Isolation enhancement of rectangular dielectric resonator antennas using wideband double slit complementary split ring resonators

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Abstract
A wideband epsilon-negative structure is employed as one-layer and two-layer isolators to reduce mutual coupling in multiple-input multiple-output systems composed of two E-coupled rectangular dielectric resonator antennas. The proposed unit cell with $-15$ dB bandwidth for $S_{21}$ extending from 1970 to 3317 MHz, is a double slit complementary split ring resonator etched on the ground plane of a stripline. Each layer is composed of a $2 \times 3$ array of the suggested unit cell. Reduction in isolation of more than 11 dB for the one-layer case and higher than 20 dB for the two-layer case are measured within the frequency range of 2.604 to 2.64 GHz which includes WiMAX. The highest isolation level of 36 dB is realized at 2.868 GHz. The impedance matching, gain, radiation efficiency, and envelope correlation are improved compared to the original case. A prototype is designed, fabricated, and tested. Simulation data and measurement results are in good agreement.

KEYWORDS
DRA, MIMO, mutual coupling, rectangular dielectric resonator antenna, single-negative (SNG) metamaterial

1 | INTRODUCTION
Data transmitting rate can be enhanced by increasing the Signal to Noise Ratio (SNR) and signal bandwidth. On the other hand, this strategy will not be able to improve spectral efficiency. Instead, the multiple-input multiple-output (MIMO) system works more effectively in the multipath environment. However, mutual coupling between antennas causes significant signal correlation and can reduce data transmission rate and the efficiency as well. Dielectric resonator antennas (DRAs) can be appropriate options for the growing technologies of wireless communications and MIMO systems. To enhance the functionality and capacity of a wireless communication node, the benefits of spatial diversity by merging several signals in the receiver should be considered. When the antenna elements are placed closer than half a wavelength, the appearance of strong coupling between antennas degrades the efficiency of the system.

Some decoupling approaches are based on the efficiency improvement of electromagnetic bandgap (EBG) structures to eliminate surface waves in printed antenna geometries, applying multilayer EBGs between two omnidirectional discone antennas as absorbers, defected ground structures (DGS) to reduce mutual coupling between DRAs and microstrip patch antennas (MPAs), superstrate constructed from hexagonal slit resonators between circular patch antennas and substrate integrated waveguide technology in dual-polarized microstrip antennas.

In recent years, metamaterials (MTMs), possessing either negative permittivity and/or negative permeability, have been utilized widely to eliminate electromagnetic coupling in antenna arrays. Some examples are employing MTM as a near-field electromagnetic insulator to mitigate the mutual coupling between passive elements in ESPAR (electronically steerable passive array radiator) monopole antenna, placing metasurfaces between H-plane coupled cylindrical antennas.
DRAs, at 60 GHz, complementary split ring resonators (CSRRs) for reducing the surface and lateral waves in planar antenna circuits, and the use of spiral resonators within the substrate and between the MPAs. An ultra-compact metamaterial surface composed of symmetrical spiral lines etched on the ground is embedded within the microstrip patch array. Other reports include complementary spiral ring resonators with single-negative (SNG) permittivity in microstrip antenna arrays, artificial magnetic conductor reflector composed of spiral resonators and thin strips in multiple antenna systems, integrating well-engineered MTMs with negative permeability between high profile monopole antennas and axial mode helical antennas. No investigation has been made for decoupling rectangular dielectric resonator antennas (RDRAs) in a MIMO system using SNG electric MTM, which is presented in this work. Moreover, the behavior of the proposed unit cell has not previously been studied as an epsilon-negative (ENG) MTM.

2 | DESIGN AND ANALYSIS OF ENG MTM RESONATOR

2.1 | Driven-mode and retrieval effective parameters

Figure 1A shows the proposed MTM unit cell. The suggested subwavelength MTM is based on an isolated symmetrical split ring resonator DGS layout, which is designed and characterized as a lowpass filter. This MTM structure is implemented by etching the double slit complementary split ring resonator (DS-CSRR) on a microstrip line ground plane. The present structure is the complementary of a double slotted symmetrical MTM unit cell, which is under study by the authors. A metallic strip line is printed on Rogers RO4003C substrate with a thickness of 32 mils, dielectric constant of εr = 3.55, tan δ = 0.0027 and a copper cladding of 35 μm. The slotted CSRRs have dimensions of R_in = 6 mm, g1 = g2 = 0.5 mm, L = 18 mm, d = 0.5 mm, w = 1 mm, w_A = 3 mm and the slot width, s, is 0.5 mm. In order to achieve a much wider rejection band through two transmission zeros, a slot is added in the middle of the inner ring, which generates an additional resonant mode. Furthermore, two or three cascaded units of CSRRs produce a broader stopband. CSRR behaves as a dipole excited by an electric field polarized along the axial direction of the ring. The Babinet's principle expresses the complementarity of the magnetic and electric fields of the split ring resonator and its complementary, CSRR.

