

A 9-psec Differential Lens-Less Digital-to-Impulse Radiator with A Programmable Delay Line in Silicon

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Abstract — In this paper, a lens-less digital-to-impulse radiator is implemented that radiates impulses with EIRP of 10dBm and a record pulse-width of shorter than 9psec using an on-chip differential inverted cone antenna. It is shown that the starting time of the radiated impulses can be locked to the edge of the input trigger with high timing accuracy. A digitally programmable delay line is implemented and used at the input of the radiator. The delay line has a resolution step of 150fs and a dynamic range of 400ps. It is shown that by programming the delay line, the starting time of the radiated impulses in the air can be controlled.

Index Terms — On-chip Antenna, Inverted Cone Antenna, Picosecond Impulse Radiation, Direct Digital-to-Impulse Transmitter, Digital Delay Line, Differential Inverted Cone Antenna, SiGe, BiCMOS, SOI CMOS.

I. INTRODUCTION

During the last decade, the performance of impulse radars has been greatly improved. These radars can be used for motion sensing, gesture detection, localization, and imaging. One of the key parameters of an impulse radar is the shortest pulse width that it can generate. The pulse width determines the depth resolution of an imaging radar. Recently, silicon-based transmitters with on-chip antennas have been reported that radiate signals in the mm-wave and sub-mm-wave regimes [1-2]. In [1], a 260GHz continuous-wave (CW) source was modulated to achieve a pulse width of 45psec. The calculated 45psec was based on frequency spectrum and no time-domain waveform was reported. The work in [1] did not offer any solution for locking the phase of the radiated signal to an external reference. In [2], the authors reported a 26psec pulse-width with 33% bandwidth based on a noisy envelope of an RF signal that was not locked to the sampling oscilloscope. Due to the non-coherent method of the measurement, the actual time-domain waveform of the 26psec pulse was not observable.

In contrast with the prior art [1-2], where a CW voltage-controlled oscillator is modulated to generate short pulses, in this work, no oscillator is used. Instead, a direct digital-to-impulse radiator is implemented that integrates a pulse-shaping circuitry and an on-chip impulse antenna. The antenna has a shape of inverted cone [3] and radiates impulses with a duration of 9psec, peak Effective Isotropic Radiate Power (EIRP) of 10dBm, and a repetition rate up of more than 10GHz. The input of this chip is a simple

digital trigger. The radiated impulses can be locked to the digital trigger with timing jitter of better than 320fsec. This low level of 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 chips that has an effective aperture that is larger than the size of each individual on-chip antenna by several orders of magnitude. A large aperture is essential in generating images with high angular resolution.

In addition to the impulse-radiating chip, a digitally programmable delay line with resolution of 150fs and dynamic range of 400ps is implemented. The delay line is placed between the trigger signal and the impulse radiator. It is used to shift the trigger signal with fine timing steps. The combined impulse radiator and the delay line are used to generate and radiate 9psec impulses and control the starting time of each impulse with a resolution of 150fsec. These results are based on direct time-domain measurements using a sampling oscilloscope.

II. CIRCUIT ARCHITECTURE

The schematic of the 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 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. 1, 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 a broadband matching and maximize the energy of each impulse while minimizing its duration. Fig. 2 shows the effect of the pulse-matching network.

One of the unique features of this design is that voltages V_0 and V_1 in Fig. 1 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 .

A distributed network of bypass capacitors is used at the biasing points to ensure fast delivery of electrical charges to the base node of transistors Q_3 and Q_4 . A differential pair of antennas is implemented using the top metal layer (M7). The matching transmission lines are fabricated using metal layers M6 and M7. The thickness of the silicon chip is $150\mu\text{m}$ and its backside is grounded.

