Optically transparent wideband CVD graphene-based microwave antennas

Marco Grande, Giuseppe Valerio Bianco, Dario Laneve, Pio Capezzuto, Vincenzo Petruzzelli, Michael Scalora, Francesco Prudenzano, Giovanni Bruno, and Antonella D'Orazio, "Optically transparent wideband CVD graphene-based microwave antennas", Appl. Phys. Lett. 112, 251103 (2018);

https://doi.org/10.1063/1.5037409

Published Online: 19 June 2018
Accepted: June 2018

Optically transparent wideband CVD graphene-based microwave antennas

Marco Grande[1,2,*], Giuseppe Valerio Bianco[2,*], Dario Laneve[1], Pio Capezzuto[2],

Vincenzo Petruzzelli[1], Michael Scalora[3], Francesco Prudenzano[1],

Giovanni Bruno[2] and Antonella D'Orazio[1]

[1] *Dipartimento di Ingegneria Elettrica e dell'Informazione, Politecnico di Bari, Via Re David 200, 70125 - Bari, Italy,*

[2] *Istituto di Nanotecnologia – CNR-NANOTEC, Via Orabona, 4, 70125 - Bari, Italy,*

[3] *Charles M. Bowden Research Center, RDECOM, Redstone Arsenal, Alabama 35898-5000 – USA*

[*]*These Authors contribute equally to this work*

marco.grande@poliba.it

giuseppevalerio.bianco@cnr.it

In this paper we numerically and experimentally demonstrate that few-layers Chemical Vapour Deposition (CVD) graphene can be employed for the fabrication of fully optical transparent antennas for microwave applications. We show how planar graphene-based antennas, having size of tens square centimeters, can achieve relative high gain over a wide operating bandwidth (> 3.5 GHz) simultaneously covering the GPS, WiFi, Bluetooth and 5G bands. The measured 3D radiation patterns show dipole-, quadruple- and hexapole- behavior. These findings open up new routes for the realization of innovative devices where "invisible and hidden" antennas could be integrated in smart windows or photovoltaic systems, fostering novel configurations for camouflage, and communications systems. Furthermore, the possibility to handle different radiation patterns could allow the engineering of complex systems such as antenna arrays devoted to beam-steering, beam-forming and healthcare applications. Finally, combining graphene transparency and its flexibility could also pay the way for the realization of wearable devices, demanding invisibility, that operate on the surface of the human body or integrated in transparent devices (for example, in contact lenses) reducing their invasiveness.

1. Introduction

Optically transparent components are attracting more and more attention thanks to their aptitude to be integrated in existing electronic and photonic devices. In this context, microwave devices play an important role in different applications. For example, one of the key and essential component is the antenna that finds wide application in wireless communication systems.

Antennas are mainly realized with metallic radiant elements that are generally opaque conductive patterns. Conversely, optically transparent antennas are interesting being invisible and suitable to be integrated in photonic systems such as photovoltaics, healthcare applications, inter-vehicle communication systems, car networks, monitors for pc and tablets, wearable electronics, and non-invasive sensors, just to mention a few.

A first analysis on transparent antennas was reported by NASA scientists in [1] while a first attempt to construct a microwave planar antenna based on RF-sputtered indium tin oxide was reported in [2]. Other attempts based on ITO and fluorine-doped tin oxide (FTO) were reported in [3-4].

A different approach was suggested in [5] where the Authors investigated the possibility to replace the continuous solid metallic layer of a microstrip patch antenna with meshed patches for both the patch itself and the ground plane. However, the fabrication protocol for meshed structures requires different and expensive technological steps and could degrade the antenna performance [6-8].

It is worth to highlight that, in the recent years, there is also an on-going debate about the sustainability of the ITO [9] and the quest for transparent conductive materials. Here, it is important to underline that replacing metals with environmentally friendly or low-cost non-metallic conductors could be highly welcomed and embraced by worldwide industries and producers.

