Metamaterial inspired triband offset feed rectangular monopole for wireless applications

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Abstract

A rectangular monopole engraved with an open complementary split-ring resonator (OCSRR) metamaterial is designed and proposed for multiband radio applications. The proposed antenna has a rectangular monopole feed with offset microstrip feed, and the OCSRR designed at 3.14 GHz is engraved in the radiating element. The OCSRR is a special type of metamaterial with small electrical size. The OCSRR modifies the current direction due to its negative permittivity, which creates another resonance at 3.16 GHz. The left offset feed and abridged ground length creates another resonance at 3.82 GHz and responsible for good impedance matching are achieved in all the resonating bands. The entire antenna is designed and fabricated on the FR4 substrate with a complete measurement equal to 27.84 mm x 23.25 mm x 1.6 mm. The proposed structure shows the multiband characteristics at 3.16 GHz, 3.82 GHz, and 5.14 GHz with a S11 of -19.83 dB, -17.90 dB, and -55.73 dB, respectively. The critical parameters of the OCSRR are decided using the parametric analysis, and the simulated results are presented. The OCSRR negative permittivity extraction is done with NRW wave guide extraction method, and the result is validated with the help of OCSRR resonant frequency calculation. The uniformity is well maintained between the measured and simulated results. The multiband characteristics, reasonable gain, compactness, low design complexity, and small size are the significant features of the proposed antenna

Graphical Abstract

Manuscript Highlights

• The proposed antenna consists of a Rectangular offset feed patch and OCSRR metamaterial.
• Design equations and its equivalent circuit of the proposed antenna is presented.
• The permittivity of the OCSRR metamaterial resonator is extracted using waveguide setup s-parameter retrieval method.
• OCSRR resonant frequency analysis is done to validate the 3.16 GHz band operation.
• Simulated and measured results are presented.

Keywords
Metamaterial, Monopole, Multiband, OCSRR, offset feed, Rectangular patch
1. Introduction

In present-day modern communication, the demand for the data rate increases day by day; thus, wideband antennas are the critical requirement since they can transfer extensive data quickly. Another critical requirement is the realization of an antenna [1] with multiband functionality, which helps in the device size reduction. Nowadays, a single device is designed to satisfy multiple wireless communication applications[2], which require a separate antenna for each application; in turn, device size and complexity will be increased. The fore-mentioned requirement attracts many researchers to focus on the realization of multiband antennas, which can simultaneously operate on multiple frequencies. The cost and size effective multiband antenna with good impedance bandwidth can be realized using the planar patch antenna, and its design with enhanced features is the major challenge for the researchers. The significant parts of the patch antenna are the ground, substrate, and the radiating element. The radiating element is of any shape [1, 3–5], such as rectangular, square, circular, or polygonal. Microstrip, CPW, CPS, and Coaxial are some of the feeding methods, out of which the microstrip line is widely used since it can be easily integrated and fabricated. There are a variety of techniques have been reported for realizing multiband patch antennas. The slots are introduced in the patch of the antenna to resonate it at multiple frequency bands, and the bandwidth is improved by using DGS. The slot in the radiating element and DGS [6, 7] can improve the antenna's gain. Defected ground structure not only provides the impedance bandwidth but also explores the multiband resonance. Usage of Slot [8–10], defected ground structures [11], fractal shapes [12], active and passive devices [13, 14] are widely used in the realization of multiband operating. Although various techniques are used for multiband realization, the major disadvantage of this method is a complex design, increased size, and reduced gain. The above-said disadvantage is overcome with the help of metamaterial due to its unusual electromagnetic properties.

Metamaterial [15–20] are the subwavelength structures that display unnatural EM characteristics such as negative values of \( \varepsilon, \mu, \eta \) and so on. In the past few decades, the metamaterials [21] gained researchers attention due to is unique EM properties. These unique properties help the researchers to design some unique electromagnetic devices and components. The unique properties are due to its structure and not from its constituents. The electromagnetic wave propagation is affected constructively by these unique EM properties[22–24]. The metamaterial [25] should satisfy the unit cell size of \( P<\lambda/4 \). SRR [26], S-shaped, CSRR [27–32], and ELC [33, 34] are the different kinds of metamaterial structures widely used in the antenna design for impedance matching, size reduction bandwidth, gain, and directivity improvement.

