A Compact Dual-Band Antenna Using Hexagonal Complementary Split Ring Resonator

Manish Mathew Tirkey and Anjini Kumar Tiwary

Abstract – **This work illustrates a novel design of metamaterial inspired structure on miniaturization of microstrip patch antenna. The proposed structure consists of a hexagonal microstrip patch antenna loaded with two hexagonal complementary split ring resonator unit cells etched in the ground plane along with a shortening pin. The proposed dual-band antenna with resonances at 3.394 GHz and 4.852 GHz possess the advantages of having simple and miniaturized structure, good impedance matching and VSWR with very low return loss at both resonances. The overall dimension of the proposed antenna is 0.22λ_0 x 0.22λ_0. Also, the electromagnetic characteristics of the resulting composite medium were evaluated from the simulated complex scattering parameters to demonstrate the extant of metamaterial.**

Keywords – **Hexagonal Complementary Split Ring Resonator (HCSRR), Metamaterial, Compact Microstrip Antenna.**

I. INTRODUCTION

With the evolution in the technology, the major restraints of the antenna include size, weight, cost, performance, power and ease of installation, which gives rise to the need for low-profile and compact antennas in both the military and commercial spheres. Microstrip patch antennas [1], [2] have profound its importance for designing such antennas. One of the very basic method for size reduction is to use a high permittivity ($\boldsymbol{\varepsilon_r}$) or artificial dielectric substrate [3] but with the increase in $\boldsymbol{\varepsilon_r}$, surface waves also increases resulting in increased impedance mismatch loss. Some of the most popular techniques [4] to reduce antenna active area are to use slots and some topologically based miniaturization [5], fractal structures [6], shortening plates or shortening pins (vias) [7], [8]. Variation in the position of via loaded in the antenna results in fine tuning of voltage null.

With the advent of metamaterials (MTMs) [9-12], an arrangement of artificial structural elements engineered to achieve advantageous and unusual properties, a new window appears with tremendous capabilities of electromagnetic (EM) applications. Since the first experimental demonstration of left handed material in 2000 by Smith *et al.* [13], a lot of research have been investigated for antenna miniaturization taking the advantages of unique characteristics offered by MTMs. Use of zeroth order resonator [14], [15], coplanar waveguide structures [16-18] with complementary split ring resonator (CSRR) etched on the ground plane results in highly compact antennas.

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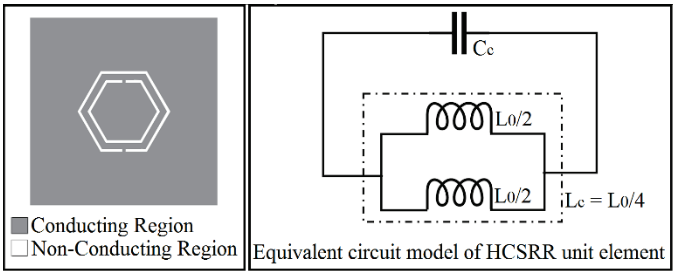


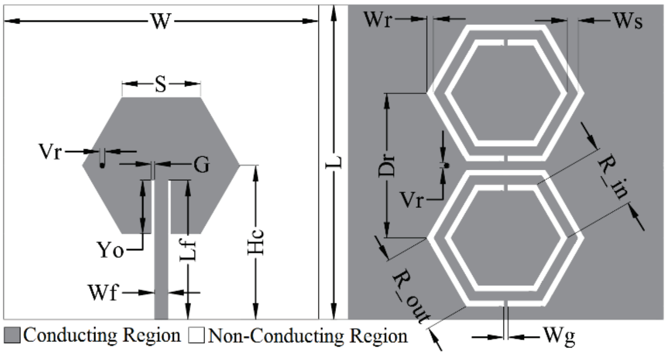
Fig. 1. The unit element of HCSRR with its equivalent circuit model

In [19], miniaturized antenna has been demonstrated by placing a CSRR horizontally between the patch and the ground plane but at the cost of increased thickness. Dual-band antennas with CSRRs etched in the ground plane can provide a great reduction in the overall size of the antenna [20-25].

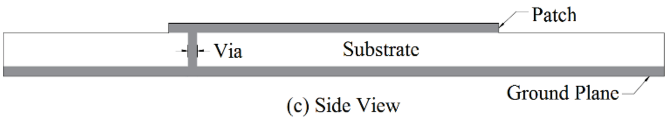
In this paper, the design, fabrication and characterization of a compact hexagonal patch antenna loaded with two HCSRR unit elements (UEs) in the ground plane along with a via is presented. The designed dual-band antenna resonates at frequencies 3.394 GHz and 4.852 GHz with good antenna characteristics. In the proposed design, the use of via is of great importance for obtaining a good impedance match at both resonances. Fig. 1 shows the UE of HCSRR with its equivalent circuit model [26]. The EM properties of the resulting composite medium are retrieved from simulated complex S-parameters using Kramers–Kronig relations [27-29]. The lower resonance at 3.394 GHz has following applications: electronic communication such as mobile and fixed broadband, International Mobile Telecommunications for a defined group of countries around the world, but with omissions including the United States, Canada, and Latin America along with many countries in Asia such as India and China. The higher resonance at 4.852 GHz has following applications: Radio Astronomy Service worldwide, TV broadcast stations and telecommunication service provider. Thus, providing application in both S- and C- band simultaneously. All the structures are simulated in the CST Studio Suite using transient solver based on the finite integration technique. Then the fabrication and measurement of the proposed antenna is carried out to prove the validity of the design.

