Surveying of Pure and Hybrid Plasmonic Structures Based on Graphene for Terahertz Antenna

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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. Radiation efficiency, reconfigurability, and miniaturization of antennas built upon this principle are qualitatively discussed and compared with those of pure plasmonic antennas. To this end, a quantitative study of pure and hybrid plasmonic one-dimensional guided-wave structures is performed. The results show that hybrid structures can be employed to design terahertz antennas with high radiation efficiency and gain, moderate miniaturization, and tunability, while terahertz antennas based on pure plasmonic structures can provide high miniaturization and tunability yet with low radiation efficiency and gain.

CCS Concepts

•**Hardware** → **Analysis and design of emerging devices and systems;** *Radio frequency and wireless interconnect;*

Keywords

Graphene; THz antennas; Plasmonic waveguides; hybrid structures; Surface plasmon waves.

1. INTRODUCTION

Graphene has garnered unprecedented attention due to its extraordinary 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 [2–8].

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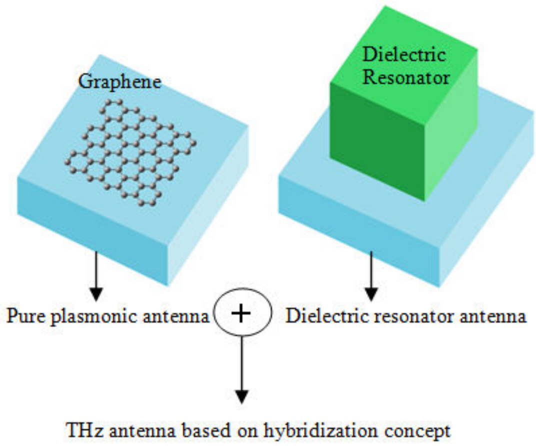


Figure 1: The conceptual scheme for hybridization of surface plasmon and dielectric wave modes to implement THz antennas.

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, as well as in novel nano-communication paradigms [9–12]. Specifically, graphene has been introduced as an attractive solution for the implementation of miniaturized antennas operating in the terahertz band. Graphene antennas can outperform their metallic counterparts owing to the unique frequency dispersion of graphene and its ability to support Surface Plasmon Polaritons (SPPs) in this frequency range, where metals act as lossy non-plasmonic conductors [13]. The outstanding properties of graphene also confer antennas with tunability, as demonstrated with a novel antenna based on hybrid graphene-metal structure that adds reconfigurability capabilities to metallic THz antennas [14].

Dipole-like and patch-like antennas based on the pure plasmonic graphene structures have been investigated in the literature [15–18]. It has been pointed out that the radiation efficiency of these antennas is low because losses of the surface plasmon modes supported by graphene are moderately

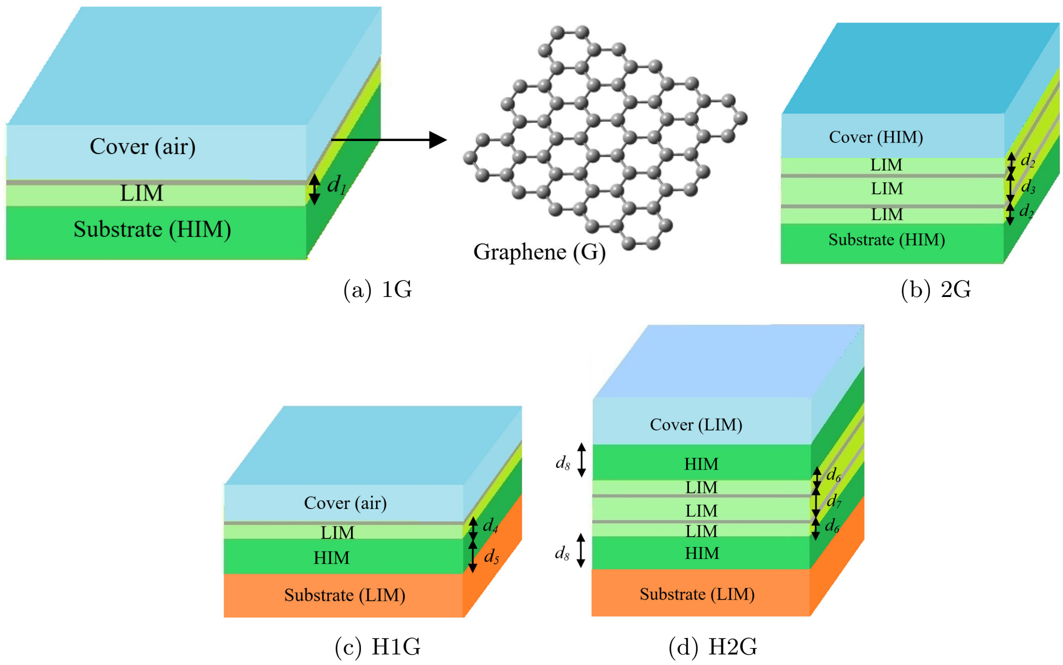


Figure 2: Geometries of one-dimensional plasmonic waveguides based on graphene including pure plasmonic structures (a-b) and hybrid structures (c-d).

