Frequency switching of electrically small patch antenna using metamaterial loading

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Received 17 May 2010; revised 18 March 2011; accepted 11 April 2011

A frequency switchable planar metamaterial loaded electrically small microstrip patch antenna, capable of resonating at different frequencies by varying the loading distance, has been presented in this paper. The rectangular microstrip patch antenna is loaded with planar metamaterial square split ring resonators (SRRs) in three different configurations at a distance of 0.25, 0.50 and 0.75 mm, respectively to get the switchable resonant frequency performance. The square SRRs reveals negative permeability ($\mu$) presenting the single negative metamaterial (SNG) characteristics. The unloaded rectangular microstrip patch antenna resonates at 23 GHz. In loading condition at different distances, the rectangular microstrip patch antenna resonates at 9.61, 9.51 and 9.41 GHz, respectively. Using Chu limit, size of the antenna, that is $ka$, reaches 0.766, 0.775 and 0.787 in respective configurations, thus, satisfies the condition $ka < 1$ for electrically small antenna. The resonant frequency of rectangular microstrip patch antenna decreases with respect to the loading distance due to magnetic coupling. As the loading distance gets reduced, the mutual inductance increases resulting in enhancement of the bandwidth of the antenna. In these three loading conditions, the radiation quality factor ($Q_{rad}$) is larger than the minimum $Q$ that is $Q_{chu}$. The directivity is more than 7.50 dBi in the presented configurations of electrically small rectangular microstrip patch antenna.

Keywords: Electrically small antenna (ESA), Planar metamaterial, Negative permeability metamaterial, Spilt ring resonator (SRR), Frequency switchable metamaterial loaded small antenna

PACS No.: 84.40.Ba

1 Introduction

The low profile antennas are gaining attention to incorporate it with the remaining circuitry on the integrated chip of the system or equipments. Electrically small antennas (ESAs) satisfy the requisite of such systems or equipments to a great extent because of their characteristics like small size, significant bandwidth, moderate gain, low cost and simple fabrication technique. In 1947, Wheeler defined an ESA whose maximum dimensions can fit inside a radian sphere, that is an imaginary sphere of radius equal to $\lambda/2\pi$ ($\lambda$ is free space wavelength). This indicates that the sphere must enclose the maximum dimensions of the antenna. This is more explicitly expressed by the relation $ka < 1$ where, $k = 2\pi/\lambda$ and ‘$a$’ is the radius of sphere enclosing maximum dimensions of the antenna. Chu derived a fundamental relationship between the size of antenna and quality factor ($Q$) called as Chu limit. This limit illustrates the minimum quality factor $Q$ to be attained by the antenna size of $ka$ (ref. 6). The performance of ESAs suffers from low radiation efficiency and gain, and it is also difficult to achieve high bandwidth. It is a challenging task to overcome these limitations and to design an ESA of desirable characteristics. There are various techniques used to enhance the performance of ESA like incorporating matching network, optimize the antenna topology. Alternatively, in microstrip patch antennas, various techniques are used to achieve better performance in compact size like slotting the radiating patch, shorting pin, meandering on the patch, and use of high dielectric substrates. But these methods have their own limitations.

Metamaterial are the artificial materials which possess simultaneously negative values of magnetic permeability ($\mu$) and dielectric permittivity ($\varepsilon$) if they are double negative (DNG) metamaterials. If the permeability is negative, the materials are termed as MNG, that is mu negative; or if epsilon, that is permittivity is negative, then it is called ENG. Hence, they are named as single negative (SNG) metamaterial. Pendry proposed an interesting subwavelength element that is split ring resonators (SRRs) to achieve negative permeability. Metamaterial has created an indelible mark in
microwave engineering applications like antennas, filters, waveguides, phase shifters, delay lines, subwavelength imagers, etc.

Richard W. Ziolkowski and group first reported a metamaterial based ESA using ENG spherical shell\textsuperscript{13-14}. In 2007, Kamil Boratay Alici & Ekmel Ozbay presented an electrically small split ring resonator antenna using monopole and circular SRRs which shows that metamaterials are the good candidates to obtain ESAs\textsuperscript{15}. In 2008, Meng Li et al. demonstrated the electrically small antenna which is an entirely planar antenna using metamaterial unit cell\textsuperscript{2}. In 2009, Z Duan et al. reported an ESA which is inspired by spired split ring resonator of the size $ka = 0.6745$ (ref. 3).

In the present paper, the feature of electrically small size is achieved by loading the conventional microstrip patch antenna by metamaterial square SRRs. In this design, a planar metamaterial square SRRs unit cell is placed at certain distance closer to the rectangular microstrip patch antenna to form a composite structure. By changing this distance, the resonant frequency of rectangular microstrip patch antenna is varied. This approach provided significant reduction in the antenna size with desired bandwidth and gain. The metamaterial based ESAs presented in literature are not entirely planar in nature, which limit their practical use especially in the planar application domain. The aim of the present study is to design planar electrically small microstrip patch antenna loaded by metamaterial with variable loading distance to achieve the frequency switching.