II. ANTENNA DESIGN

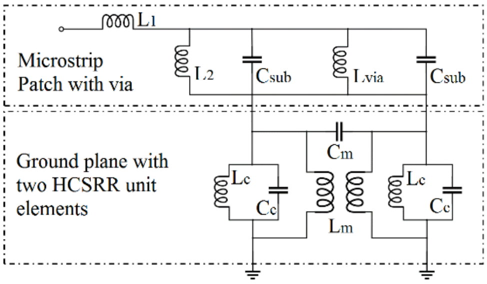
Fig. 2 shows different views of the proposed antenna structure along with its equivalent circuit model which employs a simple conventional hexagonal microstrip patch designed on a 1.6 mm thick FR-4 substrate having dielectric constant of 4.4 and loss tangent of 0.016 with 0.035 mm thick copper trace.



(a) Top View (b) Bottom View



(c) Side View



(d) Equivalent Circuit Model

Fig. 2. Proposed antenna: (a) top view, (b) bottom view, (c) side view and (d) equivalent circuit model

The dimensions of the conventional hexagonal patch have been calculated from the design equations from [1], [2]. The microstrip inset feed is given in the patch to provide a better impedance match. This hexagonal patch antenna resonates at 8.3 GHz. The concept of CSRR has been explored to achieve a dual band performance.

By embedding two HCSRRs in the ground plane, two different resonances are observed at 2.34 GHz and 4.84 GHz after optimizing the position, width and size of the resonating ring and by varying the number of HCSRR slots in the ground plane, in order to have the optimum impedance matching, bandwidth and reflection coefficient. A shift in the frequency to lower values is observed due to HCSRR loading and the return loss is found to be optimum at second resonance with very good impedance matching. Both the bands are in control of the CSRRs being used in the ground plane and both the frequencies can be adjusted to certain level by optimizing the CSRRs.

However, the return loss is increased in the first resonance and impedance matching is disturbed. In order to overcome this, a shunt inductance is formed by introducing a via at the left edge of the hexagonal patch which joins the ground plane to the patch and shifts the first resonance to 3.394 GHz by giving a bypass. The size and the position of via are adjusted in order to decrease impedance mismatch loss, thus forming a compact dual-band antenna. Via in the proposed structure plays very important role to maintain return loss and antenna impedance. Lower HCSRR is major reason for resonance at 4.852 GHz. Upper HCSRR & via altogether maintains good resonance at 3.394 GHz. Both HCSRRs are kept just to maintain simplicity in both synthesis and maintain optimization cost.

In the optimized MTM inspired structure, the geometrical parameters of the hexagonal patch are S = 5 mm, Wf = 0.85 mm, Lf = 8.85 mm, Yo = 3.4 mm, G = 0.2 mm and Hc = 9.78 mm. The physical dimensions of HCSRR UE are R_out = 5 mm, R_in = 3.9 mm, Wr = 0.4 mm, Ws = 0.7 mm, Wg = 0.3 mm. The center to center separation between two HCSRR UEs is Dr = 9.22 mm. The diameter of a via is Vr = 0.3 mm placed at 3.75 mm away from the centre of the hexagonal patch. After miniaturization of the proposed antenna, the overall dimensioncomes out to be 20 mm x 20 mm x 1.6 mm.

III. STUDY OF HCSRR

To reveal the EMproperties, such as the complex permeability (μ) and the permittivity (ε), the S-parameter retrieval method using the Kramers–Kronig relations are used. The S-parameters extracted from the actual MTM UE structure, shown in Fig. 3, are imported into MATLAB and the parameter extraction is done by developing a MATLAB script for Kramers–Kronig relations and equations given in [26-28], in order to extract accurate EMbehaviour of desired MTM UE. The extracted values at different frequencies describe MTM's propagation profile at that frequency.To extract these material parameters, appropriate boundary conditions, assumptions and excitations are assigned to the different surface of the three-dimensional UE to simulate the MTM. The extracted real and imaginary values of complex permeability (μ), permittivity (ε), refractive index (n) and impedance (z) are shown in Fig. 4 showing the single negative (SNG) behaviour (-ε) of HCSRR.

