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Geo-textile Based Metamaterial Loaded Wearable Microstrip Patch Antenna

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***Abstract-* In this paper, a geo-textile material that is polypropylene based metamaterial loaded wearable T-shaped microstrip patch antenna for public safety band applications is presented. Under unloaded condition of T-shaped microstrip patch antenna, poor matching is observed in the public safety band. Further, this antenna is loaded with metamaterial split ring resonators (SRRs). This loading provides better matched condition in the public safety band. In loading condition, the antenna resonates at 4.97 GHz with the bandwidth and gain of 50 MHz and 6.40 dBi respectively. The electrical dimension of the proposed wearable antenna is 0.369 $\lambda \times 0.369\ \lambda$. The antenna is fabricated, tested, and the measured results are presented in the paper. An equivalent circuit of the designed antenna under loading condition is also prepared and analyzed.**

***Index Terms-* Public safety band, geo-textile, polypropylene, metamaterial, split ring resonator, negative permeability, equivalent circuit.**

I. INTRODUCTION

The Federal Communication Commission (FCC) allotted a separate frequency spectrum of 4.94 GHz to 4.99 GHz that is 50 MHz band for public safety applications dedicated to the protection of human life, health, and property where point-to-point or point- to-multipoint connectivity is necessary [1-2]. It covers the applications such as fire fighter, police vehicles, offsite workers and rescue teams, private ambulance services, military services, airport and seaport surveillances so that the interior and sensitive locations can be monitored round the clock for the protection of human life and property. The compact, light weight, efficient, and easily installable antennas are essential in the public safety band. Looking into the safety of human life it is essential to develop the wearable antenna that can be easily integrated as a part of military uniforms, fire fighting and police garments, military tent clothing, seat belts and covers of military and police vehicles. The limitations of conventional microstrip patch antennas are more deposition of electromagnetic signals in the human body that is high specific absorption rate (SAR) though their physical size is large. Secondly, due to size it is difficult to integrate and make them hidden inside the clothing of wearer [3-9]. Hence, a wearable antenna that is the textile based antenna is one of the better alternatives for such type of applications. The wearable antenna should be light weight, flexible, compact, hidden and should be easily integrated within the clothing and it should not affect the health of wearer.

In practice, different natural as well as synthetic textile materials such as nylon, cotton, Jean, polyester, Teflon, Nomex, liquid crystal polymer (LCP), fleece fabric etc. are used as a substrate to manufacture the wearable antennas for industrial scientific and medical (ISM) band applications [3-9]. In the literature, different wearable antennas are fabricated on various textile substrates for body centric communication systems are reported that covers Wi-Fi, Wi-Max, WLAN, HYPER LAN, body area networks (BAN), Bluetooth applications. Hall P. S. and Hao Y. presented a study on the necessity of wearable antennas for personal area networks (PAN), body area network (BAN) and ISM band [3]. Recently, the authors reported a metamaterial embedded wearable rectangular microstrip patch antenna for IEEE

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802.11a WLAN applications [4]. C. Hertleer *et al.* presented ISM band microstrip patch antenna on flexible pad foam substrate for protective clothing of fire fighter [5].

Metamaterial inclusions are directly used as loading element for size reduction, enhancement of gain, bandwidth, directivity and efficiency of microstrip patch antennas. In the literature, different metamaterial loaded microstrip patch antennas are reported [2], [4], [11-18]. These inclusions match the impedance at frequency which is lower than the initial resonant frequency of the unloaded microstrip patch antenna. Under loading condition, the microstrip patch antenna generates sub-wavelength resonances due to modifications of the resonant modes. In 1968, Veselago theoretically predicted that metamaterial possesses negative values of magnetic permeability (μ) and electric permittivity (ε) [19]. Some Metamaterial structure consists of SRRs to produce negative permeability and thin wire elements to generate negative permittivity [11-23]. Authors have reported the effect of mutual inductance on the resonant frequency, bandwidth, gain, and size of metamaterial loaded electrically small microstrip patch antenna when the loading distance between the metamaterial element and the antenna gets varied [14]. This concept is used by the authors to design and fabricate the polypropylene based metamaterial loaded microstrip patch antenna for public safety band applications.

In this work, the authors proposed a geo-textile material that is polypropylene substrate based wearable antenna for public safety band applications. The polypropylene is a non-woven type of geo-textile which is used as a substrate because of its features such as light weight, the polypropylene sheets are available in different thickness which avoids the processes like sewing to obtain the substrate of desired thickness. The objective of this paper is to design, fabricate and test the metamaterial loaded polypropylene based wearable antenna for public safety band applications. In this antenna, a T-shaped microstrip patch is loaded with four metamaterial square SRRs of equal dimensions by placing them around the patch. The proposed antenna is fabricated, tested, and the measured results are presented in the paper. An equivalent circuit model of the T-shaped microstrip patch antenna under loading condition is also prepared and analyzed in this paper.

