A Comparative Study of Two Different Type of Metamaterial Unit Cells for Miniaturization and Multiband of Microstrip Patch Antenna at 2.4 GHz Frequency

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Abstract. In this paper we design a multiband microstrip patch antenna (MPA) metamaterial (MM). We used two different types of MM unit cells and loaded these unit cells on the antenna, respectively. Thus, it can be decided which metamaterial is more appropriate for multiband and size reduction. One MM structure is new proposed geometry. It is in the shape of a Hindu mythological symbol ‘Swastiks’ and another MM unit cell is conventional split ring resonator. Before designing the MM loaded antenna, we analyze the characteristics of both kind of MM unit cells. We use the HFSS software for the simulation purpose.

1. Introduction
Microstrip patch antennas (MPA) are very popular in the present era of wireless communication technology because of its characteristics like less weight, compact, small size moderate gain and bandwidth [1]. Mobile handsets are in demand because new applications. New frequency bands and compact miniaturized system are required for recent wireless devices. Therefore, the antenna that covers the multiband characteristics with compact size is found to be more useful in present electronics wireless devices.
Presently 21st century electromagnetic playing a vital role in the designing of microwave devices, antenna and millimeter wave technology. In the 21st century electromagnetic double negative materials are key component, they also known as metamaterials (MM). Veselago first proposed the medium with negative refractive index [2], Pendry reported a Split Ring Resonator (SRR) with negative capabilities [3] and Smith extracted the different parameters of MM from reflection and transmission coefficients [4–7]. Some other methods are also defined for extracting the parameters of MM [8–9]. In different studies, metamaterials are used for directivity enhancement [10–11], size miniaturization [12], gain enhancement [10, 13] and used to generate multiband [14] antenna. Other applications of metamaterials are microwave filter [15] design, MIMO antennas [16] Phased array antenna [17].

In this paper we are designing a multiband MPA using MM, but first are comparing the behavior of two different MM unit cells individually and then these are loaded with MPA. Both MM unit cell having the same dimension but slightly different geometry. Both unit cells are designed on RT Duroid substrate of 12 mm x 12 mm x 1.57 mm dimension and having dielectric constant \(\varepsilon_r = 2.2\), with dielectric loss tangent \(\tan \delta = 0.0009\). We analyze the variation in the resonant frequency due to different geometry of MM unit cells. In the next part of paper, we insert the MM unit cell on the antenna structure and simulate the variation in various parameters of MPA. Antenna is designed at 2.34 GHz frequency.
2. Design and analysis of metamaterial unit cells

Here we have two metamaterial unit cell designs. First design is conventional split ring resonator and the second design is swastika shaped metamaterial unit cell. We have simulated both designs and analyze the results of same dimensional and different shape MM unit cells.

The size of antenna is inversely proportional to frequency.

\[ \varepsilon_p = \frac{1 - \omega_p^2}{\omega^2 + j \omega \zeta} = 1 - \frac{\omega_p^2}{\omega^2 + \zeta^2} + j \frac{\zeta \omega_p^2}{\omega (\omega^2 + \zeta^2)} \] ........................ (1)

Where

\[ \omega_p = \sqrt{\frac{2 \pi c^2}{\mu_0 p^2 \ln(p/a)}} \] ........................ (2)

\[ \zeta = \frac{\sigma (\omega_p a^2)}{n \sigma} \] ........................ (3)

(\(c = \)speed of light , \(a = \)radius of wire) is the electric plasma frequency, tunable in the GHz, and 

\[ \sigma = \text{conductivity of the metal} \] is a dumping factor due to metal losses. It clearly appears in this formula that

\[ \text{Re}(\varepsilon_p) < 0, \ \omega^2 < \omega_p^2 - \zeta^2, \] ........................ (4)

Which reduces if \(\zeta = 0\) to \(\varepsilon_p < 0\), for \(\omega < \omega_p\).