IV. RESULTS AND DISCUSSION

Fig. 5 shows fabricated prototype of the proposed antenna. The simulated and experimental return loss characteristics of the proposed antenna along with the return loss characteristics of the conventional hexagonal patch antenna with and without HCSRRs loading are shown in Fig. 6 indicating the shift in resonances to lower values. The conventional hexagonal patch antenna has –10 dB impedance bandwidth from 8.33 to 8.45 GHz. The loading of two HCSRR UEs produced two resonances with the bandwidth of 3.35–3.42 GHz and 4.79–4.90 GHz.

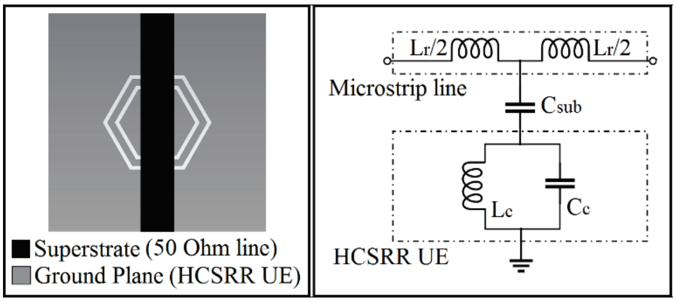


Fig. 3. Lumped equivalent circuit (right) of HCSRR UE with a 50 Ω microstrip line (left)