high at THz frequencies [16, 19]. Instead, hybrid plasmonic guided-wave structures have been introduced to provide a better balance between mode confinement and propagation loss in the terahertz band [13]. 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 [20]. Consequently, here, we propose the concept of terahertz antenna based on the hybridization of surface plasmon and dielectric wave modes (Fig. 1).

In the present work, we analyze two types of guided-wave structures at 3 THz to compare their properties and performance. First, we consider pure plasmonic structures composed by one and two isolated graphene layers. Second, we analyze 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 THz antennas, namely, radiation efficiency, tunability, and miniaturization.

The rest of this paper is organized as follows. Section II presents the investigation approach and also comparative results of one-dimensional waveguides. In Section III, antenna properties are evaluated and compared. Finally, conclusions are provided in Section IV.

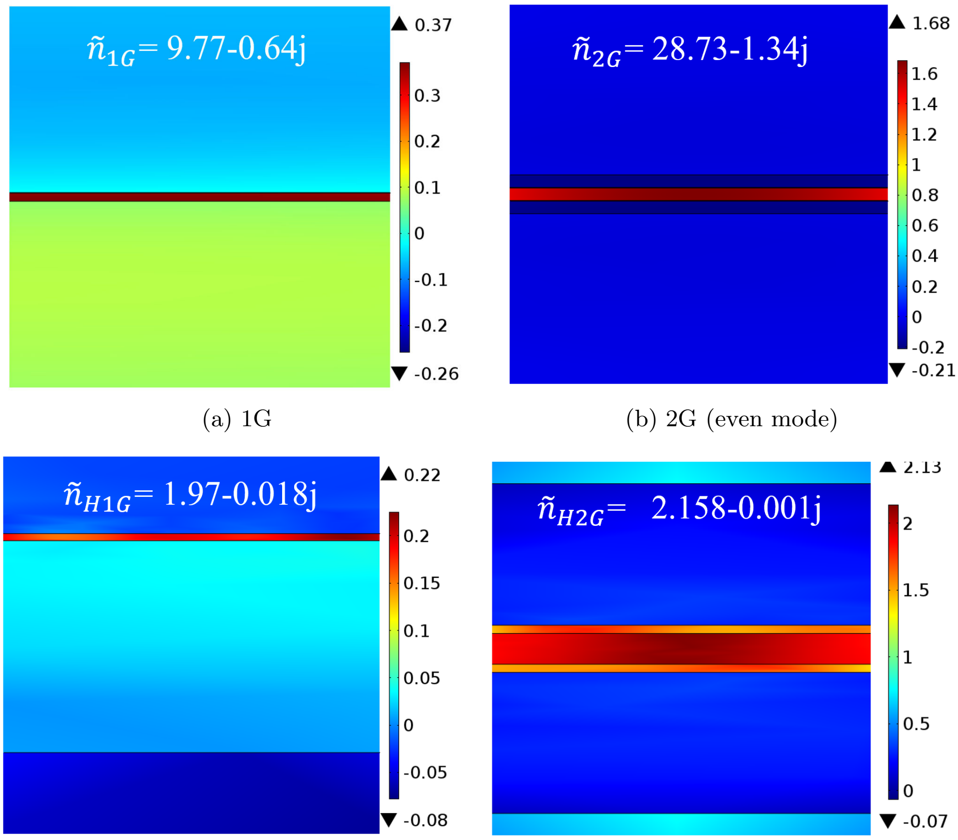
2. ONE-DIMENSIONAL STRUCTURES AS BUILDING BLOCKS OF GRAPHENE ANTENNAS

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 structures is conducted in order to guide further discussions about the performance of antennas 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. 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. 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).

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. Moreover, the dimensions of the structures are defined as $d_1 = d_2 = d_3 = 0.1$ µm, $d_4 = d_6 = 0.5$ µm, $d_5 = 15$ µm, $d_7 = 2$ µm, and $d_8 = 9$ µm. The frequency of excitation is 3 THz.

