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Flexible Terahertz Antenna Arrays based on Graphene for Body-Centric Wireless Communication

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\textbf{Abstract}—For Body-Centric Wireless Communication, a hybrid terahertz (THz) antenna array design with a three-layer structure (gold, graphene, and flexible substrate) is being investigated. Graphene and gold are the two main radiation elements employed in this design. Graphene is used to increase efficiency, whereas conventional metal (gold) is used with sufficient thickness for fabrication and measurement. When combined, these two materials provide design flexibility by manipulating shape and structure and can assist in addressing certain fabrication and measurement problems. Using an ungrounded coplanar waveguide feed (UCPW), the micro-fabricated structure provides a simulated efficiency of 98\% at the resonant frequency of 0.84 THz. Because the cost of micro-fabrication has decreased considerably due to recent technical advances, the results of this study demonstrate that highly efficient THz antennas can be achieved for widespread applications, including wearable applications, with the help of 2D materials.

\textbf{Index Terms}—Graphene, antenna, propagation, Terahertz.

\section{I. INTRODUCTION}

Body-centric wireless networks (BCWN) communication provides a wide array of applications and services for next-generation wireless technologies \cite{1}. BCWN communications have potential uses in assisted living, remote monitoring, healthcare, localization and tracking, entertainment, and defense and security \cite{2}. As a result, significant focus has been placed on the design aspects of the wearable antenna as well as body-centric propagation analysis and modelling. Research and development in the field of antennas and propagation for body-centric communication is an active area of research due to the miniaturisation of devices, new fabrication techniques, advancements in material science, and the availability of a vast portion of the electromagnetic spectrum for operation of wearable devices \cite{3}. As wearable antennas work in close proximity to the human body, the body’s absorption of transmitted energy will affect antenna performance. Therefore, wearable antennas must be carefully designed for optimal performance \cite{4}.

To ensure sufficient transmission capacity, the only alternative is to use transmission bands with higher carrier frequencies. The THz spectrum provides greater transmission capacity and data rates. Currently, existing wireless communications systems have bandwidths of a few GHz and data transfer rates of up to one gigabit per second (Gbps). Due to the narrow bandwidth of the microwave spectrum, it is extremely challenging to attain data transfer rates of 10 Gbps. The wide bandwidth available in the THz band allows for the possibility of transmitting at a high data rate. THz communication has great potential for wireless communication systems, particularly those operating in enclosed areas \cite{5}. Increasing the carrier frequency from 100 to 500 GHz increases the data rate from 10 to 100 Gbps \cite{6}. Parallel feed and series feed are dissimilar in several aspects. The parallel feed provides a higher bandwidth, often 10\% of the operating frequency, whereas the series feed offers bandwidths between 1\% and 3\% of the operational frequency. Because parallel feeding requires more space, it increases ohmic losses. The amount of discontinuities required in the parallel design also increases radiation losses. To achieve an acceptable trade-off between bandwidth, radiation loss, ohmic loss, and available space, a mixture of both types of feeding is typically used \cite{7}. There are various ways to feed a microstrip array, including serial feeding, parallel feeding via corporate feed, spatial combiners, reflect arrays, and lens antennas \cite{8} \cite{9} \cite{10}.

The first two options are typically the simplest because they can be implemented on the same layer as the array, allowing for greater optimization of antenna weight, thickness, and cost. Furthermore, they are easier to fabricate at nano and micro-scale. Other feeding methods require more complex three-dimensional structures. When the feed is coplanar to the array, however, resistive and radiation losses must be considered since they affect the gain and radiation pattern \cite{11}. Because the majority of materials have lossy properties in the THz band due to skin depth effect \cite{12}, it is critical to find or develop novel THz-appropriate materials. Since the discovery of graphene, researchers have focused on 2D materials, which often refer to single-layer materials. 2D materials, such as graphene, perovskite, and MoS2 (TMDs), offer a revolutionary stage for controlling the propagation, modulation, and detection of THz waves \cite{13}. Furthermore, 2D materials can enable SPP waves to propagate in the THz region \cite{13}. Future technological advancements might well be significantly assisted by such materials. Wearable devices made from 2D materials can be produced cheaply while still benefiting from the materials’ other significant advantages, such as their low weight, mechanical flexibility,
and low impact on the environment. Graphene has the lowest thickness of any nanomaterial known to date and is also the strongest nanomaterial (flexible strength $E \approx 1.01$TPa, greatest strength $\sigma \approx 130$ GPa) [14]. Graphene is also very transparent, reflecting only 2.3% of the light that strikes it [15].

