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RESEARCH ARTICLE

Design and manufacture of lowpass microstrip filter with high conductivity graphene films

Wenqing Zhou[1] | Chengguo Liu[1] | Guan-Long Huang[2] | Wei Xia[1] | Jingwei Zhang[1] | Daping He[1] | Zhi Wu[1]

[1]Hubei Engineering Research Center of RF-Microwave Technology and Application, Wuhan University of Technology, Wuhan, 430070, China
[2]ATR National Key Laboratory of Defense Technology, College of Information Engineering, Shenzhen University, Shenzhen, 518060, Guangdong, China

Correspondence
Chengguo Liu, Wuhan University of Technology, Hubei Engineering Research Center of RF-Microwave Technology and Application, 122 Luoshi Road, Wuhan, China.
Email: liucg@whut.edu.cn

Abstract
The design and manufacture of lowpass microstrip filter with high conductivity graphene films (HCGF) is reported, which is a proven work of the feasibility of HCGF used in microwave devices for wireless communications. The filter is designed as a fifth order Chebyshev step-impedance lowpass microstrip filter operating at 2.5 GHz, its conduct strip is the novel HCGF. Based on the parametric study in the design, the optimum structure parameters of the filter are selected to fabricate the filters using HCGF with conductivity up to 1.1×10^6 S/m. It is fabricated with precise and efficient method of laser engraving technique. The test results show that in-band microwave signals can transmit through the proposed HCGF filter effectively with insertion loss of 0.68 dB. The results in this paper show that HCGF filter has good performance comparable characteristics of the traditional copper filters.

KEYWORDS
high conductivity graphene films, laser-engraving technique, lowpass filter, microstrip filter, microwave frequency

1 | INTRODUCTION

Lowpass filters (LPFs), with good suppression of harmonics and interference, are widely used in modern wireless communication systems. Most LPFs investigated of the conductivity materials are in the form of metal.[1,2] With the technological development of wireless communication system, RF and microwave filters have to meet new requirements, such as smaller size, lighter weight, faster heat-dissipation, and lower cost. Traditional metallic filters could not achieve all of these requirements simultaneously. On the other hand, as an emerging technique, graphene based filters are capable to provide new features for filter designs.[3]

Graphene filters have been demonstrated and shown to have diverse properties; however, most investigations to-date have been involved in the terahertz band.[4–8] The concept, synthesis, analysis, and design of graphene-metal based tunable band-pass filters at terahertz frequency are reported,[6] In addition, the simulation of stepped impedance low-pass filter for the propagating surface plasmons in the terahertz band is realized by controlling graphene's field effect. In Ref. 8, wideband and dual-band transparent graphene microstrip filters are utilized to scale down the size of the wireless devices. A monolayer graphene is used in the microstrip fabrication. The prepared graphene is transferred to substrate with wet transfer process and etched with ferric chloride solution.

However, the abovementioned methods of fabricating graphene filter are more complicated and time-consuming. Moreover, the monolayer graphene is not suitable for microwave devices application since it exhibits relatively large insertion losses because of its coupling excitations.[8] On the contrary, multilayer graphene films with higher conductivity are developed and they also exhibit better durability, flexibility, and easy-process than monolayer graphene and most metals. Some graphene film-based devices have been proposed in terms of waveguides,[9,10] transistors,[11] sensors,[12] oscillators,[13] switches,[14,15] antennas,[16,17] and modulators.[18] Although the graphene films have been used in many microwave devices, electromagnetic properties and prototypes of graphene films filter in RF, microwave, and millimeter waves application have not been reported so far.

In this work, microwave LPF made of HCGF is investigated. In Section 2, the design, simulated results and parametric study of the HCGF filter are presented. The manufacturing of HCGF filter is described in detail in Section 3. Compared with traditional manual cut approach, the advantage with laser engraving technology is also discussed. In Section 4, performance of filters realized by HCGF and copper microstrip lines is measured and analyzed. Conclusions are drawn in Section 5.

