Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Monica La Mura *et al* 2024 *J. Phys.: Conf. Ser.* **2716** 012045

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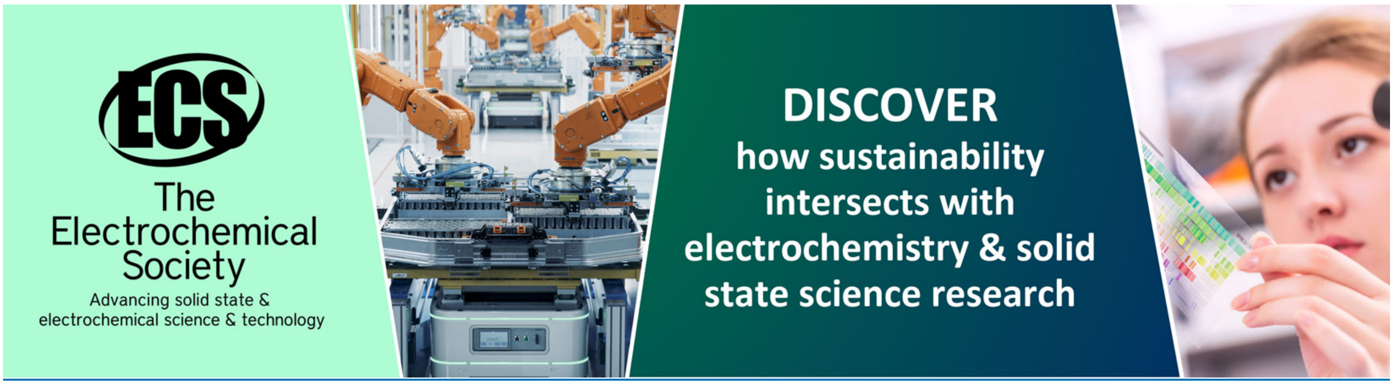

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Graphene Devices for Aerial Wireless Communications at THz

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Abstract. This paper investigates the state-of-the-art of graphene-based technologies for the prospective use cases of end-to-end terahertz (THz) communication systems, such as industrial Internet of Things (IoT) applications and unmanned aerial vehicles (UAVs). THz communications offer ultra-high throughput and enhanced sensing capabilities, enabling advanced applications like UAV swarms and integrated sensing, localization, and mapping. The potential of wireless THz communication can be unlocked by graphene technology. Graphene, owing to its remarkable electrical, thermal, and mechanical properties, emerges as a promising candidate for a multitude of applications in aerial wireless communications in the THz band, including high-speed electronic devices, tunable metamaterials, and innovative antennas. However, reliable tools for the simulation-based design of graphene components, able to account for the fabrication-related uncertainties, are still missing. This paper presents the envisaged possibilities of wireless communications in THz bands, overviews graphene devices for RF applications at THz, and discusses the open issues of modelling THz devices and THz channel.

1. Introduction

Recent advances in wireless communications and Internet of Things (IoT) open huge and promising perspectives for new applications for industrial facilities automation [1], [2] and intelligent autonomous vehicles (IAVs) including unmanned aerial vehicles (UAVs). Many Industrial IoT applications currently rely on either wired connection or Wi-Fi but fail to meet the ubiquitous service availability and the stringent criteria for latency and outage, whereas cellular technology possesses expensive licensing. 3GPP is actively working on New Radio in unlicensed bands for incorporating ultra- reliable low-latency communications (URLLC) into 5G and 6G communication networks. UAVs can strongly benefit from sensing and positioning capabilities offered by 6G systems in unlicensed bands at THz. The ultra-high throughput and enhanced sensing capabilities provided by THz communication may offer several opportunities [3],[4], opening the door for new services, such as advanced swarms of UAVs, where UAVs may need to exchange large amount of data to handle an increasing number of sensors to provide integrated sensing, localization, and mapping. However, THz technology is not yet mature enough to be commercially viable. This study aims at investigating the possibilities of end-to-end THz communication systems, as enabled by the novel graphene-based technologies. The principle diagram of such foreseen system is shown in Fig. 1.

