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Evaluation of graphene-based terahertz photoconductive antennas

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KEYWORDS

Antenna; Graphene; Impedance; Plasmonic; Terahertz. **Abstract.** Plasmonic mode propagation properties of a graphene strip placed on a substrate are studied in the THz range. Based on propagation properties (phase constant), a design guide for a dipole-like antenna made of graphene strips is presented. The input impedance and the radiation properties of such graphene-based antenna are investigated through full-wave numerical simulations. Full-wave simulations show that graphene antennas can provide higher input impedance, along with the tunability of the resonance frequency, which are two important design requirements in high performance terahertz photoconductive antenna sources and detectors.

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1. Introduction

Graphene has been recognized for its unique electronic, thermal and mechanical properties [1,13]. One of the areas on which graphene promises to have a significant impact is terahertz technology, covering the spectral range of 0.1 - 10 THz. Optical or injection pumping of graphene can exhibit negative-dynamic conductivity in the terahertz (THz) spectral range [8], which may bring new types of THz laser [9,7]. The stacked graphene-insulator-graphene layers have been explored theoretically as active terahertz devices for THz amplification or detection [10]. Graphene-based nanoantennas have been investigated for graphene-enabled wireless communication [6].

THz photoconductive antennas (PCAs) have predominantly been used for THz generation and detection [4]. PCAs are comprised of a photonic mixer made of an ultrafast photoconductive material that is

*. Corresponding author. E-mail addresses: milad@umich.edu (M. Zolfagharloo Koohi); mneshat@ut.ac.ir (M. Neshat) integrated with a metallic planar antenna. There are two major challenges in the design of such devices: One is the difficulty of impedance matching between the photonic mixer and the metallic antenna for maximum power transfer. Such difficulty arises from the fact that the intrinsic impedance of the photonic mixers is much higher than that of planar metallic antennas [4]. The other is that the resonant metallic antennas show high performance only in a narrow frequency band, which limits the overall performance of the photonic mixer that is intrinsically wideband (~0.1-4 THz) by itself.

It has been shown that a graphene layer can support plasmonic modes in THz range [2]. Moreover, the electronic properties of the graphene layer can be tuned by its chemical potential, which leads to tunable resonant antennas in a wide frequency range [12]. Such properties may be used favorably in order to overcome the above-mentioned challenges in the PCAs, by replacing the metallic antenna part with that made of graphene layers.

In this paper, we present plasmonic mode propagation properties of a graphene strip placed on a substrate in the THz range. We also propose a design guide for a dipole-like antenna made of graphene strips that is suitable for PCA application. The input impedance

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and the radiation properties of such graphene-based antenna are also investigated through full-wave numerical simulations. The matching, radiation and total efficiencies are also investigated.

2. Graphene model

A single layer graphene can be modeled by a 2D surface conductivity. We use the frequency-dependent conductivity of a single layer graphene based on the Kubo formula as [3]:

$$\sigma(\omega, \mu_c, \Gamma, T) \approx -j \frac{q_e^2 k_B T}{\pi \hbar^2 (\omega - 2j\Gamma)} \times \left(\frac{\mu_c}{k_B T} + 2\ln(e^{-\frac{\mu_c}{k_B T}} + 1) \right), \qquad (1$$

where ω is the angular frequency; μ_c is the chemical potential; Γ is the scattering rate, which is defined as $\Gamma = 1/2\tau$; τ is the transport relaxation time; T is the temperature; k_B is the Boltzmann constant; and \hbar is the reduced Planck constant. It should be noted that only the intraband term is considered in Relation (1), which gives reasonably accurate results for frequencies limited to a few THz [3].

Figure 1 shows the real and imaginary parts of the graphene surface conductivity in terms of frequency and with chemical potential as a parameter. In Figure 1, it is evident that by changing the chemical potential, the conductivity of the graphene layer is varied. Moreover, the reactive part of the complex conductivity exhibits an inductive property, which



Figure 1. Real (solid) and imaginary (dashed) parts of the graphene conductivity given in Relation (1).

is essential for supporting the Transverse-Magnetic (TM) surface wave (plasmonic wave) by the graphene sheet [3].