2 | FILTER DESIGN AND ANALYSIS

2.1 | Filter structure

The specifications for the LPF under consideration are as follows: the filter has a lowpass Chebyshev frequency response with 3 dB cut-off frequency of 2.5 GHz; the out-of-band insertion loss at 4 GHz is expected to be higher than 25 dB, and the port impedance should be 50 Ω.

According to the theory and normalized frequency curve of a Chebyshev filter,[19,20] choosing the 5th order filter, that is, N = 5, is able to fulfill the requirements with the following normalized element values of g_k: $g_0 = g_6 = 1$, $g_1 = g_5 = 1.7058$, $g_2 = g_4 = 1.2296$, and $g_3 = 2.5408$. The discrete circuit element values as shown in Figure 1 can be calculated using the following equations:

$$L_k = \frac{R_0 g_k}{\omega_c} \tag{1}$$

$$C_k = \frac{g_k}{R_0 \omega_c} \tag{2}$$

where $R_0 = 50\ \Omega$, ω_c is the cut-off angular frequency. The equations give $C_1 = 2.171$ pf, $L_2 = 3.914$ nH, $C_3 = 3.235$ pf, $L_4 = 3.914$ nH, and $C_5 = 2.171$ pf.

Based on transmission line theory, the elements in Figure 1 can be realized with microstrip lines. When the circuit is implemented using microstrip line, the series inductance and the shunt capacitance can be replaced by the high impedance (Z_h) and low impedance (Z_l) line, respectively. The electrical lengths of inductor (βl_L) and capacitor (βl_C) sections are obtained respectively by:

$$\beta l_L = \frac{g_k R_0}{Z_h} \tag{3}$$

$$\beta l_c = \frac{g_k Z_\ell}{R_0} \tag{4}$$

Figure 2A,B shows that the schematic diagram layout of the proposed LPF with graphene microstrip line sections in top-view and cross-sectional view, respectively. The proposed filter consists of three layers, including HCGF conductor strip, substrate and ground from top to bottom. In addition, the layout consists of two 50 Ω lines at two sides, and five low-impedance and high-impedance lines in the middle. The structure of filter is symmetrical along the dotted line at the center as shown in Figure 2A.

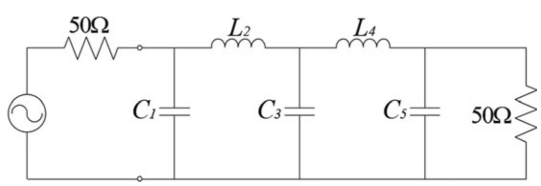

FIGURE 1 The equivalent circuit diagram of the lowpass filter

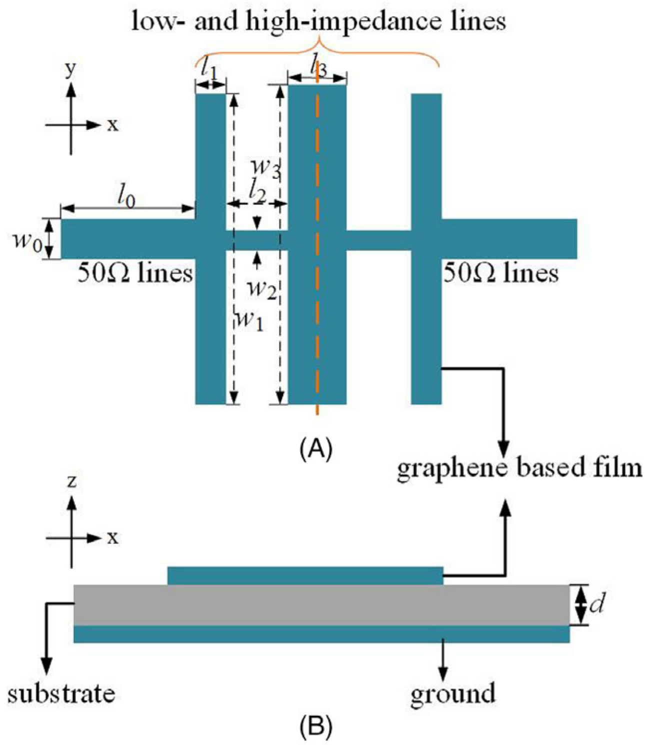

FIGURE 2 The geometry of the HCGF filter. A, Top view. B, Cross-sectional view [Colour figure can be viewed at wileyonlinelibrary.com]

