Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2012, Article ID 974315, 9 pages
doi:10.1155/2012/974315

Research Article

Metamaterial Embedded Wearable Rectangular Microstrip Patch Antenna

J. G. Joshi, Shyam S. Pattnaik, and S. Devi

National Institute of Technical Teachers' Training and Research, Sector 26, Chandigarh 160019, India

Correspondence should be addressed to J. G. Joshi, jayant100@hotmail.com

Received 30 March 2012; Revised 20 June 2012; Accepted 4 July 2012

Academic Editor: Deepti Das Krishna

Copyright © 2012 J. G. Joshi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper presents an indigenous low-cost metamaterial embedded wearable rectangular microstrip patch antenna using polyester substrate for IEEE 802.11a WLAN applications. The proposed antenna resonates at 5.10 GHz with a bandwidth and gain of 97 MHz and 4.92 dBi, respectively. The electrical size of this antenna is $0.254\lambda \times 0.5\lambda$. The slots are cut in rectangular patch to reduce the bending effect. This leads to mismatch the impedance at WLAN frequency band; hence, a metamaterial square SRR is embedded inside the slot. A prototype antenna has been fabricated and tested, and the measured results are presented in this paper. The simulated and measured results of the proposed antenna are found to be in good agreement. The bending effect on the performance of this antenna is experimentally verified.

1. Introduction

Nowadays, handheld communication devices and body centric communication systems need high-gain compact antennas which should be an integral part of the wearer clothing [1–6]. These systems are wearable computers; flexible mobile phones; personal digital assistant (PDA) devices; public safety band systems; sports activities; body area networks (BAN); industrial, scientific, and medical (ISM) band; WLAN; Wi-Fi; Wi-max; Bluetooth; HYPER LAN; and so forth. The textile- or cloth-based wearable antenna should communicate the voice, data, or biotelemetry signals at high data rates. The wearable antenna should have features like light weight, conformal, need to be hidden, and it should not affect the health of user. In practice, synthetic or natural materials are used as substrate to manufacture the textile or cloth-based wearable antennas. These materials are cotton, liquid crystal polymer (LCP), fleece fabric, foam, Nomex, nylon, conducting ribbon, insulated wire, conducting paint, copper coated fabric, and so forth Hall et al. presented a study on the necessity of wearable antennas for personal area networks (PAN), BAN, and ISM band applications [1]. In the literature different types of wearable antennas have been reported [2–4]. The bending effect due to human body movements on the impedance matching of textile-based rectangular microstrip patch antenna is investigated and analyzed [5].

It is desired to reduce the size of wearable antenna so that its performance should not be affected by the bending effect and minimum deposition of electromagnetic field in the human body. In spite of numerous advantages of microstrip patch antennas it is difficult to achieve a better trade off between the gain, bandwidth, and more prominently the size of antennas. Most recently, antenna researchers have verified and evidenced an innovative approach to overcome the limitations of microstrip patch antennas by using metamaterial [7–23]. In 1968, Veselago theoretically predicted that metamaterial possesses negative values of magnetic permeability (μ) and/or electric permittivity (ε) [17]. Metamaterial structure consists of split ring resonators (SRRs) to produce negative permeability and thin wire elements to generate negative permittivity. Metamaterial characteristics of different SRR structures have been studied and verified [7–23]. Metamaterial is used to load the microstrip patch antennas either by partially filling it beneath the substrate of patch or placing it as superstrate (metamaterial reflective surface) on the top of the patch [7–23]. These techniques significantly enhance the gain, bandwidth, directivity of the

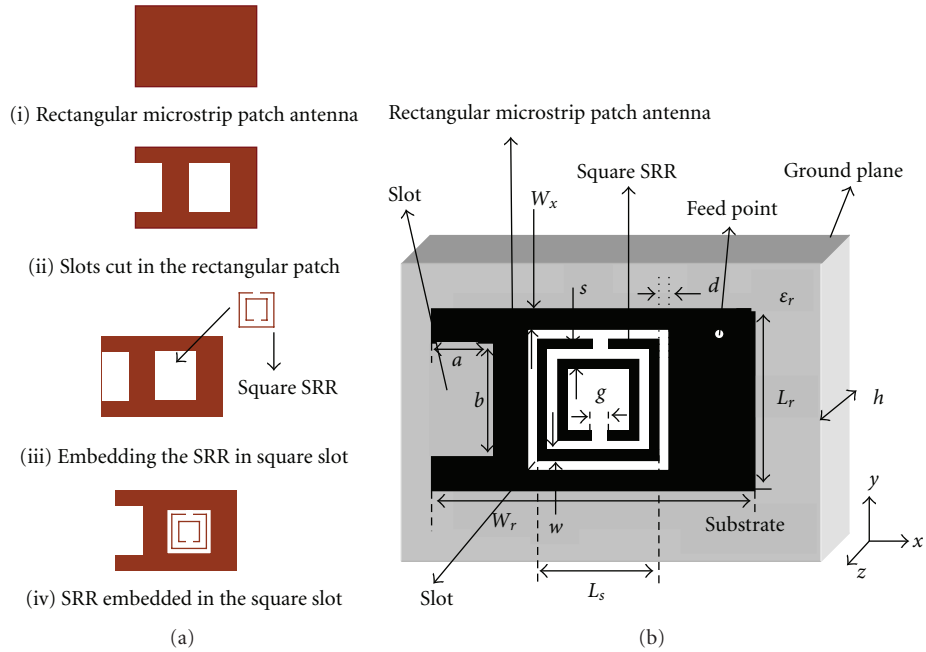


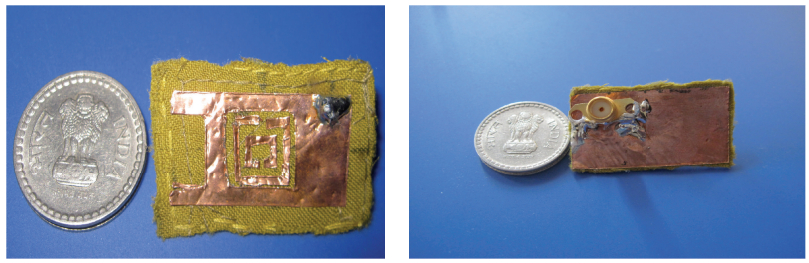
FIGURE 1: (a) Step-by-step design procedure. (b) Sketch and geometrical structure of metamaterial square SRR embedded wearable rectangular microstrip patch antenna.

