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Rectangular Slotted Microstrip Patch Antenna with Partially Loaded Metamaterial Ground Plane

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***Abstract*- In this paper, a rectangular slotted microstrip patch antenna with partially loaded metamaterial multiple-split ring resonator (MSRR) ground plane is presented. In unloaded condition, the rectangular slotted patch antenna resonates at 9.38 GHz. When the same antenna is loaded with MSRR in the ground plane, it resonates at lower resonant frequencies 4.60 GHz and 7.70 GHz respectively. The mutual coupling between the slots leading to mismatch at lower resonant frequencies is analyzed in this paper. The MSRR loading reduces the mutual coupling in order to obtain better matching at these resonant frequencies. The simulated result of MSRR is validated using the principles of equivalent circuit theory. The size of antenna at lower resonant frequency is 0.306 λ × 0.153 λ.**

***Index Terms*- Planar metamaterial, multiple split ring resonator, equivalent circuit theory, finite ground plane, mutual coupling.**

I. INTRODUCTION

There is a growing demand for compact as well as multi-band microstrip patch antennas in the rapidly changing scenario of wireless and mobile communication to simultaneously access the multimedia information. Secondly, these antennas need the features such as high gain, high directivity, and large bandwidth to achieve faster data transfer rates [1-12]. Antenna researchers are striving hard to design substantially diminutive antennas according to the progressively reducing size of the communication devices and handheld equipments.

Microstrip patch antennas have greater prospective due to their low profile, light weight and low cost. Moreover, the performance of these antennas (bandwidth and gain, multi-band characteristics, miniaturization, etc.) can be enhanced by using the state-of-art techniques such as making the slots inside the patch, meandering, stacking, use of high permittivity substrates, shorting pin etc. On the other hand the above mentioned techniques have certain limitations [1-12]. Up to a great extent use of metamaterial has appreciably eliminated these limitations. Metamaterial loading is found to be an advantageous approach not only to generate the sub-wavelength resonances but also to significantly enhance the gain, bandwidth, and directivity of the microstrip patch antennas [3-12]. In this section, a brief literature review is presented to emphasize the use of metamaterial structures to partially fill the substrate or load the microstrip patch antennas for miniaturization and performance enhancement.

In 1968, Veselago theoretically predicted the basic properties of the hypothetical material simultaneously possessing the negative values of magnetic permeability (μ) and electric permittivity (ε) termed as metamaterial or double negative metamaterials (DNG) [13]. Metamaterial structure consists of split ring resonators (SRRs) to produce negative permeability and thin wire elements to generate negative permittivity. In single negative (SNG) metamaterials, if the permeability (μ) is negative then the materials are termed as the mu negative (MNG) metamaterials and incase the permittivity (ε) is negative the materials are termed as epsilon negative (ENG) metamaterials. The metamaterial characteristics of different split ring resonators like circular, square, rectangular, omega (Ω), split squared ring resonator (SSRR), MSRR, spiral and labyrinth resonators, etc. have been reported in [7-9, 14-20]. These resonators are widely used in different microwave applications such as antennas, waveguides, filters etc. [3-12, 20].

A. Alu *et al.* in the year 2007 reported that the metamaterial loaded microstrip patch antenna generates sub-wavelength resonance [3]. Miniaturized microstrip patch antennas loaded with metamaterial are presented in [4-5]. Recently, the authors have reported the planar electrically small microstrip patch antenna loaded with metamaterial square SRR and MSRR respectively [7-8]. The desirable resonant frequency and bandwidth can be obtained by varying the loading distance between the microstrip antenna and the metamaterial element [9]. Metamaterial based magneto-inductive (MI) waveguide loading technique is used for bandwidth enhancement and size reduction of microstrip patch antenna [20]. Thus, the metamaterial loading endows the advantages of miniaturization, enhancement of bandwidth and gain.

The slotted microstrip patch antennas are commonly used in various communication applications such as radar and satellite communication systems [1-2]. The magnetic coupling between the slots restricts the performance of microstrip patch antennas [21]. In the literature, different techniques such as use of lossy superstrate, incorporating slits, incorporating electromagnetic band-gap structures etc. have been reported to reduce the mutual coupling between the slotted antennas [11, 22]. But these techniques deteriorate the antenna performance by one or the other way like reduction in antenna gain [22]. Novel methods have been reported to reduce the mutual coupling between the closely placed antennas using metamaterial split ring resonators [10-12]. In their previous work, authors used the metamaterial resonators to directly load the microstrip patch antennas to achieve miniaturization, as well as bandwidth and gain enhancement.

