Geo-textile Based Metamaterial Loaded Wearable Microstrip Patch Antenna

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

National Institute of Technical Teachers Training and Research, Sector-26, Chandigarh -160 019, India.
Tel: + 91 9872879362; +91 172 2791349; Fax: +91 172 2791366 *E-Mail: shyampattnaik@yahoo.com

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
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 ($\mu$) and electric permittivity ($\varepsilon$) [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.

![Geometrical sketch of metamaterial loaded wearable T-shaped microstrip patch antenna](image)

Fig. 1. Geometrical sketch of metamaterial loaded wearable T-shaped microstrip patch antenna on geo-textile polypropylene substrate.
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 \( (g_1) \) is also set to 7.5. The ratio of the gaps of lower square SRRs \( (g_4) \) 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 \( 0.369 \lambda \times 0.369 \lambda \) where \( \lambda \) 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 \( (g_1) \) is also set to 7.5. The ratio of the gaps of lower square SRRs \( (g_4) \) 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 \( 0.369 \lambda \times 0.369 \lambda \). 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 \( \epsilon_r = 2.2 \) 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 IESDEM 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](image-url)
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 shows the reflection ($S_{11}$) and transmission ($S_{21}$) coefficient characteristics of square SRR that resonates at 8.48 GHz. The effective medium theory is used to verify the permeability ($\mu_r$) and permittivity ($\varepsilon_r$) from the reflection and transmission coefficients ($S$-parameters). The Nicolson-Ross-Weir (NRW) approach is used to obtain the effective medium 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].

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

(1)

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

(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 $k_0 h = 0.336$ which is <<1 [21-22]. The values of $V_1$ and $V_2$ are calculated using equations (3) and (4) [13-18],[21-23].

$$V_1 = S_{21} + S_{11}$$

(3)

$$V_2 = S_{21} - S_{11}$$

(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 ($\mu_r$) characteristics of the SRR which indicates that the SRR structure is single negative (MNG) metamaterial. The value of permeability ($\mu_r$) 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. 4. Reflection ($S_{11}$) and Transmission ($S_{21}$) coefficient characteristics of square SRR

Fig. 5. Relative permeability ($\mu_r$) characteristics of the square SRR
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 shows the equivalent circuit diagram of metamaterial square SRR loaded polypropylene based wearable T-shaped microstrip patch antenna.

Fig. 9. Equivalent circuit diagram of metamaterial loaded wearable T-shaped microstrip patch antenna on polypropylene substrate.
Basically, SRR is a LC resonant circuit where \( L \) and \( C \) are the equivalent inductance and capacitance respectively. \( L_{\text{max}} \) represents the probe inductance. The inductance \((L)\) of the square SRR is calculated using equation (5) [14], [16-18], [23-24],

\[
L = \frac{\mu_0}{2} \frac{L_{\text{avg}}}{4} 4.86 \left[ \ln \frac{0.98}{\rho} + 1.84 \rho \right]
\]  

(5)

where \( \mu_0 \) is permeability of free space \((4\pi \times 10^{-7} \text{ H/m})\), \( \rho \) is the filling ratio expressed as \( \rho = \frac{(N-1)(w+s)}{L_s-(N-1)(w+s)} \), \( L_{\text{avg}} \) is the average length of square SRR and calculated as \( L_{s\text{avg}} = 4[L_s - (N-1)(w+s)] \) 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].

\[
C = \varepsilon_0 \frac{N-1}{2} \left[ 2L_s - (2N-1)(w+s) \right] \frac{K\sqrt{1-k_1^2}}{K(k_1)}
\]  

(6)

where \( \varepsilon_0 \) is the permittivity of free space \((8.854 \times 10^{-12} \text{ F/m})\), \( K \) 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 \( L = 30 \text{ nH} \) and capacitance \( C = 0.0119 \text{ pF} \). 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 \( \text{nH} \) by using equation (7) [14], [17-18], [24].

\[
M_1 = \frac{\mu_0 L_{\text{g}}}{2\pi} \left[ 0.467 + \frac{0.059 w^2}{L_{s\text{avg}}^2} \right]
\]  

(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 \( \text{nH} \) using equation (8) [14], [17-18], [24].

\[
M_2 = M_3 = M_4 = \frac{\mu_0 L_{\text{g}}}{2\pi} \left[ 0.467 + \frac{0.059 (W_r+w)^2}{L_{s\text{avg}}^2} \right]
\]  

(8)

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

\[
L_{h\text{r}} = \frac{\mu_0 L_{\text{g}}}{2\pi} \left[ \ln \left( \frac{2L_{\text{g}}}{W_r} \right) + 0.5 + \left( \frac{W_r}{3l_{\text{r}}} \right) - \left( \frac{W_r^2}{24l_{\text{r}}^2} \right) \right]
\]  

(9)

The values of \( L_{h\text{r}} \) and \( L_{v\text{r}} \) are calculated at the lengths \( L_{h\text{r}} = 22.5 \text{ mm} \) and \( L_{v\text{r}} = L_{v\text{r}} = 10 \text{ mm} \) 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.
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.

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.

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

ACKNOWLEDGEMENT

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


