Broadband Beamforming of Terahertz Pulses with a Single-Chip 4×2 Array in Silicon

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***Abstract*—In this paper, a single-chip impulse antenna array is presented that performs spatial combining of picosecond impulses radiated from 8 elements. A new broadband beamforming architecture is introduced that controls the timing of impulses radiated from each antenna by delaying a trigger signal, with resolution steps of 300fsec. This method eliminates the distortive and narrowband effects of delay blocks in conventional phased arrays by separating the delay path from the information path. Frequency domain measurements are performed up to 1.03THz and array directivities of 22dBi at 0.33THz, 25dBi at 0.57THz, and 27dBi at 0.75THz are achieved. The 8-element array is fabricated in a 90nm Silicon Germanium BiCMOS process technology.**

Keywords—On-chip Antennas; Terahertz Arrays; Coherent Spatial Combining; Beamforming; Slot Bow-Tie; Silicon; SiGe

I. Introduction

Current terahertz time-domain spectroscopy (THz-TDS) systems are based on femtosecond lasers and photoconductive antennas (PCA) fabricated on a III-V substrate. In conventional THz-TDS, an emitter PCA, which is biased with a DC voltage, radiates a picosecond impulse when exposed to a high-power fsec optical pulse. These systems can perform broadband THz spectroscopy, which has applications in gas sensing, security screening, and tablet quality control in the pharmaceutical industry. These conventional THz-TDS systems have several limitations, such as the need for an expensive and bulky fsec laser, high power consumption, and low repetition rate of the laser. They also require mechanical scanning of the object to be imaged. To overcome these problems, a fully-electronic, laser-free, THz pulse radiator is required.

Recent advancements in CMOS and BiCMOS technology processes have improved the f_T and f_{max} of transistors and resulted in successful demonstration of single chip mm-wave phased arrays. Unfortunately, the bandwidth of the phased arrays reported in silicon is small, due to the low bandwidth of on-chip radiating elements and narrowband nature of the phase-shifting techniques used in these designs. Recently, a direct Digital-to-Impulse (D2I) technique was introduced that is capable of radiating high-power picosecond impulses in silicon [1]. The timing of the radiated impulses is locked to the edge of an input trigger signal that has high timing accuracy. This highly-scalable and power-efficient architecture can be used to build coherent arrays of broadband terahertz radiators with near ideal spatial combining.

This paper reports a single-chip 4×2 slot bow-tie impulse antenna array in silicon for coherent radiation of terahertz pulses with an SNR>1 bandwidth of 1.03THz. This work introduces a trigger-based beamforming technique for the first time. This technique enables broadband beamforming by excluding any delay or phase-shifting from the signal (information) path. This is achieved by introducing a programmable delay in a separate trigger path. The input trigger signal controls the starting time of the terahertz pulse radiation with resolution of 300fsec at the location of each element. The entire terahertz array with 8 elements is implemented on a single silicon chip, which occupies 1.6mm × 1.5mm. The circuit details of the signal generation and delay blocks are discussed in [2]. This paper focuses on the antenna aspects of the design, as well as the architecture of the broadband THz array.

The paper is organized as follows. Section II focuses on the design details of a single element and the challenges of the broadband pulse radiation using on-chip antennas. Section III introduces the method of trigger-based beamforming and reports the measurement results. Section IV concludes the paper.

II. Design of a Single Element

The signal generation and radiation mechanism in a D2I architecture is shown in Fig. 1. The method of impulse radiation begins with storing DC magnetic energy in an antenna structure through a circulating current. Subsequently, by disconnecting the stored current using a fast bipolar switch through a broadband impulse-matching network, an ultra-short impulse is radiated. The impulse antenna requires a broadband flat gain and a linear phase, i.e., a constant group delay. Fig. 1 also shows the stored magnetic energy in the slot bow-tie antenna and the radiated E-field.

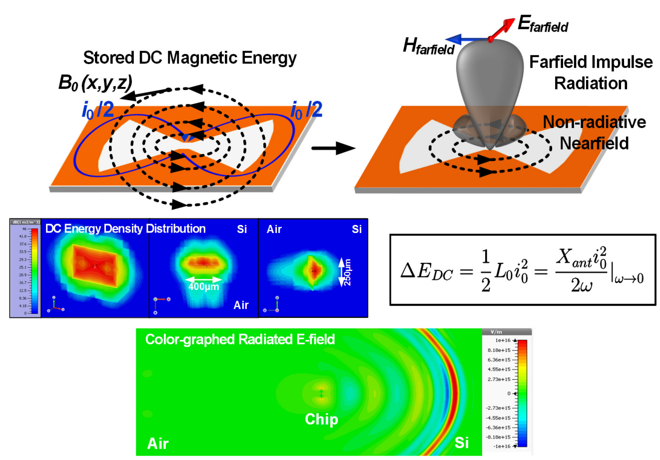

Fig. 1. Physical mechanism of impulse radiation in D2I, DC magnetic energy density distribution, and color-graphed radiated E-field

Unlike a narrowband on-chip antenna in silicon, in the design of an integrated impulse antenna, a ground plane must be avoided due to the issues caused by the image antenna. In this design, a hemispherical high-resistivity silicon lens is placed under the silicon chip to minimize the substrate modes and phase-nonlinearity of the planar substrate [3].