Graphene theoretical specific surface area is 2630 m$^2$ g$^{-1}$, its electron mobility is 15,000 cm$^2$ V$^{-1}$ s$^{-1}$, which is far higher than that of carbon nanotubes and diamonds. Its greatest strength is 5300 W m$^{-1}$ K$^{-1}$ and thermal conductivity is $5 \times 10^6 \Omega^{-1} m^{-1}$, which is more than silver and copper, making it the material with the lowest resistivity ever discovered. On the basis of graphene electrical resistivity and high electron velocity, graphene is anticipated to be effective in the development of electronic devices with minimal thickness and extreme conductivity [17].

This work describes a brand-new wideband, flat antenna array operating in the THz frequency band that is fabricated using gold and graphene material. The antenna geometry is really uncomplicated, yet it offers exceptional impedance matching, high efficiency, and gain performance. The antenna is an attractive candidate for the Ultra-Wideband (UWB) antenna for THz applications, which requires the antenna to efficiently propagate the monochrome pulses with minimal distortion.

II. ANTEenna DESIGN

Hybrid types of patch antennas can be made up of using two or more different radiating elements. Here, we used graphene material with a 0.3 nm thickness and gold with a thickness of 0.5 um. The use of gold here is to protect graphene from chemical solutes used in lift-off processes and other fabrication procedures. In addition, for measurement purposes, the measurement THz probe needs a thickness of at least 0.5 um to excite the antenna, which can not be accomplished by using graphene material only.

Graphene conductivity can be demonstrated at THz frequency by the Kubo formula [18]

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}} = \frac{e^2}{\pi \hbar^2} \left( i \left( \omega + i \tau^{-1} \right) + \frac{e^2}{4\hbar} \left[ \theta(\hbar \omega - 2|\mu|) + i \frac{1}{\pi} \ln \left| \frac{h\omega - 2|\mu|}{h\omega + 2|\mu|} \right] \right)$$

Where $e$ is the electron charge, $\tau$ is the relaxation time, $k_B$ is Boltzmann’s constant, $T$ is temperature, $\hbar$ is the reduced Planck’s constant, $\omega$ is the angular frequency, and $\mu_c$ 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 [19],

$$\mu_c = \hbar v_f \sqrt{\pi n}$$  \hspace{1cm} (2)

$$\tau = \frac{\mu_c \mu}{e v_f^2}$$  \hspace{1cm} (3)

$v_f$ Fermi velocity $(10^6 \text{ s/m})$, $\mu$ is the carrier mobility of the electrons and $n$ is the carrier density.

The chemical potential and relaxation time have a substantial influence on graphene conductivity. Furthermore, raising the chemical potential and cross-bounding relaxation time can result in frequency shifting and wider bandwidth. Increasing chemical potential, on the other hand, has an impact on radiation efficiency due to the increase in absorption level in graphene material.

So, the reflection coefficient S11 will show that the source and the feed line are a good match. However, as more power is absorbed by the graphene material, the radiation efficiency will go down, which will cause a power loss.

For simplicity, the typical value of chemical potential $0eV$ and relaxation time $0.1ps$ has been chosen in order to obtain sufficient radiation and total efficiency and minimise the absorption in the material.

Figure 1 shows the geometry and parameters of the proposed CPW-fed serial antenna. The proposed antenna is designed using CST Microwave Studio. The designed graphene-based antenna is tested in simulation at the room temperature of 293 K. Polyethylene naphthalate (PEN) flexible substrate has been used, having a dielectric constant of $\varepsilon_r = 2.2$, and loss tangent, $\tan \alpha = 0.0025$ is used with a thickness of 125 $\mu$m (the thinnest thickness available in the market.).

