

Design and Development of a Hybrid Broadband Radar Absorber using Metamaterial and Graphene

Delme Winson, Balamati Choudhury, N. Selva Kumar, Harish Barshilia and Raveendranath U. Nair

Abstract—Stealth airborne systems are low observable platforms, which bring together technologies in the field of aerodynamics, electromagnetics and material science. Radar absorbing materials/ structures play a key role in the design of such stealth airborne platforms. In this paper, a radar absorber has been fabricated based on the design of a non-periodic metallic patch coated with graphene. The simulation result of the novel design over an ultra-wideband (1 to 60 GHz) yields good absorption (99.93 %). With the constraint of fabrication facility, a small unit cell of the structure has fabricated and measured. The measurement result shows a good agreement with the simulation results. The absorption bandwidths, thickness, weight of the structure are some of the key elements that were considered in the design model. It has been observed that, the design allows the electric potential tuning by changing the Fermi energy of graphene layer. The significant absorption of the proposed design in ultra-wide band shows that it has potential applications in RF stealth technology.

Index Terms— Radar absorbing material, Fermi level, Surface conductivity, Metamaterial, Stealth

I. INTRODUCTION

Stealth technology is the most notable one in the military domain due to the rapid advancements in material science and electronics. In this regard, the RF and microwave aspects of stealth technology mainly focus on the reduction of radar cross section (RCS). RCS is a measure of target size with the backscattered radar signal from the target object in terms of electromagnetic power [1]. There are several approaches for *Radar Cross Section Reduction (RCSR)*. The primary stealth technology used to reduce RCS is shaping. In shaping, the aircraft body is designed in such a way that the incoming radar signal is reflected away from the surface, thus, providing less visibility. Shaping makes an aircraft stealthy, but it faces several challenges. Even though stealth can be achieved through proper aerodynamic design, it is frequency dependent and achieving broadband reduction becomes difficult [2]. Advanced radars that operate in ultra-wideband frequencies impose a challenge to the stealth designer for seeking technologies apart from shaping. Radar absorbers are one among the promising technologies towards *RCSR* at microwave frequencies. Hence, application of wideband light weight radar absorbers has gathered lot of attention in the

design of stealth airborne platforms. Radar-absorbing materials (RAMs) are used in stealth technology to disguise a vehicle or structure from radar detection. The absorbing material should be thin and should provide excellent absorption characteristics over a wide frequency range [3]. However, the strong trade-off between the thickness and the bandwidth is a major challenge for the development of high-performance radar absorbers. During the past one decade, metamaterial based absorbers are found to be used as potential alternatives of conventional absorbers in different frequency ranges, such as microwave, terahertz, infrared and even optical regimes. These absorbers are used in various practical applications like RCS reduction, antenna miniaturization, electromagnetic compatibility (EMC), electromagnetic interference (EMI), thermal emitter, solar cell and so on [4]. In the last few years, rapid advancements have been occurred in the field of metamaterial perfect absorber (MPA) [5]. Further, MPA for stealth applications also has been very popular [6]. A reconfigurable metamaterial absorber was designed using switchable ground plane (SGP) [7]. The patterned resonator structure and ground plane determined the resonant frequency tuning of the metamaterial absorber. A broadband metamaterial absorber was proposed in the work reported elsewhere [8], which utilized the energy harvesting from EM waves to supply power to sensor networks. A flexible metamaterial absorber was investigated for stealth applications, which consisted of a pattern of resonant structures wrapped around a metallic cylinder [9]. Modern military applications always demand for broadband radar absorbers. However, the operation of metamaterials is observable only in a narrow bandwidth. Unlike conventional metamaterials, there exist two dimensional materials that show excellent electromagnetic (EM) properties. Among such materials, graphene plays an important role in EM absorption. In one such reported work [10], a tunable broadband metamaterial absorber design composed of Jerusalem cross metal encrusted in the graphene layer was proposed. An optically transparent broadband absorber was realized using graphene and quartz substrate operating in millimeter wave regime [11]. A multilayer graphene was demonstrated by repeated transfer and etch process with tunable surface resistivity. In the present work, the authors have explored the

capabilities of metamaterial structure combined with graphene layers as broadband radar absorber for stealth application.

Graphene is a two dimensional material comprising of hexagonally arranged carbon atoms [12]. The unique optical, electrical, mechanical, and thermal properties of graphene make it an important material in cutting edge technologies. The thickness of graphene is of the order of the size of a carbon atom, but it is about 200 times stronger than steel and has a higher electrical and thermal conductivity than copper. The most interesting feature of graphene is its tunable sheet conductivity; the sheet conductivity can be tuned for a broad frequency range by shifting the electronic Fermi level either by electronic or chemical doping. Metamaterial absorber incorporating graphene sheet is a prominent area of research in stealth technology as graphene exhibits several advantages and unusual material properties [12]. Since graphene is a lightweight material, it can reduce the payload and a good option for use in stealth applications [13].