In this work, metamaterial MSRR is used to reduce the mutual coupling between the slots of rectangular microstrip patch antenna. The objective of this paper is to propose a rectangular slotted microstrip patch antenna loaded with metamaterial MSRR at the ground plane. This technique reduces the mutual coupling between the slots and generates the multi-resonant characteristics with considerably high gain and bandwidth. After making the slots in the rectangular microstrip patch, poor matching is observed at the lower resonant frequencies due to the mutual coupling between slots whereas better matching is obtained at the higher resonance band. However, impedance matching is improved at the lower frequencies by partially loading the slotted antenna with MSRR at the ground plane. This paper is organized into four sections. The detailed geometrical structure of the rectangular slotted microstrip patch antenna and the MSRR unit cell with their designs are presented in section II. The design of MSRR loaded configuration of this antenna on finite ground plane is also elaborated in this section. In section III, the metamaterial characteristics as well as the equivalent circuit analysis of the MSRR are verified and demonstrated in detail. The results of both unloaded and loaded conditions of rectangular slotted microstrip patch antenna are presented, and analyzed in this section. The mutual coupling effect between the slots is also calculated and discussed in this section. Finally, the paper is concluded in section IV.

II. ANTENNA DESIGN

Fig.1 shows the sketch and geometries of the rectangular slotted microstrip patch antenna. In this structure, initially a rectangular microstrip patch antenna of dimensions L_s = 20 mm and width W_s = 10 mm is designed. In dominant mode (TM_{010}), the resonant frequency (f_r) of rectangular microstrip patch antenna is expressed by the equation (1) [23].

$$f_r = \frac{c}{2L_s\sqrt{\varepsilon_r}} \qquad (1)$$

where c is the velocity of light (3×10^8 m/sec). Using a substrate of dielectric constant (ε_r) = 2.20, the rectangular microstrip patch antenna resonates at 5.05 GHz for the designed length L_s = 20 mm. Then in the same rectangular patch a pair of symmetric slots which are separated by a distance of 'd' are etched to excite the adjacent resonant modes of the rectangular microstrip patch antenna in order to obtain the multi-frequency bands. Each slot consists of a square slot and has extended arms in the four sides of the square slot to allow the current to travel a longer path. The dimensions of the slot are length b and width a.

By proper adjustment of the dimensions of both the slots, resonant frequencies are obtained. However, the 50 Ω impedance matched feed position at the lower resonant frequencies could not be obtained in the patch on the finite ground plane condition. Hence, the proposed MSRR unit cell is etched on the ground plane to obtain better impedance matching at the lower resonant frequencies. The design parameters of both the slots are; l_1 = 2 mm, l_2 = 1.5 mm, w_1 = 2 mm, and w_2 = 1 mm as depicted in Fig.1. These slots are etched out in the rectangular microstrip patch antenna. The slots are separated by a distance d = 1.9 mm. The design parameters of the antenna are as presented below. The aspect ratio of the rectangular microstrip patch that is width (W_s) to the length (L_s) has been fixed to 0.5. The aspect ratio of rectangular slots of slot 1 and slot 2 that is width (w_2) to the length (l_1) is fixed to 0.5. The aspect ratio of inner dimension (a) to outer dimension (b) of both the slots is also fixed at 0.5. The centre-to-centre distance between both the slots is kept to 10 mm that is 0.5 (aspect ratio) × length of rectangular microstrip patch (L_s). Both the slots due their extended arms in the four sides lengthen the excited current paths to achieve the resonant modes.

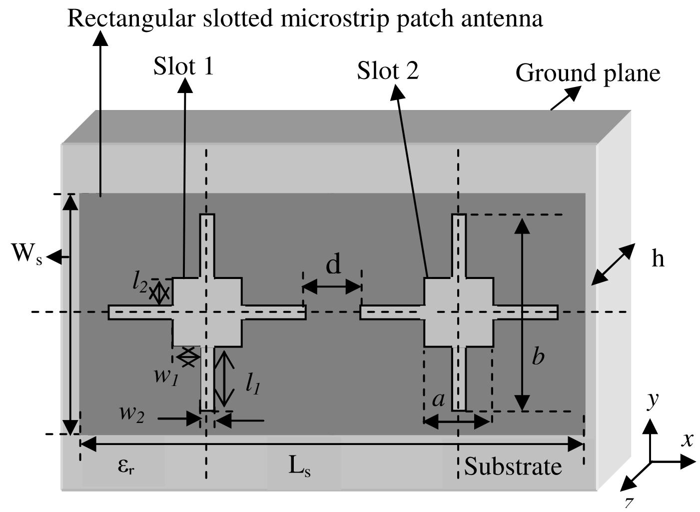


Fig. 1. Sketch and geometrical structure of rectangular slotted microstrip patch antenna

