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Flexible and Wearable Graphene based Terahertz Antenna for Body Centric Applications

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Abstract— This paper presents a graphene based wearable antenna operating in the terahertz frequency range. Graphene with its highly attractive electronic properties, and modern manufacturing techniques can yield antennas that are not only flexible, but efficient and low-profile, suited for terahertz applications. The graphene antenna investigated here has a resonant frequency of 0.647 THz. The performance of the antenna is evaluated on-body and in free space using three layers of human skin. Simulated results show that the proposed antenna has a bandwidth of 20 GHz and offers a radiation efficiency of 96% in free space and 50% on body, with respective gains of 7.8 dB and 7dB. The small and flexible structure of the antenna along with excellent impedance matching, high bandwidth and gain, and good efficiency makes it an appropriate candidate to short range wireless communication in the vicinity of human body.

***Keywords*— terahertz graphene flexible wearable**

I. INTRODUCTION

Wearable antennas have a wide variety of applications including military, healthcare and sports monitoring [1]. The demand for wearable devices is expected to increase to 187.2 million wearable units annually by 2020 [2]. Wearable antenna requirements for all modern applications require lightweight, low cost, and a flexible profile. For wireless body area network (WBAN) scenarios, the antenna design becomes more complicated than simple free-space environments, due to the absorption of the human skin. Human skin is a complex heterogeneous and anisotropic medium, where the small parts, like blood vessel and pigment content are spatially distributed in depth [3]. With the complexity of human skin, it is challenging to accurately describe the system, mainly due to the shapes and functions, and most importantly because of the absence of the dielectric constant measurements at high frequency [4]. Therefore, most of the latest research simulate the human skin using 3 layers of epidermis, dermis, and hypodermis which represent the most essential parts of the human skin [5]. As wearable antennas work close to the human body, the antenna performance will be affected as a consequence, due to absorption of the radiated energy. Therefore, wearable antennas should be carefully designed to achieve all the important properties of antenna whether they work close to the human body or inside the human body. In regard to antenna resonant frequency, terahertz (THz) bands from 0.1 to 10 THz are ready to meet the requirements of high data rate and wide bandwidth in a short-range wireless communication [6]. Applications at THz frequencies will have a general necessity for inexpensive and low-loss materials, likewise with microwave applications [7].

Graphene has enabled the short-range communication in the THz frequency owing to its extraordinary electromagnetic, mechanical, electrical, and thermal properties. It has put itself as main platform material at terahertz frequency [8]. The possibility of fabricating lightweight, thin and low-cost flexible antenna devices are the important advantages of using graphene material. Moreover, due to the atomically thin profiles and the extraordinary electronic properties, graphene-based devices are useful in designing flexible, stretchable, or even conformal aspects in any application [9]. Recent progress in graphene fabrication processes suggests a promising future.

This work is an attempt to investigate the flexible and wearable antenna design in the THz regime and explores the absorption and attenuation of the human body at 0.647 THz using a simplified experimental human skin model. The effect of graphene on the antenna radiation characteristics in the vicinity of the human body is presented and analyzed.

II. ANTENNA DESIGN

Graphene conductivity can be demonstrated at THz frequencies by of the Kubo formula [10]

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

where e is the electron charge, τ is the relaxation time, k_B is Boltzmann's constant, T is temperature, $\hbar$ is the reduced Planck's constant, ω is the angular frequency, and μ_c is graphene's chemical potential.

The response of graphene is determined by its conductivity where the chemical potential and relaxation time can be calculated by [11],

$$\mu_c = \hbar v_f \sqrt{\pi n} \quad (2)$$

$$\tau = \frac{\mu_c \mu}{e v_f^2} \quad (3)$$

v_f fermi velocity (10^6 s/m), μ is the carrier mobility of the electrons and n is the carrier density. The graphene conductivity strongly depends on the chemical potential and the relaxation time. In addition, frequency shifting, and a wider bandwidth can be achieved by increasing the chemical potential and cross bounding relaxation time. On the other hand, increasing chemical potential has an impact on the radiation efficiency due to the growth of absorption level in graphene. Consequently, the reflection coefficient (S_{11}) will show a good matching between the source and the feedline but the radiation efficiency will decline as more power will be absorbed in the graphene material and causes loss of power. For simplicity, the typical value of chemical potential 0 eV and relaxation time 0.1ps has been chosen in order to obtain sufficient radiation and total efficiency and minimises the absorption in the material.