In this work, the permittivity of the FR-4 substrate is 4.3 with thickness (d) of 1.6 mm. According to the microstrip line design equations[20] and the abovementioned (1), the lengths (l_1, l_2, l_3) and widths (w_1, w_2, w_3) of the microstrip line sections can be obtained for given value of Z_h and Z_l. Table 1 shows the values obtained by these formulas and optimization described in Section 2.2 with $Z_h = 90\ \Omega$ and $Z_l = 10\ \Omega$, and they are used for the filter fabrication.

2.2 | Parametric study

In this paper, three pivotal parameters affecting the efficiency of the HCGF filter are studied. They are the conductivity of graphene films based conductor strip (σ) and the length of the high-impedance line (l_2), length of low-impedance line (l_1).

The conductivity of graphene films is the key to the filter performance. The influence of the conductivity of graphene films on the performance of filter will be analyzed by changing parameter σ. The value is set to 1.1×10^4 S/m,

TABLE 1 HCGF filter parameters (unit: mm)

w_0	w_1	w_2	w_3
3.1	16.5	0.9	16.5
l_0	l_1	l_2	l_3
10.0	2.3	7.5	3.8

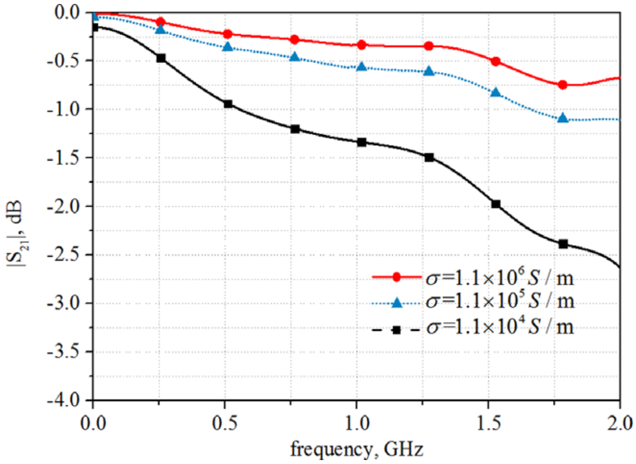

FIGURE 3 Insertion loss of the filter for various conductivity of the filter (σ) with fixed parameters: w_0 = 3.1 mm, w_1 = 16.5 mm, w_2 = 0.9 mm, w_3 = 16.5 mm, l_0 = 10.0 mm, l_1 = 2.3 mm, l_2 = 7.5 mm, l_3 = 3.8 mm [Colour figure can be viewed at wileyonlinelibrary.com]

1.1×10^5 S/m, and 1.1×10^6 S/m as shown in Figure 3, because the graphene films of these conductivities can be fabricated by the authors with controlled procedure.

The in-band return loss and insertion loss of the filter are affected by σ. In particular, the insertion loss in passband increases with the decrease of σ, mainly caused by the conductive loss. As shown in Figure 3, the corresponding insertion loss at 1.5 GHz deteriorates from 0.49 dB to 0.79 dB and 1.91 dB with decrease of the σs.

In order to illustrate the effect of the dimensions on the filter responses, l_2 is varied from 6 mm to 7.5 mm and 9 mm for $\sigma = 1.1 \times 10^6$ S/m. The simulated results of $|S_{11}|$ and $|S_{21}|$ with different l_2 values are shown in Figure 4 for comparison. When l_2 is altered to the aforementioned values, their corresponding cut-off frequencies are shifted to 2.3 GHz, 2.5 GHz, and 2.8 GHz, respectively. Analysis found that the length l_2 = 7.5 mm is thus the best for the design.