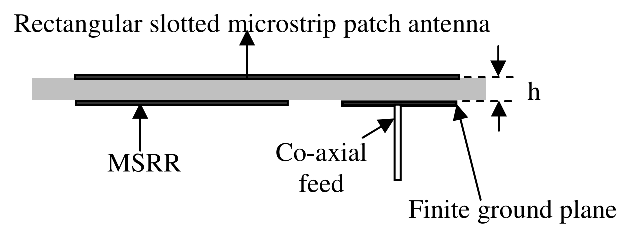


Fig.2. Cross sectional view of rectangular slotted microstrip patch antenna loaded with MSRR on the finite ground plane

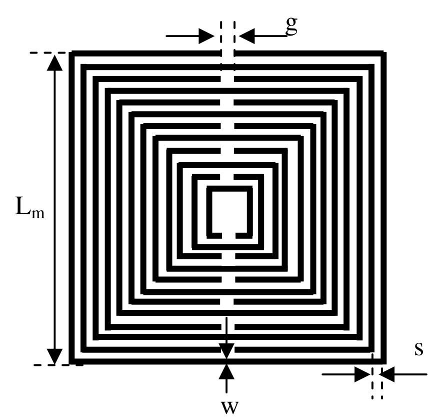


Fig.3. Geometrical structure of MSRR (Number of split rings N = 12) etched on the ground plane

The expressions of higher (f_h) and lower (f_l) resonant frequencies of the rectangular slotted microstrip patch antenna are modified and are approximated for this antenna as equation (2) and equation (3) respectively [25].

$$f_h = \frac{c}{\left[2\left(\frac{b}{4} + \frac{L_s}{4} + \frac{W_s}{2} - \frac{a}{4}\right)\sqrt{\varepsilon_r}\right]} \quad (2)$$

$$f_l = \frac{c}{\left[2\left(\frac{b}{2} + \frac{L_s}{2} + W_s - \frac{a}{2}\right)\sqrt{\varepsilon_r}\right]} \quad (3)$$

Fig.2 depicts the cross sectional view of the rectangular slotted microstrip patch antenna loaded with MSRR on the finite ground plane. The MSRR and finite ground plane are accommodated on the back side of the substrate that is beneath the rectangular slotted patch antenna with a separation of 6 mm. The proposed antenna is co-axially excited through a finite ground plane of dimension 10 mm × 4 mm. Fig.3 presents the structure of MSRR unit cell which is etched on the ground plane. The geometrical dimensions of the MSRR are; length of outer most split ring is L_m = 10 mm, width of the split rings (w), gap at the splits (g), and the separation (s) between the two adjacent split rings are set to w = g = s = 0.2 mm respectively. The dimension of the MSRR is 0.055 λ that indicates it is a sub-wavelength resonator (where λ is the free space wavelength of the MSRR at resonant frequency 1.70 GHz). RT Duriod 5880 substrate of thickness h = 3.175 mm is used to design the proposed antenna. The antenna is co-axially fed (50 Ω) at the location x = 8 mm and y = 4 mm under both unloaded and loaded configurations.

III. RESULTS AND DISCUSSION

In this section, initially, the metamaterial characteristics of the MSRR have been verified and presented. Fig. 4 illustrates the reflection (S_{11}) and transmission coefficient (S_{21}) characteristics of the MSRR which resonates at 1.70 GHz, 2.68 GHz and 3.44 GHz respectively. The S-parameters of an isolated MSRR are obtained using the method reported in [8, 16-18]. In this work, IE3D electromagnetic simulator is used to obtain the S-parameters. The obtained S-parameters and subsequently using the mathematical equations (4) and (5) along with MATLAB code, the metamaterial characteristics have been verified. The effective medium theory is used to obtain the permeability (μ) and permittivity (ε) from the reflection and transmission coefficient parameters (S-parameters) using Nicolson-Ross-Weir (NRW) approach [7-9, 14-15, 20]. The below mentioned expressions of equations (4) and (5) are used to determine the effective medium parameters.

$$\mu_r = \frac{2}{jk_0 h}\frac{1 - V_2}{1 + V_2} \quad (4)$$

$$\varepsilon_r = \frac{2}{jk_0 h}\frac{1 - V_1}{1 + V_1} \quad (5)$$

where, k_0 is the wave number = $2\pi/\lambda$, V_1 and V_2 are the composite terms to represent the addition and subtraction of the S-parameters. The values of V_1 and V_2 are estimated using equations (6) and (7) as presented below.

