

Original Research Article
**Ultra-Wideband Metamaterial-based
Rectangular Microstrip Antenna for Sub-6 GHz
5G and other Microwave Applications**

ABSTRACT

This paper presents a novel design of an ultra-wideband metamaterial-based rectangular microstrip antenna for sub-6 GHz 5G and other microwave applications. The proposed antenna consists of a rectangular patch with a partial ground plane and two metamaterial unit cells embedded on the substrate. The metamaterial unit cell is composed of a split ring resonator (SRR) to provide negative permeability and negative permittivity, respectively, resulting in a negative refractive index (NRI) medium. The NRI medium enhanced the bandwidth and radiation efficiency of the antenna by reducing the surface waves and mutual coupling. The antenna operates over a frequency range of 3.4009 to 11.721 GHz and 2.869 to 3.211 GHz, covering the sub-6 GHz 5G bands and other microwave applications such as Wi-Fi, WiMAX, and WLAN. The antenna has a compact size of $30 \times 25 \times 1.6 \text{ mm}^3$ and exhibits good impedance matching, omnidirectional radiation pattern, and stable gain across the operating band. From simulation results, a combined bandwidth of 8.66 GHz was achieved which shows good agreement with outlined objective. The proposed antenna is suitable for sub-6 GHz 5G and other microwave applications that require ultra-wideband performance and low-profile design.

Keywords: Metamaterial, ultra-wideband, antenna, microwave, sub-6 GHz

1. INTRODUCTION

Contemporarily, the noticeable rise in the number of wireless communication devices is the proof of the relentless technological innovations that has become recognisable with the age [1]. Among these innovations, [2] stated that mobile phones are adjudged to have evolved the most, now evidently possessing similar data processing power as full-fledged computers and incorporating modems for different generation standards of wireless communication including the fifth generation (5G) reported to have significantly improved data throughput in comparison to earlier generations. These wireless communication standards according [3], are in most cases deployed using different frequency bands (majorly around the sub-6 GHz bands) thus reemphasizing the need for capable multiband antennas with inherent characteristics of being of low profile, compact as well as being conformable to mounting surface. Microstrip antenna (MSA) possesses these characteristics hence making them the primary go to option for miniature antennas [4]. However, MSAs are limited by their narrow bandwidth (usually between 1 – 5% fractional) which require additional means to achieve higher bandwidth [5].

Split Ring Resonator (SRR) structures due to their ability to alter antenna electromagnetic properties have been reported by several authors as one of the mechanisms used to enhance antenna performance [1], [6], [7]. Alteration of antenna properties is aided by the dual electromagnetic behaviour of SRR (either as single negative or double negative material). Structures such as SRR are classified as metamaterials defined by [8] as artificial materials with in-built capability to exhibit electromagnetic properties not readily found in naturally occurring material, such as, negative refractive index and artificial magnetism.

Some previously published works related to the study were reviewed. Yongfeng in [9] proposed an integrated ultrawideband/narrowband rectangular dielectric resonator antenna (DRA) for cognitive radio with two symmetrical short-circuited strips for improved isolation between two ports. Compact UWB dielectric resonator antenna with dual-band-rejection characteristics for WiMAX/WLAN bands was reported by [10] from which the authors achieved bandwidth enhancement by embedding stub and slot of various lengths on a DRA. Also, [11] presented a compact bi-cone dielectric resonator antenna for ultra-wideband applications. The layout of these DRA antennas however placed an intrinsic limit on their extent of application. Thanuj et al [12] presented obround-shaped metamaterial based compact planar antenna for UWB and 5G applications; the antenna was designed on Rogers RT Duroid 5880 substrate with a thickness of 0.43 mm which achieved a fractional bandwidth of over 50% with good radiation efficiency. Metamaterial inspired multiband antenna for 5G sub-6 GHz New Radio (NR) frequency bands and wireless applications with dimensions of $36 \times 22 \times 1.6 \text{ mm}^3$ on flame resistant (FR-4) substrate which achieved a fractional impedance bandwidth of 47.20% was proposed by [13].

