Compact Tri-band Metamaterial Antenna for Wireless Applications

Sheeja K. L.[1], Prasanna Kumar Sahu [1], Santanu Kumar Behera[2] and Nabil Dakhli[3]

[1] Department of Electrical Engineering
National Institute of Technology, Rourkela, Odisha, India.
sheejakl@gmail.com, pksahu@nitrkl.ac.in

[2] Department of Electronics and Communication Engineering
National Institute of Technology, Rourkela, Odisha, India.
prof.s.k.behera@gmail.com

[3]Research Unit of Telecommunication Systems (6Tel) at Sup'Com, Tunisia.

Abstract **─** A novel compact triband coplanar waveguide fed metamaterial antenna is proposed. The left-handed (LH) inductance is provided by two parallel short ended spiral inductors. We achieved pentamodes of resonance consisting of negative modes, zeroth mode and positive modes. The resonance frequency at each of these modes are f_{-2}=1.01 GHz, f_{-1}=2.11GHz, f_0=2.48 GHz, f_{+1}= 3.04 GHz and f_{+2}=3.54GHz with triband functionality obtained at $f_{-2,}$ f_0 and f_{+2} resonances. Gain of the proposed structure at $f_{-2,}$ f_0 and f_{+2} resonances is found to be -3.4993dB, 1.559dB and 1.9515dB respectively. The proposed antenna is measured at Antenna Measurement Facility (AMF) and results were compared with the simulated results. A good agreement between the measured and the simulated results validates the proposed design. The antenna radiates omni-directional waves in the horizontal plane. The proposed antenna serves the criteria for modern multiband wireless applications with an additional feature of increased bandwidth at the zeroth mode. The proposed multiband antenna is suitable for wireless communication applications such as the Global System for Mobile Communications (GSM) 900 in 1.01GHz, Wireless Local Area Network (WLAN) in the 2.48 GHz band (2.459 - 2.4924)GHz of IEEE 802.11b/g ISM band and worldwide interoperability for microwave access (WiMax) standards in the 3.54GHz band (3.491-3.596)GHz of IEEE 802.11a. This proposed antenna is most suitable for precise multiband wireless communication systems which include the mobile and wireless local area network (WLAN) systems due to their large service area.

Index Terms **─** Composite Right/Left Handed Transmission Line, Metamaterials, Omni-directional antennas, Zeroth Order Resonant antenna.

I. INTRODUCTION

Compact antennas with omni-directional radiation patterns are useful for wireless applications. Various antennas such as dipole, monopole [1], cylindrical patch array [2] and planar back-to-back dipole antenna [3, 4] are widely employed for this purpose. However, these antennas are very complicated in structure and their large size needs to be miniaturized in order to meet the demands of portable devices. In recent years, metamaterials have drawn considerable attention for the design of compact antenna and other microwave devices [5-7]. A compact metamaterial antenna with omni-directional radiation patterns serves the above purpose. They are designed to be small in size with additional features to provide multifrequency and multifunctionality bands [8, 9]. However, the ZOR antennas reported in these papers suffered from

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low radiation efficiencies that ranged from 5-50%. In [10], an increased height ZOR antenna was presented with a size of 120 x 49mm. Though efficiency was increased to 25% but gain was only about -0.52 dBi at 7.79 GHz. The Composite Right/Left Handed Transmission Line (CRLH TL) metamaterials using zeroth order resonance (i.e.; inductive and capacitive loadings on a microstrip transmission line) are popular for their inherent multiband property which can be extensively exploited to meet various demands. Another advantage of this CRLH TL is that at zeroth order resonance infinite wavelength is supported. This is due to the CRLH TL's unique property to support a fundamental backward wave (anti parallel group and phase velocities) and zero propagation constant with zero (unbalanced CRLH TL) or finite group velocity (balanced CRLH TL) at a finite frequency [8]. This property is exploited in the miniaturization of antenna size because the frequency at zeroth order resonance is independent of the physical dimensions of the antenna. Also at zeroth mode we have uniform field distribution which maximizes directivity and minimizes dissipative losses. Popular structures that are used for the implementation of the CRLH TL are the microstrip technique based on the most popular Dan Sievenpiper's Mushroom structure [11]. Though it satisfies the LH property, it suffers from a tradeoff between the antenna's size reduction and its bandwidth. Lai et al [12] provided dual mode, dual band features; but bandwidth obtained was only about 0.75%. The peak gain and radiation efficiency of this antenna were 0.87 dBi and 70 % respectively. However small ZOR antennas employing a CRLH resonator made up of two or three cells suffer from a low radiation efficiency and poor gain in the zeroth-order resonant mode [13].

