CHAPTER 6

Mutual Coupling Reduction Between Flexible MIMO Antennas

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Abstract

In this chapter, a novel µ-negative (MNG) metamaterial structure is proposed to reduce mutual coupling between two printed monopole antennas operating at 2.45 GHz. The unit cell consists of two split ring resonator (SRR) structures bridged at the centre, which mimics a cascaded filter; hence, termed as Bridged Split Ring Resonators (BSRRs). This approach enhances the magnitude and bandwidth of the electromagnetic suppression response. Unlike the bulky nature and vertical orientation of such structures, the proposed SRRs are positioned in a planar fashion with axes parallel to the magnetic field vector of the antennas which is necessary for BSRR structures’ excitation. A reduction of 11.5 dB in the mutual coupling is achieved by inserting the proposed structures with a separation distance of 0.29 cm between the radiating elements. Moreover, the proposed design offers an ultra thin and flexible profile since it is printed on a polyimide substrate with a thickness of 50.8 µm. It can be inferred that the proposed design is a reasonable candidate for flexible and wearable wireless systems. Good agreement is obtained between the experimental and numerical results.

Keywords: Bridged split ring resonators (BSRRs), flexible electronics, mutual coupling, printed monopole antennas.

1 Introduction

The past decade has witnessed extensive research activity in areas related to the development and deployment of multiple input multiple output (MIMO) systems due to their high spectral efficiency. The performance of such systems is highly
compromised by the signal-to-noise ratio (SNR) and the correlation/isolation characteristics among the channel transfer functions of the associated transmit and receive antenna elements [1–3].

Mutual coupling reduction among closely spaced radiating elements is essential for the performance of MIMO systems due to the fact that induced currents, input impedance, and radiation patterns are affected when the antenna elements are correlated, which in turn significantly reduces the capacity of the MIMO systems [4]. A straightforward solution to reduce the correlation is through physically separating the radiating elements by a distance greater than \( \frac{\lambda}{2} \). However, this solution is impractical in contemporary hand-held wireless devices with strict space limitation constraints (Fig. 1).

Several methods to reduce the mutual coupling between the radiating elements in MIMO and antenna array systems have been reported in the literature. Some of these techniques are based on the use of electromagnetic band gap (EBG) structures [5–7], parasitic elements [8], defected ground planes [9,10], and 180° hybrid couplers [11]. In [12], three periods of planar soft surface realized by strips with metallic pins have been applied to reduce mutual coupling between patch antennas printed on a substrate with an interelement distance of 0.6\( \lambda \). In [13], a uni-planar compact photonic bandgap (UC-PBG) superstrate is utilized to reduce the coupling between two patch antennas with a 0.5\( \lambda \) separation distance. Although these techniques are quite efficient, they exhibit a high complexity in terms of fabrication process and involve multilayered components. In [14], another efficient technique based on the use of MNG metamaterial structures has been proposed to reduce mutual coupling between two high profile monopoles. It should be noted that all the above reported techniques are only suitable for microstrip patch antennas or high profile antennas, whereas practically most communication standards of hand-held devices and personal computers such as WLAN, Bluetooth, WiMAX, and GSM utilize planar monopole and dipole antennas that are preferred over microstrip antennas due to their omnidirectional radiation patterns, high efficiency, and large impedance bandwidth [15,16]. On the other hand, consumers of modern

Figure 1: Flexible printed monopole antenna system with reduced mutual coupling.
electronic devices have expressed a huge interest in portable, lightweight, low profile, and wearable/flexible electronic devices. The integration of flexible and ultra-low profile antennas and RF components with such devices is eventually needed for wireless connectivity.

In this chapter, a novel bridged SRR structure is proposed to reduce the mutual coupling between two flexible printed monopole antennas. The proposed structure is oriented in a planar fashion utilizing the vertical magnetic fields of the printed monopoles for the MNG excitation. Furthermore, the structure exhibits a better performance in terms of rejection magnitude and bandwidth compared with conventional SRRs. Unlike the bulky metamaterial-based wireless and RF systems, the proposed antenna and bridged split ring resonators (BSRRs) are fully planar and printed on a flexible kapton polyimide substrate with a thickness of 50.8 µm, which makes it suitable for flexible and wearable applications.

