Characterization of Graphene-based Nano-antennas in the Terahertz Band

(Invited Paper)

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***Abstract*—Graphene-enabled wireless communications constitute a novel paradigm which has been proposed to implement wireless communications at the nanoscale. Indeed, graphene-based nano-antennas just a few micrometers in size have been predicted to radiate electromagnetic waves at the terahertz band. In this work, the performance of a graphene-based nano-patch antenna in transmission and reception is numerically analyzed. The resonance frequency of the nano-antenna is calculated as a function of its length and width, both analytically and by simulation. The influence of a dielectric substrate with a variable size, and the position of the patch with respect to the substrate is also evaluated. Finally, the radiation pattern of a graphene-based nano-patch antenna is compared to that of an equivalent metallic antenna. These results will prove useful for designers of future graphene-based nano-antennas, which will enable wireless communications at the nanoscale.**

I. Introduction

Graphene, a flat monoatomic layer of carbon atoms tightly packed in a two-dimensional honeycomb lattice, has recently attracted the attention of the research community due to its novel mechanical, thermal, chemical, electronic and optical properties [1], [2], [3]. Due to its unique characteristics, graphene has given rise to a plethora of potential applications in many diverse fields, ranging from ultra high-speed transistors [4] to transparent solar cells [5].

Among these, a particularly promising emerging field is graphene-enabled wireless communications. Wireless communications at the nanoscale cannot be achieved by simply reducing the size of a classical metallic antenna down to a few micrometers, since that would impose the use of very high resonant frequencies. Due to the expectedly very limited power of nanosystems, the low mobility of electrons in metals when nanometer scale structures are considered, and the challenges in implementing a nano-transceiver able to operate at this extremely high frequency, the feasibility of wireless communications at the nanoscale would be compromised if this approach were followed. However, due to its groundbreaking properties, graphene is seen as the enabling technology to implement wireless communications among nanosystems. Indeed, graphene-based nano-antennas just a few micrometers in size are envisaged to radiate electromagnetic waves in the terahertz band [6], at a dramatically lower frequency and with a higher radiation efficiency with respect to their metallic counterparts. Moreover, the progress in the development of graphene-based components shows that the high electron mobility of graphene makes it an excellent candidate for ultra-high-frequency applications [7]. Recently-published work demonstrates the great potential of graphene-based ambipolar devices for analogue and RF circuits, such as LNAs, mixers and frequency multipliers [8], [9], [10], [11].

In consequence, graphene-based nano-antennas have the potential to enable wireless communications at the nanoscale and nanonetworks [12], i.e., networks of interconnected nanosystems, which will enhance the capabilities of individual nanosystems both in terms of complexity and range of operation, leading to the development of a novel networking paradigm. Nanonetworks are envisaged to create new applications in diverse fields by allowing a swarm of nanosystems to communicate and share information among them. For instance, in the biomedical field, nanonetworks will allow the implementation of technologies such as nanorobots [13], nanodiagnostic techniques [14] and cooperative drug delivery systems using nanoparticles [15], whose implementation will require a group of coordinated nanosystems to become reality.

In our previous work [16], a simple model to calculate the resonances of a graphene-based patch is presented and the dependence of its resonant frequency on the patch dimensions is obtained. In this paper, we extend this analysis by considering a graphene-based nano-patch antenna, consisting of a graphene

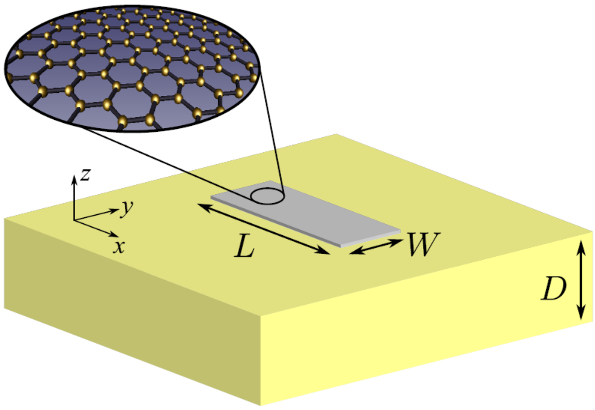


Fig. 1. Schematic diagram of a graphene-based nano-patch antenna.

