

Metamaterial Loaded Frequency Tunable Electrically Small Planar Patch Antenna

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Abstract

In this paper, we present a metamaterial loaded frequency tunable electrically small planar patch antenna. Metamaterial structure has square shaped split ring resonator (SRR) with micro-splits. Frequency tunability is achieved by using RF MEMS switches. By making RF MEMS switches ON/OFF, the reactance of SRR structure changes and thus frequency of antenna is controlled. The patch antenna resonates at 27 GHz. But when the patch antenna is loaded with SRR structure, the loaded antenna is tuned to 9.02GHz, 9.08 GHz and 9.16 GHz by making RF MEMS switches ON/OFF. The resonant frequency of loaded antenna increases because as additional micro-splits are incorporated, series capacitances are introduced in SRR which decreases the overall capacitance of SRR. In all cases the loaded antenna satisfies the condition, Chu limit $ka < 1$, for an antenna to be electrically small. Also there is no requirement of additional matching networks.

Keywords: Chu Limit, Electrically Small Antenna, RF MEMS Switch, Micro-Splits, Single Negative Material (SNG) Split Ring Resonator (SRR), Negative Mu Material (MNG).

1. Introduction

In modern era of wireless communication, main emphasis is on the reduction of size of communication devices and sensor networks. To reduce the size of devices, miniaturization of components is the critical task. Antenna requires considerable space in communication instruments. So there is expectation of design of electrically small antennas which have significant bandwidth, efficient and can be simply integrated into the system. In 1947, Wheeler defined an antenna as electrically small if it occupies a volume of a sphere whose radius is a small fraction of free-space wavelength. That means for an antenna to be electrically small (ESA) maximum dimension of an antenna should be less than $\lambda/2\pi$ ¹. This relation can be expressed by an equation as:

$$ka < 1 \quad (1)$$

Where $k = 2\pi / \lambda$, λ is free space wavelength,

'a' is radius of sphere enclosing maximum dimension of an antenna.

In 1948, Chu derived a theoretical fundamental relationship between dimension of an antenna and antenna's Quality factor. This relation can be expressed as:

$$Q_{Chu} = \frac{1}{ka} + \frac{1}{(k^3 a^3)} \quad (2)$$

This is referred as chu limit. This relation gives the minimum Quality factor Q to be attained by ESA^{2,3}.

But traditional ESA design has many constraints like as electrical size decreases, ESA radiation resistance decreases, its efficiency decreases, Quality factor increases which means bandwidth decreases. ESA has an input reactance and resistance that is very poorly matched to common transmission lines (normally they have 50Ω impedance). So there is impedance mismatch between ESA and other circuit components of communication devices. Therefore external impedance matching networks are required, but these networks have their own limitations. Impedance matching can also be achieved within the antenna structure using some optimization

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of antenna topology. These techniques are more efficient than impedance matching of ESA by using external matching network.

With the introduction of metamaterial (MTM), which is artificial materials engineered to have properties that may not be found in nature, drastic reduction in antenna dimensions have been reported⁵⁻¹¹. MTM shows simultaneously negative values of permittivity (ϵ) and permeability (μ) values over a common frequency band; hence meta-materials are also termed as double negative (DNG) materials. They are also termed as, ENG (epsilon negative) materials when permittivity is negative and permeability is positive; MNG (mu negative) materials when permeability is negative and permittivity is positive. ENG and MNG materials are also termed as single negative (SNG) materials, because one of permittivity or permeability is negative. Metamaterials are also regarded as left handed materials (LHMs) or negative refractive index materials (NRIMs). The negative values of effective permeability (μ_{eff}) can be obtained by Split ring and that of effective permittivity (ϵ_{eff}) can be obtained by using metal rod^{4,5}.

In 2005, Ziolkowski and Erentok reported the efficient ESA by enclosing the dipole antenna in DNG or SNG metamaterial spherical shell⁶. In 2006, they purposed metamaterial based efficient ESA⁷. In 2008, they presented a planar metamaterial inspired ESA that had advantage of low cost and easy fabrication; also ESA had high radiation efficiency and good impedance matching⁸. In 2007, Alici and Ekmel purposed electrically small SRR antennas in which SRR was excited by monopole antenna⁹. In 2009, Duan, Qu and Hou presented a ESA inspired by spired SRR that had advantages of high gain, low cost, small size and light weight¹⁰.

