Hybrid Terahertz Antenna Design for Body-Centric Applications

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Abstract—Short-range wireless communication at terahertz (THz) frequencies has many obstacles, given the very small antenna size (a few micrometers). Moreover, traditional radiating antenna elements such as copper, gold etc. have low mobility of electrons at THz frequencies, resulting in a high channel attenuation and low antenna efficiency. On the other hand, graphene displays remarkable electrical properties at THz frequencies and, can be an ideal material for antenna design resulting in high efficiency. However, there are challenges due to difficulties in fabrication and high absorption, particularly at higher chemical potentials. In this paper, we evaluate the performance of a graphene-based THz antenna in free-space and on-body 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 93% in free-space, whereas 50% on-body, with respective gains of 5.9 dB and 5 dB. The small and flexible structure of the antenna along with excellent impedance matching, and high bandwidth make it a suitable candidate for short-range wireless communication in the vicinity of the human body.
***Keywords*— terahertz, graphene, flexible, wearable, antenna.**

I. Introduction

The terahertz (THz) gap that ranges from 0.1 THz to 10 THz offers a spectrum with the high data rate, wide bandwidth and lower atmospheric attenuation due to rain and fog [1]. This frequency band is intended to serve future wireless communication generations beyond the 5th generation [2]. Since most materials are lossy at these frequencies, it is fundamental to discover or invent new materials suitable for THz communication [3]. Two-dimensional carbon material has remarkable electromagnetic, mechanical, electrical, and thermal properties. Due to the atomically thin dimension and the remarkable electronic properties due to which propagation of surface plasmon polaritons (SPPs) is supported, graphene has become the first candidate for THz applications ready to show strong wave limitation and moderate loss enabling short-range communication in the THz frequency [4]. There are however, some limitations of measurement capability with a thickness of 0.35 nm, which is very small and cannot be connected to feeding probes. This fact makes the necessity of using another type of connecting material in order to electrically bias graphene at this high frequency [5]. In case of conventional materials, the very small antenna size (few micrometers) coupled with the resistance per unit length being very high, which limits the utilization for RF applications, such as electrical interconnects and radiating elements at the THz band [6]. In addition, the surface resistivity of traditional conductors increases with frequency due to skin depth effect ant therefore, the radiation efficiency of nano-radius wire antennas is very low, due to the associated high ohmic losses at these sizes [7]. Thus, it is expected that the performance of graphene antenna should surpass that of metallic antennas in terms of radiation efficiency at the THz band [8]. Metals, in particular gold are commonly used to fabricate antennas in the THz frequency range. The behavior of metal at THz frequencies degrades the radiation efficiency [9]. Numerical analysis has showed that the small-scaled antennas, using sub100 nm radii compared to millimeter-sized counterparts, have much lower radiation efficiency at 1 THz due to the high surface resistance of metallic traces [10]. This lower conductivity is due to grain boundary scattering, surface scattering, and surface roughness [11]. To increase the radiation efficiency of THz antennas, the surface impedance of the conductor should be reduced by using a hybrid design with carbon material like graphene, grown on the Cu nanoparticles (NPs) which permit full electric contact and strong interactions, thereby resulting in a strong localization of the field at the graphene/copper interface. Adding graphene to conventional metals can enhance the performance of these metals at nanostructures [12].

THz antennas have a wide variety of applications including military, healthcare and sports monitoring [13]. The demand for wearable devices is expected to increase in coming years. 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 [14]. 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 this paper, a hybrid THz antenna design with three layers of structure (gold, graphene and flexible substrate) is investigated for wearable applications. In this design, we are using two different radiation elements namely graphene and gold. Graphene is used for efficiency enhancement and traditional metal (Gold) used as conducting material with sufficient thickness (>500µm) for fabrication and measurement. Combined, these two materials give an additional degree of design freedom by manipulating the shape and structure and can help address the challenges in fabrication and measurement. The effect of graphene on the antenna radiation characteristics in the vicinity of the human body is also presented and analysed.