microstrip patch antennas with considerable size reduction. Under loading condition, the microstrip patch antenna generates subwavelength resonances due to the modifications of the resonant modes [7–15, 22, 23]. The double negative (DNG) and single negative (SNG) metamaterial is used to load the microstrip patch antennas for size reduction by generating the subwavelength resonances [7, 8]. The effect of mutual inductance on the resonant frequency, bandwidth, gain, and size of metamaterial loaded electrically small microstrip patch antenna is reported in [12]. The specific absorption rate (SAR) can be reduced by placing metamaterial SRRs between the antenna and human muscles [16]. In their previous work, authors presented different techniques of loading the microstrip patch antennas using metamaterial to make them compact and simultaneously to enhance the gain as well as bandwidth [10, 12–15, 22, 23]. A high gain rectangular microstrip patch antenna for IEEE 802.11a WLAN applications is presented in [24]. The above mentioned literature study encouraged the authors to design the proposed wearable rectangular microstrip patch antenna.

The objective of this paper is to design and fabricate a polyester substrate-based metamaterial embedded rectangular microstrip patch antenna for WLAN applications. In this work, an attempt is made to remove the metal portion of the rectangular microstrip patch antenna by making the slots inside the patch to excite lower resonant frequency. The metal removing technique helps not only to reduce the bending effect due to human body movements on the antenna but also to reduce the SAR. The metamaterial square SRR is embedded inside the slot to achieve the better impedance matching in the WLAN band. The paper is organized into following sections. The detailed geometrical structure, design, and fabrication processes of the proposed antenna are presented in Section 2. The simulated and measured results of the proposed antenna are presented, compared, and analyzed in Section 3. In Section 4, the bending effects on the performance of fabricated antenna are experimentally verified and presented. Finally, the paper is concluded in Section 5.

2. Antenna Design

This is a polyester substrate-based wearable antenna designed for IEEE 802.11a WLAN applications. Figure 1(a) depicts the step-by-step design procedure of the proposed wearable antenna. The antenna design is divided into three steps—(a) design and simulations of rectangular microstrip patch antenna, (b) making rectangular and square slots in the rectangular patch to excite the desired lower resonant frequency for size reduction, (c) embedding the designed metamaterial square SRR inside the square slot for better impedance matching at WLAN frequency band. In simulations, when the SRR is embedded inside the square slot of the patch, better matching is noticed at the resonance frequency 5.10 GHz. In simulations, it is observed that a small difference in the placement of square SRR shifts the resonance frequency with considerable changes in the matching conditions. Finally, the SRR is placed inside the square slot at the distance of $d = 1$ mm as shown in Figure 1(b). The square SRR is magnetically coupled with the slotted rectangular patch to form an LC resonator that resonates at 5.10 GHz by making the antenna compact. Figure 1(b) depicts the sketch and geometrical structure of metamaterial square SRR embedded wearable rectangular microstrip patch antenna.



(a) (b)

Figure 2: Photographs of the fabricated metamaterial square SRR embedded wearable rectangular microstrip patch antenna. (a) Radiating patch. (b) Ground plane.

Figures 2(a) and 2(b), respectively, depict the photographs of radiating patch and ground plane with SMA connector of the fabricated metamaterial SRR embedded wearable rectangular microstrip patch antenna. Initially, the rectangular microstrip patch antenna of length (L_r) is designed for resonant frequency 8.65 GHz using (1) [25, 26]:

$$L_r = \frac{c}{f_r\sqrt{\varepsilon_e}}, \tag{1}$$

where, f_r is resonant frequency, c is velocity of light (3×10^8 m/sec), ε_r is relative permittivity (8.854×10^{-12} F/m), and ε_e is effective dielectric constant of the substrate which is calculated using (2):

$$\varepsilon_e = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left(1 + \frac{12h}{W}\right)^{-1/2}. \tag{2}$$

The dimensions of rectangular microstrip patch are length $L_r = 15$ mm and width $W_r = 30$ mm. The slots are cut in the rectangular microstrip patch to reduce the resonant frequency to WLAN applications as well as to reduce the metal area. Initially, a rectangular slot of dimensions $a = 6$ mm and $b = 8$ mm is cut inside the radiating edge of the rectangular microstrip patch but no better impedance matching is obtained. Hence, at the centre of rectangular patch a square slot of dimensions 10 mm × 10 mm is created. Again the better matching could not be obtained in the WLAN frequency band. Further, to obtain the better impedance matching and to achieve a subwavelength resonance a metamaterial square SRR is embedded into the square slot to load this antenna. The geometrical dimensions of the square SRR as shown in Figure 1(b), width of split rings (w), separation between inner and outer split rings (s), and gap at the splits of rings (g), are set to $w = s = g = 1$ mm, respectively. The length of outer square split ring (L_s) is 9 mm. The distance between outer square SRR and the edge of cut on the rectangular microstrip patch is $d = 1$ mm. The equations (1) and (2) are used to design the rectangular microstrip patch antenna at resonance frequency 8.65 GHz without (i) making slots in the radiating patch and (ii) embedding the SRR inside the square slot. The designed antenna resonates at 8.48 GHz which is reduced to the working frequency 5.10 GHz by making the slots and embedding the SRR inside the slot. Due to slots the resonant length of the designed rectangular patch is changed and poor matching is observed during the simulations at the working frequency. Further, the inductance and capacitance of SRR with the mutual induction between the antenna and SRR provide better matching at the working frequency 5.10 GHz.