The paper is organized into following sections. In Section II, the geometrical sketch and design of the proposed wearable antenna is presented. Section III presents the results of T-shaped microstrip patch antenna under unloaded and loaded conditions. The metamaterial characteristics of the square SRR are also studied and presented in this section. In Section IV, the equivalent circuit analysis of the designed antenna is presented. The paper is concluded in Section V.

II. ANTENNA DESIGN

Fig.1 shows the geometrical structure of metamaterial loaded wearable T-shaped microstrip patch antenna designed and fabricated on the geo-textile polypropylene substrate.

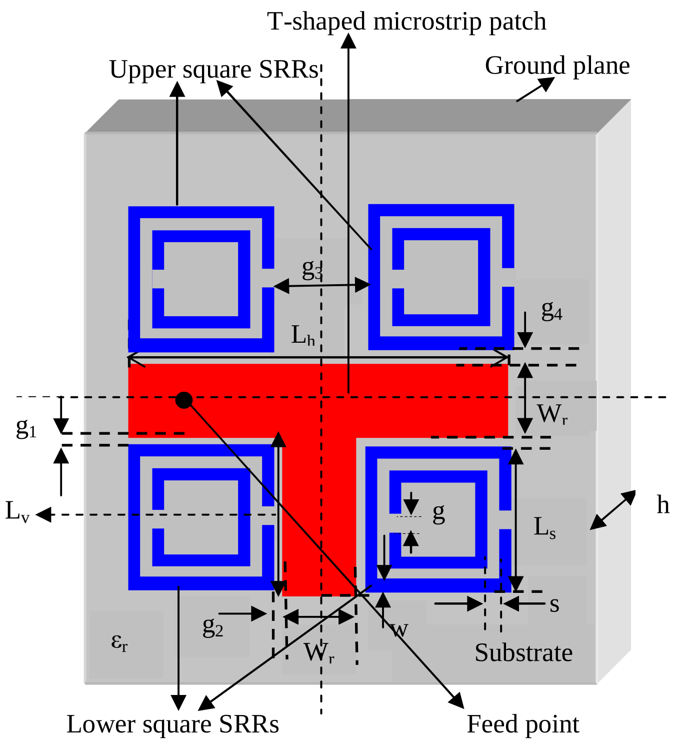
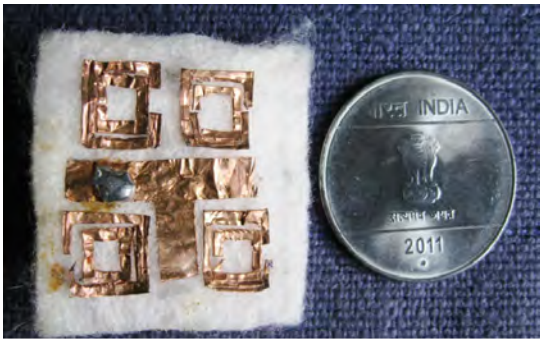
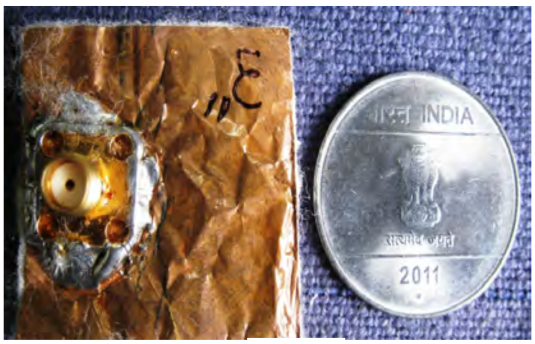


Fig. 1. Geometrical sketch of metamaterial loaded wearable T-shaped microstrip patch antenna on geo-textile polypropylene substrate



(a)



(b)

Fig. 2. Photographs of fabricated metamaterial loaded wearable T-shaped microstrip patch antenna on polypropylene substrate (a) Radiating patch (b) Ground plane

