Received: 30 October 2018 | Revised and accepted: 22 December 2018
DOI: 10.1002/mmce.21692

WILEY INTERNATIONAL JOURNAL OF RF AND MICROWAVE COMPUTER-AIDED ENGINEERING

RESEARCH ARTICLE

High-conductive graphene film based antenna array for 5G mobile communications

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Funding information
Natural Science Foundation of Hubei Province, Grant/Award Number: 2015CFB719; Fundamental Research Funds for the Central Universities, Grant/Award Number: WUT: 2017IB015; National Natural Science Foundation of China, Grant/Award Number: 51701146

Abstract
Graphene antennas and relevant microwave devices have attracted wide attention due to their lightweight, low-cost, and flexible characteristics. However, their performances are usually not satisfactory because of low conductivity of graphene materials in the macroscopic scale. In this article, an antenna array made of flexible high-conductivity graphene materials is fabricated and reported for potential application in 5G mobile communications. The antenna array has a high gain of 6.77 dBi at 3.51 GHz with an excellent return loss, which is comparable to the identical copper counterpart. Moreover, the graphene antenna has similar radiation patterns to the copper antenna.

KEYWORDS
5G, antenna array, graphene, high-conductivity, high gain

1 | INTRODUCTION

In the next generation mobile communication, that is, the fifth generation (5G), high data rates, huge system capacity, high efficiency, massive device connectivity, and lightweight are required.[1] To achieve these features, antenna plays an important role in the aspects of wireless signal transmitting and receiving. In the past, metal is the main material for antennas and other microwave devices, whose production process may be complex, and have serious environmental pollution problems. In recent years, carbon based materials have been used widely because of their excellent properties, such as chemical stability, mechanical stability, lightweight, and low-cost. It is expected that if carbon based materials can be applied to the preparation of antennas and microwave devices, it would be of great significance for wireless communications and the environmental protection.

Graphene, a two-dimensional (2D) carbon material, owns many unique properties like ultra-high electron mobility, very high sensitivity and thermoelectric current effect, lightweight, environmentally friendly, corrosion resistant, and mechanically stable.[2] It is widely used in various fields, such as humidity sensor,[3] strain sensor,[4–6] biosensor,[7] thermal conduction[8–10] and stretchable transistors.[11] However, single layer graphene limits its application in many aspects such as radio-frequency (RF) microwave devices. Making graphene into a film can be a good solution to resolve this problem. Using graphene films to fabricate antennas and relevant devices has been reported.[12–16] Nevertheless, the performance and processing technology of these reported graphene antennas are not satisfactory. In,[12–14] the maximum gain of the graphene antenna is less than 0 dBi, and the antenna has very low radiation efficiency. The antenna proposed in Sajal et al. and Sa'don et al.[15,16] have a very rough outline and its reflection coefficient is not acceptable.

In this paper, an antenna array made of a flexible graphene film (FGF) with a conductivity of 1×10^6 S/m is reported. As the 3.5 GHz band (3.4 GHz~3.6 GHz) is one of the sub-6GHz bands for 5G wireless communications,[17] therefore the central operating frequency of the proposed antenna array is 3.5 GHz. The antenna is fabricated by the laser engraving technique, which is able to provide a high machining accuracy. The antenna array has four elements and can obtain high gain and excellent $|S_{11}|$. The performances, including return loss, gain, patterns, are also compared to the identical copper array to verify the feasibility of the design.

2 | ANTENNA DESIGN

2.1 | Antenna element and feed network

Before configuring an antenna array, a single element graphene microstrip antenna with resonant frequency at 3.5 GHz is designed. Figure 1A is the schematic diagram of FGF antenna array element's top-view, cross-sectional-view, and side-view, respectively. The antenna pattern is designed on the top layer of the PCB while a ground plane with dimensions of 60 mm × 70 mm is at the bottom layer. The patch and ground are FGF with the thickness h_0 of 25 μm, and the substrate is FR-4 with the thickness h of 1.6 mm and the relative permittivity of 4.4. The practical width (W) and length (L) of the antenna patch can be obtained from the following Equations.[18]

