Design of tri-band chiral graphene based terahertz patch antenna

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Abstract. In this paper, a novel terahertz patch antenna is designed using a very thin layer of graphene as the radiating patch, to get tri-band operation. An attempt, is made to design both achiral and chiral graphene patch tri-band for 0.46/0.58/0.66-THz. The simulation has been carried out by using a full wave electromagnetic simulator based on FDTD method. We then expect these results to be of interest to scientists in the field of the interaction between the electromagnetic wave and graphene to design potential application.

1. Introduction
The graphene is a two-dimensional arrangement of a single layer of carbon atoms organized in a structure in honeycomb (Figure 1). The graphene is the building block from which many materials are formed, some known for a very long time like graphite, others more recently discovered like the nano-tubes or fullerenes. For the first time in 2004, a layer of stable graphene at ambient temperature was obtained in a physical way by A. Geim and K. Novoselov [1]. This experiment contradicted the theory stipulating that a layer of graphene was thermodynamically unstable. As this new material worked out by mechanical exfoliation present of the remarkable and single properties, they were rewarded by the Nobel Prize for physics at 2010.

The terahertz (THz) frequency range will be at the heart of the next generation of wireless communication, environment monitoring and imaging systems [2-12]. The development of THz antenna systems requires the replacement of conventional metallic conductors, heavily handicapped by the skin effect, by other conductive materials with little skin effect and high conductivity at this frequency range [2]. For this graphene is particularly attractive and constitutes an interesting candidate, with a number of THz antenna systems developed worldwide, including multi-band [3, 4], tunable wideband [5], multi-beam reconfigurable [6], dual-polarized patch version [7] or dynamic beam-tilting THz antenna [8].

In this article, the terahertz patch antenna with chiral form will be designed using a layer of graphene as radiating element. A Finite Difference Time Domain (FDTD) method based simulation shows the multi-band behavior of designed antennas with high radiation efficiency, high gain and reduced dimensions. The simulated return losses in both dual band and tri-band case are well below -10dB.
2. Electronic model of graphene

In this work we use the linear model of graphene described by Kubo’s formula [2, 3, 13]. The graphene is modeled as an infinitesimally-thin sheet with a two dimension (2D) surface conductivity tensor: \( \sigma_{\text{total}} = \sigma_{\text{intra}} + \sigma_{\text{inter}} \), where \( \sigma_{\text{intra}} \) and \( \sigma_{\text{inter}} \) denote respectively the intra band and inter band conductivities. Due to the Pauli’s blocking effect, the inter band conductivity can be neglected at the lower THz frequencies, and the total conductivity of graphene is influenced by the intra band contribution [13]. The surface conductivity of graphene is calculated by using Kubo’s formula [2]. For the numerical simulations graphene is represented as a layer of material with the Drude like intraband contribution given by [2],

\[
\sigma_{\text{intra}}(\omega) = \frac{2e^2 k_B T_i}{\pi \hbar^2 (\omega + i\tau^{-1})} \ln 2 \cosh \left[ \frac{\mu_c}{2k_B T} \right]
\]  

(1)

The interband contribution is given by [2],

\[
\sigma_{\text{inter}}(\omega) = \frac{e^2}{4\hbar} H \left( \frac{\omega}{2} \right) + i \frac{4e}{\pi} \int_0^{\infty} \frac{H(\epsilon) - H \left( \frac{\omega}{2} \right)}{\omega^2 - 4\epsilon^2} d\epsilon
\]  

(2)

Where, \( H(\epsilon) \) is defined as,

\[
H(\epsilon) = \frac{\sinh \left[ \frac{\hbar \epsilon}{k_B T} \right]}{\cosh \left[ \frac{\mu_c}{k_B T} \right] + \cosh \left[ \frac{\hbar \epsilon}{k_B T} \right]}
\]  

(3)

Where, \( e \) is the electronic charge, \( k_B \) is the Boltzmann constant, \( T \) is the temperature, \( \hbar \) is the reduced Plank's constant, \( \mu_c \) is the chemical potential and \( \tau \) is the relaxation time.

3. The antenna designs

We begin with a conventional patch antenna for which the conducting sheet is replaced by graphene materiel (Figure 2). The SiO\(_2\) substrate is used here and the patch width and length are calculated according to design formulas in [13] for a working frequency around 0.58 THz. A chiral version was designed with the introduction of resonating patterns as shown in Figure 3. The dimensions of antenna are in Table 1.
Figure 2. Graphene based rectangular (achiral) patch antenna.

Figure 3. Graphene based chiral patch antenna.

