Picosecond Impulse Radiating Arrays in Silicon

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***Abstract*— In this work, two digital-to-impulse radiating chips are reported that produce and radiate electromagnetic impulses with duration of less than 10psec and repetition frequency of 10GHz. These chips are based on fully electronic methods; no laser is used. The first chip uses a single-ended slot-bowtie antenna with a current switch to radiate impulses with record pulse-width of 8psec and EIRP of 13dBm. The radiation of this chip is coupled to air through a silicon lens attached to the backside of the substrate. The second chip uses a differential slot-bowtie antenna with an active feed to radiate impulses with record pulse-width of 9psec and EIRP of 10dBm. Both chips are fabricated in a 130nm SiGe BiCMOS process technology.**

I. INTRODUCTION

THERE is a great interest in generating and radiating ultra-short impulses in mm-wave and THz regimes for applications in 3D imaging, spectroscopy, and high-speed wireless communication. One of the key parameters of an impulse generator is the shortest pulse width that it can produce. The pulse width limits the resolution in an imaging system, frequency-content in an spectromter, and data-rate in a pulse-based communication link. Recently, we implemented laser-free, fully-electronic, silicon-based impulse generators that produce and radiate impulses with record pulse-width of smaller than 10psec [1-2]. These results are based on direct time-domain measurements using a sampling oscilloscope. In addition to the time-domain measurements, the frequency spectrum of the impulse train is measured up to 220GHz. The radiated impulses can be locked to a digital trigger, with timing jitter of better than 270fsec. This low level of the timing jitter, combined with the direct digital-to-impulse architecture of the circuit, makes it possible to build a coherent sparse array of widely-spaced impulse-radiating chips that have a large effective aperture.

The chips are fabricated in a commerical silicon foundry and can be produced in large volumes with low cost. In the next few pages, the design and measurement results of these two chips are summarized.

II. A LENS-COUPLED, SINGLE-ENDED, DIGITAL-TO-IMPULSE RADIATOR WITH PULSE WIDTH OF 8PSEC AND EIRP OF 13DBM

The block diagram of this impulse radiator is shown in Fig. 1. A digital trigger signal with a rise time of 120psec is fed to the input of the chip. A series of digital buffers reduces the rise time of the signal to 30psec and then sends it to a power amplifier (PA) for further amplification. A broadband slot-bowtie antenna is designed to radiate ultra-short impulses. The on-chip antenna is connected to a switch. When the switch is tuned on, the antenna is energized by storing a DC current. When the switch is turned off by the PA, the current stored in the antenna radiates ultra-short impulses that are coherent with the digital trigger. Fig. 1 shows the schematic of the digital-to-impulse radiator. A transmission line based pulse-matching network is used to maximize the energy of each impulse, while minimizing its duration.

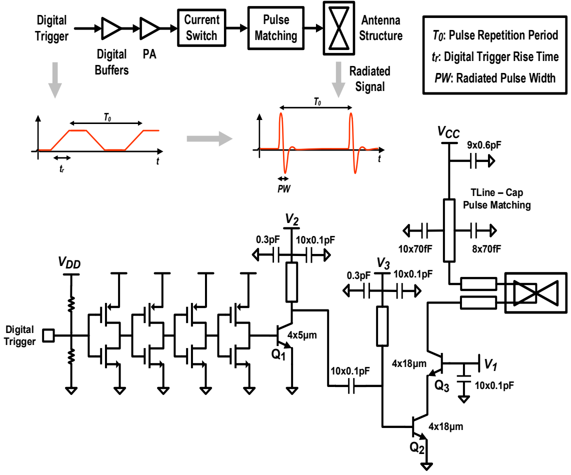


Fig. 1. Schematic of the single-ended, digital-to-impulse radiator.

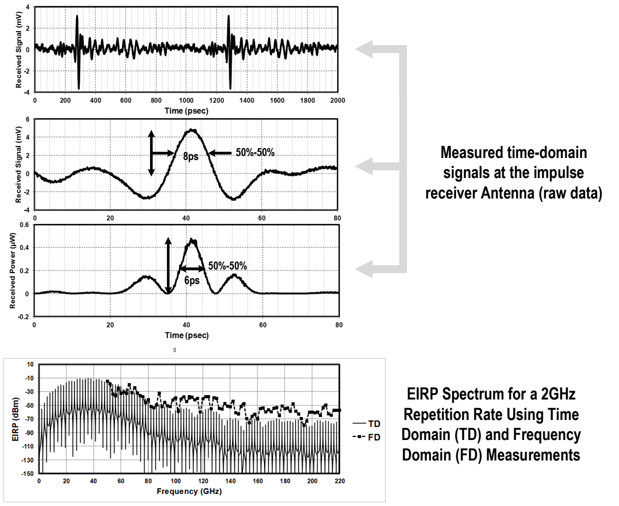
The impulse radiator can operate in two modes. In the first mode, a positive impulse is radiated that is locked to the rising edge of the input trigger. In the second mode, a negative impulse is radiated, which is locked to the falling edge of the input trigger. Depending on the biasing of node V_3, one or both of these modes can be activated. In addition, the amplitude of the radiated impulses can be modulated by the voltage at node V_2, as shown in Fig. 1.

