Towards Battery-less THz TRx with Physical Layer Security for Ultra-Miniaturized Platforms

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***Abstract*—Terahertz (THz) band has the ability to shrink communication node size down to mm² and has been applied to prevent eavesdropping in point-to-point wireless communication. However, enabling ultra-low power battery-less operation in mm-size THz transceivers is a key challenge, and the inevitable sidelobes and limited directivity of antennas still leave security loopholes. This article introduces a frequency-shifted back-scattering technique for ultra-low power THz communication, a dual-antenna architecture for efficient THz energy harvesting as well as a transformative physical-layer security scheme using the helical distribution of wavefront namely orbital-angular-momentum (OAM). Thus, enabling battery-less and physically secure THz TRx for ultra-miniaturized platforms.**

***Index Terms*—THz, RFID, Back-scattering, Orbital-angular-momentum, Energy harvesting, Wireless power transfer.**

I. Introduction

ADVANCES in silicon-integrated electronics have enabled many significant systems and applications in the terahertz (THz) band over the last decade [1]. THz band enables on-chip antenna integration leading to mm-size transceivers. However, due to their stringent challenges, ultra-low power ($<25\mu$W) or battery-less THz transceivers have not been explored yet. Likewise, the notion of wireless power transfer at THz frequency is non-existence. There is a growing demand for ultra-low power mm-size transceivers in supply chain management, assets tracking, authentication, micro-robots, micro-sensors, on-skin or close-to-skin implants, etc. With these ubiquitous THz links, the security of these wireless channels is another emerging challenge.

In this report, we present several techniques to develop physically secure battery-less THz transceivers. There are three main challenges that need to be addressed: (i) the generation of on-chip THz signals is a power-hungry process rendering battery-less applications infeasible in the THz bands. To address this challenge, we proposed a frequency-shifted back-scattering technique with no static power consumption. This technique enables communication between widely distributed THz transceivers and a centralized high-power hub. As an application, the THz identification tag or THzID is demonstrated in [2], [3]. (ii) Wireless power transfer at THz frequency of the order of $\sim25\mu$W is still required for the normal operation of these battery-less transceivers. We presented a dual-antenna topology co-designed with the FET optimal space to harvest power efficiently at low available THz power [4]. Efficient THz energy harvester will also open doors to many exciting new applications. (iii) Traditionally, wireless communication is secured at network and application layers using digital encryption techniques which rely on the trustworthy secret key distribution. Such security architectures are becoming computationally intensive and will not scale with the ubiquitous THz links. We proposed to employ helical distribution of wavefront (namely orbital-angular-momentum or OAM) to encode the secret key, thus providing an additional layer of security and relaxing requirements at other layers [5]–[7]. As a result of all these innovations, mm-size, battery-less and physically secure THz transceivers for the next generation of IoTs are made possible.

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II. THz-OAM Transceiver and THz Energy Harvester

The architecture of the THz-OAM chip, designed in a 65-nm CMOS process, is shown in Fig. 1. It consists of eight THz modulator/detector units (referred to as *pixel*) arranged in a uniform circular pattern and driven by a 310 GHz signal generator. Each pixel generates radiation with a phase difference of $\Delta\phi$ with respect to its neighboring pixels. $\Delta\phi$ is adjusted by the LO signals from the controller, and its values of 0, +45°, and -45°correspond to the OAM modes of m=0, +1, and -1, respectively. An on-chip controller configures the chip in either transmission or reception mode. In the transmission mode, a random key is mapped to the instantaneous OAM modes. In the reception mode, each pixel mixes its received wave with the local 310 GHz signal and generates an IF output. Analog phase comparison of these IF signals enables the determination of the incident OAM mode. The dynamic switching among OAM modes is demonstrated through verification of the chip output mapped from a repeated data sequence, and the time-domain outputs of the receiver with different spiral-phase plates (SPP) configurations as shown in Fig. 2. It shows good correlation with matched modes, partial correlation of the m=+1 or m=-1 modes with the m=(+1)+(-1) superposition mode, as well as the rejection of unmatched modes. The presence of superposed mode with random initial phases further increases the difficulty of eavesdropping by randomly posing intensity nulls to the eavesdropper.