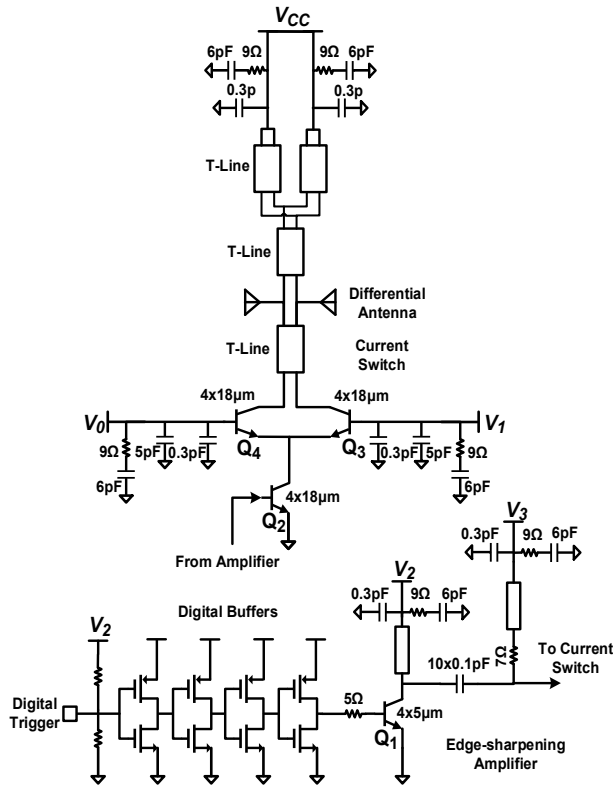


Fig. 1. The circuit schematic of the impulse transmitter.

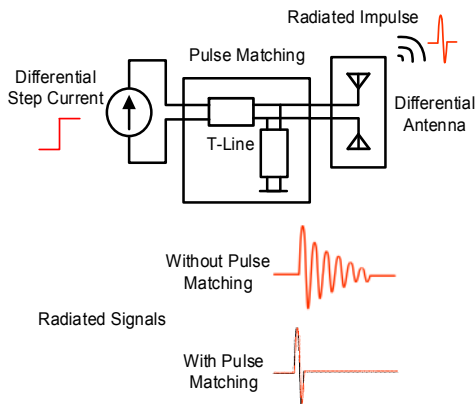


Fig. 2. A broadband impedance matching network.

III. MEASUREMENT RESULTS

One of the main challenges in 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. Although horn antennas were used in the past [2], due to the non-constant group delay of the horn antenna the received pulse becomes distorted. 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), which has a dielectric constant of 2.4. After comparing the time domain signal received by the custom receiving antenna and the horn antennas, it is confirmed that horn antennas should not be used to measure ultra-short impulses. Horn antennas are only used to extract the frequency spectrum of the impulse train. Fig. 3 shows the measured time-domain signal of the impulse-radiating chip (raw data), where the PCB-based antenna is used as the receiver.

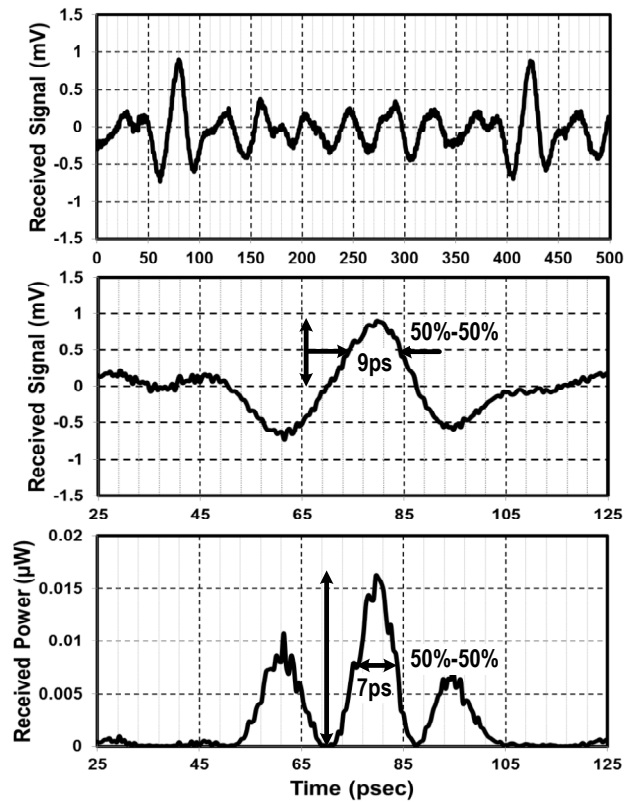


Fig. 3. Measured time-domain waveforms by the sampling oscilloscope (raw data).