In this scenario, graphene, the two-dimensional allotrope of carbon, can play an important role. The "realm" of graphene-based antennas is quite vast since graphene can be produced and used in different forms. Most of all reported examples are based on graphene produced by chemical and/or mechanical exfoliation of graphite [10-14]. In this framework, graphene sheet resistance is the critical factor and, hence, a significant reduction of surface resistivity is strictly necessary to improve the antenna performance. Several strategies have been pursued to provide graphene films with sheet resistance ranging in the order of few- up to tens- of ohm/sq including the use of free- and not free-binder films and/or post-deposition processing (e.g. mechanical compression, thermal annealing, etc.). These materials provide high and stable electrical conductivitiesx, but they result opaque due to the film thickness in the range of few up to hundreds of microns.

On the other hand, the idea of a transparent CVD graphene-based antenna was theoretically envisioned in Ref. [15] and very few attempts were reported in literature showing low gain [16-18]. This is also demonstrated and consistent with a very recent paper [19] where the authors, measuring a transmitted signal by means of a receiving horn antenna, conclude that the monolayer CVD graphene-based antenna acts as a dielectric and shows a completely different behavior with respect to the gold counterpart. Therefore, significant reduction of the graphene sheet resistance should be accomplished for CVD graphene before it can be applied for antenna design. Conversely to graphene used in [10-14], it is not possible to reduce the sheet resistance of a CVD graphene film by increasing the thickness and, hence, by simply stacking of additional graphene foils. In fact, several experimental works show that the sheet resistance of multilayer CVD graphene reduces down to a saturation value by increasing the number of layers and, then, increases again for additional stacked layers [17,20]. Partial contact or the presence of impurities between graphene layers introduce contact/series resistance whose contribute becomes more and more important as the layer number increases.

Overall, all these aspects have prevented the realization and the characterization of graphene-based antennas till now making the advent of "optically transparent graphene microwave" still a challenge.

Recently, the Authors have advanced the field of graphene microwave and graphene photonics providing the first demonstration of two large-area (in the order of tens of square centimeters), fully optically transparent basic microwave devices by introducing an innovative approach for the fabrication of highly conducting graphene that is transparent in the visible spectral range while showing an optical behavior comparable to metallic layers in the microwave range. The strength of our approach relies on the availability of graphene operating in "quasi-metallic" region that allows the substitution of metal layers in several microwave devices leading to fully transparent devices. The chemically optimized graphene was used to easily realize a graphene-based wire-grid polarizer and a transparent microwave absorber [21-22].

In this paper, we report on the radiation performance of a transparent quasi-metallic CVD graphene-based antenna. We show how this antenna is impedance-matched over a broad frequency range showing a good gain (with positive peaks). We also consider the feeding configurations and the influence of metallic parts connected to the SMA connector.

These experimental results prove that CVD graphene can be efficiently used to realize optically transparent antennas for wide applications where these antennas can be integrated in complex systems for emerging and important applications related to the 5G and Internet of Things (IoT), electromagnetic shields for security and military applications. For example, in 5G systems as the frequency increases the path losses due to the presence of walls, the use of transparent antennas on the window glasses could become a key factor for the wireless communication systems.

Moreover, transparent microwave-devices also provide the potential for integration along with photovoltaic (PV) modules as desirable in applications where RF communications and photovoltaic technologies can "compete" in terms of area coverage (nano-satellites, vehicles, wearable devices, etc.).

Last but not least, CVD graphene (from single- to few-layers) offers the possibility to tune the properties of the sheet resistance opening the way for the realization of transparent antenna arrays devoted to tunable beam-steering and forming systems.

2. Results and discussion

Figure 1(a) shows the sketch of the planar graphene-based antenna that consists of two arms with lateral dimension L×W equal to 75mm×25 mm. We choose wide planar antennas since they offer a wider bandwidth with respect to dipole antennas [23].

Graphene was grown by CVD on a 25μm thick copper foil in a typical quartz tube CVD reactor at 1000°C using CH_4/H_2 as precursors. The graphene was transferred onto corning glass substrate (treated by O_2 plasma to improve graphene adhesion) by the thermal tape method. An accurate material structural and morphological characterization is reported in the Supporting Material and the copper was etched in a solution of ammonium persulfate. Multilayer graphene samples were fabricated by transferring additional graphene layers onto graphene/glass substrates. $SOCl_2$ treatments were performed in a dry chamber by placing graphene/glass substrate and 1ml of liquid $SOCl_2$ (avoiding direct contact) at 105°C for 60min. Doping of multilayer samples was performed by repeating $SOCl_2$ treatment after transferring and stacking each graphene layer [21].