The major objective for the radar absorber design is to obtain an absorber with least thickness and wide operating frequency band. These requirements are contradictory to each other. Conventional radar absorbers are known to have good performance only within a limited waveband [14]. In this work, a radar absorber was designed and fabricated with a hybrid of metamaterial and graphene. Incorporation of graphene with a metamaterial can be used to achieve absorption in an ultra-wide band. The surface conductivity tuning of graphene is used here. This property of graphene will account for impedance matching and broadband tuning. A non-periodic metallic patch together with a layer of graphene and other layers constitute a multilayered structure of the absorber. The fabrication and measurement have been done in order to observe the absorption characteristics of the absorber. The measured absorption was more than 95% in 9.9 GHz to 10.2 GHz. The design and simulation of structure have been done using finite element method (FEM)based software tool.

II. EM DESIGN ASPECTS OF RADAR ABSORBER

The fundamental concept used in radar absorber design is the matching of characteristic impedance and the wave impedance. In the characteristic impedance matching, the impedance of the absorbing material is made equal to that of free space, by proper matching of relative permittivity and permeability. In the wave impedance matching concept, the input impedance of the front surface of the absorber is made equal to characteristic impedance of free space. As a first step, towards the design, a metamaterial based absorber has been designed with a non-periodic metallic patch. The designed absorber consists of three layers via PEC (0.017 mm), dielectric (1.2 mm) and Cu (0.005 mm) patch respectively.

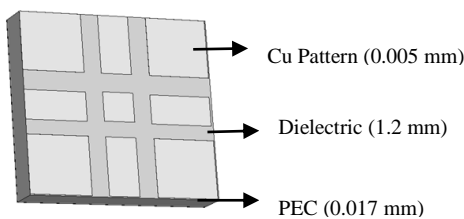


Fig. 1. Schematic of unit cell of the metamaterial based radar absorber

A metamaterial absorber can be realized by eliminating the reflected wave, and the transmitted wave can be absorbed through the conductive and dielectric losses. Zero reflection can be achieved by artificially manipulating permittivity (ϵ) and permeability (μ) of the metamaterial because the reflection condition is determined by the ϵ and μ of the medium [15].

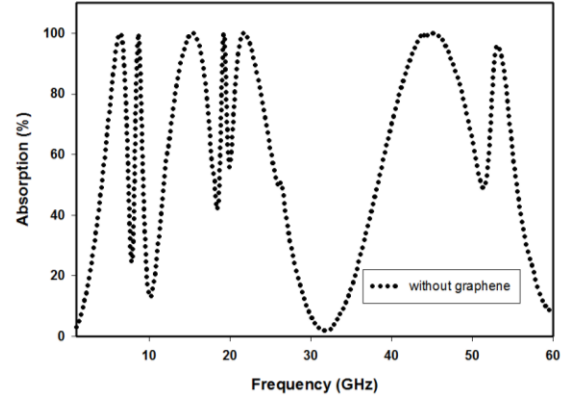


Fig. 2. Simulated absorption characteristics of metamaterial absorber without graphene layer

In the absorption characteristics shown in Fig.2, resonant peaks are observed at multiple frequencies. The electromagnetic absorption rapidly diminishes near the resonant frequencies. Such metamaterial based absorbers have limited use in stealth applications, since it demands broadband performance.

While investigating the broad-banding techniques, nano materials have significant role in improving the bandwidth. Among nanomaterials, graphene is the suitable candidate for the absorber design. This motivated us to design a metamaterial based absorber incorporating graphene for broadband absorption characteristics.

A. Tuning of Graphene

Ideally, graphene has a zero bandgap structure. In order to create a bandgap, graphene is cut into different layers as in graphene nano ribbon (GNR) [16]. In graphene tuning, the shifting of Fermi level induces hole or electron conduction. Similarly, application of biasing in graphene modifies its electric properties [17]. The molecular structure of graphene is a sp^2 hybridisation with linearly arranged sigma bond and perpendicularly arranged π bond. While applying the electric potential, π bond exhibits bonding and antibonding with neighbouring atoms which introduces conductive properties in graphene. The complex surface conductivity of graphene is modelled by using Kobo formula in the microwave frequency band [12]. The complex surface conductivity, is determined by intra-band contributions given by

$$\sigma = \frac{\sigma_0}{1 + j\omega\tau} \quad (1)$$

$$\sigma_0 = \frac{e^2 k_B T \tau}{\pi \hbar^2} \left\{ \frac{\mu_c}{k_B T} + 2 \ln(e^{-\mu_c/k_B T} + 1) \right\} \quad (2)$$

where, e -electron charge, h -reduced Planck's constant, k_B -Boltzmann's constant, μ_c -chemical potential, T -temperature, ω -operation frequency and τ -electro-phonon relaxation time. The values of τ and T are 0.2 ps and 300 K, respectively.