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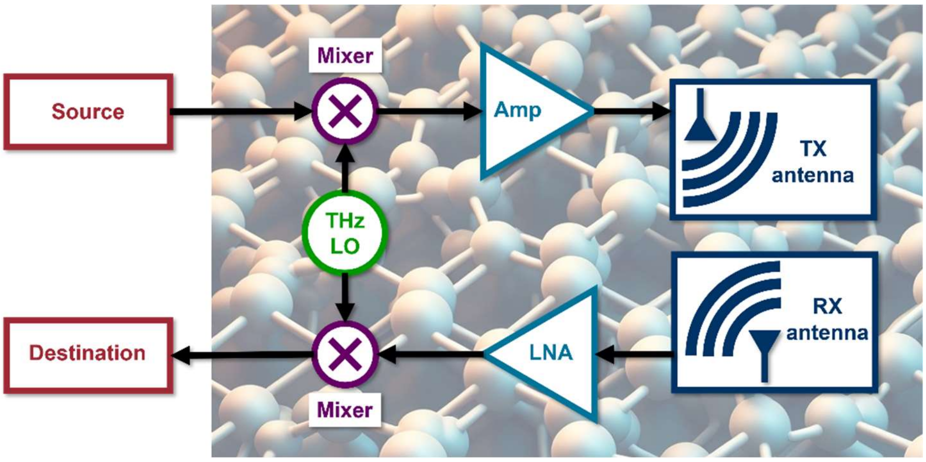


Figure 1. Principle diagram of a generic graphene-based wireless communication system: the source signal is mixed with the carrier generated by the local oscillator (LO), amplified (Amp), and provided to the transmitting (TX) antenna. The signal collected by the receiving (RX) antenna goes to the low-noise amplifier (LNA), is demodulated, and finally reaches the destination. Graphene is being considered to develop all the electronic system components.

Thanks to excellent electrical, thermal, and mechanical properties, graphene is regarded as the most valuable metal substitute material since its discovery [5]. It can be used in multiple applications of interest for aerial wireless communications, such as high-speed electronic devices (e.g. transistors for amplifiers [6], mixers [7], phase shifters [8], oscillators [9]) and tunable metamaterials [10] for both innovative antennas (e.g. reconfigurable multi-band antennas [11]) and photonic-inspired components [12] (e.g. absorbers, mirrors, detectors, polarizers, lens). Optimization of graphene-based components will provide significant energy savings, making THz technology green and sustainable. This study targets graphene-based electronic components supporting integrated THz communications and sensing for future 6G networks for application in the IAVs and UAVs scenarios. In Sec. 2, we describe use cases for THz wireless communications, discussing the need for standardization, THz-specific waveform design, and THz channel modelling. In Sec. 3, we present relevant graphene-based components for integrated sensing and communication (ISAC) at THz. In Sec. 4, we discuss the future developments expected to take graphene technology to the level of enabling THz wireless communications.

2. THz capabilities for 6G Communications

THz channels offer the promise of ultra-high data rates and low latency, making them a key enabler for next-generation communication systems in the rapidly evolving field of aerial vehicles, such as drones and autonomous aircraft. Nominal THz band is between 0.1-10 THz, but today most interest is attracted by the band 0.1-0.5 THz where a bandwidth from 10 to 100 GHz could be available.

Thanks to the progress in the last 10 years in efficient THz transceivers and antennas, such as those based on innovative carbon-based materials, new perspectives open for THz communication systems. The first IEEE 802.15.3d standardization efforts for sub-THz communications towards 6G were reported in [13], focusing on point-to-point links to support 100 Gbps over few centimeters to several hundreds of meters. Standardization of wireless communications systems in the THz band was initiated in 2008 by “Terahertz Interest Group (IGthz)” [14] in IEEE 802.15. In 2013, IEEE 802.15 TG 3d 100 Gbit/s Wireless was established in order to develop the first standard for 300 GHz wireless communication. It was released in 2017 as IEEE Std. 802.15.3d-2017 [15] for 100 Gbps wireless communication operating in the frequency range 252-321 GHz [13], [16] with bandwidths up to 69 GHz (starting from 2.16 GHz), featuring up to 69 overlapping channels between 252.72 GHz and 321.84 GHz. All these bands were cleared for THz use at the World Radiocommunication Conference (WRC)

