A Bio-degradable Textile-Based Graphene Antenna for the 5G Smart Wearables

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***Abstract*—This paper proposes a bio-degradable antenna design well-suited for the 5th generation (5G) wearables. This antenna has a graphene patterning instead of conventional metallization on a textile substrate to make it eco-friendly as it avoids copper corrosion due to repeated washing of the wearable garments. The antenna design incorporates coplanar waveguide (CPW) feeding and directive stubs to converge the radiation pattern. The antenna patch footprint is reduced by fitting the radiating length into a small area by inserting the cut-outs through an iterative design process. The proposed antenna offers a bandwidth that covers the proposed newly launched 5G band (i.e., 3.4–3.8 GHz) with a resonant frequency at 3.55 GHz, realized gain of 4.11 dB, and an efficiency of 83%.**

***Index Terms*—antennas, bio-degradable, graphene, textile, wearables.**

I. Introduction

The increasing number of user-friendly wireless applications contribute greatly towards modern lifestyles where wearables are anticipated to be of vital significance. Recently there has been a surge of research into compact, flexible and wearable antennas that can be integrated into a garment or become a part of a wearable gadget [1]. Wearable antennas have numerous applications in all sectors. Medical personnel could use them to enable bio-monitoring of outpatients to relay a patient's vitals to a doctor surgery, hospital or care home [2]. They could also be introduced into military or civil service uniforms to monitor the vitals of police officers or firefighters. In addition, a wearable antenna could be used as an automatic access card to a building or anything else that is electronically locked such as a safe or a computer [3, 4]. To accommodate these new technologies, the industrial and academic telecommunication sectors have been making a significant contribution to the newly launched 5th generation (5G) networks. More research interest has been developed in advanced antennas to increase bandwidth, channel capacity and speed [5]. Specifically, in the UK the range of 3.4–3.8 GHz has been confirmed for use in 5G networks. This enables a variety of new technologies such as ultra-HD and 3D video streaming, autonomous transport services, bio-monitoring, smart houses etc. [2, 6].

The material properties needed for such wearable antennas are very specific so there are a limited number of options. Previous attempts using metal patches [7], wire yarn [8] and nanoparticulate ink all have issues. The large patches do not conform to the body well and the yarn and nanoparticles oxide with the atmosphere or are too expensive for mass production [9]. Graphene-based structures are well-known for numerous advantages such as biodegradability, chemical stability, mechanical flexibility, non-corrosive nature, fatigue resistance and low cost [10]. Recently, several methods for the synthesis of graphene have been developed and used to develop graphene-based antennas, transmission lines and fully integrated circuits, especially where the use of metallic antennas could be costly or hazardous [11].

This paper focuses on a CPW-fed notched cross patch antenna to allow omnidirectional functionality as well as lower attenuation and dispersion characteristics [2]. This is a wideband antenna over the range of 3.4–3.8 GHz. It is comprised of graphene paper on primarily a cotton substrate to mimic clothing.

II. Antenna Design and Modelling

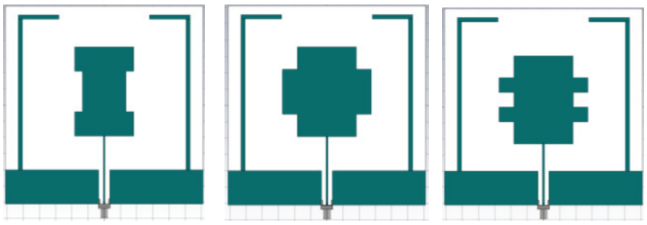
The antenna design is modelled in the CST Microwave Studio Suite simulation software. The antenna is designed on a 12.2 × 12.2 cm^2 cotton, and prototyping is proposed using a graphene paper of thickness 0.035 mm and conductivity of 5 × 10^4 S/m. A 50 Ω-matched CPW feeding is included to make the antenna prototyping single-sided and a 50 Ω SMA connector is also included in the simulation model. Moreover, the designed prototype is implemented on a wide variety of substrates with different dielectric constants to analyze the compatibility of the proposed design with different textile materials.