Another metamaterial structure with a small electrical size is the Open Split Ring Resonator (OSRR) and its dual component. Both OSRR and OCSRR are widely used in microwave device design [35, 36]. Open Split Ring Resonator is the open version of SRR. Fig 1 a and Fig 1 b depicts the OSRR topology and its equivalent circuit. Similarly, Fig 1 c and Fig 1 d depicts the OCSRR topology and equivalent circuit. The equivalent circuit of OSRR is a series LC circuit. An open complementary split-ring resonator is designed from SRR by opening it and then applying duality. The terminal is the metal region, which creates the electric short between the slot rings and capacitive connection in-between the slots. Hence the OCSRR is an open parallel resonant frequency as represented in fig 1d, and the resonant frequency of OCSRR equal to

\[
f_0 = \frac{1}{2 \pi \sqrt{C_0 L_0}}
\]  

Where capacitance \( C_0 \) is approximately equal to the CSRR capacitance with the same dimension and inductance \( L_0 \) is greater than four times the CSRR inductance. Thus, electrical size of the OCSRR will be reduced by a factor of two compared to CSRR. The resonant frequency is also equal to CSRR resonant frequency divided by two. Due to OCSRR’s small electrical size, a high-performance
multiband antenna without expanding the size can be easily realized. But the use of OSRR and OCSRR for the realization of multiband operation in antenna design is less explored.

![Fig 1](a) OSRR topology (b) Equivalent circuit of OSRR (c) OCSRR topology (d) Equivalent circuit of OCSRR

In this article, a compact tri-band rectangular monopole for multiband wireless applications is designed and presented. The OCSRR and reduced ground structure make the proposed antenna resonate at multiple frequencies. The OCSRR is accountable for creating the additional resonance at 3.16 GHz. The permittivity characteristic is retrieved using NRW method, and it is validated with the quasi-static analysis of OCSRR. Both the results are presented in the paper to validate the inclusion of OCSRR is the reason for the 3.16 GHz resonating bands. All the antenna parameters such as Gain, Current direction, E plane, and H plane are similar to conventional rectangular antenna since the patch is always rectangular. The compact size, stable radiation properties, good gain, and easy fabrication are the significant features which make the proposed OCSRR inspired rectangular printed antenna suitable for multiband wireless applications. Further, the evolution of the proposed OCSRR inspired rectangular antenna is discussed, the permittivity extraction, parametric analysis and equivalent circuit of proposed antenna are detailed. In section 3, to confirm the proposed antenna, simulated and measured results are elaborately discussed, and the article is concluded in section 4.

2. Materials and Methods

2.1 Design of OCSRR Inspired Rectangular Printed Antenna

The proposed OCSRR inspired rectangular printed antenna is printed on a substrate made up of material called FR4 which has 4.4 as its dielectric constant. The design phases of the antenna designed using CST software are depicted in fig 2. The antenna has three stages of evolution. The geometry of OCSRR inspired rectangular printed antenna is depicted in Fig 3, and in Table 1, the respective parameter values are presented. The rectangular monopole, Ant A, is fed with 50 Ω microstrip feed, and it operates at 5 GHz. Then, offset feed is introduced in stage two of evolution to achieve good impedance matching. The ground length is reduced to 3 mm to design Ant B. The Ant B is used to generate the dual-band resonance at 5.5, and 3.82 GHz. Then the proposed structure is designed by introducing the OCSRR designed at 3.12 GHz in the maximum surface current region. The dimension of the designed antenna is 27.84 mm x 23.25 mm x 1.6 mm (0.464 λ₀ x 0.3875 λ₀ x 0.0267 λ₀, λ₀ is the free space wavelength at f₀= 5 GHz ). This proposed OCSRR inspired rectangular printed antenna operates at a triband 3.16, 3.82, and 5.41 GHz.
Fig 2 Design stages of OCSRR inspired rectangular printed antenna

Fig 3 Front and Back View of OCSRR inspired rectangular printed antenna geometry

| Parameter | Dimension (mm) | \(w_s\) | \(l_s\) | \(w_p\) | \(l_p\) | \(X\) |
|-----------|----------------|--------|--------|--------|--------|------|
| \(w_s\)  | 27.84          | 23.25  | 18.24  | 13.75  | 0.3    |
| \(l_s\)  | 23.25          | 18.24  | 13.75  | 0.3    |

Table 1 OCSRR inspired rectangular printed antenna Parameters

Ant A is the seed antenna printed in a FR4 substrate with a rectangular patch of width \(w_p\) and length \(l_p\), and full ground with width \(w_s\) and length \(l_s\) is printed on the other side. Ant A is designed using Eqs 2-5. The designed antenna has a resonance at 5 GHz with an operating range from 4.87 GHz to 5.08 GHz.