2019 (160 GHz of spectrum). The Federal Communications Commission (FCC) has recently allocated 21.2 GHz of spectrum between the 116 GHz and 246 GHz bands for unlicensed usage. To finalise the standard, further technical contributions to the TG are evaluated on the reference channel models reported in the Channel Modeling Document (CMD), which, however, provides limited channel models centered around 300 GHz for specific scenarios, such as close proximity peer-to-peer communications, intra-device communications, wireless backhaul/fronthaul, and data center network. Channel modeling in the context of wireless communication for aerial vehicles, particularly when dealing with THz frequencies, presents a fascinating and intricate challenge. THz frequencies provide access to a vast amount of unused spectrum, but at the same time, they are highly susceptible to atmospheric absorption and scattering, making them particularly sensitive to weather conditions [17],[18]. The channel models for aerial vehicle THz communication must address several critical aspects, such as the dynamic nature of aerial platforms, their mobility, and the specific geometries and altitudes at which they operate. As we continue to push the boundaries of wireless communication, especially in the context of aerial vehicles, THz channel modeling will be at the forefront of innovation. To accelerate the standardization of the THz-band, further application-specific studies of THz channels are still greatly demanded. THz links will play a fundamental role to guarantee the extremely high data rates needed to transmit Extended Reality (XR) data for real-time applications as it could be the remote control of a UAV to perform unsafe, costly, or time-sensitive tasks for humans [19],[20]. In this case, THz links can be also used to sense the environment, thus offering remote cognitive capabilities that can be fundamental for highly precise interactive tasks and immersive experience [21]. Another key use case for THz links is represented by fully mobile and software-defined factory, which is one of the goals of the industry 4.0, where many industrial machines, sensors and robots will communicate cooperatively and with the access points to an advanced factory able of self-reconfigurability and autonomous operation [22]. In such a scenario, which requires a flexible, scalable, and reliable network to support the high volume of data traffic generated by machines, sensors, and robots, THz wireless links offer increased bitrates and low latency and the possibility to handle multiple simultaneous links. High bitrate and low latency requirements are also crucial for implementing Simultaneous Localization and Mapping (SLAM), a technique that enables a robot to create a map of an unknown environment while simultaneously locating itself within that environment [23], allowing robots to navigate autonomously.

THz links are gaining interest also for the so-called Non-Terrestrial Networks (NTN), where communication nodes might be UAV or satellite. We have already mentioned a scenario where THz links are used to control remotely an UAV using Augmented Reality (AR). UAVs are also envisioned to be integrated with the terrestrial networks in the beyond-5G era to enable various types of new network services as well as to assist in network operations. THz links could be enabled by the use of Reconfigurable Intelligent Surfaces (RIS) to harness non-line-of-sight (NLOS) connectivity between Base Stations (BSs) and UAVs. One THz-enabled use case is the one that foresees a swarm of UAVs to perform operations for 6G applications like surveillance, agriculture, military, search and rescue missions, and environmental monitoring. UAV swarms refer to a collective group of UAVs that operate in a coordinated manner, where individual UAVs collaborate and interact with one another to accomplish tasks efficiently and effectively [19],[20]. The use of swarms offers several advantages over single UAVs, including increased robustness, redundancy, scalability, and enhanced mission capabilities. In the above scenarios, each UAV needs to exchange large amount of data to transfer both sensing data and signaling data to coordinate the swarm. Ultra-high-throughput user-to-user (U2U) communication link can be provided in THz given the favorable line-of-sight (LoS) dominant propagation and the fact that UAVs can establish sufficiently close communication range to mitigate high path loss and molecular absorption. Finally, it is worth mentioning that for communication above-the atmosphere, THz do not undergo the typical attenuation due to the presence of water vapor molecules and other propagation effects. Therefore, they represent a natural candidate for inter-satellite links among LEO satellites to achieve ultra-high throughput with its broad spectrum [24].