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{2}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)(W/h + 0.264)}{(\varepsilon_{reff} - 0.258)(W/h + 0.8)} \tag{3}$$

$$\varepsilon_{reff} = (\varepsilon_r + 1)/2 + (\varepsilon_r - 1)/2[1 + 12h/W]^{-1/2} \tag{4}$$

where f_r is the resonant frequency, ε_r is the relative dielectric constant of the substrate, μ_0 is vacuum

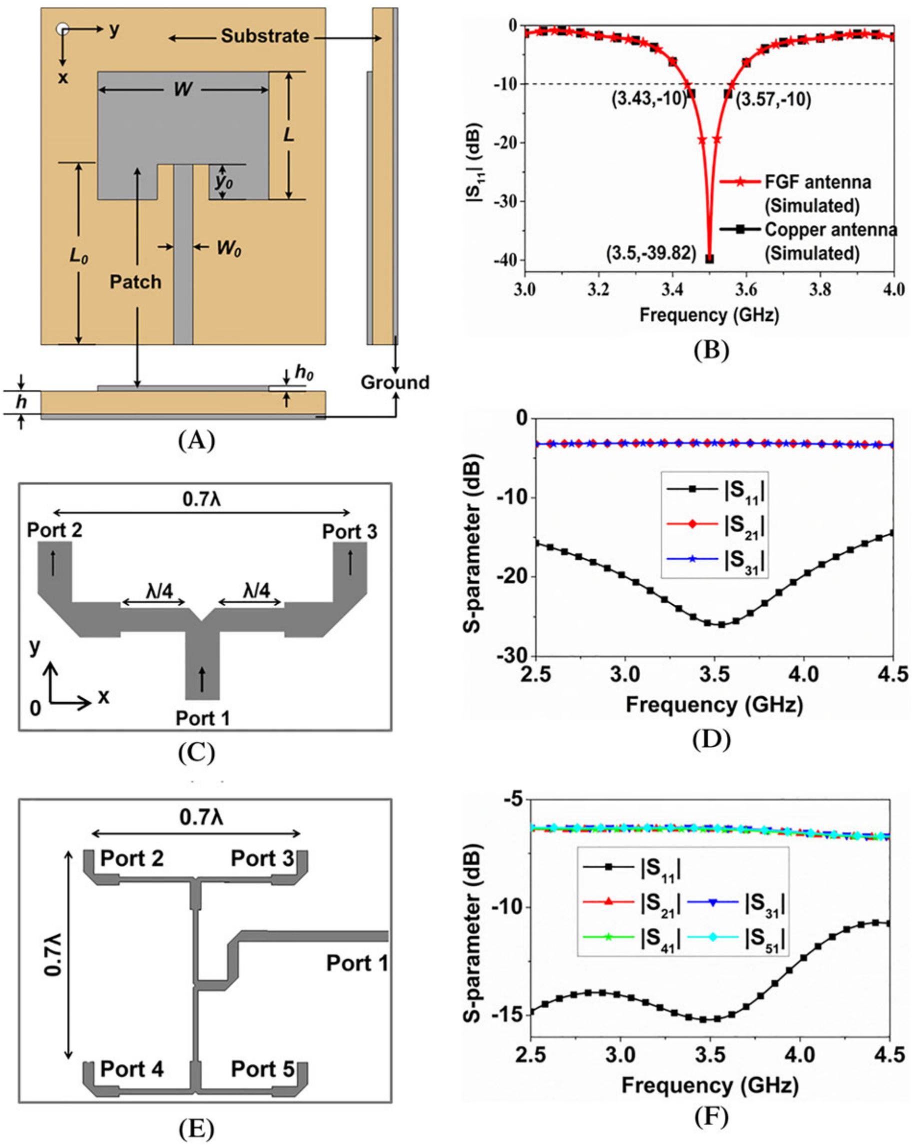

FIGURE 1 FGF array element and feed network design. A, Schematic diagram of FGF array element antenna, B, Simulated $|S_{11}|$ response of the antenna elements, C, The model of FGF power divider, D, The simulated S-parameters of power divider, E, The model of FGF feed network, and F, The simulated S-parameters of feed network