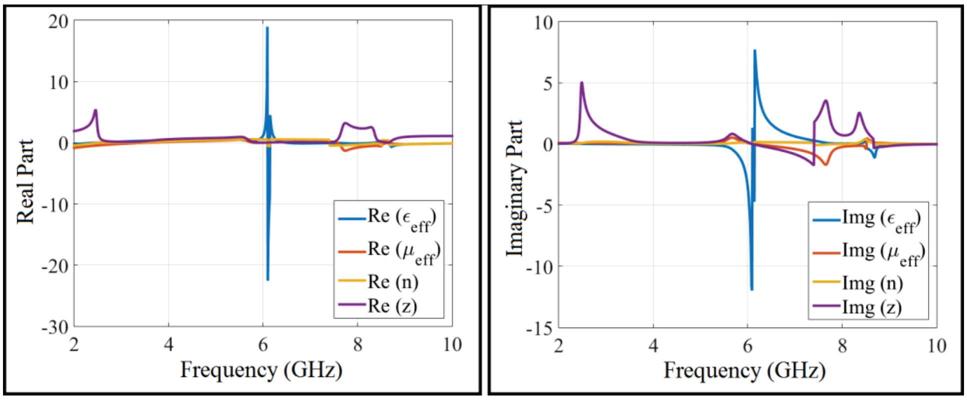


Fig. 4. Extracted electromagnetic parameters of HCSRR UE

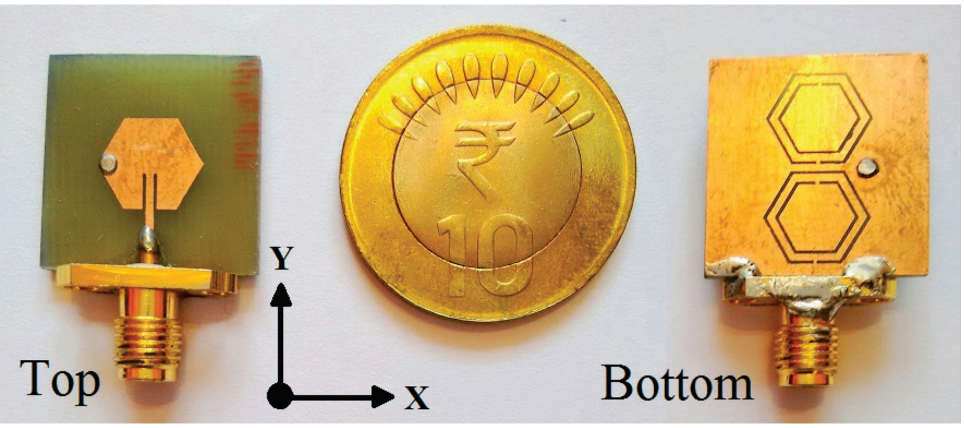


Fig. 5. Fabricated prototype (top and bottom view) of the proposed antenna

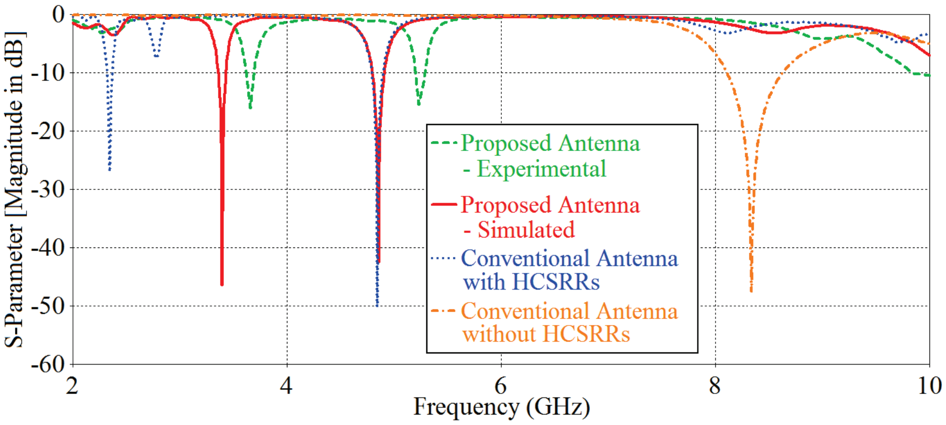


Fig. 6. S-parameter characteristics of the proposed antenna

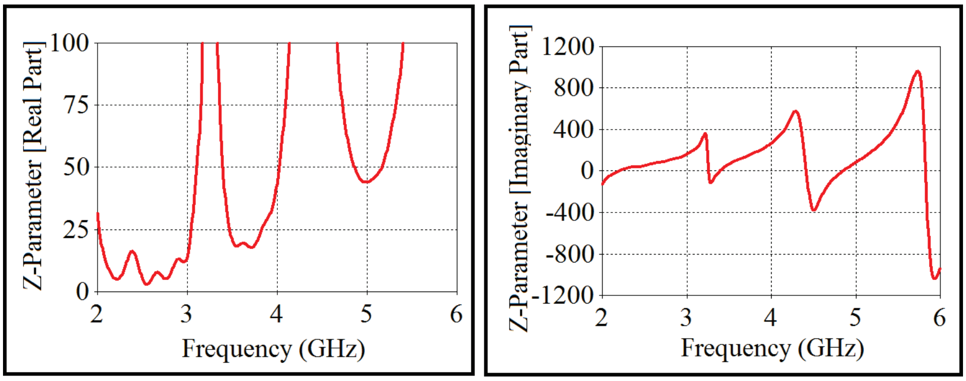
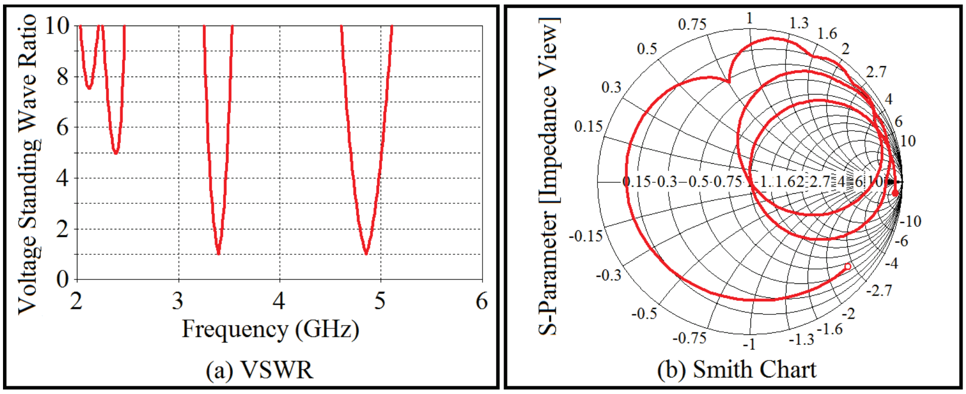


