Research Report: A Fully-Integrated SiGe Terahertz Heterodyne Imaging Transmitter

Ruonan Han and Ehsan Afshari

I. Introduction

Radiation in the terahertz (THz) frequency range (100 GHz$\sim$10 THz) is very attractive to applications like non-ionizing imaging, spectroscopy, toxic material detection, and secure high-speed communications [1]- [3]. Harnessing terahertz using solid-state circuits, in particular, is gaining high expectations for making the future THz equipment portable and affordable [4]. However, to achieve this goal, research breakthrough is in demand for overcoming the following two technical barriers:

- The operation speed and power of the THz integrated circuits are limited by the low cut-off frequency and breakdown voltage of the devices, which are only around 300 GHz and 1 V respectively in deep submicron CMOS. Meanwhile, on-chip passive components are very lossy due to the inferior metal back-end and reduced skin depth. Radiation in the presence of the substrate is also inefficient due to the loss and substrate-mode excitation.
- It is very difficult to integrate a complex, multi-functional THz system on a single chip (i.e. THz SoC). Different from the low-frequency SoC composed of separate blocks, THz SoC requires a holistic integration methodology to reduce power, interconnect loss and packaging cost []. Meanwhile, in contrast to the well-established RF radar/communication systems, on-chip architectures for new applications like imaging and spectroscopy are still to be explored.

In this report, we describe our recent research progress on a 320-GHz transmitter for imaging applications [5]. Using a 130-nm SiGe BiCMOS process, this chip not only achieves the highest radiated power in all silicon-based THz radiators, but also demonstrates the first fully-integrated phase-locked loop for the output beam. The latter enables heterodyne detection, which can significantly enhance the sensitivity of the entire THz imaging system [6]. This is a team project[1], of which the designs of the system architecture and the core radiator, as well as the measurements of the chip, are contributed by the recipient (Ruonan Han) of the MTT-S fellowship.

II. Description of the Project

The overall architecture of the transmitter is shown in Fig. 1, which consists of an array of 16 radiator units based on harmonic oscillators. Since these radiators are mutually coupled, their output waves are coherent and are combined in the free space in a quasi-optical fashion [7]. Meanwhile,

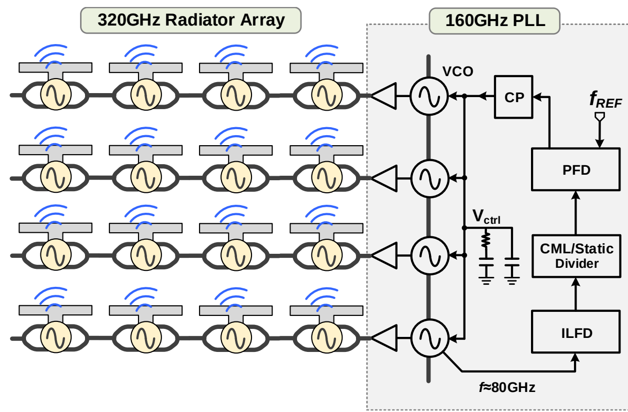

Fig. 1. The architecture of the 320-GHz transmitter with a fully-integrated phase-locking loop (CP: charge pump, PFD: phase/frequency detector, CML: current-mode logic, ILFD: injection-locking frequency divider) [5].

the frequency and phase of the radiator array are injection-locked by an on-chip phase-locked loop (PLL). The core of the PLL is a bank of 80-GHz VCO with 2nd-harmonic extraction. Since each VCO is coupled to its neighbors, and the only global signal routing is the low-frequency varactor bias control, this proposed PLL architecture is highly scalable. The divider chain has a total division ratio of 256, so the input reference clock frequency is only $\sim$312 MHz; this facilitates the synchronization between this transmitter and a THz heterodyne imaging array (to be implemented).

The design of the 320-GHz radiator is shown in Fig. 2. It is built on a differential self-feeding oscillator topology we developed [8], which achieves the optimum gain condition of transistor [9] and maximizes the oscillation power at the fundamental frequency f_0. Secondly, our device analyses indicate that it is critical to achieve harmonic-signal isolation between the transistor terminals, in order to improve the nonlinear harmonic generation efficiency. For that purpose, a novel return-path gap coupler is inserted in the oscillation feedback paths between the base and collector of the SiGe HBTs. This structure utilizes the orthogonality of different wave modes inside a metal gap structure. To be more specific, the gap only allows the propagation of differential quasi-TEM wave (i.e. oscillation at f_0), but fully blocks the balanced TM wave (i.e. harmonic signal at $2f_0$). Therefore, the self-feeding oscillation is not disturbed by the additional coupler structure, while maximum harmonic signal is extracted from the device. Without any explicit antenna structure, this gap-based structure also intrinsically radiates the harmonic signal with $\sim$50% efficiency.

