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Shobhit K. Patel
University of Nebraska-Lincoln, shobhitkumar.patel@unl.edu

Christos Argyropoulos
University of Nebraska-Lincoln, christos.argyropoulos@unl.edu

Yogeshwar P. Kosta
Marwadi Education Foundation Group of Institutions, Rajkot, India

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Broadband compact microstrip patch antenna design loaded by multiple split ring resonator superstrate and substrate

Shobhit K. Patel,[1] Christos Argyropoulos,[1] and Yogeshwar P. Kosta[2]

1 Department of Electrical and Computer Engineering, University of Nebraska-Lincoln, Lincoln, NE, USA
2 Marwadi Education Foundation Group of Institutions, Rajkot, India

Corresponding author — Shobhit K. Patel shobhitkumar.patel@unl.edu

Abstract
We present microstrip patch antenna loaded with multiple split ring resonator substrate and superstrate. We analyze how the loading of split ring resonator superstrate and substrate can improve the bandwidth compared to the simple microstrip patch antenna and microstrip patch antenna loaded with split ring resonator superstrate. Another important observation is made for multiple split ring resonator loading in superstrate and substrate of microstrip patch antenna. The design is compared for two, three, and four-ring split ring resonator loading. The designs are also compared for different gap spacing between the rings. All three designs are compared for small gap and large gap between the rings. The design results in the form of reflection coefficient and bandwidth is presented in this manuscript. The design results are also compared with previously published designs.

Keywords: Superstrate, split ring resonator, metamaterial, antenna

1. Introduction

Microstrip antennas are popular for their compactness and low weight. They are used in several wireless applications like mobile communication, GPS, Wi-Fi, Wi-Max, etc., because of these advantages.[1–2] In spite of these advantages, microstrip antennas are not used widely because of low gain and low bandwidth. The need for high gain and broadband microstrip antennas have been increasing in past decade. One of the solutions to increase the bandwidth and gain in microstrip antennas is addition of different types of superstrate structures. The fundamental effects of superstrate-substrate on microstrip antennas have been investigated to maximize gain and increase efficiency.[3] Superstrate has been used to reduce the mutual coupling between the radiating elements. This reduction in mutual coupling in turn increases antenna directivity.[4] Efficiency and bandwidth can be enhanced with the use of superstrate cover in millimeter wave transceiver integrated structures.[5] High gain and high efficient superstrate antenna has been designed for 60 GHz indoor communication. The superstrate antenna gives very high efficiency of 76% and high gain of 14.6 dBi.[6] Metamaterial superstrate has been used to increase gain and bandwidth in microstrip patch antennas.[7]

Metamaterials are the artificial materials. They have some unusual properties like negative permittivity and permeability which natural materials do not have.[8] Split ring resonators and thin wires have been the metamaterial components to achieve negative permittivity and negative permeability, respectively.[9] Improvement in antenna bandwidth gain can be achieved using metamaterials. Researchers have been working on metamaterial-based antenna designs for improvement in gain and bandwidth.[10–12] One of the ways to improve the bandwidth and gain is metamaterial superstrate loading in antennas.[7] Metamaterial inspired superstrate has been used to increase gain microstrip patch antenna.[13] High directive antenna has been designed with metamaterial superstrate for Ku band. Metamaterial superstrate has been made up of two metalic grids and foam slices.[14] A high gain wideband antenna has been designed with single layer metamaterial superstrate. The metamaterial is designed to have zero refractive index to enhance the gain of the antenna.[15] Tunable metamaterial superstrate has been used in antenna for beam steering applications. Omega shaped metamaterial unit has been added in antenna as superstrate.[16] The modified split ring resonator superstrate has been used to enhance the efficiency of the antenna by 17%. The gain of the antenna has also been improved using modified split ring resonator superstrate.[17] Directivity and bandwidth of the microstrip antenna has been enhanced using metamaterial superstrate.[18] Reflective metasurface has been used as superstrate to enhance the gain and bandwidth of microstrip patch antenna.[20] Metamaterial-inspired superstrate and substrate has been used to improve the bandwidth.[21] Gain enhancement has been done in microstrip patch antenna with metamaterial superstrate.[22] Gain has also been enhanced in antenna array with high index metamaterial superstrate cover.[23]