In 2011, Joshi JG et al. presented a frequency switchable planar metamaterial loaded electrically small microstrip patch antenna. In this to get frequency switching authors varied the loading distance. They placed the planar metamaterial SRR at different distances from microstrip patch antenna. But varying of loading distance is typical task and also they did not specify the method to vary the loading distance. Only they take three different configurations for different loading distances and show the frequency switching¹¹.

In the present paper, the authors have proposed a metamaterial loaded frequency tunable electrically small planar patch antenna. MNG structure (mu negative) of metamaterial is used; which is implemented by using

square shaped split ring resonator. The SRR has additional micro-splits with RF MEMS switches. The presence of additional micro-splits leads to increase of resonance frequency due to series capacitances effect¹². The entire antenna dimensions along with SRR are fitted inside a sphere of radius 'a'.

RF MEMS switches have better performance in terms of isolation, insertion loss, power consumption and linearity as compared to PIN diodes and FET transistors^{13,14}.

2. Design

In this design, the rectangular patch antenna of dimension: length $L = 4$ mm, width $W = 0.5$ mm is taken. The patch antenna is excited by coaxial feed at $(-3.7$ mm, -2.7 mm). The patch antenna is loaded with planar square shaped split ring resonator with micro-splits, shown in Figure 1. The dimensions of square Split ring resonator structure are: length $L_{\text{SRR}} = 4$ mm, width of each ring is $w = 0.2$ mm, the separation between inner and outer rings is $s = 0.2$ mm, split width in each ring is $g = 0.2$ mm. Two additional micro-splits are also placed in outer ring at 0.475 mm and 0.975 mm distances from main split. The width of each micro-split is 0.05 mm. The square split ring resonator with micro-splits is placed at 0.5 mm distance from the patch antenna.

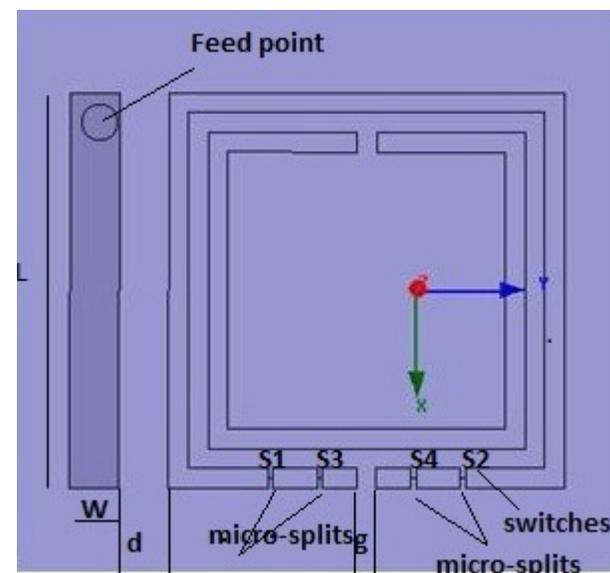


Figure 1. Structure of Electrically small rectangular patch antenna loaded with planar SRR with micro-splits.

RT Duriod 5880 is taken as substrate having relative permittivity $\epsilon_r = 2.2$ and thickness $h = 3$ mm. The RF MEMS switches (S1, S2, S3, and S4) are placed within the micro-splits. RF MEMS switches are implemented by presence and absence of metal strip. When the metal strip is presented within the micro-splits that means RF MEMS switches are in ON position, whereas when the metal strip is absent within the micro-splits that means RF MEMS switches are in OFF position. Whole structure is designed and simulated by using finite element based electro- magnetic mode solver Ansoft HFSS simulator.

Two port waveguide is formed to verify the physical properties of the designed square SRR structure with micro-splits. The waveguide has a pair of perfect magnetic conductor (PMC) walls in z-direction, perfect electric conductor (PEC) walls in y-direction and electromagnetic wave is propagated in x-direction. The value of effective permeability is extracted by using effective parameter retrieval method¹⁵.

3. Analysis and Discussion

The unloaded patch antenna resonates at frequency 27 GHz. The return loss characteristic of unloaded microstrip patch antenna is shown in Figure 2.

Metamaterials type structures can be considered as LC resonant circuit whose resonance frequency can be determined by $\omega = 1/\sqrt{LC}$, where L is equivalent inductance and C is equivalent capacitance of square SRR.