Figure 3 shows the die photo of the 320-GHz transmitter

[1]Other contributors are Chen Jiang, Ali Mostajeran, Mohammad Emadi, Hamidreza Aghasi, from Cornell University, as well as Hani Sherry and Andreia Cathelin from STMicroelectronics.

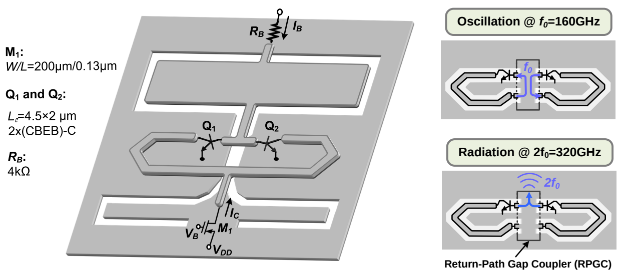

Fig. 2. Proposed THz radiator design (the drawing is not to scale), and summarized operations for fundamental oscillation and 2^{nd}-harmonic radiation [5].

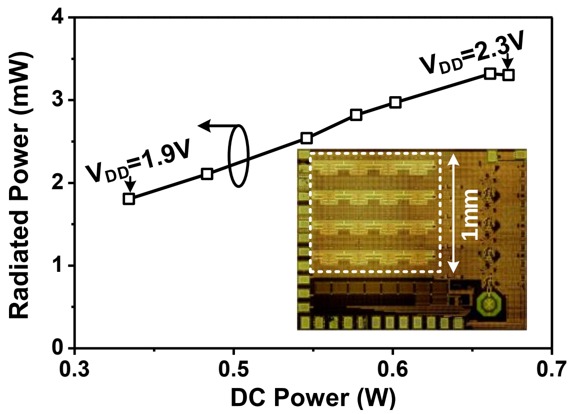

Fig. 3. The micrograph of the 320-GHz transmitter, as well as the measured total radiated power of the chip [5].

chip, as well as the measured total radiated power at various DC bias. The peak radiated power is as high as 3.3 mW. This is in fact the highest output power among all silicon-based THz sources (Fig. 4), thanks to the efficient radiator structure design. The associated DC-to-THz radiation conversion efficiency is 0.54%, which is also the highest. For the best radiation coupling to the free space, a high-resistivity silicon lens attached to the chip back is used in our measurement. Even if the lens is removed, the output power of the chip (without any post-processing) is still has high as 1.2 mW. It is also noteworthy that, due to the compactness of the radiator, we are able to integrate 16 elements within only a 1-mm^2 area. This significantly increases the power density, as well as the directivity of the output beam (17-dBi in the measurement).

This chip also demonstrates fully-integrated phase-locked loop for THz radiators for the first time. The measured phase noise at 1 MHz frequency offset is -79 dBc/Hz. This opens up numerous opportunities for novel THz system designs with higher complexity and distributed nature, such as large-area, multi-chip power combining.

III. Acknowledgement

We sincerely thank the Microwave Theory and Technique Society (MTT-S) for this fellowship award in support of Ruonan Han's research work. This project is also supported by Army Research Lab (ARL), National Science Foundation (NSF) and STMicroelectronics. With the success of this project, Ruonan Han has graduated from Cornell University with the Ph.D. in electrical and computer engineering. Receiving the recognition from MTT-S encouraged Ruonan to continue his career in academia with the pursuit in high performance THz microsystems. Towards that goal, he recently joined the faculty of Massachusetts Institute of Technology.

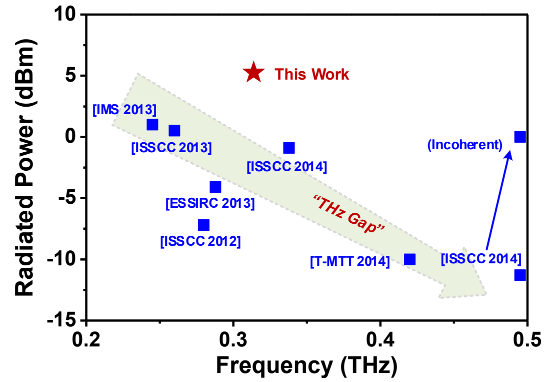

Fig. 4. The total radiated power of the state-of-the-art THz radiation sources in silicon.

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