2. Microstrip patch antenna design

The design of simple microstrip patch antenna and its results is presented in this section. The microstrip antenna is meandered at the edges to increase the bandwidth of simple patch antenna.[2] Meandering the nonradiating edges will increase the current path in the microstrip patch antenna. The meandered microstrip patch antenna design is presented in Figure 1. The rectangular shape microstrip patch antenna with dimensions 40 mm^2 × 25 mm^2 is meandered at edges to improve the bandwidth.[2] The substrate is 50 mm^2 × 35 mm^2 size with a thickness of 1.5 mm. The patch and ground parts of the proposed antenna are made of copper. The substrate is composed of a dielectric material FR4 with its permittivity 4.4. The edges of the copper patch are meandered with 9 mm^2 × 8 mm^2 and 1 mm^2 . 5 mm^2 slits to improve the bandwidth as shown in Figure 1. The electrical size of the antenna is 0.5λ × 0.3λ which is better compared to 0.75λ × 0.75λ [20] and λ × 0.6λ.[21]

The results of the meandered patch antenna are presented in Figure 2. The minimum S_{11} that is achieved by this design is −15 dB. The maximum bandwidth is 360 MHz with center frequency 8.5 GHz. The bandwidth needs to be improved further. This can be achieved by loading the simple patch antenna design with metamaterial superstrate and substrate. The metamaterial loading and its results are discussed in section 3.

3. Multiple split ring resonator loaded design

In this section, we are going to discuss the modeling of split ring resonator metamaterial loading in superstrate and substrate of microstrip patch antenna design. Multiple split ring resonator is

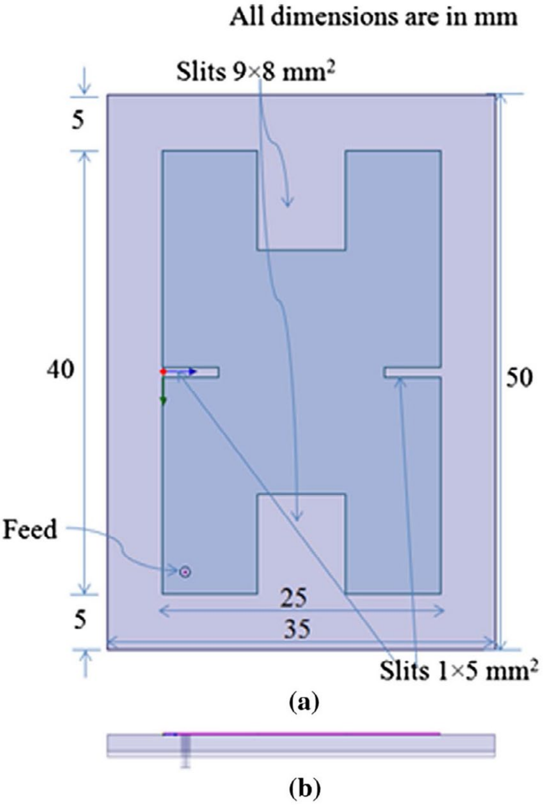

Figure 1. Microstrip patch antenna design. (a) top view (b) front view. The patch antenna is made up of copper material with 40 × 25 mm^2 size and placed above a substrate made up of 50 × 35 mm^2. The slits are taken out from edges of 9 × 8 mm^2 and 1 × 5 mm^2 size.

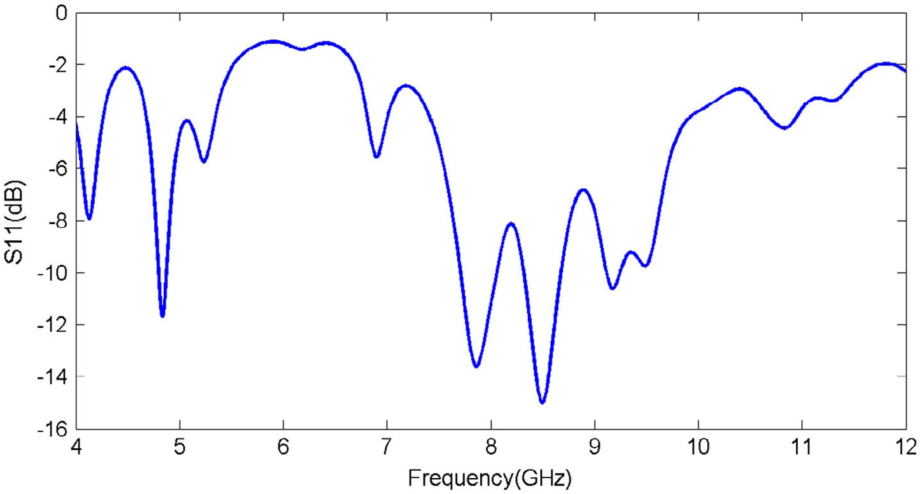

Figure 2. S_{11} result of simple microstrip patch antenna design. The minimum value of S_{11} is −15 dB. The maximum bandwidth is 360 MHz centered around 8.5 GHz.