This chapter is organized as follows: In Section 2, we present the description for our proposed BSRR structure and principle of operation along with the antenna design. In Section 3, the performance of the antennas with and without the BSRR is discussed in terms of transmission coefficient, correlation envelope, current distribution, and far-field radiation patterns. In Section 4, the performance of the proposed system is characterized when subjected to bending effects. Finally, conclusions are given in Section 5.

2 Antenna System Design and Configuration

Design and analysis of the proposed printed monopole antennas along with the BSRR structure have been carried out using the full-wave simulation software CST Microwave Studio, which is based on the finite integration technique [17].

2.1 Choice of substrate

To comply with modern flexible wireless systems requirements, low profile, compact, and high-performance antennas are required. Furthermore, embedded elements need to be highly flexible and exhibit high tolerance levels in terms of physical robustness, bending repeatability, and thermal endurance. As mentioned earlier, printed monopole antennas are preferred in wireless systems of modern electronic devices over other antenna types due to their simple configuration, wide impedance bandwidth, low profile, low fabrication cost, and omnidirectional radiation pattern.

In this research, polyimide Kapton was selected as the substrate for the antennas and MNG metamaterial since it exhibits a good balance between physical and electrical properties characterized by a low loss tangent over a wide frequency range (0.002). Moreover, Kapton substrates offer an extremely low profile solution (50.8 µm) yet highly robust with a tensile strength of 165 MPa at 73°F, a dielectric strength of 3,500–7,000 V/mil, and a temperature rating of 65 to 150°C [18].
2.2 Antenna design

For the sake of simplicity, two radiating elements are considered in this research to demonstrate the significance of the proposed BSRR based system in terms of mutual coupling mitigation. The antenna is designed to operate in the Industrial, Scientific, Medical 2.45 GHz band as a benchmark. As shown in Fig. 2, the antenna consists of a square split ring-shaped monopole. The winding lengthens the physical current path, which in turn reduces the structure size without significant efficiency degradation or disturbance to the radiation pattern. The separation distance between the arms, \( G_1 \), is optimized as 2 mm to achieve the least return loss. It is worth mentioning that a smaller separation leads to an increased capacitive coupling between the arms, which, in turn, degrade the impedance matching. The U-shaped monopole is fed by a 1.5-mm wide 50 \( \Omega \) coplanar waveguide (CPW) feed, which adds the merit of fabrication simplicity since both the radiating element and ground plane are printed on the same side of the substrate. The antenna structure is printed on a 20 mm \( \times \) 37 mm Kapton polyimide substrate with a dielectric constant of 3.4 and a loss tangent of 0.002. The geometry of the antenna and dimensions are depicted in Table 1 and Fig. 2, respectively.

2.3 Design and characterization of BSRR

Due to the current distribution’s nature of monopole antennas, they are surrounded by circulating magnetic fields when excited. The induced magnetic fields strongly couple closely spaced radiating elements. Therefore, de-correlating the antennas through the use of one of the aforementioned techniques is essential.

The prohibition of electromagnetic wave propagation is an interesting feature of MNG metamaterial media, which can be utilized when mutual coupling between radiating elements is of concern. As is well known, MNG media can be realized through SRR structures. When incident electromagnetic wave is excited with a vertical polarization (i.e. magnetic field \( \mathbf{H} \) parallel to the axes of SRR structures), induced currents will be circulated on both the inner and outer rings which leads to charge accumulation across the gaps [19]. Consequently, the SRR structures act

| \( L1 \) | 37 | \( W2 \) | 8.4 |
| \( L2 \) | 19 | \( W3 \) | 8  |
| \( L3 \) | 17 | \( W4 \) | 7.8 |
| \( L4 \) | 12.3 | \( W5 \) | 3.2 |
| \( L5 \) | 17 | \( G1 \) | 2.2 |
| \( L6 \) | 4.2 | \( G2 \) | 0.4 |
| \( W1 \) | 20 | \( T \) | 0.0508 |
as magnetic dipoles and an effective MNG medium is obtained, which prevents propagating modes. This behaviour can be represented by a matrix of $LC$ circuits with inductance $L$ (represented by the current paths in the metallic rings), and capacitance $C$ (represented by the gaps between the rings). Hence, SRR structures can be characterized by the effective capacitance and inductance with a resonance frequency $\omega_m=1/\gamma$, and a negative permeability can be achieved within a narrow frequency band slightly above the resonance frequency $\omega_m$ [19].

