Tunable Plasmonic Graphene Antenna Array for Communications at THz Frequencies

Elana P. de Santana[1], Daniel Stock[1], Zhenxing Wang[2], Kun-Ta Wang[2], Sergi Abadal[3], Max Lemme[2,4] and Peter H. Bolívar[1]

[1]Institute of High Frequency and Quantum Electronics, University of Siegen, 57076 Siegen, Germany
[2]AMO GmbH, 52074 Aachen, Germany
[3]NaNoNetworking Center in Catalunya, Technical University of Catalonia, 08034 Barcelona, Spain
[4]Chair of Electronic Devices, RWTH Aachen, Germany

***Abstract*—The existence of plasmonic waves at a graphene/dielectric interface at THz frequencies enables the use of graphene as the radiative element of antennas working at this frequency range, but with a smaller lateral dimension compared to a standard metallic antenna. Due to the low carrier mobility in large-area graphene, result of its manufacturing process, the emitted radiation of graphene antennas is still smaller than its metallic counterpart. In this work, we show that the low emission of a graphene antenna can be compensated by antenna arrays. The proposed 1x4 graphene antenna array presents a far-field radiated gain of 9.3 dBi with a resonance frequency at 269 GHz. The resonating frequency of the graphene antenna array can also be tuned by an electrostatic bias.**

I. INTRODUCTION

GRAPHENE antennas operating at THz frequencies have been considered a promising substitute for standard metallic antennas operating at the same frequency due to the existence of a surface wave traveling along a graphene/dielectric interface at THz frequencies, the so-called surface plasmon polaritons (SPP) [1]. The wavelength of such plasmons is smaller than the wavelength of radiation in free-space enabling plasmonic antennas to have smaller dimensions compared to metallic antennas. In addition to the smaller occupational area of such graphene antennas, another advantage of using graphene as the radiative patch is the possibility to tune the operating frequency without changing the dimensions of the antenna. This is only possible due to the fact that the wavelength of the SPP supported by graphene sheets is related to the graphene conductivity, which can be tuned chemically or electrically [2]. The compact graphene antenna and its frequency reconfigurability can enable agile wireless interconnects at Network-in-Package (NiP) for future 5G communications at THz frequencies [3]. Unfortunately, graphene antennas present lower gain compared to metallic antennas [4]. The low gain of an antenna can be compensated - by arrays. This would undermine the advantage of a smaller occupational area but still keep the resonance frequency tuning possibility of such antennas, also enabling beam steerability by feeding the antennas in the arrays with signals with different phases. The improvement of the far-field radiation gains of graphene antennas by using arrays is shown in terms of electromagnetic simulations.

II. ANTENNA DESIGN

The proposed antenna array consists of a line of four patch antennas placed side by side with a distance of 217 µm (~$\lambda_0/4$) between each antenna edge. The antenna is a stack of graphene, 40 nm alumina (Al_2O_3) and graphene placed one on top of each other, respectively. The high-frequency signal is driven to the antennas by a coplanar waveguide. Firstly, a single graphene patch antenna is designed using the standard antenna equations [5]. The initial resonating frequency is defined as 280 GHz and a substrate of 50 µm thick polyimide (ε = 3.5, δ = 0.0027) with a back-metal plane is selected, leading to lateral dimensions of the antenna to be 355 µm x 260 µm. Then, the array of graphene patch antennas of these dimensions is simulated using CST, with the transient solver set to acquire the resonant frequency and gain of the antenna array in the range of 220 – 325 GHz. A waveguide port was used to excite each antenna of the array at the ground-signal-ground of the structure. The graphene patch is simulated as a 2D material with surface conductivity (σ) defined by the Kubo formula, as described in Equation (1) [6].

$$\sigma(\omega) = \frac{2e^2}{\pi\hbar}\frac{k_B T}{\hbar}\ \ln\left[2\cosh\left[E_F/2K_B T\right]\right]\frac{i}{\omega + i\,\tau^{-1}} \quad (1)$$

Where, e is the electron charge, τ is the charge carriers relaxation time, ħ is the reduced Planck's constant, K_B is the Boltzmann constant, μ_c is the graphene Fermi level and ω is frequency.

