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Study of Hybrid and Pure Plasmonic Terahertz Antennas Based on Graphene Guided-wave Structures

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Abstract

Graphene is a unique material for the implementation of terahertz antennas due to extraordinary properties of the resulting devices, such as tunability and compactness. Existing graphene antennas are based on pure plasmonic structures, which are compact but show moderate to high losses. To achieve higher efficiency with low cost, one can apply the theory behind dielectric resonator antennas widely used in millimeter-wave systems. This paper presents the concept of hybridization of surface plasmon and dielectric wave modes. Then, via an analysis of one-dimensional structures, a comparison of the potential capabilities of pure and hybrid plasmonic antennas is performed from the perspectives of radiation efficiency, tunability, and miniaturization. Additionally, the impact of the quality of graphene upon the performance of the compared structures is evaluated. On the one hand, results show that hybrid structures deliver high gain with moderate miniaturization and tunability, rendering them suitable for applications requiring a delicate balance between the three aspects. On the other hand, pure plasmonic structures can provide higher miniaturization and tunability, yet with low efficiency, suggesting their use for application domains with high flexibility requirements or stringent physical constraints.

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1. Introduction

Graphene, a flat monolayer of carbon atoms tightly packed in a two-dimensional honeycomb lattice, has recently attracted the attention of the research community due to its extraordinary mechanical, electronic, and optical properties [1]. The outstanding potential of this material opens the door to its application in various fields, including nanometric integrated circuits, spectroscopy, imaging, transformation optical devices, lenses, modulators, absorbers, directional couplers and metamaterials, among others [2, 3, 4, 5, 6, 7, 8].

Graphene has been also studied in the context of terahertz (THz) band communications (0.1 - 10 THz), a key wireless technology enabling a plethora of applications in both classical networking scenarios and in novel nano-communication paradigms [9]. Specifically, graphene has been introduced as an attractive solution for the implementation of miniaturized antennas operating in the terahertz band [10]. This is of great interest in novel applications that may require smaller forms of wireless communication while maintaining certain application-dependent performance in terms of bandwidth, transmission range or energy consumption.

Wireless Networks-on-Chip (WNoCs) [11] and Wireless NanoSensor Networks (WNSNs) [12] constitute two clear examples of applications with stringent size constraints that would greatly benefit from ultra-short-range wireless communications. On the one hand, the WNoC paradigm consists in using on-chip antennas to wirelessly communicate components integrated within a chip, thereby addressing several performance challenges of current interconnects. On the other hand, WNSNs aim to enable wireless communication among nanosensors, seeking to exploit their novel sensing capabilities in locations not reachable with conventional sensors or in scenarios requiring a very high accuracy or deployment density.

Another outstanding property of antennas based on graphene is their inherent tunability. It has been demonstrated that the resonant frequency of the antenna can be shifted by simply changing the chemical potential of graphene, which can be done by means of a variable electrostatic bias [13].

As we will see in subsequent sections, this opens the door to a plethora of alternatives in terms of antenna, communications, and protocol design.

Besides miniaturization and tunability, graphene antennas show potential to outperform their metallic counterparts when operating in the terahertz band. This is because the ability of graphene to support Surface Plasmon Polaritons (SPPs) in this frequency range, where metals act as lossy non-plasmonic conductors [14]. However, initial proposals based on pure plasmonic graphene structures show a low radiation efficiency due to the relatively high loss of the supported SPP modes [15, 16, 13, 17]. Instead, hybrid plasmonic guided-wave structures have been introduced to provide a better balance between mode confinement and propagation loss in the terahertz band [14]. The use of such structures can lead to the conception of antennas combining the advantages of plasmonics with those of dielectric resonator antennas, commonly used in millimeter-wave systems due to their high miniaturization and gain [18].

In light of the above, this work proposes the concept of terahertz antenna based on the hybridization of surface plasmon and dielectric wave modes shown in Fig. 1. In order to discuss the suitability of this novel antenna structure for nano and microscale wireless applications, here we analyze two types of guided-wave structures at 3 THz and then compare their properties and performance. As baselines, we consider pure plasmonic structures composed by one and two isolated graphene layers. Then, we analyze the proposed hybridized structures that combine the plasmonic mode and dielectric mode. Based on this study of one-dimensional waveguides, we qualitatively discuss three main features relevant to graphene-based antennas, namely, radiation efficiency, tunability, and miniaturization. The results of such analysis aim to pave the way towards the development of novel graphene antenna structures tailored to the requirements of next-generation wireless networks at both the nano- and macroscale.

This paper is a direct extension of previous work by the authors [19]. The original contribution is augmented in breadth and depth by means of new analyses, namely:

- A review of the state-of-the-art on graphene-based waveguides and antennas designed to operate in the THz band (Section 2).
- A more detailed formulation of the propagation constants of guided modes in the 2D structures (Section 3).

