Terahertz Chip-scale Systems

Kaushik Sengupta, Hooman Saeidi, Xuyang Lu, Suresh Venkatesh, and Xue Wu

Electrical Engineering, Princeton University, kaushiks@princeton.edu

Abstract: In this paper, we highlight the advances in chip-scale technologies in the terahertz spectrum between 100 GHz and 10 THz, particularly focusing on silicon-based integrated chip technology that can have a transformative impact in wireless communication, sensing and imaging.

Introduction

The Terahertz spectrum above 100 GHz has the potential to lead to game-changing wireless technology including high resolution sensing, imaging, and communication. The last decade has seen a tremendous surge of research in this space through a concerted effort across electronics and photonics with the aim of enabling Terahertz chip-scale systems operable at room temperature. In this paper, I will highlight the progress made in this space, the challenges that lie ahead, and how a holistic approach towards system design can lead to a new class of chip-scale Terahertz systems.

Closing of the 'THz gap': Across Electronics and Photonics

The significant progress in enabling higher power generation in THz sources (particularly focusing on chip-scale sources) in the last decade is illustrated in Fig.1 [1]. As we can see, we are at a point where we are closing the 'THz' gap in appreciable ways. While power generation capability has improved across all technology substrates, of particular note, is silicon-based integrated chip (IC) technology. Silicon ICs, with the ability to integrate a few billion transistors in a single chip, has not only revolutionized computing, but has also enabled the wireless revolution that we are currently experiencing. The motivation towards silicon-based THz ICs comes from the same principle. The first demonstration of power generation above 300 GHz in silicon was demonstrated in 2008. Since these early experiments with tens of nanoWatts of power, demonstrations of high power generation in silicon has advanced at breakneck pace with chips now having the capability to produce 1 mW of power at 0.5 THz, and 0.1 mW of power at 1 THz [2]. These power levels start making the possibility of practical THz systems a reality. More importantly, full integration of Terahertz systems imply that they can be manufactured at low-cost, and are scalable and deployable for ubiquitous applications. These systems also incorporate more complex functionalities such as the ability to electronically scan beams in space (THz phased arrays), and allow smart reconfigurability that is extremely challenging to achieve in photonics-based THz systems, and with III-V module-based electronic systems. This is critical for the next-generation of intelligent sensing and communication technologies (Fig. 2). This paradigm of Terahertz chips opens up opportunities for cross-system design from the antennas to signal processing, allowing a new class of complex Terahertz chip-scale systems and new capabilities.

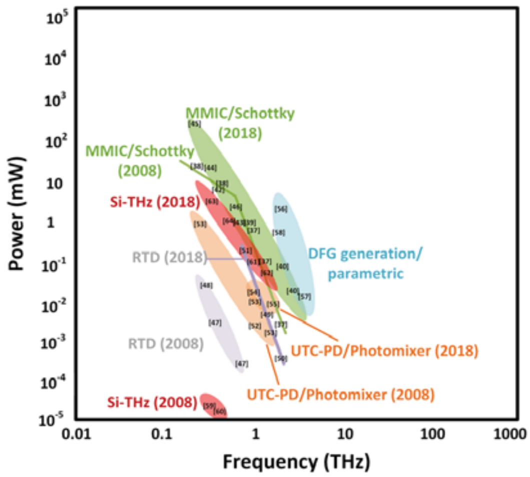

Fig. 1: THz technology evolution from 2008 and 2018, showing slow and steady closing of the 'THz gap'.

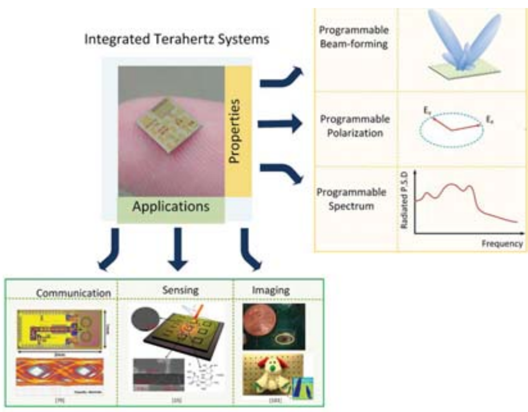

Fig. 2: The need for intelligent and programmable THz interfaces for future smart communication, sensing and imaging [1].