The commercial full-wave electromagnetic simulator, CST Microwave Studio is used for numerical analysis. For the design and characterization of the proposed unit cell, two methods of driven-mode and eigen-mode analysis are considered. For driven-mode analysis, the setup of the Perfect Electric Conductor (PEC)-Perfect Magnetic Conductor (PMC) waveguide method is displayed in Figure 1B. The setup is used to determine the scattering parameters of the proposed unit cell. The CSRR is excited by a normal electric field. Therefore, the front and rear boundaries are set as PEC, upper and lower boundaries are assigned as PMC, and the model is excited with a transverse electromagnetic mode in both ports of the waveguide, which propagates along the x-axis.

To compare stop bandwidth of DS-CSRR with and without the inner ring’s additional slot, the reflection and transmission coefficients of the proposed structure with and without the slot are computed. The magnitude of the scattering parameter, |S11|, and transmission parameter, |S21|, as well as the phase of S parameters corresponding to both unit cells, with and without the slot, are shown in Figure 1C,D. As demonstrated in Figure 1C, the DS-CSRR exhibits one rejection frequency at 2.777 GHz. Adding the slot to the inner ring of the resonator generates an additional rejected mode at 2 GHz. In addition, the frequency corresponding to −15 dB of S21 is reduced from 2.4 to 1.97 GHz and the resonant frequency of the second rejected mode is shifted from 2.777 to 2.63 GHz. Therefore, the −15 dB stop bandwidth of S21 for DS-CSRR and slotted DS-CSRR are obtained as 996 MHz (34%) and 1347 MHz (51%), respectively.

As shown in Figure 1D, the proposed unit cell exhibits four discontinuities in the phase of S21. The frequencies, in which phase shifts from +180° to −180° occur, are 2 and 2.63 GHz. These discontinuities are associated with negative permittivity response of the structure where the propagation of electromagnetic fields is blocked. As a result, proposed slotted DS-CSRR presents a wide and deep stop band with a maximum rejection of 54 dBs. The stopband extends from 1970 to 3317 MHz, which is wide enough to cover WiMAX. Since the cell size is less than λ/4, the constitutive effective permittivity and permeability of the proposed SNG MTM are extracted from scattering parameters by using the standard retrieval procedure. Referring to the retrieval method to extract effective parameters of MTMs, the impedance Z, and effective refractive index n are first evaluated. Then the effective permittivity ε and the effective permeability μ are calculated from $\varepsilon = n^2 \frac{\lambda}{Z}$ and $\mu = n^2 \frac{\lambda}{Z}$. The real and imaginary parts of the effective permeability and permittivity of the DS-CSRR bulk with the additional slot is extracted and is plotted in Figure 2. It is observed that the SNG MTM considered in this work, has a complex effective permittivity, $\varepsilon_{\text{eff}}$, with a negative real part and effective permeability, $\mu_{\text{eff}}$, with a positive real part. The electrical permittivity is negative over the wide frequency range of 1.955 to 3 GHz in which reducing the mutual coupling between Rectangular DRAs is considered.

2.2 | Eigen-mode and dispersion diagram analysis

For further investigation, the dispersion diagram is obtained by eigen-mode technique done in CST. As shown in Figure 3A, the model setup is performed by defining the
periodic boundary conditions to four planes perpendicular to x-axis and y-axis while assigning $E_z = 0$ on front and back planes, parallel to DS-CSRR surface. Next, by varying $\beta_x$ and $\beta_y$ along boundaries of the irreducible Brillouin zone, and applying a number of frequency sweeps, dispersion curves of the unit cell are depicted. The dispersion diagram associated with three resonant modes of the proposed MTM is illustrated in Figure 3B, where the light line is also shown. Since surface waves behave similar to slow waves, dispersion curves appear below the light line. The stop band of the element is defined to be the frequency band with no dispersion curves present in the dispersion diagram.