In this paper a compact metamaterial antenna consisting of two unit cells is proposed. In this proposed structure, a high gain of 1.9515dB and bandwidth of 2.964 % at 3.54 GHz along with an efficiency of 82.52 % is obtained. Further, at 2.48 GHz, gain of 1.559 dB and bandwidth of 1.36 % along with an efficiency of 55.31% is obtained. The proposed design exhibits triband, pentamode characteristics which can be used for multiband wireless precise applications [14].

II. CRLH Transmission Line and Shunt Mode Zeroth Order Resonance

A composite right/left handed transmission line structure is obtained by cascading N number of unit cells as shown in Fig. 1(a). The size p of each unit cell is much smaller than the guided wavelength ($p << \lambda_g$), so as to satisfy the effective homogeneity condition in which case the diffraction phenomena will dominate over the scattering phenomena. The dispersion diagram of the CRLH TL is shown in Fig. 1(b). It can be obtained by applying Bloch-Floquet theorem to the CRLH unit cell of Fig. 1(a).

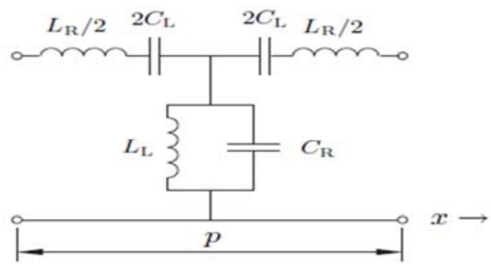

Fig. 1(a). Elemental model of CRLH TL unit cell.

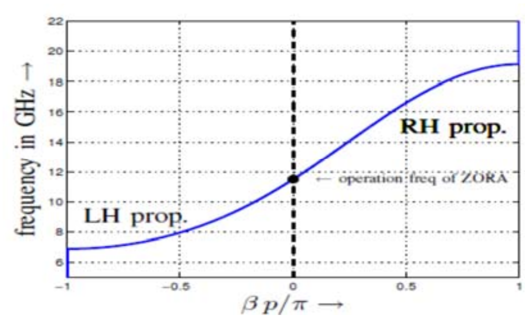

Fig. 1(b). The dispersion diagram for CRLH TL.

The CRLH TL supports a fundamental LH wave (phase advance) at lower frequencies and a RH wave (phase delay) at higher frequencies.

The dispersion relation is given as [15]:

$$\cos[(\beta - j\alpha)p] = 1 - \frac{(\omega^2 - \omega_{se}^2)(\omega^2 - \omega_{sh}^2)}{2\omega^2\omega_R^2}, \quad (1)$$

where,

$$\omega_{se}^2 = \frac{1}{L_R C_L}, \omega_{sh}^2 = \frac{1}{L_L C_R}, \omega_R^2 = \frac{1}{L_R C_R}.$$

Under balanced condition, $\omega_{se} = \omega_{sh} = \omega_0$ and one non-zero frequency point with β=0 is present. This point is referred to as the infinite wavelength point and is determined from either series resonance or shunt resonance of the unit cell of length p, repeating N times, so a CRLH TL of length $L = N * p$ is realized. The CRLH TL is used as a resonator when it is open ended or short ended under the resonance condition,

$$\beta_n = \frac{n\pi}{L}, \qquad (n = 0, \pm 1, \pm 2, ...) \quad (2)$$

where β_n is propagation constant along the TL, L is the total length of the TL, and n is the resonance mode number or resonant index and can be a positive or negative integer and also zero. In case of conventional half wavelength resonant antennas, the propagation constant β^{RH} is always positive, and this leads to positive resonant indices (n=+1, +2 ...). But for LH TL structures β^{LH} are negative, and resonant indices will be negative (n=-1,-2 ...). When β_n=0, there is a non-zero frequency. This property is utilized to create a zeroth order resonator. From these conditions, the resonant modes can be $n = 0, \pm 1, \pm 2, ...$.

Inverting Equation (1) we have

$$\omega(\beta) = \sqrt{\left(\omega_0^2 + \omega_R^2 \sin^2 \frac{p\beta}{2}\right)} + \omega_R \sin\frac{p\beta}{2}. \qquad (3)$$

From the relation given in Equation (3) we can obtain the resonance frequency of the structure and consequently the dispersion diagram.

The inherent dispersion of CRLH structures allows multiband operation. A standard CRLH TL is inherently dual band, due to its four fundamental parameters (L_R, C_R, L_L, C_L) compared to just two parameters (L_R, C_R) in a conventional transmission line.

A CRLH TL based zeroth order resonating antenna is excited either by open circuiting (by a small coupling capacitance C_c) or by short circuiting (by a small shunt inductance) the CRLH structure. In the open circuit case, the resonance occurs at ω_{sh} and therefore the energy is stored only in the shunt (admittance) elements whereas in the short circuited case, the resonance occurs at ω_{se} and therefore the energy is stored only in the series (impedance) elements. But when the structure is balanced, these two frequencies are equal. Hence, the energy stored is determined by the type of termination i.e.; by the type by which the antenna is excited. In this paper, the antenna structure is balanced and is excited by open circuiting by a small coupling capacitance so that its energy will be stored in the shunt elements.