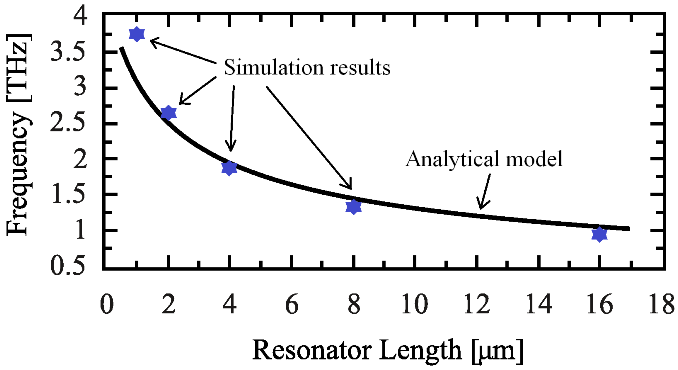


Fig. 2. Dependence of the first resonance of an infinitely wide graphene-based nano-patch antenna as a function of its length. The solid line is as calculated using the analytical model and the stars correspond to the resonance frequencies obtained by simulation.

patch over a dielectric substrate (see Fig. 1). We analyze this structure for different substrate sizes and different positions of the graphene patch with respect to the substrate. Finally, we compare the radiation pattern of a graphene-based nano-patch antenna to that of an equivalent metallic antenna of the same dimensions.

II. Model of a Graphene-based Nano-patch Antenna

Graphene presents excellent conditions for the propagation of Surface Plasmon Polaritons (SPP), waves guided along a metal-dielectric interface which are generated by an incident high-frequency radiation. Indeed, a free-standing graphene layer supports transverse-magnetic (TM) SPP waves with an effective mode index given by [17]

$$n_{\text{eff}}(\omega) = \sqrt{1 - 4\frac{\mu_0}{\varepsilon_0}\frac{1}{\sigma(\omega)^2}}. \quad (1)$$

While SPP modes are not supported by free space, in a graphene-based nano-patch antenna, the edge of the graphene patch acts as a mirror and the patch behaves as a resonator for SPP modes. The coupling of the incident electromagnetic radiation with the corresponding SPP modes leads to resonances in the graphene-based nano-patch antenna. The resonance condition is given by

$$m\frac{1}{2}\frac{\lambda}{n_{\text{eff}}} = L + 2\delta L, \quad (2)$$

where m is an integer determining the order of the resonance, λ is the wavelength of the incident radiation, L is the antenna length and δL is a measure of the field penetration outside the graphene-based nano-patch antenna. This equation determines a set of m resonance frequencies ω_m corresponding to m modes of the resonator.

We consider graphene-based nano-patch antennas with a size of a few micrometers, small enough so that they can be integrated into a nanosystem. Since the effective mode index n_{eff} in graphene is in the order of 10^2 [17], according to this model, the first resonance frequency of our envisaged graphene-based nano-patch antennas lies in the terahertz band, around two orders of magnitude below what it would be expected in a perfect metallic antenna. This is one of the main reasons why graphene-based nano-antennas are seen as the enabling technology for wireless communications at the nanoscale. Next, this prediction will be validated and the performance of these antennas will be further explored by means of simulation.

III. Simulation Results

The previous model can be used to estimate the spectral position of the resonances in a graphene-based nano-patch antenna. As a first approximation, in our previous work [16] we modeled the antenna as a graphene patch suspended in air. Fig. 2 shows the position of the first resonance of a such an antenna as a function of its length. The analytical expression, as obtained from the previous model, is compared with the results of numerical simulations done using the method of moments with surface equivalence principle [18]. The antenna is modeled as an infinitely wide graphene patch with length $L = 5$ μm, and a plane wave normally incident to the antenna is considered. The penetration length is set to $\delta L = 0.5$ μm. As it can be observed, the simulation results show a very good agreement with the analytical model.

A realistic graphene-based nano-patch antenna, however, will have a finite width. Fig. 3 shows the absorption cross section of a 5 μm-long graphene-based nano-patch antenna as a function of its width, calculated by numerical simulation. The absorption cross section is a measure of the fraction of the power of the incident wave that is absorbed by the antenna; therefore, the antenna resonant frequency coincides with the frequency at which the absorption cross section is maximum. We can see in Fig. 3 that the antenna resonant frequency is reduced as the antenna becomes narrower. These results suggest that, by adjusting the antenna dimensions, its operation frequency can be tuned in a wide spectral range.

It is worth investigating the behavior of a graphene-based nano-patch antenna when a more realistic model is used. We consider next an antenna modeled as a graphene patch

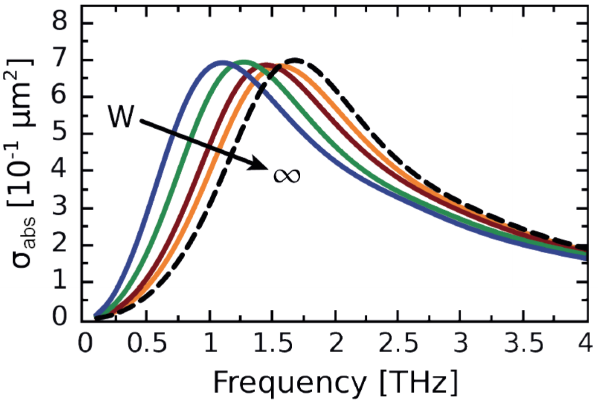


Fig. 3. Dependence of the absorption cross section of a graphene-based nano-patch antenna as a function of its width. The absorption cross section normalized to the antenna width is shown. The antenna length is $L = 5$ µm. The plots correspond to infinite, 10 µm, 5 µm, 2 µm and 1 µm wide patches (right to left).