The aspect ratio of rectangular microstrip patch, that is, length (L_r) to width (W_r) ratio, is 0.5. Similarly, the aspect ratio, of square slot is 1. The aspect ratio of rectangular slot, that is, length "a" to width "b", is set to 0.75 which is to one-half of the sum of aspect ratios of the rectangular patch and the slot. The antenna is coaxially fed by a 50 Ω SMA connector at $x = 11$ mm and $y = 7$ mm. The polyester cloth substrate of thickness $h = 1$ mm, relative permittivity $\varepsilon_r = 1.39$, and loss tangent $\tan\delta = 0.01$ is used to design and fabricate the proposed antenna. The substrate of desired thickness is prepared by cutting and sewing the polyester cloth. 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 prepared substrate. The size of this antenna at resonance frequency 5.10 GHz is $0.254\lambda \times 0.5\lambda$. This antenna is simulated using method of moment-based IE3D electromagnetic simulator.

The advantages of this antenna are as follows. (a) In this antenna design the slots are cut in the rectangular microstrip patch to make the antenna compact due to which the metal portion of the radiating patch has been removed. Thus, as compared to the conventional rectangular microstrip patch antenna (without slots), small portion of the proposed antenna (with slots) gets bent due to the body movements. Hence, the unwanted bending effects on the resonant frequency and impedance matching (S_{11}) of the antenna have been reduced. (b) This type of geometry is useful to reduce the deposition of electromagnetic field, that is, SAR, due to the fringing field entering in the body tissues. (c) Lower resonant frequency has been achieved.

3. Results and Discussion

Initially, the metamaterial characteristics of the square SRR are verified and presented before analyzing its loading effect on the proposed rectangular microstrip patch antenna. Figure 3 shows the reflection (S_{11}) and transmission (S_{21}) coefficient characteristics of the square SRR that resonates at

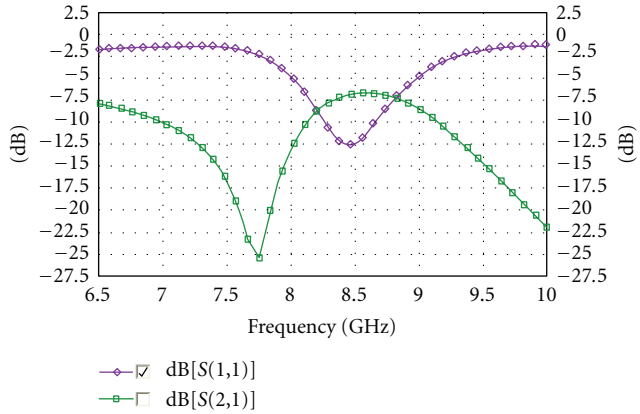


FIGURE 3: Reflection (S_{11}) and transmission (S_{21}) coefficient characteristics of square SRR.

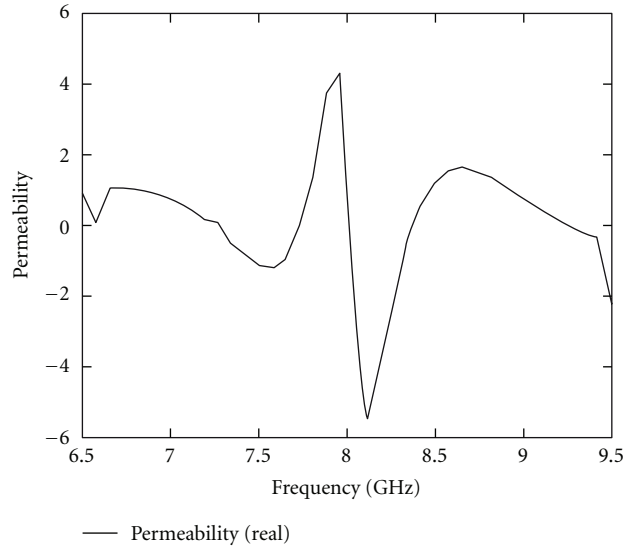


FIGURE 4: Relative permeability (μ_r) characteristics of the square SRR.

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 these effective medium parameters. The expressions of (3) are used to determine the effective parameters [10, 12, 19–23]. The metamaterial characteristics of the SRR are verified using the S-parameters obtained from IE3D electromagnetic simulator and MATLAB code with mathematical (3) [10, 12, 19–23]:

$$\mu_r = \frac{2}{jk_0h}\frac{1-V_2}{1+V_2}, \qquad \varepsilon_r = \frac{2}{jk_0h}\frac{1-V_1}{1+V_1}, \tag{3}$$

where k_0 is wave number, h is substrate thickness, V_1 and V_2 are composite terms to represent the addition and subtraction of S-parameters. The values of V_1 and V_2 are calculated as $V_1 = S_{21} + S_{11}$ and $V_2 = S_{21} - S_{11}$. The factor $k_0h = 0.336$ which is $\ll 1$ [19–23].