The substrate suitable for integration in wearables should be flexible and in common use within the textile industry, for these reasons cotton (dielectric constant (ε_r) ranges from 1.3–1.4) was chosen. For antenna modelling, a cotton substrate with ε_r of 1.35 and a thickness (h) of 1.75 mm was selected. Two L shaped reflectors stubs protrude from the ground to increase the directionality of the antenna radiation pattern. Fig. 1 shows the design iterations that the rectangular patch went through before the final optimized design. The initial design consisted of a rectangular patch of 36.51 × 54.82 mm^2 with two cut-outs on either side of it which were 4.79 × 24.58 mm^2. In 2nd iteration, the cut-outs along the radiating length were extended in an outward direction to increase the bandwidth, impedance matching and the radiating area. In the

3rd iteration, two square notches of 9.14 × 9.14 mm^2 were incorporated to either side of the extended area of the 2nd iteration for further improvement. In the final design, the width and length of the feedline are altered slightly to optimize the reflection coefficient (S11) plot which is stated as the "third highly optimized" response. The dimensions of the design parameters of the antenna shown in Fig. 2 are stated in Table I.

III. Performance Analysis and Parametric Study

This section includes the CST-based simulated results of the designed antenna to evaluate the performance.



(a) (b) (c)

Fig. 1. Three iterations of the proposed graphene antenna design for 5G wearables; (a) 1st iteration, (b) 2nd Iteration, (c) 3rd Iteration.

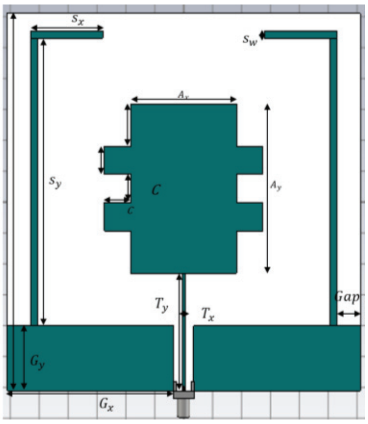


Fig. 2. Optimized graphene antenna design for 5G wearables.

TABLE I. Design Parameters of the Proposed Graphene Antenna for 5G Wearables.

Parameter	mm	Parameter	mm
A, substrate length and width	122.12	A_x, patch width	36.51
s_x, Stub Length	17.02	A_y, patch length	54.82
s_y, Stub Height	93.03	T_y, Transmission line length	38
s_wStub Width	2.5	T_x, Transmission line width	1.1
G_x, Ground Length	57.66	C, Cutout Length and Height	9.14
G_y, Ground Height	21	A_z, Antenna thickness	0.035
Gap	8	D_z, Dielectric Thickness	1.75

A. S11 and Bandwidth

In the S11 plots of Fig. 3, it can be seen that the initial antenna design (1st iteration) has a bandwidth from 3.2 – 3.42 GHz taking -10 dB as a reference. The bandwidth of the antenna is improved to 3.09 – 3.49 GHz in the 2nd iteration, though the resonant frequency is shifted to 3.28 GHz which is a shift of 30 MHz toward lower frequencies as compared to the 1st iteration. In the 3rd iteration, the resonant frequency is shifted to 3.52 GHz, i.e., an increase of 240 MHz, with a bandwidth of 3.28 – 3.8 GHz. Further optimization of the feeding dimensions leads to a final bandwidth of 3.25 – 3.8 GHz that covers the whole of the 5G range.

B. Radiation Pattern and Realized Gain

The simulated E and H-plane radiation patterns can be seen at 3.3 GHz, 3.55 GHz, 3.8 GHz in Fig. 4. The E and H-plane patterns show an almost omnidirectional response with slight convergence of radiation towards the top and bottom of the antenna due to reflector stubs. The plots show that changing the frequency has little effect on the radiation pattern which implies that the performance of the antenna is quite consistent throughout the bandwidth.