2 Antenna design

Figure 1 depicts the geometry of proposed composite structure of electrically small rectangular microstrip patch antenna loaded with metamaterial square SRRs unit cell. In this composition, the rectangular microstrip patch antenna is loaded with planar metamaterial square SRRs. The rectangular microstrip patch antenna is placed at distance, $d$, in the proximity of square SRRs. The dimensions of the rectangular microstrip patch antenna are: length, $L_r = 5$ mm; and width, $W_r = 0.5$ mm. This antenna is excited by the coaxial feed at the location $x = -3.2$ mm and $y = -2.2$ mm. The switchable configuration of the loaded antenna is obtained by varying the loading distance, $d$, to 0.25, 0.50, and 0.75 mm, respectively. This antenna is designed and simulated on RT Duriod 5880 substrate of thickness, $h = 3.175$ mm; and dielectric constant, $\varepsilon_r = 2.2$. The dimensions of the square SSRs are: length of outer split ring resonator, $L_s = 5$ mm; the gap at the split of both rings ($g$), separation between the inner and outer split rings ($s$) and width of the rings ($w$) are set to be $g = s = w = 0.2$ mm. The dimensions of the square SRRs is $0.083 \lambda \times 0.083 \lambda$ ($\lambda$ is the free space wavelength at the resonant frequency of the square SRR, that is 5 GHz). It shows that the SRR element used to load the rectangular microstrip patch antenna is subwavelength element. This antenna is simulated using method of moment based IE3D electromagnetic simulator of Zeland Software Incorporation, Fremont, USA. The unloaded microstrip patch antenna resonates at 23 GHz. Further, it is loaded with the SRRs unit cell at distance, $d = 0.25$ mm. In this configuration, the antenna resonates at 9.61 GHz and the calculated wavelength is 31.21 mm. Therefore, $k = \frac{2\pi}{\lambda} = 0.766 < 1$, which satisfies the condition that proposed antenna is an ESA. Similarly, in remaining configurations, the factor $ka$ of 0.775 and 0.787 are obtained when the loading distance ($d$) is varied to 0.50 and 0.75 mm, respectively. This indicates that in all the three configurations, the factor $ka < 1$, satisfies the condition of ESA\textsuperscript{2-7, 12-15}.

From the structure, it is seen that the SRRs unit cell is placed in the neighbourhood of coaxially fed rectangular microstrip patch antenna for loading. Due to the magnetic coupling, the field gets induced in the SRRs, which excites the inner and outer split rings...
and makes it to exhibit metamaterial behaviour. In loading condition, the resonant frequency of rectangular microstrip patch antenna is reduced by making the structure as an ESA. The increasing loading distance correspondingly reduces the resonant frequency of the antenna. Thus, the switchable frequency performance is achieved at different loading distances.

3 Results and Discussion

The inner and outer split rings of the SRRs unit cell are excited by coaxial feed at each split ring. The central conductor is connected to one side of the strip at the split and the outer is connected to the ground. Figure 2 shows the reflection ($S_{11}$) and transmission ($S_{21}$) coefficient characteristics of the square SRRs unit cell that resonates at 5 GHz.

The effective medium theory is used to extract 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 these parameters. The expressions of Eqs (1) and (2) are used to determine these effective parameters. The metamaterial characteristics of the SRRs are verified using the S-parameters obtained from IE3D electromagnetic simulator and MATLAB code with mathematical Eqs (1) and (2).

$$\mu_r = \frac{2}{j k_0 h} \frac{1-V_2}{1+V_2} \quad \ldots (1)$$

$$\varepsilon_r = \frac{2}{j k_0 h} \frac{1-V_1}{1+V_1} \quad \ldots (2)$$

where, $k_0$ is wave number; $h$, the substrate thickness; $V_1$ and $V_2$, the composite terms to represent the addition and subtraction of S-parameters. The factor $k_0h = 0.33$ which is $<<1$ (refs 10, 12). The values of $V_1$ and $V_2$ are estimated using Eqs (3) and (4):

$$V_1 = S_{21} + S_{11} \quad \ldots (3)$$

$$V_2 = S_{21} - S_{11} \quad \ldots (4)$$

This structure exhibits real negative permeability ($\mu_r$) as shown in Fig. 3, which indicates that the SRRs structure is single negative, that is mu negative (MNG) metamaterial. The value of permeability ($\mu_r$) is negative in the frequency range 4.8 - 5.3 GHz. From Fig. 3, better matching is observed near the resonant frequency of SRRs, that is, at 5 GHz in the range 4.8 - 5.3 GHz. In the same frequency band, the magnetic permeability (Fig. 3) is negative, thus, it exhibits negative refractive index.

