Modeling and Performance Analysis of a Reconfigurable Plasmonic Nano-Antenna Array Architecture for Terahertz Communications

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ABSTRACT

Terahertz-band (0.1 to 10 THz) communication is envisioned as a key wireless technology to satisfy the need for much higher wireless data rates. Recently, the use of nanomaterials such as graphene is enabling the development of novel plasmonic devices, which intrinsically operate in the THz band. In this paper, a new antenna array architecture that leverages the properties of graphene-based plasmonic devices is proposed. In this array architecture, each element consists of a plasmonic front-end integrated by a THz plasmonic signal source, a THz plasmonic direct signal modulator, and a THz plasmonic nano-antenna. The possibility to directly modulate the signal without using frequency up-converters or sub-harmonic mixers leads to very compact front-ends, which can be much more densely packed than with traditional THz technologies. After presenting the THz plasmonic nano-antenna and THz plasmonic modulator models, the performance of an integrated front-end is numerically investigated. In addition, the beamforming and beamsteering capabilities of a 2x2 array are numerically investigated and discussed.

CCS CONCEPTS

• **Hardware → Wireless devices**; **Plasmonics**; *Beamforming*; *Simulation and emulation*; *Emerging architectures*;

KEYWORDS

Terahertz Communication, Antenna Arrays, Graphene Plasmonics

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1 INTRODUCTION

Terahertz-band (0.1 to 10 THz) communication is envisioned as a key wireless technology to satisfy the need for much higher wireless data rates [2, 6]. Despite the absorption by water molecules, the THz band exhibits multiple transmission windows which are each several tens of GHz wide. The lack of compact high-power signal sources and high sensitivity detectors able to work at room temperature has traditionally hampered the use of the THz band for applications beyond sensing. However, many recent advancements are closing the so-called THz gap. Among others, the use of nanomaterials such as graphene [7] is enabling the development of novel devices, which intrinsically operate in the THz band.

Graphene is a one atom thick layer of carbon atoms in a honeycomb lattice, which has attracted a lot of attention in the scientific community due to its very unique electronic properties. Among others, it has been shown that its conductivity at THz-band frequencies drastically changes with the dimensions and chemical potential, which can be utilized to create frequency tunable devices [4, 8]. Furthermore, graphene supports the propagation of surface plasmon polariton (SPP) waves at THz-band frequencies [12, 15]. SPP waves are confined electromagnetic (EM) waves coupled to the surface electric charges at the interface between a metal and a dielectric, and have been shown to have a wavelength orders of magnitude shorter than that of free-space EM waves. By leveraging the unique plasmonic properties of graphene (i.e., tunability and highly confined wavelength), novel graphene-based communication devices can be developed which operate at THz-band frequencies.

Among others, a THz-band nano-transceiver has been proposed which tackles the issue of a lack of compact high-power signal sources [11]. This device, which is based on a high electron mobility transistor built with III-V semiconductors and enhanced with graphene, is able to generate SPP waves at THz frequencies by taking advantage of the Dyakonov-Shur instability principle [13, 17]. A plasmonic phase modulator has also been developed, which exploits the electrical tunability of graphene to modulate a propagating SPP wave without the need of sub-harmonic mixers prior to being radiated [16, 19]. Finally, a graphene-based plasmonic nano-antenna, which can be thought of as a plasmonic waveguide with lossy ends, has been developed to effectively launch SPP waves in free space [3, 10]. Used in conjunction, these devices form a complete THz front-end for THz communications.

Despite their efficiency, the low transmission power of THz sources and the small size of THz antennas turn increasing the