This paper presents a unique design of an ultra-wideband (UWB) metamaterial-based rectangular microstrip antenna for sub-6GHz 5G and other microwave applications. The proposed antenna consists of a rectangular patch with a partial ground plane and two metamaterial unit cells integrated adjacent to the feedline of the patch and located on the same side of the substrate. The metamaterial unit cell is composed of SRR which provides negative permittivity characteristics.

2. METHODOLOGY

This section presents the design of single band microstrip antenna at sub-6 GHz 5G frequency of 3.5 GHz followed by the design considerations of unit cell metamaterial as well as the final integration of the metamaterial with the patch antenna.

2.1 Single Band Patch Antenna Design

A single band microstrip antenna resonating at 3.5 GHz is first designed using transmission line model equations obtained from [5], [14], [15]. The rectangular patch structure acts as a resonator; thus, the length and width of the patch are typically selected in such a way that $L_p < W_p < 2L_p$ for efficient and enhanced radiation. The detailed design equations for the rectangular microstrip patch is outlined as follows:

- i) The width (W_p) of the microstrip patch antenna computed from Equation 1.

$$W_p = \frac{c}{2f_r \sqrt{\frac{(\epsilon_r + 1)}{2}}} \quad (1)$$

- ii) The effective dielectric constant (ϵ_{reff}) is obtained from Equation 2.

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \left(\frac{h}{W_p} \right) \right]^{-1/2} \quad (2)$$

iii) The effective length L_{eff} of the patch can be derived from Equation 3.

$$L_{\text{eff}} = \frac{c}{2f_r \sqrt{\epsilon_{\text{reff}}}} \quad (3)$$

iv) The extension length (ΔL) is deducted from calculated length L_p of the patch retaining actual length of the patch unchanged. The extension length virtually appears due to fringing field as seen in Equation 4:

$$\Delta L = 0.412h \frac{[\epsilon_{\text{reff}} + 0.3] \left[\frac{W}{h} + 0.264 \right]}{[\epsilon_{\text{reff}} - 0.258] \left[\frac{W}{h} + 0.813 \right]} \quad (4)$$

v) Calculation of actual length of patch (L_p): From Equation 5, the actual length of the patch (L_p) is:

$$L_{\text{eff}} = L_p + 2\Delta \quad (5)$$

$$L_p = L_{\text{eff}} - 2\Delta \quad (6)$$

vi) Calculation of the ground plane dimensions (L_g and W_g): A major assumption adopted by the transmission line model is the use of infinite ground planes. However, it is essential to have a finite ground plane for practical contemplations. For finite and infinite ground plane, the size of the ground plane is greater than the patch dimensions by approximately six times the substrate thickness all around the periphery [5]. Hence, for this design, the ground plane dimensions are calculated thus:

$$L_g = L_p + 6h \quad (7)$$

$$W_g = W_p + 6h \quad (8)$$

vii) Determination of the patch thickness (t): The metallic patch is selected to be very thin such that $t \ll \lambda_0$.

Inset-fed technique was used for the feedline to the patch, and the design equations were adopted from [16], [17]. Table containing computed dimensions of the 3.5 GHz patch antenna is presented in Table 1 while the schematic diagram and single band rectangular microstrip antenna modelled in CST Studio are given in Fig. 1.

Table 1. Computed dimensions of 3.5 GHz single band edge-fed RMSA

Design Parameter	Values
Patch dimensions:	
Length (L_p)	20.45 mm
Width (W_p)	26.58 mm
Dielectric constant (ϵ_r)	4.2
Substrate height (h)	1.60 mm
Patch thickness (t)	0.35 mm

Ground plane dimensions:

Length of ground plane (L_g)	30.05 mm
Width of ground plane (W_g)	36.18 mm

Feed line dimensions:

Width of 50 Ω transmission line (W_f)	3.10 mm
Length of 50 Ω transmission line (L_f)	4.80 mm
Input edge impedance of the patch (R_{in})	185.19 Ω
Characteristic impedance of the feed line (Z_0)	50 Ω
Inset fed gap (g)	1.80 mm
Inset fed distance, (y_0)	7.55 mm