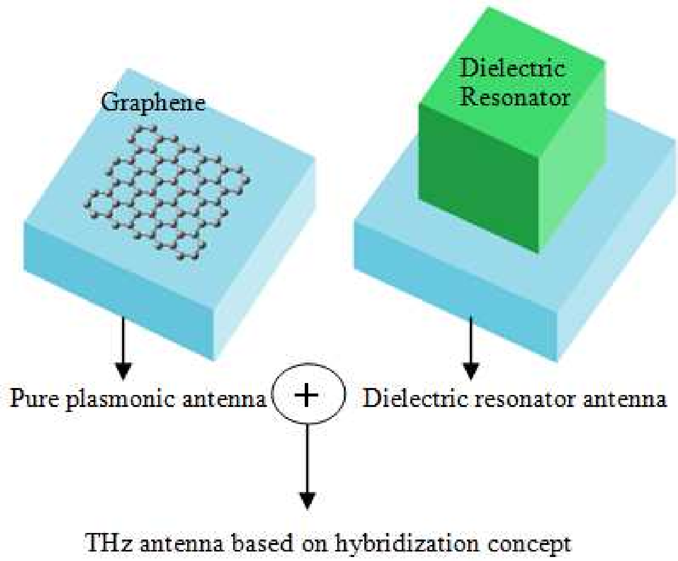


Figure 1: The conceptual scheme for hybridization of surface plasmon and dielectric wave modes to implement THz antennas.

- A comparison between the even and odd modes of pure plasmonic antennas (Section 4).
- A sensitivity analysis depicting how the purity of the graphene samples, described via the relaxation time of the material, affects the performance of the studied structures (Section 4.4).
- Deeper discussions on the suitability of the different structures in nano and microscale applications, as well as their design implications on the upper layers of the communication stack (Section 4.5).

The rest of this paper is organized as follows. Section 2 provides a brief survey of current proposals for graphene-based waveguides and antennas. Section 3 presents the investigation approach and also comparative results of one-dimensional waveguides, which can be used to determine the suitability of certain graphene-based structures as antennas. In Section 4, antenna properties are evaluated and compared based on the performance of their fundamental one-dimensional structures. Finally, conclusions are provided in Section 5.

2. Related Work in Graphene-based Waveguides and Antennas

Besides many applications in the Radio-Frequency (RF) domain [20, 21, 22], graphene has shown unique potential for the development of plasmonic waveguides and antennas operating in the terahertz band. In the following, we review the state-of-the-art in this thriving field.

2.1. Graphene-Based Waveguide Structures

Recent studies have shown that terahertz plasmons can be confined laterally in a graphene sheet [23]. Such property has led to the proposal of different waveguide structures basically consisting in a number of graphene layers interspersed within dielectric materials [24], or in graphene-dielectric-metal structures [25], obtaining excellent field confinement results. Another approach for the design of novel waveguide structures relies on the use of graphene layers to form wedges [26] or to coat grooves carved on the dielectric [27].

Zhou *et al* were among the first researchers to propose a waveguide consisting on the stacking of a dielectric with high permittivity on top of a low-index dielectric-graphene-dielectric stack, similarly to in the structures analyzed in this work [28]. Their results confirmed the subwavelength behavior of graphene-based waveguides along with its low crosstalk level, which could lead to the development of outstandingly compact devices in the terahertz band. Later, the performance of pure and hybrid waveguide structures was both explored considering several design parameters in [14]. As we will see, some of the waveguide structures proposed in the literature may serve as fundamental blocks for the creation of plasmonic antennas based on graphene [29].

2.2. Graphene-Based Antennas

The concept of antennas based on novel materials at the nanoscale was first discussed in [30, 31, 32]. Carbon nanotubes were proposed as potential dipole antennas and their impedance and radiation pattern were analyzed. However, the employment of carbon nanotubes involves several drawbacks in terms of manufacturing, tuning, and placement on planar implementation processes that may prevent its applicability in future wireless networks.

Alternatively, Jornet *et al* proposed the use of micrometric graphene patches as radiating elements of planar antennas [33]. Following the work by Hanson on the propagation of electromagnetic waves on laterally-infinite graphene layers [34], it was demonstrated that a graphene patch a few micrometers long and wide would exhibit a plasmonic resonance in the terahertz band [33, 35, 36].

Antennas with graphene as the radiating element: Following the seminal work by Jornet, recent years have seen the surge of graphene antenna proposals for terahertz band communication based on the principles mentioned above. In essence, such antennas would consist of a number of finite-size graphene layers (the radiating elements) mounted over a metallic flat surface (the ground plane), with a dielectric material in-between and a feed to drive the signals to the antenna. It has been demonstrated that these antennas could be lithographically defined with current techniques [37], easing the compatibility with CMOS processes. Patch antenna configurations [38, 39, 40] and dipole-like designs [41, 17, 16], where the feed is placed in the middle of two identical graphene patches, have been also proposed. While most works assume an idealized photomixer with high impedance as the feed of the antenna, more advanced proposals study advanced terahertz sources based on photoconductive materials [17] or high electron mobility transistors [42].

To take advantage of the unprecedented potential for tunability offered by graphene, different electrostatic biasing schemes have been explored [13, 39, 17]. Tunability is also exploited in a design that considers an array of graphene-based Multiple-Input-Multiple-Output (MIMO) system where antennas are individually and dynamically tuned according to the communication requirements [43]. In a similar fashion, Akyildiz *et al* proposes to take advantage of the miniaturization of graphene antennas to create MIMO systems with an unprecedented number of radiating elements [44].