The antenna patches were realized by stacking 6 CVD graphene layers on a thin glass substrate (Figure 1(b)) with a total optical transmittance of about 85% (Supplementary Figure 1). The electrical properties of the graphene patches were analyzed by means Rs measurements in the Van der Pauw configuration (4×4mm^2) in air and at room temperature. Sheet resistance values of about 18 ohm/sq were measured over the whole patch permitting the operation of CVD graphene in the quasi-metallic region [21-22]. This is in evident contrast with the results reported in [19], where the authors use only a single layer concluding that the graphene is a dielectric material, and, hence, this clearly demonstrates the necessity of our approach for the realization of graphene films with low sheet resistance.

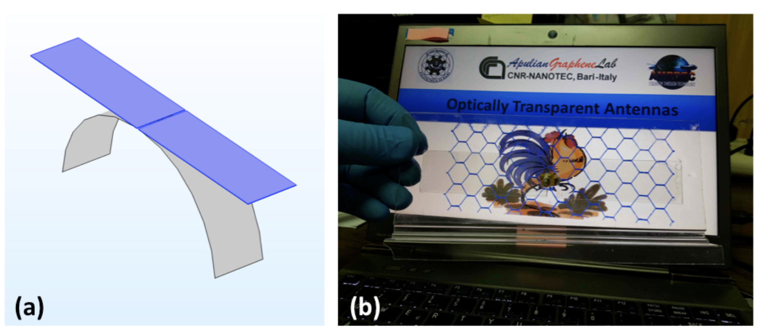

FIG. 1. (a) Sketch and (b) picture of the proposed optically transparent CVD graphene-based antenna. The picture demonstrates the device transparency (85%).

The antenna was simulated by means of 3D-FEM software (COMSOL-MultiPhysics) where graphene is modeled as a sheet current ($J=\sigma\cdot E_{x,y}$ [21-22]). It is worth stressing that the proposed antennas operate with a thickness in the range that varies between $\lambda/10^8$ and $\lambda/10^7$ over the whole operating frequency range. This defines a real case of "sheet current" as defined in the implemented numerical model.

The scattering parameter S_{11} was measured by means of a VNA (Keysight N9923A FieldFox VNA) over the 0.8-6 GHz frequency range covering the GPS, WiFi, Bluetooth and 5G bands. This range corresponds to the operating frequency range of the measurement system for characterization of the gain and the radiation pattern of the antennas. Figure 2 compares the numerical and measured scattering parameters S_{11} (solid blue line) for the antenna with central feeding (i.e. the SMA is connected to the center of the two patches) revealing a -10dB bandwidth of about ~3.5 GHz.

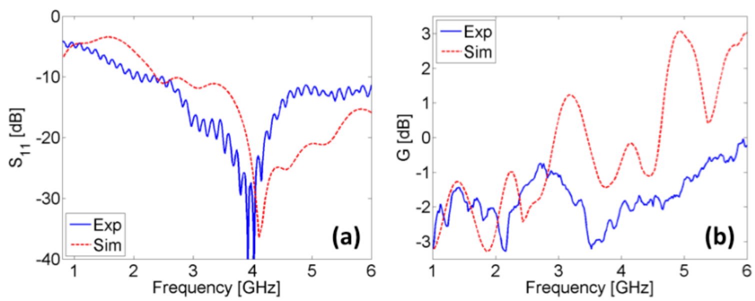

FIG. 2. Measured (blue solid line, Exp) and simulated (dashed red curve, Sim) scattering parameter S_{11} (a) and gain when W=25 mm (b).