Moreover, l_1 has a great effect on the filter's return loss. With the determines values of $\sigma = 1.1 \times 10^6$ S/m and l_2 = 7.5 mm, when the value of l_1 is changed to 2.3 mm, 3.3 mm, and 4.3 mm, different responses can be found in $|S_{11}|$ within the passband. Figure 5 is the simulated results and show that the corresponding maximum value of in-band $|S_{11}|$ increases from −14.52 dB to −8.29 dB and −5.44 dB, respectively.

After optimizing the calculated values, the parametric dimensions which meet the design requirements are obtained, as shown in Table 1.

The simulated electric fields distributions of HCGF filter at 2 GHz and 3 GHz are shown in Figure 6A,B, respectively. In the passband at 2 GHz, it can be observed that low loss propagation of signal can be realized using the HCGF filter. On the other band, the electric signal at 3 GHz is restrained inside step-impedance microstrip lines. These results show the effective selectivity of signal propagation in passband and stopband.

3 | FABRICATION

3.1 | The HCGF used

Graphene, as a famous two-dimensional material, has recently attracted tremendous interest because of its unique electrical, mechanical, and optical properties. Though some monolayer graphene-based devices have been proposed recently, it is not suitable for microwave devices due to its complex fabrication of large sizes sheet.

Multilayer graphene films are found to be a good candidate for microwave design as its excellent characteristics in

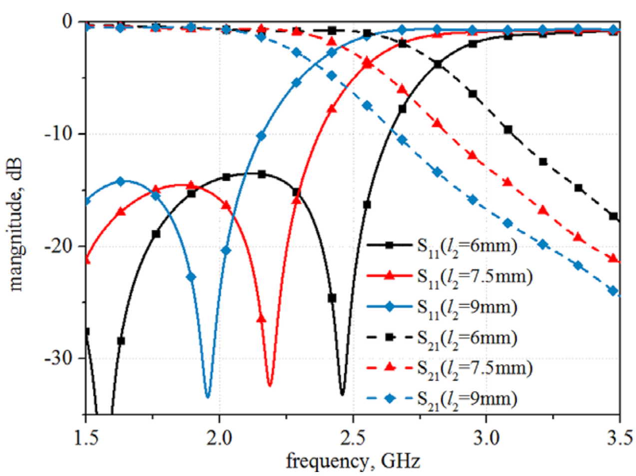

FIGURE 4 $|S_{11}|$ and $|S_{21}|$ responses of the filter for various length of the filter (l_2) with fixed parameters: w_0 = 3.1 mm, w_1 = 16.5 mm, w_2 = 0.9 mm, w_3 = 16.5 mm, l_0 = 10.0 mm, l_1 = 2.3 mm, l_3 = 3.8 mm [Colour figure can be viewed at wileyonlinelibrary.com]

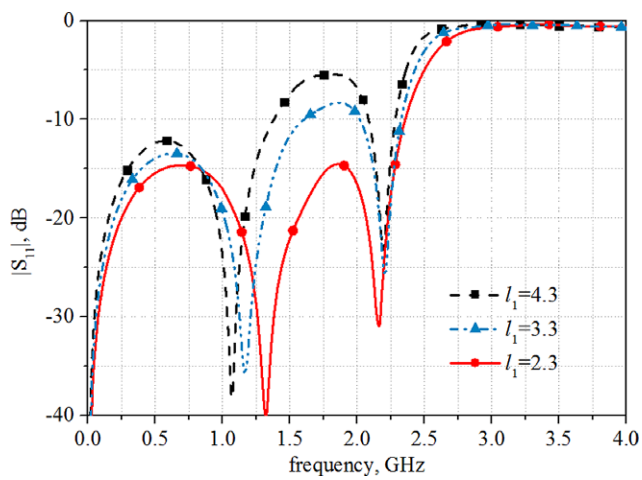

FIGURE 5 $|S_{11}|$ responses of the filter for various length of the filter (l_1) with fixed parameters: w_0 = 3.1 mm, w_1 = 16.5 mm, w_2 = 0.9 mm, w_3 = 16.5 mm, l_0 = 10.0 mm, l_2 = 7.5 mm, l_3 = 3.8 mm [Colour figure can be viewed at wileyonlinelibrary.com]