Antennas with graphene as an auxiliary element: One of the main motivations of MIMO systems mentioned above is to overcome the losses of graphene in pure plasmonic structures. In consonance with that research line, some works have proposed to focus on the tunability of the material and avoid losses by not using graphene as the radiating element. For instance, Tamagnone *et al* employ the graphene sheets between the source and a metallic radiating element to retain the tunability while having a fair efficiency [45]. Hosseininejad *et al* design a novel antenna based on hybrid graphene-metal structure that adds reconfigurability capabilities to metallic THz antenna [29]. Aldrigo *et al* propose an antenna structure which switches between omnidirectional and broadside radiation depending on the bias applied to a graphene sheet that acts as the ground plane [46]. A generalization of this idea includes a set of graphene patches that form a switchable High Impedance Surface (HIS) used as the ground plane as well [47]. By reconfiguring the HIS at real time, this technique allows to perform beam steering in a fast and fine-grained fashion. Others have proposed to use a similar technique for the design of reflectarrays [48] and backscattering modulators [49] with very low complexity.

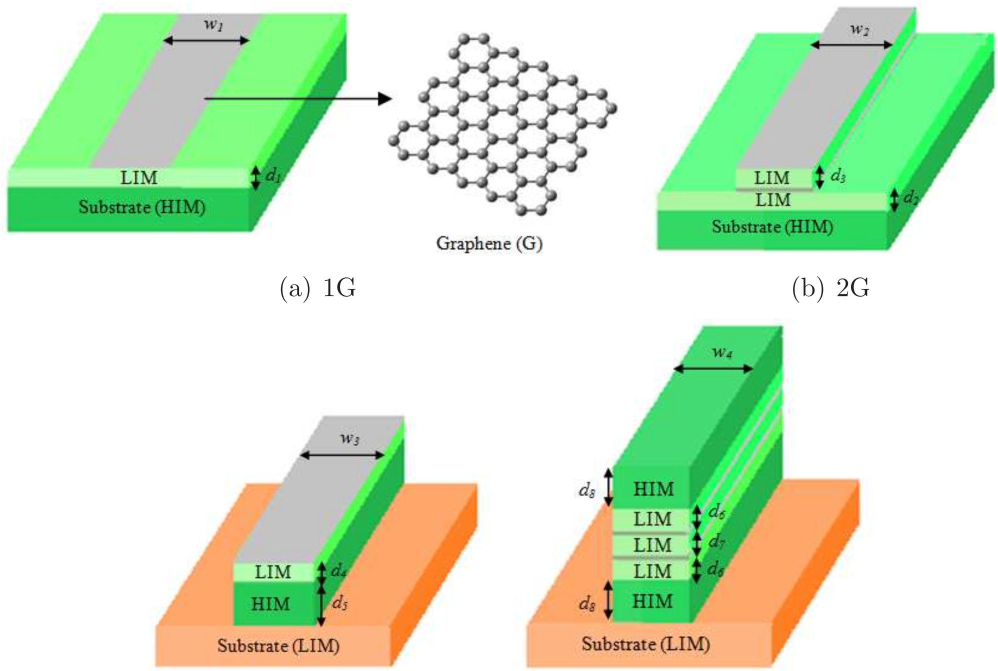
3. Guided-wave Structures as Building Blocks of Graphene Antennas

The study of guided-wave structures is a basic step for designing efficient antennas based on those structures. For example, consider patch antenna which is a well-known radiated-wave device in the microwave frequencies. Knowing the propagation properties of the microstrip waveguide is very helpful to design an appropriate patch antenna.

Here, an analysis of one-dimensional and two-dimensional structures is conducted in order to guide further discussions about the performance of antennas (three-dimensional structures) based on graphene. Two kinds of structures are considered: pure plasmonic structures supporting SPP wave modes, and hybrid graphene-dielectric structures providing coupling of surface plasmons with dielectric waveguide modes. The geometries of two-dimensional waveguides are depicted in Fig. 2.

In the first category, a monolayer graphene structure (1G, Fig. 2(a)) and a structure composed of two graphene monolayers separated by thin dielectric (2G, Fig. 2(b)) are studied. Most of the current antenna proposals that use graphene as active radiator (see Sec. 2) would fall within this group.

In the second category, a hybrid structure with a single graphene monolayer (H1G, Fig. 2(c)) and hybrid structure with two graphene monolayers (H2G, Fig. 2(d)) are investigated. These hybrid alternatives include a layer with a High Index Material (HIM) supporting a dielectric mode, located close to the graphene layer supporting a plasmonic mode, but separated by a spacer with a Low Index Material (LIM). In the literature, this type of structures have been mainly proposed for waveguide devices as reviewed in Sec. 2, whereas its application for antenna design has unregarded. Notice, in any case, that the one-dimensional structures are resulted by removing the lateral limits (w).