According to Kobo formula, the conductivity of graphene changes dynamically with chemical potential, however it is almost frequency-independent in the microwave region. In addition, as the chemical potential varies from 0 to 0.4 eV, surface conductivity of graphene varies from 0.9 mS to 9 mS. The surface impedance of graphene is given by

$$Z_s = \frac{1}{\sigma} = \frac{j\omega\tau + 1}{\sigma_0} \quad (3)$$

As $\omega\tau \ll 1$ in microwave frequencies, the reactance component (inductive) of the impedance is small and hence negligible.

B. Design of radar absorber

Wideband impedance matching is necessary to reduce the reflections from the absorber and it increases the power attenuation within the design. The schematic of the basic unit cell of the proposed absorber is shown in Fig.3. The model of the non-periodic structure was constructed using 4 pieces of similar squares, with dimension of 3mm and 4 rectangles of 1.6mm length and 3mm width and a square of 1mm placed at the center. The metallic patch consists of 4 big squares; the 4 long strips and small square used in the design structure is made of copper with an electrical conductivity of 5.96×10^7 S/m. The thickness of the patch used is 0.017mm, which is greater than the skin depth. This helps to reduce the transmission through the structure and the patch, which is placed under the graphene sheet of 3.06 nm thickness.

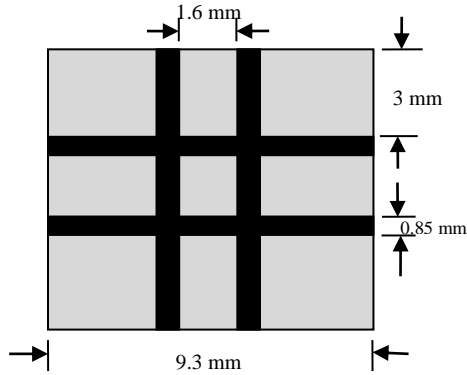


Fig. 3. Schematic of the unit cell of the proposed radar absorber.

The EM power absorption in this structure has been improved by placing a sheet of conductivity tuneable graphene above the metallic patch. It matches the impedance of the metamaterial patch to that of free space impedance and maximum absorption is obtained for a wide frequency range. The metal patch structure used has a non-periodic geometry. The frequency independent surface conductivity of the graphene sheet is due to intra band contribution and these characteristics are ideal for wideband impedance. With the combination of the metal patch and graphene over a large surface area, the

surface conductivity of graphene can be effectively tuned. Two extremely thin layers, 50 nm thick silicon dioxide layer and 50nm thick poly silicon layer, are placed under graphene, as shown in Fig.4. This is because, the thickness of these two layers (around 100 nm) is only $0.5 \times 10^5 \lambda$ (at 15 GHz), and the relative dielectric constants of silicon dioxide and polysilicon are 3.9 and 3 respectively. These layers are placed on a dielectric layer with thickness of 1.6mm and a dielectric constant of $\epsilon_r=4.3$. The dielectric layer supports the above layers, and also provides space for destructive interference. The whole structure was grounded with perfect electric conductor (PEC) to eliminate transmission. It should be pointed out that, influences of the extremely thin silicon dioxide layer and poly silicon layer can be safely neglected [12]. The size of each unit cell is 9.3 mm \times 9.3 mm.

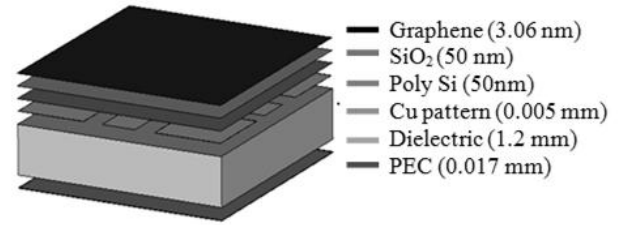


Fig. 4. Schematic of the layered structure of radar absorber.

III. SIMULATION AND ANALYSIS STUDIES

In order to analyze the absorbing properties of the hybrid model, simulations were carried out using EM simulation software based on the FEM. The absorption was calculated from the S parameters.