The schematic of the 0.26 THz energy harvester, designed in a 22-nm FinFET process, is shown in Fig. 3a. The antenna length determines the resonance frequency and the width being proportional to the radiation aperture has a near linear relation with the antenna gain. Given the uniform power density of the incident plane wave, the received power ratio of two antennas is well controlled by the patch width ratio. This

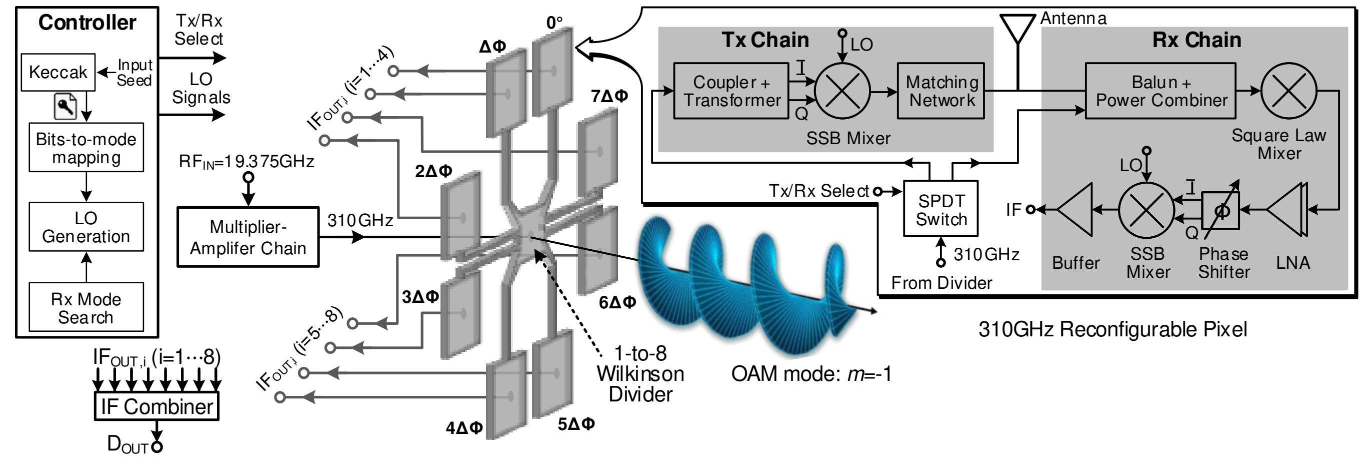

Fig. 1. Architecture of the 0.31 THz-OAM transceiver in CMOS.

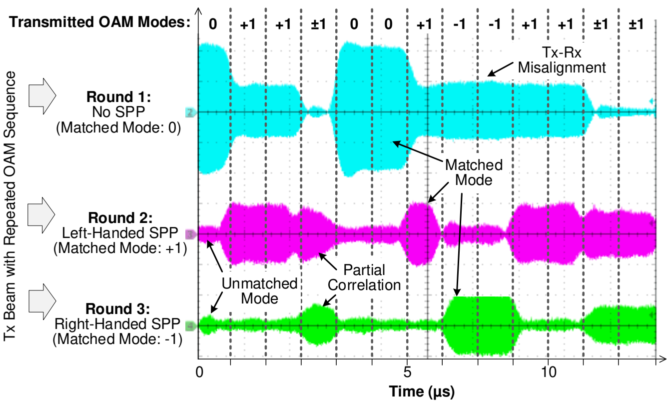

Fig. 2. Time-domain output of the receiver configured to respond to different OAM modes when it is illuminated by the same OAM sequence.