(a) 1G (b) 2G

(c) H1G (d) H2G

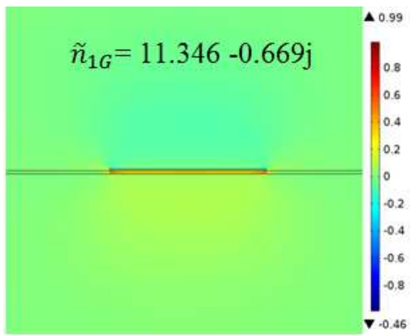
Figure 2: Geometries of two-dimensional plasmonic waveguides based on graphene including pure plasmonic structures (a-b) and hybrid structures (c-d).

In this work, graphene is represented as a layer of bulk material with small thickness ($d_G = 0.5$ nm). We can define a volume conductivity for this d_G-thick monolayer and then consider a volume current density. Finally, the equivalent permittivity $\tilde{\varepsilon}_G$ is calculated by recasting the Maxwell equation with the assumption of harmonic time dependence $e^{+j\omega t}$ as

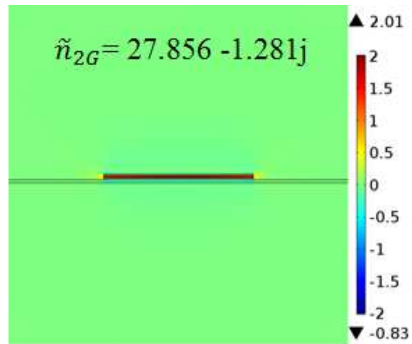
$$\tilde{\varepsilon}_G = (+\frac{\sigma_{G-imag}}{\omega d_G} + \varepsilon_0) + j(-\frac{\sigma_{G-real}}{\omega d_G}). \tag{1}$$

The complex conductivity σ_G can be calculated by the well-known Kubo formula [50] as

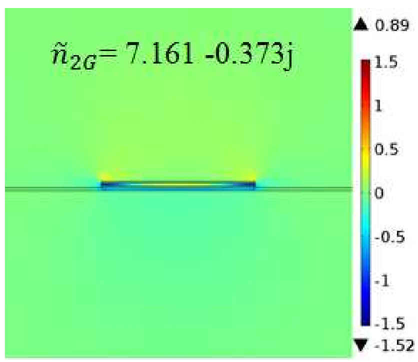
$$\begin{aligned} \sigma_G = & \frac{-j}{\omega - j\tau^{-1}} \frac{e^2 k_B T}{\pi \hbar^2} \left(\frac{\mu_c}{k_B T} + 2ln(e^{-\frac{\mu_c}{k_B T}} + 1) \right) + \\ & + \frac{-j(\omega - j\tau^{-1})e^2}{\pi \hbar^2} \int_0^\infty \frac{f(-\varepsilon) + f(+\varepsilon)}{(\omega - j\tau^{-1})^2 - 4(\varepsilon/\hbar)^2} d\varepsilon, \end{aligned} \tag{2}$$



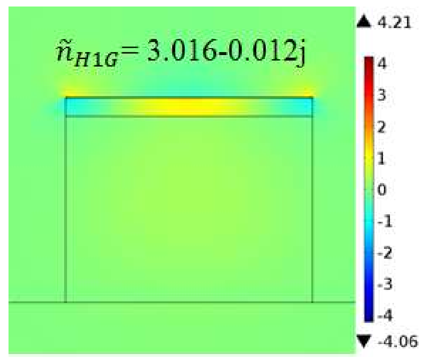
(a) 1G



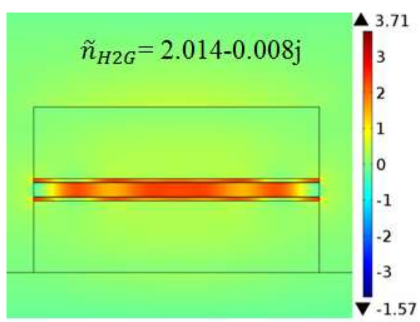
(b) 2G (even mode)



(c) 2G (odd mode)



(d) H1G



(e) H2G

Figure 3: Normal electric fields and effective refractive indices of the evaluated structures.

where ω is the radian frequency, e is the electron charge, $\hbar$ is the reduced Plank constant, k_B is the Boltzmann constant, T is the temperature ($T = 300$ K in this paper), μ_c is the chemical potential, and τ is the electron relaxation time of graphene ($\tau = 0.6$ ps in this paper). Finally, $f(\varepsilon)$ is the Fermi-Dirac distribution function, which can be evaluated with

$$f(\varepsilon) = \frac{1}{1 + e^{\frac{\varepsilon - \mu_c}{k_B T}}}. \tag{3}$$

In order to calculate the complex effective index of guided modes in the graphene-integrated structures, the formulations of transfer matrix theory provided in [7] are applied. The dispersion relation of Transverse Magnetic (TM) mode propagated in a general multilayer one-dimensional structure is defined as follows:

$$+j\left(\frac{\tilde{\gamma}_{xS}}{\varepsilon_{rS}} m_{11} + \frac{\tilde{\gamma}_{xC}}{\varepsilon_{rC}} m_{22}\right) = \frac{\tilde{\gamma}_{xS}\tilde{\gamma}_{xC}}{\varepsilon_{rS}\varepsilon_{rC}} m_{12}, \tag{4}$$

where ε_{rC} and ε_{rS} are the dielectric constants of cover and substrate layers, respectively, m_{ij} are the elements of the total transfer matrix M as defined in [7].