$$V_1 = S_{21} + S_{11} \quad (6)$$

$$V_2 = S_{21} - S_{11} \quad (7)$$

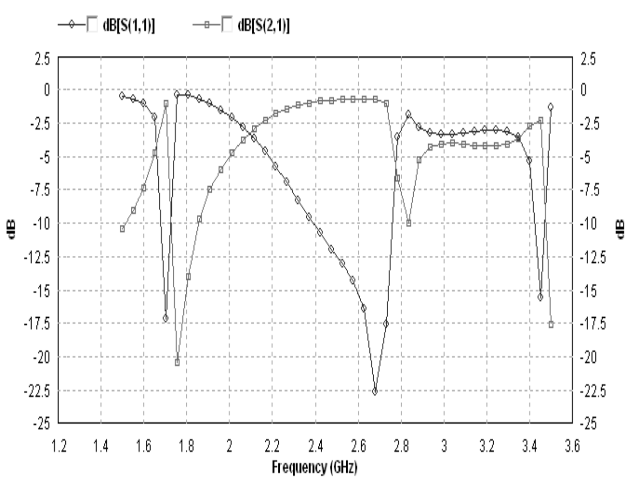


Fig. 4. Reflection coefficient (S_{11}) and transmission coefficient (S_{21}) characteristics of MSRR

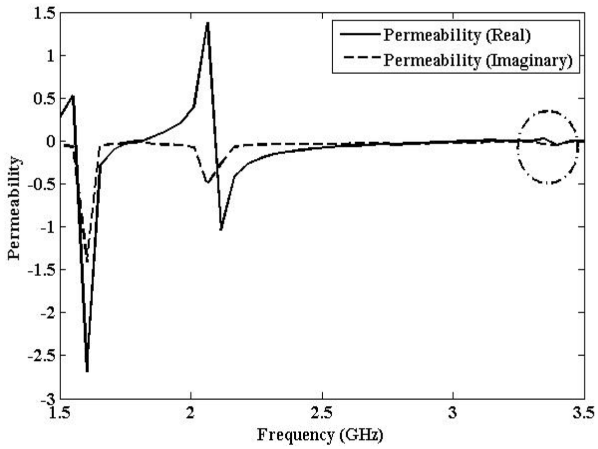


Fig.5(a). Relative permeability (μ_r) characteristics of MSRR as a function of frequency

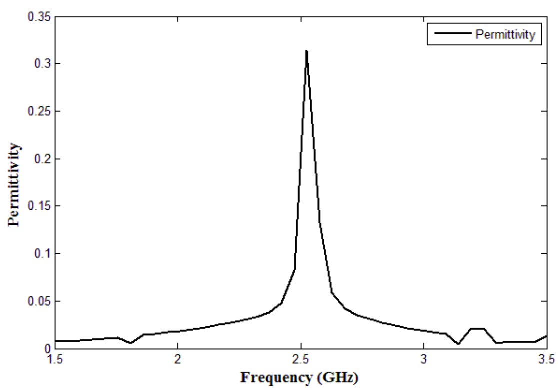


Fig.5(b). Relative permittivity (ε_r) characteristics of MSRR as a function of frequency

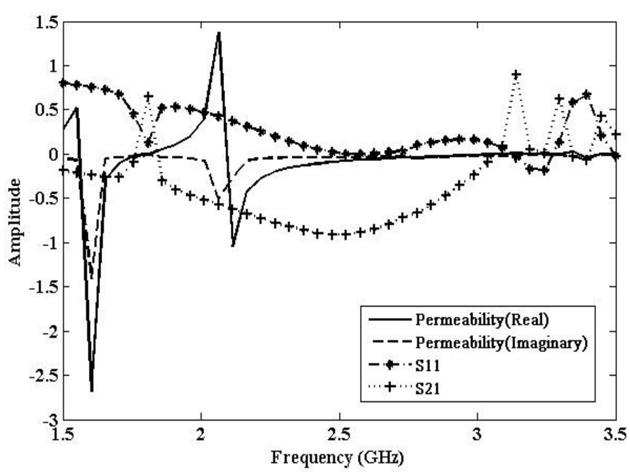


Fig.5(c). S-parameters and relative permeability (μ_r) characteristics of MSRR as a function of frequency

