Terahertz to Bits and Bits to Terahertz : Universally Programmable Chip-scale TeraHertz Systems

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ABSTRACT

The high millimeter-Wave and Terahertz spectrum above 100 GHz will form the underpinning of a broad set of game-changing future technology including high resolution sensing, imaging, robotics, autonomous systems, and wireless communication. In the last decade, we have seen a tremendous surge in efforts towards enabling chip-scale technology to address signal generation and detection in the THz spectrum. However, there lie several fundamental challenges to translate these efforts into versatile technology that can operate in complex environments that requires properties such as dynamic reconfigurability and rapid adaptability. In this paper, we highlight a new design space that emerges by eliminating the classical block-by-block design approach. The fundamental principle behind this approach is that the unique wavelength scale at THz (of the order of millimeter/sub-millimeter) is comparable to a typical chip dimension. This wavelength/chip dimension equivalence allows the chip to operate in a new electromagnetic (EM) regime with novel scattering and radiating properties, while the integrated active devices have the ability to actively synthesize, manipulate and sense THz EM fields at sub-wavelength scales. This approach opens up the a new design space that can break many of the trade-offs in the classical design regime. In this paper, we provide design examples that aims towards the ultimate programmable THz sensor/source in silicon-based chips that range from fully integrated chip-scale THz spectroscopes to programmable THz sensors, sources and spatio-temporal modulated arrays for physical layer security. These design examples serve to illustrate the unique opportunities enabled through such a holistic design approach.

CCS CONCEPTS

- Applied computing → Physical sciences and engineering;
- Hardware → Integrated circuits.

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KEYWORDS

wireless communication, Terahertz, 5G, 6G, millimeter-wave, security, sensor, spectroscopy, imaging, phased arrays, MIMO

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1 INTRODUCTION

The last decade can be regarded as an inflection point in massive research efforts focused towards enabling highly salable, efficient, miniaturized THz chip-scale technology above 100 GHz [30]. The application domain has spanned across wireless communication (primarily motivated by the opening of the millimeter-Wave bands for 5G) to high-resolution sensing and imaging [2]. While currently there is no frequency allocation beyond 300 GHz, the IEEE 802.15.3d-2017 standard is the first standard addressing bands beyond 300 GHz over the 69.12 GHz span across 252.72-321.84 GHz. The perceived use cases include high data-rate wireless links in data centers, kiosk downloading, inter-chip/inter-board radio communication, and front and back haul links. The THz spectrum is particularly attractive for its higher bandwidths supporting highly directive, ultra high-speed data rates with compact and electronically steerable MIMO arrays. The spectrum is regarded as the next frontier beyond 5G (often termed as 6G) and can have transformative impact on the next-generation of wireless connectivity and intelligent sensing technologies for future robotics and autonomous systems [21][23].

While commonly known as the 'THz gap' due to the lack of efficient technology in the spectrum, the research community has progressed steadily towards closing the 'THz gap' over the last decade. The approaches have ranged across both electronics and photonics as shown in a representative technology landscape evolution from 2008 to 2018 in Fig. 1a [30]. The improvement of silicon-based chip technology in the THz space is particularly noteworthy. Silicon-based integrated circuit technology with its extremely high levels of integration has transformed the wireless technology landscape and the resulting opportunities over the last twenty years, and is continuing to do so. This can be seen in radio-frequency and millimeter-wave chips, large-scale phased array systems in silicon for 5G and other applications [4–13, 17, 22, 24, 25, 34, 35, 37, 38].

Figure 1: Closing the ‘THz gap’ and, the ‘THz and application gap.’ (a) THz technology landscape evolution from 2008 to 2018 showing the steady closing of the ‘THz gap’. (b) Closing the ‘THz and application’ gap requires embedded intelligence, programmability and adaptability to enable versatile sensing and communication technologies [30].