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



(a) 1G

(b) 2G (even mode)

(c) H1G

(d) H2G (even mode)

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

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

The complex conductivity σ_G can be calculated by the well-known Kubo formula [21] as

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

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 (τ = 0.6 ps in this paper). Finally, $f(\varepsilon) = 1/\{1 + exp[(\varepsilon - \mu_c)/(k_B T)]\}$ is the Fermi-Dirac distribution function.

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:

$$+j\left(\frac{\tilde{\gamma}_{xS}}{\varepsilon_{rS}} m_{11} + \frac{\tilde{\gamma}_{xC}}{\varepsilon_{rC}} m_{22}\right) = \frac{\tilde{\gamma}_{xS}\tilde{\gamma}_{xC}}{\varepsilon_{rS}\varepsilon_{rC}} m_{12}, \quad (3)$$

where $\tilde{\gamma}_{xC} = \sqrt{\tilde{\gamma}_{eff}^2 - k_0\varepsilon_{rC}}$, $\tilde{\gamma}_{xS} = \sqrt{\tilde{\gamma}_{eff}^2 - k_0\varepsilon_{rS}}$, while ε_{rC} and ε_{rS} are the dielectric constants of cover and substrate layers, respectively, and m_{ij} are the elements of the total transfer matrix M as defined in [7]. The zeroes of this equation, which are the guided mode complex propagation constants

$$\tilde{\gamma}_{eff} = k_0\tilde{n}_{eff} = k_0(n_{eff} - jk_{eff}) = \beta_{eff} - j\alpha_{eff}, \quad (4)$$

are obtained analytically. The full-wave solver COMSOL [22] is used to verify the results of this method.

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 μ_c = 0.5 eV. It should be noted that there are two possible modes for 2G and H2G structures, including even mode, in which the normal electric fields is even symmetric, and odd mode in which the symmetry is odd. Here, the even mode is preferred because of a much better confinement in comparison with the odd mode. A detailed comparison among pure and hybrid structures is performed in the following section.

3. QUALITATIVE DISCUSSION ON GRAPHENE ANTENNA PERFORMANCE

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. Then, we summarize the outcome of the discussion.

3.1 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 [23]

$$L_{res} = n\frac{\lambda_{eff}}{2} \overset{n=1}{=} \frac{\lambda_0}{2n_{eff}}. \tag{5}$$

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

$$L_s = \frac{1}{Re(\tilde{\gamma}_{xS})} + \sum_{i=1}^{N} d_i + \frac{1}{Re(\tilde{\gamma}_{xC})} \tag{6}$$

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, 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).

3.2 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 [16]. The radiation efficiency e_r of an antenna can be expressed in terms of radiation resistance R_r and ohmic resistance R_o as [23]

$$e_r = \frac{R_r}{R_r + R_o}. \tag{7}$$

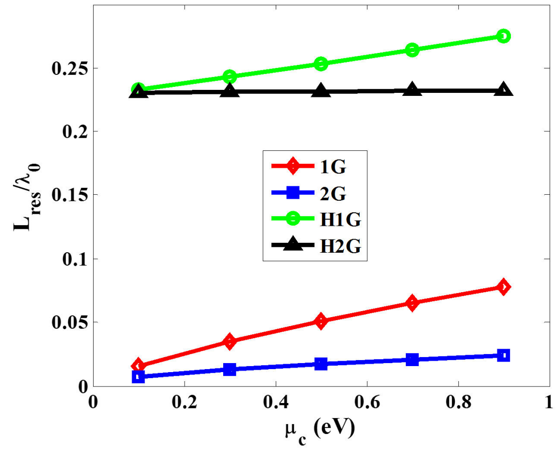
With this fundamental equation, it is straightforward to see that, for a fixed radiation resistance, the efficiency decreases as the ohmic resistance increases. This ohmic loss is directly related to the attenuation constants of the mode propagating in the specified structure. A suitable qualitative 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

$$L_p = \frac{1}{k_0 Im(\tilde{n}_{eff})} = \frac{1}{Im(\tilde{\gamma}_{eff})} = \frac{1}{\alpha_{eff}}. \tag{8}$$

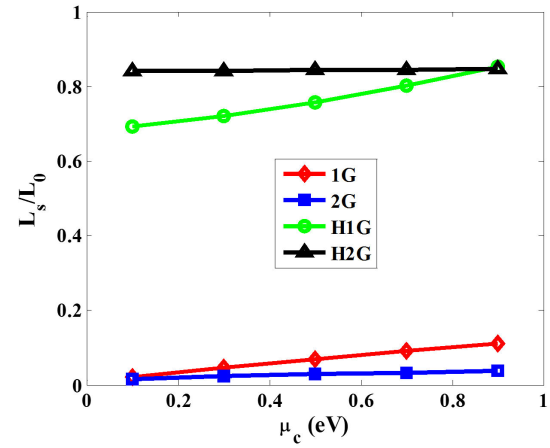
It is more convenient to represent the propagation length in the following normalized form

$$\frac{L_p}{\lambda_{eff}} = \frac{1}{k_0 Im(\tilde{n}_{eff})}\frac{Re(\tilde{n}_{eff})}{\lambda_0}. \tag{9}$$