A. EM simulation

The absorption rate of the proposed absorber can be analyzed and studied by using the method of EM absorption. The tetrahedral mesh and unit cell boundary conditions were applied during the simulation.

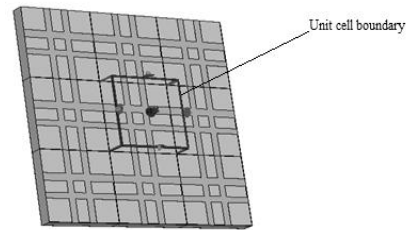


Fig. 5. Radar absorber with unit cell boundary conditions.

At a chemical potential of 0 eV, the surface impedance is around 120 Ω . As the chemical potential varies from 0.1 eV to 0.4 eV, the surface impedance value is reduced from 420 Ω to 110 Ω . Absorber shows an impedance of 377 Ω at 0.1 eV and it is comparable with the characteristic impedance of free space. Therefore, impedance matching is obtained for entire microwave spectrum. This makes graphene to be most suitable in designing broadband radar absorbing structures especially in microwave region.

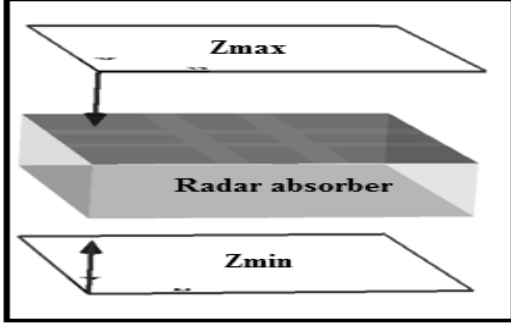


Fig. 6. Unit cell of the radar absorber with ports.

The unit cell boundary conditions were efficiently applied in this hybrid structure for FEM analysis. Floquet modes were also used for absorption of the higher order wave patterns. The ports were given in the Z direction and the simulations were performed in the frequency domain. The simulation analysis was conducted to observe the S parameters and the corresponding plot of absorption was obtained. Fig.6 shows the unit cell porting model in simulation software (CST Microwave Studio).

B. Comparison of absorption characteristics at different electric potentials

In this part, we examined and investigated the theoretical analysis of the proposed absorber to verify numerical results for wide bandwidth.

According to the well-known formula of absorption rate [2]:

$$A(f) = 1 - R(f) - T(f) \quad (4)$$

where $R(f)$ and $T(f)$ represent energy reflectivity and transmittance, respectively. A perfect absorbing effect (absorption $> 99\%$) is achieved in the frequency range of 1 to 60 GHz. When an EM wave interacts with a graphene sheet, the tuning of the electric potential controls the amount of energy that gets absorbed. In Fermi level tuning, graphene affords extensive control of its conductivity. The adjustability of conductivity of graphene yields control over its electromagnetic absorption.

Based on the previously reported literature values, simulations were carried out for different electric potentials, (i.e., 0.1, 0.2 and 1 eV) to analyze the tuning of graphene and the variation of absorption at different potentials [18]. In order to tune the conductivity of graphene, multilayer graphene was transferred on the top of the metamaterial structure. The electric potential at 0.2 eV resulted in maximum absorption and the impedance at this particular electric potential matches with that of free space. Therefore, the absorption obtained is $>90\%$. Similarly, the simulations were performed at an electric potential of 1eV. The impedance at this electric potential is greater than $377\ \Omega$. This indicates that the absorption has decreased significantly. The average value was measured to be 68.6 % as shown in Fig. 7. The comparison of absorption at different electric potentials is shown in Fig. 7.

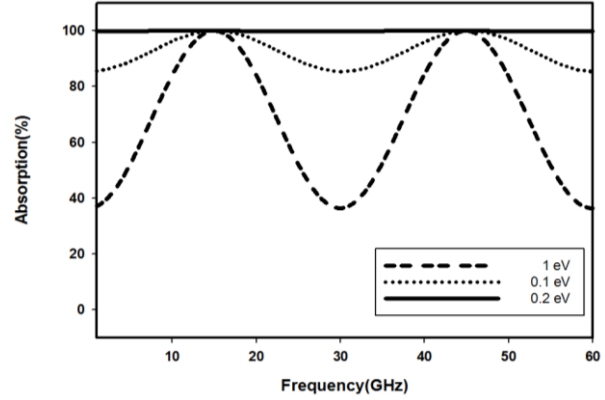


Fig. 7. Simulated absorption characteristics at different electric potentials

The absorption decreases significantly, when the simulation was done without the graphene layer. In this case the metallic patch layer was placed directly on top of the dielectric layer. The average absorption observed is 56.81%. From this graph it is noticeable that, the graphene has its own significant property of absorption for radar waves. The absorption characteristics in three different cases were analyzed through the simulations. It is evident that the electric potential of graphene can be tuned externally to obtain a high value of absorption.

