Broadband 0.03-1.03THz Spectroscopic Imaging based on a Fully-Integrated 4×2 Digital-to-Impulse Radiating Array in Silicon

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Abstract

This paper presents a broadband THz frequency-comb spectroscopic imager based on a fully-integrated 4×2 picosecond Direct Digital-to-Impulse (D2I) radiating array. By employing a novel trigger-based beamforming architecture, the chip performs coherent spatial combining of broadband radiated pulses achieving an SNR>1 BW of 1.03THz (at the receiver) with a pulse peak EIRP of 30dBm. Time-domain radiation is characterized using a fsec-laser-based THz sampler and a pulse width of 5.4ps is measured. Spectroscopic imaging of metal, plastic, and cellulose capsules (empty and filled) are demonstrated. This chip achieves signal generation with an available full-spectrum of 0.03-1.03THz. The 8-element single-chip array is fabricated in a 90nm SiGe BiCMOS process.

Keywords: THz, Spectroscopy, Spectroscopic Imaging, Direct Digital-to-Impulse (D2I), On-Chip Antenna, BiCMOS, SiGe.

Introduction

During the past few years, there has been a growing interest in picosecond pulse generation and radiation in silicon [1-4]. These pulse radiators can be used for 3D imaging, broadband THz time-domain spectroscopy (THz-TDS), and Tbit/sec wireless communication. Conventionally, pulse generation methods in silicon employ fast switches to modulate the amplitude of a continuous-wave (CW) signal and turn it to a radiated pulse. The smallest pulse width generated with this method is limited to 26psec with a limited instantaneous bandwidth [1]. In 2014, the method of Direct Digital-to-Impulse (D2I) was introduced that generates and radiates ultra-short pulses with a pulse width of smaller than 8ps [3]. Unlike oscillator-based pulse techniques, this method does not employ any oscillators. Instead, a circulating current stores a DC magnetic energy in an on-chip slot bow-tie antenna. After this step, the current is disconnected by a fast bipolar cascode switch and the stored energy is transferred into impulse radiation. An intermediate broadband matching network minimizes the pulse width, reduces ringing, and maximizes the peak power of the radiated pulse. In D2I, a digital input trigger signal with a rise time of 150ps passes through digital buffers, that reduce the rise time to 30ps, and a delay generator that controls the timing of the edge. Next, an edge-sharpening amplifier amplifies the signal and further sharpens the edge of the trigger to less than 10ps by employing inductive peaking. This fast edge is fed to a current switch that disconnects the stored circulating current of the antenna. A cascode design is chosen to mitigate the Miller effect and to enhance bandwidth of the current step. By disconnecting the current, the DC magnetic energy stored in the impulse antenna is radiated in the form of an ultra-short picosecond impulse.

In this paper, broadband THz spectroscopic imaging is demonstrated based on a single-chip 4×2 D2I array. Each array element is equipped with a programmable delay line that controls individual timing of radiation to perform coherent spatial combining of broadband impulses from all elements. The 8-element array achieves a record peak pulse EIRP of 30dBm (1W) due to its near ideal spatial combining. The chip radiates broadband signals with SNR>1 bandwidth of higher than 1THz. The measured SNR at the receiver is 1dB at 1.032THz, 10dB at 0.927THz, and 28dB at 0.75THz. The full-spectrum frequency-comb radiated from the array is used to demonstrate THz imaging using Off-Axis Parabolic Mirrors (OAPM) to focus the beam into a spot size smaller than 1mm. The high SNR at the receiver enables fast scanning of the imaged sample with a few number of averaging.