However, it was only recently that signal generation and detection were demonstrated in silicon at THz frequencies above 300 GHz [16]. Since these early works, the field of silicon-based THz circuits and systems has experienced tremendous surge, and has shown remarkable advancement demonstrating fully integrated phased arrays with tens of mW of effective isotropic radiated power (EIRP) near 0.3 THz [26–29], fully integrated active imaging systems [31, 32], and integrated THz camera with more than 1000 pixels [51] operating across 0.7–1.1 THz [1]. This noteworthy progress in the field of silicon THz has been partially facilitated by device scaling that has pushed cut-off frequencies (f_t , f_{max}) of silicon-based integrated devices up to the sub-THz and THz frequency range (CMOS devices $\sim$ 250–350 GHz, SiGe hetero-junction bipolar transistors (HBTs) $\sim$ 300–500 GHz [30]). However, while proofs-of-concept chips have demonstrated the ability to synthesize and detect signals in this spectrum, there are still fundamental challenges to overcome before these innovations can translate into versatile technologies capable of operating in a complex environment. As illustrated in Fig. 1b, properties that are essential for such systems include fast adaptability and reconfigurability. This has been a major challenge in the field owing to the fact that the devices are already pushed to their limits when operating near or beyond their cut-off frequencies. Therefore, the degree of flexibility in each of these devices as unit elements is low. On the other hand, optical methods of generating THz signals are generally inefficient, and such components are typically bulky, non-integrable with less reconfigurability.

Given the limitations of the capabilities of unit THz devices, enabling versatile, programmable, complex and intelligent THz systems-on-chip (SOCs) requires a complete overhauling of the traditional design approach. This is where we see an opportunity for a shift in design methodology. The THz spectrum is unique in the sense that at these frequencies, the wavelengths are somewhat comparable to typical chip dimensions, a property that does not correspond to the neighboring spectral regions either in the microwave or in the optical frequencies. By Maxwell’s laws, it opens

up possibilities of allowing efficient radiating and scattering properties of integrated electromagnetic (EM) interfaces in a substrate that also supports potentially billion THz devices. This, therefore, creates an opportunity for realizing complex and reconfigurable 2D radiating surfaces that can be synthesized, manipulated and sensed at sub-wavelength scales using both active and passive elements [29]. Through these fundamental techniques of synthesis, control, manipulation and processing of THz fields in space and time, we see and highlight the following design examples.

- New forms of THz information processing systems and programmable sensors (THz-to-Bits)
- Programmable THz source architectures (Bits-to-THz)
- New functionalities and capabilities for wireless sensors and communication (such as physical layer security)

2 A NEW DESIGN SPACE: EM-TO-DEVICES-TO-SYSTEMS

In a traditional partitioned approach, functionalities are separated into classical circuit blocks and EM interface, as shown in the example in Fig. 2 to generate and radiate signals above f_{max} . At the highest level of abstraction, for a sensor, we are interested in extracting information from the incident fields and for a source, the interest is to generate the desired THz field distribution. This is fundamentally related to the 2D radiating current configuration on the EM interface on-chip. Instead of a static metal surface sustaining the current distribution with a single-port connection, such a radiating surface can now be interfaced with a multitude of high-frequency active devices (either for synthesis or sensing) integrated in the same substrate. This approach opens up novel ways of processing information from incident fields in a distributed fashion that breaks the limitations of the classical partitioned approaches [15]. In addition, through sub-wavelength digital control, small perturbations in the active devices can lead to large system property changes as we demonstrate with examples in the paper. The exploration of this new design space will need to rely on new optimization-based (or even AI-based) techniques that might take the intuition out of the

design approach. However, in the end, it can lead to novel systems with properties outside the space of the classical partitioned design methodology [7, 18, 20, 33].

Figure 2: A new design space through a electromagnetics-devices-systems co-design approach: Direct sub-wavelength synthesis and sensing of THz fields.

3 TERAHERTZ TO BITS: THZ INFORMATION PROCESSING SYSTEMS AND PROGRAMMABLE SENSORS

3.1 Extracting THz spectral information through sub-wavelength spatial sensing

THz spectroscopy is one of the most promising applications of THz technology. Traditional optics-based time-domain terahertz spectroscopy (THz-TDS) techniques can cover wide bandwidth (3-10 THz) with low resolution (1-10 GHz), but is expensive and bulky with low integration level which has limited its use beyond laboratory settings. On the other hand, the solid-state electronic design approach can achieve much higher frequency resolution over a much narrower frequency range. A wide-band, low-power, room temperature, chip-scale THz spectroscopy with hundreds of GHz of analysis range with moderate resolution (~ 10 MHz) can enable a wide range of applications, but needs fundamentally new ways of spectrum sensing.