As expected, two band gaps occur from 1.69 to 1.79 GHz and 1.950 to 3.026 GHz, respectively. Good agreement is observed in the frequency range of negative permittivity, 1.955 to 3 GHz, obtained from driven-mode analysis and the second band gap indicated by eigen-mode analysis, 1.950 to 3.026 GHz.

3 | TWO ELEMENT RDRA ARRANGEMENT

DRAs are typically manufactured from low-loss high-permittivity microwave dielectric materials. DRAs possess various advantages over common metallic antennas, such as higher radiation efficiency, typically greater than 95% due to lack of conductor and surface wave losses, and broader impedance bandwidth in comparison to MPAs. RDRAs have attracted great attention compared to cylindrical and hemispherical versions. They feature more degrees of freedom.
design and control the bandwidth. Feeding by microstrip line excites magnetic fields within the RDRA and generates a short horizontal magnetic dipole. This direct feeding is simple and cost-effective in fabrication and therefore it is commonly employed in linear DRA arrays.

Figure 4 shows the schematic view of the microstrip line fed RDRA arrangement. Two RDRAs with dimensions of $a \times b \times h = 18 \times 18 \times 8.9$ mm$^3$ and dielectric constant of $\varepsilon_r = 35.9$ are located on a $L_g \times W_g = 140 \times 110$ mm$^2$ substrate. They are excited by a 50 $\Omega$ microstrip line with a width of $w_s = 2.388$ mm, which is printed on a 31 mils Rogers RT5870 with $\varepsilon_r = 2.33$ and $\tan\delta = 0.0012$. The bottom side is metalized and grounded.

It has been shown by Van Bladel that a rectangular DR supports “nonconfined” modes only. There is no analytical approach to predict the resonant frequency of each excited mode in RDRA. However, applying the dielectric waveguide model and ignoring the dielectric substrate, the resonant frequency of all possible modes can be determined. Presence of the ground plane inhibits $E$ even modes and $H$ modes. Furthermore, the eigen-mode solver of CST was used to compute resonant frequencies of the first six modes in RDRA. According to dimensions of DR ($a = b > 2h$), the fundamental radiation mode is $\text{TE}_{11\delta}$ and the antenna radiates similar to a short magnetic dipole, with strong radiation at boresight direction. In the microstrip line fed RDRA, excited modes are regulated simply by varying the stripline length, $L_s$, and the length, $L_0$, of the microstrip line covered by the DR (Figure 4). The antenna is excited to radiate two resonant modes at 2.6 and 2.86 GHz.

4 | MUTUAL COUPLING REDUCTION MEASUREMENTS AND DISCUSSION

The experimental prototype is examined to verify efficient decoupling capability of the proposed broadband DS-CSRR by suppressing electromagnetic coupling at stopband frequencies. When these structures are excited by an electromagnetic field having appropriate polarization, they exhibit negative effective permittivity over a certain frequency range.

Two closely spaced E-coupled RDRAs with a separation of $D = 0.3\lambda_0 ($= 36 mm) is arranged, where $\lambda_0$ is the free
space wavelength corresponding to the resonant frequency of RDRA, that is, 2.6 GHz. To investigate the results of inserting one layer as well as two layers of metasurface between DRA’s, the separation of the antennas’ adjacent faces is selected as 18 mm with the two layers 10 mm apart. The setup is connected to the Vector Network Analyzer (VNA) through coaxial SMA connectors. The two ports of VNA are calibrated over the desired bandwidth. The reflection and transmission coefficients for each antenna are recorded.

4.1 Scattering parameters

To verify the effectiveness of the proposed ENG isolator, a number of cases are examined. By setting the length of the microstrip line $L_s = 36.4$ mm and the location of the antenna relative to the open end of the microstrip line, $L_0 = 12.9$ mm, the resonant frequency of the array is set around 2.6 GHz. Then, a one-layer MTM composed of a $2 \times 3$ array of the proposed slotted DS-CSRR unit cell is aligned vertically in midway between the two antennas with a distance of 10 mm from the substrate edge. A photograph of the array and the setup with one-layer isolator is presented in Figure 5A. It was observed that the position of the slab relative to antennas is sensitive and critical for impedance matching; therefore, the location of the isolator is fine-tuned where the best impedance matching is achieved and the reflection coefficients are minimized.

To quantify the performance of the proposed one-layer ENG isolator, a perfectly conducting (PEC) plate is simulated and its results are compared. The dimensions of the PEC plate correspond to the case of one-layer isolator.