Measurement Results− One of the main challenges of measuring a time-domain waveform of a short impulse is the receiver of the measurement setup. The receiving antenna must have a constant group delay to prevent signal distortion. In this work, a custom impulse antenna with flat gain and constant group delay is used as the receiver. This receiving impulse antenna is fabricated on a printed circuit board (PCB) and attached to a 1.85mm coaxial connector. Fig. 2 shows the measured time-domain signal of the impulse-radiating chip (raw data), where the PCB-based custom antenna is used as the receiver. In this measurement, the receiving antenna is directly connected to an Agilent 86118A sampling head. A mm-wave lens with a focal point of 60mm is used to focus the power to the PCB antenna. In order to calculate the peak EIRP, the mm-wave lens is removed from the setup, and the loss of the cable/connector (~4dB) is de-embedded. By using a center frequency of 50GHz in the Friis formula, a peak EIRP of 13dBm is calculated.

The time-domain radiation pattern of the impulse-radiating chip is measured. Fig. 2 shows the time-domain waveform as a function of angle in the E-plane of the antenna. In both E- and H- planes, it is confirmed that the waveform of the impulse is not distorted by changing the angle.

In addition to time-domain measurements, the frequency response of the impulse-radiating chip is measured using an

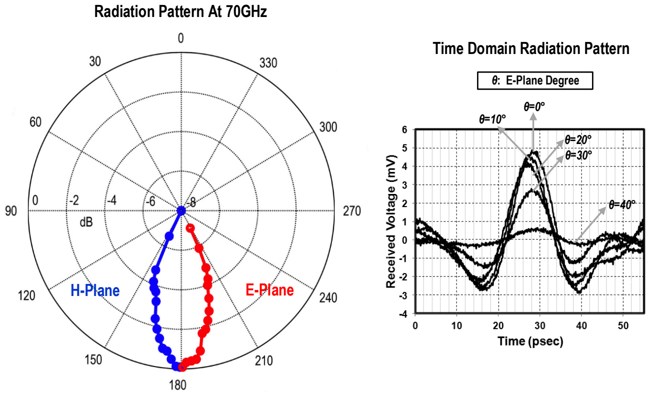
Agilent N9030A PXA signal analyzer, horn antennas, and OML harmonic mixers WR-15, WR-10, WR-08, and WR-05. The horn antennas and mixers cover the frequency range 50GHz to 220GHz. A distance of 370mm between the impulse radiating chip and the horn antenna is chosen. In this measurement no focusing lens is used. Fig. 2 shows the frequency-domain EIRP of the impulse radiator. In this measurement the loss of the mixer is de-embedded. The frequency spacing between the points in this diagram is equal to the repetition rate of 2GHz. The radiation pattern of the impulse-radiating chip at 70GHz is reported in Fig. 3.



Measured time-domain signals at the impulse receiver Antenna (raw data)

EIRP Spectrum for a 2GHz Repetition Rate Using Time Domain (TD) and Frequency Domain (FD) Measurements

Fig. 2. Measured time-domain waveforms by the sampling oscilloscope. Spectrum of the EIRP calculated with both TD and FD measurements.



Measured Directivity: 15dBi

Fig. 3. Radiation pattern of the impulse radiator in FD (left) and TD (right) measurements.

Coherent Combing in Space– The precision synchronization of the digital trigger with the radiated impulses makes it possible to build a coherent sparse array with widely-spaced antennas to increase the effective aperture size. To demonstrate a coherent array, the radiated impulses from two separate chips are combined in the far-field. The digital trigger signal of each chip is provided by Tektronix Arbitrary Waveform Generator AWG7000. The AWG generates two synchronized trigger signals that can be shifted with respect to each other with a resolution of 1ps. Fig. 4 shows the time-domain waveform of two impulse-radiating chips and their combined signal.