III. METHODOLOGY

The novel CRLH TL based ZOR antenna was implemented using CPW technique. The compact vialess ZOR antenna proposed by Jang et al [16] was designed to operate over a single band although it was simple and easy to fabricate. In this paper the proposed metamaterial antenna is designed to operate over multiband suitable for precise wireless applications especially point to point wireless communication. Coplanar waveguides are uniplanar transmission line structures where the ground plane and the signal trace are placed on the same side of the substrate. The advantage of such a structure is that to get enhanced bandwidth it is more flexible to change the shunt parameters (C_R, L_L) of a CRLH TL. It provides smaller shunt parasitic RH capacitance C_R if the distance between the CPW grounds from the radiating patch is increased and larger shunt LH inductance L_L if the lengths of the short ended spiral inductors are increased. But in case of microstrip technique as the signal trace is separated from the ground plane by a dielectric layer (i.e; by a substrate material), C_R tends to be large. This is because it depends on the capacitance of the host microstrip line to the ground plane. Also here the shunt inductance, L_L is small because the LH inductance provided by the vias is directly proportional to its height, which in turn is restricted by the substrate's height. So in case of microstrips bandwidth enhancement is just about 0.75 % with a low gain of 0.87 dBi [12].

IV. ANTENNA DESIGN

The geometrical model of the proposed compact triband, pentamode metamaterial antenna is shown in Fig. 2(a) and 2(b) with two unit cells. The fabricated prototype is shown in Fig. 2(c). It consists of a single layer substrate of size 29.2mm x 25.4mm x 1.6mm made up of Rogers RT/Duroid 5880 having dielectric constant $\varepsilon_r = 2.2$ and a thickness of 1.6mm. Each unit cell (6mmx7.8mm) consists of symmetrically placed spiral inductors on both sides of the unit cell. The electrical size of the unit cell is $0.1182\lambda_0$ x $0.0645\lambda_0$ x $0.0132\lambda_0$

at 2.48 GHz (n=0 mode). Some of the main features of these spiral inductors being that, firstly, it increases the shunt LH inductance L_L because the length of these spiral inductors is directly proportional to the shunt LH inductance which in turn leads to bandwidth enhancement [12] and secondly, with increase in the length of the inductive stubs, the resonant frequency of ZOR's decreases [13]. Additionally, CRLH TL's has an inherent property to provide multi frequency multi-band resonances. The unit cells or the radiating patch is separated by a small gap of 0.2 mm. This gap provides the series LH capacitance C_L while the magnetic flux produced by the current flow along the radiating patch provides the parasitic series RH inductance L_R. Each unit cell is parallel connected to the two short ended spiral inductors having 5 turns. These spiral inductors of width 0.4mm introduce the LH inductance L_L. The gap between the spiral inductor strips is also equal to 0.4 mm. As the whole CRLH TL structure is excited by open circuiting (with a small coupling capacitance), shunt resonance ω_{sh} initiates, with energy storing taking place in the shunt elements.

When the structure is balanced then the two resonant frequencies ω_{sh} and ω_{se} are identical. Bottom ground is placed to provide an impedance matching of about 42 ohms. Figures 3(a) and 3(e) show the simulated reflection coefficients and VSWR of the proposed antenna respectively. It is observed that a reflection coefficient of -20.2014 dB at the zeroth mode (2.48 GHz) is obtained. Figure 3(a) shows the comparison of the simulated and measured reflection coefficients of the proposed design. A very good agreement between the measured and the simulated results are obtained. The measured reflection coefficient is slightly shifted from that of the simulated one which can be attributed to minor errors in the fabrication of vias or due to improper etching. Figure 3(b) shows the radiation patterns at E-plane (x-z plane) and H-plane (y-z plane) for different operational frequencies. In all these different frequencies, a dumb-bell shaped E-radiation patterns and very good omni-directional H-radiation patterns are obtained. Figure 3(c) shows the 2D gain patterns of the proposed antenna for different operational frequencies. Figures 3(d) shows the 3D gain at each operational frequency. Highest gain of 1.9515 dB is achieved at 3.54 GHz. The simulated radiation efficiency (%) and gain (dB) according to the operating band are presented in Fig. 3(d). In this proposed antenna, a bandwidth of 1.36% and radiation efficiency of 55.31% are achieved at zeroth order resonance of 2.48 GHz with a gain of 1.559 dB. The radiation efficiency is enhanced to approximately 83% at 3.54 GHz but drops to 7% at 1.01 GHz due to a high rise of conductivity loss. Figs. 5(a, b) and 6(a, b) show the measured radiation patterns at 2.528 GHz and 3.684 GHz respectively. Since, radiation pattern measurements were undertaken with the test antenna mounted onto an aluminum plate fixture which was aligned to a reference wideband horn antenna so there is a slight variation in the simulated and measured radiation patterns. The antenna is tested at Antenna Measurement Facility (AMF), Space Application Centre, ISRO Ahmedabad. Real time flight model testing was carried out in an anechoic chamber shown in Fig. 4. Table1 shows the performance characteristics of the proposed antenna with substrate, RT Duroid (ε_r=2.2), no. of unit cells = 2 and no. of resonating modes/bands = 3. All simulations were carried out using Ansoft HFSS using Driven set up. No. of passes used is 6 and convergence ratio (Delta S): 0.02 is the maximum change in the magnitude of the S-parameters between two consecutive adaptive passes. The antenna is excited with wave port excitations. Measurements were undertaken with Agilent E8363B Network Analyzer.