The measured and simulated scattering parameters corresponding to the first configuration are given in Figure 5. The $S$ parameters without the wideband ENG isolator are provided as a reference for the design. It is observed that inserting a PEC plate between the two antennas, compared to the reference case, results in an improvement of about 5 dB isolation, while more reduction of mutual coupling is obtained by the proposed isolator at the resonant frequency. Placing one layer of MTM isolator between the two antennas leads to a small resonant frequency shift. The measured magnitude of reflection coefficients for each antenna element is improved in the presence of the isolator and; from $-7$ dB at 2.581 GHz without isolator to $-18$ dB at 2.589 GHz with one isolator. The isolation level between RDRA’s, $S_{21}$, is enhanced by 11 dB. As expected, the
antennas are effectively isolated ($S_{21} < -18 \, \text{dB}$) in the presence of one isolator. The ENG isolator blocks most of the radiated electromagnetic energy. According to the comparison of $|S_{11}|$ shown in Figure 5B, it is found that utilizing the one-layer isolator improves the reflection coefficient. Better impedance matching level is obtained at the resonant frequency by almost $-32 \, \text{dB}$.

Since the two-element antenna array with the isolator is asymmetrical along the $x$-direction, the reflection coefficients of the two antennas, $S_{11}$ and $S_{22}$, are not identical, while both parameters are improved as shown in Figure 5C. From these results, it is demonstrated that one layer of the proposed slotted DS-CSRR isolator improves the impedance matching level more than $17 \, \text{dB}$, and increases the isolation level more than $11 \, \text{dB}$ across a wide frequency range.

An array of the suggested structure has a negative permittivity and inhibits wave propagation. In fact, all transiting waves across the ENG slab are evanescent since the propagation constant is purely imaginary.

For further investigation, a two-layer configuration of the proposed ENG is arranged between the original antenna arrays. The spacing of the rear layer is set at 10 mm; Figure 6A displays the fabricated prototype.

Figure 6 presents the results of simulator and experimental investigation of the antenna array with and without a two-layer isolator. Referring to the figure, the array with two-layer isolator possesses an isolation level more than $21 \, \text{dB}$ within the frequency range of 2.604 to 2.64 GHz. Furthermore, 30 dB isolation is measured at a resonant frequency of 2.621 GHz. The two-layer isolator case shows superior isolation, which is 20 dB better than the array
without the spacer. Comparing the results of using one-layer and two-layer insulators in the reference array indicates that the two-layer isolator reduces mutual coupling a further 11 dB.

To validate the capability of decoupling mechanism across the wide stop band, the microstrip line is set to excite another mode of RDRA. By tuning $L = 36.8$ mm and $L_0 = 7.8$ mm while other parameters are as before, the resonant frequency of the antenna is changed to 2.86 GHz. The scattering parameters of this structure with the two-layer isolator are examined and presented in Figure 7.

### 4.2 Envelope correlation

The functionality of a MIMO antenna system is usually considered by using the envelope-correlation factor, which is often derived from the mutual impedance between the antenna elements, far-field patterns, or directly from scattering parameters. Low correlation and high isolation are essential for better performance. By considering uniform radiation and fine impedance matching, the envelope correlation coefficient (ECC), $\rho_e$, is given as

$$\rho_e(i,j,N) = \frac{\sum_{n=1}^{N} S_{n,i}^* S_{n,j}}{\prod_{k=i,j}^{N} [1 - \sum_{n=1}^{N} S_{n,k}^* S_{n,k}]}$$

where $N$ is the number of antennas. When $N = 2$, and each antenna is considered as transmitter/receiver in a MIMO system, the envelope correlation of a $2 \times 2$ MIMO system, between elements $i = 1$ and $j = 2$, is calculated from

$$\rho_e(1,2,2) = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{\left[1 - \left(|S_{11}|^2 + |S_{21}|^2\right)\right] \left[1 - \left(|S_{22}|^2 + |S_{12}|^2\right)\right]}$$

Both auto-correlation and cross-correlation coefficients derived from scattering parameters are shown in a matrix form as

![Figure 8](image8.png)

**FIGURE 8** The correlation coefficients of the RDRA system calculated from measured scattering parameters with/without ENG isolator, where the operating resonant frequency is around 2.6 GHz. A, The envelope correlation coefficient ($\rho_e$). B, The auto-correlation ($C_{11}$). C, The cross-correlation ($C_{21}$).

Abbreviations: RDRA, rectangular dielectric resonator antenna; ENG, epsilon-negative

![Figure 9](image9.png)

**FIGURE 9** Measured and simulated far-field power patterns for the first configuration with and without ENG isolators, at resonant frequency ($f = 2.6$ GHz).

