

# MTT-S Graduate Fellowship Project Report: Standing Wave Integrated Circuits for mm-Wave/THz Power Generation, Radiation and Beam Steering in Silicon Technology

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**Abstract**—In this report, we discuss the motivation, main idea, progress and results of our project that is focused on implementing silicon integrated circuits for Millimeter Wave (mm-wave) and Terahertz (THz) sources for power generation, radiation and beam steering. We describe our novel approach of using distributed structures based on standing and traveling waves in order to realize high-power, wideband and scalable Voltage Controlled Oscillators (VCO), array sources and phased arrays.

**Index Terms**—Standing wave, mm-Wave/THz VCO, harmonic oscillator coupling, wideband frequency tuning, mm-wave/THz power generation, phased array, beam steering.

## I. INTRODUCTION

Millimeter Wave (mm-wave) and Terahertz (THz) spectrum offers unique and significant applications in spectroscopy, imaging, radar and high-speed communication. The large available bandwidth in these bands can lead to superior performance in terms of data rate, resolution and sensitivity. However, currently, THz systems are mainly implemented using bulky and expensive devices. Integrated implementation of THz systems in available low cost and reliable technologies can unleash the potentials of this band and make them accessible to more consumers. In this endeavor, several challenges must be overcome. The available gain and power generation capability of transistors drop with frequency and maximum oscillation frequency ( $f_{max}$ ) denotes the theoretical limit for maximum possible frequency of oscillation in a fabrication process. Increasing propagation loss as well as losses of passive elements, particularly varactors, presents further obstacles for implementing THz integrated circuits that are capable of delivering sufficient output power and bandwidth. The design process is also complicated by process model uncertainties and the necessity of extensive electromagnetic simulation of the structure.

To overcome the effects of the described challenges, we have proposed, implemented and verified fully integrated THz circuits using distributed and scalable standing/traveling wave structures that are capable of delivering high output power, wideband operation and wide-angle beam steering.

Section II describes the progress of our project and the implemented circuits and section III concludes the report.

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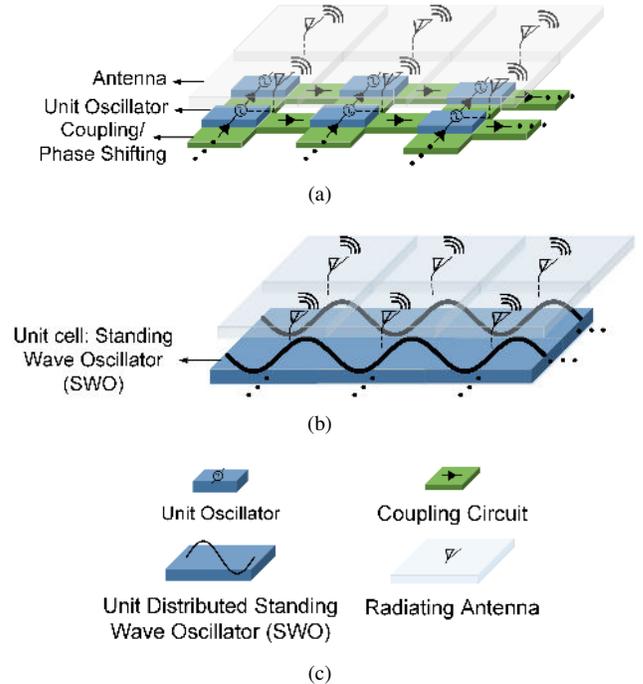


Fig. 1. (a) Conventional approach to implementing mm-wave and THz array sources by employing coupling circuits and/or phase shifters, and (b) our approach using distributed, continuous and scalable standing wave structures [2].

## II. PROJECT DESCRIPTION

Fig. 1 illustrates a comparison between the conventional approach of implementing array sources and phased arrays with our method. As shown in Fig. 1(a), coupling circuits are conventionally used between harmonic oscillators in order to synchronize the individual VCO sources and produce coherent radiation. Distinct phase shifters are required in this case for electronic steering of the radiation beam. Both coupling elements and phase shifters add unwanted losses to the circuit and the low quality factor of varactors significantly restricts the phase shifting range hence steering range of the system. In contrast, in our approach, the employed standing wave oscillators deliver inherently in-phase even harmonics and can be scaled by extending the electrical length of the standing wave by replicating the unit cell of the structure [1]- [3]. Using this technique, we implemented a  $1 \times 4$  0.34-THz radiator array with 5.9% frequency tuning range and on chip patch antennas