Designing efficient THz-specific waveforms is crucial for unleashing the THz-band's true capabilities. At THz, bandwidth and spectral efficiency are not the priority. The waveform should instead guarantee low complexity, robustness to propagation and hardware impairments, Doppler spreads, and high-power efficiency. Many different waveforms have been studied for use in THz communication/sensing links. Ultra-wideband pulse-based modulations are serious candidates for THz communications in which short pulses in time span the entire THz range in frequency [25].

Good overviews of waveform design for THz can be found in [26],[27]. As already mentioned, the first sub-THz standard IEEE 802.15.3d offers two modes: (1) single-carrier (SC) modulation (long-range; high-rate) and (2) on-off keying (OOK) (low-complexity; short-range). OOK utilizes femtosecond long pulses that could span an ultra-wideband THz spectrum [28]. Several Single Carrier (SC) and Multi-Carrier (MC) techniques have been also considered and analyzed. In [27], authors analyze a plethora of SC/MC candidate schemes to be able to draw recommendations on the suitable waveforms for specific THz use cases. The paper recommends the use of DFT-s-OFDM and DFT-s-OTFS, but also CP-OFDM have been recommended in sub-THz indoor scenarios. An option that is gaining interest for high mobility scenarios is the OTFS waveform, that modulates the information in the delay-Doppler (DD) domain rather than in the Time-Frequency (TF) domain. While OFDM transforms a frequency-selective channel to multiple parallel frequency-flat subchannels, OTFS transforms a time-varying channel into a 2D quasi-time-invariant channel in the DD domain.

However, the above mentioned analyses have been done using either simplified channel models extrapolated by the channel models at lower frequencies, or using newly developed channel models for very specific application scenarios. To get more insights into the selection of the waveforms, more accurate channels models are needed but also a characterization of the HW impairments such as low output power, limited resolution of high-speed low-power Analog-to-Digital Converters and important Phase Noise (PN) introduced by the Local Oscillator. Few works have made analysis considering HW impairments [29],[30]. However, the models are very simplified, extrapolated by low frequency models and independent from the specific technology used for making the HW circuits and antennas.

A better characterization of the HW impairments will be crucial to make more meaningful selection of the waveform and physical layer.

3. Innovative components for THz communications

Wireless communication at THz frequencies was demonstrated in lab environments. The establishment of solid THz communication systems is limited by the lack of components able to generate, manipulate, and process THz signals in a stable and reliable way. Up to now, the highest data rates were achieved using photonic transmitters and III-V semiconductor compounds receivers [31]. However, the future of THz systems possibly lies in the combination of photonic and electronic devices [32]. Two-dimensional materials, such as graphene, are not transparent to THz radiation, and are therefore suitable to develop efficient components for THz communication [33]. Thanks to its unique electrical properties, graphene has been proposed for the design of THz antennas, modulators, detectors, amplifiers, mixers, and phase shifters.

3.1. Graphene Antennas

Graphene's unique electromagnetic properties enable miniaturized reconfigurable antennas, offering functional flexibility. These antennas have potential applications in Wireless Nano-Sensor Networks (WNSNs) and Wireless Network-on-Chip (WNoCs) [34].

Graphene-based antennas in the THz regime show versatility but can have reduced efficiency, mainly due to the challenges related to the manufacturing, e.g. to the growth and transfer of high-purity single-layer graphene. Designs proposed in the literature include dipole, slot, and patch antennas, each with distinct advantages. Dipole antennas offer simplicity and omnidirectional radiation, with tunability achieved through changes in graphene's chemical potential [11]. Slot antennas, fabricated by opening apertures in graphene layers, offer wideband performance and high directivity, and are therefore suitable for point-to-point communication. On the other side, their design is complex and the fabrication is challenging. Patch antennas, consisting of graphene patches on a dielectric substrate, provide versatility with high gain and ease of fabrication [35].