C. Realized Gain and Efficiency

Fig. 5 (a) presents the simulated peak realized gain versus frequency of the proposed 5G antenna. It can be seen that the antenna has a fairly consistent gain response with the highest point being at 3.2 GHz is 5.08 dBi and the lowest at 3.8 GHz is 3.63 dBi, which is well-suited for short-range on-body applications. The simulated antenna gain at the resonant frequency of 3.55 GHz is 4.11 dBi. The plot in Fig 5 (b) shows the simulated efficiency of the designed antenna. It shows that the efficiency of the antenna does not drop below 75% while reaching a maximum of 87% at 3.55 GHz which is relatively high for a graphene antenna due to relatively lower conductivities compared with copper.

D. Surface Current Distribution

The simulated surface current distribution of the radiating part of the antenna is shown below in Fig. 6. The maximum value of surface current is observed within the notches and on either side of the patch along the radiating length.

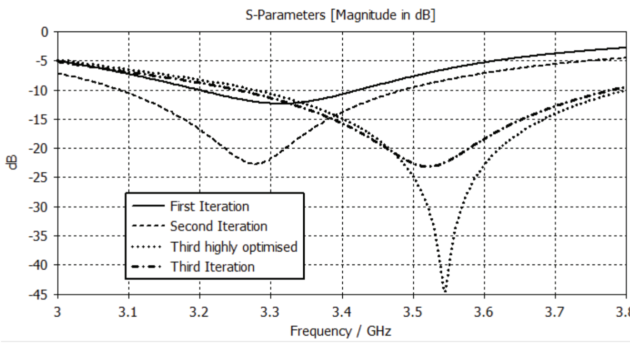
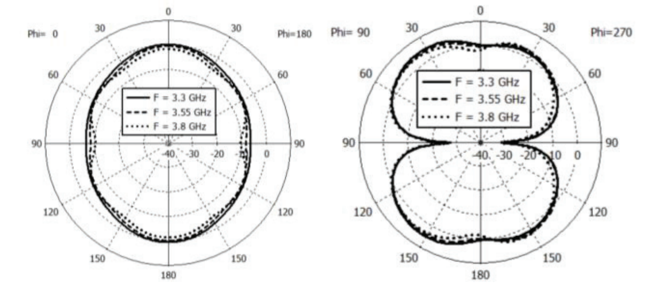
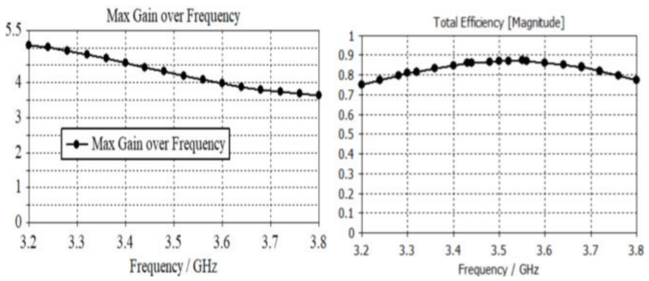


Fig. 3. Reflection coefficient (S11) plots of the three iterations of the optimized graphene antenna design for 5G wearables.



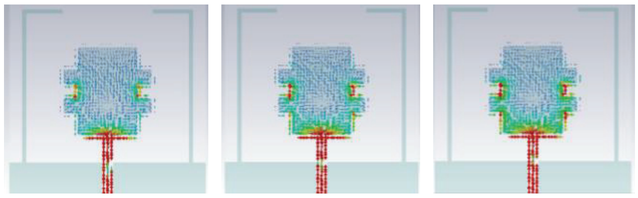
(a) (b)

Fig. 4. Radiation pattern plots of the graphene antenna design for 5G wearables: (a) at phi = 0º (H-plane), (b) at phi = 90º (E-plane).



(a) (b)

Fig. 5. Simulated results of the graphene antenna design for 5G wearables: (a) peak gain vs. frequency plot, (b) total efficiency.