A. Antenna Geometry

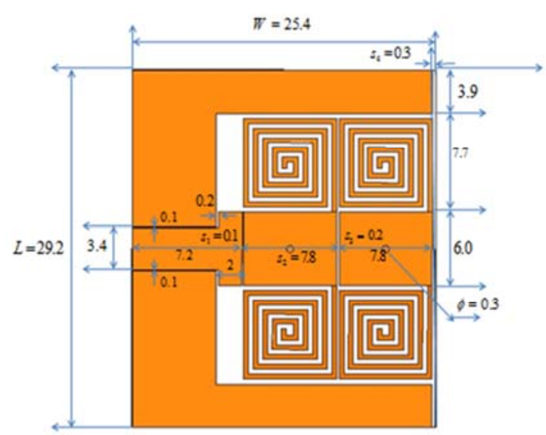

Fig. 2(a). Geometrical model of the proposed triband antenna (Top Patch with two unit cells).

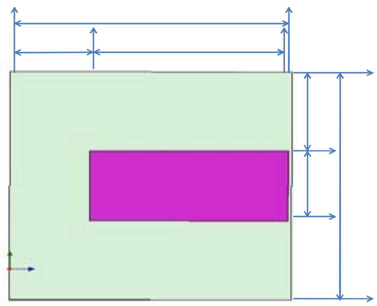

Fig. 2(b). Geometrical model of the proposed triband, pentamode antenna (with two unit cells).

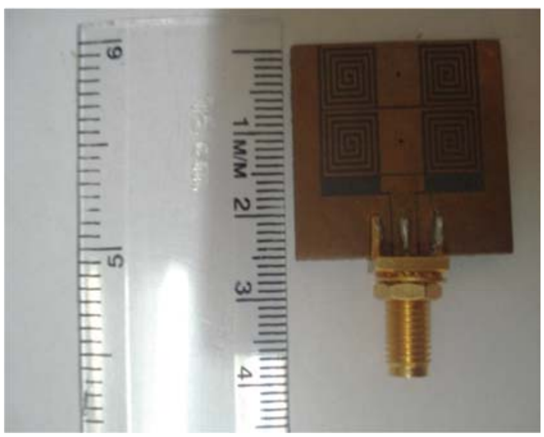

Fig. 2(c). Fabricated prototype of the proposed antenna.

V. SIMULATION RESULTS

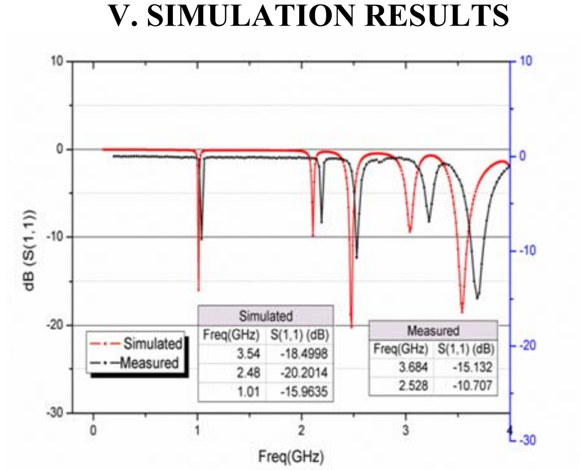

Fig. 3(a). Comparison of simulated and measured reflection coefficients of the proposed antenna.