To induce resonating currents in the loop and generate equivalent magnetic dipole moments, this MM exhibits a plasmonic type permeability frequency function of the form

\[ \mu_r(\omega) = 1 - \frac{F \omega^2}{\omega^2 - \omega_{0m}^2 + j \omega \zeta} \] ........................ (5)

\[ \mu_r(\omega) = 1 - \frac{F \omega^2 (\omega^2 - \omega_{0m}^2)}{(\omega^2 - \omega_{0m}^2)^2 + (\omega \zeta)^2} + j \frac{F \omega^2 \zeta}{(\omega^2 - \omega_{0m}^2)^2 + (\omega \zeta)^2} \] ........................ (6)

Where \(F = \frac{(a/\rho)^2}{\alpha}, (a = \text{inner radius of the smaller ring})\)

And

\[ \omega_{0m} = c \left( \frac{3p}{\pi \ln(2 \rho a^2/\delta)} \right)^{1/2} \] ........................ (7)

(w = width of the rings, \(\delta = \)radial spacing between the rings)

2.1 Conventional metamaterial unit cell

The conventional split ring resonator unit cell as shown in Figure 1 having the dimensions are R1 (Outer radius of outer ring) = 5.2 mm and R2 (outer radius of inner ring) = 4.5 mm. Split ring width ‘w’ and gap between split rings ‘g’ = 0.5 mm. RT Duroid dielectric substrate is used with thickness 1.57mm. Unit cells were analyzed by wave guide mode analysis using Ansoft HFSS V.15 EM simulator. Master and slave boundaries are assigning to the waveguide wall and MM unit cell slab is placed in it. Floquet port excitation was applied to simulate periodic structure of unit cell. Solution frequency was 8 GHz; maximum number of passes was 15 and maximum delta was 0.02. In frequency sweep setting, sweep type was interpolating and frequency setup was linear count with 201 number of count. Frequency range for simulation was set from 6 GHz to 10 GHz. S11 and S21 parameters of the metamaterial unit cell are shown in Figure 2. S21 parameter is below -10dB from 7.6 GHz to 8 GHz frequency band and S21 is zero dB at the same frequency. S11 is below -10dB at 8.5 GHz frequency.
Figure 1. Proposed metamaterial unit cell where R1=5.2 mm R2 = 4.5 mm and g=w=0.5 mm.

Figure 2. S11 & S21 parameters of SRR.

The behaviour of the real and the imaginary parts of the effective magnetic permeability and permittivity for a system of split ring resonator is shown in Figure 3. At 7.8 GHz frequency real value of effective permeability is negative and permittivity is zero. This material is characterized as Mu negative material or MNG.

Figure 3. Re and Im part of $\epsilon$ and $\mu$ of SRR.

Equivalent circuit of the SRR structure is shown in Figure 4, where we are using parallel combination of $L_{eq}$ & $C_{eq}$. After simulation in ADS software we found $L_{eq} = 1$nH and $C_{eq} = 0.39$ pF. Resonant frequency can be calculated by following formula.
\[ f = \frac{1}{2\pi\sqrt{L_{\text{eq}}C_{\text{eq}}}} \quad \ldots \ldots \ldots (8) \]

By Figure 4 we have \( L_{\text{eq}} = 0.8\text{nH} \) and \( C_{\text{eq}} = 38\text{pF} \). Substituting these values in above equation and we found

\[ f = \frac{1}{2\pi\sqrt{1 \times 10^{-9} \times 0.38 \times 10^{-12}}} \]
\[ f = \frac{1}{2\pi\sqrt{0.038 \times 10^{-20}}} \]
\[ f = 8 \text{ GHz} \]

We get the resonance frequency of the above structure is 8 GHz. There is good agreement between calculated and the simulated results.

![Figure 4. Equivalent circuit conventional SRR](image)

2.2 Swastik shaped metamaterial unit cell

The swastika shaped SRR is shown in Figure 5. The unit cell dimension is 12 mm x 12 mm. Outer circle radius of outer ring \( R_1 = 5.2 \text{ mm} \) and outer circle of inner ring \( R_2 = 4.5 \text{ mm} \), \( g = w = 0.5 \text{ mm} \) as we used in previous design. RTDuriod dielectric substrate is used with thickness 1.57 mm. We added two strips, both are perpendicular to each other with the inner ring of the geometry to make swastika shaped MM unit cell. Width of the strips is 0.5 mm.

![Figure 5. Swastika shaped metamaterial unit cell](image)

Where Simulation results of swastika shaped MM is shown in Figure 6 Reflection parameter (S11) & transmission parameter (S21) is plotted w.r.t. frequency band. Simulation was done over the frequency
range from 2 to 10 GHz. S21 is below -10dB at 6 GHz frequency and S11 is below -10 dB is at 7.5 GHz frequency. Real and imaginary effective permittivity and permeability is shown in Figure 7. Real μ is negative at 7.4 GHz frequency. The equivalent circuit diagram of the swastika shaped MM unit cell is shown in Figure 8. The equivalent circuit diagram is designed on ADS software. Equivalent circuit diagram is a combination of lumped L & C. Resonant frequency of the equivalent circuit is 7.5 GHz.