II. ANTENNA DESIGN

A. Antenna design

Hybrid types of patch antennas can be made up of using two or more than two different antenna materials. In this work, we use graphene and gold as radiation elements. Graphene conductivity can be demonstrated at THz frequencies by the Kubo formula [15],

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

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. Increasing the chemical potential has an impact on the radiation efficiency due to the growth of absorption level in graphene. Consequently, the antenna 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. For simplicity, the typical values of chemical potential 0 eV and relaxation time 0.1ps have been chosen. On the other hand, gold with a thickness of 18 µm has been used as a second resonant element in this design.

The design procedures of hybrid antenna based on graphene/gold are schematically summarized in Fig. 1. The proposed antenna is designed using CST Microwave Studio 2018, and simulated at room temperature (293 K). The substrate material supervises the variation in radiation qualities of the graphene antenna. Rogers 5888 is used as the substrate with thickness of 20 µm (dielectric constant, ε_r = 2.2, loss tangent, tan δ = 0.0009). coplanar CPW line is designed for on-wafer measurements (ground-signal-ground probes). Graphene can act as an optically thin oxidation barrier to a pure unoxidized metal to enhance the radiation properties of the gold. Thus, simultaneous improvement in radiation efficiency expectable by coating graphene onto gold to form the graphene/gold hybrid nanostructures design.

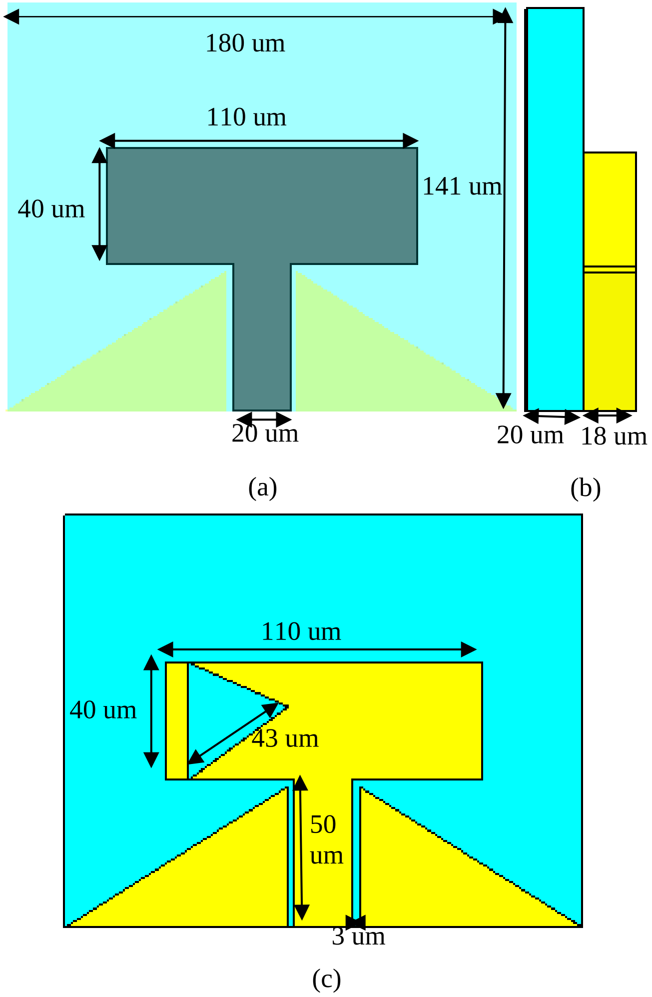

Fig. 1. Geometry of the proposed patch antenna (a) Front view of gold patch (b) thickness of substrate (c) graphene antenna demission.

B. Electromagnetic Properties of Human Tissues.

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 vessels and pigment content are spatially distributed in depth [16]. With the complexity of human skin, it is challenging to accurately simulate the structure, mainly due to the shapes and functions (see Fig 2), and the lack of the permittivity measurements at THz frequency [17]. However, most of the research represents the human skin using 3 layers of the epidermis (two layers) and dermis [18]. It was, therefore decided that the model would have the 3 layers of the epidermis (two layers), and dermis to simulate a signal going in a human skin model.