Fig. 2 (a) and 2 (b) respectively depicts the photographs of the radiating patch and ground plane of the fabricated antenna. The antenna consists of two rectangular microstrips which are overlapped on each other to form a T-shaped microstrip patch. The purpose to select the T- shape is to increase the resonant length of the antenna so as to reduce the size of antenna and to accommodate the metamaterial SRRs to achieve the further size reduction. The dimensions of the T-shaped microstrip patch are; length of horizontal and vertical microstrips $L_h = 22.5$ mm and $L_v = 10$ mm respectively. The width of both micostrips is $W_r = 3$ mm. The geometrical dimensions of a square SSR are; length of outer split ring is $L_s = 9$ mm, gap at the split of both rings (g), width of the rings (w) are set to; g = w = 1 mm, and separation between the inner and outer split rings (s) is 0.5 mm. The electrical size of the square SRR is 0.253 λ × 0.253 λ (λ is the free space wavelength at resonance frequency of square SRR 8.45 GHz). The T-shaped microstrip patch antenna is loaded with such a four square SRRs that are placed at the distances $g_1 = 1$ mm, $g_2 = 0.75$ mm, $g_3 = 4.5$ mm, and $g_4 = 0.6$ mm to obtain the resonance frequency of public safety band. The aspect ratio of horizontal rectangular microstrip that is length (L_h) to width (W_r) is fixed to 7.5 similarly, the ratio of the gaps between upper square SRRs (g_3) to (g_4) is also set to 7.5. The ratio of the gaps of lower square SRRs (g_1) to (g_2) is set to 1.33.The length of vertical rectangular microstrip (L_v) is fixed to 1.33 times the aspect ratio of horizontal microstrip. According to the designed dimensions and shapes the radiating patch, square SRR, and ground plane of the antenna are cut from the self adhesive copper tape of thickness 0.1 mm and tightly adhered on the polypropylene substrate. The size of this antenna at resonance frequency 4.97 GHz is 0.369 λ × 0.369 λ. The finely cut microstrip patch and the SRRs are tightly adhered on the polypropylene substrate. This antenna is designed and simulated on polypropylene (PR 30) substrate of thickness h = 1.9 mm and dielectric constant $\varepsilon_r = 2.2$ supplied by TECHFAB India, Mumbai, India. The antenna is co-axially fed at $x = -7.2$ mm and $y = 0$ mm. The proposed antenna is entirely handmade and high degree of accuracy is maintained in the entire fabrication processes. Method of moment based IE3D electromagnetic simulator is used to simulate this antenna.

III. RESULTS & DISCUSSION

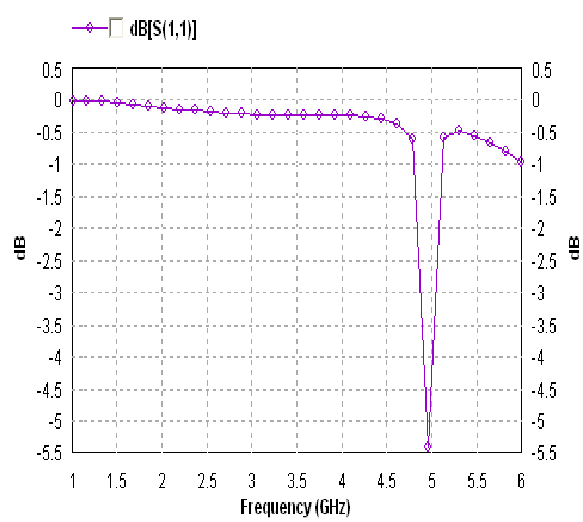


Fig.3. Simulated return loss (S_{11}) characteristics of unloaded wearable T-shaped microstrip patch antenna on polypropylene substrate

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Fig. 3 shows the return loss (S_{11}) characteristics of unloaded T-shaped microstrip patch antenna. In this configuration, poor impedance matching is observed at 4.95 GHz that is in the public safety band. However, the feed point location is rigorously determined on the entire patch to obtain the good matched condition in the proposed frequency band. Hence, to obtain the good impedance matching of the antenna at the public safety band the proposed T-shaped patch is loaded with metamaterial square SRR inclusions as shown in Fig. 1. The metamaterial characteristics of the square SRR are verified and presented before analyzing the loading effect on microstrip patch.

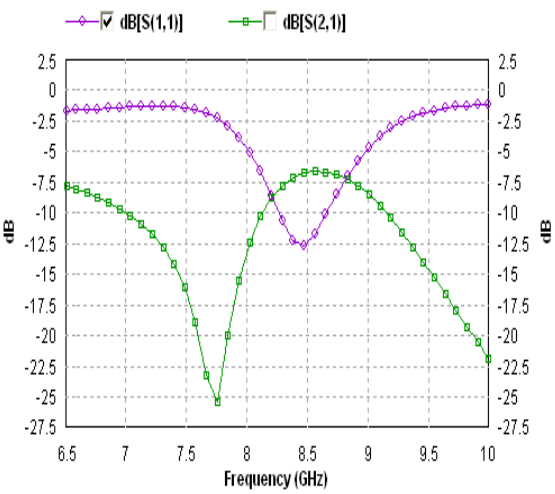

Fig. 4. Reflection (S_{11}) and Transmission (S_{21}) coefficient characteristics of square SRR