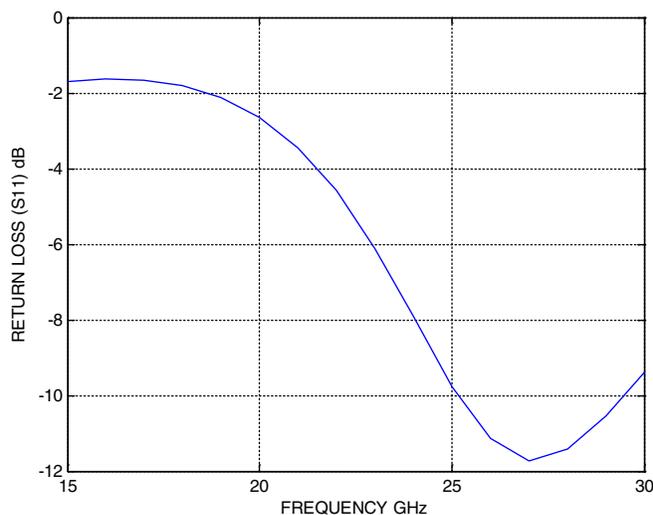


Figure 2. Return Loss (S₁₁) of unloaded patch antenna.

values of L and C can be calculated by using mathematical equations [16]. The equivalent inductance is given as:

$$L = \frac{\mu_0 l_{avg}}{2} \frac{4.86}{4} \left[\ln \left(\frac{0.98}{\rho} \right) + 1.84 \rho \right] \quad (3)$$

where μ_0 is permeability of free space ($4\pi \times 10^{-7}$ H/m); l_{avg} is average strip length calculated over all the N rings as $l_{avg} = 4[l - (N - 1)(w + s)]$; ρ , fill ratio expressed as $\rho = \frac{(N - 1)(w + s)}{l - (N - 1)(w + s)}$; N is number of split rings (in this case N = 2); l is side length of outer ring; w is width of rings; s is separation between the inner and outer split rings.

The equivalent capacitance is given as:

$$C = \frac{(N - 1)}{2} [2l - (2N - 1)(w + s)] C_0 \quad (4)$$

where $C_0 = \epsilon_0 \frac{K(\sqrt{1 - k^2})}{K(k)}$; K(o) is complete elliptic integral of first kind and $k = \frac{s/2}{w + s/2}$.

By equation (3) and (4), the values of L and C are 26.17 nH and 0.0267 pF respectively. Theoretically, the calculated resonant frequency of isolated square SRR without any additional micro-splits is 6.0 GHz.

Figure 3 shows the reflection coefficient (S₁₁) and transmission coefficient (S₂₁) of square SRR without any additional micro-splits i.e. all the switches are in ON position. The resonant frequency of isolated square SRR

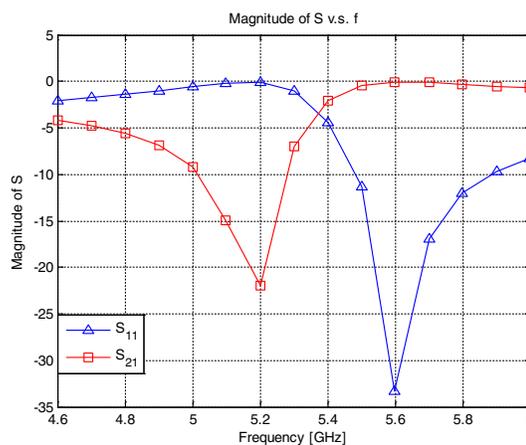


Figure 3. Reflection coefficient (S₁₁) and transmission coefficient (S₂₁) of square SRR without any additional micro-splits.

without any additional micro-splits is 5.2 GHz, which is near to theoretical calculated resonant frequency 6.0 GHz. Effective permeability is extracted by using effective parameter retrieval method¹⁵, the real value of magnetic permeability is found negative in the frequency regime 5.2–5.5 GHz (figure 4). This indicates that the square SRR structure is mu negative metamaterial (MNG).

When we consider square SRR with one micro split (when switches S1, S2 are ON and S3, S4 are OFF) and with two micro splits (when all switches OFF) then resonant frequency shifted to 6.4 GHz (Figure 5) and 6.8 GHz (Figure 6) respectively; because of additional series capacitance of micro splits.