Figure 1(a) shows the geometry and parameters of the proposed CPW-fed antenna. The proposed antenna is designed using CST Microwave Studio (2018). The designed graphene-based antenna is tested in simulation at the room temperature of 293 K. The antenna design with dimensions of 260µm × 195µm × (0.35×2) nm (two layers of graphene), consisting of a graphene-based rectangular patch with feedline 120µm × 100µm × (0.35×2) nm made from graphene. The substrate material supervises the variation in radiation qualities of the graphene antenna. Rogers 3006 is used as substrate with thickness of 175 µm (dielectric constant, $\varepsilon_r = 6.5$, loss tangent, $\tan\delta = 0.002$). Three layers of human skin model as shown in Fig. 1 (b), the thickness of which differ between various human skins. For the epidermis, the typical thickness ranges from 0.05 to 1.5 mm, 1.5-4 mm for the dermis, the hypodermis has no typical value [10] [11]. The epidermis contains two layers, stratum corneum with only dead squamous cells and the living epidermis layer, where most of the skin pigmentation stay. The stratum corneum is a thin accumulation on the skin outer surface [11]. The dermis, that supports the epidermis, is thicker and mainly composed of collagen fibers and intertwined elastic fibers enmeshed in a gel-like matrix. The subcutaneous fat layer is composed of the packed cells with considerable fat, where the boundary is not well defined, thus, the thickness of this layer differs widely for various part of the human body. The permittivity of the human skin tissues can be obtained using, [13] [14].

$$\varepsilon_r' = n^2 - e^2 \quad (4)$$

$$\varepsilon_r'' = 2nk \quad (5)$$

where ε_r' and ε_r'' are respectively, the real and imaginary parts of the permittivity of the tissues, n is the refractive index, and k is the extinction coefficient. The refractive index is 1.97, 1.73 and 1.58 for blood, skin, and fat, respectively [14]. The extinction coefficient is calculated using the measured absorption coefficient data available in [15] [16] through,

$$k = \frac{\alpha \times \lambda_0}{4\pi} \quad (6)$$

where, $\lambda_o = c/f$ is the wavelength in free-space, and α the absorption coefficient.

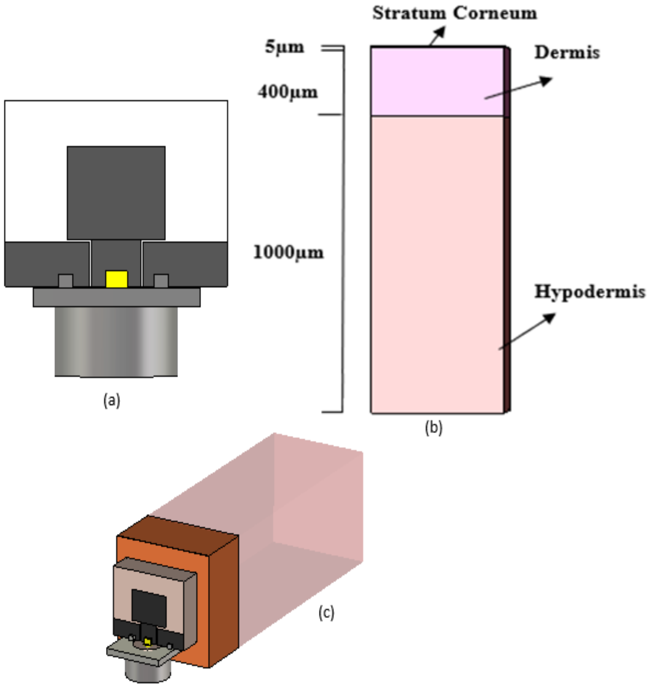

Fig. 1 Geometry of the proposed patch antenna (a) Front view and (b) Human skin model (c) side view of the antenna on the human body.