In MSRR, the factor k_0h = 0.113 which is <<1 [7-9, 14-15, 20] also satisfies the condition of sub-wavelength element. Fig. 5 (a) signifies the relative permeability (μ_r) characteristics of MSRR as a function of frequency. As seen from this figure, the negative permeability is observed near the respective resonant frequencies of the MSRR. Therefore, it exhibits the negative refractive index. In Fig.4, three resonant regions at frequencies 1.70 GHz, 2.68 GHz and 3.44 GHz respectively have been observed. Fig.5 (a) similarly shows the three negative permeability regions at these respective resonant frequencies. The first peak corresponds to narrow resonance with better matching whereas the second peak indicates the broader resonance with a good matched condition. The encircled portion in the figure (Fig.5 (a)) shows a small negative permeability peak that is observed at the third resonant frequency 3.44 GHz in the frequency range 3 GHz to 3.5 GHz. Thus, the MSRR structure used for loading the rectangular slotted microstrip patch antenna shows the metamaterial characteristics. Fig. 5 (b) shows the relative permittivity characteristics as a function of frequency. Fig.5 (c) depicts the S-parameters and relative permeability characteristics of MSRR as a function of frequency. The visible difference between the locations of MSRR resonances of negative relative permeability areas (Fig.4) and (Fig.5(a)) is due to the extraction formula for the relative permeability (equation 4) which particularly depends upon the values of V_1 and V_2 (in the form of S_{11} and S_{21}) which are the frequency dependent composite terms in that frequency region. This minor difference may therefore due to the approximation made between V_1 and V_2 and S_{11} and S_{21}. However, as seen the permeability has strong resonances and the transitions from the positive to negative values are closer to the resonant frequencies of MSRR in the respective frequency bands.

According to the principles of equivalent circuit theory, the MSRR is modeled as a *LC* resonant circuit. The values of equivalent *L* and *C* are calculated using mathematical equations (8) and (9) respectively [8, 16-20].

The equivalent inductance (L) is calculated using equation (8) [8, 16-20].

$$L = \frac{\mu_0}{2}\frac{L_{m\,avg}}{4} 4.86\left[\ln\left(\frac{0.98}{\rho}\right) + 1.84\rho\right] \quad (8)$$

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

The equivalent capacitance (C) of the MSRR is calculated using equation (9) [8, 16-20].

$$C = \varepsilon_0 \frac{N-1}{2}\left[2L_m - (2N-1)(w+s)\frac{K\sqrt{1-k^2}}{K(k)}\right] \quad (9)$$

where ε_0 is permittivity of free space (8.854×10^{-12} F/m), K is the complete elliptic integral of first kind, k is the argument of integral and determined by $k = \frac{s/2}{w+s/2}$. Thus, the estimated values of equivalent circuit elements are; L = 28.4 nH and C = 0.320 pF. Theoretically, using the values of L and C the calculated resonant frequency of the MSRR is 1.67 GHz. The simulated resonant frequency of an isolated MSRR is f_r = 1.70 GHz (Fig. 4) which is in good agreement with the theoretical results. Fig. 6 depicts the retrurn loss (S_{11}) charateristics of unloaded rectangular slotted microstrip patch antenna on a finite ground plane.

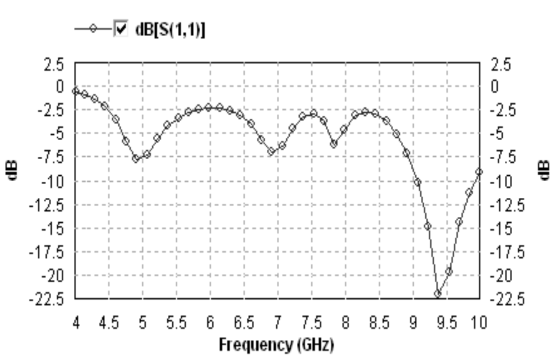


Fig.6. Return loss (S_{11}) characteristics of unloaded rectangular slotted microstrip patch antenna on the finite ground plane

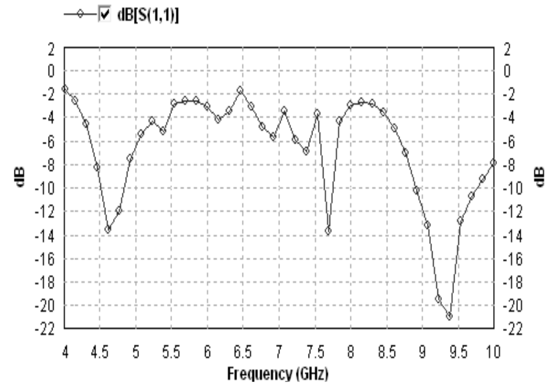


Fig.7. Return loss (S_{11}) characteristics of metamaterial MSRR loaded rectangular slotted microstrip patch antenna on the finite ground plane

In the unloaded configuration good matching is obtained at 9.38 GHz whereas poor matching is observed at the lower resonant frequencies. Thus, the antenna resonates at 9.38 GHz with the gain and bandwidth of 2.50 dBi and 9.18 % respectively. Hence, to obtain a good matching at lower frequencies, the slotted antenna is loaded with MSRR on the finite ground plane.