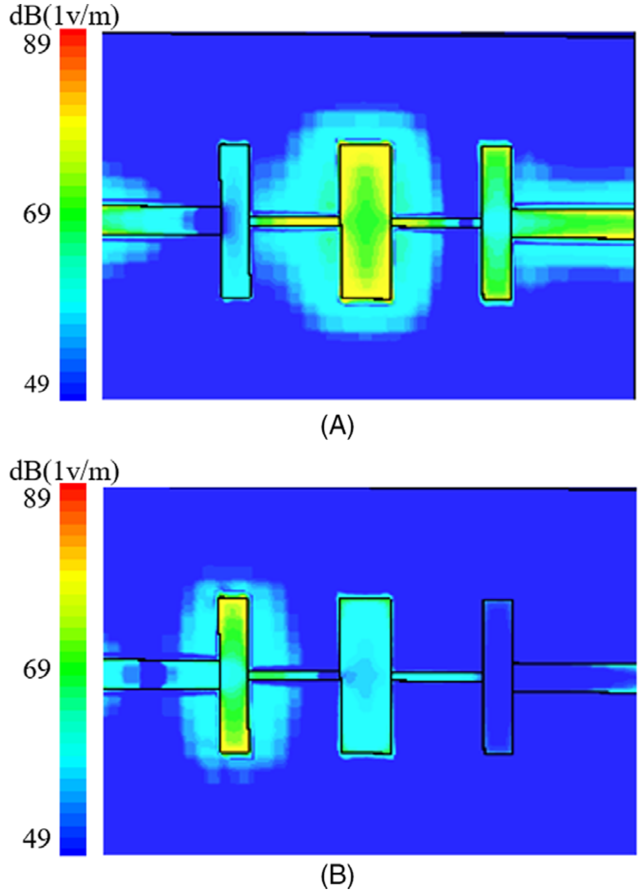

FIGURE 6 The simulated electric fields distributions of HCGF filter. A, In passband at 2 GHz. B, In stopband at 3 GHz [Colour figure can be viewed at wileyonlinelibrary.com]

terms of high conductivity, durability, and flexibility.[21,22] A method for manually attaching graphene elements to the Kapton substrates with glue is proposed.[23] However, there are many air gaps existing in the process of the stickiness, which affect the performance greatly. In Ref. 17, the films made of many layers of graphene with large area size and conductivity comparable to good conducting metals can be fabricated, it is possible for using the films to design microwave devices such as filters in this paper.

The filter proposed in this paper is made of graphene films with conductivity up to 1.1×10^6 S/m with good durability and flexibility. The preparation of large size graphene films has three steps. First, the graphene oxide (GO) suspension is diluted until the concentration reached to 15 mg/mL with ultrapure water. Thereafter, the diluted GO aqueous solution is scraped on the polytetrafluoroethylene (PTFE) film, and evaporated at room temperature to obtain the GO films. The GO films are annealed with high temperature at 1300°C for 2 hours, then 3000°C for 1 hour all in argon (Ar) gas flow environment. Finally, high conductivity graphene films (HCGF) are acquired by rolling compressed. The microstructure shows that the stacking of graphene layer is more regular and the correlation length is longer. As the high plane orientation structure, HCGF has excellent planar conductivity and low resistance. The measured results show that electrical conductivity of HCGF is verified by the four-probe detection, and $\sigma = 1.1 \times 10^6$ S/m. So, the film is used as the conducting material of the microstrip in the filter.