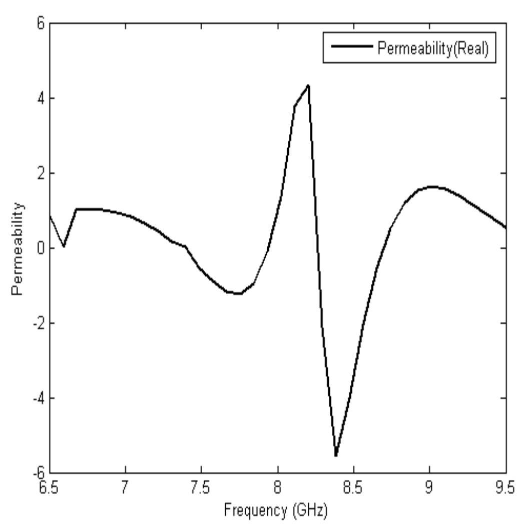

Fig. 5. Relative permeability (μ_r) characteristics of the square SRR

Fig. 4 shows the reflection (S_{11}) and transmission (S_{21}) coefficient characteristics of the square SRR that resonates at 8.48 GHz. The effective medium theory is used to verify the permeability (μ_r) and permittivity (ε_r) from the reflection and transmission coefficients (*S*-parameters). The Nicolson-Ross-Weir (NRW) approach is used to obtain the effective medium parameters. The expressions of equations (1) and (2) are used to determine these effective parameters. The metamaterial characteristics of the SRR are verified using the *S*-parameters obtained from IE3D electromagnetic simulator and MATLAB code with mathematical equations (1) and (2) [13-18],[21-23].

$$ {}_r = \frac{2}{jk_0 h}\frac{1-V_2}{1+V_2} \tag{1}$$

$$ {}_r = \frac{2}{jk_0 h}\frac{1-V_1}{1+V_1} \tag{2}$$

where k_0 is wave number, h is substrate thickness; V_1 and V_2 are composite terms to represent addition and subtraction of *S*-parameters. The factor k_0h = 0.336 which is <<1 [21-22]. The values of V_1 and V_2 are calculated using equations (3) and (4) [13-18], [21-23].

$$V_1 = S_{21} + S_{11} \tag{3}$$

$$V_2 = S_{21} - S_{11} \tag{4}$$

From Fig. 4 good matching is observed near the resonant frequency of SRR that is at 8.48 GHz in the range of 8.35 GHz to 8.7 GHz.

Fig. 5 depicts the relative permeability (μ_r) characteristics of the SRR which indicates that the SRR structure is single negative that is mu negative (MNG) metamaterial. The value of permeability (μ_r) is negative in the frequency range of 8.35 GHz to 8.7 GHz. Such four square shaped SRRs are used to load the T-shaped microstrip patch as shown in Fig.1 In loading condition, a good matching is obtained in the public safety band.

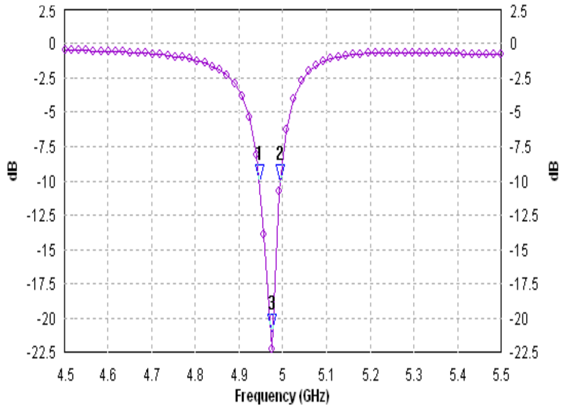

Fig.6. Simulated return loss (S_{11}) characteristics of metamaterial loaded wearable T-shaped microstrip patch antenna on polypropylene substrate

Fig.7. Photograph of experimental set up to test metamaterial loaded polypropylene based wearable T-shaped microstrip patch antenna

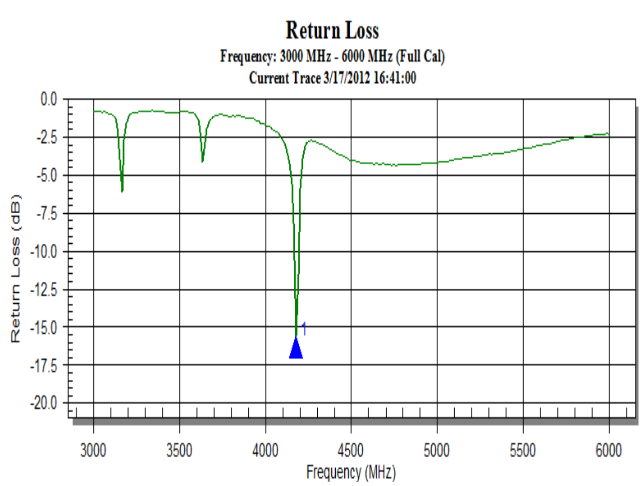

Fig. 8. Measured return loss (S_{11}) characteristics of wearable T-shaped microstrip patch antenna on polypropylene substrate.

