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Synthetic Ultra-Wideband Phased-Array Transceiver for Millimeter-Wave Imaging Applications With On-Chip Antennas

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***Abstract*— This paper discusses the design of a synthetic ultra-wideband phased-array transceiver front-end in SiGe BiCMOS that is capable of providing the largest bandwidth among all RF millimeter-wave imagers reported in the literature. An ultra-wide imaging bandwidth of 100 GHz (10–110 GHz) is achieved by the integration of three adjacent, disjointed frequency sub-bands. Each sub-band includes a fully-integrated 4×2 array of transceivers. Each transceiver includes a low-power differential pulse generator, a delay generator, a transmit-receive (T/R) switch, a low-noise amplifier (LNA), a multiplier, and an on-chip slot bowtie antenna.**

Keywords*— *Ultra-wideband imaging, on-chip imaging systems, millimeter waves, phased arrays

I. Introduction

Imaging and communication systems can leverage the wide bandwidths available at millimeter-wave frequencies to achieve high-resolution imaging and high-speed communication [1]. Over the past decade, several silicon-based millimeter-wave imaging systems have been reported for biomedical applications with the goal of achieving high resolutions, large image ranges, and short acquisition times. However, there exists no imaging chip in the literature with the capability of providing sufficient resolutions for the visualization of biological tissues. In wideband imaging applications, the resolution is directly proportional to the system bandwidth [2]. It has been suggested that an ultra-wideband millimeter-wave imaging bandwidth of approximately 100 GHz is needed for attaining sufficient resolutions in images of the human skin tissue [2].

In [3], we presented three integrated pulse generators that collectively provide an ultra-wide imaging bandwidth of 100 GHz in the millimeter-wave regime. The pulse generators produce pulses with frequency ranges of 10–40 GHz, 40–75 GHz, and 75–110 GHz. A fully-integrated ultra-high-resolution imaging chip can then be developed using the imaging approach introduced in [2], i.e. the synthetic ultra-wideband imaging method. In this work, we design a phased-array transceiver front-end that employs the mentioned imaging approach to realize a fully-integrated ultra-high-resolution imaging chip for biomedical applications. The ultra-wide imaging bandwidth of 100 GHz will be achieved by integrating three adjacent, frequency sub-bands of 10–40, 40–75, and 75–110 GHz. The imaging elements are designed in a Global Foundry 130-nm SiGe BiCMOS process technology.

The schematic of the proposed synthetic ultra-wideband imaging chip is shown in Fig. 1. As seen in this figure, each sub-band includes a separate imaging transceiver which operates only within that specific sub-band. Phased-array transceivers are used so that the sub-band antenna beams can be electronically steered to scan the entire region of the target. The received IF signals are filtered and delivered to the image reconstruction module in which an integrated signal over the entire bandwidth is synthesized and a 3-D image is formed.

II. System Design

The inset of Fig. 1 demonstrates the schematic of each sub-band transceiver phased array, consisting of 4×2 elements. Each element is equipped with a programmable delay line that controls the individual timing of radiation to perform low-loss signal distribution and coherent combination of broadband pulses of all elements. On-chip antennas are used to eliminate

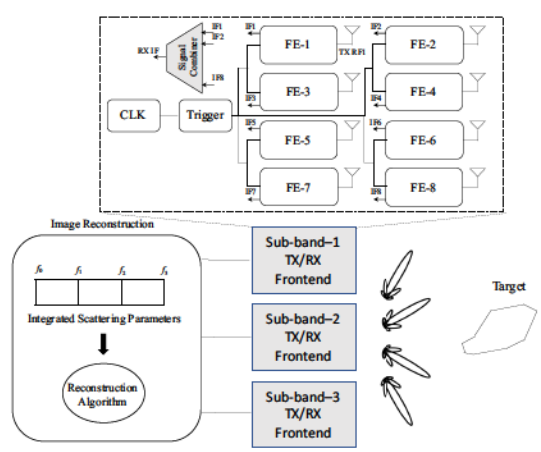

Fig. 1. The schematic diagram of the synthetic ultra-wideband millimeter-wave imaging approach. Three sub-band transceivers transmit their signals in their respective sub-bands and receive the backscattered signals. The received sub-band signals are then filtered and delivered to the image reconstruction module. The inset demonstrates the schematic of each sub-band transceiver phased array, consisting of 4×2 elements

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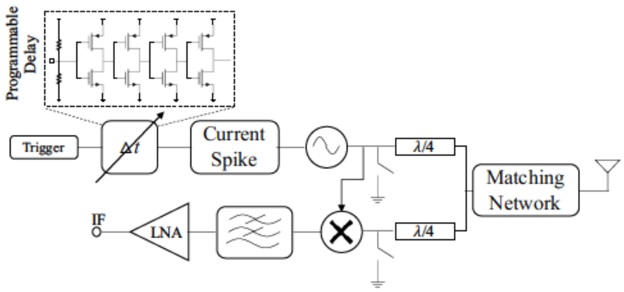


Fig. 2. Schematic of a phased-array element. The digital trigger is passed through a programmable delay generator. The element also includes a pulse generator, a multiplier, a low-noise-amplifier (LNA), a transmit/receive (T/R) switch, and an on-chip antenna.

the power loss and phase distortion caused by connections to off-chip antennas. In addition, each antenna is used for both radiation and reception of the waves towards and from the target respectively.