(a) (b) (c)

Fig. 6. The surface current distribution of the proposed graphene antenna design for 5G wearables; (a) at 3.3 GHz, (b) at 3.55GHz, (c) at 3.8GHz.

E. Graphene's Conductivity Variation Analysis

The proposed antenna is designed with standard quality graphene paper (conductivity of 5×10^4 S/m) however there are a variety of qualities with varying conductivity. Thus, the simulated antenna model was tested with differing levels of conductivities as well as a copper antenna for reference and results are plotted in Fig. 7. Due to copper and monoatomic graphene being similar, copper is not included for plot clarity. Table II shows that despite the change in conductivity there is a very little change in the bandwidth (BW) which shows the robustness of this antenna.

Fig. 8 shows the antenna efficiency when different graphene papers are used. The graph shows that as long as a low-quality graphene paper isn't used then there is only a small change in the efficiency of a maximum of 8.2%. In the case of the low-quality graphene paper, there is a decrease of 20.5%. This implies that the more conductive the material the better the efficiency will be.

TABLE II. PERFORMANCE ANALYSIS OF DIFFERENT MATERIALS FOR ANTENNA PROTOTYPING.

Material	Results			
	Conductivity (S/m)	***Freq. (GHz)***	***Max. S11 (dB)***	***BW (GHz)***
Standard Quality Graphene Paper	Optimised	3.54	44.58	0.52
	5×10^4	3.52	23.14	0.52
Copper	5.8×10^7	3.54	26.47	0.49
Monatomic Graphene Layer	5×10^8	3.54	26.28	0.49
High Quality Graphene Paper	5×10^5	3.54	29.66	0.5
Low Quality Graphene Paper	5×10^3	3.46	20.64	0.54

F. Substrate Material Variation Analysis

Due to the variety of materials and thicknesses used in the textile industry the antenna needs to be robust to perform in these non-linearities. Fig. 9 (a) shows the S11 plots of the designed antenna on various substrates commonly used for garments. The gradual change in the permittivity shifts the resonant frequency of the antenna, yet the desired bandwidth is almost intact in response to these variations. Fig. 9 (b) shows the impact of change in substrate material on the antenna efficiency. The efficiency plot is shifted towards higher frequencies same as the S11 plot, but the overall efficiency in the complete bandwidth is above 70% regardless of the type of substrate used. This shows the robustness of the antenna towards the material variations.

The proposed antenna is optimized on a cotton substrate thickness of 1.75 mm, suitable for several heavy-duty uniforms. This choice of substrate is substantially thicker than standard cotton clothing ranges from 0.15 – 0.35 mm. Fig. 10 (a) shows a parametric study in simulation within this standard range, where the antenna frequency increases as the thickness decrease. The S11 plot in Fig. 10 (a) shows a bandwidth from 3.5 – 4 GHz where the impact of heavy, light and medium weight fabric on the antenna performance is investigated. The plots in Fig. 10 (b) shows the efficiency is greater than 80% in all three cases of heavy, light and medium weight fabric which is highly desired for the wearables. Table III below shows the performance analysis of common textiles. At $\varepsilon_r = 1.4$, the antenna performs similar to the final optimized design at $\varepsilon_r = 1.35$, so was redacted from Figure 10 (a) and (b) for clarity but included in Table III.

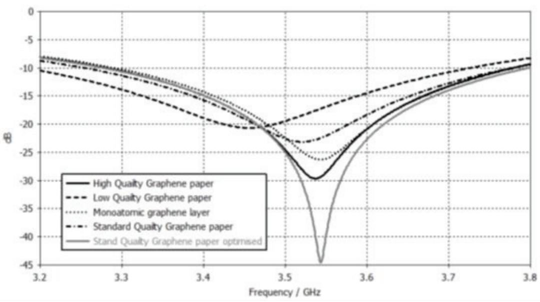


Fig. 7. S11 plots of the graphene antenna with a range of variations in the conductivities based on the graphene synthesis.