Fig. 7 shows the return loss characteristics of MSRR loaded rectangular slotted microstrip patch antenna on finite ground plane. In this configuration, the antenna resonates at 4.60 GHz and 7.70 GHz in addition to 9.38 GHz. Table 1 shows the comparion of resonant frequencies, bandwidth and gain under loaded and unloaded configurations of rectangular slotted microstrip patch antenna. The dimension of the antenna at lowest resonant frequency 4.60 GHz is 0.306 λ × 0.153 λ. Thus, in loading condition, multi-band performance is obtained by keeping the same physical size whereas the electrical size of the antenna has been reduced with a good bandwidth and gain at the respective resonant frequencies. The rectangular slotted microstrip patch antenna resonates at 9.38 GHz. The slots have been cut in this parch antenna to obtain the lower and higher resonant frequencies i.e. multi-band performance. But as seen from Fig. 6 poor matching is observed at lower resonant frequencies due to the mutual coupling between the slots. When the slotted patch is loaded with MSRR its effective capacitance provides good impedance matching at lower resonant frequencies 4.60 GHz and 7.70 GHz respectively in addition to the higher resonant frequency 9.38 GHz (refer Fig.7). Thus, three resonances are obtained after loading the MSRR.

Table 1: Comparison of parameters of the proposed antenna in unloaded and loaded configurations

Antenna parameters → / ↓ Antenna Configuration	Resonant Frequency, GHz	Gain, dBi	Bandwidth, MHz
Without loading	9.38$	2.30	861
With MSRR loading (loaded)	4.60 }	4	324
	7.70 }	5.57	112
	9.38 }	2.06	827

$: One band without loading ; }: Three bands with loading

In the unloaded configuration, due to reactive loading, the mutual coupling between the slots leads to mismatching of the impedance at lower resonant frequencies and a good gain and bandwidth is obtained at the matched higher resonant frequency 9.38 GHz as mentioned in Table 1. Under loading condition, the MSRR reduces the mutual inductance between the slots which significantly improves the matching at 4.60 GHz, 7.70 GHz and 9.38 GHz and hence considerable gain is obtained at the respective resonant frequencies as presented in Table 1. From equations (2) and (3) the frequency ratio of lower and higher resonant frequencies is found to be $f_l/f_h = 0.5$.

Effect of mutual coupling between the two slots

The mutual coupling between the slots of microstrip patch plays an important role in determining the input impedance of the antenna. In unloaded condition, the slotted antenna is not properly matched at the lower resonant frequencies. Hence, the mutual coupling contributed by the slots is analyzed. The edge-to-edge distance between slots is λ/16.8 that is 1.9 mm and a centre-to-centre distance is 10 mm. The mutual coupling factor 'F_g' between the slots is expressed as equation (10) [24].

$$F_g = \frac{g_m}{g_s} \qquad (10)$$

where g_m is the per unit length mutual conductance and g_s is the per unit length self-conductance.

The per unit length mutual conductance (g_m) is calculated by equation (11) [24].

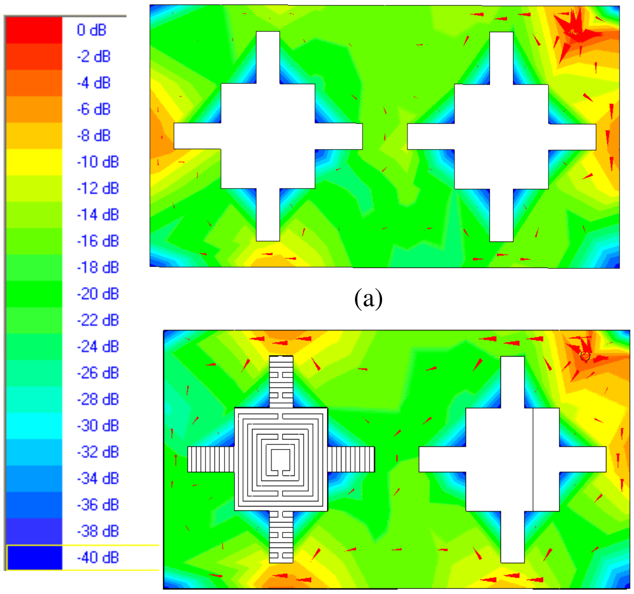
$$g_m = \frac{k_0}{\pi\eta_0}\left\{\left(1-\frac{s^2}{24}\right)J_0(L_w)+\frac{s^2}{24}J_2(L_w)\right\} \qquad (11)$$

where η_0 is the free space impedance, $s = k_0W_s$ is the normalized slot width, W_s is the width of slot, $L_w = k_0L_e$ and L_e is centre-to-centre distance between the two slots.