$$\begin{aligned} \tilde{\gamma}_{xC} &= \sqrt{\tilde{\gamma}_{eff}^2 - k_0 \varepsilon_{rC}}, \\ \tilde{\gamma}_{xS} &= \sqrt{\tilde{\gamma}_{eff}^2 - k_0 \varepsilon_{rS}}. \end{aligned} \tag{5}$$

The zeroes of Equation (4), which are the guided mode complex propagation constants

$$\tilde{\gamma}_{eff} = k_0 \tilde{n}_{eff} = k_0(n_{eff} - j k_{eff}) = \beta_{eff} - j\alpha_{eff}, \tag{6}$$

are obtained analytically.

For the two-dimensional structures, the Effective Index Method (EIM) is applied to obtain propagation constants of the guided modes [29]. Considering a refractive index profile which depends on two coordinates $n = n(x, y)$ and z direction as the propagation direction, the wave equation can be written as

$$\nabla_{xy}^2 \psi(x, y) + (k_0^2 n^2(x, y) - \tilde{\gamma}_{eff}^2)\psi(x, y) = 0, \tag{7}$$

where $\Psi(x, y, z) = \psi(x, y) e^{-j\tilde{\gamma}_{eff} z}$ can be any of the fields components, $k_0 = 2\pi/\lambda_0$ is the wave number in free space, $\tilde{\gamma}_{eff} = k_0(\tilde{n}_{eff})$ is the complex propagation constant and $\tilde{n}_{eff}$ is the complex effective index of the guided modes. In EIM, an approximate solution can be written as

$$\psi(x,y) = \psi_1(x,y)\psi_2(y), \tag{8}$$

wherein $\psi_1(x,y)$ is a slowly varying function of y ($\partial\psi_1/\partial y = 0$). Therefore, a system of two coupled differential equations is obtained as

$$\begin{cases} \frac{1}{\psi_1}\frac{\partial^2\psi_1}{\partial x^2} + k_0^2 n^2(x,y) = k_0^2 n_{eff}^2(y) \\ \frac{1}{\psi_2}\frac{d^2\psi_2}{dy^2} - \tilde{\gamma}_{eff}^2 = -k_0^2 n_{eff}^2(y) \end{cases} \tag{9}$$

The first step in the EIM procedure consists of solving the first equation of (9) that gives the eigenvalue solution $n_{eff}(y)$. In order to find the solution of this equation, the two-dimensional waveguide is divided into one-dimensional waveguides for which we can assume the refractive index profile i.e. $n(x,y)$ as being independent of y i.e. $n(x)$. In the second step, using the function $n_{eff}(y)$, we can solve the second equation of (9) that results in the propagation constant. This equation is for a one-dimensional waveguide with refractive index profile $n_{eff}(y)$.

Furthermore, the full-wave solver COMSOL [51] is used to verify the results of analytical methods. As shown in the previous works [7, 29], the results of these methods are near same. Therefore, the results of one of them are observed.

The dimensions and materials employed in each structure are illustrated in Fig. 2. As a primary assumption, Gallium Arsenide (GaAs) and polymethylmethacrylate (PMMA) are used for HIM and LIM with dielectric constants of 12.9 and 2.4, respectively.

It is well known that electromagnetic field profiles of structures help to design efficient antennas and also to identify their radiation mechanism. Normal electric field profiles and complex effective indices $\tilde{n}_{eff}$ of the four waveguides are shown in Fig. 3 for $\mu_c = 0.5$ eV, $d_1 = d_2 = d_3 = 0.1$ μm, $d_4 = 3$ μm, $d_5 = 30$ μm, $d_6 = 0.5$ μm, $d_7 = 2$ μm, and $d_8 = 10$ μm (see Figure 2). The frequency of excitation is 3 THz. Notice that two possible modes are shown for 2G structures, including even mode, in which the normal electric fields is even symmetric, and odd mode in which the symmetry is odd. A detailed comparison among pure and hybrid structures is performed in the following section.

4. Discussion on Performance of Graphene Antenna with the help of One-dimensional structures

Choosing from all mentioned structures for the construction of the antenna can be challenging task, but surveying the guided-wave characteristics facilitates it. Even though it is not possible to find the structure that will perfectly fit to the needs of a given application due to inherent trade-offs, there are some criteria that can be used to find the most suitable structure in a particular case. In what follows, we describe and discuss three criteria relevant to antenna design, namely, miniaturization, radiation efficiency, and tunability with the help of study of one-dimensional structures, considering $d_1 = d_2 = d_3 = 0.1$ μm, $d_4 = d_6 = 0.5$ μm, $d_5 = 15$ μm, $d_7 = 2$ μm, $d_8 = 9$ μm, and frequency of 3 THz. Furthermore, the effect of graphene purity on the antenna performance is surveyed. Then, we summarize the outcome of the discussion.