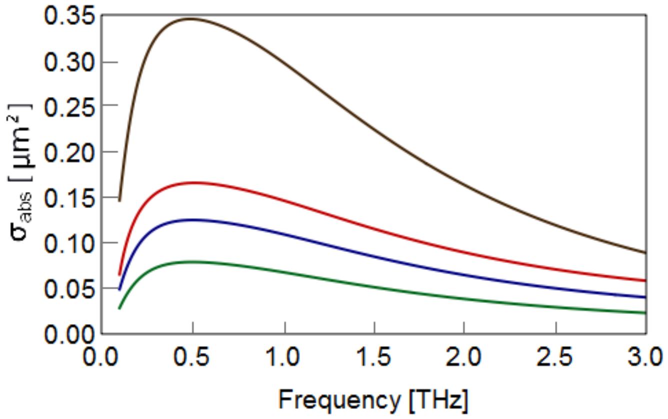


Fig. 4. Absorption cross section of a graphene-based nano-patch antenna, for different substrate sizes: 6x6 µm, 10x10 µm, 16x16 µm and infinite (below to above).

deposited on a dielectric substrate. We analyze the dependence of the antenna absorption cross section on the substrate size, when a plane wave is normally incident to the antenna. We consider an antenna made of a graphene patch with a size of 5x0.5 µm located on the center of a silicon substrate with a square shape and a thickness of 1 µm. Fig. 4 shows the absorption cross section of this graphene-based nano-patch antenna for different substrate sizes, from 6x6 µm to infinity. On the one hand, it can be seen that a larger substrate improves the antenna performance, since the absorption cross section increases with the substrate size, up to a certain limit. On the other hand, the antenna resonant frequency is shown to be virtually constant at 0.5 THz, independently of the substrate size.

Next, we evaluate the influence of the patch position relative to the substrate in a graphene-based nano-patch antenna. The considered substrate has dimensions of 6x6 µm and a thickness of 1 µm. The graphene patch measures 5x0.5 µm and is located in three different positions, as shown in Fig. 5: in

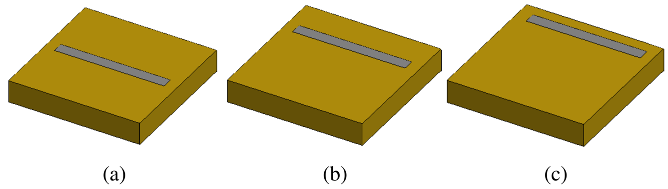


Fig. 5. Different positions of the graphene patch with respect to the substrate: patch in the center of the substrate (a), at 1.25 µm from the center (b) and at 2.5 µm from the center (c).

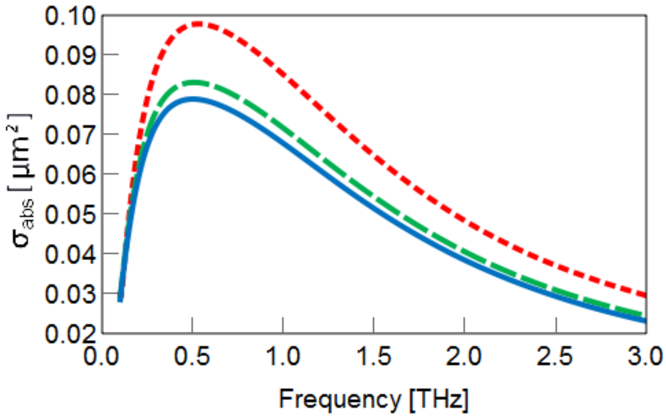
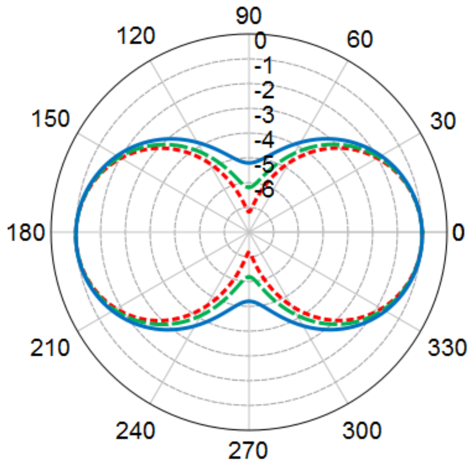


Fig. 6. Absorption cross section of a graphene-based nano-patch antenna, for different positions of the graphene patch: in the center of the substrate (blue solid line), at 1.25 µm from the center (green dashed line) and at 2.5 µm from the center (red dotted line).