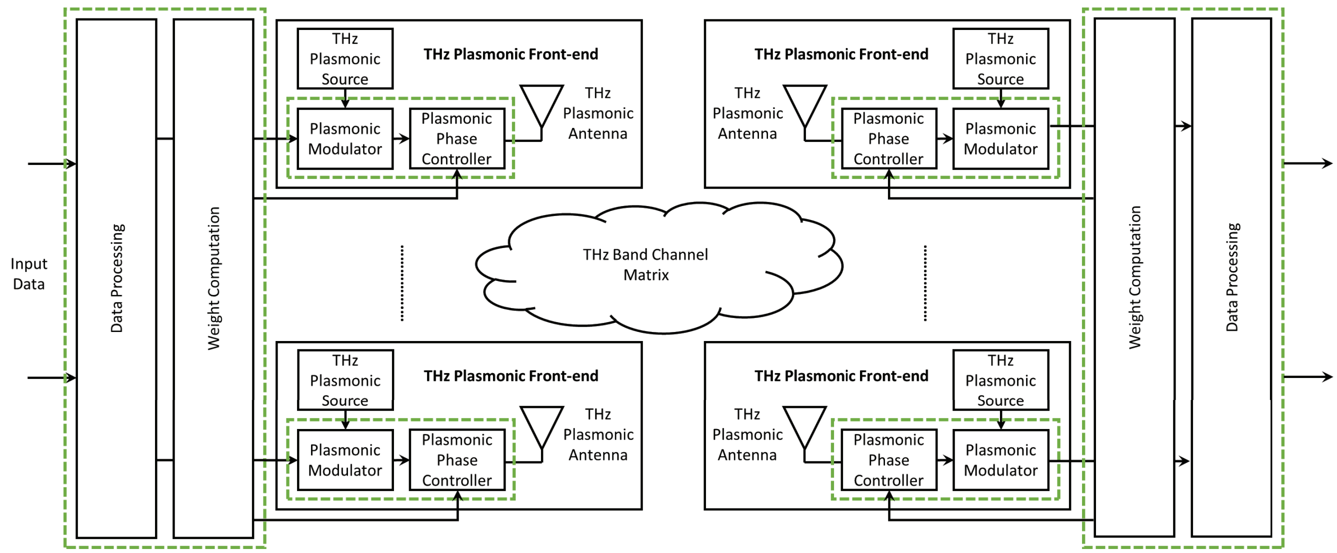

Figure 1: Schematic of the proposed plasmonic nano-antenna array architecture.

transmission distance into a challenging problem for THz communications. However, recent work has demonstrated that graphene-based plasmonic nanoantennas can be packed into very dense arrays, allowing for higher energy output through beamforming gain [21] and are at the basis of ultra-massive MIMO systems [1]. This work showed that graphene-based plasmonic nano-antennas can be placed as close as their plasmonic wavelength without any significant mutual coupling, as opposed to the free-space wavelength separation required of classical antennas.

Existing analysis have been focused on looking only at individual elements (i.e. transceiver, modulator or antenna) or antenna array. This paper numerically investigates the performance of a fully-plasmonic antenna array architecture, in which each radiating element is modeled as an integrated THz modulator and THz antenna. Full-wave simulations with COMSOL Multi-physics are utilized to design and illustrate the performance of a binary plasmonic phase shifter, a plasmonic nano-antenna, and the plasmonic front-end resulting from their integration. Then, an array of front-ends is simulated to investigated the beamforming capabilities of the resulting system.

The remainder of the paper is organized as follows. In Section 2, we introduce our novel graphene-based plasmonic antenna array architecture. We describe the detailed antenna design and modulator design in Section 3 and Section 4, respectively. In Section 5, we investigate the beamforming performance and generated radiation patterns of an array of plasmonic front-ends. In Section 6, we draw up some conclusions and discuss the future steps to realize this technology.

2 ANTENNA ARRAY ARCHITECTURE

A new antenna array architecture has been developed that leverages the key features of THz plasmonic devices (Figure 1). The proposed architecture differs from traditional digital and analog architectures in many ways. In analog architectures, the modulated baseband signal is up-converted to the target center frequency and split into N transmission lines, each with its phase controller, power amplifier and antenna. In digital architectures, the amplitude and phase control is applied to each of the N baseband signals, before being up-converted. This approach provides the maximum control on the transmitted signals, but requires N up-conversion chains. Hybrid architectures, in which some of the phase and amplitude control is done in baseband and others are done after up-conversion, have also been proposed.

Instead, in this novel architecture, the modulation, amplitude and phase control are directly applied to the carrier signal, i.e., there is no up-conversion but direct modulation of the carrier signal. As illustrated in Figure 1, the modulation and phase control can be done in sequential blocks, or, ideally, with a single plasmonic phase modulator [14]. Such devices allow the continuous control of phase, but does not allow the control of the amplitude. Given the lack of power amplifiers at THz frequencies, the only way to control the amplitude of the signal radiated by each antenna is by controlling the THz source itself. The Dyakonov-Shur principle by which the THz plasmonic source is governed, is a non-linear process which can only be switch on or off, i.e., it does not allow continuous support of the amplitude [11].