The timing jitter of the combined signal is calculated by an Agilent sampling oscilloscope 86100DCA, as shown in Fig. 5. An RMS jitter of 270fs is measured, with an averaging of 64. Averaging is used to reduce the noise of the Agilent 86118A sampling head. The measured RMS jitter for averaging of 256 and 512 is 220fs and 130fs, respectively. One of the unique features of the coherent impulse-radiating chip is the high spectral purity of the radiated impulses. Based on the measured spectrum, 99% of the power of the 220GHz tone is concentrated between frequencies 220,000,022,180Hz and 220,000,022,190Hz, which is a difference of only 10Hz (Fig. 5). This level of frequency stability is essential in performing high-resolution frequency-domain spectroscopy. This measurement is performed by an Agilent N9030A PXA signal analyzer and an OML harmonic mixer.

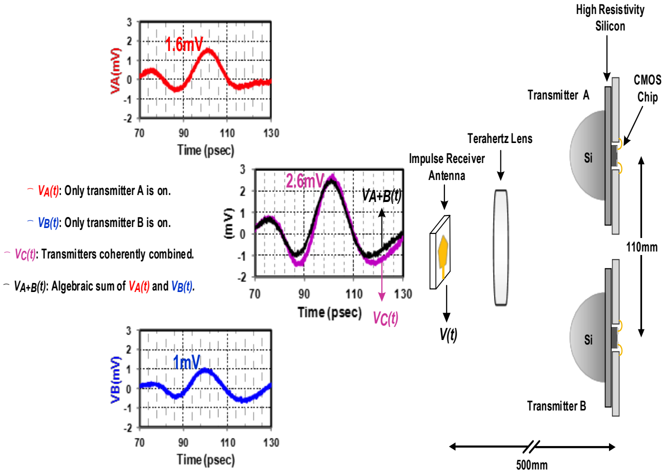


Fig. 4. Coherent combining of widely spaced impulse radiating chips, set-up, and measurement results.

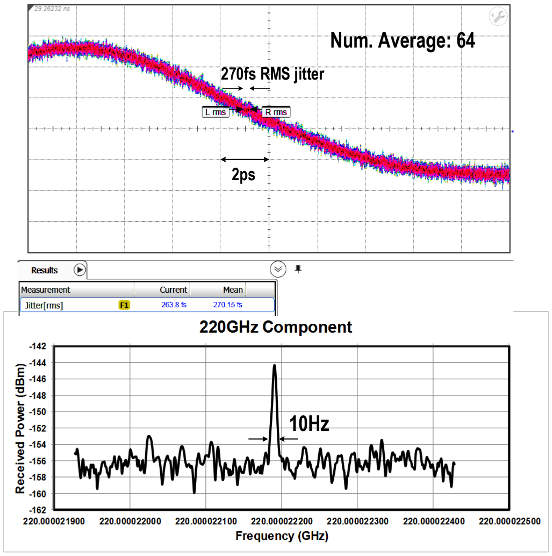


Fig. 5. Jitter of the coherently combined signal measured by a sampling oscilloscope (Top). The power spectrum around 220GHz measured by an spectrum analyzer. 99% of the 220GHz tone is confined in less than 10Hz frequency range (Bottom).

The chip was fabricated in a 130nm SiGe BiCMOS process technology with f_T=200GHz and f_{max}=270GHz. A micrograph of the chip is shown in Fig. 6. The size of the chip, including the on-chip antenna and the pads, is 0.55mm×0.85mm, and it has a maximum power consumption of 220mW.

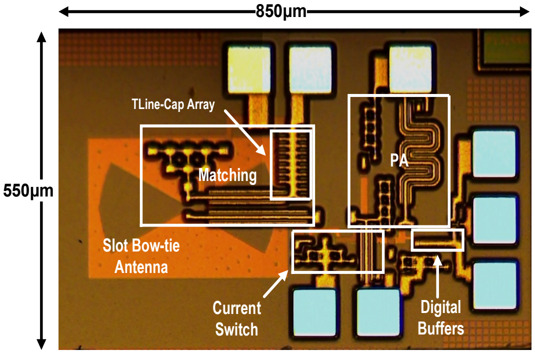


Fig. 6. Micrograph of the single-ended chip fabricated in 130nm SiGe BiCMOS process.