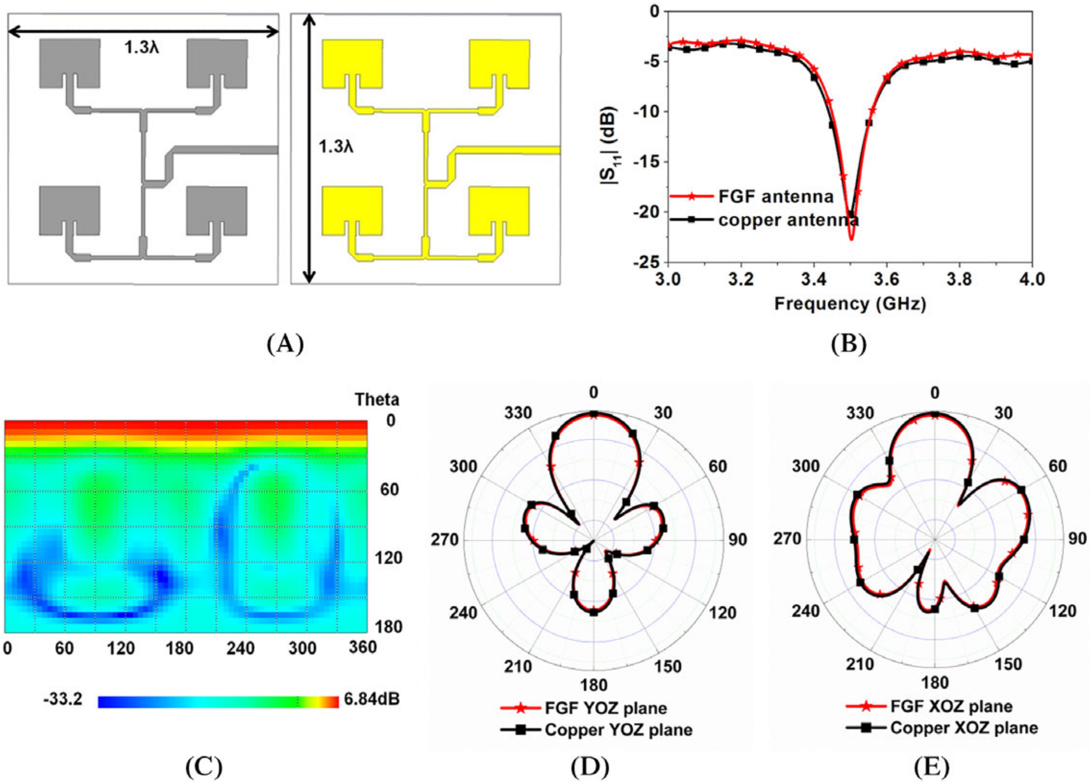

FIGURE 2 FGF array antenna design and simulate. A, The model of FGF and copper antenna array, B, The simulated $|S_{11}|$ of FGF and copper antenna array, C, The simulated gain of FGF antenna array, D, E, The simulated radiation pattern of FGF and copper antenna array

permeability, ε_0 is vacuum permittivity and ε_{reff} is effective dielectric constant.

In order to reduce the overall size, the proposed antenna is fed by a 50-Ohm microstrip-line. Changing the inset depth y can effectively match the impedances of the antenna patch and the microstrip-line. Under vacuum conditions, the input resistance (Z_{in}) for the feed line is given approximately by.[19]

$$Z_{in}(y = y_0) = Z_{in}(y = 0)\cos^2\left(\frac{\pi}{L}y_0\right) \quad (5)$$

When $y_0 = 5.8$ mm, the input resistance of antenna patch is 50-Ohm. The length and width of the feed are $L_0 = 30$ mm and $W_0 = 2.98$ mm, respectively.