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.

In order to control the timing of the radiated impulses, a digitally controlled delay line chip is used at the input of the impulse radiator. The external digital trigger is fed to the input of the delay line and its output is used to trigger the radiator. Fig. 4 shows the measurement setup.

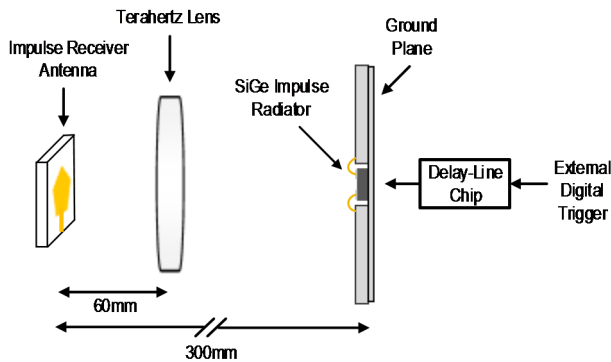


Fig. 4. Measurement set-up.

By changing the input delay, the timing of the radiated impulse is controlled. A dynamic range of 400ps, with fine resolution steps of 150fs, is measured. Fig. 5 shows zoomed time-domain radiated signals generated by two different delay values. The difference between these two delay values is 150fs. Averaging is used to reduce the timing jitter and noise of the oscilloscope.

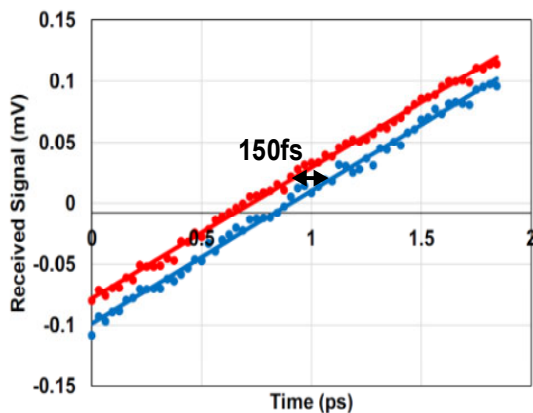


Fig. 5. Two radiated impulses delayed by 150fs.

The timing jitter of the signal is calculated by an Agilent sampling oscilloscope 86100DCA as shown in Fig. 6. An RMS jitter of 320fs is measured with an averaging of 64.

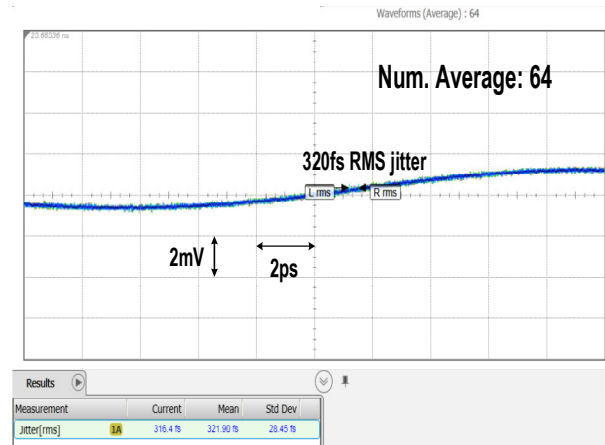


Fig. 6. Timing jitter of the received signal.

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. 7 shows the H-plane and E-plane radiation patterns at 70GHz. The measured directivity of the antenna at this frequency is 8dBi.

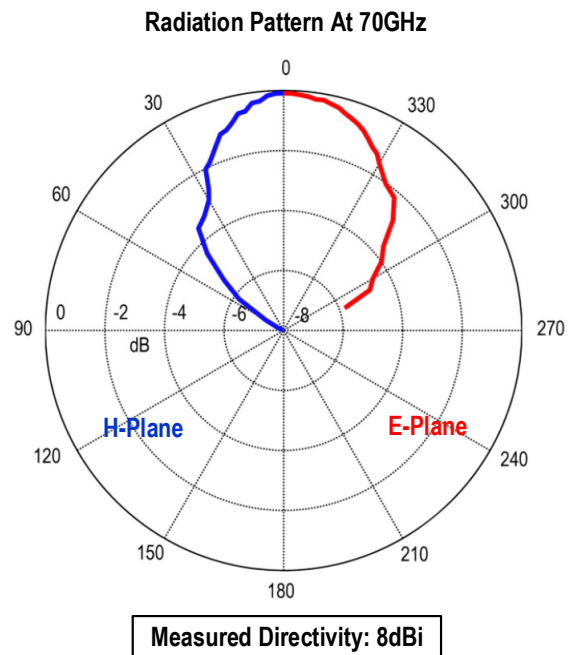


Fig. 7. Radiation pattern of the impulse transmitter.