3.2 | Manufacturing process

In Ref. 24, micro-cutter is used to cut graphene films, and the patch is attached to a grounded substrate with an adhesive. Although this method is better than manual cutting, it is difficult to make a structure with high precision and more complexity. An ultrathin switchable microwave filter based on graphene and slot array is proposed in Ref. 25. Though the filter works at microwave band, it has complex hybrid structure and is only realized in simulation. In summary, most graphene-based microwave devices either remain in simulation with complicated structure, or are fabricated with crude processing technology. The laser-engraving technique is used in this paper to enhance the precision and obtain perfect microstrip line edge.

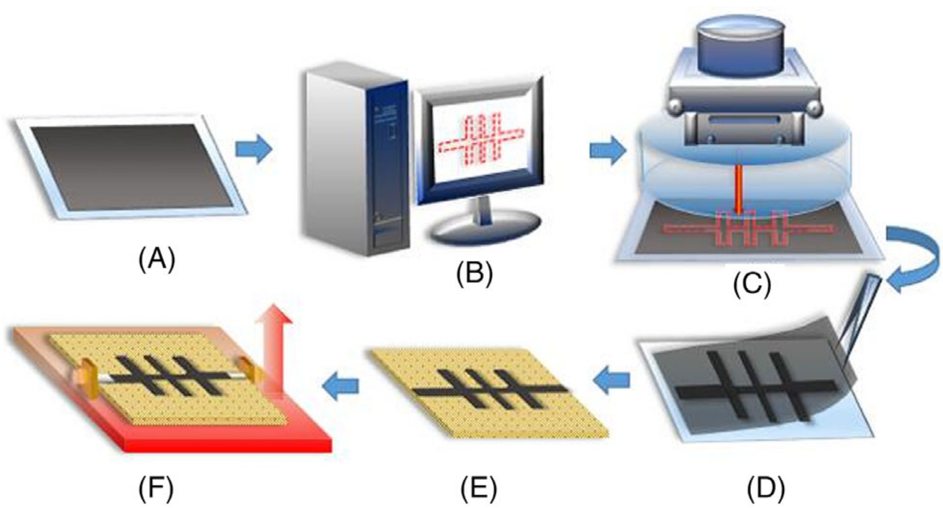

FIGURE 7 Process of fabricating the presented HCGF filter [Colour figure can be viewed at wileyonlinelibrary.com]

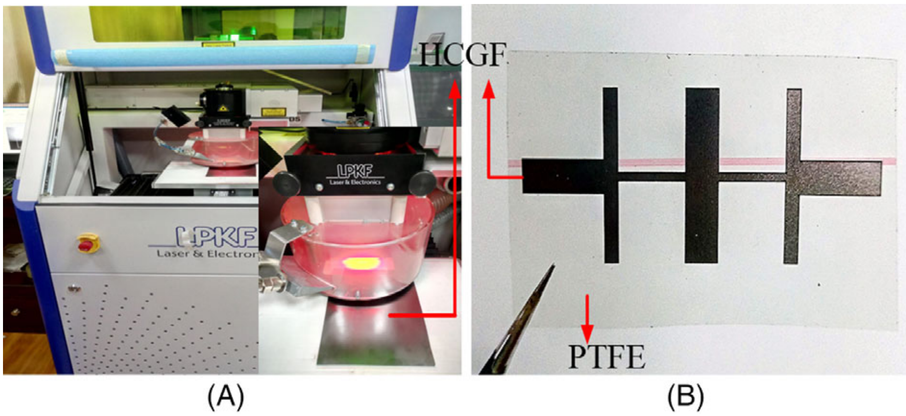

FIGURE 8 The photo of laser-engraving (A) and prototypes of HCGF films microstrip engraved (B) [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 7 shows the procedure of the laser-engraving technique used for fabricating the proposed graphene film microstrip filter, including six steps. The graphene films are cut into a designed size by laser cutting technology with precision of 0.03 mm. The cut graphene films can be attached to the substrate by the adhesive tape in order to avoid the air gap between the films and the substrate.