4.1. Miniaturization

Nanotechnology is providing a plethora of new tools to design and manufacture miniaturized devices which are able to perform different tasks at the micro/nanoscale such as computing or data storage [9]. Such devices require wireless communications to expand their limited range through information sharing and coordination. Graphene enables the miniaturization of wireless communication units in general and of the antennas in particular, due to its ability to support SPP waves in the terahertz frequency range. For giving a good measure of the miniaturization, the mode confinement should be considered from two directions including vertical confinement and longitudinal confinement.

Here, the resonant length L_{res} of dipole-like or patch-like antennas is evaluated here as a measure of longitudinal confinement. The resonant length can be written as [52]

$$L_{res} = n\frac{\lambda_{eff}}{2} \overset{\text{n=1}}{=} \frac{\lambda_0}{2n_{eff}}. \tag{10}$$

The spatial length L_s describes the vertical extent of the propagating mode. It can be defined as

$$L_s = \frac{1}{Re(\tilde{\gamma}_{xS})} + \sum_{i=1}^{N} d_i + \frac{1}{Re(\tilde{\gamma}_{xC})} \tag{11}$$

where d_i $(i = 1, 2, \ldots, N)$ is the thickness of i-th layer and N is number of layers. It is more convenient to express L_s as normalized to the free space diffraction limit ($L_0 = \lambda_0/2$) where λ_0 is the free space wavelength.

Fig. 4 shows the ($L_{res}/\lambda_0 - \mu_c$) and ($L_s/L_0 - \mu_c$) plots, which are useful to compare the structures from the aspect of miniaturization in longitudinal and vertical directions, respectively. Considering $\mu_c = 0.5$ eV, the normalized resonance lengths of 1G, 2G, H1G, and H2G are 0.05, 0.02, 0.25, and 0.5 and their normalized spatial lengths are 0.07, 0.03, 0.75, and 0.84, respectively. It is thus concluded that pure plasmonic structures (1G and 2G) have better confinement in both directions than hybrid structures (H1G and H2G).

4.2. Radiation Efficiency

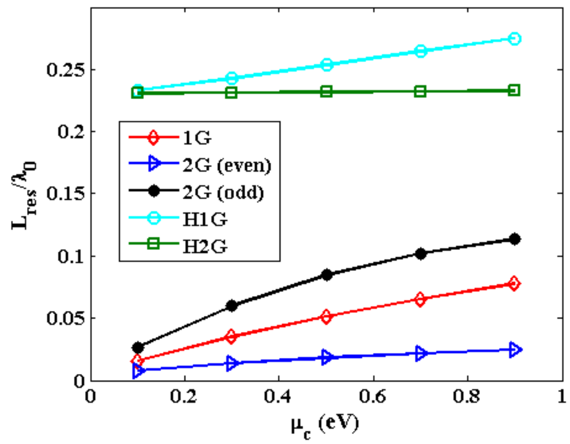
Radiation efficiency is an important factor for any antenna. In terahertz antennas, the efficiency is particularly concerning due to the already low efficiency of existing sources based on photomixing [13]. The radiation efficiency e_r of an antenna can be expressed in terms of radiation resistance R_r and ohmic resistance R_o as [52]

$$e_r = \frac{R_r}{R_r + R_o}. \tag{12}$$

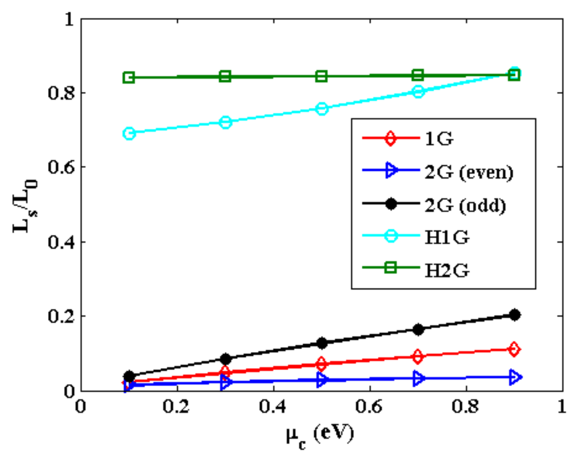
With this fundamental equation, it is straightforward to see that, for a fixed radiation resistance, the efficiency decreases as the ohmic resistance increases. This ohmic loss is directly related to the attenuation constants of the mode propagating in the specified structure. A suitable qualitative measure of superiority of the structures from the aspect of radiation efficiency is the *propagation length*. This metric is defined as the distance that a SPP must travel to reduce its electric field intensity to $1/e$ of its initial value, and is mathematically represented by

$$L_p = \frac{1}{k_0 Im(\tilde{n}_{eff})} = \frac{1}{Im(\tilde{\gamma}_{eff})} = \frac{1}{\alpha_{eff}}. \tag{13}$$

Consequently, the structures are compared from aspect of radiation efficiency using the ($L_p/\lambda_0 - \mu_c$) plot in Fig. 5. Note that a structure with a high propagation length is desirable. Moreover, radiation efficiency can be significantly affected by the radiation aperture. As a matter of fact, a larger electrically antenna results in a higher radiation resistance and, therefore, a higher efficiency. For all this, the ($L_{res}/\lambda_0 - \mu_c$) plot shown in Fig. 4(a) is useful to compare the structures from this aspect as well.