The designed antenna is modeled and simulated in an electromagnetic simulation software package. The final optimized length L and width W of the patch are 24.44 mm and 19.76 mm respectively. In order to demonstrate the performance of the FGF antenna, a copper antenna with same structure and size is simulated for comparison. Figure 1B shows the simulated reflection coefficient (characterized by $|S_{11}|$ in dB) responses of the FGF antenna and copper antenna. The FGF antenna and copper antenna have identical reflection coefficient of −39.82 dB at 3.5 GHz, indicated that 99.99% of the energy is transmitted to the antenna and radiated into the free space.

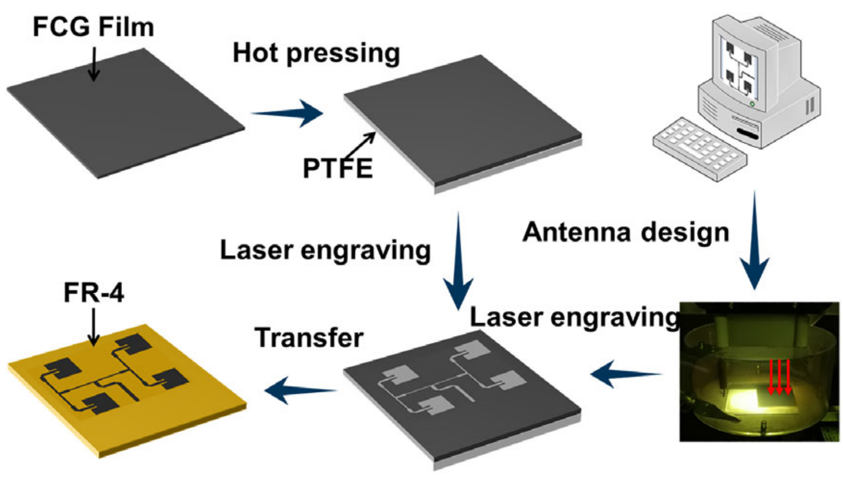

FIGURE 3 The manufacturing process of FGF antenna array

After the design of the antenna element is completed, it is derived into an antenna array, which needs to be fed by a feed network. Unlike a single antenna, which is fed by a simple microstrip-line, the feed network of the antenna array is more complicated. In this article, the T-type power divider is used to feed the antenna array.[20] Firstly, a single T-type power divider is simulated. The T-type power divider have two quarter-wavelength impedance transformers with width of 1.62 mm, corresponding to a characteristic impedance of 70.7 Ω for impedance matching, and the discontinuity compensation of the microstrip-line is realized by the chamfering method. Two output ports are separated by 0.7 λ, as shown in Figure 1C. Figure 1D shows the S-parameters of the power divider. The reflection coefficient of the input port 1 is −25.97 dB at 3.5 GHz while the insertion loss is only 0.08 dB, which implies that 99.75% of the energy at the input port is delivered to the output port. The port 2 and port 3 have same transmission coefficient of 3.08 dB. The results show that the T-type power divider of this design is an excellent candidate for the feed network construction. Figure 1E shows the feeding network model of the designed antenna array which consists of three T-type power dividers. The feed network has one input port (port 1) and four output ports (ports 2-5). The element spacing is 0.7 λ in both *x*- and *y*-direction. The selection of this value is trade-off with consideration of reducing mutual coupling between two adjacent antennas and suppressing the grating lobes at the same time. Basically, the distance between two antennas is recommended to be less than a λ (λ is the operating wavelength in the dielectric substrate). A four-port feed-network is designed to connect the four antenna elements. The S-parameters of each port are obtained as shown in Figure 1F. The input port 1 has a reflection coefficient of