1. The high-conductivity graphene films with PTFE are prepared by the method described in Section 3.1. Both of them are electrostatically attracted together.
2. The contour of filter is exported from simulation tool (CST or others). The model data cannot be handled directly by laser machine, which has to be reprocessed in a calculation software so as to match with the laser machine. In this way, the laser path is calculated.
3. The engraving process is launched once the graphene films with PTFE are put into the laser machine as shown in Figure 8A. The graphene films can be accurately cut and easily removed from the carving platform with the PTFE. This method can accurately engrave minima 0.03 mm lines with smooth edges, and the flat and smooth surface of graphene films is maintained. In addition, the whole engraving process takes only 5 seconds for the proposed filter.

The HCGF microstrip filter has been fabricated from a sheet of HCGF with conductivity $\sigma = 1.1 \times 10^6$ S/m using laser engraving technique. With the substrate and connectors in place, the final HCGF microstrip filter is shown in Figure 9A. For comparison, a counterpart made from copper is shown in Figure 9B.

4. Graphene microstrip filter is separated from remainder by a tweezer.
5. The graphene microstrip is glued with transparent adhesive tape and the PTFE is replaced by substrate. To avoid inaccuracies during the adhesion, the outline of the microstrip line can be engraved on the substrate in advance. All the process needs to be handled carefully.
6. This is the last step, the SMA connectors are connected with the filter by silver gel after heated at 80°C for several hours. After the heating process, the HCGF filter is ready to use without any post-processing. The prototype of graphene films microstrip filter after laser-engraving is shown in Figure 8B.

4 | RESULTS AND DISCUSSION

The fabricated HCGF and copper filters are measured with a Network Analyzer (PNA, Keysight N5247A). The measured and simulated results of $|S_{11}|$ and $|S_{21}|$ responses of the

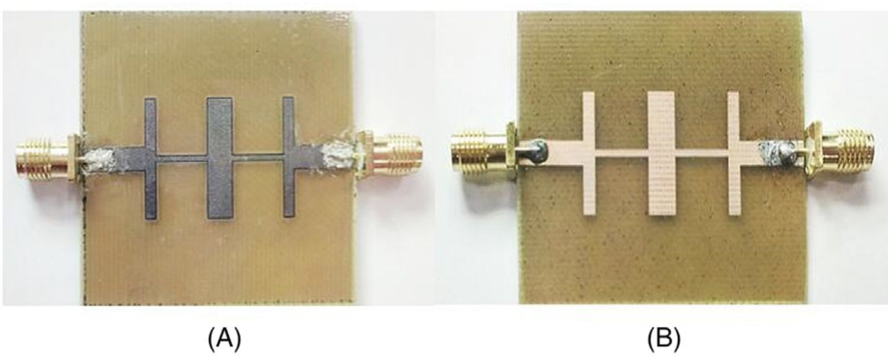

FIGURE 9 The prototypes of filters. A, HCGF filter. B, Copper filter [Colour figure can be viewed at wileyonlinelibrary.com]

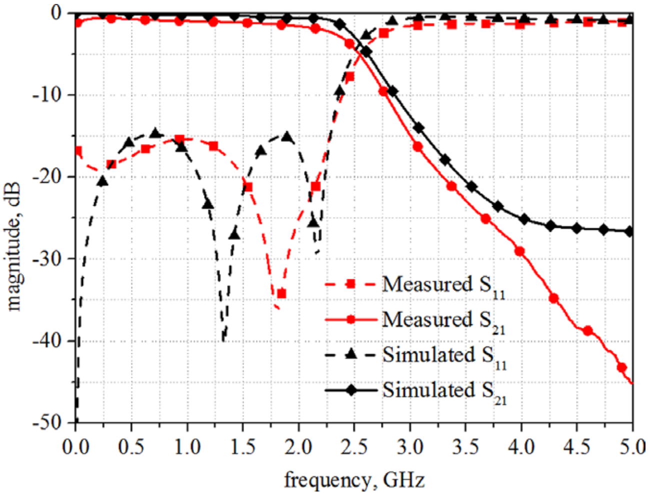

FIGURE 10 $|S_{11}|$ and $|S_{21}|$ response for HCGF filter [Colour figure can be viewed at wileyonlinelibrary.com]