To dynamically operate the array, the derivation of the array weights that maximize the gain in the intended direction while minimizing the side lobes can be formulated as an optimization problem with architecture specific constraints. To create a highly directional beam pattern, the expected total received beam power will be minimized while ensuring unity gain in the desired beam direction so that the signal of interest is not eliminated. The solution to this optimization problem is certainly non-trivial, and is the subject of on-going future work. In this work, we focus on the design and performance analysis of the architecture in light of the plasmonic device physics.

3 ANTENNA DESIGN

The proposed graphene-based plasmonic nano-antenna resembles a nano-patch antenna, and it is composed of a graphene-layer (the active layer), a metallic ground plane and a dielectric layer in between. As with traditional patch antennas, the plasmonic nano-antenna can be thought of as a plasmonic waveguide with lossy ends. The performance of the plasmonic nano-antenna depends on the propagation properties of the SPP waves on the graphene layer, which in turn depend on the conductivity of the graphene layer. By using the surface conductivity model for infinitely large graphene sheet obtained using the Kubo formalism [5, 9], the graphene's conductivity can be written as:

$$\sigma^g = \sigma^g_{\text{intra}} + \sigma^g_{\text{inter}}, \tag{1}$$

$$\sigma^g_{\text{intra}} = i\frac{2e^2}{\pi\hbar^2}\frac{k_BT}{\omega + i\tau_g^{-1}}\ln\left(2\cosh\left(\frac{E_F}{2k_BT}\right)\right), \tag{2}$$

$$\sigma^g_{\text{inter}} = \frac{e^2}{4\hbar}\left(H\left(\frac{\omega}{2}\right) + \mathrm{i}\frac{4\omega}{\pi}\int_0^\infty \frac{H(\epsilon) - H(\omega/2)}{\omega^2 - 4\epsilon^2}\,d\epsilon\right), \tag{3}$$

with

$$G(a) = \frac{\sinh(\hbar a/k_BT)}{\cosh(E_F/k_BT) + \cosh(\hbar a/k_BT)}, \tag{4}$$

where $\omega = 2\pi f$ is the angular frequency, $\hbar = h/2\pi$ is the reduced Planck's constant, e is the electron charge, k_B is the Boltzmann constant, T is temperature, τ_g is the relaxation time of electrons in graphene, and E_F refers to the Fermi energy of the graphene sheet.

As is the case in the following design, this model is accurate for graphene strips larger than 50 nm in each direction, and within the long wavelength limit (i.e. $\omega \gg k_{spp}v_f$, where k_{spp} is the SPP wave number and $v_f \sim 8 \times 10^5 m/s$ is graphene's Fermi velocity) [18]. With this model, the propagation properties of SPP waves on graphene can be determined by solving the following dispersion equation:

$$-i\frac{\sigma^g}{\omega\varepsilon_0} = \frac{\varepsilon_1 + \varepsilon_2\coth(k_{spp}d)}{k_{spp}}, \tag{5}$$

where ε_1 is the relative permittivity of the dielectric above graphene, ε_2 is the relative permittivity of the dielectric between graphene and the ground plane, and d is the separation distance between graphene and the ground plane.

The reference nano-antenna design in our analysis is shown in Figure 2. COMSOL Multi-physics is utilized to simulate the behavior of a graphene-based plasmonic nano-antenna by modeling the graphene layer as a transition boundary condition having the conductivity defined above. The design is a 9 μm by 15 μm patch of graphene with E_F = 1.25 eV and τ = 0.5 ps (based on analysis of Raman spectra for CVD-grown graphene) [20], on top of a 90 nm-thick SiO_2 layer, resting on a metallic ground plane with a 9.9 μm feedline, all at room temperature (300 K). Figure 3 illustrates the S11 parameter of this nano-antenna as a function of frequency. The result shows that this antenna is resonant at 1.03 THz, which corresponds to the center of the first absorption-defined transmission window above 1 THz, and has a confinement factor $\gamma \sim 20$, in line with what is expected for realistic graphene-based nano-antennas. The reflection coefficient seen in Figure 3 is not fully optimized, as this antenna was designed under the assumption that a feed network could be made to match the antennas impedance, but this in fact set by the output impedance of the modulator, described in the next section.