III. FABRICATION

The suggested array was fabricated at the James Watt Nanofabrication Centre (JWNC) at the University of Glasgow. The fabrication is carried out in three steps, beginning with
cleaning the sample, followed by spinning the photoresist on the wafer, as illustrated in Fig. 3. The antenna was then constructed with a tuning stub using electron beam (e-beam) lithography. An adequate undercut was developed to assist the liftoff process using a bi-layer e-beam resist system consisting of polymethyl methacrylate (PMMA). The first layer was around 1200 nm thick. Following that, a second layer of 10% PMMA 2041 was spun at 5000rpm and baked for two minutes at 143°C. The second (top) PMMA layer was 100 nm thick. Afterwards, the Vestec VB6 beam writer was used to e-beam pattern-write through the spinning PMMA layers. The exposed PMMA was then developed with a 1:1 mixture of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA). The undercut profile is caused by the bottom layer being more vulnerable to the e-beam dosage than the top layer. An electron beam evaporator was used to deposit a Ti/Au metal scheme (10nm/450nm), and then acetone was used to remove the film. For 4 hours, the resist was dissolved in an acetone solution to remove any extra gold. Dry etching is used to finish the process of forming the graphene patch and feed line. Here, the graphene is protected by gold from the O2 plasma etching. Figure 6a shows the antenna profile under the microscope and Fig. 6b shows the small antenna dimension compared with a finger. A scanning electron microscope (SEM) for the fabricated antenna shown in Fig 5. The image clearly shows the CPW gap (1 um) and the feed line width. Surface metrology performance measurement was obtained using Optical Profiler Contour GT in Fig 6. The shown profile indicates that there is no damage or cracks on the antenna array structure.

IV. RESULTS AND DISCUSSION

The reflection coefficients of the five-element array shown in Fig.7, have a complete antenna response that is less than -10 dB reflection range, indicating good performance. Due to the large bandwidth available in the THz range, the antenna is an excellent contender for future high-speed wireless communication. The resulting structure was then optimised with the CST-integrated trust-region framework (TSF) algorithm [20]. The TSF algorithm finds local minimum points within a specified region. However, based on the framework’s input parameters, the algorithm can also operate locally. To find the best antenna structure, the University of Glasgow’s high-performance
computing resources were used to solve a multidimensional problem in which all the physical dimensions of the array were set as parameters. The antenna array is small in size and has a large impedance bandwidth. The impedance bandwidth of the antenna is 37.50%, covering the frequency range of 0.75 to 0.9 THz. The VSWR (voltage standing wave ratio) is less than 1.5. Figure 8 shows the S11 of the antenna for various patch lengths throughout the frequency range. 8.

A. Efficiency and radiation pattern

Due to a lack of measurement facilities at these THz frequencies band, the radiation patterns of the antenna was only evaluated through CST simulation studio. The overall efficiency and radiation efficiency of the simulated antenna are presented in Fig 9 and Fig 10 respectively. At the lowest frequency in the band, 0.75 THz, the antenna’s overall efficiency is 90%, at 0.9 THz, the efficiency rises to 95%. Over the simulated frequency band, the radiation efficiency (defined as the ratio of emitted to accepted power) is around 92% on average.

The performance of the antenna array may be increased further by introducing an external voltage to increase the conductivity of the graphene sheet. In Fig. 10, the radiation patterns show high main lobe magnitudes along with lower back lobe levels. The radiation patterns are presented at E and H planes. Due to the dielectric constant of the PEN substrate, and the absence of a ground plane at the back, the radiation is directed towards the substrate. The radiation pattern can be improved by using a substrate with a near-zero dielectric constant or using a hemispherical lens. The side lobe level is increased and the maximum side lobe is observed at 0.8 THz. Therefore, the ripples in the radiation pattern are mainly caused by metal
loss and the skin depth effect of gold metal on the top of graphene.

V. CONCLUSION

Using graphene and gold, a THz antenna array that can be worn has been designed and fabricated. The PEN flexible substrate was used in the fabrication of the design. Simple geometrical dimensions and gold materials are used to ease the fabrication process and protect the graphene material during the etching process. The antenna array is designed for on-wafer measurement considering the pitch size of the THz measurement probe. The design concept was verified through simulation results in CST Studio. The microfabricated structure’s simulated efficiency at the resonance frequency of 0.84 THz with an ungrounded coplanar waveguide feed (UCPW) is 98%. The antenna is regarded as a potential candidate for the future short-range wireless body area network (WBAN) scenario.

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