For loaded antenna, when all the switches were made in ON positions (Square SRR without any additional micro-splits); the loaded antenna structure resonates at frequency 9.02 GHz with a -10 dB bandwidth of 740 MHz (Figure 7 Blue curve) and a gain of 2 dB; while when the

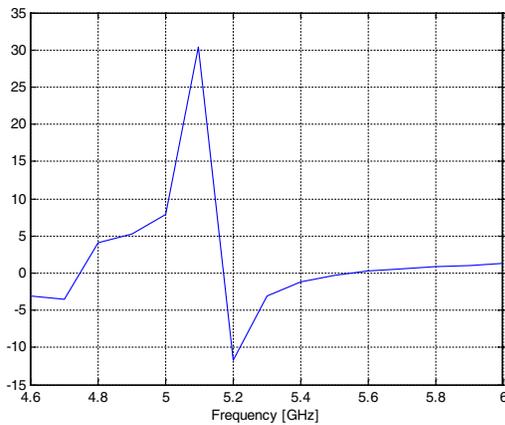


Figure 4. Real part of permeability of square SRR without any additional micro-splits.

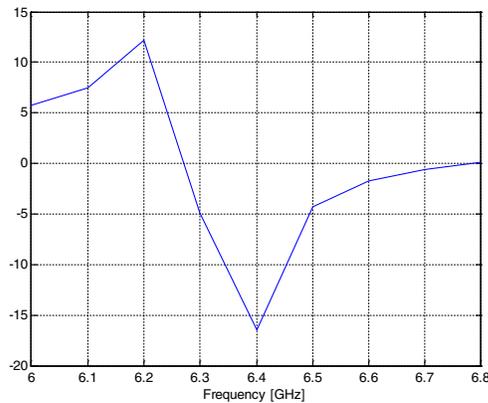


Figure 5. Real part of permeability of square SRR with one micro-split.

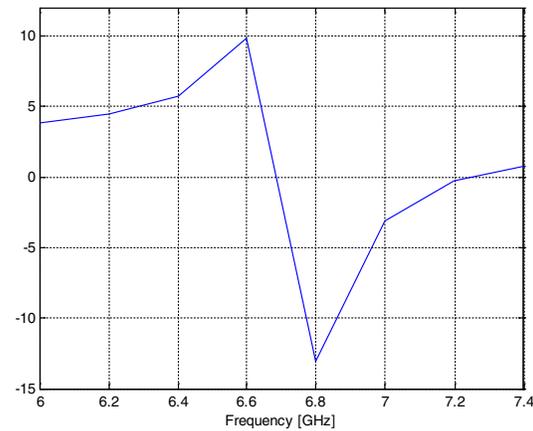


Figure 6. Real part of permeability of square SRR with two micro-splits.

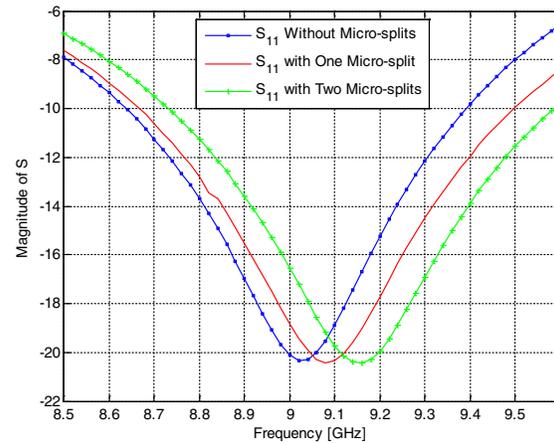


Figure 7. Return Loss (S_{11}) of loaded patch antenna with square SRR with No, One and two micro-splits.

patch antenna is loaded with square SRR with One (when switches S1, S2 are ON and S3, S4 are OFF) and with two micro splits (when all switches OFF), the loaded antenna structure resonates at frequency 9.08 GHz with a -10 dB bandwidth of 800 MHz (Figure 7 Red curve) and a gain of 2.16 dB and 9.16 GHz with a -10 dB bandwidth of 840 MHz (Figure 7 Green curve) and a gain of 2.11 dB respectively. Thus we get frequency tunability. The wavelength of loaded structure is 33.26 mm (without micro-splits), 33.04 mm (with one micro-split) and 32.75 mm (with two micro-splits). Therefore ka values for loaded structure is 0.755, 0.760, and 0.767 respectively; which satisfies the condition $ka < 1$ that means purposed antenna structure is an ESA.

Using equation (2) minimum Quality factor (chu limit) is calculated for the purposed antenna $Q_{chu} = 3.65$ (without micro-splits), 1.75 (with one and

two micro-splits); whereas the radiation Quality factor $Q_{rad} = (f_r/B.W)$ for purposed ESA is 12.2, 11.35, 10.9 respectively, which is quite large than Q_{chu} .