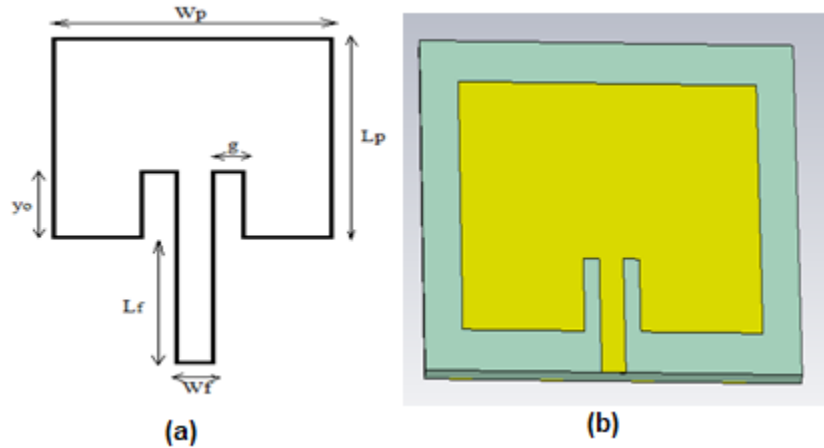


Fig. 1. Designed antenna (a) schematic diagram (b) 3.5 GHz patch

2.2 Unit cell metamaterial

Depending on the structure and size of a unit cell, different corresponding values of permittivity (ϵ), permeability (μ) and resonant frequencies (f_r) can be obtained. For each unit cell type, the dimensions of unit cell can be adjusted to satisfy condition at resonant frequency (f_r) [7]. According to [3], unit cell size is approximately one-tenth of the operating wavelength (λ_{air}), that is, the retrieval of effective parameters from reflection and transmission data depends on the fact that unit-cell dimension should be smaller than the operating wavelength in the media. Hence, taking the one-tenth of the wavelength of the reference antenna (3.5 GHz antenna) to be the external length (L_m) of the metamaterial (MTM), the external ring length of the MTM is computed to be 8.57 mm. The MTM shape of choice for this study is the split ring resonator (SRR) selected mainly for ease of design and analysis. Based on the report put forward by [18], every dimension of the complementary square SRR (see Fig. 2(a)) is duly accounted for with a simplified relationship between the components typified in the equivalent circuit presented in Fig. 2(b) such as capacitance (C), inductance (L) and f_r given in Equation 9.

$$L_m = \frac{85.71}{10} = 8.57 \text{ mm}$$

Parameters of focus are – the ring's outer radius, a , thickness, c , height, h , and the width of gap, g . The square SRR is modelled by an inductance, L ; the gap in the ring corresponds to capacitance, C_{gap} which is modelled as a parallel plate capacitor; the charges on the surface

are the surface capacitance, $C_{surface}$. According to [19], with magnetic field applied along the z-axis, an electromotive force appears around the SRR making the structure behave in similar fashion like an L-C network having resonant frequency (f_r) expressed in Equation 9.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (9)$$

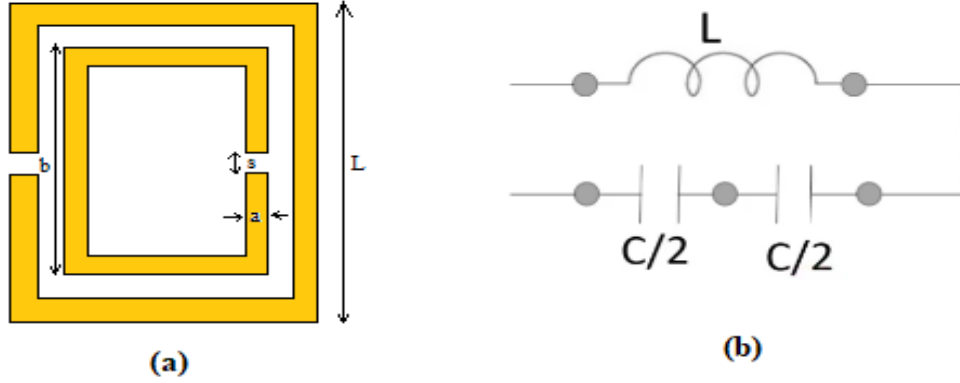


Fig 2. Metamaterial (a) Geometry of unit cell SRR (b) Equivalent circuit representation of unit cell SRR [18]