Additionally, graphene-based reconfigurable antennas can benefit from metamaterials and metasurfaces to improve radiated power and operational bandwidth. Metamaterials are artificial materials constructed from arrays of subwavelength unit cells. The geometric attributes of these subwavelength unit cells primarily dictate the electromagnetic properties of metamaterials, also called metasurfaces if the pattern variability pertains to one plane [36]-[39]. This characteristic enables significant flexibility in tailoring the electromagnetic response of metamaterials, which can therefore be engineered to meet specific targets. While metamaterials are engineered materials with unique electromagnetic properties, metadevices are practical applications of these materials designed to fulfil specific functions or tasks [40]. Hence, metadevices are functional devices or systems that leverage the unique properties of metamaterials to perform specific tasks or functions. They are electronic or optical elements enabled by metamaterials, designed to achieve desired functionalities. Metamaterials, metasurfaces, and metadevices based on graphene owe their tunable electromagnetic properties both to the designed pattern and to the peculiar property of graphene to change its electric conductivity according to the chemical potential, i.e. to the applied electric field [10].

High-performing graphene-based reconfigurable antennas have been proposed, enabled by intelligent reconfigurable metasurfaces and metamaterials. For instance, in [41], a reconfigurable Vivaldi antenna based on graphene load is described, showing wide bandwidth of 120% among 0.5 to 2 THz, and employing a hyperbolic metamaterial lens to focus the electric field and compensate for the graphene loss. In [42], two metasurfaces are designed to work as superstrate of planar THz antennas, achieving 8 dB gain improvement and 12% efficiency enhancement at 1 THz, and exploiting graphene strips to tune the response of the antenna.

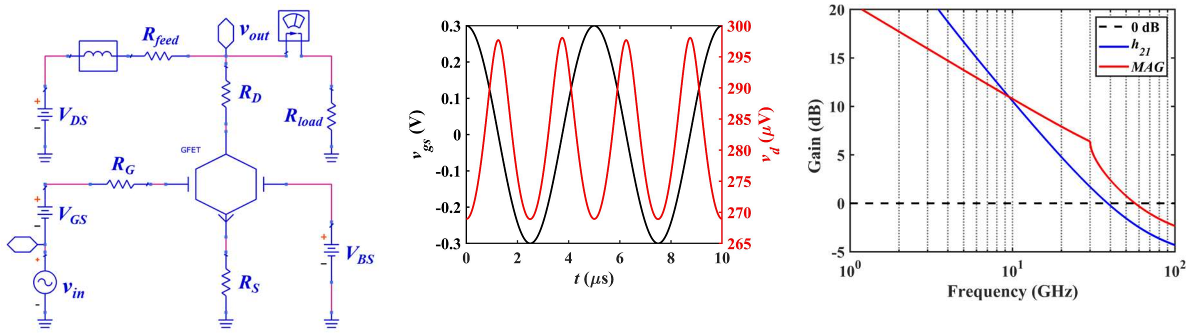
3.2. High-frequency RF electronic circuits

Graphene-based electronic circuits utilise Graphene Field-Effect Transistors (GFETs) as their basic component [43]. GFETs are characterised by high carrier mobility, low power consumption, and potential for miniaturization. Therefore, there is a strong interest for GFETs aiming at high-speed electronic circuits that can enable THz wireless communication systems. A GFET consists of a layer of graphene on a substrate, covered by an oxide layer. The gate contact on top of the oxide provides the voltage that controls the flow of current across two points of the graphene channel, i.e. the drain and source contacts. The graphene can be either single-layer or bilayer. Single-layer graphene lacks a natural bandgap to enable current saturation, but using an ultrathin top gate high-k dielectric can partially overcome this limitation [44]. GFETs find their natural application in RF wireless communication due to their unique ability to control both electron and hole conduction, i.e. they can switch between p-type (hole-based) and n-type (electron-based) behaviour by varying the gate voltage. This ambipolar capability has led to the development of single-device circuits in place of traditional multi-transistor circuits, offering advantages in terms of reduced area, mass, and power consumption.