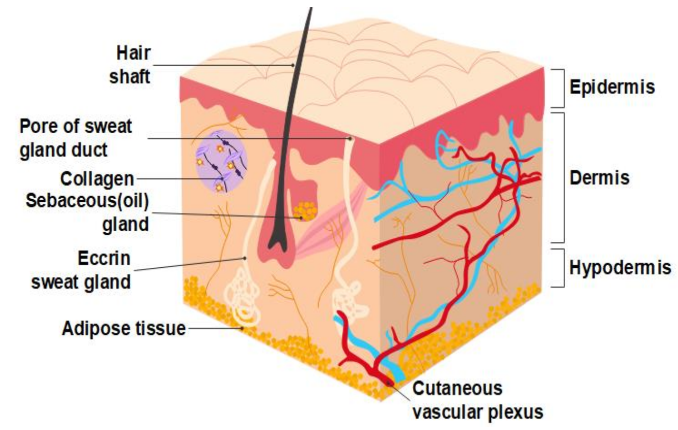

Fig. 2. Human skin layers

Layers of the human skin is shown in Fig. 2, where the thickness of each layers varies from person to person. For the epidermis, the typical thickness ranges from 0.05 to 1.5 mm, and 1.5-4 mm for the dermis. The hypodermis has no typical value [19]. 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 [20]. 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 [21].

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + (\omega\tau_1)^2} + \frac{\varepsilon_2 - \varepsilon_\infty}{1 + (\tau_2)^2} \qquad (2)$$

$$\varepsilon''(\omega) = \frac{(\varepsilon_{s-}\varepsilon_2)(w\tau_1)}{1 + (\omega\tau_1)^2} + \frac{(\varepsilon_2 - \varepsilon_\infty)(\omega\tau_2)}{1 + (\omega\tau_2)^2} \qquad (3)$$

Where ε_s is the static dielectric constant, ε_∞ is the limiting value at high frequency, and ε_2 is an intermediate frequency limit [22] [23].

Table 1 parameter human skin values

Reference	Model	ε_s	ε_2	ε_∞	τ_1(ps)	τ_2(ps)
Ref [22]	Epidermis	58	3.6	3	10.0	0.20
Ref [23]	Dermis	60.0	3.6	3	9.4	0.18

Using Eq. (2,3) and the values in Table. 1 the permittivity can be calculated for frequencies between 0.1-1.2 THz. The real part of the dielectric constant of the two layers human skin model can be seen in Fig.3, while the imaginary part of the dielectric constant for the same layers can be seen in Fig. 4. Both Figures (3,4) contains the information that describes how electromagnetic waves behave in this frequency range for these three layers. Three layers of human skin model as shown in Fig. 5, and the hybrid antenna placed on the top.

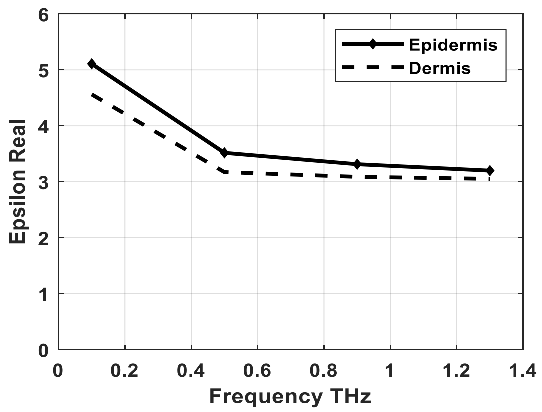

Fig. 3. Real part of permittivity of human skin (Dermis and Epidermis)

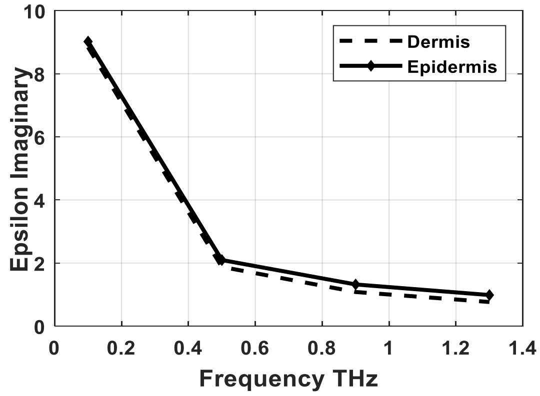

Fig. 4. Imaginary part of permittivity of human skin (Dermis and Epidermis).