loaded in superstrate and substrate of simple microstrip patch antenna. Three types of multiple split ring resonators (two ring, three ring, four ring) are used as metamaterial loading.

The periodic array of interspaced conducting nonmagnetic split ring resonators and thin wires can exhibit a frequency region in the microwave regime with negative effective permeability and permittivity.[9] We are interested only in the split ring resonator, which can exhibit negative effective permeability. The split ring resonator unit cell and its equivalent circuit is presented in Figure 3. The copper rings of split ring resonator induce inductance and the gap between the rings induces capacitance. The equivalent induced inductance is shown by L and can be calculated by the split ring wire length and its thickness. The total series capacitance between the rings is shown by C^s. The inductance per unit length of two rings can be calculated from Equation (1) and the series capacitance from Equation (2) [19]:

$$L = \frac{\mu_0 b}{\sqrt{\pi}}\left[\log\left(\frac{32b}{a\sqrt{\pi}}\right) - 2\right] \tag{1}$$

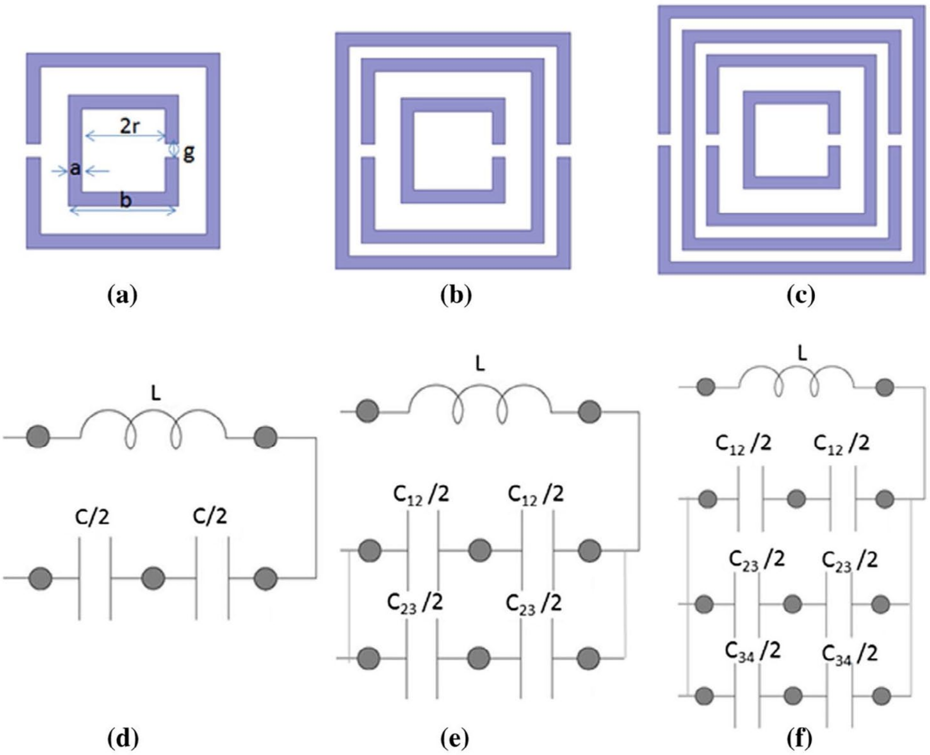

Figure 3. Split ring resonator and its equivalent circuit (a) Two-ring split ring resonator design, mutual coupling capacitance between the two rings is C. (b) Three-ring split ring resonator design, mutual coupling capacitance between the corresponding rings is C_{12} and C_{23}. (c) Four-ring split ring resonator design, mutual coupling capacitance between the corresponding rings is C_{12}, C_{23}, and C_{34}. (d) (e) and (f) Equivalent electric circuit of split ring resonator shown in (a) (b) and (c), respectively. L is the equivalent inductance of the ring.

$$C_s = \varepsilon \frac{at}{2g} \tag{2}$$

where, μ_0 is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ NA^{-2}), a is the ring width, g is the split gap, b is the ring length, ε is the permittivity of the material, t is the thickness of the split ring. In this paper, the dimensions are chosen to be: $a = 1$ mm, $g = 2$ mm, $b = 6$ mm, $t = 1.3$ mm.