Table 1. Dimensions of the antenna.

| Parameters       | Dimensions (µm) |
|------------------|-----------------|
| Patch length (Lp)| 210             |
| Patch width (Wp)| 114             |
| Substrate length (Ls) | 735             |
| Substrate width (Ws) | 345             |
| Substrate height (h) | 30              |
| Microstrip feed length (L) | 350             |
| Microstrip feed width (W) | 20              |

4. Results and discussion

We first check the return loss of these antennas in terahertz frequency range. The simulated return losses are given in Figure 4 for both achiral and chiral antennas. For the achiral antenna the return loss is well below -10dB at 0.58 THz. A second band near 0.85 THz shows also very good matching condition so the achiral antenna can work in dual-band. For the chiral antenna we have three interesting band-widths which vary from 0.4 to 0.46 THz, 0.53 to 0.58 THz and 0.63 to 0.67 THz, with corresponding return loss of -33.7 dB, -17.72 dB, and -18.59 dB respectively.
Figure 4. Simulated return loss for both achiral and chiral antennas for multi-band operation.

The radiation characteristics have been calculated for both achiral and chiral antennas. Only chiral antenna’s E-plan pattern will be given here (Figure 5 (a), (b), (c)). One can observe the difference in beam width for each working frequency, so as for the radiating direction. In Table 2, the comparison of the achiral and chiral antennas illustrates the difference between the two antennas. We can note that the chiral antenna adding the chirality to the graphene material is more interesting than the achiral one for multi band applications. This type of configuration is therefore interesting to explore in the future for other multi band applications.

Figure 5. Radiation patterns of tri-band chiral patch antenna (a) for 0.46 THz, (b) for 0.58 THz and (c) for 0.66 THz.
Table 2. Comparison between the achiral antenna and the chiral antenna.

| Antenna          | Frequencies of resonance(THz) | Number of Frequency bands |
|------------------|--------------------------------|---------------------------|
| achiral patch    | 0.58 / 0.85                    | Dual-band                 |
| chiral patch     | 0.46/0.58/0.66                  | Tri-band                  |

Figure 6 shows the voltage standing wave ratio (VSWR) for the chiral antenna. The good impedance matching can be observed for three working frequencies in the low THz bands.

5. Conclusion
Two graphene-based patch antennas have been designed and studied for terahertz applications. We have shown that the association of a chiral structure with graphene materials makes it possible to obtain a tri-band antenna. This offers perspective for the design of other multi-band antenna systems while keeping the compact size of antenna structure.

References
[1] Geim A K and Novoselov K S 2007 The rise of graphene (Nature Materials vol 6) pp 183-191
[2] Hanson G W 2008 Dyadic Green's Functions for an Anisotropic, Non-Local Model of Biased Graphene IEEE Transactions on Antennas and Propagation vol 56 issue 3 pp 747-757
[3] Zhang B, Jornet J M, Akyildiz I F and Wu Z P 2019 Mutual Coupling Reduction for Ultra-Dense Multi-Band Plasmonic Nano-Antenna Arrays Using Graphene-Based Frequency Selective Surface IEEE Access vol 7 pp 33214-33225
[4] Khan Md A K, Shaem T A and Alim M A 2019 Analysis of graphene based miniaturized terahertz patch antennas for single band and dual band operation Optik vol 194 163012
[5] Tripathi S K, Kumar M and Kumar A 2019 Graphene based tunable and wideband terahertz antenna for wireless network communication Wireless Networks vol 25 pp 4371-4381
[6] Luo Y, et al. 2019 Graphene-Based Multi-Beam Reconfigurable THz Antennas IEEE Access vol 7 pp 30802-30808
[7] Shalini M and Ganesh Madhan M 2019 Design and analysis of a dual-polarized graphene based microstrip patch antenna for terahertz applications Optik vol 194 163050
[8] Luo Y, et al. 2019 A graphene-based tunable negative refractive index metamaterial and its application in dynamic beam-tilting terahertz antenna Microwave and Optical Technology Letters vol 61 pp 2766-2772
[9] Llatser I, et al. 2012 Graphene-based nano-patch antenna for terahertz radiation Photonics and Nanostructures-Fundamentals and Applications vol 10 issue 4 pp 353-358
[10] Gao M, et al. 2020 Graphene-Based Composite Right/Left-Handed Leaky-Wave Antenna at Terahertz Plasmonics pp 1-6

[11] Varshney G 2020 Reconfigurable graphene antenna for THz applications: a mode conversion approach Nanotechnology vol 31 no 13 135208

[12] Khan Md A K, Shaem T A and Alim M A 2020 Graphene patch antennas with different substrate shapes and materials Optik vol 202 163700

[13] George J N and Madhan M G 2017 Analysis of single band and dual band graphene based patch antenna for terahertz region Physica E: Low-dimensional Systems and Nanostructures vol 94 pp 126-131