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Tunable Graphene-based Metasurfaces for Multi-Wideband 6G Communications

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Abstract – **The next generation of wireless communications within the framework of 6G will be operational at the low THz frequency band. Although THz systems will dramatically enhance several performance indicators such as the data rate, spectral efficiency, and latency, exploiting such technology is challenging. Electromagnetic waves confront severe propagation losses including atmospheric attenuation and diffraction. Thus, such communications are limited to line-of-sight scenarios. In 5G networks, Reconfigurable Intelligent Surfaces (RISs) are introduced to solve this issue by redirecting the incident wave toward the receiver and implement *virtual*-line-of-sight communications. In this paper, we aim to employ this paradigm for 6G networks and design a graphene-based RIS optimized to perform at *multiple* low atmospheric attenuation channels. We investigate the performance of this multi-wideband design through numerical and analytical analysis.**

I. Introduction

The arrival of the fifth-generation (5G) of mobile and wireless communication systems is promising a plethora of technologies. Yet, while 5G networks are still being deployed, the sixth generation (6G) is already under intense development to satisfy the ever-growing communication demands. It is expected the 6G networks will need to enter the low Terahertz band (0.1–1 THz) to increase the data rate, the network efficiency, the area traffic capacity, while cutting down the latency with respect to 5G networks [1]. If it is successful, THz band communications would enable current networks to access unprecedented spots, bridging them with nanonetworks ranging from human body implants to air-space networks [1]. Consequently, 6G is expected to play a key role in the future of transportation, providing immersive experiences, and developing medical procedures.

However, in contrast to its advantages, THz band communications has to solve serious challenges to achieve the aforementioned goals. Among them, very large attenuation due to spreading loss, penetration loss, and molecular absorption which is crucial in the THz band. These factors impose the use of highly directive antennas which is not trivial in THz band and strong Line-of-Sight (LoS) requirements that are hard to meet in dense scenarios. To communicate with mobile users, the source usually uses a static beamforming radiation pattern that distributes the Electromagnetic (EM) wave in a wide space. So, the received energy by the users is weak, and the established link is incompatible with 6G standards.

Nevertheless, the concept of Reconfigurable Intelligent Surfaces (RISs) has been widely regarded as a promising solution to provide reliable, fast, and versatile communications at THz frequencies [2]. A RIS is composed of an array of tunable unit cells whose collective response allows to control the strength, direction, and shape of the reflected waves. If the separation between unit cells is much smaller than the wavelength, such an array is referred to as a metasurface (MS). By implementing multi-channel RISs with dynamic beamforming, the incident waves from the source can be redirected toward the user with increased directivity.

The constituting unit cells of an MS-based RIS that can communicate at multiple THz bands concurrently, need to be widely tunable to provide the required amplitude/phase response at the operational THz bands. Tuning mechanisms used in lower frequencies are slow and bulky hence ineffective for THz bands. Instead, graphene is an excellent candidate for this purpose thanks to its optoelectronic properties, which allow the development of

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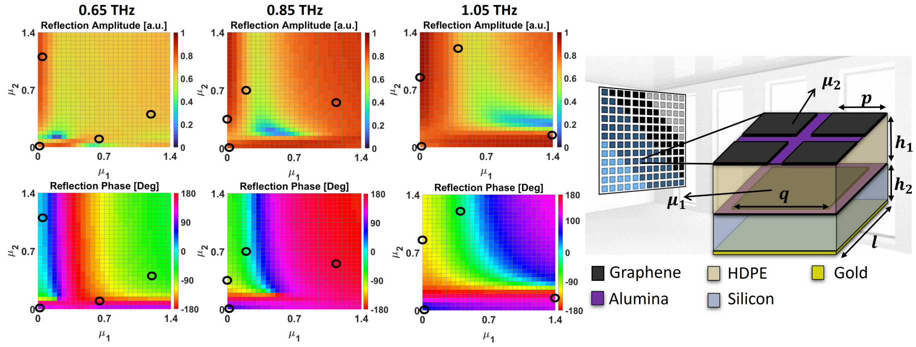

Fig. 1: Schematic representation of the unit cell layout. This unit cell is composed of two dielectric layers, four parasitic graphene patches on top (μ_2 is the corresponding chemical potential) and one graphene sheet (μ_1 is the corresponding chemical potential) sandwiched between the dielectrics. The unit cell is back plated with a thin layer of gold. The color maps are showing the reflection characteristics of the unit cells versus chemical potentials (μ_1 and μ_2) at respective operation frequencies 0.65 THz, 0.85 THz and 1.05 THz. Black circles represent the selected 4-states covering 2π phase range and high reflection amplitude.

ultrafast and highly integrative devices whose resonance can be tuned within a wide range [3]. In spite of their potential, work on graphene-based MS design has been mainly limited to a single functionality with a single-band operational frequency [4, 5]. In this paper, we present and evaluate a RIS design capable of operating at *three distinct bands* based on a widely tunable graphene-based MS.