(a)



(b)

Figure 4: Comparing one-dimensional structures based on graphene from aspect of longitudinal and vertical miniaturization using (a) normalized resonant length (b) normalized spatial length.

From both the mentioned points, it is observed that an antenna based on the 2G structure with even mode has the lowest radiation efficiency among all the structures, whereas the implementation of terahertz antennas based on the hybrid structures are faced with a higher radiation efficiency than the pure plasmonic structures.

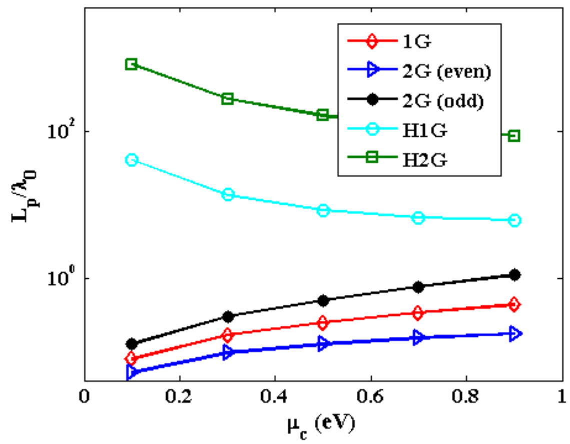


Figure 5: Comparing one-dimensional structures based on graphene from aspect of radiation efficiency using normalized propagation length on a logarithmic scale.

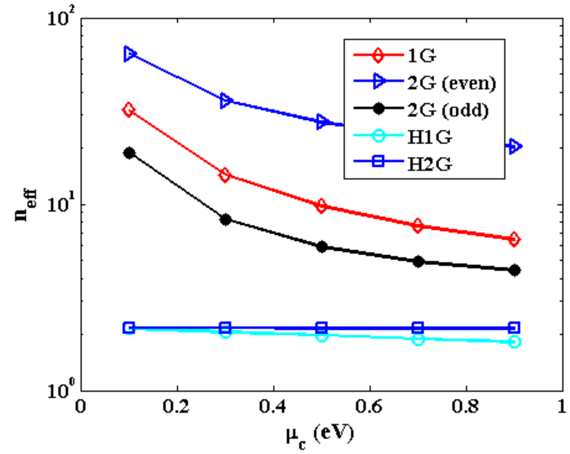


Figure 6: Comparing one-dimensional structures based on graphene from aspect of tunability using effective index on a logarithmic scale versus chemical potential.

4.3. Tunability

Tunability of terahertz antennas is a desirable feature in wireless communication at both of the macroscale and micro/nanoscale. One of the extraordinary advantages of graphene with respect to other materials is that the chemical potential (Fermi level) can be dynamically modified by changing the electrostatic voltage applied to the graphene sheet. Since the chemical potential determines the resonance frequency of graphene-based antennas

[29], this gives antenna engineers an opportunity to design graphene-based radiated-wave structures that can be reconfigured while in operation.

In order to compare the structures from the aspect of reconfigurability, ($n_{eff} - \mu_c$) plot is depicted in Fig. 6. It is clearly seen that the tunability of 1G and 2G structures is much wider than those of H1G and H2G. The reason of this result is that the 1G and 2G structures support only a pure plasmonic mode which is tunable by changing chemical potential, while H1G and H2G structures provide a hybrid mode which is a combination of plasmonic and dielectric modes.

4.4. Impact of Graphene Quality

Various guided-wave and radiated-wave applications will require high-quality graphene to make efficient devices. Graphene has been synthesized by a multitude of techniques such as exfoliating graphene, desorption of silicon from silicon carbide (SiC) single-crystal surfaces, or surface precipitation process of carbon in some transition metals. However, Chemical Vapor Deposition (CVD) remains as the most economical approach and is widely used in both research and industry [53]. After obtaining the graphene layer, different processes are required to lay down and cut the layer into the desired shape. Notably, a Focused Ion Beam (FIB) can be used to perform the latter [37].

Both the fabrication process and the methods required to transfer, shape, and wash away the material affect the quality of the graphene patch that will serve as radiating element. Generally, the quality of the graphene samples is described via the relaxation time τ and impacts on the conductivity of the material as observed in Equation (2). Previous works have demonstrated that the relaxation time has a strong impact on the resonant behavior of antennas that would fall within the 1G category used in this work [38]. However, the impact of such parameter on the performance of the rest of device types has not been evaluated explicitly.

In this section, we evaluate the impact of the relaxation time on the radiation efficiency of the evaluated structures, namely, 1G, 2G (even and odd), H1G, and H2G. To this end, Table 1 shows the propagation length normalized to the effective wavelength of the antenna L_p/λ_{eff} for each particular case. Remind that this metric is a strong indicator of the potential radiation efficiency of the structure.