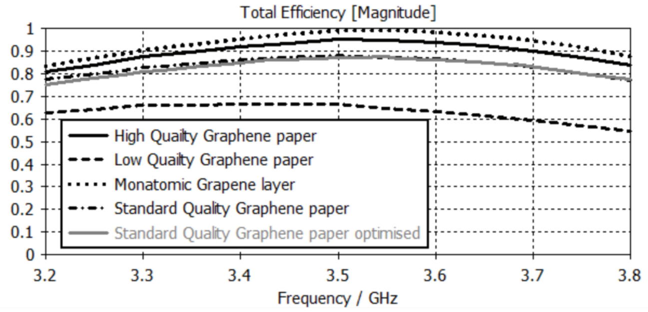
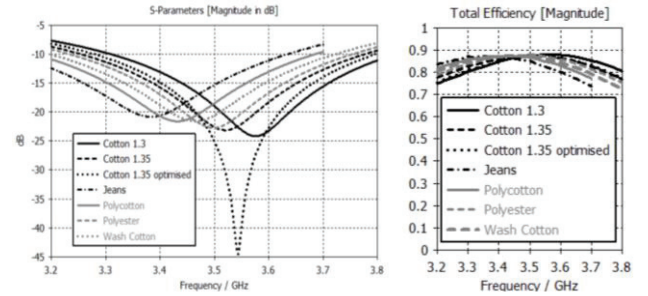
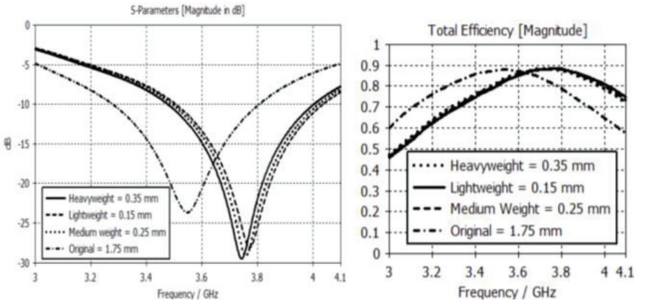


Fig. 8. Antenna efficiency plots of the graphene antenna design with a range of variations in the conductivities based on the graphene synthesis.



(a) (b)

Fig. 9. Parametric analysis of the graphene antenna on a range of common textile-based substrates: (a) S11, (b) Antenna efficiency.



(a) (b)

Fig. 10. Parametric analysis of the graphene antenna on a range of common textile-based substrates based on thickness: (a) S11, (b) Antenna efficiency.

TABLE III. PERFORMANCE ANALYSIS OF DIFFERENT DIELECTRIC MATERIALS ON PROPOSED GRAPHENE ANTENNA

Material	Results			
	Relative Permittivity	***Resonant Freq. (GHz)***	***Max. S11 (dB)***	***Bandwidth (GHz)***
Cotton	Optimised	3.54	44.58	0.52
	1.35	3.52	23.14	0.52
Cotton	1.3	3.58	24.17	0.53
Cotton	1.4	3.52	23.14	0.52
Wash Cotton	1.51	3.46	22.09	0.52
Jean Cotton	1.67	3.38	20.82	0.51
Polycotton	1.56	3.43	21.61	0.52
Polyester	1.44	3.5	22.74	0.52

IV. CONCLUSION

This paper has proposed a biodegradable, recyclable and environmentally friendly antenna solution for 5G wearables. The antenna suggested the use of graphene paper on a cotton substrate, that can be integrated as a part of a uniform of fire-fighters, military personals etc. as well as integrated with wearables for biomedical applications, security and tracking. The proposed antenna covers a 5G band of 3.4–3.8 GHz. The peak realized gain at 3.2 GHz is 5.08 dBi and the lowest at 3.8 GHz is 3.63 dBi. The efficiency is above 75% which is reasonably higher than conventional graphene antennas. The parametric analysis based on textile permittivity and thickness has shown the robustness and reliability of the proposed antenna. In future, authors are looking forward to extending the research by fabricating and testing the design to validate the simulated findings.

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