Figure 3 shows that the square SRR resonates at 8.48 GHz in the range of 8.35 GHz to 8.7 GHz with good impedance matching. Figure 4 depicts the relative permeability (μ_r) characteristics of the square SRR which indicate that the SRR is a 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. This SRR is embedded inside the slot to load the rectangular microstrip patch. The negative magnetic permeability of the SRR in the frequency range 8.35 GHz to 8.7 GHz significantly improves the impedance matching to the source at desired resonance frequency 5.10 GHz which is much lower than the isolated antenna. Thus, MNG SRR provides the miniaturization of the rectangular microstrip patch antenna to obtain the desired subwavelength performance. In this frequency range, the equivalent capacitance of MNG SRR has large capacitance and the patch has large inductance which forms LC resonator that resonates at 5.10 GHz. The value of relative magnetic permeability at working frequency 5.10 GHz is real.

Basically, SRR is an LC resonant circuit. The resonant frequency of the square SRR is calculated by using equivalent circuit theory to validate it with the simulated frequency. The inductance (L) of the square SRR is calculated using (4) [12, 21–23]:

$$L = \frac{\mu_0}{2}\frac{L_{s\,\mathrm{avg}}}{4}4.86\left[\ln\frac{0.98}{\rho} + 1.84\rho\right], \tag{4}$$

where μ_0 is the free space permeability ($4\pi \times 10^{-7}$ H/m), ρ is the filling ratio expressed as $\rho = (N-1)(w+s)/[L_s - (N-1)(w+s)]$, the average length of square SRR ($L_{s\,\mathrm{avg}}$) is calculated as $L_{s\,\mathrm{avg}} = 4[L_s - (N-1)(w+s)]$, and N is the number of split rings.

The equivalent capacitance (C), that is, capacitance per unit length of the square SRR, is calculated using (5) [12, 21–23]:

$$C = \varepsilon_0\frac{N-1}{2}[2L_s - (2N-1)(w+s)]\frac{K\sqrt{1-k_1^2}}{K(k_1)}, \tag{5}$$

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

Thus, by using 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 SRR is calculated to 8.43 GHz. The simulated resonant frequency of SRR is 8.48 GHz (Figure 3) which is in good agreement with the theoretical results. Figure 5 depicts the simulated return loss (S_{11}) characteristics of the rectangular microstrip patch antenna without the slots and metamaterial SRR. In this configuration, the antenna resonates at 8.97 GHz which is in good agreement with the designed frequency. Further, to decrease the resonant frequency of this antenna to WLAN frequency-band applications the slots are cut in the radiating patch. To obtain

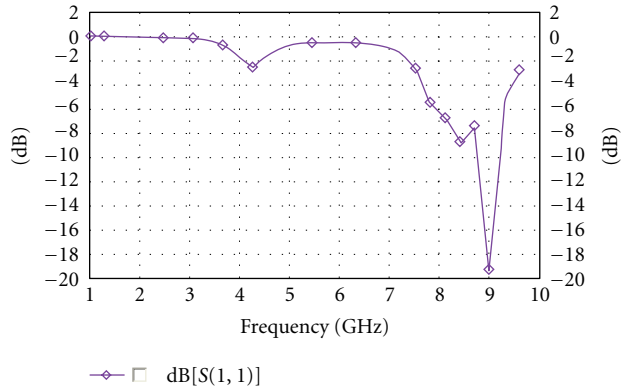


Figure 5: Simulated reflection coefficient characteristics of rectangular microstrip patch antenna without cut and square SRR.

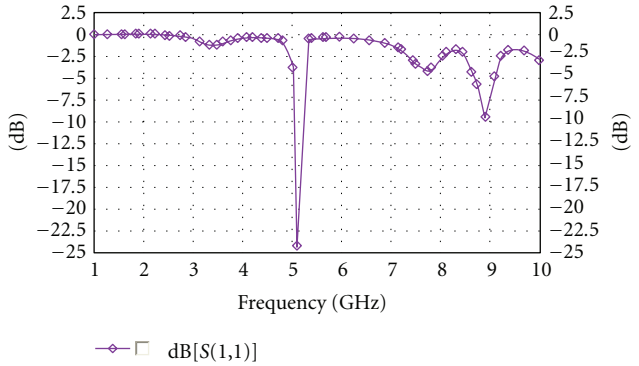


Figure 6: Simulated reflection coefficient characteristics of metamaterial embedded wearable rectangular microstrip patch antenna.

the better impedance matching a square SRR is placed in the square slot.

Figure 6 depicts the simulated reflection coefficient (S_{11}) characteristics of proposed wearable antenna with the slots and embedded square SRR. In this condition, the antenna resonates at 5.10 GHz with a bandwidth and gain of 97 MHz and 4.95 dBi, respectively. Further, to validate the simulated and measured results the fabricated antenna is tested.

Figure 7 shows the photograph of experimental set up of testing and measurement of the fabricated antenna. Bird site analyzer (Model no. SA-6000EX, Frequency range 25 MHz to 6 GHz) interfaced with a personal computer is used to measure the return loss characteristics of the fabricated antenna.

Figure 8 shows the measured reflection coefficient (S_{11}) characteristics of the fabricated metamaterial square SRR loaded wearable rectangular microstrip patch antenna which resonates at 5.34 GHz with the better matching at −27.96 dB. Figure 9 shows the measured VSWR 1.07 at the resonance frequency 5.34 GHz. The weight of fabricated antenna is measured by a digital weighing machine Essae (DS-852) and found to 2.8 gm with SMA connector (1.2 gm without SMA connector).

Figures 10(a) and 10(b), respectively, illustrate the azimuth and elevation radiation patterns of the proposed

Figure 7: Photograph of experimental set up of fabricated metamaterial square SRR embedded wearable rectangular microstrip patch antenna.