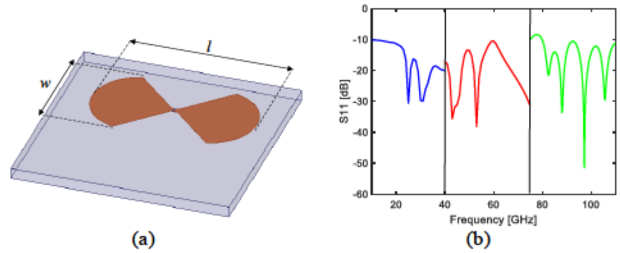
In conventional millimeter-wave imaging approaches, the synthetic-aperture radar (SAR) method is used for creating three-dimensional reconstructions of objects. SAR uses a two-dimensional (2D) array of antennas to scan the target region and collect data. However, scanning over a 2D aperture plane increases the size of the system and is not a reasonable approach in silicon-based systems. In this work, we use electronic beam-forming to scan the target region. Phased-array beam-forming and beam-steering capabilities increase the range and improve the signal-to-noise ratio (SNR).

A. Phased-Array Architecture

Fig. 2 shows the front-end schematic of an array element. A low-power digital trigger is fed to the input of the chip. We focus on the design of a phased-array transceiver front-end, capable of both transmit (TX) and receive (RX) operations. This is a key building-block for a scalable system in which a unit cell is repeated in the X and Y directions. The digital trigger is passed through a programmable delay generator. The delay generator is a cascaded series of inverter stages which control the timing of the digital signal based on their supply voltage. Other key building blocks in the front-end include a pulse generator, a multiplier, an LNA, a T/R switch, and an on-chip antenna in silicon. In the TX mode, the delayed input signal from the pulse generator is radiated through an antenna. A T/R switch switches the antenna between TX and RX. In the RX mode, the front-end receives the backscattered signal and mixes it with the delayed pulse generated by the pulse generator. It is worth noting that for each component, three separate circuits need to be designed corresponding to the three frequency sub-bands of 10–40, 40–75, and 75–110 GHz.

B. On-Chip Antenna

A differential antenna, fed by two signals of equal amplitude and opposite phases, would significantly reduce the feedline radiation. As such, a broadband slot bow-tie antenna, as demonstrated in Fig. 3 (a), is designed. The edges of the antenna are curved to improve the bandwidth. In designing on-chip millimeter-wave antennas, surface waves are a major concern as they degrade radiation efficiency. A silicon lens can be used to mitigate surface waves by collecting and converting them to useful radiation [4]. However, attaching a silicon lens significantly increases the directivity of the on-chip antenna and limits the field-of-view. This is not a good option in our application in which wide field-of-view imaging is required.



Sub-band	*Antenna Dimension (l×w) [μm²]*	*Peak Gain [dBi]*
10–40 GHz	594 × 387	-4.3
40–75 GHz	501 × 310	-5.4
75–110 GHz	468 × 286	-5.3

(c)

Fig. 3. (a) Schematic of an on-chip bowtie antenna. (b) Simulated reflection coefficient of the three sub-band antennas. Dimensions of the Sub-Band On-Chip Antennas

The thickness of the silicon substrate can be optimized to increase the antenna radiation efficiency. Since wire bonds may affect the topside radiation, the on-chip antennas are designed to radiate through the substrate (bottom side). Additionally, due to die area constraints, the dimension of the antennas is limited to 300 μm. The HFSS electromagnetic simulator is used to simulate and optimize the on-chip antennas. Fig. 3 (b) demonstrates that with a 1500-μm silicon substrate, the on-chip sub-band bowtie antennas have 3-dB bandwidths of approximately 30 GHz, 35 GHz, and 35 GHz for the 10–40-GHz, 40–75-GHz, and 75–110-GHz sub-bands, respectively. Fig. 3 (c) presents the antenna dimensions. The peak gain is also presented in Fig. 3 (c) for each sub-band.

III. Conclusion and Future Direction

The reported phased-array transceiver forms the first fully-integrated silicon-based phased-array transceiver with an ultra-wide bandwidth of 100 GHz at millimeter-wave frequencies. Our future direction will be towards the fabrication of the designed chip described in Fig. 1.

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