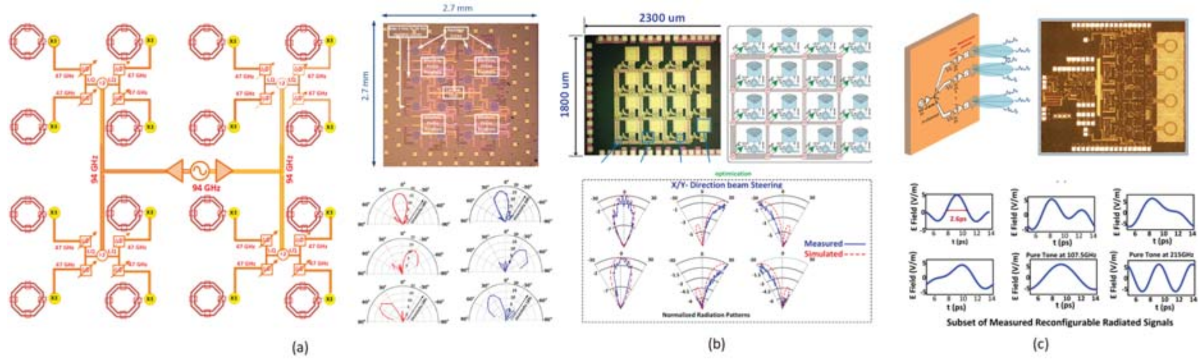

Fig. 3: Terahertz chip-scale radiating silicon sources including phased arrays and programmable THz signal generators [4]-[6].

THz Sources-on-chip: From power generation above f_{max} to programmability

The limitation of power generation in solid-sate circuits is primarily due to the finite cut-off frequency of integrated devices. This is defined by a metric commonly known as f_{max} that is the highest frequency up to which oscillators can be realized that can convert DC power to high frequency signals. For integrated circuit chip technology, while f_{max} of InP-based devices have crossed 1 THz, f_{max} of CMOS is still in the 300 GHz range and has stopped scaling.

The approach to overcome this limit has been to exploit harmonic generation at frequencies beyond f_{max}, exploiting the nonlinear operation of the integrated devices. While the efficiency of conversion is still poor, and the absolute power generation per single device is weak, full chip integration allows the capability of harnessing collective power of many devices.

Fig. 2 shows examples of a single chip THz phased array transmitter that allows free-space power combining with multiple on-chip radiating sources. Since wavelengths at these frequencies are smaller than the chip size, antennas can be integrated on chip. To ensure phase and frequency synchronization, there are multiple approaches. As shown in Fig. 3(a), all the radiating sources at 282 GHz are locked to a central frequency source of 94 GHz. In addition, each radiating source in the 4x4 array on chip has independent digitally controlled phase control allowing electronic beam-scanning in 3D over 80° in both azimuth and elevation [3],[4]. This first THz integrated phased array, realized in a commercial 45 nm CMOS SOI platform generates +9.4 dBm of effective-isotropic-radiated power (EIRP) at 0.28 THz.

Another example of synchronization of multiple sources on chip is to exploit nonlinear dynamical interaction as shown in Fig. 3(b), where a single distributed oscillator over the chip establishes a low-noise frequency reference. Local frequency up-conversion creates a 4x4 array at 0.42 THz with a record EIRP of +14 dBm with electronic beamforming in space [5].

With the ability to create moderately high power THz signals with fully integrated silicon chips, the next challenge is to chart a path towards the ultimate programmable THz source that has arbitrary control of spectrum, polarization and spatial field configuration (Fig. 2). Fig. 3(c) illustrates one approach that shows arbitrary THz waveform synthesis in space in a single chip system that is fully digitally programmable. By exploiting multiple sources that combine harmonically rich signals in space, and with individual delay control, one can achieve dynamic waveform shaping in space from pico-second pulses to continuous-wave signals [6]. A THz programmable source can revolutionize systems with new capabilities across hyper-spectral imaging, sensing, and spectrally agile communication for operation in real-world complex environment [7].