Abbreviation: ENG, epsilon-negative
\[ C = \frac{1 - \left( |S_{11}|^2 + |S_{21}|^2 \right) - (S_{11}^* S_{12} + S_{21}^* S_{22})}{1 - \left( |S_{22}|^2 + |S_{12}|^2 \right)} \]

where, the auto-correlation, \( C_{ii} \), indicates the amount of radiated power from antenna \( i \), and the cross-correlation, \( C_{ij} \), gives information of cross-coupling between antenna elements \( i \) and \( j \).

Figure 8A-C shows the ECC, \( \rho_e \), the auto-correlation, \( C_{11} \), and the cross-correlation, \( C_{21} \), respectively. These were computed using measured S parameters of RDRAs with and without ENG isolators. The ECC between RDRAs at resonant frequency is reduced by 30 dB when using a one-layer MTM isolator, and more than 65 dB reduction is achieved with a two-layer isolator. The auto-correlation of the antenna system is improved by employing MTM isolators. The cross-correlation given in Figure 8C indicates that RDRAs with SNG electric isolators are well-decorrelated across the antenna array operating frequency band when compared with no isolators case.

### 4.3 Far-field characteristics

The radiation patterns of the first configuration with and without isolators were simulated at both H-plane and E-plane and were measured at E-plane. The far-field patterns at E-plane (\( \phi = 90^\circ \)), are illustrated in Figure 9. The outcomes do not present notable changes in radiation characteristics at the half space above the substrate when loaded by the ENG.
MTMs at the resonant frequency ($f = 2.6$ GHz). However, the back-lobe level is reduced significantly. On the other hand, simulation results show that directivity of the radiation pattern in the H-plane ($\phi = 0^\circ$), is slightly enhanced, which is not shown here.

The realized gain obtained from CST simulation results, as well as, measured gain of the RDRA arrays are presented in Figure 10. By situating one-layer and two-layer MTM isolators, a gain of 4 and 5.4 dB is measured, respectively, with 1.4 and 2.8 dB improvements. Furthermore, simulation results demonstrate that the radiation efficiency is enhanced from 82% to 92% with one-layer isolator and is 98% with two-layer isolator around 2.6 GHz. Therefore, the antenna array performance will significantly improve due to decreased element mutual coupling and retained radiation performance.

The CST-simulated results of H-field distributions for the two-layer isolator array antenna and the reference antenna without the isolator are illustrated in Figure 11. Port #1 is excited to transmit at 2.6 GHz, while port #2 is terminated by a 50 $\Omega$ load.

Comparing the snapshots of the magnetic fields in the transverse plane confirms how the mutual coupling fields are eliminated using the proposed ENG MTMs. The negative electrical permittivity region is attributed to the presence of evanescent electromagnetic fields, which prevents transmission of electromagnetic energy within such MTMs. Therefore, ENG layers behave as decoupler and provide a strong effect on the mutual coupling reduction.

5 | CONCLUSION

In this research, a wide stop bandwidth, high-isolation ENG spacer composed of slotted DS-CSRR backed by a metal strip was characterized by driven-mode and eigen-mode analysis. A $2 \times 3$ array of the proposed ENG MTM unit cell was utilized to construct a one-layer isolator. The one-layer and two-layer isolators were embedded between two closely spaced E-coupled RDRAs to efficiently reduce mutual coupling at two resonant modes within the bandgap region of the isolator. Experimental results show a significant reduction in mutual coupling across operating frequency including WiMAX (2.6 GHz IEEE standard 802.16e) spectrum. More than 20 dB isolation for the one-layer case and higher than 30 dB isolation for the two-layer case is measured. Moreover, an improvement of more than 10 dB was achieved in impedance matching.

The functionality of the RDRA array as a $2 \times 2$ MIMO system was characterized. The envelope correlation between RDRA systems has been reduced more than 30 dB when embedding a one-layer isolator and more than 65 dB by using a two-layer isolator. The auto-correlation and cross-correlation of the antenna system has been improved by employing MTM isolators.

The measured gain of the antenna array is 1.4 and 2.8 dB better than the original case by situating a one-layer and a two-layer ENG isolators, respectively. The simulated radiation efficiency is enhanced from 82% to 92% with the one-layer isolator and is 98% in the two-layer case. The simulation results agree with measurement data, which shows the efficient capability of the proposed ENG MTM to enhance the performance of the RDRA array.

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REFERENCES


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