The radiation pattern of the fabricated antenna was characterized with the test station StarLab from Satimo (Supplementary Figures 2-3). This system is able to perform accurate 3D measurements of the pattern radiated by antennas using a circular probe array to allow real time elevation cuts and volumetric 3D radiation pattern measurements within a few minutes. It operates between 800 MHz and 18 GHz. The system exploits indirect measurement techniques based on the Near Field measurement (NF). This system allows performing rapid 3D measurements of the radiation pattern reconstructing the Far Field (FF) from the Near Field (NF) by means of the Huygens' principle.

During the measurements, the antenna was placed on a cardboard support that sandwiches the 50 ohm-SMA connector. This support allowed us to connect the antenna arms at different positions over the width as shown afterwards. The two SMA pins come out from the cardboard support and are connected to antenna patches by means of a conductive silver paste. It is worth stressing that the dimension of the SMA fixes the gap (about 5mm) between the antenna arms that is constant for all the measurements.

The measured maximum gain (solid blue line) of the planar antenna is depicted in Fig. 2(b) showing an average value of about -1 dBi with an average efficiency of about 0.21 (directivity of the antenna is equal to about +5dBi over the whole frequency range of interest). The comparison between the experimental results and the numerical ones (indicated with the dashed red curves) shows a good agreement. The numerical results also prove that the gain for the proposed antenna could achieve about +3 dBi. At the same time, the measured gain can be increased showing several peaks above 0 dBi when an "edge" feeding scheme is exploited (Supplementary Figure 4).

These values compare those of the opaque graphene antennas reported in literature [10,13]. For example, the maximum gain with graphene-based ink is +0.2 dBi at about 2 GHz in Ref. [10], -0.6 dBi at 962 MHz and -4 dBi/-10 dBi at 1052 MHz in Ref. [13] while our CVD graphene-based antenna having width w=25 mm provides 0 dBi (experimental central feeding), +1 dBi (experimental edge feeding) +3dBi (numerical) at 6 GHz, -0.7 dBi at about 2.5 GHz.

In order to verify the effect of the SMA connector on the antenna performance, the gain of the SMA connector was measured ((Supplementary Figure 2). The SMA gain is about -20/-15 dB over all the operating -10 dB bandwidth fully confirming that the gain is only due to the presence of the graphene patches.

Figure 3 shows the comparison between the experimental (EXP) and numerical (SIM) radiation patterns (with a resolution of 3°×3° in both planes) for the operating frequency equal to 1 GHz, 2 GHz, 3 GHz and 6 GHz, respectively. The experimental results are in good agreement with the simulations revealing the dipole- (1 GHz, 2 GHz), quadrupole- (3 GHz) and hexapole-like (6 GHz) behavior of the wide planar antenna. All the antennas show a nodal axis that is aligned with the two graphene-based patches. We realized also an ITO version of our antenna, with similar sheet resistance, and compared its performance with the graphene-based counterpart. The comparison between the two antennas reveals that the measured radiation patterns and gain are in a very good agreement (please see Supplementary Figure 5).

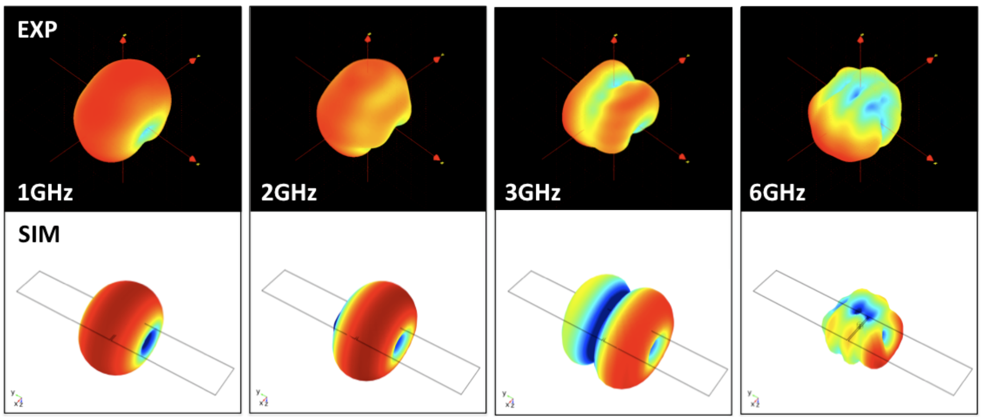

FIG. 3. Comparison between measured (top, EXP) and numerical (bottom, SIM) 3D radiation patterns for several operating frequencies. The color gradient relates to the gain.