Fig. 2 shows the designed slot bow-tie impulse antenna with its feeds and substrate. The corners of the two triangles in the slot bow-tie are curved to improve the impulse response. A distributed array of high-frequency capacitors is used along the transmission line feed of the antenna to achieve broadband termination. Two transmission lines carry the circulating current through the slot bow-tie antenna.

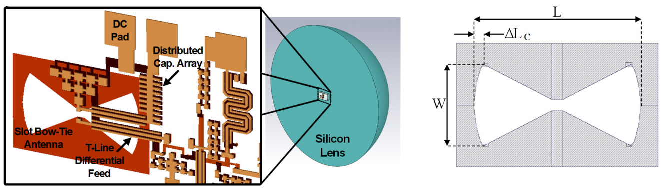

Fig. 2. The slot bow-tie with its feed and substrate. Slot length, width, and curved corner length change are 290μm, 130μm, and 17μm, respectively.

III. Array Architecture and Measurement Results

Conventional phased arrays utilize different methods for adjusting the time delay required for beamforming. The most common method is introducing delay elements in the signal path (RF path). These delay blocks distort the signal due to their nonlinear behavior. In addition, the generated delay in these architectures depends on the time-domain waveform of the RF signal, which is an undesirable effect. LO-path phase shifting is another method, where the phase shift is implemented in the LO path [4]. Unfortunately, the LO-path phase shifting method is narrowband and cannot be used in broadband arrays.

In this work, for the first time, a novel broadband beamforming architecture is presented that excludes the time delay from the signal (information) path. As shown in Fig. 3, delay generators are implemented on the trigger path that control the timing of the impulse radiation. In this array architecture, the information is stored on the amplitude of the ultra-short impulse, and beam-steering is performed by adjusting the timing of the trigger that fires the impulse. Fig. 4 shows successful time-domain measurement of two radiated impulses delayed by 300fsec.

The chip micrograph of the reported 8-element terahertz array is shown in Fig. 5. The entire array occupies an area of 1.6mm × 1.5mm including pads, while a single element occupies only 650µm × 300µm. The antennas are fabricated on the top metal layer, which is made of aluminum and has a thickness of 4µm. The measured radiation patterns at 0.33THz, 0.57THz and 0.75THz are shown in Fig. 5. Maximum antenna array directivities of 22dBi at 0.33THz, 25dBi at 0.57THz, and 27dBi at 0.75THz are achieved in measurement.

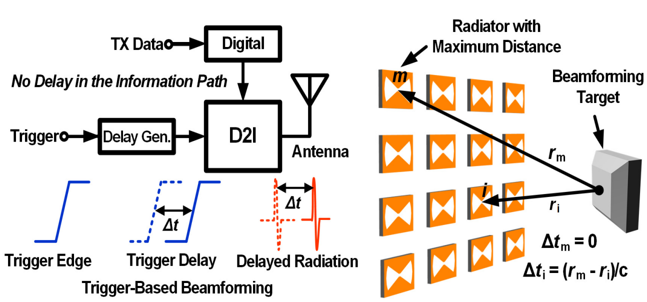

Fig. 3. Trigger-based beamforming architecture for broadband beamforming of terahertz pulses.

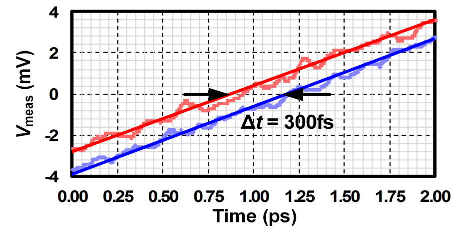

Fig. 4. Two radiated impulses delayed by 300fsec in time-domain measurement.

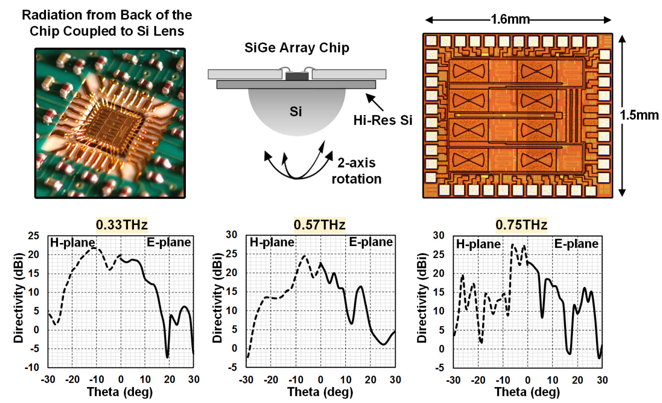

Fig. 5. Board setup configuration and array chip micrograph (top), E- and H-plane radiation pattern at 0.33THz, 0.57THz and 0.75THz (bottom)

IV. Conclusion

An 8-element terahertz impulse-radiating array with integrated slot bow-tie antennas is implemented in a 90nm SiGe BiCMOS process. Radiation is coupled to a silicon lens with a diameter of one inch and an extension of 500µm, through the back of the chip. Spatial combining of broadband radiated impulses is demonstrated with a novel trigger-based beamforming architecture. A 300-fsec delay resolution is successfully measured.

Acknowledgment

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