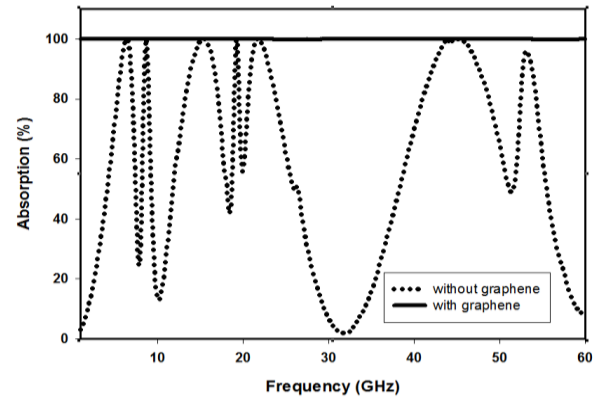


Fig. 8. Simulated absorption characteristics with and without graphene layer

Fig.8 shows the simulated absorption characteristics obtained with and without graphene layer. It is obvious that the absorption without graphene layer is lower. It indicates that most of the energy absorption is consumed by the graphene layer. Hence, the design with graphene shows the maximum value of absorption, while the structure without graphene shows less absorption.

IV. FABRICATION AND MEASUREMENT

The fabricated model is a planar absorber of size 23 mm*23 mm and it consists of four unit cells with 0.2 mm spacing width. The fabrication of the absorber includes a step by step process, as it consists of a multilayered structure. Three different fabrication techniques (i.e., 3D printing, sputtering and HFCVD) were used to fabricate the radar absorber structure.

A. Fabrication of metamaterial structure

The prototype of the proposed structure, consisting of 2×2 -unitcell, was fabricated on a 1.6 mm dielectric substrate using prototype printing machine as shown in Fig.9. The printing process includes drilling, milling, and routing mechanisms. The non-periodic metallic patch of Cu with thickness 0.017 mm was printed as patches on the dielectric layer.



Fig. 9. Prototype printing machine

B. Si/SiO₂ deposition on dielectric substrate

The designed model consists of a top graphene layer. Two thin layers of poly Si and Silicon dioxide are embedded below the graphene layer as supporting layers. The growth of ultra-thin graphene was achieved using hot-filament chemical vapor deposition (HFCVD).

Poly silicon and SiO₂ coatings were deposited on dielectric substrate (23 mm * 23 mm * 1.6 mm) using a reactive pulsed magnetron sputtering system [19]. Before putting the substrates into the vacuum chamber, they were ultrasonically cleaned in isopropyl alcohol and acetone for 15 minutes. The vacuum chamber was pumped down to a base pressure of 5.0×10^{-4} Pa. High purity Si (99.99 %) targets (diameter = 0.075 m) were used for the deposition of the coatings. An asymmetric bipolar-pulsed generator (frequency = 100 kHz, pulse width = 2976 ns, positive pulse bias = +37 V) was used to sputter the Si target. The Si layer was deposited from the non-reactive sputtering of the silicon target in Ar + O₂ plasma at a pressure of 1.0×10^{-1} Pa. For the deposition of the Si and SiO₂ layers, the power density was 1.586 W/cm² and the Ar flow rate was 28 sccm. The oxygen flow rate was 4 sccm for the deposition of SiO₂ layer. The substrate bias voltage of approximately -1000 V was applied during the deposition. The thickness of Si and SiO₂ layers were approximately 50 nm each.

C. Growth of graphene and deposition on metal patched substrate

Multilayer graphene was grown on high purity Cu foils using hot filament chemical vapor deposition and the details are explained [20]. The growth of multilayer graphene was confirmed using the micro-Raman spectroscopy technique. Micro-Raman spectroscopy was extensively used to characterize graphene and also to identify the thickness of graphene based on I_{2D}/I_G ratio. The details of the measurement and the instrument set up are explained [20]. The 'D' peak in the Raman spectrum originates from the edge configurations of graphene. The 'D' band known as the 'disorder' or 'detect' mode originates from the edge configurations in graphene, where the planar sheet configuration is disrupted. The G band

or 2D band is an overtone mode of the D band. Fig. 10 shows the Raman spectra of multilayer graphene grown on Cu foil. The low intensity 'D' peak confirms the high quality of graphene. The number of layers of graphene can also be identified by the I_{2D}/I_G ratio. For monolayer graphene, I_{2D}/I_G ratio is greater than or equal to 2 ($I_{2D}/I_G \geq 2$). If the I_{2D}/I_G ratio is less than 2 and greater than 1 ($1 < I_{2D}/I_G < 2$), it represents bi-layer graphene, whereas for multilayer graphene, the I_{2D}/I_G ratio is less than 1 ($I_{2D}/I_G < 1$, Fig. 10). The Raman spectrum confirms the growth of multilayer graphene and it was transferred on Si/SiO₂ coated metal patched substrate using lift off technique [20].