The variation of the radiation pattern can be related to the distribution of the surface current as shown in Fig. 4. In particular, it can be seen that, at lower frequencies, the surface current is confined at the boundaries of the graphene patches while, as the frequency increases, it is localized at the two edges close to the SMA-connector pins. The formation of nodal points (or circles) as the frequency increases that shape the radiation patterns can also be visualized.

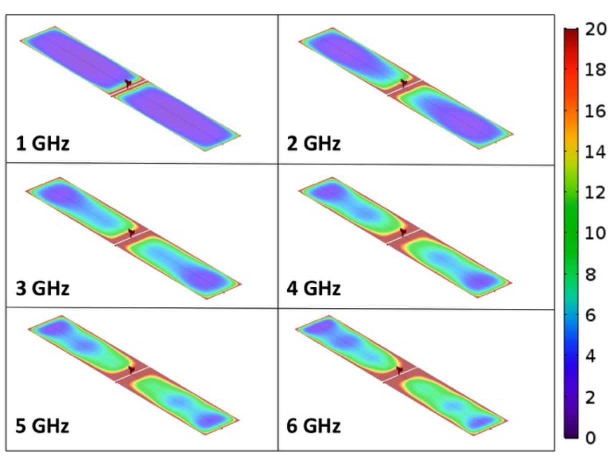

FIG. 4. Simulated distribution of the surface current on the antenna arms.

Finally, we verified the performance of the antenna when the width W is decreased from 25 mm down to 12.5 mm and 5 mm (towards a "dipole-like" configuration), respectively. The corresponding gains are shown in Fig. 5(a). The plot reveals that the gain ranges between about -8 dBi (-12 dBi) and -1 (-2 dBi) when the width W is equal to 12.5 mm (5 mm). This behavior is fully confirmed by the simulations shown in Figure 5(b) where the gain ranges between about -5 dBi (-10 dBi) and +2 (+0.1 dBi) when the width W is equal to 12.5 mm and 5 mm, respectively. The reduction of the gain in both configurations can be addressed to the impedance mismatch between the SMA impedance (equal to 50 ohm) and the antenna input impedance Z. In particular, Figures 5(c-d) reveal that the Z module is higher than that of the SMA impedance due to a reactive component. Conversely, when W is equal to 25 mm, the Z module almost coincides with the real component and the reactive part is almost negligible over the operating frequency range.

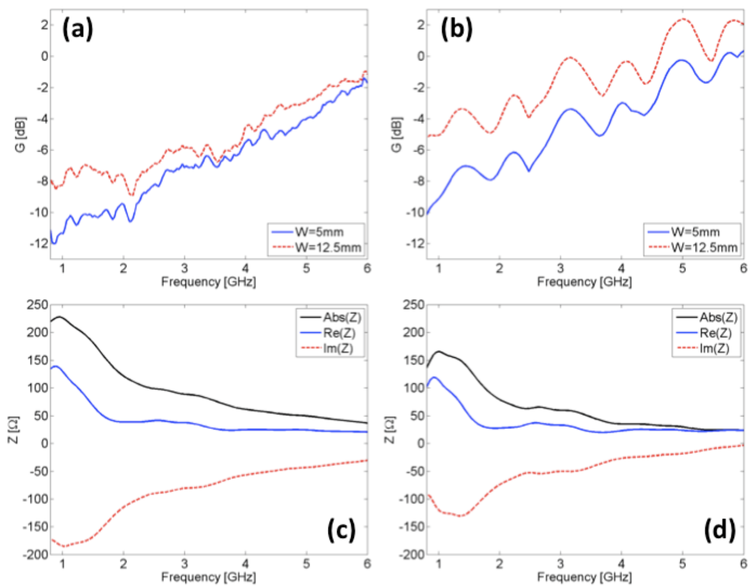

FIG. 5. (a) Measured and (b) theoretical gain for the CVD graphene-based planar antennas when W is equal to 5 mm (blue solid curve) and 12.5 mm (dashed red curve), respectively. Simulated input impedance Z when W is equal (c) 5 mm and (d) 12.5 mm, respectively: module (solid black curve), real (solid blue curve) and imaginary part (dashed red curve).