The per unit length self-conductance (g_s) is calculated using equation (12) [24].

$$g_s = \frac{k_0}{2\eta_0}\left(1-\frac{s^2}{24}\right) \qquad (12)$$

The calculated mutual coupling factor using equation (8) is 0.78. It is necessary to reduce this factor to achieve better input impedance matching. When the rectangular slotted microstrip antenna is loaded with MSRR, the time varying magnetic flux generated by the antenna induces the current on MSRR. It results in the large electric field across the capacitance associated with the MSRR. This capacitance compensates the inductance due to the fringing field developed at the slots of the antenna and good matching is obtained at the lower resonant frequencies. Thus, the capacitance of the MSRR is sufficiently large to match with the inductance of the rectangular slotted microstrip antenna which leads to reduce the mutual coupling between the slots. Therefore, the negative permeability MSRR acts as matching element at the lower resonant frequencies 4.60 GHz and 7.70 GHz respectively keeping the same matched condition at 9.38 GHz. In loading condition, the gain is enhanced because the MSRR acts as matching element and accepts maximum power from the source for radiation. Thus, the MSRR loading reduces the lowest resonant frequency of the proposed antenna to 4.60 GHz by reducing the antenna size. Fig. 8(a) illustrates the simulated current distribution along the unloaded rectangular slotted microstrip patch antenna, in which the current flows at the perimeter of slot number 2 whereas, there is almost no current flow path around the slot 1.

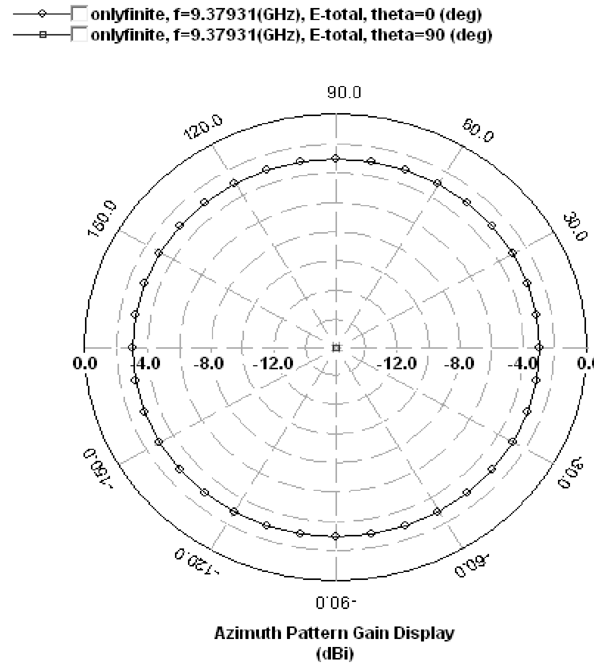


(b)

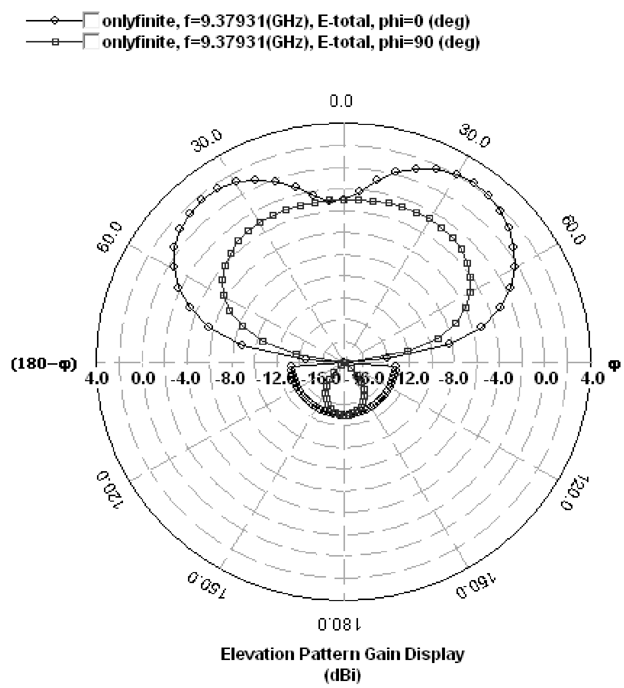
Fig.8. Simulated surface current distribution on the rectangular slotted microstrip patch (a) without MSRR loading (b) with MSRR loading conditions

Fig. 8(b) depicts the simulated current distribution along the MSRR loaded slotted microstrip patch. At the lower resonant frequencies, the loading capacitor of MSRR reduces the mutual coupling and forces the current to flow around the perimeter of slot 1 in the circular manner. Thus, the uniform current distribution around the edges of both the slots increases the current path length on the patch. This reduces the resonant frequencies of the loaded antenna and contributes to the radiations.