3. THz wave propagation in a single layer graphene strip

Assuming a graphene strip, with the width of w and the surface conductivity given in Relation (1), that is placed on a substrate, one can study the propagation behaviour of the plasmonic modes along the strip, namely, complex propagation constant ($\gamma = \alpha + j\beta$) and the field confinement through full-wave EM simulations. In order to calculate γ , the scattering parameters (S-parameters) of two identical strip waveguides with length difference of Δl are simulated over the desired frequency range. We use HFSS, a commercial fullwave EM simulator based on the finite element method, for such a purpose. The S-parameters of the strip waveguides are then transformed into the transmission matrix (T). It has been shown that the complex propagation constant can be obtained from the eigenvalues of the T-matrix as [14]:

$$\gamma = \alpha + j\beta = \frac{\ln\left(eig(T)\right)}{\Delta l},\tag{2}$$

where $\ln(.)$ is the natural logarithm function, and $\operatorname{eig}(T)$ gives the eigenvalues of the T-matrix. Figure 2 shows the normalized real and imaginary parts of the propagation constant of a graphene strip on the glass substrate with relative permittivity of $\epsilon_r = 3.8$. In Figure 2, the width of the strip varies between



Figure 2. Normalized real (dashed) and imaginary (solid) parts of the propagation constant of a graphene strip on a glass substrate. Width of the strip varies as a parameter and $\mu_c = 0.13$ eV. $k_0 = \omega/c$ is the propagation constant in free-space.



Figure 3. Normalized real (dashed) and imaginary (solid) parts of the propagation constant of a graphene strip on glass substrate. Chemical potential varies as a parameter and $w = 8 \ \mu m$.



Figure 4. Electric field confinement (side view) of the plasmonic mode propagating along a graphene strip with $w = 8 \ \mu \text{m}$ and $\mu_c = 0.15 \text{ eV}$ on the glass substrate at f = 1 THz.

 $w = 2 - 10 \ \mu \text{m}$ as a parameter, whereas the chemical potential is fixed at $\mu_c = 0.13$ eV. As seen in Figure 2, by decreasing the strip width phase constant (β) and attenuation coefficient (α) both increase. Figure 3 shows the normalized propagation constant for a fixed $w = 8 \ \mu m$, and different chemical potentials. From Figure 3, it is important to note that by changing the chemical potential, the phase constant varies. This interesting feature, as shown in the next section, provides a tuning tool for the resonance frequency of an antenna made of graphene strips. Figure 4 shows the electric field confinement of the plasmonic mode propagating along a graphene strip with $w = 8 \ \mu m$ and $\mu_c = 0.15$ eV on the glass substrate at f = 1THz. As expected from a plasmonic mode, in Figure 4, the transverse confinement is much smaller than the free-space wavelength ($\lambda_0 = 300 \ \mu m$). Also, the effect of attenuation is clearly visible in Figure 4, when the mode propagates along the graphene strip.



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Figure 5. Dipole-like antenna made of two graphene strips on a substrate and integrated with a photonic mixer in the center gap.

4. Antenna design and simulation

Figure 5 shows a dipole-like antenna made of two graphene strips on a substrate and integrated with a photonic mixer in the center gap. The photonic mixer is made of a thin layer ($\sim \mu$ m) of an ultra-fast photoconductor, such as low-temperature-grown GaAs (LTG-GaAs). In the photonic mixer, two CW infrared lasers are mixed in the DC biased fast photoconductive layer acting as a nonlinear medium. Due to the photomixing, a CW photocurrent is generated with the beat frequency in THz range [4]. The resultant photocurrent excites the dipole-like antenna, as shown in Figure 5. The antenna radiates waves at the THz beat frequency of the two IR lasers.

In Figure 5, for a given strip width, w, the length of the strips, L, can be estimated from the dispersion plot in Figure 2. For maximum input impedance, the length of the antenna should be around one wavelength, i.e. $L = \lambda = 2\pi/\beta$. Using HFSS, Figure 6 shows



Figure 6. Simulated real (solid) and imaginary (dashed) parts of the input impedance of the dipole-like antenna made of graphene strips with $L = 23 \ \mu \text{m}$ and $\mu_c = 0.13 \ \text{eV}$, and w as a parameter.

the simulated real and imaginary parts of the input impedance of the dipole-like antenna made of graphene strips, with $L = 23 \ \mu m$ and $\mu_c = 0.13 \ eV$, and w as a parameter. For the excitation of the antenna, a lumped port was used to model the photonic mixer. As seen in Figure 6, the value of the peak resistivity and the resonance frequency, at which the imaginary part vanishes, strongly depends on the width of the graphene strips, w. In our simulations, we noticed that for narrower strips, the length of the antenna becomes closer to the design value of $L = \lambda = 2\pi/\beta$ at the peak resistivity. Figure 7 shows the simulated real and imaginary parts



Figure 7. Tuning effect on real (solid) and imaginary (dashed) parts of the input impedance of the graphene antenna with $L = 16 \ \mu m$ and $w = 1 \ \mu m$, and μ_c as a parameter.