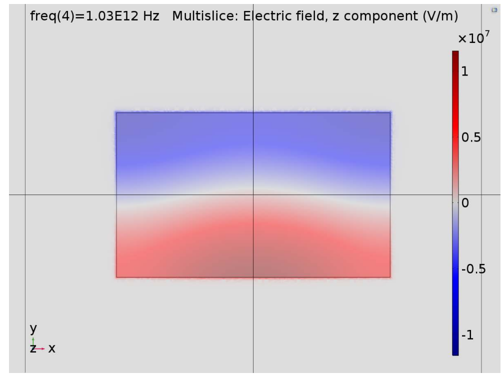

Figure 2: Graphene-based nano-antenna resonant at 1.03 THz.

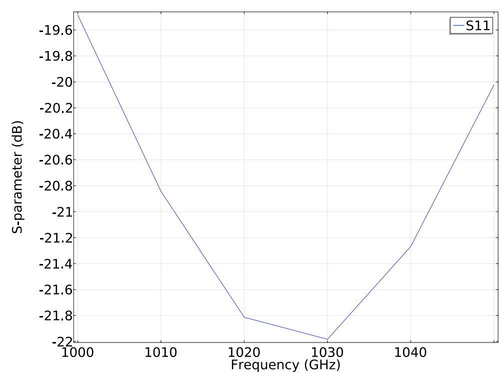

Figure 3: Reflection coefficient of graphene-based plasmonic nano-antenna as a function of frequency.

4 MODULATOR DESIGN

As was first introduced in [19], the working principle of the modulator relies on the fact that, by tuning the chemical potential of the graphene layer, or Fermi energy E_F, the SPP wave velocity can be modified. By this mechanism, the modulator acts as a delay line to change the phase of SPP waves entering the graphene-based plasmonic nano-antenna. The graphene layer in the modulator is modeled in COMSOL Multiphysics the same way as the antenna, only now with a variable Fermi energy. In our reference design, the size of the modulator is set to 6 μm long by 9.9 μm wide to fit with the dimensions of the graphene-based nano-antenna described above. This design allows continuous control of the SPP phase radiated by a single antenna. As an example, Figure 4 illustrates a phase change of π on the antenna by switching the modulator between Fermi energies of 0.15 and 0.65 eV.

Given the nature of the device, a feeding network cannot be perfectly impedance matched to the modulator. For the values shown

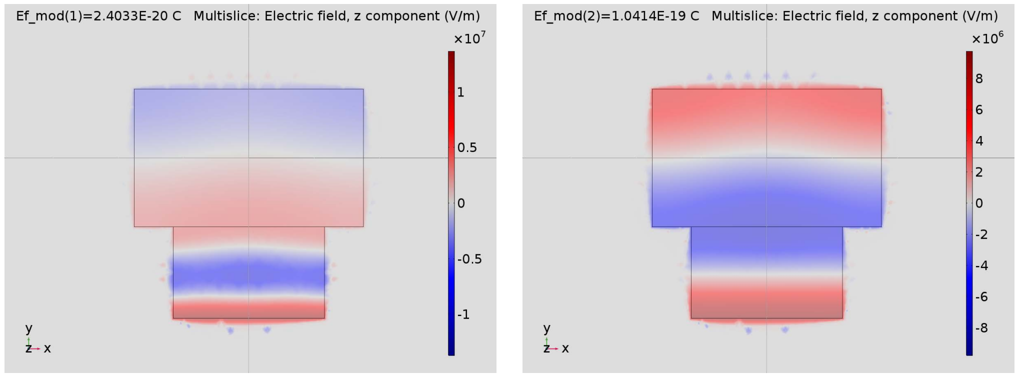

Figure 4: Nano-antenna front end with modulator set to (left) E_F = 0.15 eV and (right) E_F = 0.65 eV.

in Figure 4 (0.15 and 0.65 eV), the antenna front end has a characteristic impedance of 33.4 and 18.7 Ω, respectively. Therefore, the feed network should have a characteristic impedance within this range that is sufficient for all values that may be used in operation. For instance, using a feedline impedance equal to 22.6 Ω yielded acceptable radiation behavior for both values, with S11 equal to approximately 15 dB and radiated power equal to in the order of 0.1 μW. While these values can be used to create orthogonal symbols, continuous phase control using non-discrete Fermi energies is also possible, and will allow beamforming when used in an array.