In the same vein, the inductance can be approximated by that of a closed ring [19].

$$L = \mu_0 a_m \left(\ln \frac{8a_m}{h+c} - 0.5 \right) \quad (10)$$

Note: $a_m = a + \frac{w}{2}$

$$C_{gap} = \epsilon_0 \left(\frac{ch}{g} + \frac{2\pi h}{\ln \frac{2.4h}{c}} \right) \quad (11)$$

$$C_{surface} = \frac{2\epsilon_0 h}{\pi} \ln \frac{4a}{g} \quad (12)$$

$$\frac{1}{C} = \frac{1}{C_{gap}} + \frac{1}{C_{surface}} \quad (13)$$

where μ_0 is the permeability of free space, a is the outer radius of ring and a_m is the mean radius of the ring.

The dimensions of the metamaterial unit cell are given in Table 2.

Table 2. Dimensions of SRR

Parameter	Value (mm)
L_m	8.57
s	1
a	1
b	6

2.3 Patch Antenna with Metamaterial

The single band patch antenna and two SRR structure simulated were integrated on a single substrate, partial ground plane was introduced to offset current flow and consequently alter the impedance bandwidth by shifting the antenna resonance frequency. This resulted in the patch antenna size reduction for the same designed frequency as well as change in the antenna layout as illustrated further in Fig. 3. The augmented patch dimensions are given in Table 3.

Table 3. Dimensions of proposed antenna

Design Parameter	Values
Patch and feedline dimensions:	
Length (L_p)	13 mm
Width (W_p)	14 mm
Dielectric constant (ϵ_r)	4.2
Substrate height (h)	1.60 mm
Patch thickness (t)	0.35 mm
Width of 50 Ω transmission line (W_f)	4 mm
Length of 50 Ω transmission line (L_f)	14 mm
Ground plane dimensions:	
Length of ground plane (L_g)	25 mm
Width of ground plane (W_g)	30 mm

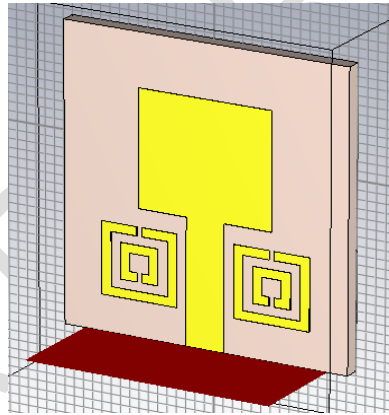


Fig 3. Proposed MTM-based patch antenna

3. RESULTS AND DISCUSSION

The return loss of the single band patch antenna designed at 3.5 GHz showed minimum return loss value of -27.16 dB at 3.52 GHz as illustrated in Fig. 4 while the S_{11} and S_{21} plot of the metamaterial is given in Fig. 5 showing minimum return loss at 13.69 GHz at values of 22.49 and 60.47 dB. Real and imaginary plots of permittivity and permeability of the MTM is presented in Fig. 6 and Fig. 7.

From Fig. 6 and Fig. 7, negative permittivity and permeability values at resonance frequency of 11.95 GHz confirming the SRR adopted to be a double negative (DU) metamaterial. Fig. 8 gives the return loss plot of the plot of the proposed metamaterial antenna from where a combined bandwidth of 8.66 GHz was obtained over two distinct frequencies of (3.4009 GHz – 11.721 GHz and 2.869 GHz – 3.211 GHz).