A single unit of the array can be seen in Figure 1 and the dimensions of the simulated antenna array can be found in Table 1.

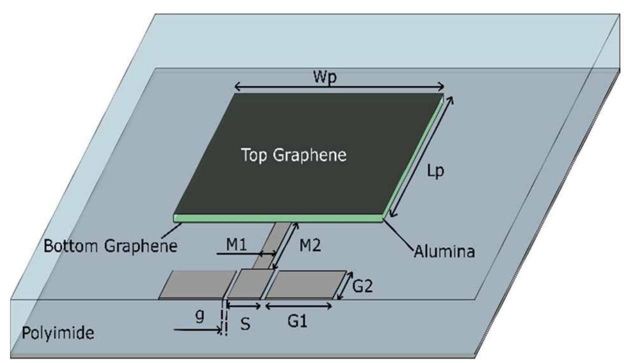

Fig. 1. Design of one graphene patch antenna unit fed by a coplanar waveguide used for simulations.

TABLE I
GRAPHENE ANTENNA DESIGN PARAMETERS

Parameter	Value (µm)
Patch Width (W_p)	355
Patch Length (L_p)	260
Signal Pad Width (S)	75
Ground Pad Width (G1)	100
Ground Pad Length (G2)	60
Microstrip Width (M1)	40
Microstrip Length (M2)	95
Gap (g)	10

 DOI 10.1109/IRMMW-THz57677.2023.10299218

III. Simulation Results

The simulated return loss of the antenna array, which consist of top and bottom graphene patches with 1.2 ps of relaxation time and 0.3 eV, 0.6 eV, 0.9 eV and 1.2 eV of chemical potential are shown in Figure 2. At the frequency range of interest, the antenna array presents a resonant frequency that can be shifted to different values from 245 GHz to 269 GHz based on the increase of the chemical potential of the graphene

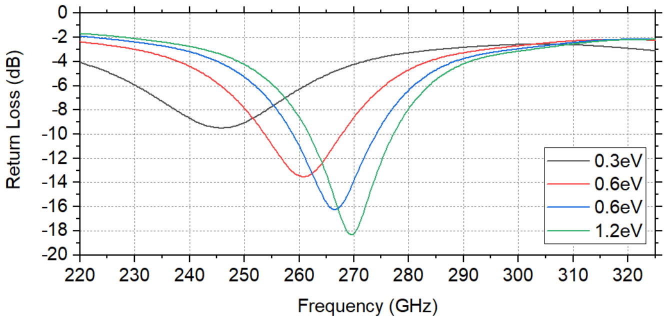

Fig. 2. The overall return loss plot of the graphene antenna array with graphene patches with 1.2 ps of relaxation time and different chemical potentials.

patches. The chemical potential of graphene can be tuned based on an electrostatic bias applied between the top and bottom graphene. This way, the graphene patch antenna array can operate at different frequencies, while keeping its dimensions. The top graphene patch act as a top gate and is transparent for the THz radiation. Even though the -10 dB operating bandwidth is decreased with increased chemical potential, the antenna accepts more of the input power and, consequently, also will present a higher emitted power. A low return loss will also be affected by the graphene relaxation time, as can be seen in Figure 3. The relaxation time of graphene is directly related to the material quality, i.e. only high-quality graphene patches will present antenna behavior.

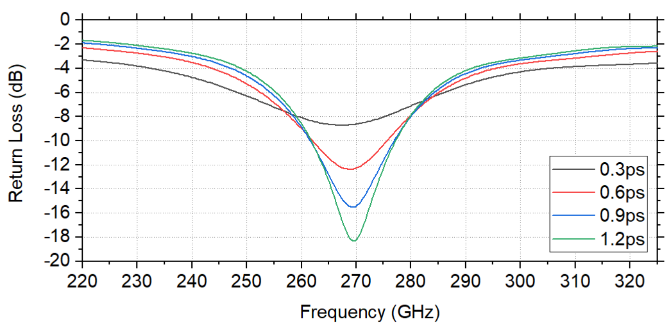

Fig. 3. The overall return loss plot of the graphene antenna array with graphene patches with 1.2 eV of chemical potential and different relaxation times.