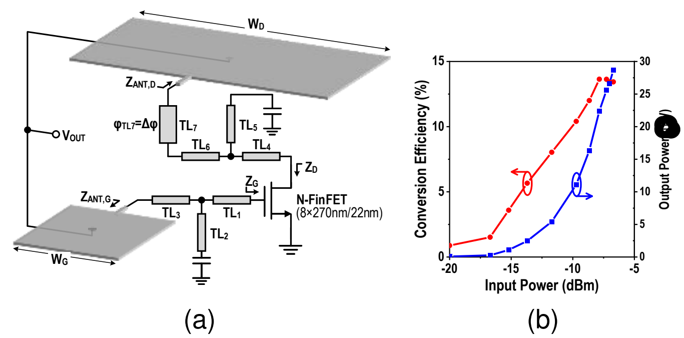

Fig. 3. (a) Schematic of the THz energy harvester. (b) Measured η and $P_{OUT,DC}$ with 1-kΩ load.

allows to achieve the optimum ratio of power injected into the device nodes. The optimum phase difference is provided by TL_7. Lastly, connecting the central AC ground nodes of the patch antennas together enables the self-biasing of the transistor. Such a scheme also ensures that the self-bias voltage is close to the transistor V_{th} when driving an optimum load. The same connection is also used to extract DC output power, thus avoiding lossy RF chokes. Fig. 3b shows the measured efficiency η and $P_{OUT,DC}$ at various attenuated input power levels. At P_{in}=-8 dBm, η_{max} of 13.6% and $P_{OUT,DC}$ of 22 μW are obtained.

III. Career Plan and Fellowship Impact

I would like to sincerely thank the IEEE Microwave Theory and Technique Society (MTT-S) for this prestigious fellowship award in support of my Ph.D. research work. This fellowship has been instrumental in the successful completion of this project. I look forward to further contributing to the MTT-S from academia and industry through exciting research in integrated mm-Wave/THz transceivers.

References

[1] X. Yi, C. Wang, Z. Hu, J. W. Holloway, M. I. W. Khan, M. I. Ibrahim, M. Kim, G. C. Dogiamis, B. Perkins, M. Kaynak, R. T. Yazicigil, A. P. Chandrakasan, and R. Han, "Emerging Terahertz Integrated Systems in Silicon," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 68, no. 9, pp. 3537–3550, 2021.

[2] M. I. Ibrahim, M. I. W. Khan, C. S. Juvekar, W. Jung, R. T. Yazicigil, A. P. Chandrakasan, and R. Han, "THzID: A 1.6mm² Package-Less Cryptographic Identification Tag with Backscattering and Beam-Steering at 260GHz," in *IEEE International Solid-State Circuits Conference (ISSCC)*, 2020, pp. 24–26.

[3] M. I. W. Khan, M. I. Ibrahim, C. S. Juvekar, W. Jung, R. T. Yazicigil, A. P. Chandrakasan, and R. Han, "CMOS THz-ID: A 1.6-mm² Package-Less Identification Tag Using Asymmetric Cryptography and 260-GHz Far-Field Backscatter Communication," *IEEE Journal of Solid-State Circuits*, vol. 56, no. 2, pp. 340–354, 2021.

[4] M. I. W. Khan, E. Lee, N. M. Monroe, A. P. Chandrakasan, and R. Han, "A Dual-Antenna, 263-GHz Energy Harvester in CMOS for Ultra-Miniaturized Platforms with 13.6% RF-to-DC Conversion Efficiency at -8 dBm Input Power," in *2022 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, 2022, pp. 291–294.

[5] M. I. W. Khan, J. Woo, X. Yi, M. I. Ibrahim, R. T. Yazicigil, A. Chandrakasan, and R. Han, "A 0.31THz CMOS Uniform Circular Antenna Array Enabling Generation/Detection of Waves with Orbital-Angular Momentum," in *2021 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, 2021, pp. 203–206.

[6] M. I. W. Khan, J. Woo, X. Yi, M. I. Ibrahim, R. T. Yazicigil, A. P. Chandrakasan, and R. Han, "A 0.31-THz Orbital-Angular-Momentum (OAM) Wave Transceiver in CMOS With Bits-to-OAM Mode Mapping," *IEEE Journal of Solid-State Circuits*, vol. 57, no. 5, pp. 1344–1357, 2022.

[7] J. Woo, M. I. W. Khan, M. I. Ibrahim, R. Han, A. P. Chandrakasan, and R. T. Yazicigil, "Physical-Layer Security for THz Communications via Orbital Angular Momentum Waves," in *2022 IEEE Workshop on Signal Processing Systems (SiPS)*, 2022, pp. 1–6.