Fig. 6 depicts the simulated return loss (S_{11}) characteristics of the metamaterial loaded polypropylene based wearable microstrip patch antenna. This antenna resonates at 4.97 GHz (in the frequency band of 4.94 GHz to 4.99 GHz) with the bandwidth and gain of 50 MHz and 6.38 dBi respectively. The directivity of the proposed antenna is 7.56 dBi. Fig. 7 shows the photograph of the experimental set up of return loss measurement of the fabricated antenna using Bird site analyzer® (Model No. SA-6000 EX, Frequency range 25 MHz to 6 GHz). Fig. 8 shows the measured return loss (S_{11}) characteristics of the T-shaped microstrip patch antenna loaded with SRRs. This antenna will find its applications in different public safety band applications.

IV. EQUIVALENT CIRCUIT ANALYSIS & THEORETICAL DISCUSSION

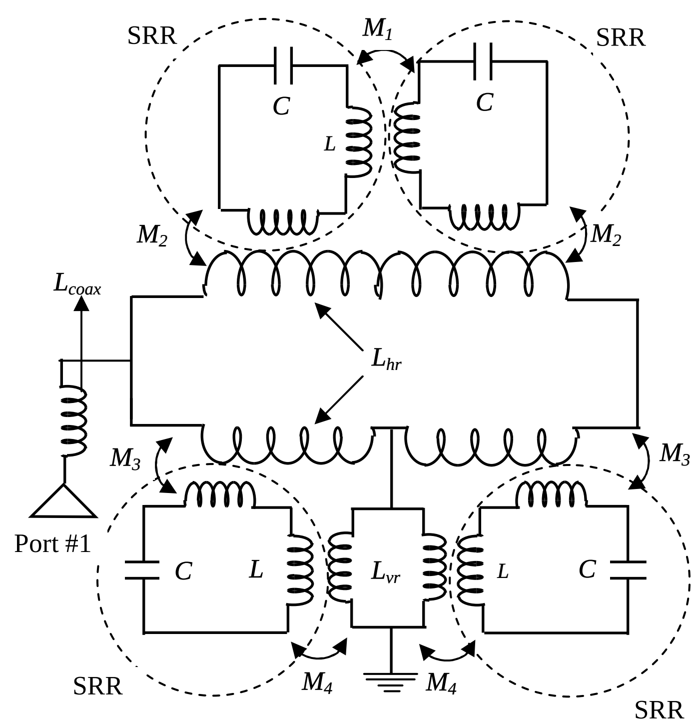

Fig. 9. Equivalent circuit diagram of metamaterial loaded wearable T-shaped microstrip patch antenna on polypropylene substrate

Fig. 9 shows the equivalent circuit diagram of metamaterial square SRR loaded polypropylene based wearable T-shaped microstrip patch antenna.

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Basically, SRR is a *LC* resonant circuit where *L* and *C* are the equivalent inductance and capacitance respectively. L_{coax} represents the probe inductance. The inductance (*L*) of the square SRR is calculated using equation (5) [14], [16-18], [23-24].

$$L = \frac{{}_0}{2}\frac{L_{savg}}{4}4.86\left[\ln\frac{0.98}{} + 1.84\right] \qquad (5)$$

where μ_0 is permeability of free space ($4\pi \times 10^{-7}$ H/m), ρ is the filling ratio expressed as $= \frac{(N-1)(w+s)}{\left[L_s - (N-1)(w+s)\right]}$, L_{savg} is the average length of square SRR and calculated as $L_{s\,avg} = 4\left[L_s - (N-1)(w+s)\right]$ and *N* is number of split rings. The equivalent capacitance (*C*) that is capacitance per unit length of the square SRR is calculated using equation (6) [14], [16-18], [23].

$$C = {}_0\frac{N-1}{2}\left[2L_s - (2N-1)(w+s)\right]\frac{K\sqrt{1-k_1{}^2}}{K(k_1)} \qquad (6)$$

where ε_0 is the permittivity of free space (8.854×10^{-12} F/m), *K* is the complete elliptic integral of first kind, k_1 is the argument of integral expressed as $k_1 = \frac{s/2}{w+s/2}$.

By using the principles of equivalent circuit theory and mathematical equations, the calculated values of equivalent circuit elements are; inductance *L* = 30 *nH* and capacitance *C* = 0.0119 *pF*. Theoretically, using the values of *L* and *C* the resonant frequency of square SRR is calculated to 8.43 GHz. The simulated resonant frequency of square SRR is 8.48 GHz (Fig. 4) which is in good agreement with the theoretical results.