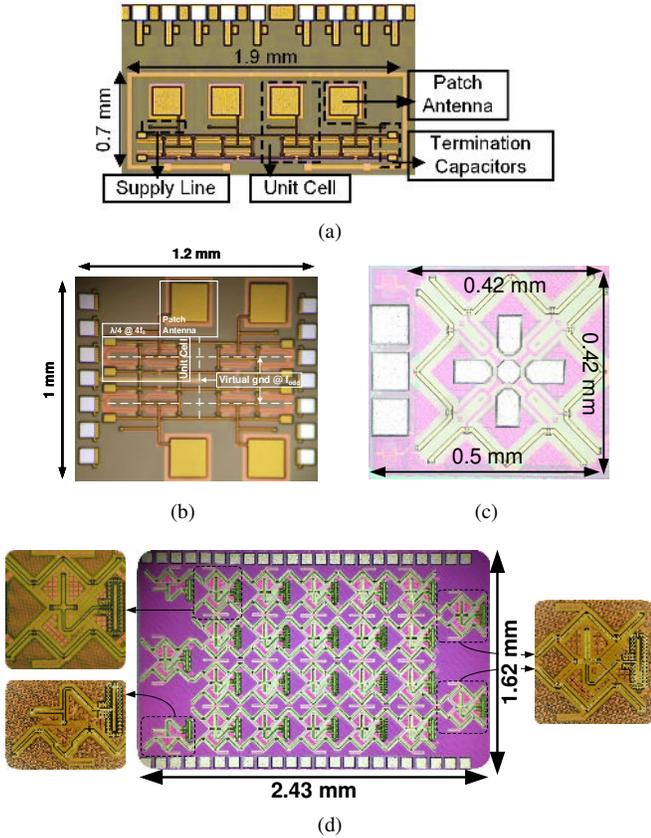


Fig. 2. Chip photographs of the implemented circuits, (a) a 0.34-THz wideband radiator array in  $0.13\mu\text{m}$  BiCMOS, (b) a wideband wide-angle 2D phased array in  $0.13\mu\text{m}$  BiCMOS, (c) a high-power wideband VCO in 65nm CMOS, and (d) a high-EIRP wideband 0.46-THz radiator array in 65nm CMOS.

in a  $0.13\mu\text{m}$  BiCMOS process. The chip photograph and structure of this circuit is shown in Fig. 2(a) and Fig. 3(a) respectively. This work was first presented in IEEE Radio Frequency Integrated Circuits (RFIC) conference in 2016 [1] and the details of this work were published in an IEEE Transactions on Microwave Theory and Techniques (TMTT) paper in 2018 [2].

Fig. 2(b) shows a 0.34-THz phased array chip that was implemented in a  $0.13\mu\text{m}$  BiCMOS process and is capable of wideband operation (318-to-370 GHz and 15.1% tuning range) and 2D wide-angle beam steering ( $128^\circ/53^\circ$ ). The structure of the implemented circuit is shown in Fig. 3(b). A novel approach of combining standing and traveling waves is used in this circuit to create phase shift between power radiated from on chip patch antennas and steer the beam in a 2D plane. This work was first presented in IEEE International Solid-State Circuits Conference (ISSCC) in 2017 [4] and a comprehensive presentation and analysis of the technique, design approach and results of this work are to be submitted to IEEE Journal of Solid State Circuits (JSSC) shortly.

Fig. 2(c) shows a wideband (219-to-238 GHz) standing wave VCO implemented in a 65nm CMOS process with 3.4-dBm peak output power. This work has been accepted to the 2019 IEEE Custom Integrated Circuits (CICC) conference and will be presented in Austin, TX in April, 2019.

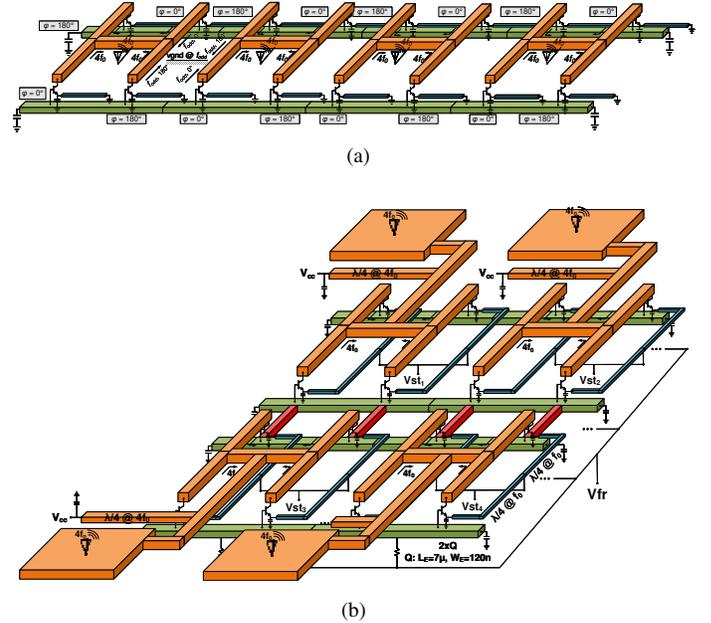


Fig. 3. Structure of the implemented (a) 0.34-THz wideband radiator array in  $0.13\mu\text{m}$  BiCMOS, (b) wideband wide-angle 2D phased array in  $0.13\mu\text{m}$  BiCMOS.

A 23-element 0.46-THz wideband high-EIRP radiator array was implemented in a 65nm CMOS process based on a scalable coupling scheme of standing wave harmonic oscillator sources. The THz power is radiated through the substrate using folded slot dipole antennas and high resistivity silicon lens. The implemented chip is shown in Fig. 2(d). The circuit is currently fully measured and characterized and will be submitted for publication to IEEE Journal of Solid State Circuits (JSSC) shortly.

### III. CONCLUSION

In this project, we have succeeded in proposing, implementing and verifying new techniques to overcome some of the challenges that are facing circuit designers in realizing fully integrated mm-wave and THz sources, radiator and phased arrays. We introduced techniques for coupling of oscillators, frequency tuning, phase shifting and beam steering that deal with restrictions posed in mm-wave/THz band.

### REFERENCES

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