Fig. 7. Z-parameter characteristics of the proposed antenna



(a) VSWR

(b) Smith Chart

Fig. 8. (a) VSWR and (b) Smith chart of proposed antenna

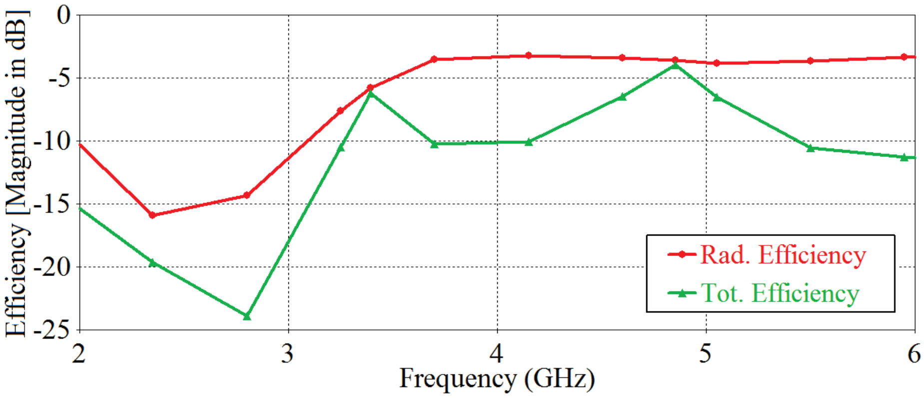
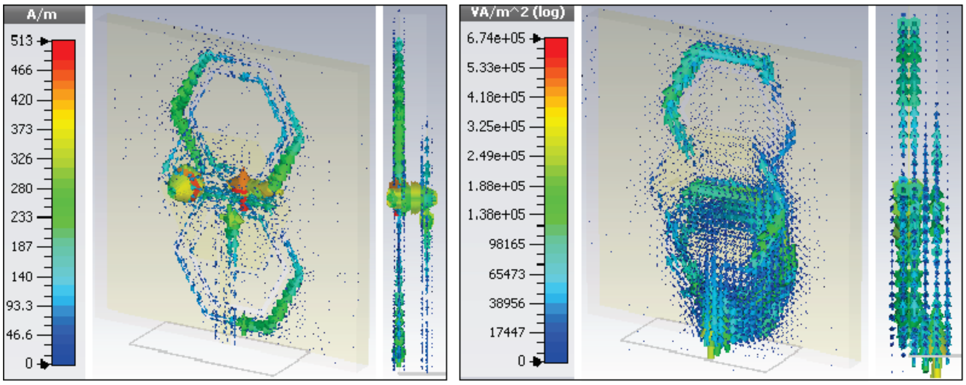
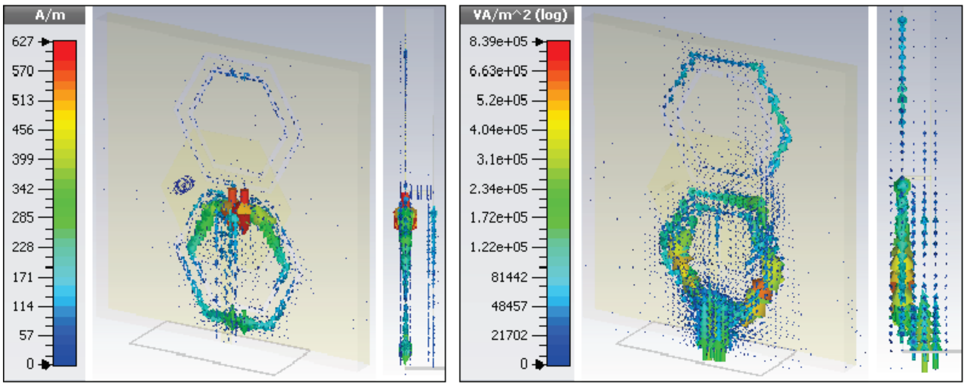


Fig. 9. Antenna efficiencies of proposed antenna.



(a) Surface current at 3.394 GHz and Power flow at 3.394 GHz



(b) Surface current at 4.852 GHz and Power flow at 4.852 GHz

Fig. 10. Perspective (left side) & side view (right side) of surface current and power flow of proposed antenna at (a) 3.394 GHz & (b) 4.852 GHz