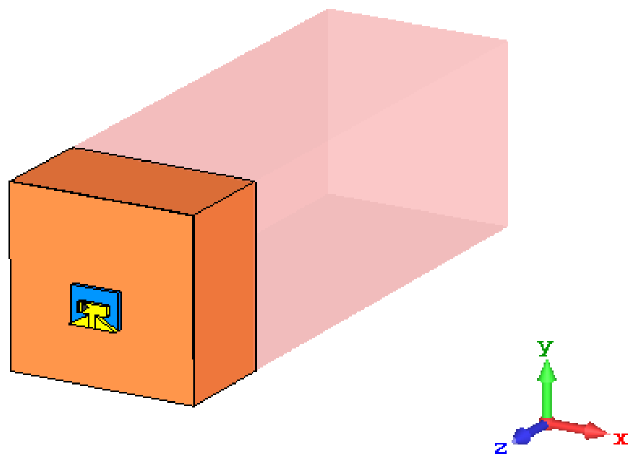

Fig. 5. Final design, hybrid antenna design on the human skin model.

III. RESULT AND DISCUSSION

Figure 6 demonstrates the scattering parameter (S_{11}) in free-space and on the human body. It has been observed that the resonant frequency shifted towards lower range from 1.4 THz to 1.20 THz. The shift accompanied by the decrease in the reflection coefficient S_{11} from -36 dB to almost -24 dB. The antenna yields a wide bandwidth of 120 GHz which is the main advantage of this high frequency for wearable applications. Because of these properties of the human body, most of the radiated waves propagate through the human body and dissipate in the form of heat resulting in a wider -10 dB bandwidth. For the on-body condition, the bandwidth increased to 150 GHz.

Various parameters such as gain, efficiency and radiation pattern of the proposed antenna are compared under free-space and on body conditions. 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, due to the body absorption, the antenna gains decrease from 5.6 dB to 4.9 dB. It is clear from Fig. 7 that for the antenna on the on-body case, the value of gain at 1.02 THz decreases by 0.7 dB. The decrease of the gain in the on-body state is accompanied with an increase in the directivity, the directivity increased by 2.8 dB from 5.6 to 8.2 dB, this because of the superposition of reflected pulses from the interfaces between antenna back lobe and the human body.

The lower gain value obtained due to a decrease in radiation efficiency, down from 93 % to almost 38 % (Fig. 8). Therefore, the total radiated efficiency of the antenna on flat body phantom decreases by (56%). This is due to the higher conductivity of the outer most layer skin. An improvement on the efficiency can be obtained by increasing the distance between the antenna and the human skin and this is depending on the application being used. 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 proposed antenna on the body and on free-space are shown in Figs. 9 and 10 respectively. The radiation pattern of both states is adequately consistent at the desired resonant frequency. The main lobe with 4.94 dB is obtained at the resonance frequency, while an increase in the magnitude of the main lobe is observed at on-body state with 5.7 dB. Similarly, the side lobe on the body is -5 dB while on free space is -2 dB due to higher reflections from the back lobe.