THz sensors-on-chip: From Electronics to Hybrid Electronic-Photonic Systems

The ability to exploit nonlinearities to generate signals at THz can also be leveraged to allow THz signal detection on chip. Integration of antennas on-chip opens up a new dimension of antenna-to-detector-to-system co-design space. An example of a 16 pixel single-chip THz camera is shown in Fig. 4(a). With the CMOS 0.28 THz source in Fig. 3(a), we demonstrated one of the first all-silicon THz imagers [8]. Progress in this space has come a long way demonstrating more than 1000 pixel integration in a single chip across 0.7-1 THz [9].

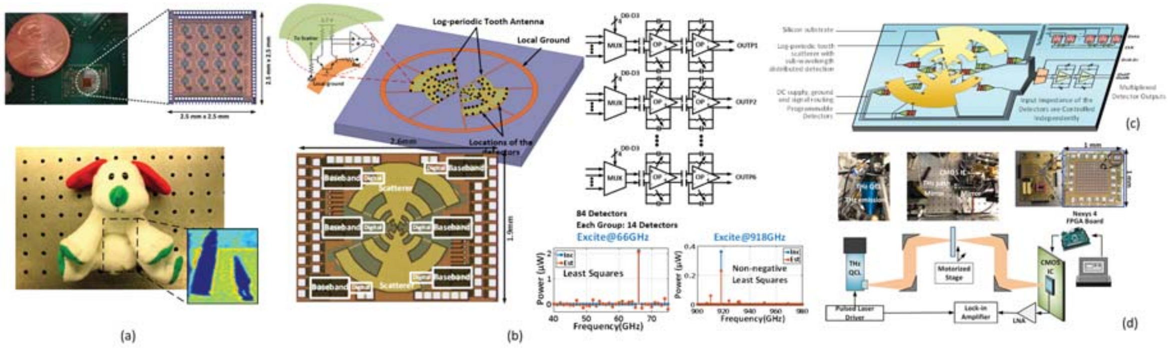

Fig. 2: Terahertz chip-scale sensors from reconfigurable and adaptive imagers to fully integrated THz spectroscopes.

However, the ability to integrate radiating and scattering surfaces on chip, along with millions of active devices whose cut-off frequencies are in the sub-Terahertz range, opens up new possibilities of fundamentally different method of extracting information from incident THz fields and new sensor architectures. An example is shown in Fig. 4(b), where a single-chip THz spectroscope is realized operating across 0.04-0.99 THz eliminating all complexities of a photonics-based THz spectroscope (such as femtosecond lasers, lasers, photo-conductive detectors, reconfigurable delay lines), and all complexities of a solid-state spectroscope (such as mixers, amplifiers, signal sources etc). Spectral information of incident fields is estimated through on-chip detection of impressed spectrally dependent surface currents on an on-chip scatterer with 84 detectors, and subsequent noise-immune estimation techniques. The chip achieves 10 MHz accuracy is estimation of the spectrum from C.W. signals across 0.04-0.99 THz [9].

The ability to sense the near-fields at sub-wavelength scales also opens up the possibility to reconfigure the scattering surface at sub-wavelength sales to optimally program the sensor response for varying incident THz fields. Fig. 4(c) is another example, where 15 detectors (each with 5 states) interfacing with scattering surface has the ability to create 5^{15}=152+ billion electromagnetic (EM) states. For arbitrary incident THz spectrum, polarization and angle of incidence, the task is then to find the optimal EM state, as show in [10]. For frequencies beyond 1 THz, hybrid electronic-photonic systems can emerge. Fig. 4(d) shows an example of a 100-pixel CMOS THz imager operating in the 3 THz range with quantum-cascade laser sources.

Conclusions

The future of Terahertz technology will rest on realization of integrated THz chips. While significant strides have been made in that effort, enabling complex THz systems that are reconfigurable and adaptive are important to enable the next-generation of sensing and communication interfaces. Electronics and photonics will play an important role in that.

Acknowledgements

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