The co-design approach as illustrated in Fig. 2 provides a guidance where we can consider the antenna that receives an incident EM flux as a distributed scatterer. As the THz field impinges on the passive antenna, an instantaneous frequency-dependent current distribution is excited on the antenna surface. It can be shown that given the incident direction and polarization, the impressed surface-current on the antenna is uniquely related to the incident spectrum, as shown in Fig. 3. Therefore, if we were able to sense the 2D current distribution on the surface of on-chip antenna with distributed sub-wavelength active devices, it might allow us to estimate the incident spectrum without any receiver electronics [42]. It can be noted that for spectroscopy applications, since the signal is periodic and the spectrum is discrete, one can represent

the spectrum as $E_{\text{frep}} \in \mathbb{R}^{M \times 1}$ and the spatial sensor response as $S_{\text{frep}} \in \mathbb{R}^{N \times 1}$. Expectedly, the incident spectrum and the spatial sensor response are related with respect to the scattering property of the interface and its boundary conditions. It can be shown that $S_{\text{frep}} = R_{\text{frep}} E_{\text{frep}} + V_n$, where the EM responsivity matrix of the antenna represented as $R_{\text{frep}} \in \mathbb{R}^{N \times M}$ is determined by its scattering property, and $V_n \in \mathbb{R}^{N \times 1}$ represents the noise of the detector array [44].

Figure 3: THz-to-Bits: Extracting incident spectral information across 40GHz-990 GHz without a LO source through direct on-chip measurement of distributed current distribution on the antenna surface. The chip is implemented in a $0.13 \mu\text{m}$ SiGe BiCMOS technology [42, 44]

This characterization reduces spectroscopy to a linear estimation problem where the input spectrum information (E_{frep}) is estimated by observing the outputs S_{frep} through a linear filter function R_{frep} . This approach, therefore, eliminates the need for complex THz sources, mixers, amplifiers and miniaturizes an entire wideband THz spectroscopy receiver to a single chip architecture with one antenna, multiple detectors, and the associated signal processing. The choice of the number of detector, their locations and the design methodology to interface the on-chip scatterer with multiple distributed detector arrays is a complex multi-port matching and optimization problem as elaborated in [44]. Essentially, the goal of the design strategy is to shape the best possible R_{frep} through this design procedure that allows robust spectral estimation in presence of noise with the desired resolution. The chip is implemented in a $0.13 \mu\text{m}$ SiGe BiCMOS technology. Some example measurement results in Fig. 4 demonstrate the spectral estimation from the measured sensor data across multiple incident spectra from 40 GHz to 990 GHz. The sensor has been tested with continuous-wave (C.W.) single frequency, multi-frequency and even broadband excitations and demonstrates robust spectral estimation.

The sensor achieves a frequency accuracy of 10 MHz for C.W. excitations over the 40-990 GHz frequency range. The reduction of spectral estimation to an estimation problem opens the door to exploring various estimation algorithms and investigate the achievable spectral estimation noise floor [45]. In particular, we

Figure 4: Measured spectral estimation with varied incident spectra from 40 GHz to 990 GHz [45].

Figure 5: Measured estimation spectral noise floor as a function of the estimation algorithms [45].

explored minimum least square estimation (MLSE), generalized LASSO (with Ridge regression) and non-negative estimators. Fig. 5 demonstrates that LASSO and non-negative estimators can push down the estimation noise floor of C.W. signals by 10-15 dB to nearly -40 dB to -50 dB for a high estimation quality [45]. Such levels of sensitivity without any receiver architecture was achieved through the proposed co-design approach and exploration of the devices-EM-systems design space. The chip demonstrated the first fully integrated source-free spectroscopy across 40-990 GHz.

3.2 Programmable THz Sensor: Active EM Surfaces

The removal of the partition between the EM interface and electronics, that allows us to extract information from the incident fields, can also allow us to reconfigure the properties of the EM interfaces utilizing the embedded devices. The sensitivity of a THz sensor to the properties of the incident field is ultimately decided by the fundamental modes of the EM interface, that dictates its resonance features and its response to spectrum, angle of incidence and polarization. Secondly, the frequency dependent response also arises due to the interface between the EM structure and the detector circuits. The ability to distribute sensor arrays over the scattering surface can also now allow us to manipulate the local near-fields, and thereby re-engineer the current distribution on the surface [39].