![Figure 6. S11 and S21 parameters of swastika SRR.](image)

![Figure 7. Re and Im ε and μ of swastika SRR](image)

![Figure 8. Equivalent circuit model of swastika SRR](image)

In the above equivalent circuit the values of various components are L1 = 0.5nH, L2 = 0.5nH, L3 = 0.517nH, L4 = 1.84nH, C1 = 7.0 pF, C2 = 0.72 pF and C3 = 0.70pF.
2.3 Antenna design with MM unit cell.

In the previous section we have seen the characteristics of two MM unit cells of same dimension but with slightly changed geometry. In this section a simple MPA is designed at 2.4 GHz frequency and both kind of MM unit cell is loaded on the antenna respectively for miniaturization and multibanding. Patch made-up of copper, having a dimension of 29.66 mm x 38.1 mm. Quarter wave transformer is 24.05 mm long and 1.5 mm wide and feed is 15 mm long and 5 mm wide. The dielectric substrate material is RT duroid having the dimension 110 mm x 98.5 mm. Thickness of the substrate is 1.57 mm. Over all dimension of the antenna is 110 mm x 98.5 mm with the same size of ground plane. Simulation of microstrip antenna was done on HFSS software. MPA is shown in Figure 9 and its corresponding S11 vs frequency curve is show in Figure 10.

**Figure 9.** Microstrip patch antenna with a = 29.66 mm, l = 38.1 mm, b = 24.05mm, s = 1.5 mm, w = 5mm, L = 98.5mm and W = 100mm.

**Figure 10.** Reflection parameter vs frequency plot of MPA.

MPA is resonant at 2.4 GHz frequency and gain of the antenna is 7.1dB. In Table1 antenna parameters are summarize.
Table 1. Simulation results of MPA without MM cell

| Parameters          | MPA   |
|---------------------|-------|
| S11                 | -32dB |
| Resonating frequencies | 2.4 GHz |
| VSWR                | 1.647 |

We coupled both of the unit cells (Proposed SRR and conventional SRR) with the MPA respectively. The MPA with both types of MM cells is shown in Figure 11. Wavelength of the unit cells is taken approximately 1/3\(^{rd}\) wavelength of antenna. Here three unit cells are inserted on the both side of the antenna and the location of the unit cells are on the radiation side of the antenna. When we loaded the MM unit cell on antenna then electric field of the unit cell disturbs the electric field of the antenna and results variation in the antenna parameters.

Figure 11. (a) MPA loaded with SRR (b) MPA loaded with SSRR

MPA with SRR loading is resonant on two frequencies, 2 GHz and 4.5 GHz. Whereas MPA with swastika shaped split ring resonator loading is resonating at 4 GHz, 4.5 GHz and 5 GHz. Simulation results are showing in Figure 12.

Figure 12. Simulation result of SRR & SSRR loaded MPA
Table 2. is showing the comparison between both type of MM loaded antenna

| Antenna Parameters | MPA with SRR | MPA with SSRR |
|--------------------|--------------|---------------|
| Resonating frequencies | 2 and 4.5 GHz | 4, 4.5 and 5 GHz |
| S11(dB)           | -12 and -18  | 23, 15 and 15 dB |
| VSWR              | 2 and 1.6    | 1.2, 1.9 and 1.9 |

As we have seen that the MPA is resonant at 2.4 GHz frequency and MPA loaded with SRR having one frequency band is 2 GHz. So miniaturization is also obtaining with multiband using MM with antenna. Reduction in the size of antenna can be calculated as

\[
\{ (2.4 - 2) / 2.4 \} \times 100 = 17\%
\]

We are getting approximately 17% reduction in the size of the antenna.

3. Conclusions
We have simulated the two different configurations of metamaterial unit cells and analyze their behavior with antenna. We find that MM cell can be used for miniaturization of antenna or for design a multiband antenna. We miniaturized the antenna and also generating multiband at the same time. This technique can be used in wireless communication or in mobile communication.

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