of the input impedance of the dipole-like antenna made of graphene strips with $L = 16 \ \mu m$ and $w = 1 \ \mu m$, and μ_c as a parameter. As seen in Figure 7, the peak resistivity has the value of more than 6 k Ω , which is in the same range of the photonic mixer impedance [4]. It is worth noting the impedance of a metallic (e.g. gold) antenna counterpart is around 670 Ω , which is about one order of magnitude smaller. Also, the length of the metallic antenna is 355 μ m, compared to 16 μ m for the graphene. Moreover, from Figure 7, it is clear that by changing the chemical potential, one can tune the peak resonance and, therefore, enjoy the wideband feature of the photonic mixer while keeping a high performance in the whole frequency range. Figure 8 shows the radiation pattern of the graphene antenna. As seen in Figure 8, by tuning the resonance frequency, the radiation pattern only changes slightly. In Table 1, the bandwidth of the graphene based resonant antenna is compared for different chemical potential values with the same antenna simulated in Figure 7. As is clear, by increasing the chemical potential, the bandwidth degrades.

5. Graphene antenna loss and efficiency

Figure 9 compares the real and imaginary parts of the input impedance of two antennas made of graphene and gold with resonance frequencies close to 0.85 THz and $w = 5 \ \mu m$. The length of the graphene antenna is 27 μm , as compared to 385 μm for the gold antenna. It is worth noting that, at resonance, the peak resistivity of the graphene antenna is 5 times that of the gold antenna, the bandwidth of the antenna degrades, as tabulated in Table 2; one could design the antenna for specific applications considering this trade off.



Figure 8. Radiation pattern (directivity) of the graphene antenna with $L = 25 \ \mu \text{m}$ and $w = 12 \ \mu \text{m}$, and μ_c as a parameter in E-plane (a) and H-plane (b). The substrate has the thickness of 160 μm and lateral dimension of 240 $\mu \text{m} \times 250 \ \mu \text{m}$.

Table 1. Bandwidth variation with chemical potential.							
Chemical potential (eV)	0.05	0.10	0.15	0.20	0.25		
$f_r (\mathrm{THz})$	0.61	0.85	1.04	1.20	1.33		
Bandwidth (THz)	0.1295	0.1207	0.1172	0.1166	0.5855		
FBW $\%$	21.23	14.20	11.26	9.70	4.40		

Table 2. Bandwidth comparison of graphene and gold antennas.



Figure 9. Comparing the real (solid) and imaginary (dashed) parts of the input impedance of antennas made of graphene and gold with close resonance frequency.

Our simulations with HFSS affirm the tunablity, miniaturization, and high input impedance characteristics of the graphene antenna, which is in agreement with previous reports [12,11]. The higher impedance of the graphene antenna results in a better impedance, matching the photonic mixer, which shows around 10 k Ω dynamic resistance [4]. Figure 10 shows the circuit model of a THz photoconductive antenna at



Figure 10. Circuit model of a THz photoconductive antenna at resonance

resonance. In Figure 10, the photonic mixer is modeled by a source and a dynamic resistance (R_s) , whereas the antenna is represented by radiation (R_{rad}) and loss (R_l) resistances. At resonance, the reactive part of the antenna impedance becomes zero (see e.g. Figure 6) and the resistive part is given by $Z_{in} = R_{in} = R_{rad} +$ R_l .

The total efficiency, e_t , of the PCA can be divided into the matching efficiency, $0 < e_m < 1$, and radiation, efficiency $0 < e_r < 1$ as follow:

$$e_t = \frac{P_{rad}}{P_{av}} = e_r e_m, \tag{3a}$$

$$e_m = \frac{P_{in}}{P_{av}} = \frac{4R_s R_{in}}{(R_{in} + R_s)^2},$$
 (3b)

$$e_r = \frac{P_{rad}}{P_{in}},\tag{3c}$$

where P_{av} is the available power of the photonic mixer when conjugate match is satisfied. P_{in} and P_{rad} are the delivered power to the antenna and radiated power from the antenna, respectively. In the following calculations, the efficiencies defined above are calculated for two cases of graphene and gold antennas with almost similar resonance frequencies. e_r and R_{in} are obtained from full-wave HFSS simulations, whereas e_t and e_m are calculated from Eqs. (3a) and (3b), respectively. The dynamic resistance of the photonic mixer is assumed to be $R_s = 10 \ k\Omega$ [4].

5.1. Graphene antenna case

In this case, the graphene strips shown in Figure 5 were modeled in HFSS by 2D conductive sheets, with the conductivity given in Relation (1). The strip width and length are $w = 5 \ \mu m$ and $L = 27 \ \mu m$, respectively. The resonance frequency and the maximum input resistance were obtained as $f_r = 0.85$ THz and $R_{in} = 1800 \Omega$. The efficiencies for this case are given in Table 3.