3. Conclusion

We have detailed the design, fabrication and characterization of wide planar CVD graphene-based antennas. We have demonstrated that CVD graphene can be exploited for the fabrication of antennas that are optically transparent (transmittance equal to about 85%). The -10dB bandwidth is wide enough to cover the GPS, WiFi, Bluetooth and 5G bands.

All these results encourage the possibility to combine together two other important features offered by graphene: flexibility and tunability, i.e. the "ambipolar effect". This last feature could pave the way to the realization of tunable antenna arrays for beam-steering (or beam-forming) applications and extend the range of operation to THz frequencies [24,25]. At the same time, our approach is ideal for realizing consumable devices for wearable systems.

The combination of all the CVD graphene properties and the integration of all these functionalities could be strategic for new applications in photovoltaics systems, camouflage, and communications systems and healthcare, security and military applications.

Supplementary Material

The Supplementary material contains: (1) the optical transmittance of the graphene-based antenna; (2) the pictures of the antenna in the (3) anechoic chamber along with the gain of the SMA connector; (4) the performance of the edge feeding scheme; (5) the comparison between the ITO- and graphene-based antennas.

Funding

U.S. Army International Technology Center Atlantic (W911NF-16-2-0236); Apulia Region program "FutureInResearch" (7K76VI3); National Laboratory Sens&Micro LAB Project (POFESR 2007–2013, code number 15).

Acknowledgments

A. Sacchetti at CNR-NANOTEC is also acknowledged for his technical assistance during graphene growth and transferring.

References

1. R. N. Simons and R. Q. Lee, “Feasibility study of optically transparent microstrip patch antenna,” in Proceedings of the 1997 IEEE Antennas and Propagation Society International Symposium. Part 4 (of 4), pp. 2100–2103, July (1997).
2. N. Outaleb, J. Pinel, M. Drissi, and O. Bonnaud, “Microwave planar antenna with RF-sputtered indium tin oxide films,” Microwave and Optical Technology Letters, 24, no. 1, pp. 3–7 (2000).
3. N. Guan, H. Furuya, K. Himeno, K. Goto, K. Ito, “Basic Study on an Antenna Made of a Transparent Conductive Film”, IEICE Transactions on Communications Vol.E90-B No.9 pp.2219-2224 (2007).
4. Yuan Yao, Wanzhong Chen, Xiaodong Chen, and Junsheng Yu, “Design of Optically Transparent Antenna with Directional Radiation Patterns,” International Journal of Antennas and Propagation, (2017).
5. G. Clasen and R. Langley, “Meshed patch antennas” IEEE Trans. Antennas Propag. 52, 1412 (2004).
6. J. Hautcoeur, F. Colombel, X. Castel, M. Himdi, and E. Motta Cruz, “Optically transparent monopole antenna with high radiation efficiency manufactured with silver grid layer (AgGL),” Electronics Letters, 45, no. 20, pp. 1014–1016 (2009).
7. J. Hautcoeur, F. Colombel, X. Castel, M. Himdi, and E. Motta- Cruz, “Radiofrequency performances of transparent ultra-wideband antennas,” Progress In Electromagnetics Research C, 22, pp. 259–271 (2011).
8. N. Guan, H. Furuya, R. Hosono, H. Tayama, and K. Yamagami, “A see-through wire-grid film antenna for WLAN applications,” in Proceedings of the 2012 IEEE Asia-Pacific Conference on Antennas and Propagation, APCAP 2012, pp. 273-274 (2012).
9. K. Ghaffarzadeh, R. Das, “Transparent Conductive Films (TCF) 2017-2027: Forecasts, Markets, Technologies”, IDTechEX.
10. X. Huang, T. Leng, M. Zhu, X. Zhang, J. Chen, K. Chang, M. Aqeeli, A. K. Geim, K. S. Novoselov, Z. Hu,“Highly Flexible and Conductive Printed Graphene for Wireless Wearable Communications Applications”, Scientific Reports, 5, 18298 (2015).
11. T. T. Tung, S. J. Chen, C. Fumeaux and D. Losic, “Scalable realization of conductive graphene films for high-efficiency microwave antennas,” J. Mater. Chem. C, 4, 10620-10624 (2016).
12. T. Leng, X. Huang, K. Chang, J. Chen, M. A. Abdalla and Z. Hu, "Graphene Nanoflakes Printed Flexible Meandered-Line Dipole Antenna on Paper Substrate for Low-Cost RFID and Sensing Applications," in IEEE Antennas and Wireless Propagation Letters, 15, no. , pp. 1565-1568 (2016).
13. Xianjun Huang, Ting Leng, Xiao Zhang, Jia Cing Chen, Kuo Hsin Chang, Andre K. Geim, Kostya S. Novoselov, and Zhirun Hu, “Binder-free highly conductive graphene laminate for low cost printed radio frequency applications,” Appl. Phys. Lett. 106, 203105 (2015).
14. Xianjun Huang, Ting Leng, Kuo Hsin Chang, Jia Cing Chen, Kostya S Novoselov and Zhirun Hu, "Graphene radio frequency and microwave passive components for low cost wearable electronics", 2D Mater. 3 025021 (2016).
15. J. Perruisseau-Carrier, "Graphene for antenna applications: Opportunities and challenges from microwaves to THz," 2012 Loughborough Antennas & Propagation Conference (LAPC), Loughborough, pp. 1-4 (2012).
16. M. Dragoman, D. Neculoiu, Al. C. Bunea, G. Deligeorgis, M. Aldrigo, D. Vasilache, A. Dinescu, G. Konstantinidis, D. Mencarelli, L. Pierantoni, et al., “A tunable microwave slot antenna based on graphene”, Applied Physics Letters, 106, 153101 (2015).
17. B. Wu, H. M. Tuncer, A. Katsounaros, W. Wu, M. T. Cole, K. Ying, L. Zhang, W. I. Milne, Y. Hao, “Microwave absorption and radiation from large-area multilayer CVD graphene”, Carbon, 77, 814–822 (2014).