Fig. 9 (a) and Fig. 9 (b) respectively shows the radition patterns of the unloaded rectangular slotted microstrip patch antenna with finite ground plane. Fig. 10 (a) and Fig. 10 (b) respectively depicts the radition patterns of MSRR loaded recatngular slotted microstrip patch antenna on finite ground plane. The back lobe is observed in the radiation patterns of both configurations due to the field scattered from the edges of finite ground plane and the leakage radiation through the slots.

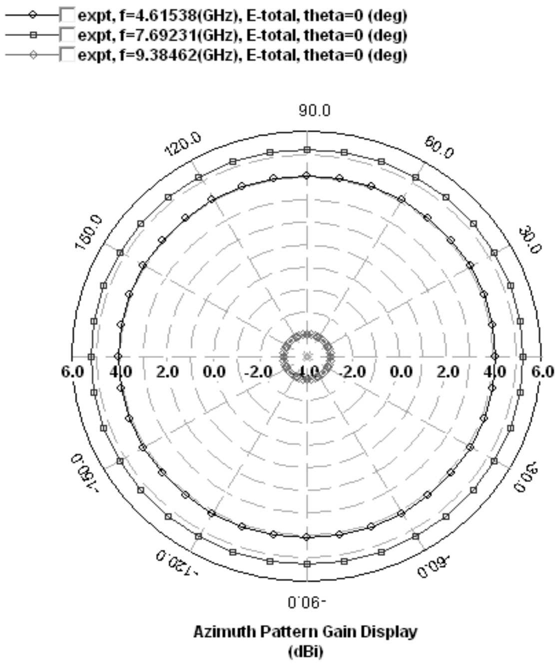


(a)

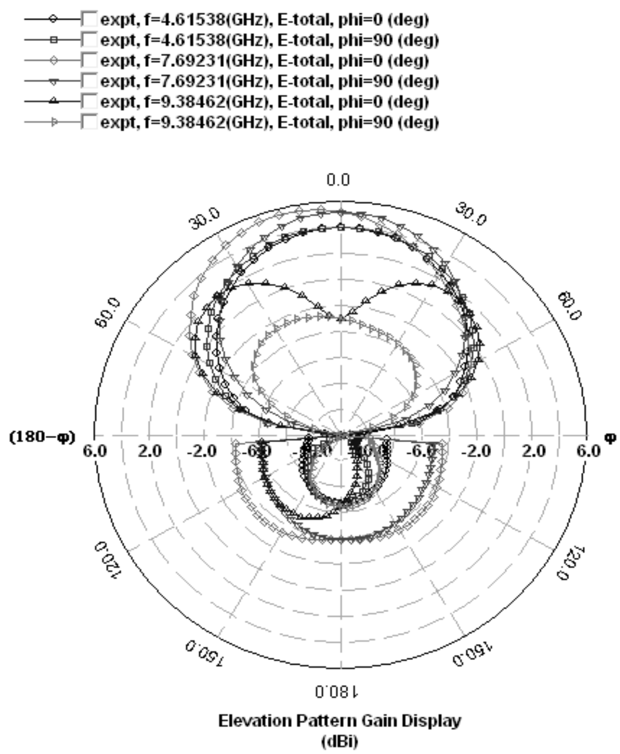


(b)

Fig.9. Radiation patterns of unloaded rectangular slotted microstrip patch antenna with finite ground plane (a) azimuth (b) elevation



(a)



(b)

Fig.10. Radiation patterns of metamaterial MSRR loaded rectangular slotted microstrip patch antenna with finite ground plane (a) azimuth (b) elevation

IV. CONCLUSION

The paper presents a metamaterial MSRR loaded slotted rectangular microstrip patch antenna. The metamaterial MSRR loading reduces the mutual coupling between the slots of microstrip patch antenna to obtain good impedance matching at lower resonant frequencies. Therefore, this loading technique resulted in multi-band operation with considerably good bandwidth, gain, and the miniaturization. Following interesting features are noted for the proposed antenna. There is flexibility to optimize the number of split rings (N) of MSRR to obtain better impedance matching at desired resonant frequencies. Different metamaterial resonators like spiral, labyrinth and circular MSRRs can be used without changing the slotted antenna structure. The current flow around the slots can be controlled with respect to the geometrical dimensions of the MSRR. This type of antenna can further be used to design the antenna array for various RF communication applications.

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