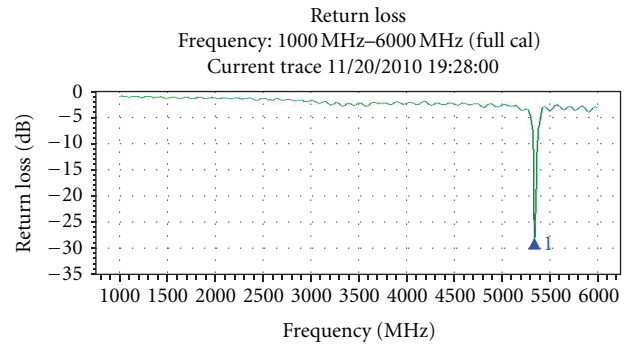


Figure 8: Measured reflection coefficient (S_{11}) characteristics of metamaterial square SRR embedded wearable rectangular microstrip patch antenna.

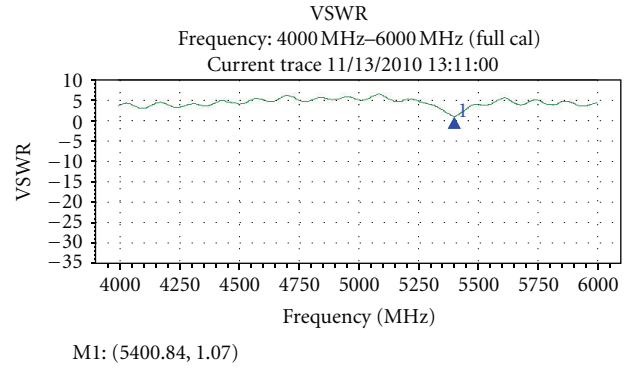


Figure 9: Measured VSWR characteristics of metamaterial square SRR embedded wearable rectangular microstrip patch antenna.

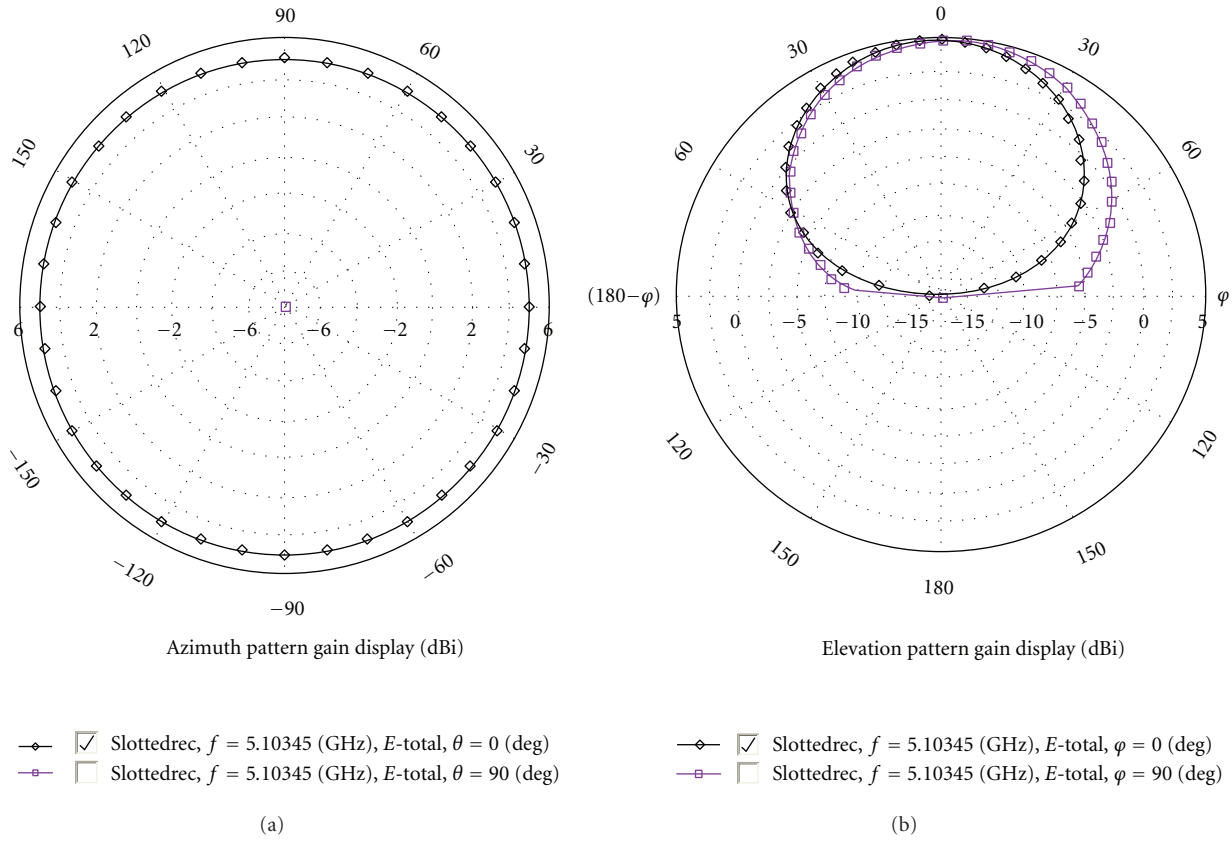


Figure 10: Radiation patterns of metamaterial square SRR embedded wearable rectangular microstrip patch antenna. (a) Azimuth. (b) Elevation.

antenna. The gain and directivity of this antenna is 4.95 dBi and 8.60 dBi, respectively.

Figures 11(a) and 11(b), respectively, depict the simulated surface and vector current distribution along the proposed wearable rectangular microstrip antenna without and with the square SRR embedded inside the slot. The current is not uniformly distributed when the SRR is not embedded as shown in Figure 11(a).