Figure 6: Programmable THz sensor with sub-wavelength detection and reconfiguration. (a) Mapping digital sensor states to the optimal state for reception of the incident THz field across spectrum, angle of incidence and polarization. (b) The chip architecture implemented in a 65-nm CMOS process with an on-chip log-periodic scatterer and 16 sub-wavelength detectors. Each detector has a 5-state local reconfiguration capability leading to a total number of $5^{16} = 152.5$ billion sensor states. Optimal programmable reception against incident THz fields is now obtained by finding the optimal code setting [39].

To allow a programmable THz sensor, we can now dynamically reconfigure the EM surface to allow for optimal reception of the incident field. An example of this approach is shown in Fig. 6 that shows an electromagnetic scatterer with 16 sub-wavelength detectors interfaced with it directly. The detector array collectively absorbs the incident power distributed over the surface. Each detector boundary condition can be manipulated by a switched capacitor setting with thermometer-coded 5 bits leading to a total of $5^{16} = 152.5$ billion sensor states. To realize a fully programmable THz sensor, the key is now to map a subset of these possible states to optimal reception of the incident THz fields across spectrum, angle of incidence and polarization. This, of course, depends on the scatterer structure, location, and the number of detectors. We follow an optimization algorithm with randomized initial settings to navigate the non convex space. While details are included in [39], here, we show an example of the capability of the approach in a dynamic sensor reconfiguration. Fig. 7a shows that through programming the codes, the responsivity of the sensor and its beam configuration can be reconfigured for optimal broadside reception from 0.3 THz to 0.75 THz. The measured result for a 65-nm CMOS chip in Fig. 7b demonstrates that nearly 9x enhancement in responsivity across the frequency range can be achieved as the sensor is dynamically

Figure 7: Programmable THz sensor reconfiguration. (a) Dynamic reconfiguration of the detector states as the chip is reconfigured for optimal broadside reception from 0.3 THz to 0.75 THz. The circles represent the position of the detectors, the colors represent the detector configuration, and the sizes of the circles qualitatively illustrate the magnitude of the power absorbed. (b) Measured reconfigurable sensor response across 100 GHz-990 GHz showing up to 8.9x enhancement in responsivity through optimal code selections [39].

reconfigured for optimal states across 100 GHz-990 GHz. Similar enhancements have been observed for angle of incidence and polarization. While we demonstrate this co-design space with one example of a THz sensor programmable across all properties of the incident field, we believe that further exploration of this space can lead to break-through architectures and functionalities enabled through new design methodologies.

4 BITS TO TERAHERTZ: PROGRAMMABLE SOURCES AND SPATIO-TEMPORAL ARRAYS

4.1 THz radiating chip-scale source with dynamic spectrum shaping

The ultimate programmable THz source is one that has the capability to synthesize arbitrary fields with absolute control of spectrum, field configuration and polarization. A subset of this, in the form of beamforming arrays, have been demonstrated at THz frequencies [27]. Spectral control on the other hand can enable a new range of applications including hyper-spectral imaging, spectroscopy and sensing in complex environment. We demonstrate here with an example that allows radiated time-signatures with programmable time-evolutions ranging from broadband pico-second pulses to C.W. frequencies. As shown in Fig. 8, pulses of width (Δ_T) at a pulse repetition frequency of f_{rep} contains harmonics of f_{rep} where the spectral envelope follows the spectrum of the pulse shape and the phase

is ideally linear (constant group delay) extending up to the highest harmonic Mf_{rep} in the THz frequency range ($Mf_{rep} \sim \frac{1}{\Delta_T}$) [40, 41]. This is analogous to a mode-locked optical laser where the multiple harmonics align up in phase only for short intervals resulting in femtosecond pulses emanating from the output (Fig. 8). Therefore, the key towards reconfigurable generation of THz time-signatures is to harness multiple harmonics up to (f_0 to Mf_0) above f_{max} with simultaneous amplitude and phase control. When the harmonics align up in phase, sharp pulses are generated with time-widths given by $\Delta_T \sim \frac{1}{2nf_0} < \frac{1}{f_{max}}$. As an example, for a 65 nm bulk CMOS process with f_{max} of 190 GHz, pulse widths of the order of 1.31 picoseconds can be generated with harmonic control up to 380 GHz [43].