The results illustrate how implementing graphene with higher τ results in longer propagation lengths and, therefore, higher radiation efficiencies for all

Table 1: Effect of relaxation time on the normalized propagation length as an indicator of radiation efficiency for the evaluated antenna structures.

Relaxation time	1G	2G (even)	2G (odd)	H1G	H2G
0.2 ps	0.80	–	0.97	5.84	112.22
0.6 ps	2.41	3.46	2.95	16.62	316.99
1 ps	4.02	5.75	4.92	27.57	525.48

the evaluated cases. The difference in terms of absolute value suggests that not all antenna structures have the same requirements in terms of graphene quality. For instance, it is observed that the even mode does not propagate in 2G structure for small relaxation time, thus requiring a moderately high graphene quality to be able to operate. On the other hand, it is worth noting that the relative variations in terms of propagation length are almost identical for all the structures. This indicates that improving the fabrication and integration methods will be equally beneficial in all cases.

4.5. Summarizing Discussion

The process of graphene antenna design implies a fundamental choice between the different basic structures shown in Fig. 2 or other novel structures. Table 2 summarizes the properties of the four structures analyzed throughout the paper illustrating a clear design tradeoff: in general terms, high tunability and miniaturization are incompatible with high radiation efficiency. Indeed, we have observed that pure plasmonic structures capture the essence of graphene properties, delivering a strong subwavelength behavior and dependence on frequency via chemical potential variation. However, this comes at the cost of losses due to the relatively low quality of the graphene samples provided by current fabrication and integration techniques. This has been discussed in several works, notably in [54].

The introduction of hybrid graphene-dielectric structures provides an interesting counterpoint to this. The coupling of plasmonic and dielectric modes in the H1G and H2G structures analyzed in this paper delivers much higher efficiency at the cost of losing a great deal of the miniaturization or reconfigurability properties of pure plasmonic antennas. This, by itself, represents an opportunity for the implementation of practical antennas with graphene as part of the radiating elements. Moreover, we anticipate that this will represent a crucial first step on the quest of a compromise between efficiency, miniaturization, and tunability in graphene-based RF devices. A

Table 2: Comparison the antenna performance using the one-dimensional structures.

Structure	1G	2G (even)	2G (odd)	H1G	H2G
Radiation Efficiency	↓↓	↓↓	↓	↑	↑↑
Miniaturization	↑	↑↑	↑	↓	↓
Tunability	↑↑	↑↑	↑↑	↓	↓

fine-grained tweaking of parameters such as the permittivity of the dielectric, the number of graphene layers and their characteristics, or the geometry of the structure, could be used to find a graceful balance between the different features.

In the end, making the right choice of the basic structures for the desired antenna will depend upon the type of application. Applications heavily constrained by the size of the wireless communication unit, e.g. nanosensor networks [9], may require the use of pure plasmonic antennas despite of their lower radiation efficiency. The compact nature of such structures are also useful for the creation of ultra-massive MIMO systems [44] capable of overcoming the losses of single antennas while providing multiple beams for spatial multiplexing purposes.

In advanced applications such as wireless on-chip communication [11, 55], the choice will be driven by the upper layers, which may require either very high performance or flexibility through the unprecedented tunability provided by graphene. Indeed, tunability becomes a highly interesting feature as it can be used to implement unique MAC protocols capable of finding free frequency channels in the terahertz band to transmit, perhaps with the help of an omnidirectional access point [56]. This could be seen as a first step towards the next generation of *cognitive radio*. Also, the fast tunability of such pure plasmonic structures could trigger the development of novel frequency-hopping schemes for enhanced security [9] or to adapt to time-varying channels [57].

In applications where efficiency has priority over tunability and miniaturization, neither pure plasmonic nor hybrid structures may be a suitable option. There, as mentioned in Section 2, graphene may be pushed into playing a role as an auxiliary element of the antenna structure.

Finally, it is worth noting that the one-dimensional analysis presented in this paper represents a first step that may be extended with further evaluations of three-dimensional structures. The shape of the antennas and feeding structures are two important factors in real antennas affecting the radiation properties and, consequently, a deep study on these parameters would be necessary to design antennas uniquely tailored to the requirements of each application context. As we have seen, the quality of the graphene samples may also have a significant impact upon the propagation properties of the guided modes and, therefore, should be carefully studied in future work.

5. Conclusions

The combination of dielectric resonator antenna and graphene plasmonic antenna provides new degrees of freedom in the design of graphene-based antennas for terahertz band operation. Through the analysis of one-dimensional structures, we have demonstrated that hybrid antenna designs provide higher efficiency at the cost of reduced miniaturization and tunability with respect to existing purely plasmonic proposals. Precisely, there is a difference of approximately one order of magnitude in terms of miniaturization and tunability, and up to two orders of magnitude in terms of radiation efficiency between pure and hybrid structures. Understanding such fundamental tradeoff is key to develop a family of hybrid structures capable of providing a compromise between the different characteristics. Eventually, the choice of the particular antenna design will be driven by the specific application requirements at the macroscale or at the nanoscale.

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