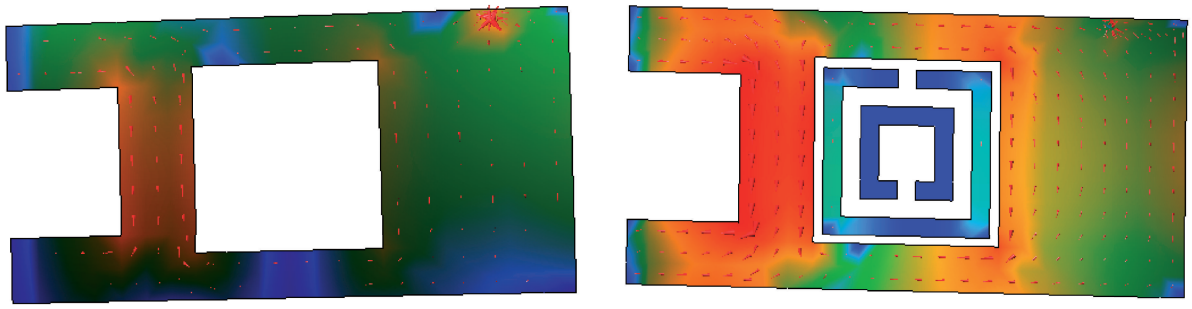
When the square SRR is embedded inside the slot current flows along slotted portion and due to the electromagnetic induction the time varying flux induces the current on the outer and inner split rings of square SRR (Figure 11(b)). The arrow shows current flow along the microstrip patch and the square SRR. The current is uniformly distributed along the slot of the antenna. Thus, the SRR embedding makes the uniform current distribution along the antenna. It results in inducing the large electric field across the gap capacitance at the splits and mutual capacitance between the split rings. Under loading condition, the mutual inductance between the square SRR and the edge of rectangular patch is calculated to $M = 0.873$ nH using (6):

$$M = \frac{\mu_0 L_s}{2\pi}\left[0.467 + \frac{0.059(W_x + w)^2}{{L_s}^2}\right], \quad (6)$$

where W_x is the edge width of the slotted rectangular patch as shown in Figure 1(b). The inductance of slotted antenna and the equivalent capacitance of the square SRR form the LCresonator circuit of the SRR embedded rectangular microstrip patch antenna which in turn provides the better impedance matching at resonance frequency 5.10 GHz.

4. Experimental Study of Bending Effects on the Wearable Antenna Performance

In Section 3, the performance of the proposed antenna is theoretically and experimentally verified under the flat surface condition. In practice, the wearable antenna is installed as an integrated part of the clothing on different parts of the human body like shoulder, forearm, wrist, waist, and thigh. The bending of wearable antenna takes place according to the frequent movements of the human body. Therefore, an experimental study is executed to examine the bending effect on impedance matching and the resonance frequency of proposed wearable antenna under different bending conditions. In this experiment, the shoulder, wrist, knee shapes of human body are realized by using the curved surfaces of two cylindrical polyvinyl chloride (PVC) pipes of internal radius 54.5 mm and 44.5 mm, respectively. The proposed antenna is tested by properly bending and swaddling it on surface of both of the PVC pipes. Figure 12 represents the photographs of PVC pipes used in this experimentation. Figure 13 shows a snapshot of experimental set up to study



(a) (b)

Figure 11: Simulated surface and vector current distribution along wearable rectangular microstrip patch antenna. (a) Without embedding the square SRR. (b) With embedded square SRR inside the slot.

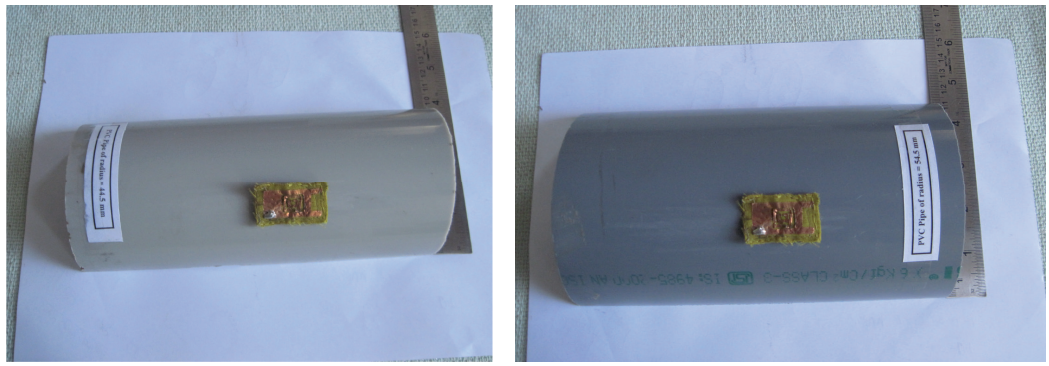


Figure 12: Photographs of proposed antenna bent on PVC pipes of 54.5 mm and 44.5 mm radii.

Figure 13: Photograph of experimental set up to test the bending effect on fabricated metamaterial SRR embedded wearable rectangular microstrip patch antenna.

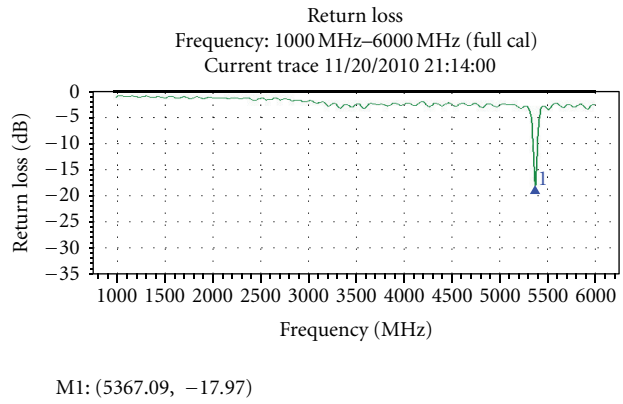


Figure 14: Measured reflection coefficient (S_{11}) characteristics of the proposed wearable antenna bent on 54.5 mm radius PVC pipe.

the bending effect on proposed wearable antenna swaddled on the PVC pipe.

