Terahertz Antenna based on Graphene for Wearable Applications

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Abstract— This paper presents the potential of a graphene antenna in the terahertz band for flexible and wearable telecommunication applications. Graphene with its extraordinary electronic properties can be used to fabricate low-profile antennas that provide wearability. Here we investigate the possible resonant frequencies of graphene antenna in the terahertz band by varying the graphene chemical potential from 0.1 eV to 0.4 eV and the relaxation time from 0.1 ps to 0.8 ps. We show that the antenna can resonate at three different frequencies of 4.546 THz, 4.636THz and 5.347 THz. An improved bandwidth at higher chemical potential 0.4 eV observed at 5.5 THz but it is accompanied by a lower directivity compared with the other two resonant frequencies. Moreover, we evaluated the effect of the substrate thickness on surface plasmon polarities (SPPs). Such flexible antennas with a large bandwidth and tunability point to a bright future of terahertz frequency wearable applications.

***Index* — terahertz, graphene, antenna, flexibility**

I. Introduction

In both radio frequency and optical communication, the data rates have increased exponentially [1], however, the spectral resources are extremely limited because of the heavy use of the conventional frequency range up to 60 GHz [2]. A significant capacity enhancement to multi-gigabit or even terabit wireless transmission requires a larger bandwidth, which is available in the terahertz region. The frequency spectrum from 0.1 THz to 10 THz between the optics and microwave band provides an opportunity with the high data rate, wide bandwidths and more importantly, much less affected by weather conditions (rain and fog) than the free space optical communication [1], [2]. In addition, Flexibility, lightweight, and small size are important mechanical properties when discussing wearable antennas, particularly for medical applications [3]. The reduction of skin depth and conductivity of copper metal at THz frequency lead to a high propagation loss and consequently reduce the radiation efficiency. Owing to support of low loss plasmonic resonance at THz frequencies, the usage of graphene for THz antenna application has recently been explored [4]. In related work, graphene with only a two-dimensional carbon material has remarkable mechanical, electrical, and thermal properties with the advantage of supporting surface plasmon polaritons (SPPs) at terahertz frequencies. Graphene ready to display strong wave control, moderate loss, and the exceptional property of being tuneable over external bias or chemical doping [5][6]. This paper presents a novel flexible graphene terahertz antenna for a wireless wearable application, takes advantage of the tunability of graphene conductivity by using different values of chemical potential and relaxation time. Different flexible substrate materials have been used and tested. The graphene patch antenna investigated here resonates at three different frequencies in THz band.

II. ANTENNA BASED ON GRAPHENE

A. *Graphene conductivity*

Graphene conductivity can be demonstrated at THz frequencies by of the Kubo formula [7], [8].

$$\sigma = \frac{2e^2 k_B T}{\pi\hbar^2(\omega - j\tau^{-1})} ln\left\{2\left[1 + cosh\left(\frac{\mu_c}{k_B T}\right)\right]\right\} + \frac{e^2}{4\hbar}\left(\frac{1}{2} + \frac{1}{\pi} tan^{-1}\left(\frac{\hbar\omega - 2\mu_C}{2k_B T}\right) - \frac{i}{2\pi} ln\left(\frac{(h\omega - 2\mu_c)^2}{(\hbar\omega - 2\mu_c)^2 + 4(k_B T)^2}\right)\right)$$

where e is the electron charge, τ is the relaxation time, kB is Boltzmann's constant, T is temperature, $\hbar$ is the reduced Planck's constant, ω is the angular frequency, and μc is graphene's chemical potential. Certainly, one of the most significant features of graphene is the ability of control its complex conductivity, this done exploiting graphene's field effect by merely applying an external bias or by chemical doping [11], [12].

B. *Graphene Antenna Design*

Graphene antenna was designed utilizing CST microwave studio (2018), at the temperature of 293 K. The patch antenna consisting of a graphene patch, ground plane, and dielectric substrate, the antenna design shown in Fig 1.

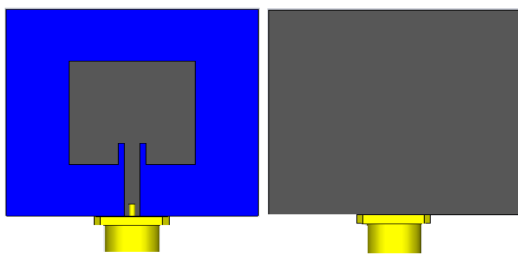

Fig 1 Flexible terahertz graphene antenna for wearable application

The ground plane and transmission feedline made of graphene material to enhance the flexibility and fitness of the antenna to different fabrication techniques. In terms of chemical potential, this paper examines the antenna in the range of chemical potential between 0.1 to 0.4 eV and relaxation time from 0.1 to 0.8 ps. Figure 2 shows the resonant frequencies of the proposed antenna. As the relaxation time continues to increase, higher order resonances appear, and an intense resonant behavior is noted.