18. A. Katsounaros, M.T. Cole, H.M. Tuncer, et al., "Near-field characterization of chemical vapor deposition graphene in the microwave regime", Applied Physics Letters, 102, 233104 (2013).

19. Shohei Kosuga, Ryosuke Suga, Osamu Hashimoto, and Shinji Koh, “Graphene-based optically transparent dipole antenna”, Appl. Phys. Lett. 110, 233102 (2017).

20. Kasry, A., Kuroda, M. A., Martyna, G. J., Tulevski, G. S. & Bol A. A. “Chemical Doping of Large-Area Stacked Graphene Films for Use as Transparent”, Conducting Electrodes. ACS Nano 4, 3839–3844 (2010).

21. M. Grande, G. V. Bianco, M. A. Vincenti, D. de Ceglia, P. Capezzuto, M. Scalora, A. D’Orazio, G. Bruno, "Optically Transparent Microwave Polarizer Based On Quasi-Metallic", Scientific Reports 5, 17083 (2015).

22. M. Grande, G. V. Bianco, M. A. Vincenti, D. de Ceglia, P. Capezzuto, V. Petruzzelli, M. Scalora, G. Bruno, and A. D’Orazio, "Optically transparent microwave screens based on engineered graphene layers," Opt. Express 24, 22788-22795 (2016).

23. N. P. Agrawall, G. Kumar and K. P. Ray, "Wide-band planar monopole antennas," in IEEE Transactions on Antennas and Propagation, vol. 46, no. 2, pp. 294-295, Feb 1998.

24. X. Qin, J. Chen, C. Xie, N. Xu and J. Shi, "A tunable THz dipole antenna based on graphene," 2016 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Chengdu, pp. 1-3 (2016).

25. D. Correas-Serrano and J. S. Gomez-Diaz, "Graphene-based Antennas for Terahertz Systems: A Review", Forum for Electromagnetic Research Methods and Application Technologies, FERMAT (2017).