The SRRs is modelled as a LC resonant circuit. According to the principles of equivalent circuit theory, $L$ and $C$ are the equivalent inductance and capacitance of square SRRs, respectively. Mathematical Eqs (5) and (6) are used to estimate the values of $L$ and $C$. The inductance ($L$) is calculated using Eq. (5) (ref. 16).

$$L = \frac{\mu_0 L_{avg}}{2} \left[ \frac{0.98}{\rho} + 1.84 \rho \right] \quad \ldots (5)$$

where, $\mu_0$ is the permeability of free space ($4\pi \times 10^7$ H m$^{-1}$); $\rho$, the filling ratio expressed as
\[ \rho = \frac{(N-1)(w+s)}{L_s - (N-1)(w+s)} \]

\[ L_s = \text{the average length of the square SRRs, which is calculated as} \]

\[ L_s = \frac{4L_s - (N-1)(w+s)}{4} \]

\[ N = \text{number of split rings (N = 2).} \]

The equivalent capacitance \( C \) of an isolated square SRRs is estimated using Eq. (6) (ref 16).

\[ C = \varepsilon_0 \frac{N-1}{2} \left[ 2L_s - (2N-1)(w+s) \frac{K\sqrt{1-k_1^2}}{K(k_1)} \right] \]  \hspace{1cm} \text{(6)}

where, \( \varepsilon_0 \) is the permittivity of free space \((8.854 \times 10^{-12} \text{ F m}^{-1})\); \( K \), complete elliptic integral of first kind; \( k_1 \), argument of integral \( k_1 = \frac{s/2}{w+s/2} \).

By using equivalent circuit theory and mathematical equations, the estimated values of equivalent circuit elements are: \( L = 37 \text{ nH} \) and \( C = 0.0311 \text{ pF} \). Theoretically, the calculated resonant frequency \( f_r \) of square SRRs is 4.8 GHz. The simulated resonant frequency of an isolated SRRs is \( f_r = 5 \text{ GHz} \) (Fig. 2), which is in good agreement with the theoretical results.

Figure 4 shows the return loss \( S_{11} \) characteristic of an unloaded rectangular microstrip patch antenna which resonates at \( f_r = 23 \text{ GHz} \). Figure 5 (a) presents the return loss \( S_{11} \) characteristics of the proposed antenna when the SRRs is placed at distance, \( d = 0.25 \text{ mm} \) from the rectangular microstrip patch antenna. The antenna under this condition resonates at 9.61 GHz with a bandwidth of 524 MHz. The minimum radiation quality factor \( Q_{chu} \) of the proposed antenna is estimated by using Eq. (7) and is found to be \( Q_{chu} = 3.57 \).

\[ Q_{chu} = \left( \frac{1}{k^3 a^3} + \frac{1}{k a} \right) \]  \hspace{1cm} \text{(7)}

The radiation quality factor \( Q_{rad} \) of an ESA should be adequately large and it should be greater than 10 \((Q_{rad} > 10)\), hence it is to be calculated. The radiation quality factor is mathematically expressed by Eq. (8):

\[ Q_{rad} = \frac{1}{BW} \]  \hspace{1cm} \text{(8)}

In this configuration, the fractional bandwidth of this antenna is 5.40%. Therefore, the estimated radiation quality factor is \( Q_{rad} = 18.51 \), which is much larger than the minimum radiation factor \((Q_{min} = 3.57)\).
In this configuration, the dimension of the antenna is 0.160 λ × 0.185 λ. When the loading distance (d) is switched to d = 0.50 mm, the rectangular microstrip patch antenna resonates at 9.51 GHz as shown in Fig. 5(b). In this configuration, the bandwidth and gain obtained is 514 MHz and 3.24 dBi, respectively with the dimension of 0.161 λ × 0.192 λ. In third configuration, the loading distance is kept at 0.75 mm in which the antenna resonates at 9.41 GHz with the bandwidth and gain of 306 MHz and 3.59 dBi, respectively. Figure 5(c) shows the return loss (S11) characteristics of this configuration. In this condition, the size of the antenna is 0.157 λ × 0.196 λ (5 mm × 6.25 mm).

Table 1 illustrates the comparison of results and calculated parameters of the metamaterial SRRs loaded rectangular microstrip patch antenna at different loading distances. As seen from the results, the resonant frequency of the loaded antenna decreases with the increasing distance (d). Amongst all the three configurations, the second configuration, that is at distance d = 0.50 mm, delivers the best fractional bandwidth, directivity, gain and antenna efficiency. The antenna structure in first configuration (at d = 0.25 mm) delivers better fractional bandwidth and directivity but low antenna efficiency. In the third configuration, radiation quality factor (Q_rad) is considerably high. But in this, the fractional bandwidth decreases and the gain is high.