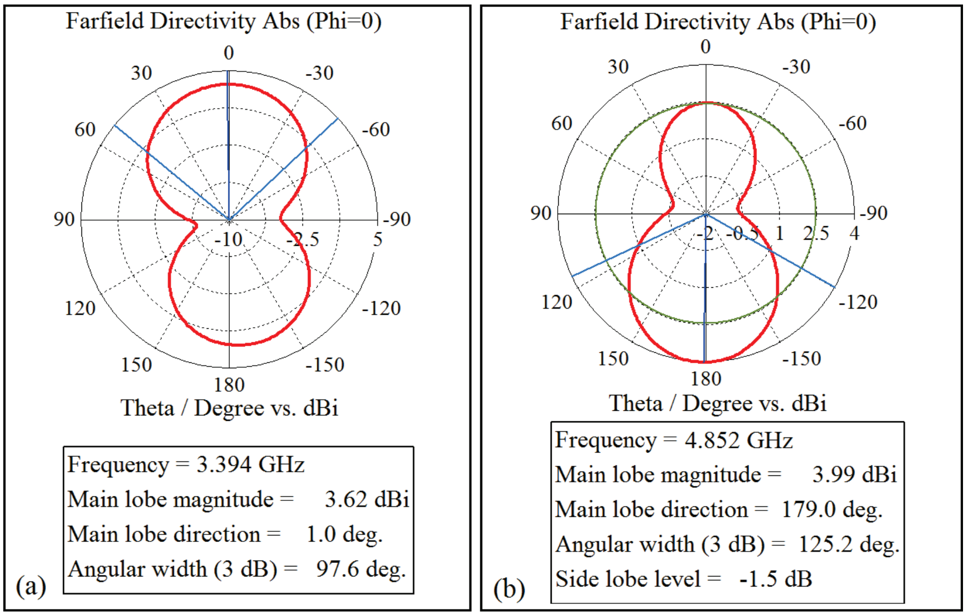


Fig. 11. Directivity of proposed antenna at (a) 3.394 GHz & (b) 4.852 GHz

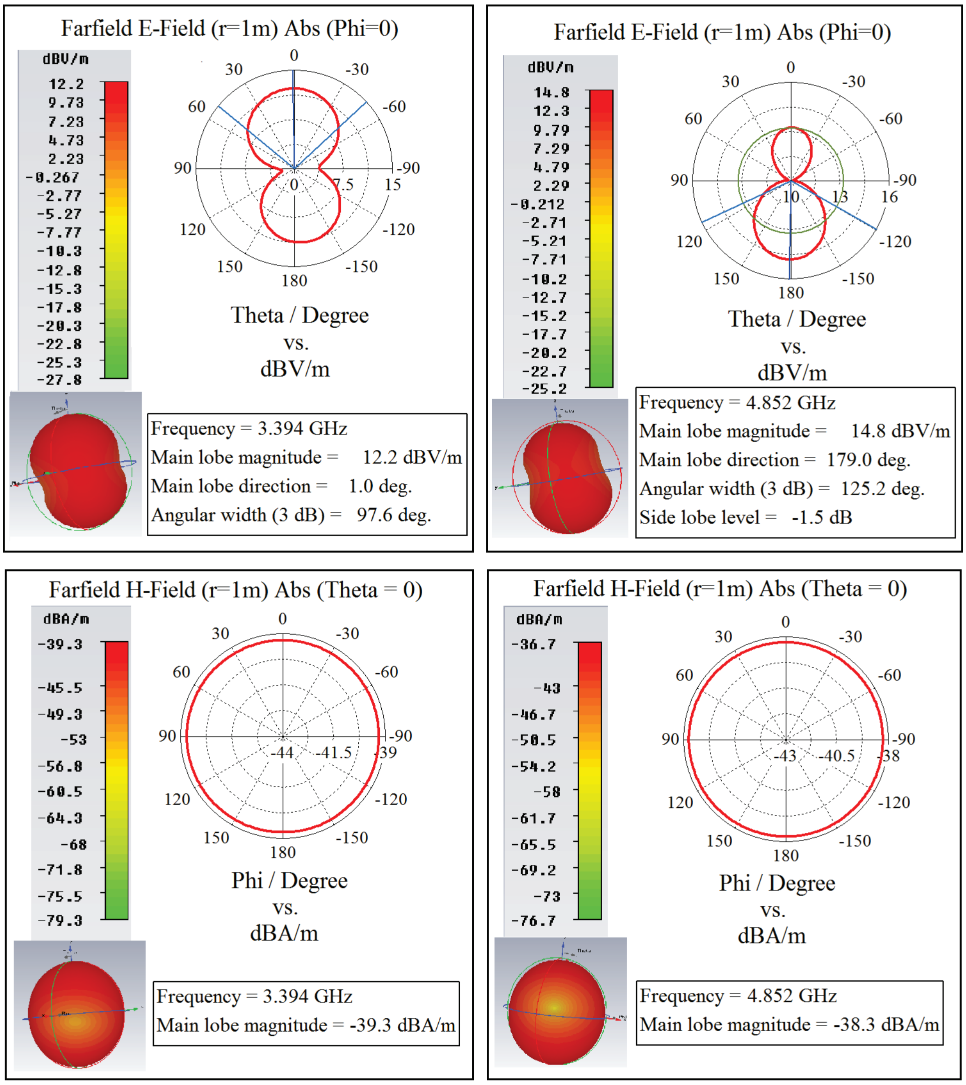


Fig. 12. Radiation pattern characteristics of proposed antenna

TABLE 1
COMPARISON OF THE PROPOSED WORK WITH OTHER PUBLISHED MTM INSPIRED DUAL BAND ANTENNA

Design	**Overall Antenna Size**	**Frequency**	**Return Loss**	**Substrate Height**	**Feeding Technique**
Proposed structure	20 mm x 20 mm	3.394 GHz	-46.45 dB	1.6 mm	Microstrip
		4.852 GHz	-43.43 dB		
[22]	17.7 mm x 17.5 mm (Only patch dimension)	3.73 GHz	-19.4 dB	1.5 mm	Microstrip
		5.25 GHz	-17.8 dB		
[23]	17.7 mm x 17.5 mm (Only patch dimension)	3.87 GHz	-22.5 dB	1.5 mm	Microstrip
		5.46 GHz	-31.6 dB		
[24]	32 mm x 24 mm	2.46 GHz	-26.5 dB	1.59 mm	CPW
		5.50 GHz	-21.0 dB		
[25]	36 mm x 36 mm	2.76 GHz	-18.7 dB	3 mm	Coaxial
		5.23 GHz	-15.0 dB		
[26]	50 mm x 50 mm	2.52 GHz	-27.5 dB	1.524 mm	Coaxial
		3.74 GHz	-11.5 dB		

A nearly 50 Ω of Z-Parameter and approximately unity voltage standing wave ratio (VSWR) at both the resonances illustrate optimum impedance matching as shown in Figs. 7 and 8*a*, respectively. Similar behavior is verified with the Smith chart plot of Fig. 8*b*. As far as antenna impedance matching is concerned, the proposed structure is perfectly matched by using the concept of inset feed in the radiating plane and concept of metamaterial in the ground plane as both are major reason for antenna impedance variation. Via in the proposed structure plays a very important role to maintain return loss and antenna impedance.Finally, proposed antenna is optimized to desired requirements.