Figures 14 and 15, respectively, depict the measured return loss (S_{11}) characteristics of the antenna under bending conditions on the PVC pipes of radii 54.5 and 44.5 mm, respectively.

When this antenna is bent on the pipe of radius 54.5 mm it resonates at 5.367 GHz with return loss of −17.97 dB as shown in Figure 14. Similarly, when the antenna is bent on pipe radius of 44.5 mm the resonant frequency of the antenna is shifted to 5.388 GHz with the return loss is −20.22 dB as shown in Figure 15. From the experimental results it is observed that in bending condition the resonant frequency of the proposed antenna is shifted to higher side when the antenna is more bent because the resonant length of the antenna is reduced. When the reflection coefficient

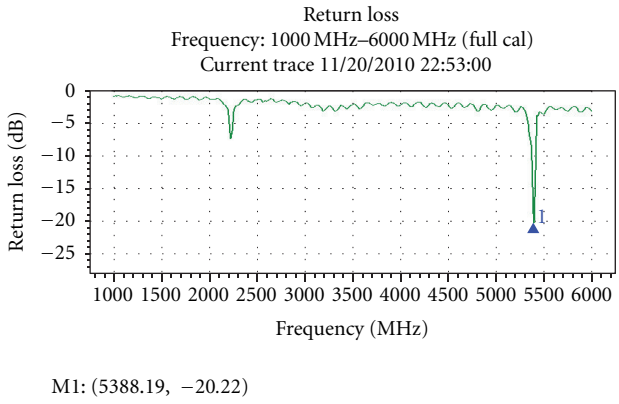


Figure 15: Measured reflection coefficient (S_{11}) characteristics of the proposed wearable antenna bent on 44.5 mm radius PVC pipe.

Figure 16: On body positioning of the fabricated metamaterial SRR embedded wearable rectangular microstrip patch antenna.

(S_{11}) and impedance bandwidth of measured results in bending conditions are studied, no extensive changes in the performance of the proposed antenna are observed.

Figure 16 shows the photographs of on body positioning of the fabricated wearable antenna on the helmet and shoulder, respectively. Thus, it is observed that the slotting means metal removing technique which is an advantageous approach to (a) reduce the adverse effects on wearable antenna due to bending and (b) minimize the electromagnetic absorption (SAR) in the human body. The impedance mismatch due to slotting in the microstrip patch at the subwavelength resonance is well matched by embedding the metamaterial SRR. This technique avoids the complex techniques to reduce the size and to enhance the performance of microstrip patch antennas like meandering, shorting pin, and so forth.

5. Conclusion

In this paper, a metamaterial square SRR embedded wearable rectangular microstrip patch antenna for IEEE 802.11a WLAN applications is presented. The bending effect on the performance of wearable antenna can be reduced making slots in the radiating patch but it leads to mismatching the impedance at the subwavelength resonance, that is, at desired lower resonance frequency. It is found that the embedding a metamaterial SRR is an advantageous approach to obtain the better impedance matching at the desired resonance frequency. This SRR introduces additional inductance, capacitance, and mutual inductance to match the impedance at the required frequency. The simulated and measured frequency of the proposed wearable antenna is found to be in good agreement. The important features of this antenna are light weight, simple fabrication, and low cost. In further study, the authors have extended their work to measure the SAR of the proposed antenna.

Acknowledgments

The authors sincerely express their gratitude to the anonymous reviewers for their valuable comments. The support of Director, National Institute of Technical Teachers Training and Research (NITTTR), Chandigarh, India, is thankfully acknowledged. J. G. Joshi is highly indebted to Director, Directorate of Technical Education, Mumbai (M.S.), India, and Principal, Government Polytechnic, Pune, India, for sponsoring him to pursue full time Ph.D. under AICTE sponsored Ph.D. QIP (POLY) scheme.

References

[1] P. S. Hall, Y. Hao, and S. L. Cotton, "Advances in antennas and propagation for body centric wireless communications," in *Proceedings of the 4th European Conference on Antennas and Propagation (EuCAP '10)*, April 2010.

[2] C. Hertleer, H. Rogier, L. Vallozzi, and L. Van Langenhove, "A textile antenna for off-body communication integrated into protective clothing for firefighters," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 919–925, 2009.

[3] 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.

[4] A. Tronquo, H. Rogier, C. Hertleer, and L. Van Langenhove, "Robust planar textile antenna for wireless body LANs operating in 2.45 GHz ISM band," *Electronics Letters*, vol. 42, no. 3, pp. 21–22, 2006.

[5] 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*, no. 22, pp. 53–71, 2010.

[6] P. Salonen 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.

[7] A. Alù, F. Bilotti, N. Engheta, and L. Vegni, "Subwavelength, compact, resonant patch antennas loaded with metamaterials," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 1, pp. 13–25, 2007.

[8] P. Y. Chen and A. Alu, "Dual-mode miniaturized elliptical patch antenna with μ-negative metamaterials," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 351–354, 2010.

[9] F. Bilotti, A. Alu, and L. Vegni, "Design of miniaturized metamaterial patch antennas with μ-negative loading," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 6, pp. 1640–1647, 2008.

[10] J. G. Joshi, S. S. Pattnaik, S. Devi, and M. R. Lohokare, "Electrically small patch antenna loaded with metamaterial," *IETE Journal of Research*, vol. 56, no. 6, pp. 373–379, 2010.