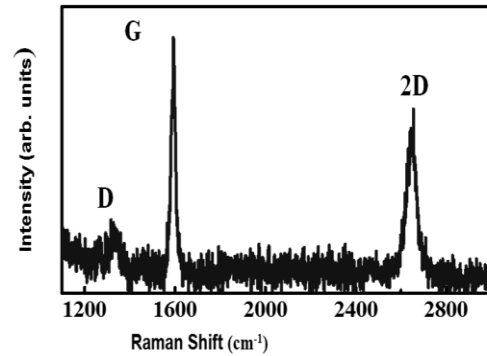


Fig. 10. Raman spectrum of graphene on Cu foil.

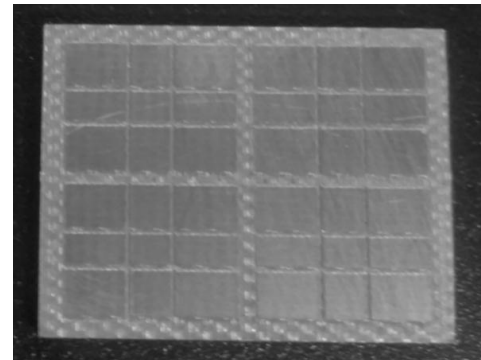


Fig. 11. Fabricated structure of the hybrid radar absorber with graphene and metamaterial

The as-grown multilayer graphene on Cu foil was etched using ferric chloride solution for transferring the graphene on Si/SiO₂/Cu structure. In the present work, multilayer graphene (no of layers, $n=5$) was used to prepare the graphene based metamaterial structure [20]. The total thickness of the fabricated absorber is 1.676 mm. The fabricated model of the absorber is shown in Fig.11.

V. EXPERIMENTAL RESULTS

In order to estimate the absorption characteristics, measurements of the S parameters of the radar absorber were conducted using waveguide system in the frequency range from 9.9 GHz to 10.2 GHz. Due to the difficulty of growing graphene on a large surface area and considering the wave guide measurement constrains, measurement has been done for 9.9 GHz to 10.2 GHz. Wideband absorption property of

graphene based absorber was experimentally proved using graphene nano-flakes [21]. The proposed design in this paper uses graphene in conjunction with metamaterial facilitates ultra-wideband microwave absorption characteristics.

The measurements were also conducted for the fabricated model with and without graphene layer and the result is shown in Fig. 12. It is evident that graphene plays a significant role in radar absorption. The measured absorption decreased in the absence of the graphene layer. The measured results are in good agreement with the simulated results except some variations, which may be attributed to fabrication tolerance. Therefore, the measurement response verifies the claim of using the proposed model of absorber for EM applications.

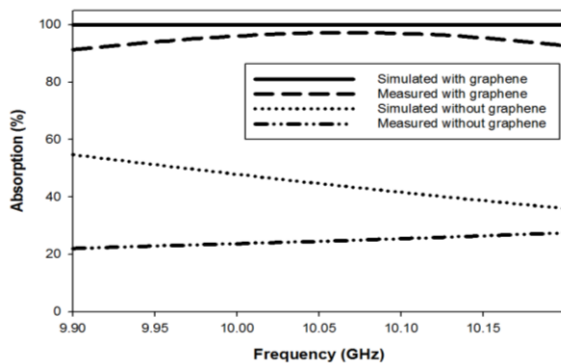


Fig. 12. Measured and simulated absorption characteristics.

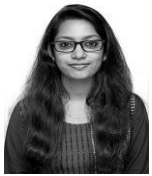
VI CONCLUSION

In this work, a hybrid radar absorber based on graphene and metamaterial was designed and fabricated. The absorption characteristics of the developed radar absorber were analyzed in view of airborne applications. The simulation studies for the proposed radar absorber showed a maximum absorption of 99.93 % in ultra-wideband frequencies ranging from 1 to 60 GHz. The tuning of surface conductivity of graphene sheet was used to control the reflection and transmission of EM waves. The simulated and the measured results show excellent absorption (96.05 %) in the frequency range of 9.9 GHz to 10.2 GHz. The absorption obtained is comparable with the PMA (92 %) which was designed for infrared stealth technology (as mentioned in Section 1, Ref. 6). The proposed metamaterial-graphene hybrid radar absorber is a potential candidate for stealth airborne platforms as it facilitates excellent broadband absorption characteristics and light weight.