The resonance frequency of SRR is given by $f = (LC_s)^{-1/2}/2\pi$, where C_s is the series capacitance of the upper and lower halves of the SRR, i.e. $C_s = C/4$. The equivalent circuit analysis can be extended to multiple SRRs shown in Figure 1(c). The series capacitance C_s of the split ring resonator with three rings can be calculated from the mutual capacitance between the rings C_{12} and C_{23}, and it is equal $C^s = (C_{12} + C_{23})/4$. The series capacitance Cs of the split ring resonator with four rings can be calculated from the mutual capacitance between the rings C_{12}, C_{23}, and C_{34}, and it is equal $C_s = (C_{12} + C_{23} + C_{34})/4$.

The split ring resonator is loaded in the simple microstrip patch antenna as shown in Figure 4. Here two-ring split ring resonator is loaded in microstrip patch antenna substrate and superstrate. Same way three-ring split ring resonator and four-ring split ring resonator are also added in the microstrip patch antenna. Two-ring SRR, three-ring SRR, and four-ring SRR are shown with different gap spacing between the rings in Figure 5. Here total six variations have been shown in the figure. All six variations are loaded one by one in microstrip patch antenna, and designs are

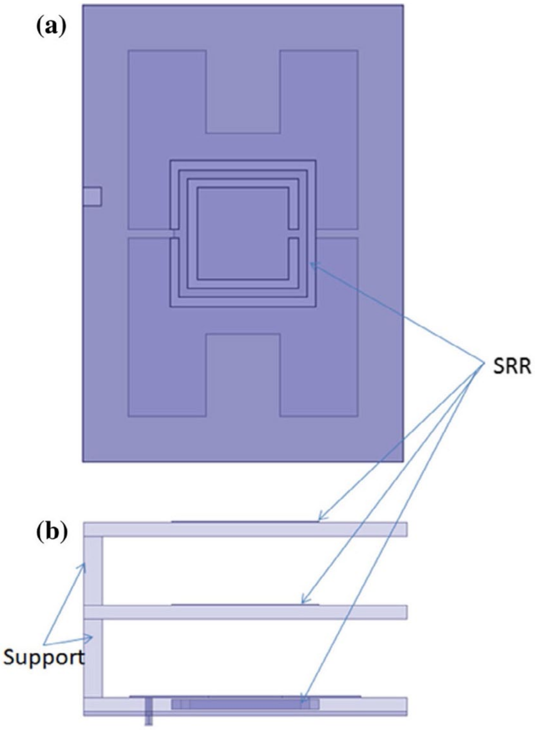

Figure 4. Microstrip patch antenna loaded with two-ring split ring resonator superstrate and substrate. (a) top view (b) front view. Two superstrate layers are added in the design. SRR of copper material is loaded in superstrate and substrate. The thickness of SRR added in substrate is 1.3 mm.