5 BEAMFORMING PERFORMANCE ANALYSIS

In this section, we numerically analyze and discuss preliminary results related to the beamforming abilities of the proposed antenna array architecture. Although graphene-based plasmonic nano-antennas can be operated in an extremely dense array (spacing equal to the plasmonic wavelength on graphene [21]), due to computational complexity, we focus our analysis on a sparse array (with spacing equal to the 1.03 THz free-space wavelength) with 2x2 elements. The results can be extrapolated to an array with the same footprint but more elements to display similar beamforming patterns with higher radiated power. Figures 5 and 6 illustrate the directionality of a 2x2 array, as well as how beam steering is enabled by the modulators ability to perform continuous phase control.

The 2x2 array is further illustrated in Figure 7 (left), which shows what the EM wave would look like on each antenna for energy states that may be used during continuous phase modulation (arbitrarily chosen as follows: top left E_F = 0.65 eV, top right E_F = 0.35, bottom left E_F = 0.25 eV, bottom right E_F = 0.15 eV). Using these carefully selected energy states, one can see from the radiation patterns in Figure 7 (middle and right) how the amplitude of side lobes is altered by varying the plasmonic phase modulators Fermi energy. These results demonstrate the possibility to perform beamforming with co-designed plasmonic phase modulators and antennas, without the need for separate phase shifters.

6 CONCLUSION AND FUTURE WORK

In this paper we proposed a novel antenna array architecture where modulation is applied directly to the signal source without the need for up-converters or sub-harmonic mixers, and front-ends can be packed much more densely than classical antennas. Antenna and modulator has been designed and simulated with COMSOL Multiphysics to operate in the THz-band, and allow continuous phase control. An assembly of 2x2 elements is utilized to demonstrate the beamforming and beamsteering capabilities. Future work will focus on incorporating the THz signal source to complete the fully-plasmonic front-end model, in addition to investigating the time delay associated with beamforming and steering.

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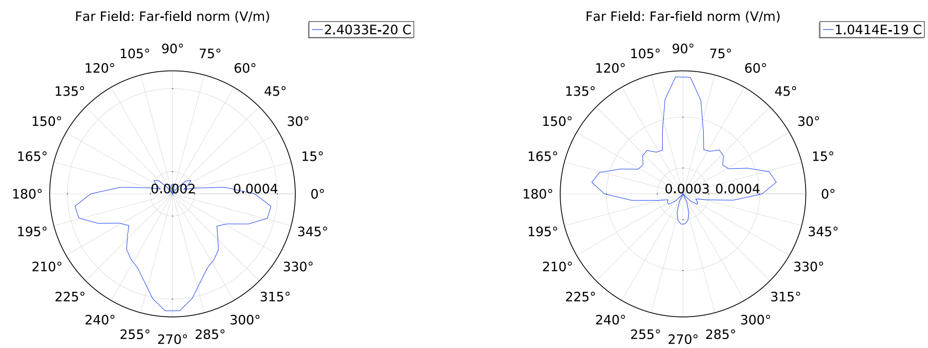

Figure 5: 2D far field of xy-plane for 2x2 array, all modulators (left) E_F = 0.65 eV and (right) E_F = 0.15 eV.