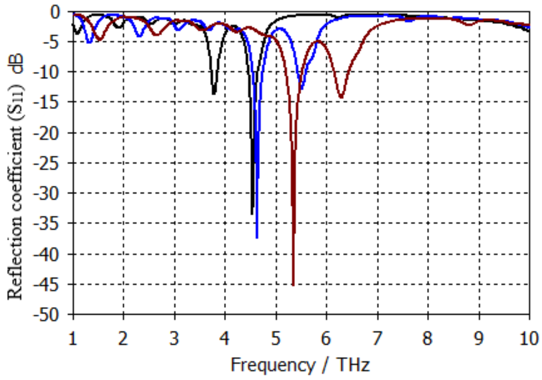

Fig 2 Reflection coefficient (S_{11}) at range of chemical potential and relaxation time (black 0.2 eV, blue 0.3 eV and brown 0.4 eV), relaxation time from 0.1 to 0.8 ps.

The greater value of the reflection coefficient (S_{11}) is -45 dB obtained at 0.4 eV chemical potential and 0.5 ps relaxation time. The resonant frequency changes when varying the chemical potential as shown in Figure 2, at 0.3 eV the resonant frequency is converted to 4.636 THz as an alternative of 4.546 THz at 0.2 eV and the S_{11} raised from -34 dB to almost -37.5 dB. Similarly, at 0.4 eV, S11 still below -10 dB at 0.1ps relaxation time, to obtain greater reflection coefficient, relaxation time need to be increased. As a result, S11 improved to -45 dB at relaxation time of 0.5 ps. Therefore, the resonant frequency shifted to 5.3 THz as an alternative to 4.7 THz at 0.3 eV. Overall the antenna has three possible resonant frequencies as shown in table 1.

TABLE 1 THE EFFECT OF CHEMICAL POTENTIAL AND RELAXATION TIME ON RESONANT FREQUENCIES AND BANDWIDTH

Frequency	Chemical potential	Relaxation time	Bandwidth
4.546 THz	0.2 eV	0.8 ps	185 GHz
4.636 THz	0.3 eV	0.8 ps	204 GHz
5.347 THz	0.4 eV	0.5 ps	310 GHz

The thickness of the substrate is evaluated to optimize the antenna performance in terms of the reflection coefficient and bandwidth. From figure 3, the substrate thicknesses obviously affect the S11 value, however, the bandwidth becomes narrower with increasing substrate thickness (Table 2).

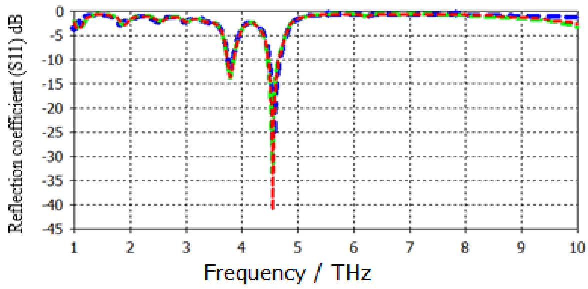

Fig 3 Substrate thickness (red 7 micrometers, green 10 micrometers, blue 4 thickness)

The 7-micrometer substrate thickness has the greater negative S11 of -41 dB and bandwidth of 192 GHz. Obviously, select a substrate thickness is a critical choice, the substrate thickness has a huge influence on the reflection coefficient and the bandwidth of the antenna.

TABLE 2, THE EFFECT OF SUBSTRATE THICKNESS ON THE REFLECTION COEFFICIENT VALUE AND BANDWIDTH

Substrate thickness	Frequency	Bandwidth	reflection coefficient (S11)
4 µm	4.546 THz	193.9 GHz	-26 dB
7 µm	4.546 THz	192 GHz	-41 dB
10 µm	4.546 THz	185 GHz	-33.3 dB

The flexible substrate material is a significant part of the wearable antenna. To compare various flexible substrate materials, 0.2 eV chemical potential and 0.8 ps relaxation time values are selected.

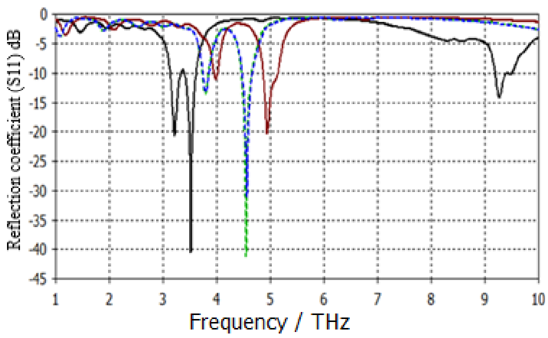

Fig 4 Reflection coefficient (S_{11}) of different substrate material thickness 7 micrometer, black Rogers 3006, blue Polyethylene terephthalate, green polyimide, brown paper.