Complementary split ring resonator (CSRR) structures are considered as the dual counterpart of SRR since they exhibit a resonant behaviour when subjected to a vertically polarized electric field. In [20], a slotted CSRR structure is proposed to effectively reduce the mutual coupling between two square microstrip antennas. The slot combining two unit cells is proven to enhance the bandwidth and the stop band behaviour of the reported structure. By applying the duality principle, we propose the dual structure where SRR unit cells are bridged to enhance the stop band performance when magnetic fields are dominantly vertically polarized. Such combined structures can be thought of as cascaded filters [21]. Next, the optimized dimensions were obtained such that the structure resonates at the frequency range under consideration (2.45 GHz). Figure 3a depicts a unit cell of the BSRR, which is modelled to have an effective negative permeability around 2.45 GHz.

The optimized parameters for the BSRR to operate at the desired resonant frequency are as follows: $R_1 = 3$ mm, $R_2 = 4.9$ mm, $S_1 = 1.63$ mm, $S_2 = 3$ mm, $D_1 = 0.4$ mm, and $D_2 = 0.3$ mm. To characterize the SRR model, the scattering

Figure 2: Geometry of the proposed flexible printed monopole antenna.
parameters of the unit cell must be obtained. A BSRR unit cell is positioned at the centre of a waveguide excited by an incident wave with \( E \) and \( H \) fields oriented as described in Fig. 3b where perfect electric conductor (PEC) boundary conditions are assigned to the side walls of the waveguide, whereas perfect magnetic conductor (PMC) boundary conditions were assigned to the top and bottom walls in order to enforce the transverse electromagnetic mode (TEM). Generally, the effective permeability and permittivity are calculated through the refractive index and impedance matrix, which are extracted from the scattering parameters of the SRR unit cell. In this work, the complex effective permeability was retrieved based on a procedure reported in [21]. Figure 4 depicts the retrieved complex permeability of the BSRR structure.
To demonstrate the effectiveness of the bridged SRR in comparison to the conventional SRR structure, a numerical comparative study is conducted where the scattering parameters of a microstrip transmission line positioned over two SRR unit cells, with and without the joining bridge, are obtained. It is evident from Fig. 5 that the proposed structure exhibits an enhanced stop band performance over the conventional SRR.

2.4 Fabrication and experimental setup

The two antenna elements along with the BSRR structure were printed on a 50.8-μm flexible Kapton polyimide substrate with a dielectric constant of 3.4 and a loss tangent of 0.002. A silver nanoparticle-based conductive ink is ink-jetted over the substrate by a Dimatix DMP 2831 material printer followed by a thermal annealing at 100°C for 9 h. It is worth mentioning that three layers of ink were deposited on the substrate to achieve physical robustness and continuity to the printed pattern. Both antennas were fed by SMA connectors for measurement purposes. The prototype scheme of the printed antenna system with two sets of BSRR structures inserted in between is shown in Fig. 6.

3 Results and Discussion

3.1 Scattering parameters

The scattering parameters were measured using an Agilent PNA-X series N5242A Vector Network Analyser with 10 MHz to 26.5 GHz frequency range. First, the

Figure 5: Transmission coefficient $S_{12}$ for the BSRR structure compared with a conventional SRR obtained from the transmission line method.
scattering parameters of the two printed monopole antennas separated by 35 mm (0.29λ) are obtained for comparison purposes. Next, two experiments were conducted to study the influence of the number of BSRR sets on the mutual coupling as well as on the impedance matching of the antennas. When one set of BSRR (as developed in Section 2) is horizontally inserted between the printed monopoles, a 6-dB reduction in the mutual coupling at the resonant frequency (2.45 GHz) is achieved while on the other hand, a 11.5-dB reduction is achieved when two sets are inserted with the same separation distance. A good impedance matching is maintained for all the cases despite the increase in the return loss and the slight shift in the resonance frequency, which is covered by the relatively wide bandwidth of the monopole antennas. Figure 7 shows the simulated and measured reflection coefficient $S_{11}$ of the antenna system with one set, two sets, and without the MNG metamaterial; while Fig. 8 shows the mutual coupling of the aforementioned cases in terms of the transmission coefficient $S_{12}$.