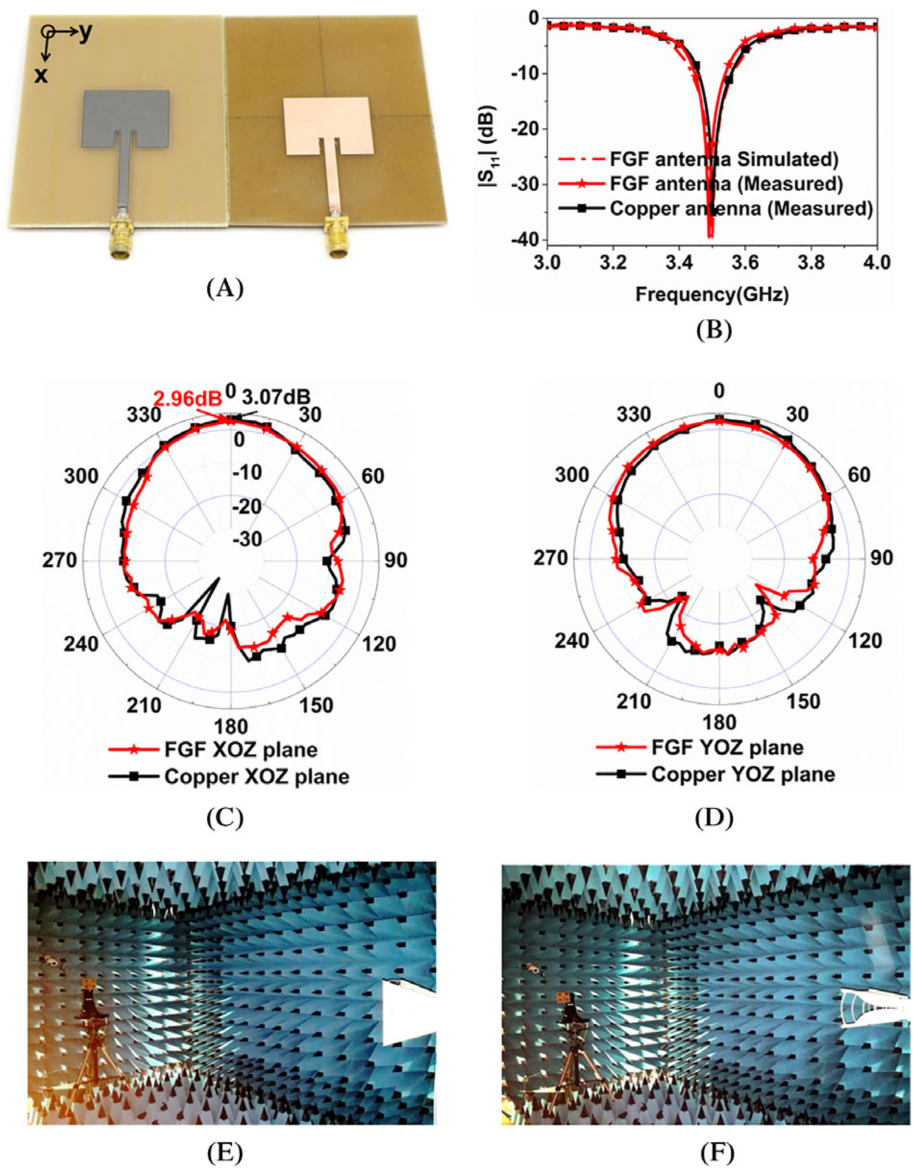

FIGURE 4 Measurement of antenna element. A, Photo of FGF and copper antenna element, (B) $|S_{11}|$ response of the antenna elements, C, D, Radiation patterns of FGF and copper antennas, E, F, Radiation pattern measurement

−15.2 dB at 3.5 GHz. The output ports 2-5 have similar transmission coefficient of 6.3 dB, indicated that the feed network can achieve equal distribution of energy from the input port with low insertion loss.

2.2 | Antenna array

The four FGF antenna array elements and the feed network were co-simulated, as well as the copper antenna arrays of the same structure and size.

