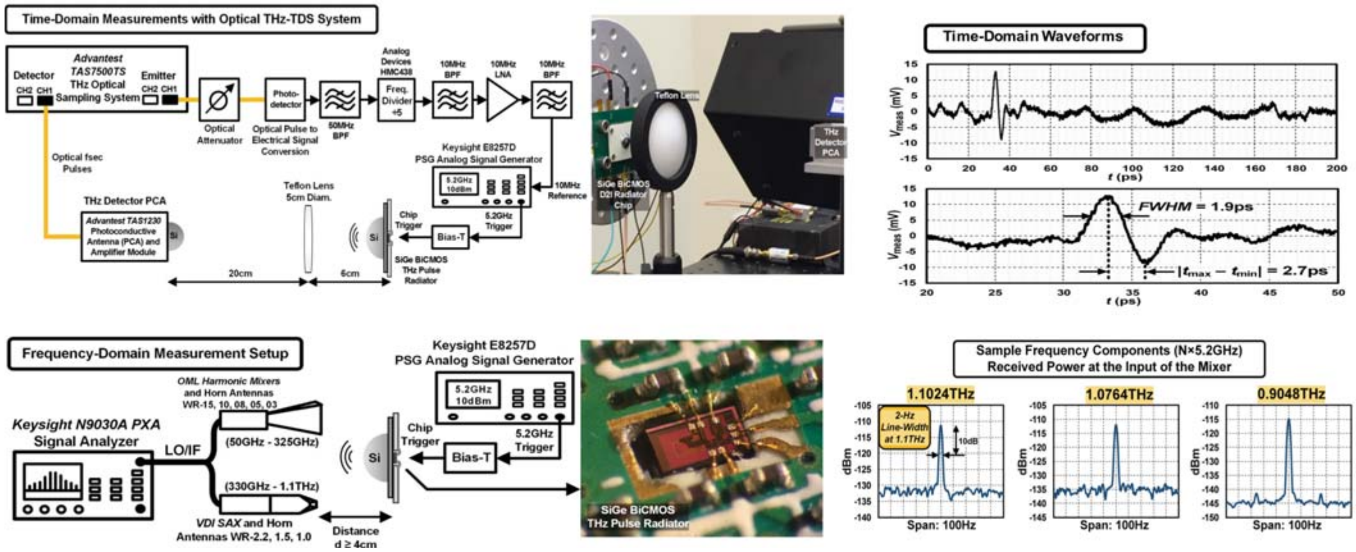

Fig. 1. Time-domain and frequency-domain measurement results of a single-element 1.9ps THz pulse radiator [1]

Time-domain results are obtained by using the fully electronic radiator in an optical THz-TDS system for the first time.

III. Array Measurement Results

Conventional phased-array architectures introduce the time delay required for each element in their signal path by using nonlinear varactor-based delay lines, which result in narrowband signal-dependent behavior and only work at a single frequency. In the D2I architecture, the information signal is stored at the location of the radiator. By delaying the trigger signal, the radiated pulse is delayed. Since the delay path is separated from the signal path (information path), the information content of the signal does not affect the generated delay. Since the time-domain waveform of the trigger signal is always constant and depends on the information signal, nonlinearity of the delay generator does not degrade the performance of the system. This method enables broadband delaying of the radiated signal with accuracy of close to 150 fsec [2], [3], which is limited by the timing jitter of the system.

A digitally programmable eight-element 0.03-1.03THz pulse radiating array in 90nm SiGe BiCMOS is presented in [3]. Fig. 2 summarizes the measurement results. A pulse-width of 5.4 ps is measured for the combined signal with a peak pulse EIRP of 1 W from eight on-chip radiators. This chip was used to demonstrate spectral imaging experiments, for which the results are also presented in Fig. 2.

IV. Career Plans, Fellowship Impact, and IMS Impressions

I intend to pursue a career in academia. With the microwave industry's growing interest in mm-wave and THz systems for communication and sensing, I believe academic research in these fields will need to prosper significantly in the next ten years to solve major challenges of high frequency systems. Numerous new design challenges are being added to the list of problems that circuit and antenna designers need to address, which requires stronger collaboration between academia and industry.

The IEEE MTT-S Graduate Fellowship had a significant impact on my decision to choose an academic career. In a smaller scale than as a professor, the funding support from this fellowship helped me practice how to propose and lead a project. In addition, the travel grant from IEEE MTT-S for attending IMS 2017 created the opportunity to gain further exposure on my project and to network with the most talented researchers in the field of integrated mm-wave and THz systems.

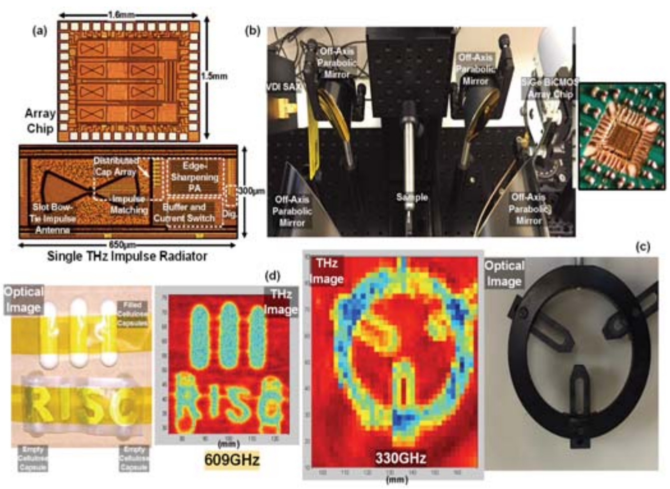

Fig. 2. Spectral imaging results based on a single-chip 4x2 THz pulse radiating array [3]

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