The positive permeability values below the BSRR resonance have contributed partially to the mutual coupling rejection. This is noticeable when the transmission coefficient begins to first drop around 2.43 GHz. On the other hand, the negative permeability value that occurs above the resonance is more influential on the rejection of mutual coupling. This is mainly attributed to the existence of the evanescent fields in the negative region of the magnetic structure, which prohibits electromagnetic energy from being propagated from one element to another [14]. It should be noted that the simulated results exhibit around 7 dB better rejection than the measured values for the case with two sets. This could be attributed to the fabrication tolerances.
Figure 7: Simulated and measured $S_{11}$ for the printed monopole antenna system without, with one set, and two sets of BSRR.

Figure 8: Simulated and measured $S_{12}$ for the printed monopole antenna system without, with one set, and two sets of BSRR.
3.2 Far-field radiation pattern

The monopole antennas adopted in this chapter provide an omnidirectional radiation pattern. The influence of the MNG metamaterial structures on the far-field radiation patterns of the monopole antennas is investigated in the two principal cuts (E and H planes), which were measured inside the University of Arkansas at Little Rock’s anechoic chamber. The Antenna Under Test (AUT) was placed on an ETS Lindgren 2090 positioner and aligned to a horn antenna with adjustable polarization. It is evident from Fig. 9 that using MNG structures affects the antenna’s direction of the maximum gain. For the resonant frequency under consideration (2.45 GHz), the E-plane (XY-cut) is turned to a hemi-spherical type where the null area is pushed in the direction opposite to the BSRR structure. On the other hand, the H-plane (XZ-cut) gain has increased by 2.5 dB when BSRR structures are inserted between the two antenna elements. Good agreement between the simulated and measured results is observed in terms of radiation patterns shape; however, the measured gain values are less than the simulated. This is attributed to the reduced efficiency of the fabricated prototype due to the finite conductivity of the silver nanoparticle based ink (8.9 \times 10^4 \text{S/m}) compared with the infinite conductivity (PEC) approximation used in the simulated model, which is assumed to reduce the processing time.

3.3 Current distribution

The reduction of mutual coupling by virtue of the MNG’s property of wave propagation prohibition is clearly noticeable in Fig. 10, in which the distribution of the tangential surface currents is plotted when one antenna element is excited while the second element is terminated with a 50-Ω load. Without the BSRRs, high surface current concentration is observed in the loaded antenna. For comparison purposes, two sets of conventional SRR structures (i.e. un-bridged) are also simulated. Obviously, the mitigation of surface current is less effective than the BSRR case where less energy concentration is observed in the loaded antenna.

3.4 Envelope correlation

In this section, the performance of the proposed antenna system is investigated in the context of MIMO systems. In a multipath environment, the correlation among the system’s antenna elements can be manifested using one of the following criteria: far-field patterns [22], mutual impedances [23], and the scattering parameters [24]. The envelope correlation can be obtained either from the scattering parameters or from the far-field radiation patterns. In this chapter, the scattering parameters matrix is used in the calculation of the envelope correlation and compared with that obtained from the far-field method.

The envelope correlation of the proposed two antenna system using the scattering parameter method is computed using (1) [22]:

\[ w_{\text{w}} w_{\text{i}} t_{\text{p}} r_{\text{e}} s_{\text{c}} o_{\text{m}}, I \]
Figure 9: Measured and simulated radiation pattern of the proposed system (with and without MNG): (a) E-plane (XY cut) and (b) H-plane (XZ cut).
Figure 10: Snapshots of the tangential surface current distribution: (a) normal case (no MNG), (b) non-bridged SRR case, and (c) proposed BSRR case.

\[ \rho = \frac{|S'_{11} S_{12} + S'_{21} S_{22}|^2}{(1 - |S_{11}|^2)(1 - |S_{21}|^2)(1 - |S_{22}|^2)} \]  

(1)

While it can be computed via the far-field method using (2) [24]:

\[ \rho = \frac{\iint \bar{G}_1 \bar{G}_2^* \, d\Omega}{\sqrt{\iint \bar{G}_1 \bar{G}_1^* \, d\Omega \iint \bar{G}_1 \bar{G}_2^* \, d\Omega}} \]  

(2)
Figure 11: Correlation coefficients for the printed monopole antenna system with and without BSRR.