The dimension of the substrate and the ground is 1.3 λ × 1.3 λ, as shown in Figure 2A. Figure 2B shows the simulated reflection coefficients of FGF antenna array and copper antenna array. The resonant frequency of both antennas is 3.5 GHz, while the FGF antenna array has a reflection coefficient of −22.59 dB which is a bit lower than the copper one (−20.23 dB). Figure 2C is the simulated far-field gain of the FGF antenna array with a maximum value of 6.84 dBi. The simulated radiation patterns of FGF antenna array and copper antenna array in *xoz*- and *yoz*-plane are shown in Figure 2D,E, respectively. From the results, it can be concluded that both antenna arrays have similar radiation patterns.

3 | MANUFACTURING

In order to solve the reported problem of rough preparation process as stated previously, this paper proposes a high precision laser engraving method[17,21] to fabricate the antenna. The laser engraving method is mainly composed of three parts: hot pressing, laser engraving and transfer. The schematic diagram of the manufacturing process is shown in Figure 3. Firstly, the FGF is attached to poly tetra fluoroethylene (PTFE) substrates through 200°C hot pressing. Thereafter, the antenna model is output by the simulation software, and the FGF with PTFE substrate is cut by LPKF laser engraving machine to obtain an FGF antenna. Finally, the FGF antenna is transferred from the PTFE substrate to the FR-4 substrate. It is worth pointing out that the cutting precision of the LPKF laser engraving machine is 25 μm.

4 | MEASURED RESULTS

The FGF and copper antenna array element produced by laser engraving is shown in Figure 4A. A Sub-Miniature-A (SMA) connector is used to connect the feed line and ground. To

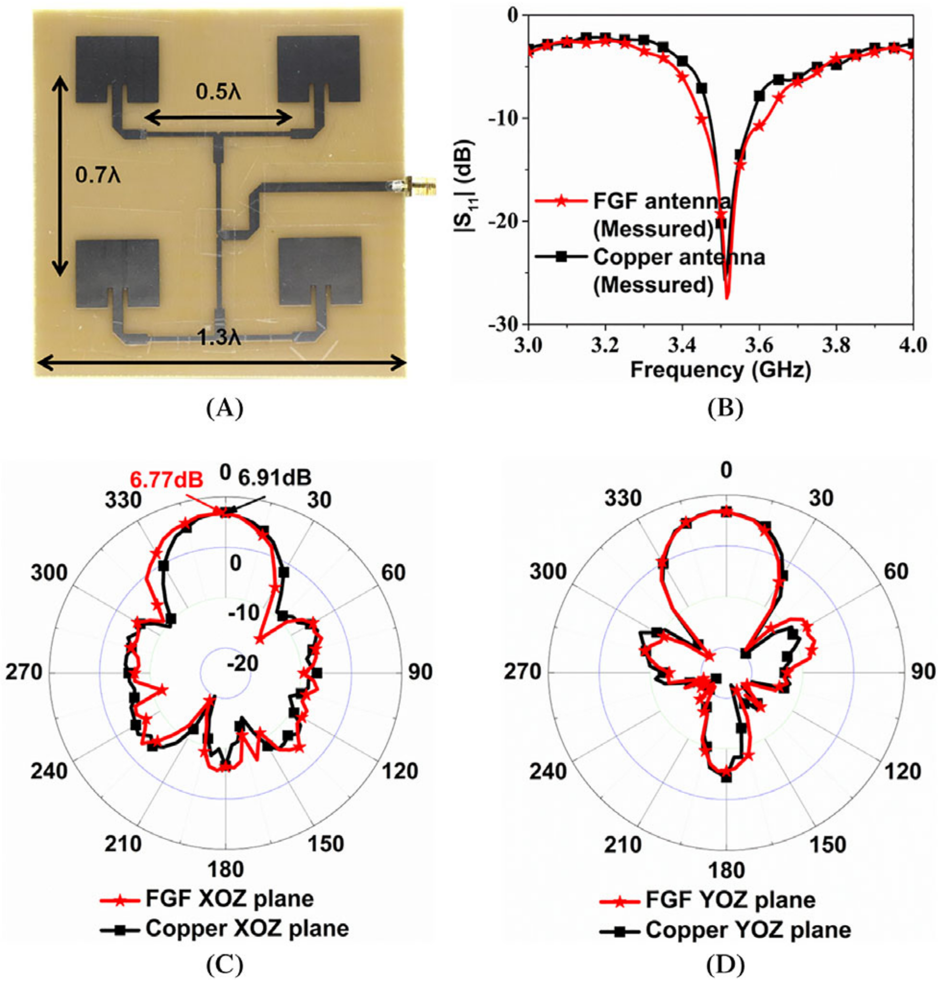

FIGURE 5 Measurement of antenna array. A Photo of FGF antenna array, B $|S_{11}|$ response of the FGF and copper antenna array, C, D, Radiation patterns of FGF and copper antenna arrays