Consequently, the structures are compared from aspect of radiation efficiency using the $(\frac{L_p}{\lambda_{eff}} - \mu_c)$ plot in Fig. 5. For $\mu_c = 0.5$ eV, the normalized propagation lengths of 1G, 2G, H1G, and H2G are 2.4, 3.4, 16.6, and 188.2, respectively. Note that a structure with a high propagation length is desirable. It is thus observed that an antenna based on 1G



(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.

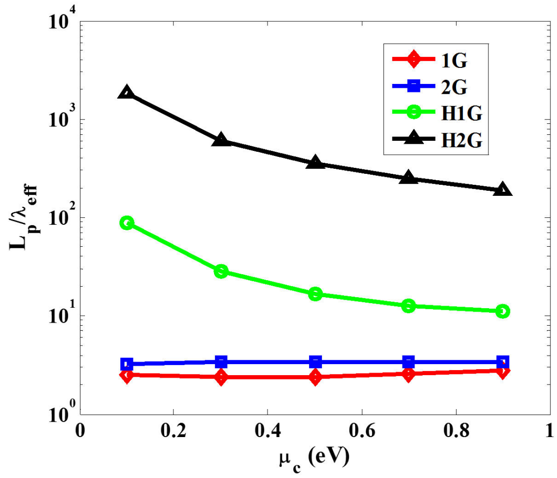


Figure 5: Comparing one-dimensional structures based on graphene from aspect of radiation efficiency using normalized propagation length on a logarithmic scale.

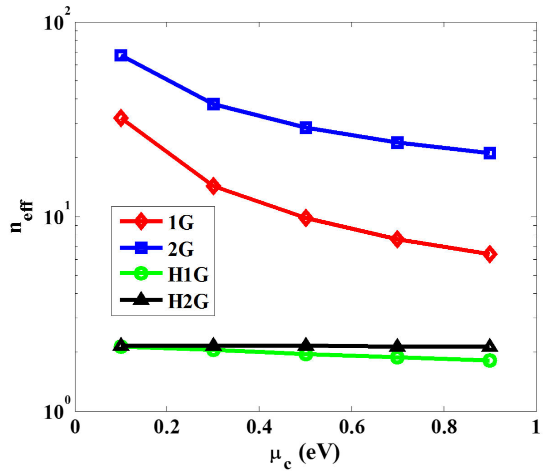


Figure 6: Comparing one-dimensional waveguides based on graphene from aspect of tunability using effective index on a logarithmic scale versus chemical potential.

structure has the lowest radiation efficiency among structures while the implementation of terahertz antennas based on the hybrid structures are faced with a higher radiation efficiency compared with the pure plasmonic structures.

3.3 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 [14], 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.

3.4 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 1 summarizes the properties of the four structures mentioned above. In general terms, a tradeoff between the different characteristics of the structures is observed. Making the right choice of the basic structures for the desired antenna will generally 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. In applications such as wireless on-chip communication [10], the choice will be driven by the upper layers,

Table 1: Comparison the antenna performance using the one-dimensional structures (1G, 2G, H1G, and H2G).

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

which may require either very high performance or flexibility through a wide tunability.

Another point concerns the implementation of real antennas as three-dimensional structures. Various kinds of antennas can be conceived using the above mentioned one-dimensional structures. The shape of the antennas and feeding structures are two important factors in real antennas affecting the radiation properties. Consequently, a deep study on these parameters would be necessary to design efficient THz antennas.

It is worthy to note that the results of the basic structures with respect to the chemical potential of graphene are presented in this paper. Another parameter is relaxation time which mainly depends on graphene quality achieved during the fabrication process. Its value may have a significant impact upon the propagation properties of the guided modes and, therefore, on the radiation performance of the designed antennas.

4. CONCLUSIONS

This paper has surveyed the features of four one-dimensional plasmonic structures that may be employed in the development of graphene antennas. Results reveal fundamental tradeoffs between efficiency and miniaturization, and between efficiency and tunability. These can be used to steer the design of appropriate structures for terahertz antennas according to the specific application requirements at the macroscale or at the nanoscale.

5. ACKNOWLEDGMENTS

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