

# Integrated Millimeter-Wave and Terahertz Pulse Receivers for Wireless Time Transfer and Broadband Sensing

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**Abstract**—Millimeter-wave and terahertz systems based on ultra-short pulses have a broad range of applications in precision wireless time transfer, high-resolution 3D imaging, high-speed wireless communication, and broadband molecular spectroscopy. This report discusses the progress on developing fully integrated picosecond pulse receivers for high-precision wireless clock synchronization and broadband sensing. Wireless clock synchronization between widely spaced array elements is demonstrated with sub-ps accuracy using self-mixing and injection-locked pulse detectors. Finally, tunable frequency combs are exploited for high-resolution spectrum sensing over a broad frequency range.

**Index Terms**—Broadband, CMOS, frequency combs, impulse receivers, injection-locking, millimeter-wave, on-chip antennas, self-mixing, SiGe BiCMOS, wireless synchronization.

## I. INTRODUCTION

WIRELESS systems and integrated circuits in mm-wave and terahertz frequencies offer low-cost solutions for a variety of applications, such as imaging and spectroscopy. A picosecond-pulse-based system is a novel example of such systems that uses ultra-short pulses to communicate over a short period of time. The short pulse duration, which is transformed to a broad bandwidth in frequency domain, allows us to achieve higher depth resolutions in imaging radars. However, in order to achieve better angular resolutions, widely spaced arrays of pulse-radiating elements are required. Due to limitations on the size of silicon chips, wireless synchronization of multiple chips facilitates implementation of a large-aperture array. In this project, which was generously supported by the IEEE MTT-S Graduate Fellowship, self-mixing and injection-locked pulse detectors were investigated as solutions for wireless clock synchronization using picosecond pulses. In another part of this project, mm-wave frequency combs are used as a tool for broadband spectrum sensing with high resolution.

## II. MILLIMETER-WAVE PULSE RECEIVERS

In order to detect ultra-short picosecond pulses, a fully integrated receiver is required to detect the high-frequency tones of the pulse and generate a reference signal locked to the repetition rate of the incoming pulse train. An oscillator-free self-mixing impulse receiver was designed to detect picosecond pulses. This receiver is based on the idea that when

a frequency comb with a fixed repetition rate is passed through a non-linear block, such as a bipolar-junction transistor, self-mixing occurs among various frequency tones so the frequency of the mixer output becomes equal to the repetition rate. This receiver was implemented in a SiGe BiCMOS process and could successfully detect the amplitude and the repetition rate of picosecond pulses with a center frequency of 50 GHz [1]. In [2], we demonstrated that widely spaced chips can be wirelessly synchronized using low-jitter picosecond pulses and the resulting synchronized array can be used to increase the effective aperture size of an imaging array, and thus, enhance its angular resolution. Fig. 1 depicts a micrograph of this impulse detector and its measurements to demonstrate sub-ps wireless clock synchronization. In the setup, shown in Fig. 1(b), two receiver chips are placed more than 10 cm from each other. When only one chip is turned on, it recovers the repetition rate of the received pulses, as shown in Fig. 1(c). When both receivers are turned on (Fig. 1(d)), the combined output waveform shows low-jitter coherent combining of synchronized clocks. The mean measured jitter of this signal is 0.6 psec, which verifies the low-jitter wireless synchronization scheme when compared to the 0.35-psec jitter of the 50-GHz signal generator for the same amplitude.

A pulse-based injection-locking technique was introduced in [3] for detection of mm-wave picosecond pulses. In this receiver, shown in Fig. 2(b), a high-power tone near the center frequency of the pulse (80 GHz) is selected and amplified to injection-lock a chain of three cross-coupled oscillators at frequencies of 40, 20, and 10 GHz. Assuming the repetition rate of the pulse is within the locking range around 10 GHz, the receiver output will be locked to the received pulses with low jitter. This chip, which was fabricated in CMOS, consists of an on-chip slot planar inverted cone antenna, a low-noise amplifier centered at 80 GHz, and three stages of injection-locked frequency dividers to produce the synchronized repetition rate at the output. It is shown in Fig. 2(c) that the output of the receiver can be locked to the input repetition rate and the output phase noise improves significantly when it is exposed to radiated picosecond pulses (Fig. 2(d)). In [4], a wireless time transfer test using two impulse detector chips demonstrated that a low-jitter 9.5-GHz clock signal can be distributed among widely spaced nodes in a large-aperture array.

