RF Characteristics of Graphene for Reconfigurable Antennas

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Abstract. This paper is to explore RF characteristics of the graphene for antenna applications. The electrical tunability of the graphene material with applied fields and chemical means can be used for the innovative designs of tunable and reconfigurable antennas and antenna arrays at mmw and Thz wave range, which is verified by a model graphene patch antenna around 1THz in this paper.

Introduction

Monolayer graphene materials have been successfully developed for the first time [1] and now available by CVD methods with large size and industrial quantity. Excellent properties of the graphene include high electron mobility and conductivity have been widely investigated for device applications. The radio frequency (RF) characteristics of the graphene and its use for reconfigurable antennas has been explored based on CST simulations of the graphene antenna designed around 1THz with the tunability by applied fields and chemical potentials.

Graphene RF Characteristics

The theoretical research by Hanson [2-4] shows that the conductivity of the graphene can be controlled by chemical potentials and applied electric fields. It is greatly significant in millimeter and terahertz wave range. Graphene as a two-dimensional nanomaterial and nanostructure ideally consists of a single layer with atomic thickness. Without consider a magnetic filed, the graphene conductivity is composed of both interband conductivity and intraband conductivity, which can be deduced from the Kubo formula [4].

\[
\sigma(\omega, \mu_c, \Gamma, T) = \frac{je^2}{\pi \hbar^2} \left\{ \frac{1}{(\omega-j2\Gamma)^2} \int_0^\infty \epsilon \left( \frac{\partial f_d(\epsilon)}{\partial \epsilon} - \frac{\partial f_d(-\epsilon)}{\partial \epsilon} \right) d\epsilon - \int_0^\infty \frac{f_d(-\epsilon) - f_d(\epsilon)}{(\omega-j2\Gamma)^2 - 4(\epsilon/\hbar)^2} d\epsilon \right\}, \tag{1}
\]

where, \(\hbar\) is the Planck constant, \(\omega\) is the angular frequency of the electromagnetic wave, \(\mu_c\) is the chemical potential of graphene, \(\Gamma\) is the electron scattering rate, \(T\) is the temperature (Kelvin), and \(f_d(\epsilon)\) is the Fermi Dirac distribution. From Equation (1), the first part of the conductivity is contributed by the intraband electron transition, and the second part of the conductivity is contributed by the interband electron transition, which can be expressed as:

\[
\sigma_{\text{intra}}(\omega, \mu_c, \Gamma, T) = \frac{-je^2}{4\pi \hbar} \left( \frac{\mu_c}{k_B T} + 2\ln \left( e^{\frac{\mu_c}{k_B T}} + 1 \right) \right) \tag{2}
\]

And when \(k_B T \ll |\mu_c|\), the latter term can be simplified from an interband contribution to:

\[
\sigma_{\text{inter}}(\omega, \mu_c, \Gamma, T) \approx \frac{-je^2}{4\pi \hbar} \ln \left( \frac{2|\mu_c| - (\omega-j2\Gamma)\hbar}{2|\mu_c| + (\omega-j2\Gamma)\hbar} \right) \tag{3}
\]

The properties of graphene can be expressed by its surface conductivity. The surface conductivity \(\sigma_s\) of graphene is given by the sum of \(\sigma_{s,\text{intra}}\) and \(\sigma_{s,\text{inter}}\). When the graphene material works in the terahertz band, the intraband conductivity will play a major role, and it is considered that \(\sigma_s \approx \sigma_{s,\text{intra}}\), when only discusses the intraband conductivity [5].
\[
\sigma_s \approx \sigma_{s,\text{intra}}(\omega, \mu_c, T, \tau) = \frac{2e^2 k_B T}{\pi h} \ln \left[ 2 \cosh \left( \frac{\mu_c}{2k_B T} \right) \right] \frac{i}{\omega + \tau^{-1}}
\]

When the electron relaxation time of graphene is taken as \(\tau = 1.0 \times 10^{-12}\) s [2-4] and the temperature \(T\) is fixed to 300K, the relationship among surface conductivity, frequency, and chemical potential of graphene can be obtained by using MATLAB. As shown in Figure 1(a), the surface conductivity curves of graphene with the \(\mu_c\) as parameters are plotted as Y-axis based on the X axis of frequency. Fig. 1 (b) shows that the surface conductivities are changed with chemical potentials from -1.5 to 1.5 in terms of ev at specific frequencies from 0.3THz to 10 THz. The graphene surface conductivities are greatly tunable under 2 THz by changing the chemical potential \(\mu_c\). This unique RF characteristic of graphene can be utilized for the design of reconfigurable antennas. Moreover, the conductivity of graphene can be controlled by changing the value of the chemical potential. The chemical potential can be obtained by the bias voltage and the level of graphene doping. Therefore, by adjusting the bias voltage, we can easily control both real and imaginary parts of the graphene conductivity for realizing electrically tunable and reconfigurable antennas, especially at mmw and THz range.

Graphene Applications to Reconfigurable Antennas

Graphene has been recently used as transmission line, high impedance surface coating of antennas. Adding bias voltage can make the antenna such performance as tunable resonate frequency, reconfigurable radiation directions, tunable impedance, and flexible form factors [5-8].