\[
W = \frac{c}{2f_r \sqrt{\varepsilon_r+1}}
\]  

(2)
\[ L = \frac{c}{2f_r \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L \]  

(3)

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12h}{W} \right]^{-1} \]  

(4)

\[ \Delta L = 0.412h \frac{(\varepsilon_{\text{eff}} + 0.3)}{(\varepsilon_{\text{eff}} - 0.258)} \frac{W}{\pi} + 0.264 \]  

(5)

Where \( c \) is the light velocity, \( f_r \) is the frequency of resonance, \( h \) is the height of the dielectric substrate used in the design and \( \varepsilon_{\text{eff}} \) is the substrate effective dielectric constant. The impedance matching is improved by left offsetting the feed. The reduced ground plane improves the impedance bandwidth at 5 GHz and creates the additional resonance at 3.8 GHz. The Ant B has dual-band resonance at 3.8, and 5.7 GHz. Then the OCSRR is designed at 3.14 GHz is placed at the maximum surface current region to generate the additional resonance at 3.16 GHz. The final proposed OCSRR inspired rectangular printed antenna operates at tri-band at 3.16, 3.82, and 5.41 GHz. The operating frequency of the designed antenna is 3.14 to 3.30 GHz, 3.79 to 3.93 GHz, and 4.15 to 7.01 GHz. In fig 4, \( s_{11} \) of the various design stages of OCSRR based rectangular printed antenna is presented. It is clearly observed with the inclusion of OCSRR, the new resonance at 3.16 GHz created, and in all the other resonating band impedance reasonably matched.

![Figure 4](image_url)

**Fig 4.** \( s_{11} \) Comparison (Ant A vs Ant B vs Proposed Antenna)

In Fig 5, the simulated \( s_{11} \) is compared for different ground length, from which it is observed, the ground length with 3 mm of length and offset feed is capable of creating good impedance bandwidth matching, and a new band is created.
Analysis of the OCSRR and its permittivity extraction

In the proposed final configuration, the OCSRR is engraved in rectangular radiating element, which creates the extra resonance at 3.16 GHz. From [29], the SRR resonant frequency is given by

$$f_{csrr} = \frac{c}{2\pi} \sqrt{\frac{3(x_2-x_1-w)}{Re(\varepsilon) x_1^3}}$$  \hspace{1cm} (6)

The OCSRR resonant frequency is equal to half of the CSRR resonant frequency. Therefore, the resonant frequency of OCSRR is given by

$$f_{ocsrr} = \frac{c}{4\pi} \sqrt{\frac{3(x_2-x_1-w)}{Re(\varepsilon) x_1^3}}$$  \hspace{1cm} (7)

$x_2$ is outer ring slot radius, $x_1$ is the radius of the inner ring slot, and $w$ is the ring width. Substituting, corresponding values $x_1$ (inner slot radius) as 2.7 mm, $x_2$ (outer slot radius) as 3.5 mm in Equations 5 and 6, the resonant frequency of the SRR and OCSRR are 6.28 GHz and 3.14 GHz, respectively.

Fig. 6 illustrates OCSRR - S parameter retrieval waveguide setup in CST environment, and the waveguide provides the PEC and PMC boundary conditions. The OCSRR is excited with the EM wave.
through the input port. The reflection and transmission coefficient of the designed OCSRR is computed and it is presented in Fig. 7. The passband characteristic is observed at 3.16 GHz, which is verified by the theoretical resonant frequency calculation using equation 6. These characteristics are accountable for the operating band from 3.14 GHz to 3.30 GHz.

In Fig. 8, the negative permittivity of OCSRR extracted with the help of the NRW method [37]

\[ v_1 = s_{21} + s_{11} \]  \hspace{1cm} (8)

\[ v_2 = s_{21} - s_{11} \]  \hspace{1cm} (9)

\[ s_{11} = \text{re}(s_{11}) + j(\text{im}(s_{11})) \] \hspace{1cm} (10)

\[ s_{21} = \text{re}(s_{21}) + j(\text{im}(s_{21})) \] \hspace{1cm} (11)

\[ \mu = \frac{2}{jK_0d} \frac{1-v_2}{1+v_2} \] \hspace{1cm} (12)

\[ \varepsilon = \frac{2}{jK_0d} \frac{1-v_1}{1+v_1} \] \hspace{1cm} (13)

Fig 8 Permittivity Characteristics of proposed OCSRR

The code is implemented with MATLAB. The negative permittivity is retrieved from \( s_{11} \) reflection characteristics and \( s_{21} \) transmission characteristics of the designed OCSRR which are simulated and taken from the CST. The proposed OCSRR displays a negative permittivity at 3.16 GHz.