TABLE I
COMPARISON TABLE

	This Work	[1] ISSCC 2013	[2] JSSC 2013
Shortest Radiated Pulse (psec)	9 (50%-50%)	45	26 (50%-50%)
Peak EIRP (dBm)	10	15.7	13
Phase Synchronization with an External Reference	Yes	No	Yes
Time-domain Measurements	Yes (with locking)	N/A	Yes (without locking)
Frequency-domain Measurements	Yes	Yes	Yes
Pulse Generation Method	Digital-to-Impulse	Oscillator-based	Oscillator-based
Power Consumption (mW)	260	800	580
Technology	0.13 μ m SiGe BiCMOS	65nm CMOS	0.13 μ m SiGe BiCMOS
Die Area (mm ²)	0.88	2.25	6.16

Table I compares the specifications of the reported chip with the prior art. To the best of Authors' knowledge, this is the first impulse radiator with the ability to generate sub-9psec impulses with delay resolution of 150fs. The reported digital-to-impulse radiating chip was fabricated in a 130nm SiGe BiCMOS process technology with $f_T=200$ GHz and $f_{max}=270$ GHz. The programmable delay line is fabricated in a 45nm SOI CMOS process technology. Micrographs of the chips are shown in Fig. 8. The size of the impulse transmitter chip including the on-chip antennas and the pads is 0.8mm \times 1.1mm and the size of the delay line is 0.5mm \times 1.9mm.

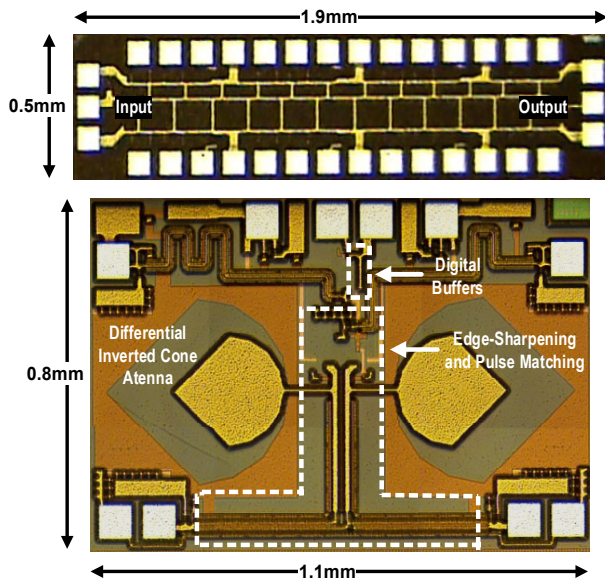


Fig. 8. Micrographs of the chips.

ACKNOWLEDGEMENT

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REFERENCES

- [1] R. Han and E. Afshari, "A 260GHz broadband source with 1.1mW continuous-wave radiated power and EIRP of 15.7dBm in 65nm CMOS," *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2013 IEEE International*, pp.138,139, 17-21 Feb. 2013.
- [2] A. Arbabian, S. Callender, S. Kang, M. Rangwala, and A.M. Niknejad, "A 94 GHz mm-Wave-to-Baseband Pulsed-Radar Transceiver with Applications in Imaging and Gesture Recognition," *Solid-State Circuits, IEEE Journal of*, vol.48, no.4, pp.1055,1071, April 2013.
- [3] S. Cheng, P. Hallbjorner, and A. Rydberg, "Printed Slot Planar Inverted Cone Antenna for Ultrawideband Applications," *Antennas and Wireless Propagation Letters, IEEE*, vol.7, no., pp.18,21, 2008.