4×2 D2I Array

The circuit architecture of the THz impulse radiating array is shown in Fig. 1. A low-power 150-ps rise-time digital trigger is fed to the input of the chip and is passed through a cascaded series of inverter stages that control the timing of the digital signal based on the change in their supply voltage. The delay elements have a step resolution of 300fsec and a dynamic range of 95ps. At this stage, the signal reaches a rise time of smaller than 30ps, and is fed to the input of an edge-sharpening amplifier that amplifies the signal, and with inductive peaking, reduces the rise time to less than 6ps. The resulting high power signal disconnects the stored DC current in each slot bow-tie antenna by switching a cascode pair of transistors and causes radiation of an impulse with a Full Width at Half Maximum (FWHM) of 5.4ps, locked to the edge of the input trigger. A distributed array of transmission line-capacitors is used at the output node to ensure fast charge delivery at the time of switching. The design parameters of this network are optimized to provide a near-ideal supply voltage for the impulse radiator. Fig. 1 also illustrates the physical mechanism of impulse radiation in the D2I architecture and how the spatially-confined stored magnetic energy enables building massive dense arrays of D2I radiators.

Impulse radiation from the array chip is characterized in both time and frequency domains (Fig. 2). In time-domain measurements, an Advantest TAS7500TS laser-based THz sampling system is used to capture the radiated signal from the chip. The time-domain waveform of the combined signal from

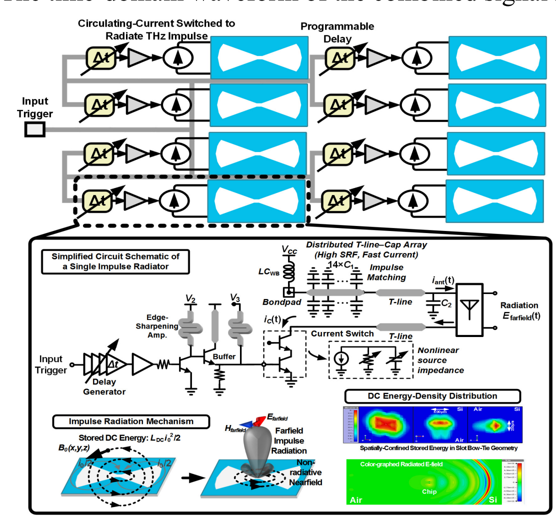

Fig. 1. Architecture of the 4x2 D2I radiating array

TABLE I

COMPARISON TABLE

Performance	This work	[1] JSSC 2013	[2] IMS 2015	[3] IMS 2014	[4] RFIC 2014
Highest Frequency Measured with SNR>1	**1.032THz**	110GHz	214GHz	220GHz	N/A
Shortest Radiated Pulse Width	**5.4ps**	26ps	2.6ps*	8ps	9ps
Peak EIRP (dBm)	**30**	13	-3.4	13	10
Time-Domain Measurement	**Yes (with locking)****	Yes (w/o locking)	No	Yes (with locking)	Yes (with locking)
Frequency-Domain Measurements	**Yes**	Yes	Yes	Yes	No
Pulse Generation Method	**Digital-to-Impulse**	Oscillator-based	Oscillator-based	Digital-to-Impulse	Digital-to-Impulse
Power Consumption (mW)	**710**	580	N/A	220	260
Die Area (mm²)	**2.4**	6.16	2.5	0.47	0.88
Technology	**90nm SiGe BiCMOS**	130nm SiGe BiCMOS	65nm CMOS	130nm SiGe BiCMOS	130nm SiGe BiCMOS

** Simulated result, not a true time-domain measurement, only two tones used*

8 elements is shown in Fig. 2. The time-domain impulse achieves a FWHM of 5.4ps in this measurement. In addition, a Keysight N9030A signal analyzer with VDI SAX WR-2.2, 1.5, 1.0 harmonic mixers as well as OML WR-15, 10, 08, 05, 03 are used to receive the frequency tones of the radiation up to 1.1THz. A horn antenna couples the received radiation to the waveguide input of the mixer of each frequency band. Fig. 2 also shows the average EIRP spectrum of the chip that is calculated by the Friis formula at each frequency tone. It should be noted that the EIRP spectrum measured is for an impulse train with a repetition rate of 3GHz, in which an impulse only exists for few picoseconds and the numbers reported are average values over the whole period. A SNR>1 BW of 1.03THz is measured. The radiation patterns of the array chip are measured at 0.33THz, 0.57THz, and 0.75THz (Fig. 3). Highly-directive radiation is achieved by employing a novel trigger-based beamforming architecture, in which only by delaying a trigger signal, near-ideal spatial combining of broadband pulses is performed.