The resonant frequency of loaded patch antenna becomes lower than the resonant frequency of unloaded patch antenna. The resonant frequency of loaded antenna is controlled by capacitance developed at the SRRs¹⁷. So when we introduce more series gap capacitances, the overall capacitance of SRR decreases, hence resonant frequency of loaded patch antenna increases. Also the bandwidth of loaded antenna increases. Large bandwidth and high gain suggest that patch antenna is perfectly

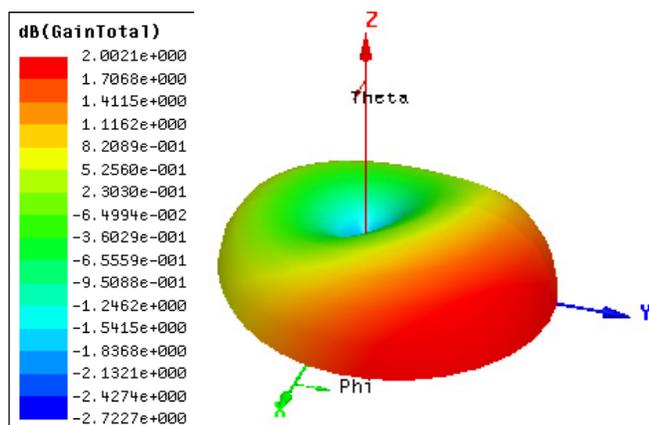


Figure 8. Gain of loaded patch antenna with square SRR with No micro-splits.

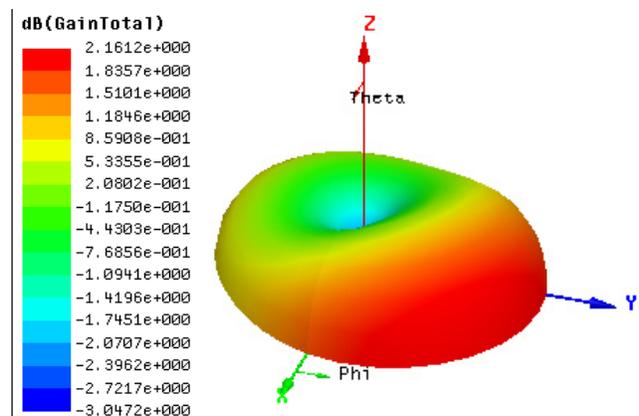


Figure 9. Gain of loaded patch antenna with square SRR with One micro-split.

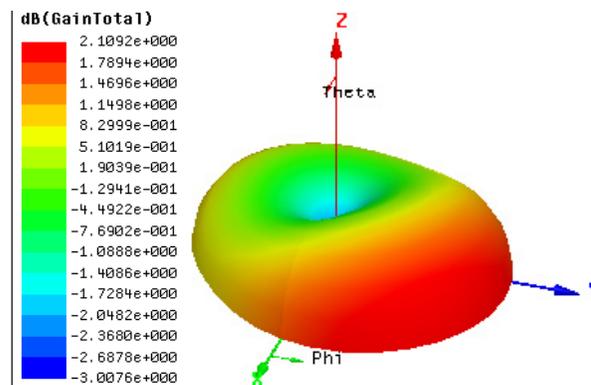


Figure 10. Gain of loaded patch antenna with square SRR with two micro-splits.

matched with square SRR. So there is no requirements of additional matching networks^{10,18-19}

4. Conclusion

In this paper, metamaterial (MNG structure) loaded electrically small planar patch antenna is presented. The metamaterial has square shaped split ring resonator with micro-splits. By introducing micro-splits and hence changing the reactance of structure, frequency tunability has been achieved. These micro-splits are implemented by using RF MEMS switches and thus the number of micro-splits is considered by making RF MEMS switches ON/OFF. SRR structure is considered with no, one and two additional micro-splits. In all three configurations, condition $ka < 1$ by Chu limit is satisfied as required for an ESA. The resonant frequency of loaded structure shifted to 9.02 GHz (No additional Gap), 9.08 GHz (One additional Gap) and 9.16 GHz (Two additional Gaps). Thus we get frequency tunability by simply making RF MEMS switches ON/OFF. There is no need to vary the distance between patch and SRR. The proposed antenna finds its application in multi-band mobile communication, handheld devices, body area network (BAN) due to its miniaturized size, good bandwidth and high gain.

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