For example, a frequency multiplier can be obtained by using only one graphene transistor. The schematic of a single-device GFET-based frequency doubler is shown in Figure 2(a). To demonstrate the frequency multiplication capabilities, the circuit was simulated by means of a commercial circuit simulator considering a GFET device with channel length $L = 500$ nm and width $W = 30$ µm, gate voltage offset $V_{\mathrm{GS0}} = 2$ V, saturation velocity $v_{sat} = 2\mathrm{x}10^7$ cm/s, mobility $\mu = 2000$ cm^2/V·s, potential inhomogeneity $\Delta = 0.1$ eV, contact resistance $\rho = 180$ Ω·µm [45]. When an input sine wave ($v_{in} = V_{in} \sin(2\pi ft)$) is applied to the top gate ($v_{gs} = v_{in}$), the quadratic relation between the drain current and the gate voltage produces a doubled-frequency voltage signal ($v_d \propto \sin^2(2\pi ft)$) on the load resistor ($R_{load} = 50\ \Omega$) at the drain terminal. The input and output signal of a GFET frequency doubler, obtained by circuit simulations, are shown in Figure 2(b).

GFETs have shown potential as high-frequency amplifiers, although their performance is not yet on par with Silicon or III-V compound transistors. The main figures of merit used to evaluate the quality of a RF amplifier are the transition frequency, f_{T} (0-dB crossing frequency of the short-circuit current gain, h_{21}), and the maximum oscillation frequency, f_{MAX} (0-dB crossing frequency of the maximum available gain, MAG). The high-frequency amplification performance of the same GFET of Figure 2(a) was assessed by circuit simulation, computing the h_{21} and MAG shown in Figure 2(c). The obtained transition frequency is $f_T = 38.2$ GHz and the maximum oscillation frequency is $f_{MAX} = 56.8$ GHz. These values are not competitive with the state-of-the-art RF amplifiers, although better-performing GFETs with $f_T > 100$ GHz and $f_{MAX} > 70$ GHz have been demonstrated [6]. It is also important to notice that the high-frequency performance of GFETs is strongly impaired by the fluctuations of the design parameters related to the fabrication issues [46],[47].

GFETs can also be used to design RF phase shifters [8], used for instance to modulate the RF signal phase for the beamforming in phased array antennas, and ring oscillators [9], as local oscillator for the carrier signal generation



(a) (b) (c)

Figure 2. (a) Schematic of a single-device GFET-based frequency doubler. (b) Input and output signal of the simulated GFET frequency doubler at $f_{in} = 200$ kHz. (c) GFET Simulated short-circuit current gain (h_{21}) and maximum available gain (MAG).

4. Conclusions and future developments

This paper presented the state-of-the-art of graphene-based technologies for the prospective use cases of future THz communication systems, such as industrial Internet of Things (IoT), Extended Reality and Non-Terrestrial Networks (NTN). Due to the availability of tens of GHz of unlicensed bands, THz transmissions may provide joint ultra-high throughput communications and enhanced sensing, enabling advanced applications like UAV swarms and integrated sensing, localization, and mapping. In this paper, we proposed an accurate evaluation of the remarkable electrical, thermal, and mechanical properties of graphene technology to demonstrate the feasibility of high-speed electronic devices and components that could be proficiently used in the context of wireless THz communications, unlocking its great potential. Of course, open issues and challenges still remain in the modelling of THz devices and THz channels, especially to account for fabrication-related uncertainties. Future work includes investigations on the communication channel and waveforms for 300-450 GHz integrated communication and sensing in 6G scenarios, potential improvements in systems modelling, e.g., electronic devices and antennas, study of the effect of fabrication tolerance, sensitivity analysis and robust design by considering uncertain parameters. Including process-related tolerance and variability in simulation models during the design phase will support the transition to industrial-scale production by enabling designers to assess the impact of manufacturing imperfections and make informed choices. This approach will have an impact on the device design for industrial production, beyond the scientific interest by research community.

Acknowledgments

This work was partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on “Telecommunications of the Future” (PE0000001 - program “RESTART”), Horizon 2020 research and innovation programme under Graphene Flagship GA No 881603, and PRIN-PNRR-2022 UPWARDS CUP E53D23014490001.

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