In loading condition, the four SRR inclusions are inductively coupled with the T-shaped microstrip patch. The *LC* resonant circuit of the corresponding square SRR gets mutually coupled with the T-shaped microstrip patch through the mutual inductance '*M*' which is modeled as the magnetic coupling between these two elements. Let, M_1 is mutual inductance between the upper neighbouring SRRs and calculated to 0.819 *nH* by using equation (7) [14], [17-18], [24].

$$M_1 = \frac{{}_0 L_s}{2}\left[0.467 + \frac{0.059w^2}{L_s{}^2}\right] \qquad (7)$$

Consider, M_2 is mutual inductance between the upper SRRs and the horizontal microstrip of the T-shaped patch. Let M_3 is mutual inductance between the two lower SRRs and horizontal microstrip of the patch. M_4 is mutual inductance between the two lower SRRs and vertical microstrip of the patch. The mutual inductance M_2 *to* M_4 are respectively calculated to 0.861 *nH* using equation (8) [14], [17-18], [24]

$$M_2 = M_3 = M_4 = \frac{{}_0 L_s}{2}\left[0.467 + \frac{0.059(W_r + w)^2}{L_s{}^2}\right] \qquad (8)$$

The inductance of horizontal (L_{hr}) and vertical (L_{vr}) rectangular microstrips of the T-shaped patch is calculated to 14.6 *nH* and 5 *nH* respectively using equation (9) [14], [17-18], [24].

$$L_{hr} = L_{vr} = \frac{{}_0 L_r}{2}\left[\ln\left(\frac{2L_r}{W_r}\right) + 0.5 + \left(\frac{W_r}{3L_r}\right) - \left(\frac{W_r^2}{24L_r{}^2}\right)\right] \qquad (9)$$

The values of L_{hr} and L_{vr} are calculated at the lengths $L_r = L_h = 22.5$ mm and $L_r = L_v = 10$ mm respectively. In loading condition, the SRRs are positioned proximity to the horizontal and vertical microstrips of the T-shaped patch. The microstrip patch is coaxially excited hence, due to electromagnetic induction the time varying flux induces the current on each of the square SRR used for loading the patch. Thus, the electric field is induced across the gap capacitance of the splits and mutual capacitance (capacitance per unit length) between the inner and outer splits rings of the SRRs. The inductance of rectangular microstrip patch antenna with the capacitance of SRRs and the mutual inductances forms the *LC* resonant circuit

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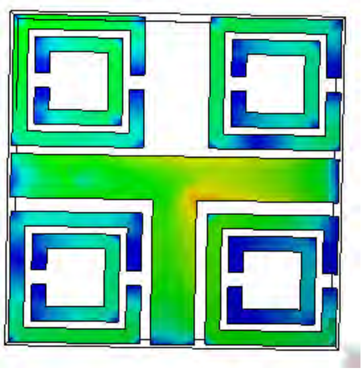
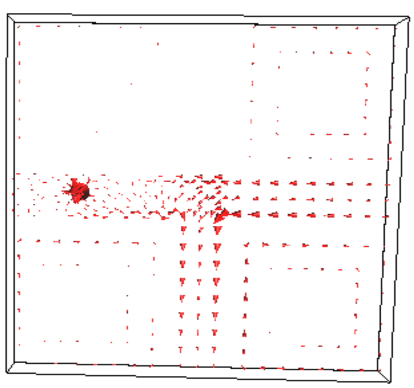
of the loaded antenna. This capacitance compensates inductance of T-shaped microstrip patch and the good matching is obtained at the lower resonant frequency 4.97 GHz. Thus, the capacitance of SRRs and the mutual inductance are sufficiently large to match with inductance of the T- shaped microstrip patch. Therefore, the negative permeability SRRs acts as matching elements at the lower resonant frequency 4.97 GHz. In loading condition, the gain of antenna is enhanced because the SRRs acts as matching elements and accepts maximum power from the source for the radiation. Thus, the SRR loading reduces the resonant frequency of the proposed antenna by better impedance matching at 4.97 GHz by reducing the antenna size.