III. RESULT AND DISCUSSION

Figure 2 demonstrates the scattering parameter (S_{11}) in free space. It has been observed that resonant frequency can be shifted towards lower range with the increase in length patch from 195 µm to 215 µm. The S_{11} of the graphene patch antenna is -46 dB at 0.647 THz obtained with length of 195 µm. The antenna gives a wide bandwidth 29.2 GHz which is the main advantage of this high frequency at wearable applications. Various parameters such as gain, reflection coefficient, efficiency, and radiation pattern of the proposed antenna are compared under free space and on body conditions. From Fig. 3, the reflection coefficient of the patch antenna in the on-body state is shifted slightly towards the right side of the 0.6482 THz resonant frequency. The S_{11} parameter of the graphene patch antenna on the body is -25 dB. The detuning of frequency is due to the high dielectric constant property of three layers of the human body. Because of these properties of the human body, most of the radiated waves propagate through the body and dissipate in the form of heat resulting in a wider -10 dB bandwidth. Due to the body absorption, the antenna gains decrease from 7.8 dB to 7.2 dB. The gain of the antenna is a figure of merit of how well the antenna converts delivered power into radiated waves toward a specified direction. The decrease of the gain in the on-body state is accompanied with an increase in the directivity. It is clear from Fig. (4) that for the antenna in the on-body case, the value of gain at 0.647 THz decreases by 0.3 dB, while the directivity increased by 3dB. The lower gain value obtained due to a decrease in the radiation efficiency, down from 96% to almost 50% (Fig. 5). Therefore, the total radiated efficiency of antenna on flat body phantom decreases by (46%). This is due to the higher conductivity of the outer most layer skin. The antenna total efficiency in the presence of the human body also decreases due to absorptions in the lossy human body tissues.

The H and *E*-plane radiation patterns of the graphene patch antenna on the body and free space are shown in Fig. (6). The radiation pattern of both states is adequately consistent at the desired resonant frequency. The main lobe with 6.87 dB is obtained at the resonance of 0.647 THz, while an increase in the magnitude of the main lobe is observed at on-body state with 9.7 dB. Similarly, the side lobe in the on-body case is -8 dB and on free space is -2 dB due to higher reflections from the body surface.

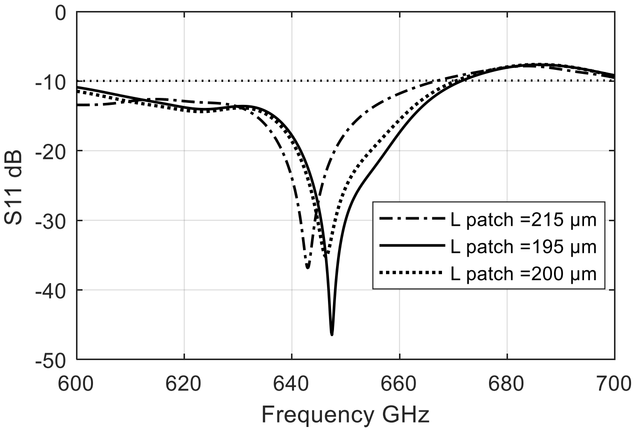

Fig. 2 Simulated S11 profile of the designed graphene antenna.

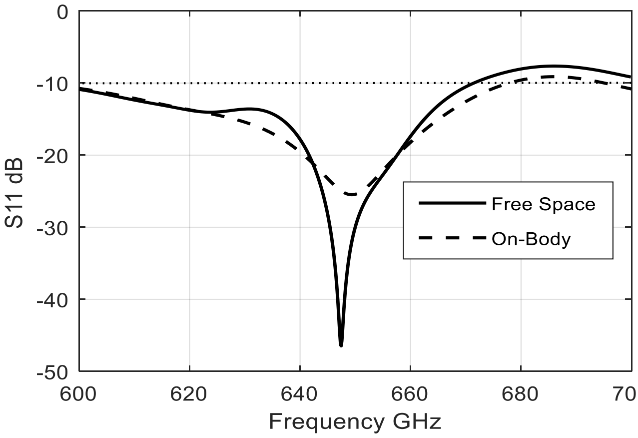

Fig. 3 The reflection coefficient of the patch antenna in the On-body and free space state.