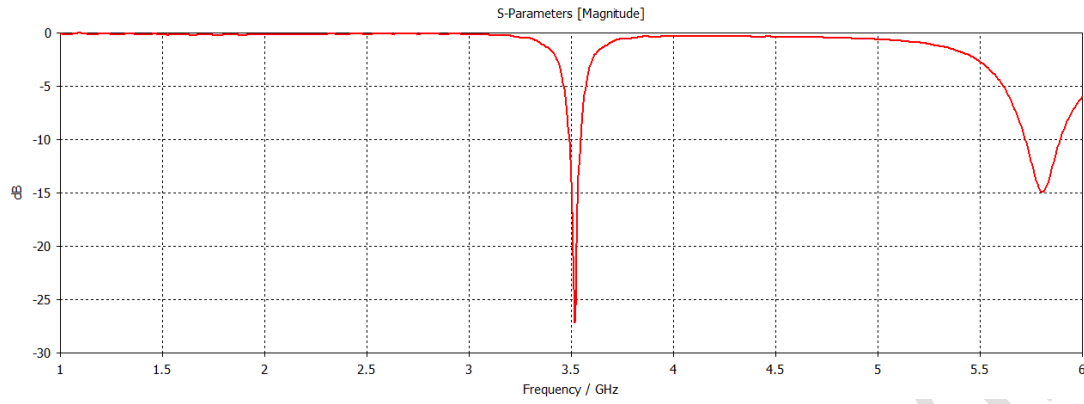


Fig 4. Return loss of 3.5 GHz RSA

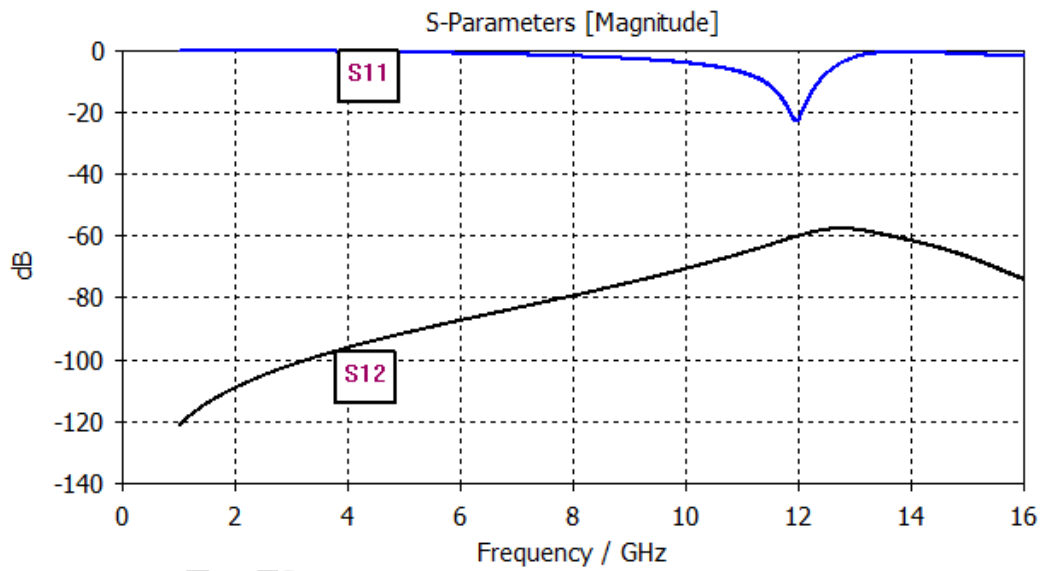


Fig 5. S_{11} and S_{12} plot of SRR structure

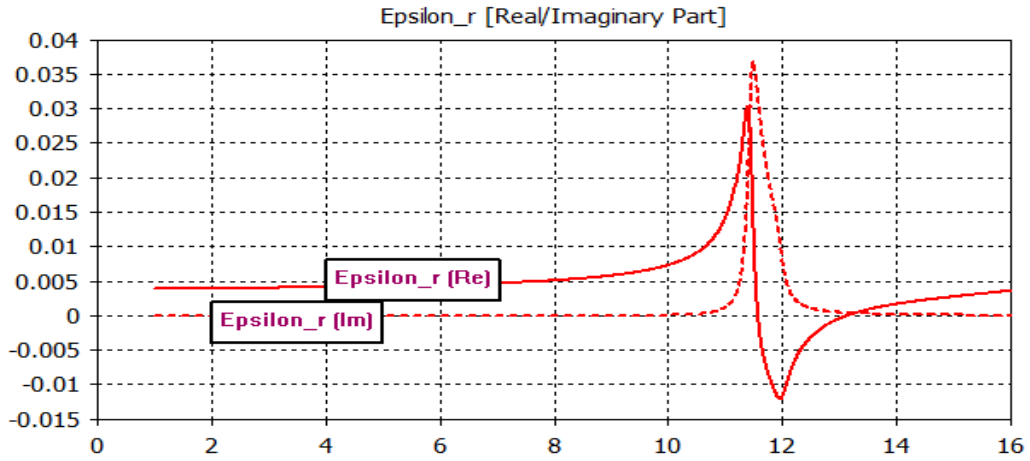


Fig 6. Real and Imaginary values of permittivity

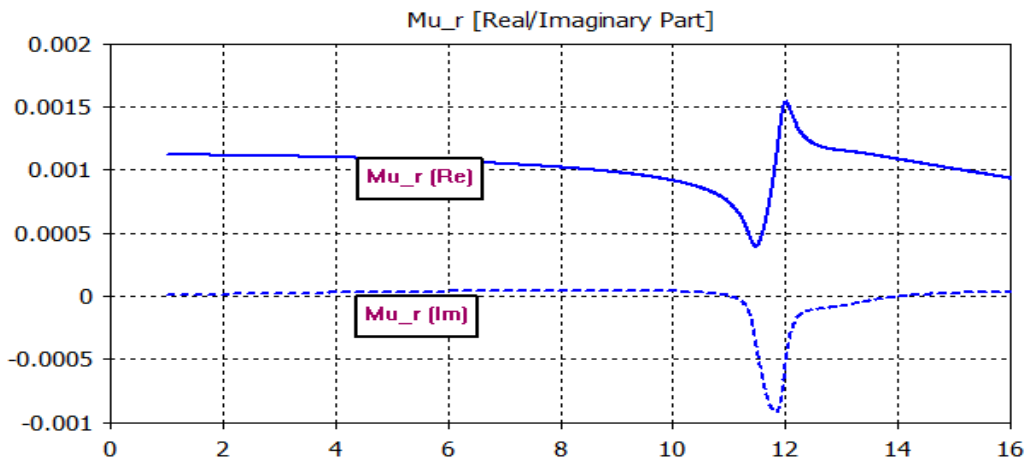


Fig 7. Real and Imaginary values of permeability

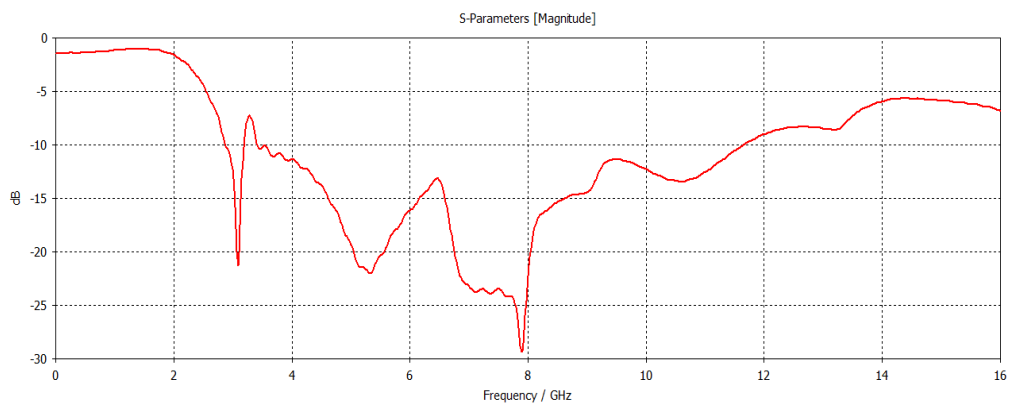


Fig 8. Return loss of proposed metamaterial antenna

4. CONCLUSION

In this paper, MTM-based patch antenna has been designed for sub-6 GHz 5G and other microwave applications. The proposed antenna comprises a rectangular patch, two metamaterial unit cells on one side with a partial ground plane on the opposite side having an FR-4 substrate sandwiched between. A combined bandwidth of 8.66 GHz was achieved by the antenna indicating a 50% fractional frequency which along with its compact form makes the antenna suitable for integration in handheld devices.

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