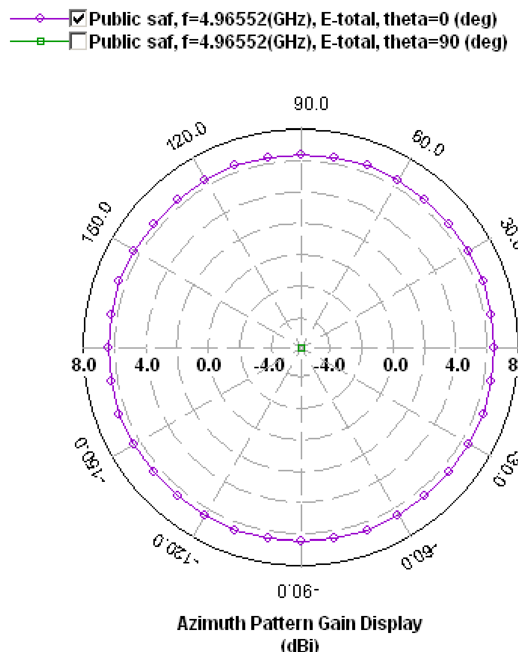
(a)



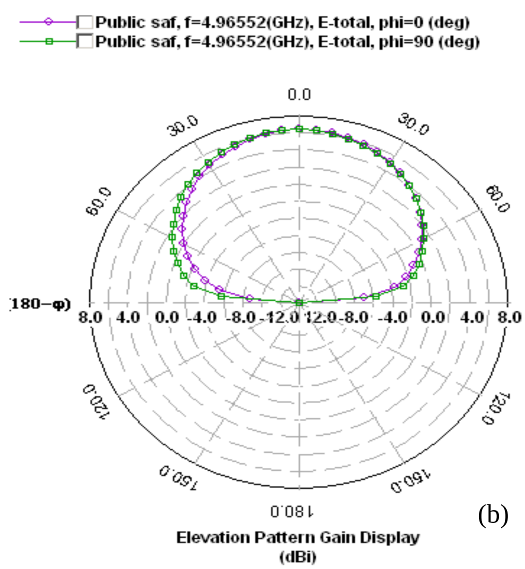
(b)

Fig. 10**.** Simulated current distribution of metamaterial loaded wearable T-shaped microstrip patch antenna on polypropylene substrate (a) Surface (b) Vector

Fig. 10 (a) and Fig. 10 (b) respectively depict the simulated surface and vector current distribution along the designed metamaterial loaded wearable T-shaped microstrip patch antenna. The current is uniformly distributed along the antenna structure as shown in Fig. 10 (a). The arrow shows current flow along the T-shaped microstrip patch and the square SRRs as depicted in Fig. 10 (b). The current is induced in the SRRs because of mutual coupling. Fig. 11 (a) and 11 (b) respectively depicts the azimuth and elevation radiation patterns of the polypropylene based metamaterial loaded T-shaped microstrip patch antenna indicating the gain of 6.38 dBi.



(a)



(b)

Fig. 11. Radiation patterns of metamaterial loaded wearable T-shaped microstrip patch antenna on polypropylene substrate (a) Azimuth (b) Elevation

(a)

(b)

Fig. 12. Positioning of the metamaterial loaded polypropylene based wearable T-shaped microstrip patch antenna

Fig. 12 (a) shows the photograph of on body positioning of the fabricated wearable antenna on the clothing of security personnel. Fig.12 (b) depicts the integration of fabricated antenna in the seat cover of a vehicle.

V. CONCLUSION

In this paper, a geo-textile material polypropylene based metamaterial SRR loaded T-shaped microstrip patch wearable antenna for public safety band applications is presented. Under loading condition, the T-shaped microstrip patch resonates in the public safety band. Thus, metamaterial loading is an advantageous approach for size reduction with considerable gain and bandwidth. The SRR loading introduces the inductance, capacitance and mutual inductance to match the impedance at desired resonance frequency. The advantages of proposed antenna are small size, inexpensive, light weight, and easy integration within the clothing. This antenna will find its application in the clothing and helmets of rescue teams, military, fire fighters, security and police personnel, as well as garments of the military tents.

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REFERENCES

[1] "Point-to-Point Connectivity in the 4.9 GHz public safety band," *Solutions Paper, Motorola,* pp. 1-8, 2007.

[2] J.G. Joshi, Shyam S. Pattnaik, S. Devi, and M.R. Lohokare, "Microstrip patch antenna loaded with magneto-inductive waveguide," *Proceedings of Twelfth National Symposium on Antennas and Propagation* (APSYM 2010), Department of Electronics, Cochin University of Science and Technology (CUSAT), (Cochin, India), pp.101-105, 2010. This antenna structure has been published in the *IEEE Antennas and Propag. Magazine,* Vol.53, No.1, pp.123-126, 2011 under "Report on APSYM'2010: National Symposium on Antennas and Propagation".

[3] P. S. Hall and Y. Hao, "Antennas and propagation for body centric communications," *Proceedings of First European Conference on Antennas and Propagation* (EuCAP 2006), 2006 (Invited Paper).

[4] J. G. Joshi, Shyam S. Pattnaik, and S. Devi, "Metamaterial embedded wearable rectangular microstrip patch antenna," *International Journal of Antennas and Propaga, Special issue on Wearable Antennas and Systems,* Hindwai Publication Corporation, ID. 974315, pp.1-9, doi: 10:1155/2012/974315, 2012.