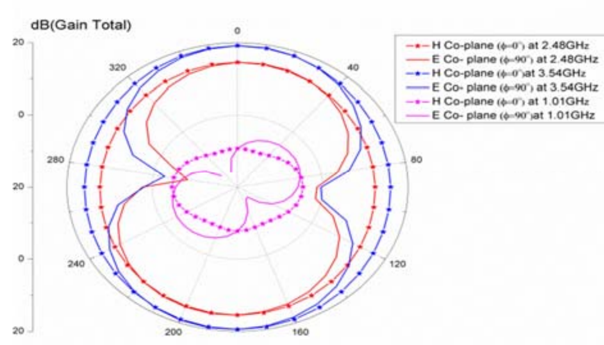

Fig. 3(b). Radiation Patterns $Eplane(\phi = 90^{\circ})$ and $Hplane\ (\phi = 0^{\circ})$ at different operational frequencies.

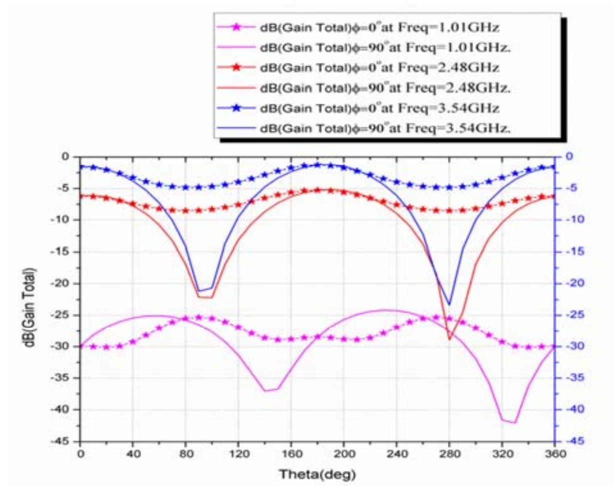

Fig. 3(c). Gain Patterns at different operational frequencies.

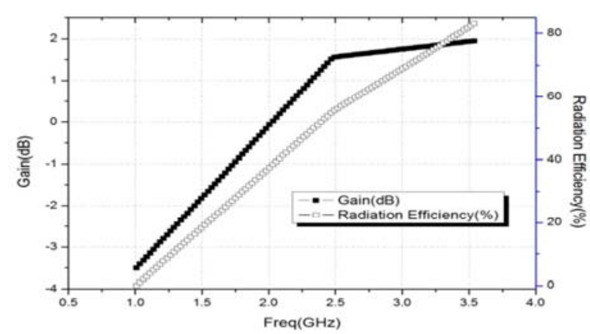

Fig. 3(d). Simulated radiation efficiency and gain for the proposed structure.

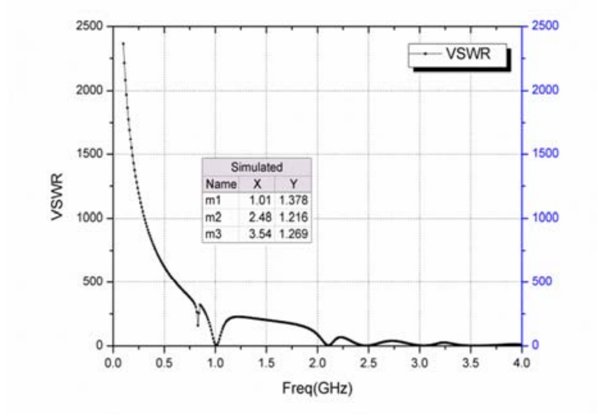

Fig. 3(e). V.S.W.R. for the proposed structure.

VI. ANTENNA/FEED MEASURED PERFORMANCE

A. INTRODUCTION: ANECHOIC CHAMBER

SPACE APPLICATIONS CENTRE (SAC), ISRO, Ahmedabad, has an Anechoic Chamber for characterizing feed system and electrically small antennas radiation pattern measurement at very low power levels in far field configuration. The Anechoic chamber is having size of 13m x 8m x 8m (L x W x H) respectively, quiet Zone of 1m³ and has been designed for the frequency range of 1.0 GHz to 40 GHz and currently it can cater the frequency range up to 60 GHz.

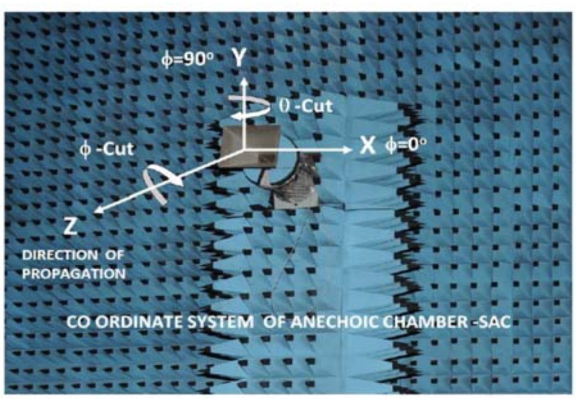

Fig. 4. - Photograph showing axis definition in the Anechoic Chamber. For clarity, a co-ordinate system has been superimposed on the picture.