III. A Lens-Less Differential Radiator with Pulse Width of 9psec and EIRP of 10dBm

The schematic of the impulse radiator is shown in Fig. 7. A digital trigger signal with a rise time of 120psec is fed to the input of the chip. A series of digital buffers reduces the rise time of the signal to 30psec, and then sends it to an edge-sharpening amplifier. The output of the edge-sharpening amplifier controls the current source of a differential pair. The base voltages of the differential pair, nodes V_0 and V_1 in Fig. 7, are biased at different voltages. Due to this asymmetric bias, the pair generates a non-zero differential current when the edge-sharpening amplifier turns on the tail current source. This differential step current feeds a transmission-line-based matching network and an on-chip impulse antenna. The antenna radiates high-frequency components of the step current. A combination of series and parallel transmission lines are designed to provide broadband matching and maximize the energy of each impulse, while minimizing its duration. One of the unique features of this design is that voltages V_0 and V_1 in Fig. 7 can control the amplitude and sign of the radiated impulse. For $V_0 > V_1$, a positive impulse is radiated while for $V_1 > V_0$, a negative impulse is radiated. The amplitude of the impulse is also set by the difference between V_0 and V_1.

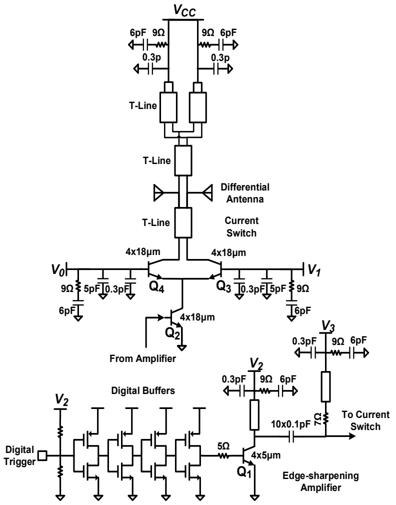


Fig.7. The circuit schematic of the lens-less differential impulse radiator.

Fig. 8 shows the measured time-domain signal of the impulse-radiating chip (raw data), where the PCB-based antenna is used as the receiver. In this measurement, the receiving antenna is directly connected to an Agilent 86118A sampling head and a mm-wave lens with focal point of 60mm is used to focus the power onto the PCB antenna. In order to calculate the peak EIRP, the mm-wave lens is removed from the setup and the loss of the cable/connector (~4dB) is de-embedded. By using a center frequency of 50GHz in the Friis formula, a peak EIRP of 10dBm is calculated. The frequency response of the impulse-radiating chip is also measured using an Agilent N9030A PXA signal analyzer, horn antennas, and OML harmonic mixers. Fig. 9-left shows the H-plane and E-plane radiation patterns at 70GHz. The measured directivity of the antenna at this frequency is 8dBi. Fig. 9-right shows the chip micrograph. The size of the impulse transmitter chip, including the on-chip antennas and the pads, is 0.8mm×1.1mm. It consumes a maximum power of 260mW. The chip is implemented in a 130nm SiGe process technology.

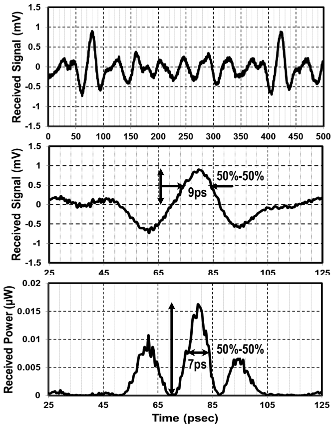


Fig. 8. Measured time-domain waveforms by the oscilloscope (raw data).

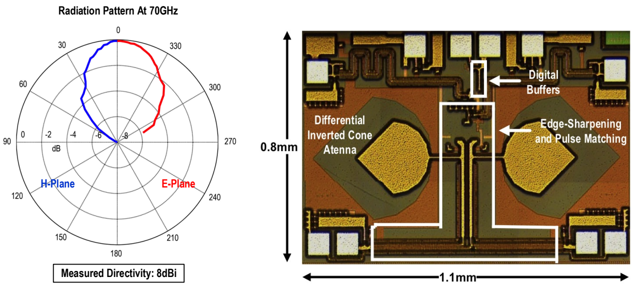


Fig. 9. The Radiation pattern (Left) and chip micrograph (Right).

IV. Conclusions

In this article, the circuit architecture of two impulse-radiating chips is presented and the measurement results are reported. These two chips represent the first picosecond impulse radiators that are based on fully-electronic methods.

References

[1]. M. Assefzadeh and A. Babakhani, "An 8-psec 13dBm Peak EIRP Digital-to-Impulse Radiator with an On-chip Slot Bow-Tie Antenna in Silicon," *IEEE MTT-S Int. Microwave Symposium*, pp. 1-4, Tampa, USA, Jun. 1-3, 2014.

[2]. M. Assefzadeh and A. Babakhani, "A 9-psec Differential Lens-Less Digital-to-Impulse Radiator with 150-fs-Resolution Delay Line in Silicon," *IEEE RFIC Symp. Dig. Papers*, Tampa, USA, Jun. 1-6, 2014.