Figure 8: Fully integrated CMOS chip with THz signal synthesis and dynamic waveform shaping. (a) Amplitude and phase control of multiple harmonics for reconfigurable time-domain signal synthesis. (b) Array architecture with harmonic signals and delay control allowing radiated THz signal synthesis with dynamic spectral control [43].

Figure 9: Measured radiated THz signals with dynamically programmable time evolution from pico-second pulses to C.W. frequencies [43].

Eliminating the need for highly in-efficient amplitude control, phase control and filtering at THz frequencies, we achieve all of these simultaneously through free-space combining of multiple delayed versions of radiated harmonically rich signals (8). We showed that by expanding the number of channels one can achieve both amplitude and phase control of all the radiated harmonics through simple phase control at the fundamental. Fig. 9 shows the chip micrograph and the measured far-field radiated waveforms showing the ability to dynamically program the time-evolution of the

radiated THz signatures from pico-second pulses to C.W. frequencies [43].

4.2 Spatio-temporal control for physical layer security

In the previous example demonstrating dynamic spectral control in space, it can be noted that the spectral content of the radiated signal is dependent on the spatial angle of observation. Taking a cue from this approach, it can be shown that the ability to map spectrum into space can enable physical layer security techniques that incorporate security features in wireless links without the need for an explicit key exchange. The concept is illustrated in Fig. 10. A phased array based wireless link preserves constellation, spectrum and fidelity of information across all angles in space [3]. An eavesdropper at any of the side lobes (~ 15 dB lower) can therefore exploit this as an attack vulnerability with sensitive receivers [14]. With spatio-temporal control of the radiated fields, we show that one can preserve the fidelity of the signal at the direction of interest, while garbling up constellation and aliasing the spectrum at other directions to obfuscate eavesdropper attacks [19].

As shown in Fig. 11, this can be systematically achieved with spatio-temporal arrays that can modulate the radiating signals before the antenna to allow the signal to reconstruct in space at the direction of interest, while spectrally aliasing in other directions. In the example, we show a symbol-to-antenna mapping principle through this spatio-temporal modulated array, where each symbol ($S_1, S_2, \dots$) is mapped to each antenna ($A_1, A_2, \dots$). With the ability to incorporate on-chip digital-to-analog converters, more complex modulations can be synthesized that allows asynchronous or irrational chopping of symbols and mapping them into antennas to mitigate distributed attacks. Fig. 11 also shows the custom 2-element spatio-temporal array in 65-nm CMOS and the 4-element packaged antenna/CMOS chip interface. The figure shows the measured constellation and spectrum at the direction of interest and at various angles outside the main beam showing the spectral aliasing at the eavesdropper sites almost emulating noise-like spectrum [19]. Distributed eavesdropper attacks, while still possible, will require highly synchronized and coordinated attacks with a large number of eavesdroppers that is impractical [36]. Enabling such space-time control of the THz fields, therefore, can enable new functionalities and capabilities in wireless communication.

5 CONCLUSION

The wavelength/chip dimension equivalence that we experience in the THz regime opens up opportunities for new design methodologies exploiting a close EM-to-devices-to-systems co-design space. Architectures arising out of such an approach breaks many of the classical design trade-offs, but requires techniques harnessing advances in optimization methods and machine learning to fully explore the design space outside the realm of intuition based system design. We present several design examples that highlight this approach with new information processing systems, programmable THz sensors sources. The techniques are agnostic to the device technology to the first order, and can be translated to III-V based substrates to address even higher portions of the THz spectrum.

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Figure 10: Physical layer security in sub-THz directional links. (a) Phased array based wireless link where information spectrum and constellation is fully preserved outside the main beam. This can allow eavesdropper attacks with sensitive receivers. (b) Spatio-temporal modulated arrays that map into spectrum preserve the signal and constellation in the direction of interest, and enforce spectral aliasing and loss of information at the eavesdropper outside the main beam [19].

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Figure 11: Spatio-temporal modulated architecture and measured spectrum, constellation at the desired direction and measured spectral aliasing (leadign to information loss) and constellation garbling outside the main beam. The figure also shows the chipset demonstrating the 4-element spatio temporal modulated array operating across 71-76 GHz [19].

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