B. MEASURED RADIATION CUTS:

The radiation pattern cuts H-plane and E-plane for given patch antennas are shown below.

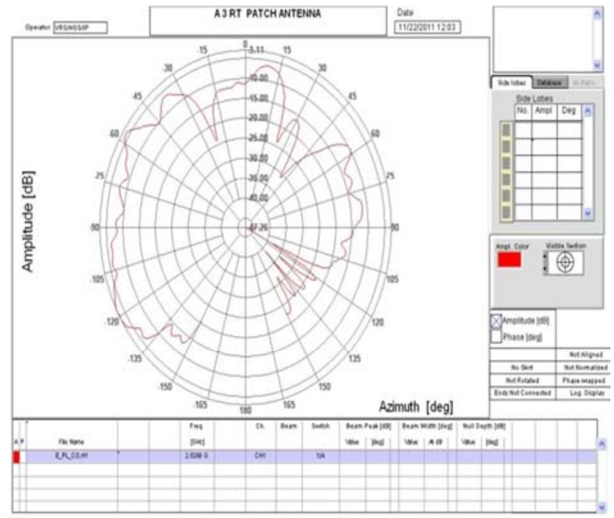

Fig. 5(a). Measured Radiation Pattern E co-plane at 2 .528 GHz.

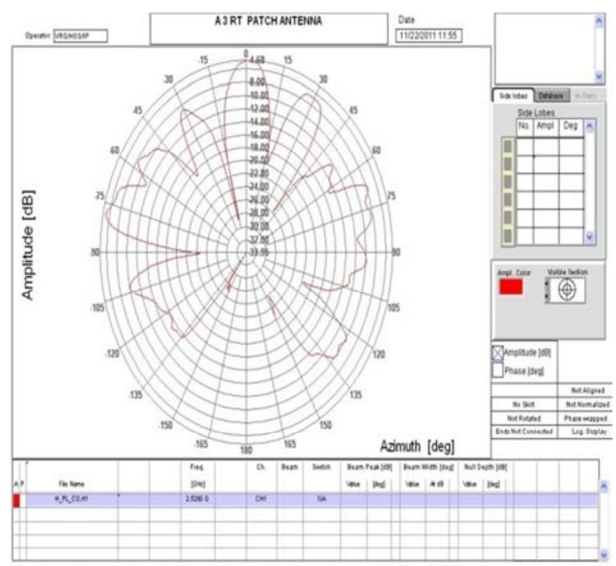

Fig. 5(b). Measured Radiation Pattern H co-plane at 2 .528 GHz.

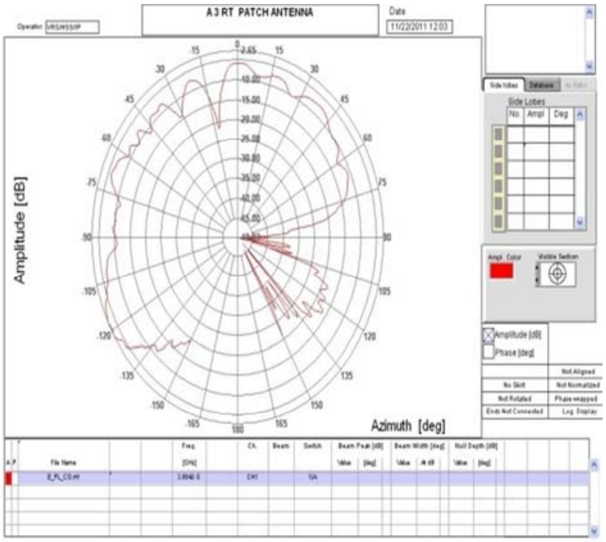

Fig. 6(a). Measured Radiation Pattern E co-plane at 3.684 GHz.

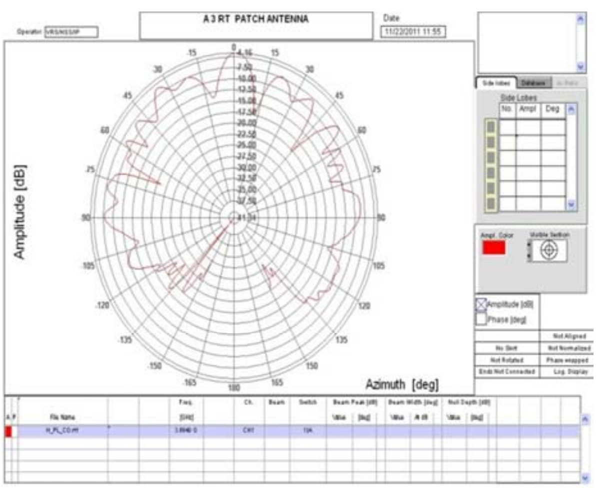

Fig. 6(b). Measured Radiation Pattern H co-plane at 3.684 GHz.