In Figure 4 the far-field gain of the antenna array at the resonant frequency of 269 GHz, for a graphene patch with 1.2 eV of chemical potential and 1.2 ps of relaxation time, is shown. For these given graphene characteristics, the return loss is -18.3 dB at 269 GHz, the resonance frequency of the array, while the far-field gain in the direction 0° is 9.3 dBi with angular width (3 dB) of 19.7° and side lobe level of -13.7 dB from a 0.5 W individual input power. The overall far-field gain pattern of the antenna at its resonance frequency will change in dependence of the graphene chemical potential value.

Based on the previous simulation of a single graphene

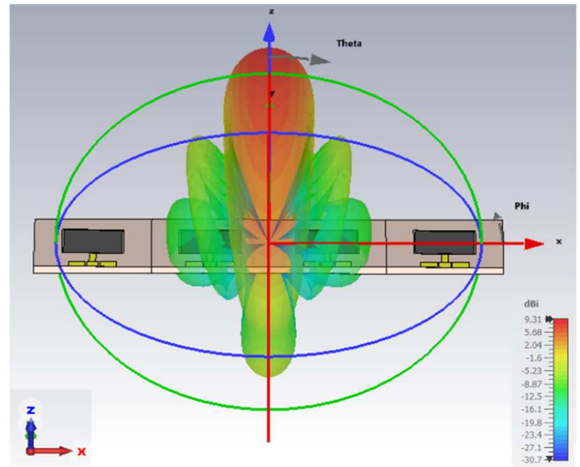

Fig. 4. The 3D radiation plot of the graphene antenna array at the resonating frequency of 26 9GHz with graphene patch of 1.2 eV of chemical potential and 1.2 ps of relaxation time.

antenna with the same dimensions [7], this antenna array provides an increase of gain from 2.7 dBi for the single antenna to 9.3 dBi for the presented antenna array.

IV. Summary

The 1x 4 graphene antenna array presented compensates the low emission of a single graphene antenna leading to a far-field gain of 9.3 dBi at resonance frequency 269 GHz, but still keeps the frequency tuning capability of such graphene antennas. The resonance frequency can be shifted from 245 GHz to 269 GHz by tuning the graphene chemical potential from 0.3 eV to 1.2 eV.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement N° 863337.

References

[1] T. Low and P. Avouris, "Graphene Plasmonics for terahertz to Mid-infrared Applications," *ACS Nano,* vol. 8, no. 2, pp. 1086-1101, January 2014.

[2] Y. Yu, Y. Zhao, S. Ryu, L. E. Brus, K. S. Kim and P. Kim "Tuning the Graphene Work Function by Electric Field Effect," *Nano Letters*, vol. 12, n. 10, pp. 3430-3434, August 2010.

[3] S. Abadal, R. Guirado, H. Tagvaee, and others, "Graphene-based Wireless Agile Interconnects for Massive Heterogeneous Multi-chip Processors," *IEEE Wireless Communications*, pp. 1-8, August 2022.

[4] M. Dashti and J. D. Carey, "Graphene microstrip patch ultrawide band antennas for thz communications," Advanced Functional Materials, vol. 28, no. 11, p. 1705925, 2018.

[5] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed.Hoboken, NJ: Wiley, 2016

[6] M. Tamagnone, J. S. Gómez-Días, J.R. Mosig, and J. Perruisseau-Carrier, "Analysis and Design of Terahertz Antennas based on Plasmonic Resonant Graphene Sheets," *Journal of Applied Physics*, vol. 112, no. 114915, pp. 1-4, December 2012.

[7] E. P. de Santana, A. K. Wigger, Z. Wang, K. Wang, and others, "Integrated Graphene Patch Antenna for Communications at THz Frequencies", *2022 47th International Conference of Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, pp. 1-2, 2022.