Another objective of this project was to use frequency combs in mm-wave and THz frequencies for high-resolution broadband sensing. Picosecond pulses used in [3] are locked to an external clock, e.g. a 5-GHz signal, which sets their

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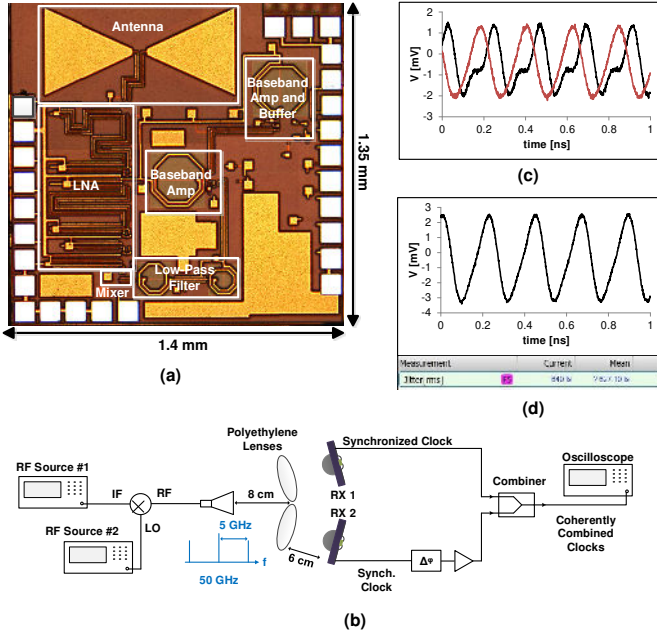


Fig. 1: (a) Self-mixing impulse detector implemented in a SiGe BiCMOS technology [1], (b) measurement setup to demonstrate high-precision wireless synchronization of widely spaced chips, (c) output waveforms of each individual receiver, and (d) coherently combined outputs of widely spaced receivers [2].

repetition rate. Therefore, the spacing between adjacent tones in their comb-shaped spectrum is equal to the same frequency. In [5], we showed that by tuning this comb spacing, received frequency components over a wide bandwidth can be detected with a resolution of 2 Hz. This high-resolution coherent detector can be used for broadband spectrum sensing and spectroscopy applications. We have also shown that picosecond pulses offer an excellent choice for rotational spectroscopy of gas molecules due to their large bandwidth and small linewidth. Frequency components of picosecond pulses in mm-wave/THz regime were used to detect absorptions of trace gases, such as hydrogen sulfide and ammonia [6].

### III. FELLOWSHIP IMPACTS AND CAREER PLANS

I am truly honored to receive the IEEE MTT-S Graduate Fellowship in 2018 and to be recognized as one of the top PhD students in the area of microwave engineering. This fellowship allowed me to complete my research project during the last stage of my doctoral studies. It also provided me with the opportunity to travel to 2018 IEEE International Microwave Symposium in Philadelphia and attend many intriguing sessions on the latest developments in microwave and millimeter-wave research. I had the opportunity to engage in helpful discussions with other researchers and discuss their work on mm-wave and THz systems.

Having identified and studied the challenges facing high frequency CMOS IC design throughout my doctoral research, I plan to pursue a career in academia as a postdoctoral researcher and ultimately as a professor. Developing circuits

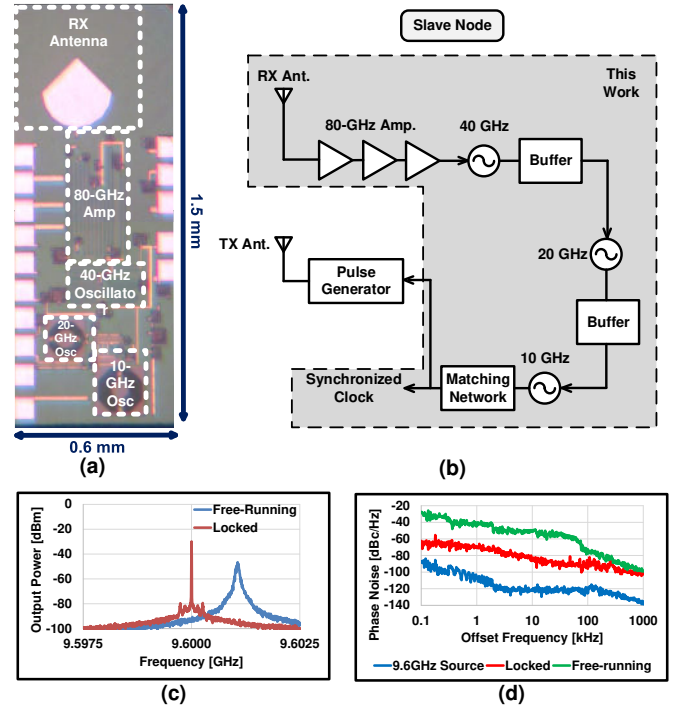


Fig. 2: (a) Injection-locked picosecond pulse detector implemented in a 65-nm CMOS technology, (b) the topology of the impulse detector, (c) measurement results of picosecond pulse detection, (d) phase noise improvement of the receiver output after locking to received picosecond pulses [3].

that can generate and detect signals beyond the  $f_{\max}$  of the transistors have continuously been one of the major challenges in the field of electronics. I intend to do research on developing THz radiators and coherent THz detectors which will be eventually be used in building Tb/sec wireless communication links and hyperspectral imaging radars. The MTT-S Graduate Fellowship was one of the factors influencing my career decision since it allowed me to engage in developing and implementing new ideas as the leader of a research project.

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