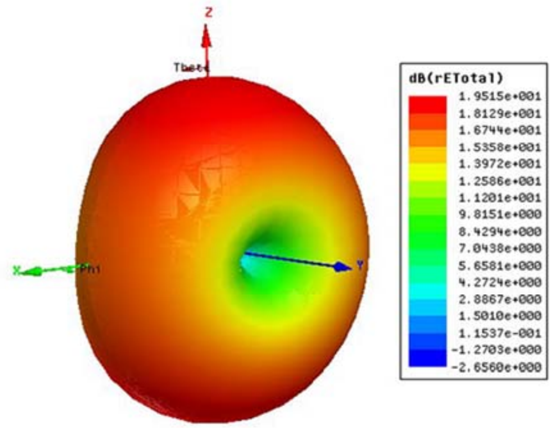

Fig. 7(a). Gain of the antenna at n=+2 mode (freq= 3.54GHz).

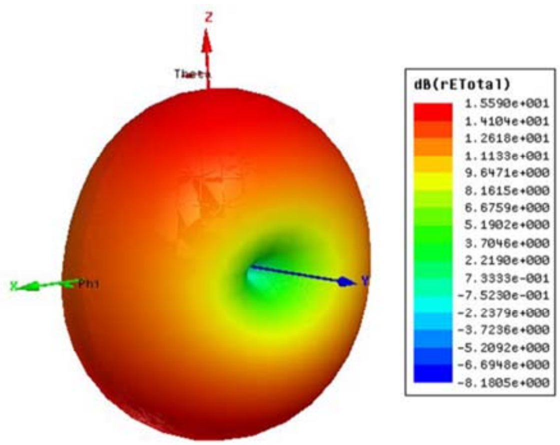

Fig. 7(b). Gain of the antenna at n=0 mode (freq= 2.48GHz).

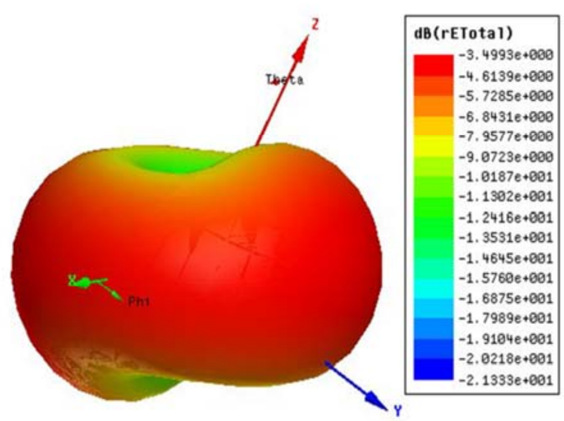

Fig. 7(c). Gain of the antenna at n= -2 mode (freq= 1.01 GHz).

Table 1: Performance Characteristics of the proposed metamaterial antenna.

Resonant Freq (GHz)	Return Loss (dB)	Gain (dB)	Band-width (%)	Radiation Efficiency
f_{+2}=3.54	-18.4998	1.9515		0.8252
f_{+1}=3.04	-9.4013	1.5256		0.51737
f_0=2.48	-20.2014	1.5590	1.36	0.5531
f_{-1}=2.11	-9.8419	6.2652		0.087649
f_{-2}=1.01	-15.9635	-3.4993		0.069301

VII. CONCLUSION

A compact, triband metamaterial antenna with novel spiral inductors is proposed. The LH shunt inductance contributed by the spiral inductors leads to bandwidth of about 1.36% with an impedance matching of 42Ω. A dumb-bell shaped E plane radiation pattern and omni-directional based H plane radiation pattern are obtained along with triband characteristics making it most suitable for point to point wireless applications.

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REFERENCES

[1] Y. Ge, K. Esselle and T. Bird, "Compact Triple-arm Multiband Monopole Antenna," in *Proc. IEEE Int. Workshop on: Antenna Technology Small Antennas and Novel Metamaterials,* pp. 172-175, Mar. 2006.

[2] N. Herscovici, Z. Sipus and P. S. Kildal, "The Cylindrical Omnidirectional Patch Antenna," *IEEE Trans. Antennas Propagat.*, vol. 49, no.12, pp.1746-1753, 2001.

[3] T. H. Lam, M. J. Milicic Jr and D. M. Pritchett, "Dipole Antenna having Co-axial Radiators and Feed," U. S. Patent 5 387 919, Feb. 7, 1995.

[4] T. E. Koscica and B. J. Liban, "Simplified Stacked Dipole Antenna," U. S. Patent 6 014 112, Jan. 11, 2000.