II. Graphene-based Multi-Wideband Metasurface

Graphene's tunability margin begins to degrade in the lowest THz frequencies. At the same time, due to the resonances of water molecules in THz frequencies, we need to be very careful about the selection of the operating frequency. Also, it is evident that high frequencies are more prone to propagation losses. In light of the above, three channels including 0.65, 0.85, and 1.05 THz are selected. To realize multi-band communication with MS-associated RIS, we need to design a unit cell that resonates at these frequencies and provides a wide reflection phase margin. Fig. 1 shows the proposed unit cell whose lateral size is ($l = \lambda/10$) small enough to allow for fine resolution of the reflection phase profile. The unit cell consists of a multi-layer structure with four parasitic graphene patches ($p = 15$ µm) atop an alumina layer with 0.1 µm thickness. Synthesis of graphene/alumina composite improves the strength, toughness, and wear-resistance of the structure with a low-cost process. This composite is stacked on high-density polyethylene (HDPE) substrate, due to its particularly low loss in the THz band. HDPE permittivity is $\epsilon_r = 2.37$ and its thickness is selected $h_1 = 15$ µm. The combination of graphene and HDPE leads to high electrical conductivity with good thermal and mechanical properties. Another layer of graphene/alumina composite ($q = 20$ µm) is sandwiched between HDPE and silicon ($h_2 = 10$ µm) to allow for supporting multiple resonances and, thereby, to operate in three disjoint bands.

The frequency and reflection phase of a graphene-based unit cell can be controlled via changes in its biasing voltage. This is modeled through the frequency-dependent surface conductivity of graphene $\sigma(f)$, which in the THz band is given by

$$\sigma\left(f\right) = \frac{e^2\mu}{\pi\hbar^2}\frac{i}{2\pi f + i\tau^{-1}}, \tag{1}$$

where e and $\hbar$ are constants, while μ and τ are variables that correspond to the chemical potential and the relaxation time of the graphene layer, respectively [3]. The relaxation time of graphene is assumed to be $\tau = 1$ ps, which has been considered in multiple works and is realizable with state-of-the-art fabrication and encapsulation techniques. All full-wave EM simulations at the unit-cell level were conducted in CST Microwave Studio (frequency domain solver). We explore the chemical potential design space by sweeping the values of μ_1 and μ_2 in the three desired operational frequencies (see Fig. 1). Hence, by controlling the bias voltage we can tune the reflection characteristics. The Huygens-Fresnel principle allows us to evaluate the scattering pattern of the MS for a given configuration as the aggregated response of its unit cells to a given incidence (frequency, polarization, wavefront

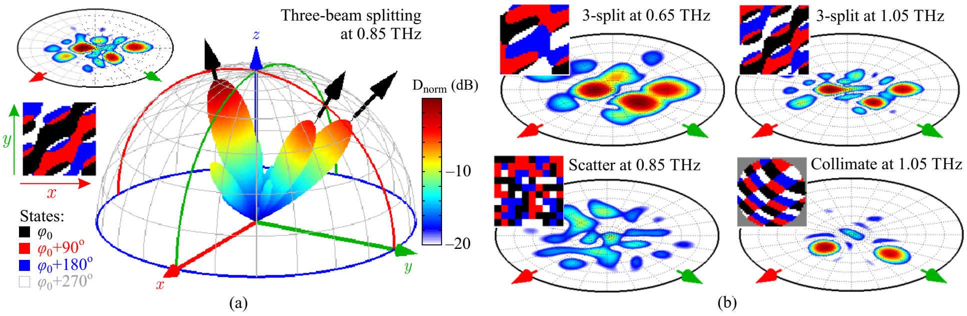

Fig. 2: A set of scattering patterns assuming 40×40 35 µm-wide cells; scattering heatmaps are normalized to theoretical maximum directivity. (a) 3D scattering pattern of a normally incident 0.85 THz plane-wave, split/steered in 3 predetermined directions: $(\theta, \varphi) = (15°, 315°)$, $(30°, 90°)$, and $(45°, 135°)$; left-hand insets depict the cylindrical-coordinate representation of the same pattern, the orthogonal color-coded view of the MS cells configuration, and the color-mapping of the phase-states. (b) MS configuration and corresponding cylindrical scattering pattern for various supported functionalities, clockwise from top left: 3-beam splitting at various frequencies, collimation/steering of a spherical wavefront towards two distinct directions, and diffused scattering.

shape, and direction) [6]. Tuning of the two voltages applied at each mn-cell alters graphene's local $\mu_{1,2}$ and consequently the cell's response. In Fig. 2, we present scattering patterns for normal illumination that demonstrate the potential of the proposed multi-wideband multi-functional RIS, assuming 40×40 35 µm-wide cells. This figure contains a selection of configurations and functionalities interesting in 6G contexts, demonstrated in three different frequencies.

III. Conclusion

The concept of multi-wideband MS in the THz band has been explored in an attempt to extend the RIS paradigm to 6G networks operating at multiple frequencies concurrently. Embedding multiple layers of graphene into the design of the unit cells allows for reconfiguring the local reflection phase at multiple frequencies by tuning the biasing voltage of each layer independently. With the aggregated response of the unit cells within the MS, we show that beam steering, beam splitting, diffused scattering, and collimation functionalities can be achieved at the desired frequencies (i.e., 0.65, 0.85, and 1.05 THz), which are characterized by low atmospheric attenuation.

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