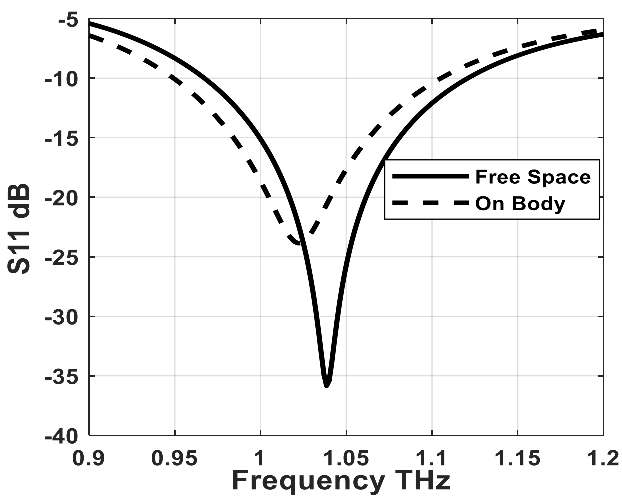

Fig. 6. Simulated S11 profile of the designed graphene antenna

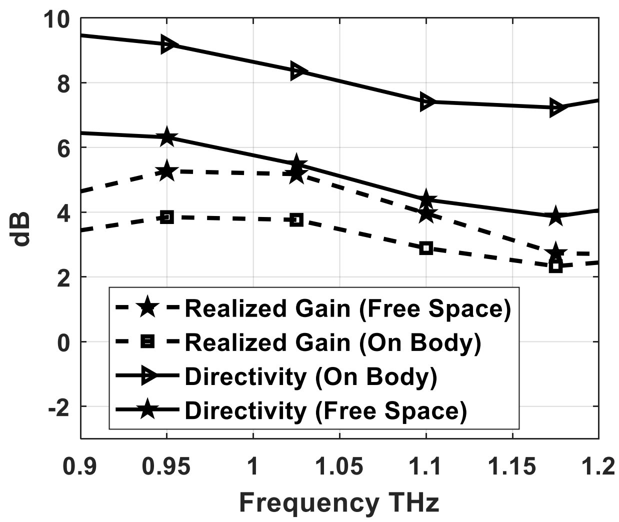

Fig. 7. Simulation gain and directivity on free-space and on body.

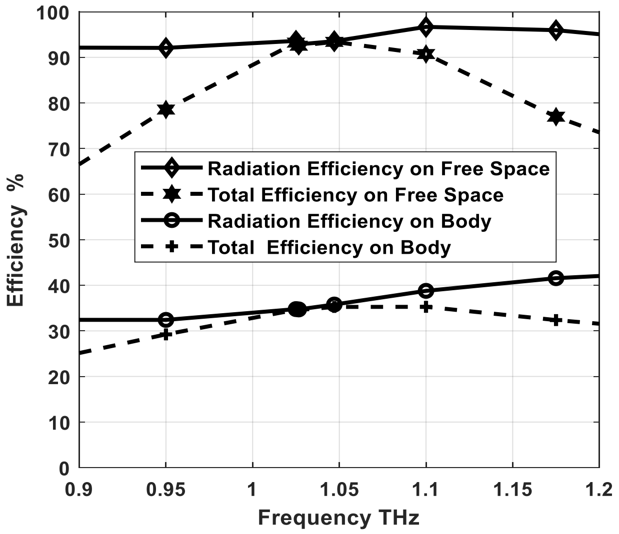

Fig. 8. Radiation and total efficiency on free-space and on body.

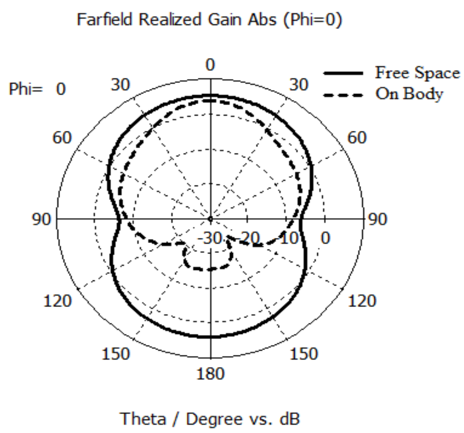

Fig. 9. The E-plane radiation pattern of the graphene patch antenna and on and space.

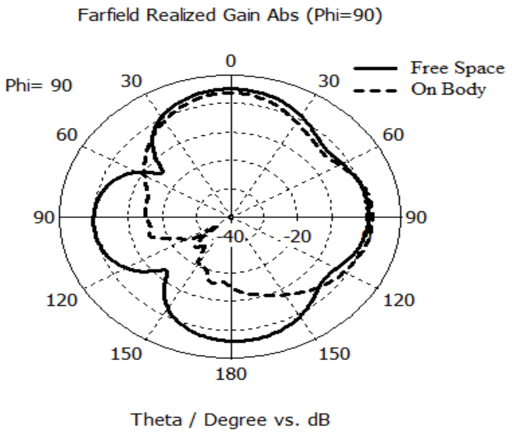

Fig. 10 . The H-plane radiation patterns of the graphene patch antenna and on and space.

IV. CONCLUSIONS

In this paper, we have proposed a novel technique to design the hybrid nanostructures made of gold and graphene. The efficiency obtained from the hybrid design is 93% in free-space while 36 % efficiency was observed for the on-body case. We believe that the antenna will perform well when positioned at a distance of 1 or 2 mm from the human body surface. The proposed technique has potential of deployment in modern THz systems to achieve high performance. 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 the future short-range THz communications.

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