[5] D. Braaten, R. P. Scheeler, M. Reich, R. M. Nelson, C. Bauer-Reich, J. Glower, G. J. Owen, "Compact Metamaterial-Based UHF RFID Antennas: Deformed Omega and Split-Ring Resonator Structures," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25, no. 6, pp. 530-542, June 2010.

[6] J. C. Liu, W. Shao, B. Z. Wang, "A Dual-Band Metamaterial Design using Double SRR Structures," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 6, pp. 459-463, June 2011.

[7] M. Tang, S. Xiao, D. Wang, J. Xiong, K. Chen, B. Wang, "Negative Index of Reflection in Planar Metamaterial Composed of Single Split-Ring Resonators," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 3, pp. 250-258, March 2011.

[8] C. Caloz and T. Itoh, "Electromagnetic Metamaterials, Transmission Line Theory and Microwave applications," Wiley and IEEE Press, Wiley and IEEE Press, Hoboken-Piscataway, New Jersey, 2005.

[9] A. Lai, C. Caloz, and T. Itoh, "Composite Right/Left-handed Transmission Line Metamaterials," *IEEE Microwave Mag.*, vol. 5, no. 3, pp. 34-50, Sep. 2004.

[10] D. Verba, M. Polivka, "Improvement of the Radiation Efficiency of the Metamaterial Zero-order Resonator Antenna", *Radio Engineering*, vol. 18, pp. 1-8, April 2009.

[11] D. Sievenpiper, L. Zhang, F. J. Broas, N. G. Alexopulos, and E. Yablonovitch, "High-impedance Electromagnetic Surfaces with a Forbidden Frequency Band," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 11, pp. 2059-2074, Nov. 1999.

[12] A. Lai, K. M. K. H. Leong, and T. Itoh, "Infinite Wavelength Resonant Antennas with Monopolar Radiation Pattern based on Periodic Structures", I*EEE Trans. Antennas and Propagation*, vol. 55, no. 3, pp. 868-876, March 2007.

[13] J. Lee, K. M. K. H. Leong, and T. Itoh, "Compact Dual-band Antenna using an Anisotropic Metamaterial," *Proc. 36th Eur. Microw. Conf.*, Manchester, U. K., pp. 1044-1047, Sept. 2006.

[14] J. Lu, H. Chin, "Planar Compact U-Shaped Patch Antenna with High-Gain Operation for Wi-

Fi/WiMAX Application," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 1, pp. 82-86, January 2011.

[15] Rennings, T. Liebig, C. Caloz, P. Waldow, "MIM CRLH Series Mode Zeroth Order Resonant Antenna (ZORA) Implemented in LTCC Technology," *Asia Pacific Microwave Conference 2007,* Bangkok, pp.191-194, Dec. 2007.

[16] Taehee Jang and Sungjoon Lim, "A Compact Zeroth Order Resonant Antenna on Vialess CPW Single Layer", *ETRI Journal*, vol. 32, no. 3, June 2010.

Sheeja K. L. received the M. Tech degree in Electronics Systems and Communication from National Institute of Technology, Rourkela, Odisha, India in 2009. She is currently pursuing her PhD degree from the same institute. Her research interest includes the design and analysis of resonant antennas using metamaterial transmission lines and synthesis of electrically small antennas.

Prasanna Kumar Sahu received the B.Sc.(Engg.) degree from UCE Burla, Sambalpur University in the year 1986, M Sc. (Engg.) from REC, Rourkela, Sambalpur University in the year 1991 and PhD. (Engg.) from Jadavpur University in the year 2007 respectively. He is presently working as an Associate Professor in the Department of Electrical Engineering, National Institute of Technology, Rourkela, India. His current research interest includes Nanoelectronics, Metamaterials and Dielectric Resonator Antennas. Dr. Sahu is a Member of IEEE (USA), Life Member of Institute of Engineers, India.

Santanu Kumar Behera received the BSc.(Engg) degree from UCE Burla, Sambalpur University in the year 1990, ME and PhD(Engg) from Jadavpur University in the year 2001 and 2008 respectively. He is presently working as an Associate Professor in the Department of Electronics and communication Engineering, National Institute of Technology Rourkela, India. His current research interests include Planar Antenna; Dielectric Resonator Antenna and Metamaterials. Dr. Behera is a Life Member of IETE (India), Computer Society of India, Society of EMC Engineers (India), ISTE (India) and Member of IEEE (USA).

Nabil Dakhli recieved the Master degree in electrical engineering from Tunis University of Science, Tunisia, in 2005, and is currently working toward the Ph.D. degree at the High Institute of Telecommunication Engineering SUP'COM, Ariana, Tunisia. His research interests antennas, periodic structures, and metamaterials.