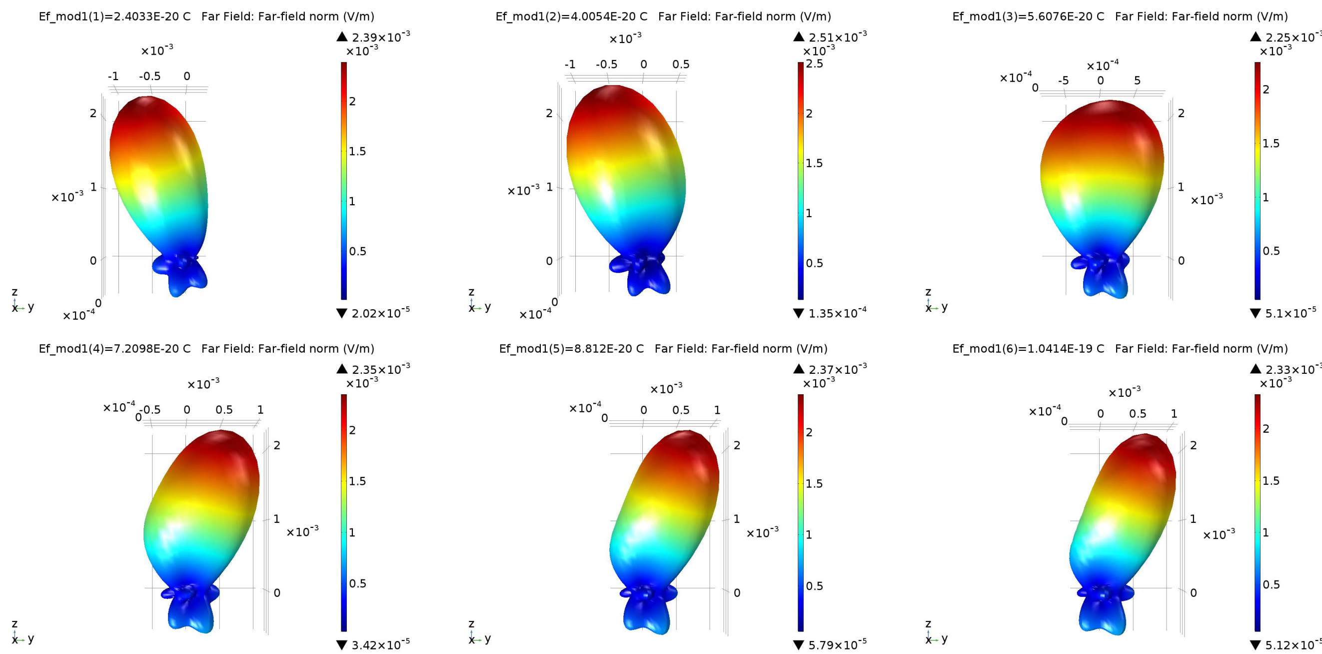

Figure 6: 3D far field of yz-plane for 2x2 array, incremental E_F change by 0.1 eV from 0.15 eV to 0.65 eV (increasing left to right, top to bottom).

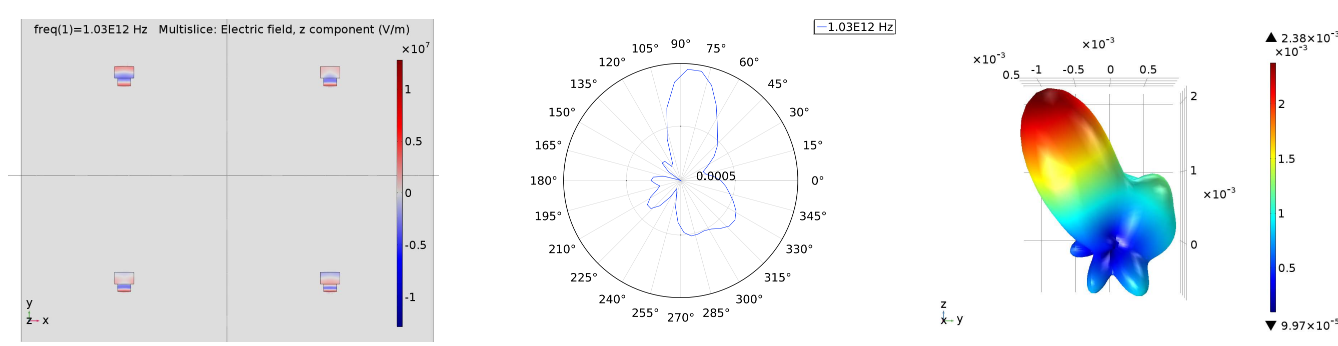

Figure 7: (Left) Electromagnetic fields on the nano-antennas at different phase modulation states in 2x2 array, (middle) resulting 2D far field, and (right) resulting 3D far field plots.

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