[5] C. Hertleer, H. Rogier, L. Vallozzi, and L.Van Langenhove, "A textile antenna for off-body communication integrated into protective clothing for firefighters," *IEEE Trans. Antennas and Propag;* Vol.57, No.4, pp. 919-925, 2009.

[6] S.H. Choi, T.J. Jung, and S. Lim, "Flexible antenna based on compact right/left-handed transmission line," *Electronic Letters,* Vol. 46, No.17, pp.1181-1182, 2010.

[7] A. Tronquo, H. Rogier, C Hertleer, and L. V. Langenhove, "Robust planar textile antenna for wireless body LANs operating in 2.45 GHz ISM band," *Electronic Letters,* Vol. 42, No.3, 2006.

[8] S. Sankaralingam, and B. Gupta, "Development of textile antennas for body wearable applications and investigations

on their performance under bent conditions," *Progress In Electromagnetics Research B,* Vol. 22, pp.53-71, 2010.

[9] Salonen, P; and Y. Rahmat-Samii, "Textile antennas: Effects of antenna bending on input matching and impedance bandwidth," *IEEE Aerospace and Electronic Systems Magazine*, Vol. 22, No.3, pp. 10-14, 2007.

[10] Jiunn-Nan Hwang, and Fu-Chiarng Chen, "Study of SAR reduction with split ring resonators," *Proceedings of International Symposium on IEEE Antennas and Propagation Society*, Washington DC, USA, Vol.2B, pp.780-783, 2005.

[11] P. Y. Chen, and A. Alu, "Dual-band miniaturized elliptical patch antenna with μ–negative metamaterials," *IEEE Antennas and Propag. Letters,* Vol. 9, pp. 351-354, 2010.

[12] A. Alu, F. Bilotti, N. Engheta, and L. Vegni, "Subwavelength, compact, resonant patch antennas loaded with metamaterials," *IEEE Trans. Antennas and Propag;* Vol.55, No.1, pp.13-25, 2007.

[13] J. G. Joshi, Shyam S. Pattnaik, Swapna Devi, and M.R.Lohokare, "Electrically small patch antenna loaded with metamaterial," *IETE Journal of Research*, Vol. 56, No.6, pp.373-379, 2010.

[14] J.G. Joshi, S. S. Pattnaik, S. Devi, and M.R. Lohokare, "Frequency switching of electrically small patch antenna using metamaterial loading," *Indian Journal of Radio and Space Physics*, Vol.40, No.3, pp.159-165,2011.

[15] Montero-de-Paz, E. Ugarte-Munoz and F. J. Herraiz-Martnez, "Multifrequency self-diplexed single patch antennas loaded with split ring resonators," *Progress In Electromagnetics Research*, Vol.113, pp. 47-66, 2011.

[16] J. G. Joshi, Shyam S. Pattnaik, and S. Devi, "Partially metamaterial ground plane loaded rectangular slotted microstrip patch antenna," *International Journal of Microwave and Optical Technology*, Vol.7, No.1, pp. 1-10, 2012.

[17] J. G. Joshi, Shyam S. Pattnaik, S. Devi, and S. Raghavan, "Magneto-inductive waveguide loaded microstrip patch antenna," *International Journal of Microwave and Optical Technology*, Vol.7, No.1, pp. 11-20, 2012.

[18] J. G. Joshi, S. S. Pattnaik, S. Devi, and M. R. Lohokare, "Bandwidth enhancement and size reduction of microstrip patch antenna by magneto-inductive waveguide loading," *Journal of Wireless Engineering and Technology*, Vol. 2, No. 2, pp. 37-44, 2011.

[19] V.G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics Uspekhi*, Vol.10, pp. 509-514, 1968.

[20] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory Tech;* Vol. 47, No.11, pp.2075-2084, 1999.

[21] D.R. Smith, D.C. Vier, Th. Koschny, and C.M. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Physical Review*, Vol. E71, pp.036617-1-10, Equivalent 2005.

[22] R. W Ziolkowski, "Design, fabrication, and testing of double negative metamaterials," *IEEE Trans. Antennas and Propag;* Vol. 51, No. 16, pp.1516-1529, 2003.

[23] F. Bilotti, A. Toscano, L. Vegni, K. Aydin, K.B. Alici, and E. Ozbay, "Equivalent-circuit models for the design of metamaterials based on artificial magnetic inclusions," *IEEE Trans. Microwave Theory and Tech;* Vol.55, No.12, pp.2865-2873,2007.

[24] S. S. Mohan, Design, modeling and optimization of on-chip inductor and transformer circuits, A Ph.D. Dissertation submitted to The Department of Electrical Engineering, and The Committee of Graduate Studies of Stanford University, December 1999.