[11] J. Montero-de-Paz, E. Ugarte-Muñoz, F. J. Herraiz-Martínez, V. Gonzáalez-Posadas, L. E. García-Muñoz, and D. Segovia-Vargas, "Multifrequency self-diplexed single patch antennas loaded with split ring resonators," *Progress in Electromagnetics Research*, vol. 113, pp. 47–66, 2011.

[12] 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.

[13] J. G. Joshi, S. S. Pattnaik, S. Devi, and M. R. Lohokare, "Microstrip patch antenna loaded with magnetoinductive waveguide," in *Proceedings of the 12th National Symposium on Antennas and Propagation (APSYM '10)*, pp. 101–105, Department of Electronics, Cochin University of Science and Technology (CUSAT), Cochin, India, 2010.

[14] F. E. Gardiol, "Report on APSYM'2010: national symposium on antennas and propagation," *IEEE Antennas and Propagation Magazine*, vol. 53, no. 1, pp. 123–126, 2011.

[15] S. S. Pattnaik, J. G. Joshi, S. Devi, and M. R. Lohokare, "Electrically small rectangular microstrip patch antenna loaded with metamaterial," in *Proceedings of the International Symposium on IEEE Antennas and Propagation Society*, pp. 247–250, Guangzhou, China, December 2010.

[16] J. N. Hwang and F. C. Chen, "Study of SAR reduction with split ring resonators," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium and USNC/URSI Meeting*, vol. 2, pp. 780–783, Washington, DC, USA, July 2005.

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

[18] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 11, pp. 2075–2084, 1999.

[19] D. R. Smith, D. C. Vier, T. Koschny, and C. M. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Physical Review E*, vol. 71, no. 3, Article ID 036617, 11 pages, 2005.

[20] R. W. Ziolkowski, "Design, fabrication, and testing of double negative metamaterials," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 7, pp. 1516–1529, 2003.

[21] 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 Transactions on Microwave Theory and Techniques*, vol. 55, no. 12, pp. 2865–2873, 2007.

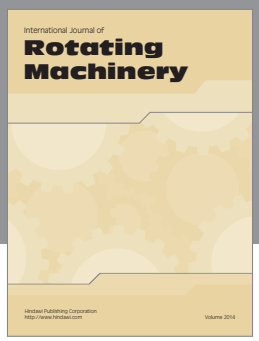
[22] J. G. Joshi, S. S. Pattnaik, S. Devi, and M. R. Lohokare, "Bandwidth enhancement and size reduction of microstrip patch antenna by magnetoinductive waveguide loading," *Journal of Wireless Engineering and Technology*, vol. 2, no. 2, pp. 37–44, 2011.

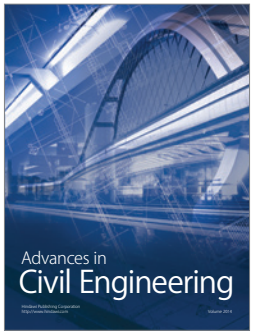
[23] J. G. Joshi, S. S. Pattnaik, and S. Devi, "Partially metamaterial ground plane loaded rectangular slotted microstrip patch antenna," *International Journal of Microwave and Optical Technology*, vol. 7, no. 1, pp. 1–11, 2012.

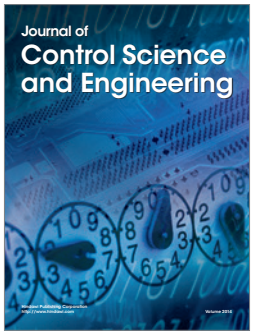
[24] A. K. Agrawal, S. S. Pattnaik, S. Devi, and J. G. Joshi, "Broadband and high gain microstrip patch antenna for WLAN," *Indian Journal of Radio and Space Physics*, vol. 40, no. 5, pp. 282–286, 2011.

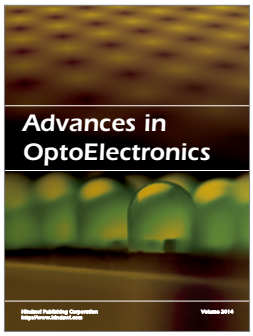
[25] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House, Norwood, Mass, USA, 1980.

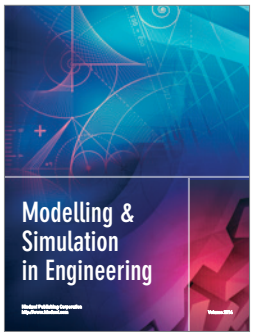
[26] I. J. Bahl and P. Bhartia, *Microstrip Antennas*, Artech House, Dedham, Mass, USA, 1980.

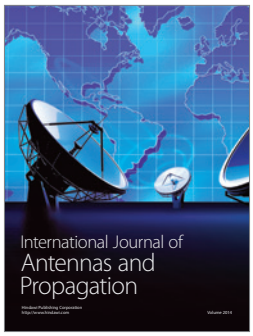


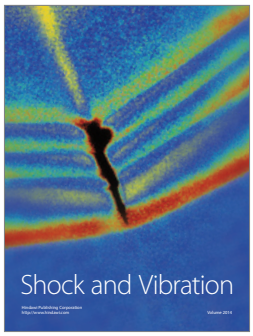


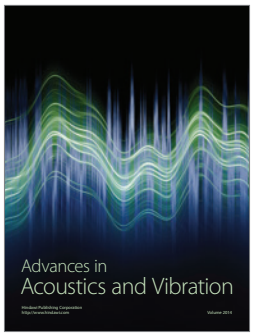












Hindawi

Submit your manuscripts at
http://www.hindawi.com