Besides these some other characteristics of the proposed antenna have been investigated because these are the necessary parameters to ensure proper impedance matching and optimum return loss of an antenna but are not sufficient because losses will occur in practical use affecting power transmission. The result of the radiation and total efficiencies shown in Fig. 9. The vector surface current distribution and power flow at 3.394 GHz and 4.852 GHz are given in Fig. 10 to illustrate the radiation mechanism of the proposed antenna.

It is seen that the resonant surface current concentrates more on the lower HCSRR at 4.852 GHz, while the surface current mainly resides on the upper HCSRR and via at 3.394 GHz. This indicates that the lower and higher radiation modes of the antenna are contributed by both the HCSRRs and via. This signifies that the proposed structure has obviously satisfying directional properties. Fig. 11 shows directivity of the proposed antenna indicating good directional properties at both radiating modes.

The 2D & 3D E- & H- plane radiation patterns at both the radiating modes are shown in Fig. 12, indicating that the structure radiates in a dipolar fashion and there is no radiation blockage because the ground plane itself is radiating at both radiating modes with nearly omnidirectional characteristics. Since the size of the proposed antenna is small with MTM being used in the ground plane, it causes an increase in backward wave level. This results in the reduction of the front to back ratio of the patch antenna. The experimental results are found to be in good agreement with respect to the simulation. Some discrepancies in the experimental result may be attributed to the manufacturing tolerances and the variation in material characteristics of the sample supplied. Table 1 shows the comparison of the proposed antenna with other published MTM inspired dual band antennas. The comparison validates the compactness of the proposed work significantly.

V. CONCLUSION

A simple and compact hexagonal patch employing two HCSRR slots in the ground plane along with a shortening pin to create dual band antenna at resonant frequencies 3.394 GHz and 4.852 GHz have been designed and fabricated. Both of the resonances exhibit optimum impedance mismatch loss and return loss with nearly 50 Ω of Z-parameter and approximately unity VSWR. Similar behaviour is verified with the Smith chart plot. The HCSRR UE is investigated for knowing its EMbehaviour and the HCSRRs being used in the ground plane is found to have SNG characteristics proving itself as a MTM. Also, lumped equivalent circuit of the proposed antenna and MTM has been discussed.

REFERENCES

[1] C.A. Balanis, *Antenna Theory Analysis and Design*, Hoboken, NJ, USA: Wiley, 2005.

[2] N. Kushwaha and R. Kumar, “Design of Slotted Ground Hexagonal Microstrip Patch Antenna and Gain Improvement with FSS Screen”, *Progress in Electromagnetic Research B*, vol. 51, pp. 177–199, 2013.

[3] K. Skrivervik, J.F. Zürcher, O. Staub, and J.R. Mosig, “PCS Antenna Design: The Challenge of Miniaturization”, *IEEE*

Antennas Propagation Magazine, vol. 43, no. 4, pp. 12–27, 2001.

[4] M.U. Khan, M.S. Sharawi, and R. Mittra, "Microstrip Patch Antenna Miniaturization Techniques: A Review", *IET Microwaves Antennas Propagation*, vol. 9, pp. 913–922, 2015.

[5] J. Oh and K. Sarabandi, "A Topology-Based Miniaturization of Circularly Polarized Patch Antennas", *IEEE Transactions Antennas Propagation*, vol. 61, no. 3, pp. 1422–1426, 2013.

[6] A. Reha, A.E. Amri, O. Benhmammouch and A.O. Said, "Fractal Antennas: A Novel Miniaturization Technique for Wireless Networks", *IEEE Antennas Propagation Magazine*, vol. 2, no. 5, pp. 165–193, 2014.

[7] M. Yang, Z.N. Chen, P.Y. Lau, X. Qing, and X. Yin, "Miniaturized patch antenna with grounded strips," *IEEE Transactions Antennas Propagation*, vol. 63, no. 2, pp. 843–848, 2015.

[8] M. Hosseini, D. M. Klymyshyn, G.Wells, and X. Liu, "Short and Open Circuited EBG Resonator Antennas: Miniaturization with a Shorting Plate and Dielectric Loading", *IEEE Transactions Antennas Propagation*, vol. 63, no. 10, pp. 4305–4314, 2015.

[9] C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. Hoboken, NJ, USA: Wiley, 2006.

[10] Y. Dong and T. Itoh, "Metamaterial-Based Antennas", *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2271–2285, 2012.

[11] Y. Dong, H. Toyao, and T. Itoh, "Design and Characterization of Miniaturized Patch Antennas Loaded with Complementary Split-Ring Resonators", *IEEE Transaction Antennas Propagation*, vol. 60, no. 2, pp. 772–785, 2012.