HCGF filter are depicted in Figure 10. The results show that the measured cut frequency is 2.4 GHz and the simulated 2.525 GHz, they are in agreement within 150 MHz. And the HCGF filter has a relatively sharper frequency response in the stop band, because the insertion loss is 29.61 dB at 4 GHz otherwise it is 25 dB in the simulated results. The minimum insertion loss it has is up to 0.68 dB in the passband. The measured result of the maximum return loss is greater than 15.35 dB and better than simulated about 0.35 dB below 2.25 GHz.

The results of the HCGF filter are also compared to those of the copper filter in Figure 11. It can be seen that both HCGF and copper filters have similar minimum in-band insertion loss, the minimum up to 0.68 dB. The insertion loss of the HCGF filter also has a better frequency response in the stop band when at frequencies above 4 GHz. The troughs of the curves in return loss is changed in different manner compared with simulated as shown in Figure 10, it

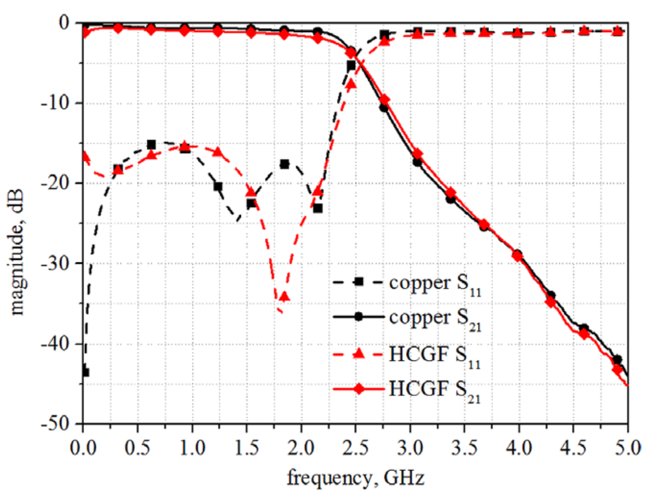

FIGURE 11 Measured $|S_{11}|$ and $|S_{21}|$ response for copper and HCGF filters [Colour figure can be viewed at wileyonlinelibrary.com]

is degraded for the copper filter from about -40 dB to about -25 dB at 1.3 GHz, for the HCFG filter it is located at 1.55 GHz with minma less than -35 dB.

All these results demonstrate that using graphene films is able to meet requirements as good as metal in planar microwave filter applications and better in some sense.

5 | CONCLUSIONS

A 5th order Chebyshev HCGF step-impedance microstrip LPF has been studied and verified through simulation and measurement. The HCGF filter operates at 2.5 GHz with 0.68 dB in-band minimum insertion loss and a 25 dB insertion loss at 4 GHz is designed, and fabricated precisely and efficiently with laser-engraving technique. The measured results show the HCGF filter operates at cutoff frequency 2.4 GHz with 0.68 dB in-band minimum insertion loss and a relatively sharper frequency response in the stop band with 29.61 dB insertion loss at 4 GHz. And the comparison with the identical copper filter shows that the HCGF microstrip LPF is able to meet requirements as good as copper filter. The work proves that HCGF can provide a more efficient and convenient method for the fabrication of RF filters in wireless communication.

ORCID

Chengguo Liu https://orcid.org/0000-0002-0982-6402
Jingwei Zhang https://orcid.org/0000-0003-0657-6193
Daping He https://orcid.org/0000-0002-0284-4990
Zhi Wu https://orcid.org/0000-0002-4879-3279

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