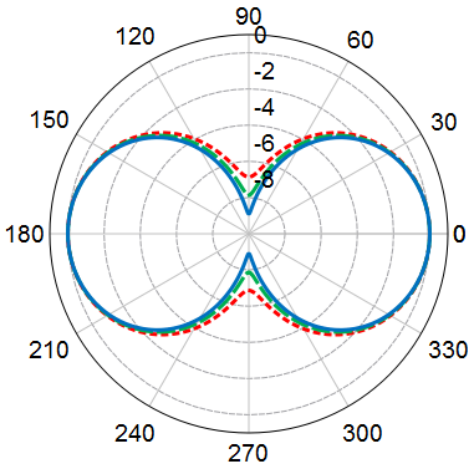
the center of the substrate (5a), at 1.25 µm from the center (5b) and at 2.5 µm from the center (5c). Fig. 6 shows the antenna absorption cross section as a function of frequency, for each of these three configurations. As it can be observed, the absorption cross section increases as the graphene patch is located closer to the side of the substrate. Moreover, the resonant frequency becomes higher when the patch is farther from the center. These results indicate that, for a given substrate size, the optimal location for on-chip graphene-based nano-antennas may be near the edge of the substrate, in order to maximize their efficiency.

Finally, it is also interesting to study the properties of graphene-based nano-patch antennas in transmission. With this purpose, a terahertz signal is driven into the antenna, modeled as a freestanding graphene patch by means of a pin feed. A simulation study of a transmitting graphene-based nano-patch antenna is performed, which allows obtaining its radiation pattern. The antenna has a fixed length $L = 5$ µm, while its width takes the values $W = 1$, 2 and 5 µm (the geometry for the case $W = 1$ µm is shown in Fig. 7). The pin feed is located at a distance of 0.1 µm from the antenna edge. Fig. 8a shows the radiation pattern of graphene-based nano-patch antennas with the described properties, in the plane parallel to the graphene patch.

Fig. 8b shows the radiation pattern of equivalent metallic antennas, modeled as perfect electric conductor patches of



(a) Graphene-based nano-antenna



(b) Metallic nano-antenna

Fig. 8. Radiation pattern of a graphene (a) and metallic (b) nano-patch antenna as a function of its width. The plots show the normalized gain in dB, in the plane parallel to the antenna patch, for an antenna with a length $L = 5$ µm. The results correspond to antenna widths of $W = 1$ µm (blue solid line), 2 µm (green dashed line) and 5 µm (red dotted line).

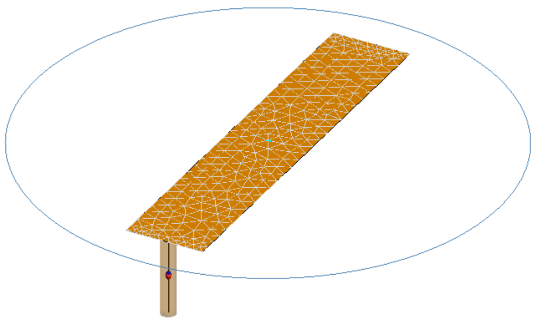


Fig. 7. Schematic diagram of the graphene-based nano-patch antenna in transmission. The antenna is composed of a graphene patch with a length $L = 5$ µm and a width $W = 1$ µm, and a pin feed located at 0.1 µm from the antenna edge. The blue circle shows the plane in which the radiation diagram is measured.

the same dimensions. The radiation pattern is computed at a frequency of 1.3 THz, which approximately corresponds to the resonant frequency of a graphene-based nano-patch antenna of the previous dimensions. Even though the metallic antenna is expected to resonate at a higher frequency band, the analysis is performed at the same frequency for the sake of comparison. As it can be seen, in both cases the radiation pattern is similar to that of a half-wave dipole antenna, and the differences between the patterns of graphene and the metallic antennas are minimal. We therefore conclude that, as it could be expected, the radiation pattern of future graphene-based nano-patch antennas will not differ significantly with respect to that of equivalent metallic antennas.

IV. Conclusion

Graphene-based nano-antennas are envisaged to allow nanosystems to transmit and receive information, creating a novel paradigm known as graphene-enabled wireless communications. In this work, we provided a simple model for a graphene-based nano-patch antenna, which we used to characterize the antenna by means of simulation. The obtained results confirm that a graphene-based nano-patch antenna with dimensions of a few micrometers resonates in the terahertz band, consistently with the theoretical model. Moreover, the dependence of the antenna resonant frequency on the dimensions of both the graphene patch and the dielectric substrate have been observed. The radiation pattern of a graphene-based nano-patch antenna was found to be very similar to that of an equivalent metallic antenna. These results will prove useful for designers of future nano-antennas for graphene-enabled wireless communications.

Acknowledgment

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