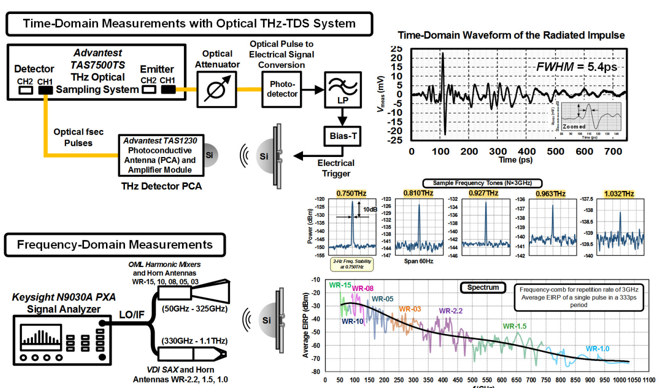

Fig. 2. Time-domain and frequency-domain measurements

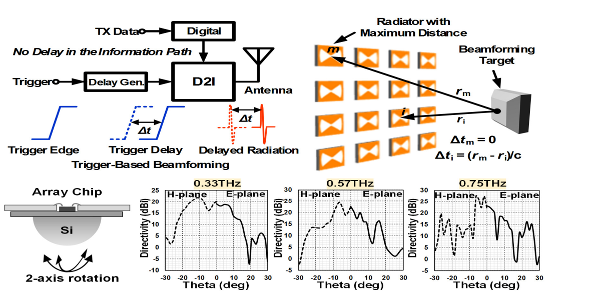

Fig. 3. Trigger-based broadband beamforming (top) Radiation pattern measurement results (bottom)

Terahertz Spectroscopic Imaging

The broadband highly-dense spectrum of the impulse radiating array enables producing high resolution images with spectral information of more than 1THz. As shown in Fig. 4, a THz transmission imaging setup is built using four Off-Axis Parabolic Mirrors (OAPM). The center of radiation of the chip is aligned at the focal point of the first OAPM, hence the radiated beam is collimated and then focused by the second OAPM into a focal point with a spot size of less than 1mm (for frequencies higher than 330GHz). The imaged object is placed and scanned by the focal point. On the receiver side, a third OAPM collimates the transmitted beam and a fourth OAPM focuses the beam on the receiver horn antenna. The dense frequency-comb nature of an impulse train spectrum allows multi-color full-spectrum imaging of samples. Fig. 4 shows sample THz images acquired at 330GHz and 609GHz from different samples.

Table I compares the performance of the chip with prior work. Fig. 4 shows the die micrograph of the array and the on-chip building blocks. The 4×2 array chip size is 1.6mm × 1.5mm while a single element only occupies 300um × 650um. The chip is fabricated in a 90nm SiGe BiCMOS process technology.

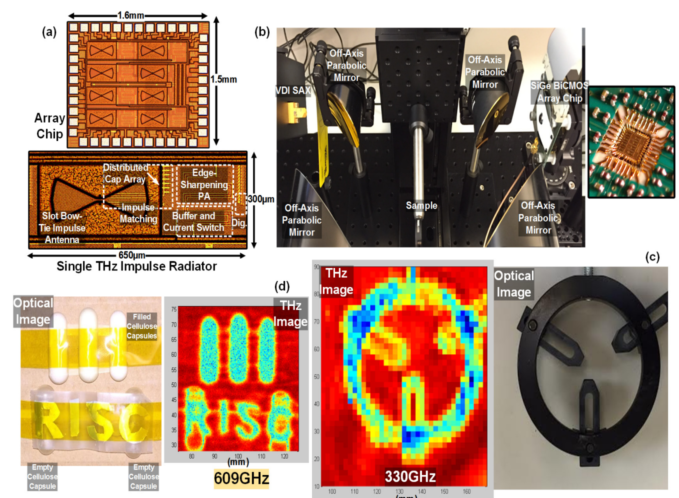

Fig. 4. (a) Chip micrograph (b) Imaging setup (c) 330GHz image of a plastic-metallic sample object (d) 609GHz image of filled and empty cellulose capsules

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