better illustrate the design and test, a specified coordinate system is included in Figure 4A. Figure 4B shows the simulated and measured reflection coefficient (characterized by $|S_{11}|$ in dB) responses of the FGF antenna and copper antenna. The measured $|S_{11}|$ of the FGF antenna at the resonant frequency of 3.5 GHz is −29.47 dB, which is quite consistent to the simulated result. It is noted that the graphene antenna has a similar reflection coefficient to the copper antenna which is −34.97 dB at the resonant frequency of 3.5 GHz. The radiation patterns and gains of the FGF antenna and copper antenna are shown in Figure 4C,D. Figure 4C shows the radiation patterns on the *xoz*-plane of each antenna while Figure 4D depicts those on the *yoz*-plane. One can observe that the FGF antenna and copper antenna have similar radiation patterns. In addition to the radiation patterns, the maximum gain of the graphene antenna is 2.96 dBi, which is comparable to that of the copper antenna with 3.07 dBi. The radiation patterns of both the FGF and copper arrays at the resonant frequency are measured in a microwave anechoic chamber, as shown in Figure 4E,F.

A 2 × 2 antenna array consisting of predesigned antenna element is shown in Figure 5. Both FGF and copper antenna arrays are fabricated by laser engraving technique. Figure 5A presents the prototype of the FGF antenna array. The reflection coefficient of the FGF antenna array and copper antenna array are all measured with a Network Analyzer (PNA, Keysight N5225A), and the results as shown in Figure 5B. It can be seen that the resonant frequency of the FGF antenna locates at 3.5 GHz with $|S_{11}| = -20.23$ dB, which is similar to that of the copper array, which is −19.27 dB. Figure 5C shows the radiation patterns of the FGF antenna and copper antenna on the *xoz*-plane while the *yoz*-plane patterns are shown in Figure 5D. As can be seen from the experimental results, the maximum gain at $\phi = 0^\circ$ is 6.77 dBi for the FGF array and 6.91 dBi for copper array. The minor deviation is mainly due to the fact that the conductivity of the FGF used in this work (1×10^6 S/m) is a bit lower than the copper (1.32×10^7 S/m), causing a certain level of conductive loss. However, the current results are acceptable while taking other excellent merits of the graphene in antenna applications into account. Therefore, a conclusion can be drawn that the graphene antenna array and the copper antenna array have similar gains and radiation patterns, indicating that both arrays have the similar performances. This work is a preliminary research, which hopes to inspire more potential applications for graphene in antenna and microwave device applications.

5 | CONCLUSION

In summary, an antenna array with excellent performance at 3.5 GHz for 5G mobile communications has been proposed based on a flexible high-conductivity graphene film in this article. The FGF antenna array has an excellent return loss of −20.23 dB and a high gain of 6.77 dBi at 3.51 GHz. From the experimental results of reflection coefficient, gain, and radiation pattern, the graphene antenna shows a comparable performance to its copper counterpart. The high-conductive graphene film can be used to fabricate good performance and environment-friendly antenna and relevant microwave devices.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (51701146), the Fundamental Research Funds for the Central Universities (WUT: 2017IB015) and the Natural Science Foundation of Hubei Province of China (2015CFB719).

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How to cite this article: Song R, Huang G-L, Liu C, et al. High-conductive graphene film based antenna array for 5G mobile communications. *Int J RF Microw Comput Aided Eng*. 2019;e21692. https://doi.org/10.1002/mmce.21692