2.3 Parametric Analysis of OCSRR

The optimum value of the critical parameters of the OCSRR is identified using parametric analysis in CST software. The parametric analysis is done in the final proposed structure. The outer ring radius \( x_1 \) is varied from 3.3 to 3.7 mm in steps of 0.2 mm. The simulated \( s_{11} \) plot for various values of \( x_1 \) is presented in Fig 9. From the figure, it is observed that \( x_1 = 3.5 \) mm is having good impedance matching in all the resonating bands, and there is a shift in frequency in the 3.16 GHz band. From which we can conclude that the OCSRR is responsible for 3.16 GHz.
Then the ring width $x$ is increased from 0.2 to 0.4 mm, and their simulated $s_{11}$ is compared in Fig 10. The increment is done in steps of 0.1 mm and it is pragmatic that the $x= 0.3$ mm is having excellent impedance matching in all the resonating bands. And there is the shift in frequency created by the OCSRR. In Fig 11, the reflection characteristics is compared for the different values of $Y$. The value of $y$ is increased from 0.75 to 1.25 mm in steps of 0.25 mm; it has also affected the 3.16 GHz band, which reveals that this 3.16 GHz band is due to the inclusion of OCSRR. The value $y=1$ mm has good impedance matching in all the resonating bands without affecting bandwidth. Therefore, it is chosen for the final fabrication.

![Fig 9 $s_{11}$ evaluation for different values of $x_1$](image)

![Fig 10 $s_{11}$ evaluation for different values of $x$](image)
2.4 Equivalent Circuit of OCSRR inspired rectangular monopole

In Fig 12, the equivalent circuit of the OCSRR inspired rectangular printed antenna is presented. $Z_0$ and $l_f$ is the characteristic impedance (50 Ω) and transmission line electrical length. $R_f$ represents the loss resistance. The $R_{rm}$, $C_{rm}$, and $L_{rm}$ elements are used to represent the rectangular monopole antenna. The elements $C_{OCSRR}$ and $L_{OCSRR}$ are used to represent the OCSRR engraved in the rectangular monopole. The inductance $L_{OCSRR}$ is due to the conductive metal region between the slots, and the capacitance $C_{OCSRR}$ is due to the capacitance arise across the slots. The resonant frequency of OCSRR equal to

$$f_0 = \frac{1}{2 \pi \sqrt{e_{OCSRR} L_{OCSRR}}}$$  \hspace{1cm} (14)

3. Result and Discussion

The current distribution at the resonating band is presented in Fig 13, from which we can perceive that the surface current is maximum centred around the OCSRR at 3.16 GHz. It is evident from the distribution of surface current that the OCSRR is responsible for the 3.16 GHz, and it also has a
negligible effect on 3.82 GHz. At 5.41 GHz, the surface current is spread over the entire designed antenna. From fig 8, the negative permittivity of the OCSRR is observed at 3.14 GHz, which follows the ENG metamaterial characteristics, and hence we can conclude that OCSSR engraved is responsible for 3.16 GHz. It is also validated with the help of analysis of OCSRR presented in section 2.2.

Fig 13. Surface current distribution at resonating frequency

In Fig 13, the simulation s11 plot of Ant a and proposed OCSRR inspired rectangular Antenna is depicted. It is observed from the figure a single band Ant A is enhanced to operate at triband with good
impedance bandwidth and matching in all the resonating bands. It is achieved with the reduced ground, offset feeding, and inclusion of OCSRR at the radiating element. In Fig 14, the measured E-plane and H plane is compared with their simulated results. It is observed that a stable radiation pattern is achieved in all the resonating bands. The E plane has an eighth-shaped dipole pattern, and the H plane has an omnidirectional radiation pattern. The snapshot of the fabricated antenna is presented in Fig 15. The fabricated antenna is measured using VNA Anritsu S820E, and the measured result is compared with the simulated results are presented in Fig 16. There is a slight deviation between the results due to fabrication error and SMA connector soldering.

![Fig 14 E-plane & H-plane pattern (Measured and simulated) at resonating frequencies](image)

a) 3.16 GHz  
b) 3.82 GHz  
c) 5.41 GHz
In Table 2, measured values are compared with the simulated results, and in Table 3, the OCSRR inspired rectangular printed antenna is compared with the antenna which is previously available in the literature.