[12] S. Kumar and D.K. Vishwakarma, "Miniaturization of Microstrip Patch Antenna Using an Artificial Planar Magneto-Dielectric Meta-Substrate", *IET Microwaves Antennas Propagation*, vol. 10, pp. 1235–1241, 2016.

[13] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite Medium with Simultaneously Negative Permeability and Permittivity", *Physics Review Letters*, vol. 84, no. 18, pp. 4184–4187, 2000.

[14] M.S. Majedi and A.R. Attari, "A Compact and Broadband Metamaterial-Inspired Antenna", *IEEE Antennas Wireless Propagation Letters*, vol. 12, pp. 345–348, 2013.

[15] G.K. Singh, R.K. Chaudhary, and K.V. Srivastava, "A Compact Zeroth Order Resonating Antenna Using Complementary Split Ring Resonator with Mushroom Type of Structure", *Progress in Electromagnetics Research Letters*, vol. 28, pp. 139–148, 2012.

[16] L.M. Si, W. Zhu, and H.J. Sun, "A Compact, Planar, and CPW-Fed Metamaterial-Inspired Dual-Band Antenna", *IEEE Antennas Wireless Propagation Letters*, vol. 12, pp. 305–308, 2013.

[17] J.Y. Siddiqui, C.Saha, and Y. M.M. Antar, "A Novel Ultrawideband (UWB) Printed Antenna with a Dual Complementary Characteristic", *IEEE Antennas Wireless Propagation Letters*, vol. 14, pp. 974–977, 2015.

[18] W.T. Li, Y.Q. Hei, W. Feng, and X.W. Shi, "Planar Antenna for 3G/Bluetooth/WiMAX and UWB Applications with Dual Band-Notched Characteristics", *IEEE Antennas Wireless Propagation Letters*, vol. 11, pp. 61–64, 2012.

[19] R.O. Ouedraogo, E.J. Rothwell, A.R. Diaz, K. Fuchi, and A. Temme, "Miniaturization of Patch Antennas Using a Metamaterial-Inspired Technique", *IEEE Transaction Antennas Propagation*, vol. 60, no. 5, pp. 2175–2182, 2012.

[20] K. Saurav, D. Sarkar, and K.V. Srivastava, "Dual-Polarized Dual-Band Patch Antenna Loaded with Modified Mushroom Unit Cell", *IEEE Antennas Wireless Propagation Letters*, vol. 13, pp. 1357–1360, 2014.

[21] Y.H. Xie, C. Zhu, L. Li, and C. H. Liang, "A Novel Dual-Band Metamaterial Antenna Based on Complementary Split Ring Resonators", *Microwave Optical Technology Letters*, vol. 54, pp. 1007–1009, 2012.

[22] A. Gupta, S.K. Sharma, and R.K. Chaudhary, "A Compact Dual-Mode Metamaterial-Inspired Antenna Using Rectangular Type CSRR", *Progress in Electromagnetics Research C*, vol. 57, pp. 35–42, 2015.

[23] B. Zong, G. Wang, C. Zhou, and Y. Wang, Compact low-profile dual-band patch antenna using novel TL-MTM structures, *IEEE Antennas Wireless Propagation Letters*, vol. 14, pp. 567–570, 2015.

[24] T.Cai, G.M. Wang, and J.G. Liang, "Analysis and Design of Novel 2-D Transmission-Line Metamaterial and its Application to Compact Dual-Band Antenna", *IEEE Antennas Wireless Propagation Letters*, vol. 13, pp. 555–558, 2014.

[25] M.S. Majedi and A.R. Attari, "Dual-Band Resonance Antennas Using Epsilon Negative Transmission Line", *IET Microwaves Antennas Propagation*, vol. 7, pp. 259–267, 2013.

[26] J. Naqui, M.D. Sindreu, and F. Martín, "Modeling Split-Ring Resonator (SRR) and Complementary Split-Ring Resonator (CSRR) Loaded Transmission Lines Exhibiting Cross-Polarization Effects", *IEEE Antennas Wireless Propagation Letters*, vol. 12, pp. 178–181, 2013.

[27] V. Milosevic, B. Jokanovic, and R. Bojanic, "Effective Electromagnetic Parameters of Metamaterial Transmission Line Loaded with Asymmetric Unit Cells", *IEEE Transactions Microwave Theory Techniques*, vol. 61, no. 8, pp. 2646–2653, 2013.

[28] A.B. Numan and M.S. Sharawi, "Extraction of Material Parameters for Metamaterials Using a Full-Wave Simulator", *IEEE Antennas Propagation Magazine*, vol. 55, no. 5, pp. 202–211, 2013.

[29] D. Cohen, and R. Shavit, "Bi-Anisotropic Metamaterials Effective Constitutive Parameters Extraction Using Oblique Incidence S-Parameters Method", *IEEE Transaction Antennas Propagation*, vol. 63, no. 5, pp. 2071–2078, 2015.