From figure 4, polyamide substrate appears to deliver the largest negative S11 (-42 dB). Polyimide substrate is suitable for applications demanding a high degree of dimensional stability after the experience to extreme temperatures. Moreover, polyimide offers high flexibility, low profile and enhancing the efficiency in THz band. The Rogers 3006 substrate materials achieved -40.6 dB, Polyethylene terephthalate (PET) -30dB, and paper is below -30dB.

Based on 7 micrometers substrate thickness and polyimide substrate, three resonant frequencies can be obtained from graphene antenna (Figure 5).

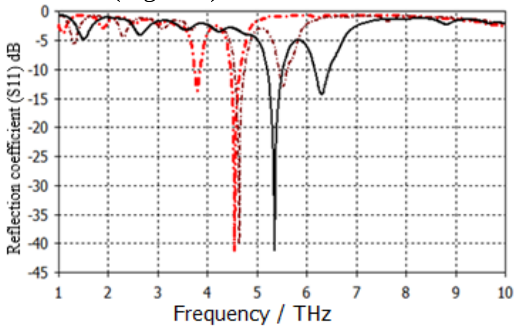

Fig 5 Antenna resonant frequencies at 7- micrometers thickness(0.2 eV and 0.8 ps red, 0.3 eV and 0.8 ps , black 0.4 eV and 0.5 ps)

Table 3 breakdown comparison between the three different resonant frequencies at 7-micrometer substrate thickness. All the frequencies have approximately the same S11 with the difference in bandwidth which increases with higher chemical potential value.

TABLE 3, RESONANT FREQUENCIES AT 7-MICROMETER SUBSTRATE THICKNESS

Frequency	Chemical potential	Relaxation time	Reflection coefficient (S_{11})	Bandwidth
4.546 THz	0.2 eV	0.8 ps	-41.258 dB	199 GHz
4.636 THz	0.3 eV	0.8 ps	-40.187dB	279.9 GHz
5.347 THz	0.4 eV	0.5 ps	-41.283 dB	314 GHz

In fact, as the chemical potential increase to a higher value, the bandwidth accordingly increased. On the other hand, the transmission range becomes shorter with a high chemical potential value due to the increment of the absorption energy which influences the resonant energy. High main lobe magnitudes and lower side-lobe levels can be observed from Figure 6 and 7. The main lobe magnitude in E-plane started at 2.93 dB corresponding to 0.2 eV chemical potential. At higher chemical potential, side lobe declines to 1.51 dBi at 0.3 eV and 1.41 dBi at 0.4 eV chemical potential.

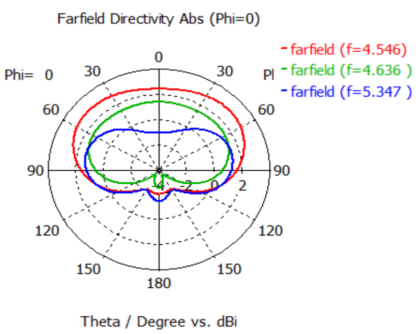

Fig 6 Simulations of the normalized field patterns in the E-plane (a) frequency 4.546 THz, (b) 4.636 THz (c) 5.347 THz

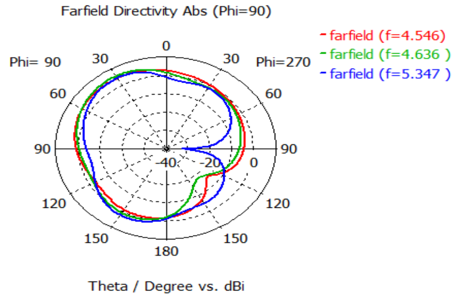

Fig 7 Simulations of the normalized field patterns in the H-plane (a) frequency 4.546 THz, (b) 4.636 THz (c) 5.347 THz

III. CONCLUSION

This paper presents an efficient flexible antenna design at terahertz frequencies band. The proposed antenna has proved the tunability of graphene antenna to resonate at various frequencies in the terahertz band, 4.546 THz, 4.636THz and 5.347 THz as consequences of varying the chemical potential and relaxation time. On one hand, varying the chemical potential lead to increase the bandwidth from 199 GHz at 0.2 eV to 314 GHz at 0.4 eV chemical potential. On the other hand, chemical potential has affected the radiation pattern by increasing the side lobe and reducing the directivity of the proposed antenna. Analysis has also been performed to evaluate the antenna bandwidth and reflection coefficient (S_{11}) at resonant frequencies. Moreover, a comparison between different flexible substrate allows us to evaluate the effect of substrate material on the antenna performance, graphene antenna with polyamide substrate shows the maximum S11 of -42 dB. Flexibility and unique performance of designed antenna recommended for wearable applications.

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