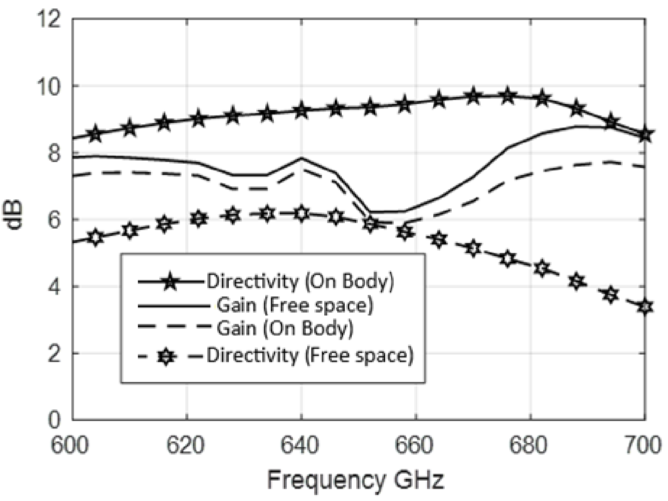

Fig. 4 Simulation gain and directivity on free space and on Body

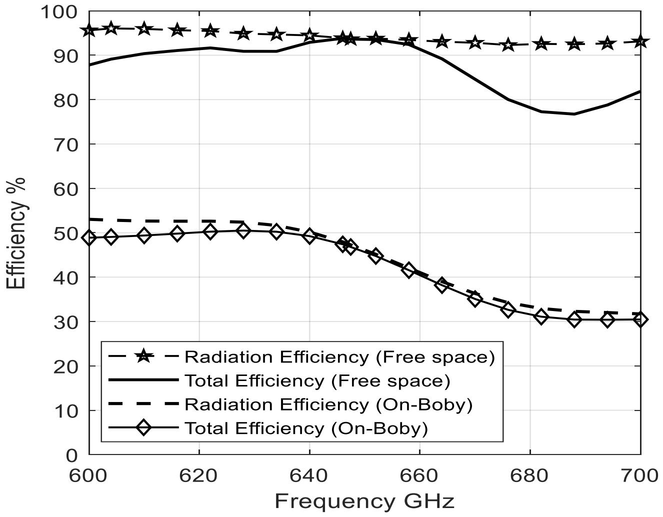

Fig. 5 Radiation and total efficiency on Free space and on body

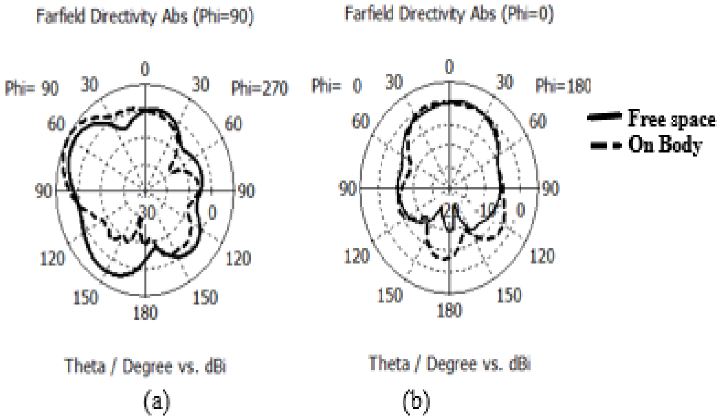

Fig. 6 The Hand E-plane radiation patterns of the graphene patch antenna and on and space

IV. CONCLUSIONS

A wearable graphene THz antenna is presented and tested on three layers of human skin to serve the wearable applications in modern THz systems to achieve high performance. The results show that the designed antenna presented at 0.647 THz, have a realized gain of 7.8 dB and 7.2 dB on free space and on-body cases respectively. The radiation efficiency dropped from 96 % to 50% when placed on-body. We believe that the antenna will perform well when positioned at a distance of 1 or 2 mm from the human body surface. The antenna is regarded as a potential candidate for the future short-range wireless body area network (WBAN) Scenario.

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