In loading condition, the rectangular microstrip patch antenna is positioned near the metamaterial SRRs. Due to magnetic coupling, the electric field is developed across the gap capacitance at splits and the capacitance between inner and outer split rings of the SRRs. Hence, the resonant frequency of loaded microstrip rectangular microstrip patch antenna becomes lower than the resonant frequency of single uncoupled structure and is controlled by the mutual inductance. The strength of magnetic coupling and magnetic flux induced in the SRRs depends on the distance, d. This distance has a dramatic influence on the total magnetic flux in the antenna which is an important factor to decide the resonant frequency of loaded antenna. The capacitance of SRRs is sufficiently large to match the effective inductance of the rectangular microstrip patch. The mutual inductance (M) between the rectangular microstrip patch antenna and the square SRRs produces strong electric field at the capacitance of the SRRs that effectively reduces the resonant frequency. Thus, the metamaterial loading significantly reduces size of the antenna through magnetic coupling. The mutual inductance (M) varies with respect to the loading distance (d) and is calculated using Eq. (9) for d << L_e (L_e = L_s) (ref.18).

\[
M = \frac{\mu L_r}{2\pi} \left[ \ln \left( \frac{2L_e}{d} \right) - 1 \right] \quad \ldots (9)
\]

The calculated values of mutual inductance (M) are 2.68, 1.99, and 1.59 nH at the loading distance (d) 0.25, 0.50 and 0.75 mm, respectively. This shows that the mutual inductance decreases with increasing distance, d. It is noticed that the fractional bandwidth get enhanced with the increasing mutual inductance.

From these results, it is concluded that depending upon the application requirements, the frequency can be switched by changing the distance, d. The elevation and azimuth radiation patterns at different loading conditions are depicted in Figs (6-8), respectively. The gain of antenna structure at the respective loading distance 0.25, 0.50 and 0.75 mm is 3, 3.2 and 3.59 dBi, respectively.

4. Conclusion

In this paper, varied frequency electrically small rectangular microstrip patch antenna loaded with metamaterial square SRRs is presented. The loading distance between rectangular microstrip patch antenna and the SRRs unit cell is varied at 0.25, 0.50 and 0.75 mm, respectively. In all the three configurations, the condition ka < 1 by the Chu limit is satisfied as required for an electrically small antenna. The resonance frequency decreases from 23 to 9.61, 9.51 and 9.41 GHz, respectively with loading distances. The fractional bandwidth at respective resonance frequency is 5.40, 5.37 and 3.24%. Thus, the

<table>
<thead>
<tr>
<th>Distance (d), mm</th>
<th>Frequency (f_r), GHz</th>
<th>Fractional bandwidth, %</th>
<th>Gain, dBi</th>
<th>Directivity, dBi</th>
<th>Antenna efficiency, %</th>
<th>Q_rad</th>
<th>Q_chu</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>9.61</td>
<td>5.40</td>
<td>3</td>
<td>7.57</td>
<td>36</td>
<td>18.86</td>
<td>3.57</td>
</tr>
<tr>
<td>0.50</td>
<td>9.51</td>
<td>5.37</td>
<td>3.2</td>
<td>7.8</td>
<td>42</td>
<td>18.51</td>
<td>3.43</td>
</tr>
<tr>
<td>0.75</td>
<td>9.41</td>
<td>3.24</td>
<td>3.59</td>
<td>7.68</td>
<td>40</td>
<td>30.86</td>
<td>3.34</td>
</tr>
</tbody>
</table>
Fig. 6—Metamaterial loaded electrically small rectangular microstrip antenna at distance $d = 0.25$ mm: (a) Elevation pattern; (b) Azimuth pattern

Fig. 7—Metamaterial loaded electrically small rectangular microstrip antenna at distance $d = 0.50$ mm: (a) Elevation pattern; (b) Azimuth pattern

Fig. 8—Metamaterial loaded electrically small rectangular microstrip antenna at distance $d = 0.75$ mm: (a) Elevation pattern; (b) Azimuth pattern
frequency switching is possible by changing the loading distance \(d\). This is an exclusively planar electrically small antenna structure which uses an approach of metamaterial loading. The desired configuration of the proposed antenna will find its application in handheld devices and future mobile communications due to its miniaturized size, good bandwidth with better gain and high directivity.

Acknowledgements
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. One of the authors is highly indebted to Director, Directorate of Technical Education (MS), Mumbai and Principal, Government Polytechnic, Pune for sponsoring him to pursue the full time PhD under AICTE sponsored PhD-QIP (POLY) scheme.

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