REFERENCES

- [1] P. Saville, *Review of Radar Absorbing Materials*, Defence R and D Canada Atlantic, Dartmouth, Canada, pp. 19-22, 2005.
- [2] K. J. Vinoy, and R. M. Jha, *Radar Absorbing Materials from Theory to Design and Characterization*, Kluwer Academic Publishers, Boston, ISBN 0-7923-9753-3, 1996.
- [3] D. Micheli, C. Apollo, R. Pastore and M. Marchetti, "Nano materials in radar absorbing material design using particle swarm optimization and genetic algorithm," *Israel Annual Conference on Aerospace Sciences*, 2007.

- [4] H. Wang, D. Nezich, J. Kong and T. Palacios, "Graphene frequency multipliers," *IEEE Electron Device Letters*, vol. 30, pp. 547-549, 2009.
- [5] C. M. Watts, X. Liu and W. J. Padilla, "Metamaterial electromagnetic wave absorbers," *Advances optical materials*, Vol. 24, pp. 98-120, May. 2012.
- [6] J. Kim, K. Han and J. W. Hahn, "Selective dual-band metamaterial perfect absorber for infrared stealth technology," *Scientific Reports*, June. 2017.
- [7] H. Jeong and S. Lim, "Broad band frequency- reconfigurable metamaterial absorber using switchable ground plane," vol. 8, no. 9226, 2018.
- [8] K. S. L. Al-badri, "Electromagnetic broad band absorber based on metamaterial and lumped resistance," *Science Direct*, Mar. 2018.
- [9] K. Iwaszczuk, A. C. Strikwerda, K. Fan, X. Zhang, R. D. Averitt and P. U. Jepsen, "Flexible metamaterial absorbers for stealth applications at terahertz frequencies," *Optics Express*, vol. 20, pp. 635-643, 2012.
- [10] H. Huang, H. Xia, W. Xie, Z. Guo, H. Li and D. Xie, "Design of broadband graphene-metamaterial absorbers for permittivity sensing at mid-infrared regions," *Scientific Reports*, vol. 8, no. 4183, 2018.
- [11] B. Wu, H. M. Tuncer, M. Naeem, B. Yang, M. T. Cole, W. I. Milne, and Y. Hao, "Experimental demonstration of a transparent graphene millimetre wave absorber with 28% fractional bandwidth at 140 GHz," *Scientific Reports*, vol. 4, Feb. 2014.
- [12] S. He and T. Chen, "Broadband THz absorbers with graphene-based anisotropic metamaterial films," *IEEE Transactions on Terahertz Science and Technology*, vol. 3, no. 6, pp.757 – 763, Oct. 2013.
- [13] J. L. Wallace, "Broad-band magnetic microwave absorbers: Fundamental limitations," *IEEE Transactions on Magnetics*, vol. 29, no. 6, pp. 4209-4214, Nov. 1993.
- [14] X. Huang, Z. Ha and P. Liu, "Graphene based tuneable fractal Hilbert curve array broadband radar absorbing screen for radar cross section reduction," *AIP Advances*, vol. 4, Nov. 2014.
- [15] Y. Jang, M. Yoo and S. Lim, "Conformal metamaterial absorber for curved surface," *Optics Express*, vol. 21, no. 20, Oct. 2013.
- [16] Y. W. Son, M. L. Cohen and S. G. Louie, "Energy gaps in graphene nanoribbons," *Physical Review Letters*, vol. 97, no. 21, Nov. 2006.
- [17] M. Bozzi, L. Pierantoni and S. Bellucci, "Applications of graphene at microwave frequencies," *Radio Engineering*, vol. 24, no. 3, Sept. 2015.
- [18] G. Deng, T. Xia, J. Yang and Z. Yin, "Graphene based broadband terahertz metamaterial modulator," *Journal of Electromagnetic Waves and Applications*, vol. 31, no. 18, pp. 1-9, Jan. 2017.
- [19] H. C. Barshilia and K. S. Rajam, "Surface coating and technology," vol. 201, Issue. 6, pp. 2109-38184, 2006.
- [20] N. Selvakumar, B. Vadivel, D. V. S. Rao, S. B. Krupanidhi and H. C. Barshilia, "Controlled growth of high-quality graphene using Hot filament chemical vapour deposition," *Applied Physics A*, vol. 122, no. 11, ISSN 0947-8396, Nov. 2016.
- [21] X. Huang, K. Pan and Z. Hu, "Experimental demonstration of printed graphene nano-flakes enabled flexible and conformable wideband radar absorbers," *Scientific Reports* 6, Dec. 2016.