**Table 2 Measured Vs. Simulated Results**

| Centre Frequency (GHz) | Operating band (GHz) | Return loss (dB) | Impedance Bandwidth (MHz) | Centre Frequency (GHz) | Operating band (GHz) | Return loss (dB) | Impedance Bandwidth (MHz) |
|------------------------|----------------------|------------------|---------------------------|------------------------|----------------------|------------------|--------------------------|
| Simulated              | Measured             |                  |                           |                        |                      |                  |                          |
| 3.22                   | 3.14 to 3.30         | -19.71           | 160                       | 3.16                   | 3.07 to 3.25         | -19.83           | 180                      |
| 3.85                   | 3.79 to 3.89         | -17.67           | 100                       | 3.82                   | 3.73 to 3.92         | -17.9            | 190                      |
| 5.45                   | 4.15 to 7.00         | -60.725          | 2850                      | 5.41                   | 4.10 to 6.85         | -55.73           | 2750                     |
The measured and simulated gain of the OCSRR inspired rectangular printed antenna is presented in Fig 17. The maximum peak gain of 2.19, 2.27, and 2.82 dBi are observed at 3.16, 3.82, and 5.41 GHz, respectively.

Table 3 Comparison between Various antenna in the Literature and OCSRR inspired rectangular antenna

| Reference Number | Technique used                          | Dimensions (mm) | Resonant Frequency (GHz) | Equivalent Circuit Analysis | Metamtrial Property Verification |
|------------------|-----------------------------------------|-----------------|--------------------------|-----------------------------|----------------------------------|
| 2                | Hexagonal patch, fractal                | 75 x 75         | 1.575, 5.9, 7.2          | Not Presented               | NA                               |
| 8                | Triangular patch, slot                  | 30 x 28         | 1.6, 2.8, 5.7, 9.6       | Not Presented               | NA                               |
| 9                | Crescent shape patch                    | 31 x 35         | 11.30, 18.07, 20.72     | Not Presented               | NA                               |
| 11               | Fractal, L shape slot and SRR           | 30 x 24.8       | 3.3, 5.5, 7.3, 9.9      | Not Presented               | Not Presented                    |
| 12               | U slot                                  | 30 x 40         | 1.8, 2.4, 3.5           | Not Presented               | NA                               |
| 13               | SRR                                     | 22 x 24         | 2.48, 3.49              | Not Presented               | Not Presented                    |
| 24               | QWSIW, Fractal, CSRR                    | 23 x 20.5       | between 4.96 to 5.88 (tunable by rotating the CSRR) | Not Presented               | Not Presented                    |
| 25               | CSRR and reduced ground                 | 20 x 25         | 4.5, 8                  | Not Presented               | Not Presented                    |
| 27               | Slot, ELC, Koch Fractal                 | 40 x 40         | 1.5, 3.5, 5.4           | Not Presented               | Not Presented                    |
| 26               | ELC                                     | 35 x 35         | 3.77, 5.4               | Not Presented               | Not Presented                    |
| OCSRR inspired Rectangular antenna (Proposed) | offset feed, OCSRR | 27.84 x 23.25 | 3.16, 3.82, 5.41 | Presented | Substantiated |
4. Conclusion

A rectangular monopole engraved with an open complementary split resonator is proposed for wireless communication. The structure designed is having a compact size and capable of resonating at three frequencies. The resonating frequencies are 3.16, 3.82, and 5.41 GHz. The simulated return loss, gain, E-plane, and H-plane radiation pattern results are compared with the measured results, and it is observed that the measured results are on a par equal with simulated results. With the parametric analysis the critical OCSRR dimensions are identified, and the results are presented. The negative permittivity of the OCSRR is extracted using the waveguide extraction method. The negative permittivity is achieved at 3.14 GHz, and it is also validated with the help of OCSRR resonant frequency calculation in section 2.2. The measured impedance bandwidth of the proposed OCSRR inspired rectangular printed antenna is 180 MHz (3.07GHz - 3.25 GHz), 190 MHz (3.73 GHz - 3.92 GHz), and 2750 MHz (4.10 GHz - 6.85 GHz). The stable radiation pattern, reasonable gain, simple edifice, compactness with tri-band characteristics makes the proposed structure more suitable for the wireless applications like RADAR, long-distance radio communication, WLAN, WAIC, and WiMAX.

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