Figure 11 shows the computed correlation coefficient in the 2–3 GHz range for both the aforementioned scenarios (i.e. with and without BSRR). Due to the computational overhead of the far-field method, the correlation coefficient values are obtained only at the resonant frequency (i.e. 2.45 GHz). The computed correlation coefficient (S-parameter method) for the normal case (without MNG structures) averages on 0.38 along the antenna’s bandwidth, while it is reduced to around 0.04 when the BSRRs are inserted between the antenna elements. Good agreement is achieved with the far-field method where the correlation coefficient reads 0.44 and 0.085 at resonance for the aforementioned cases, respectively.

4 Flexibility Tests

Since the antennas are expected to be bent, rolled, and twisted when integrated within a flexible electronic device, some qualitative tests are required for operative validation. Resonance frequency and return loss are required to be evaluated under bending effect since they are prone to shift/decrease due to impedance mismatch and a coupling between the arms of each individual antenna element. Repeatability testing of the antennas and all other embedded structures under the effects of bending, rolling, and twisting are required to verify durability and to monitor the inkjetted patterns for any cracks, deformations, or discontinuities. More importantly, the effect of bending on the mutual coupling should be studied as it is expected to increase when the structure is bent down. Furthermore, the radiation patterns and gains of each radiating element need to be tested for distortion and/or degradation, which might compromise the antennas performance and technology compliance.
As mentioned earlier, a polyimide substrate was selected for the targeted application mainly due to its physical robustness, low loss, and high flexibility (Fig. 12).

To test the performance of the antennas under different bending extents, the system was conformed on foam cylinders with different radii to mimic different bending extents. The following results were observed: a minor shift (20-40 MHz) in the resonance frequency is observed when the antenna system is conformed over the foam cylinders. Fortunately, the large impedance bandwidth of the proposed monopoles could accommodate this shift; on the other hand, a 3.5 dB increase in the mutual coupling is observed when the antenna system is bent on a foam cylinder with a radius of 40 mm; while almost 6 dB increase is experienced when it is conformed on a 30-mm foam cylinder. Figure 13 depicts the S-parame-

Figure 12: Flexibility test setup (AUT is conformed over a cylindrical foam with different radii to reflect different extents of folding/bending).

Figure 13: Measured S-parameters for the proposed system when bent on a foam cylinder with different radii ($r = 40$ mm and 30 mm) to mimic different bending extents.
ners of the proposed antenna system when conformed on foam cylinders with different radii (30 and 40 mm) representing different extents.

This increase in the mutual coupling is attributed to the alignment disorientation of the radiating elements with respect to the de-correlating network in addition to the fact that the separation distance between the radiating elements becomes relatively closer. Moreover, the effectiveness of the BSRR structures becomes less when subjected to bending due to the change in the effective permeability and the orientations of the electric and magnetic fields with respect to the BSRR structures.

5 Conclusion

A novel realization of SRR structures, referred to as nridged SRR (BSRR), is proposed in this chapter to effectively reduce mutual coupling between two flexible printed monopoles. Unlike the usual bulky orientation of such artificial structures or the involvement of vias/multilayer components as in EBG structures and soft surfaces, the proposed BSRR are placed in a planar fashion utilizing the monopoles magnetic fields for self-excitation to mitigate the mutual coupling. It is demonstrated that this technique exhibits more effectiveness over the conventional SRR structures in terms of rejection magnitude and bandwidth. The BSRRs achieve 11.5 dB reduction in mutual coupling between two printed monopoles when separated by 0.29λ. More importantly, the proposed system offers an ultrathin and flexible profile as it is printed on a polyimide kapton substrate with a thickness of 50.8 µm, which renders it as a reasonable candidate for flexible and wearable wireless systems.

References