Using graphene as an innovative RF modulation feature, we designed a reconfigurable antenna around 1 THz based on graphene. After optimization, the specific parameters of the patch antenna and feeding structure are obtained with the dimensions in terms of microns, as shown in Table 1.

<table>
<thead>
<tr>
<th>(W)</th>
<th>(L)</th>
<th>(W_1)</th>
<th>(L_1)</th>
<th>(W_2)</th>
<th>(L_2)</th>
<th>(T)</th>
<th>(W_S)</th>
<th>(L_S)</th>
<th>(H)</th>
</tr>
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<tr>
<td>100</td>
<td>71.5</td>
<td>5.9</td>
<td>47.4</td>
<td>23.6</td>
<td>44.9</td>
<td>0.05</td>
<td>300</td>
<td>143</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2. Structure of copper microstrip antenna.
W and L are the width and length of the patch antenna, respectively. $W_1$, $L_1$ is the size of microstrip line with characteristic impedance of 100 ohm; $W_2$, $L_2$ is the size of microstrip line with standard characteristic impedance of 50 ohm; and the dimensions of $W_s$, $L_s$, H are the substrate sizes. $T$ is the thickness of microstrip line, as shown at the right side of the Table 1.

From the CST simulation and $S_{11}$ curve, the resonate frequency range of the full copper patch antenna was obtained from 979.8 GHz to 1022.1 GHz with the bandwidth about 40 GHz. The good impedance match was also obtained. Moreover, the copper metal patch and feeding structure are then replaced by the graphene film as shown in Figure 3(a). The patch thickness was changed to the thickness of monolayer graphene. $S_{11}$ curves in Figure 3(b) show that the resonate frequencies of graphene patch antennas are reduced to lower than 1 THz with different chemical potentials. There are also excellent impedance matching by tuning the chemical potentials from 0.3 eV to 0.6 eV. The graphene antenna under zero chemical potential was poorly matched for impedance.

![Figure 3. (a) Structure of graphene microstrip antenna and (b) CST simulations of $S_{11}$ performance.](image)

Compared with the graphene patch antenna, the vertical section of the antenna radiation is shown in Figure 4 (a). The main lobe directions of the antenna varies from 40 to 50 degrees, and the change range is small, and the main lobe gain is not significant. The section of horizontal direction, such as Figure 3(b), changes in the direction of the main lobe from 0 to 115 degrees. It can be found that the electrical tunability of the graphene microstrip antenna can also change the directivity of the antenna system, and the change in the vertical direction is not significant. However, the horizontal direction can produce a large range of direction reconstruction near 120 degrees.

![Figure 4. Pattern of graphene microstrip antennas (a) vertical and (b) horizontal.](image)

On the other hand, by replacing the patch part of the microstrip antenna structure with graphene material, as shown in Figure 5(a), it shows that the electrical tunability of graphene is very significant. The resonant frequencies of the microstrip antenna are shifted to higher than 1 THz with the increase of graphene conductivity. When the chemical potential is taken as 1 eV, the best impedance matching and performance of the antenna structure are obtained with the minimum of $S_{11}$ of -36 dB as shown in Figure 5(b), which is better than that of pure copper microstrip antenna.
Similarly, for the analysis of graphene conductivity changes on the directivity of the patch antenna system, Figure 6 (a) shows the vertical section of the antenna system. The main lobe direction varies from 17 degrees to 34 degrees, and the main lobe gain decreases with the increase of conductivity. Figure 6(b) is a horizontal section. The direction of the main lobe varies from 13 degrees counterclockwise to 170 degrees. The directional change of antenna system is larger than that of all graphene microstrip antennas. It can be seen that the $\phi$ direction of the microstrip antenna changes greatly with the process of the chemical potential regulating the conductivity.

RF performance comparison of three different graphene patch antennas is summarized in Table 2. The all-copper microstrip antenna operates at 1000 GHz with a relative narrow bandwidth of 4% and a gain of 7.7 dB. The resonate operating frequency of the graphene microstrip antenna can be dynamically tunable with the graphene conductivity, and the operating frequency range is between 560 and 760GHz. The microstrip antenna which replaces the patch part with graphene material has the advantages. The resonate frequency and gain are also dynamically tunable, which can be shifted from 1080 to 1400GHz, and the bandwidth is wider than that of copper microstrip antenna. All these RF characteristics can be effectively utilized for the innovative designs of reconfigurable antennas and arrays, specifically at mmw and THz wave range.

<table>
<thead>
<tr>
<th></th>
<th>Copper patch antenna</th>
<th>Graphene patch antenna</th>
<th>Copper-graphene patch antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>bandwidth(GHz)</td>
<td>40</td>
<td>416</td>
<td>102</td>
</tr>
<tr>
<td>center frequency</td>
<td>1000.5</td>
<td>560~760</td>
<td>1080~1400</td>
</tr>
</tbody>
</table>
Conclusions

The RF characteristics of graphene and its potential applications to tunable and reconfigurable antennas are explored by a model patch antenna in this paper. The CST simulations of 1THz patch antenna show that the graphene has unique RF characteristics with tunability and reconfiguration by applying fields and chemical means in terms of its conductivity. These RF characteristics can be effectively utilized for the innovative designs of tunable and reconfigurable antennas and antenna arrays, specifically at mmw and THz wave range.

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References