Ms. Delme Winson, is currently working as a Project Assistant at Centre for Electromagnetics (CEM), CSIR-NAL, Bangalore. She obtained her M. Tech in Electronics and Communication Engineering from Cochin University of Science and Technology, Kerala. She obtained her B. Tech (ECE) degree in 2015, from University of Calicut, Kerala. Her research interests include metamaterials and radar absorbers, and low observable coatings.



Dr. Balamati Choudhury is working as a Scientist at Centre for Electromagnetics of CSIR-National Aerospace Laboratories, Bangalore, India. Her active areas of research and teaching interests are in the domain of: Soft Computing Techniques in Electromagnetic Design and Optimization, Computational Electromagnetics for Aerospace Applications, Metamaterial Design Applications, RF and Microwaves. She was recipient of ICCCES/ Outstanding Young Investigator Award, USA for the year 2016-2017 for her contributions in Metamaterial Science. Dr. Balamati has authored or co-authored over 190 scientific research papers and technical reports, besides two books, five Springer Briefs and three book chapters. The book entitled: Soft Computing in Electromagnetics: Methods and Applications have been published by the Cambridge University Press, Cambridge, UK (2015). Another Book "Metamaterial Inspired Electromagnetic Applications: Role of Intelligent Systems" has been published by Springer, Singapore. She was the author of five Springer Briefs published by Springer, Germany which covers all the cutting edge technologies such as Terahertz technology, invisibility cloaking and HF ray based methods for space applications. She is also an Asst. Professor of the Academy of Scientific and Innovative Research (AcSIR), New Delhi.



Dr. N. Selvakumar received the M. Sc degree in Materials Science from Madurai Kamaraj University, India in 2003 and Ph. D degree in Materials Science from the Indian Institute of Science, Bangalore, India in 2017. Since September 2004, he has been with the Surface Engineering Division, CSIR-National Aerospace Laboratories, Bangalore, where he was a Trainee, became a Junior Scientist in 2008 and Scientist in 2011. His current research interests include optical coatings, nanostructured thin films, nanomaterials synthesis and metamaterials. He is a Life Member of Solar Energy Society of India, Materials Research Society of India and Indian Vacuum Society. He has received the GC Jain Best thesis award from Materials Research Society of India, in 2019. He was the recipient of CSIR Young Scientist Award in 2014 and NAL Young Scientist Award in 2013 for his contributions to the field of solar energy conversion using carbon nanotubes and graphene. He has published more than 30 papers in the peer-reviewed International Journals.



Dr. Harish Barshilia works as Chief Scientist & Head of the Department at Surface Engineering Division, CSIR-National Aerospace Laboratories, Bangalore, India. Concurrently, he is Professor of Physical Sciences at AcSIR, New Delhi. His broad areas of research interests include: Nanoscience and Nanotechnology, Solar Energy, Surface Engineering, Optical Coatings, 1-D & 2-D Materials, PVD Coatings, etc. He has published 180 SCI journal papers, 3 review articles, 30 conference proceeding papers and 4 book chapters. Dr. Barshilia has also authored 5 World, 3 US and 12 Indian Patents and has delivered 95 invited lectures.



Dr. Raveendranath U. Nair is the Senior Principal Scientist and Head of Centre for Electromagnetics (CEM), CSIR-NAL Bangalore, India. He is actively involved in a variety of fields pertaining to "Electromagnetics for Aerospace Applications". These activities include electromagnetic design and analysis of radomes, design and development of FSS based structures for airborne platforms, radar cross section (RCS) studies, design and development of artificially engineered materials etc. He has contributed significantly to the various radome programs in India. Dr. R U Nair has authored/co-authored over 200 research publications including peer reviewed journal papers, symposium papers and technical reports. He has co-authored a chapter in a book "Sensors

Update" published by Wiley-VCH, Germany, in 2000. The electromagnetic (EM) material characterization techniques developed for his doctoral work were included in the section "Perturbation Theory" in RF and Microwave Encyclopedia (Vol. 4) published by John-Wiley & Sons, USA in 2005. He has published Springer Briefs entitled "Electromagnetic Characterization Techniques for Metamaterials" in 2017 and "Electromagnetic Performance Analysis of Graded Dielectric Inhomogeneous Radomes" in 2018 respectively. He is also a Professor of the Academy of Scientific and Innovative Research (AcSIR), New Delhi.