5.2. Gold antenna case

In this case, the graphene strips shown in Figure 5 were replaced by gold strips. The conductivity of

Table 3. Comparison of efficiencies for graphene and gold antenna

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	Material	e_r	e_m	e_t
	Graphene	0.0212	0.5171	0.0110
	Gold	0.8965	0.1237	0.1109

$\begin{array}{c} \textbf{Chemical potential} \\ \textbf{(eV)} \end{array}$	$\mathrm{Max}\;\mathrm{Re}(\mathrm{Z})\; @\; f_r(\Omega)$	$f_r(\mathrm{THz})$	$e_r(\%)$
0.15	2300	0.923	2.07
0.20	2300	1.046	3.59
0.25	2300	1.193	5.51

Table 4. Comparison of efficiencies for different chemical potentials for an antenna with $w = 4 \ \mu m$, $L = 26 \ \mu m$.

Table 5. Comparison of efficiencies of double vs. single layer structure.

Antenna type	$\mathrm{Max}\;\mathrm{Re}(\mathrm{Z})\;@\;f_r(\Omega)$	$f_r(\mathrm{THz})$	$D_{ m m}({ m dB})$	$e_r(\%)$
Single layer	2300	0.86	1.80	1.54
Double layer	1756	1.12	0.56	5.21

$w(\mu { m m})$	$L(\mu m)$	$\mathrm{Max}\ \mathrm{Re}(\mathrm{Z}) @ f_r(\Omega)$	$f_r(\mathbf{THz})$	$D_m(\mathrm{dB})$	$e_r(\%)$			
2	21.4	4060	0.88	0.26	0.77			
4	26.0	2300	0.86	1.75	1.56			
8	33.3	1190	0.78	7.81	3.56			
10	35.3	1000	0.77	9.28	4.53			

Table 6. Comparison of efficiencies for different antenna width.

Гable	7.	Designed	graphene	antenna	with	enhanced	radiation	efficiency.
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Chemical potential $\mu { m m}$	$\mathbf{W}(\mathbf{\mu m})$	$L(\mu m)$	$\mathrm{Max}\;\mathrm{Re}(\mathrm{Z})\; @\; f_r(\Omega)$	$f_r(\mathbf{THz})$	$\boldsymbol{D_m}(\mathbf{dB})$	e_r
0.25	10	35.3	650	1.36	1.96	34.74

gold is almost frequency independent in the range of interest and was chosen as $\sigma = 3.1 \times 10^7$ S/m, which was measured for thin film gold in [5]. The strip width and length are $w = 5 \ \mu m$ and L = $385 \ \mu m$, respectively. The resonance frequency and the maximum input resistance were obtained as $f_r = 0.85$ THz and $R_{in} = 330 \ \Omega$. The efficiencies for this case are given in Table 3.

Comparing the efficiencies given in Table 3 reveals that although the matching efficiency in the graphene antenna is more than 4 times higher than that in the gold antenna, the radiation efficiency is reduced by a factor of around 42. Therefore, for this example structure, the total efficiency of graphene-based PCA is around one order of magnitude less than that of the conventional metallic-based PCA.

6. Enhancing radiation efficiency

In this section, we study the parameters that can enhance the radiation efficiency of the graphene antenna. We realized that parameters such as chemical potential, number of graphene layers and the geometrical dimensions of the antenna have a significant effect on radiation efficiency, as discussed below.

6.1. Chemical potential

Based on the intraband term of the Kubo formula, by increasing the chemical potential (μ_c) , the real part of the graphene conductivity grows (see Figure 1), and, therefore, the antenna loss decreases. The simulation results in Table 4 clearly show that radiation efficiency is enhanced by increasing the chemical potential.

6.2. Multilayer graphene vs. single layer

Using a double layer graphene provides higher effective conductivity, and enhances radiation efficiency. This is evident in the simulation results in Table 5. Alternatively on the other hand, the antenna directivity $(D_{\rm m})$ decreases for a double layer graphene antenna.

6.3. Geometrical dimension

As shown in Table 6, by increasing the width of the graphene strips (w), radiation efficiency and directivity are enhanced. This could be used favorably in the design of graphene-based PCAs.

By combining the effect of all the abovementioned parameters, one can reach an acceptable radiation efficiency, as shown in Table 7.

7. Conclusion

In this paper, various aspects of graphene-based PCAs were discussed. It was shown that such antennas exhibit higher input impedance, as compared to their metallic counterpart. Besides, these antennas are tunable and miniaturized. The main drawback of

graphene antennas is their loss, which leads to lower radiation efficiency when compared with metallic antennas. Although the bandwidth of these graphene based antennas is lower than that of the gold, their tunable behaviour compensates for this issue, and one could receive the signal in wide range by tuning the antenna's resonance frequency. Finally, we showed that parameters such as chemical potential, number of graphene layers and the geometrical dimensions of the graphene antenna can be used to enhance the radiation efficiency.

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Biographies

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