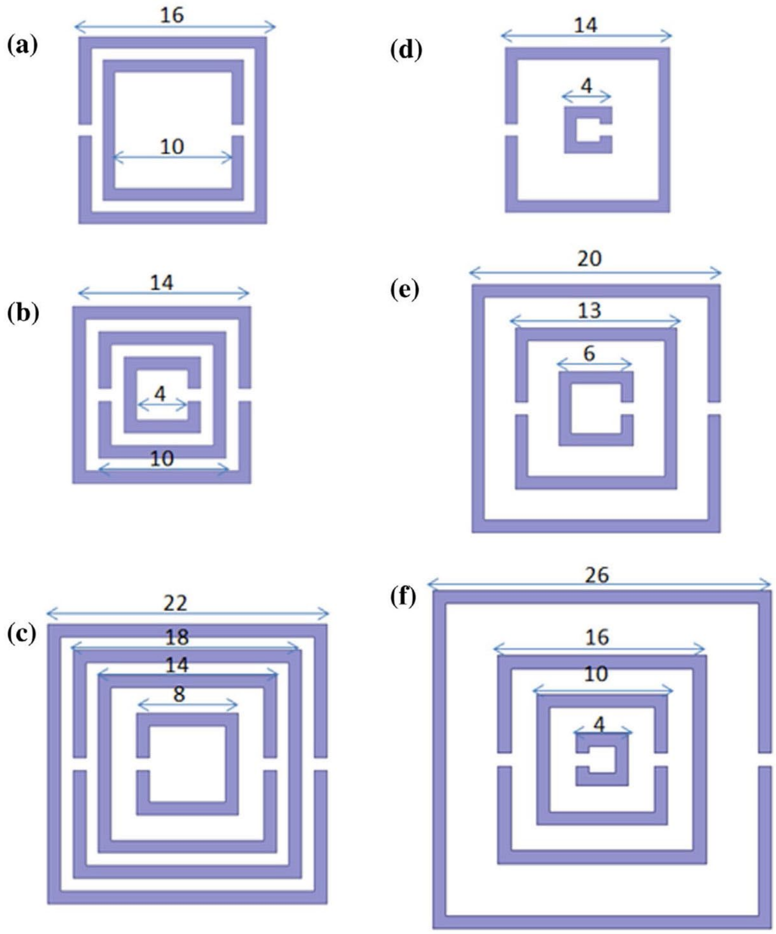

Figure 5. Split ring resonator loading (a) Two ring (small gap) (b) Three ring (small gap) (c) Four ring (small gap) (d) Two ring (large gap) (e) Three ring (large gap) (f) Four ring (large gap).

simulated. The designs are simulated with High-Frequency Structure Simulator (HFSS). The results of designs loaded with different variations of split ring resonator are shown in Figure 6–8.

The results for microstrip patch antenna with and without SRR is shown in Figure 6 and compared in Table 1. The simple microstrip patch antenna has minimum S_{11} of −15 dB compared to SRR design with small gap having minimum S_{11} of −32 dB. The bandwidth of simple microstrip patch antenna design is 360 MHz .The bandwidth is enhanced using SRR design with small gap to 980 MHz. The comparison of superstrate and substrate SRR design with small gap and large gap is shown in Figure 6. The design with small gap has better bandwidth compared to the large gap design.

We have also simulated the designs with three-ring SRR and four-ring SRR for different gap spacing and the results are shown in Figure 7–8. The design results of three-ring SRR superstrate and substrate loading is shown in Figure 7 for two different gap spacing. The minimum S_{11} is −32 dB for small gap design. Maximum bandwidth is 400 MHz for the small gap design.

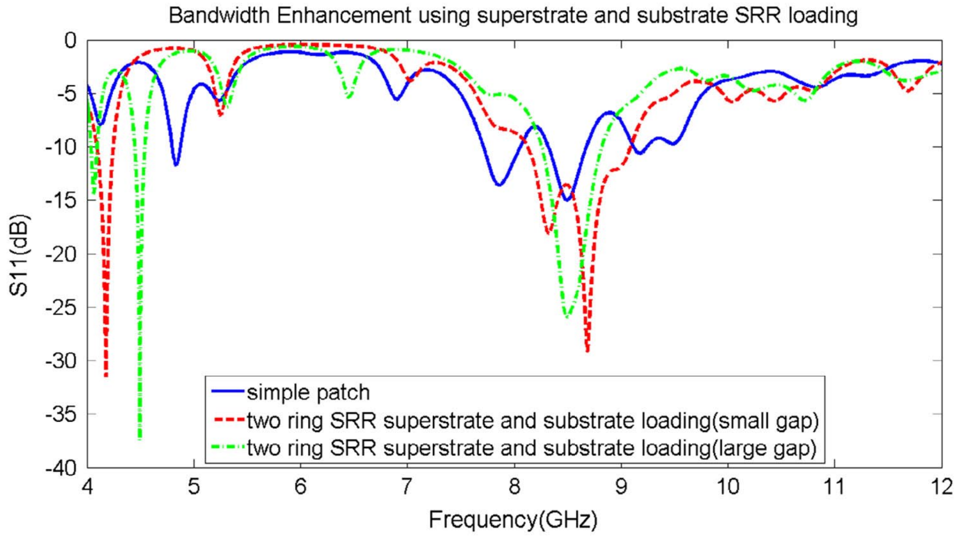

Figure 6. Bandwidth enhancement using superstrate and substrate loading. Blue line is the result for simple microstrip patch design. The result of microstrip patch antenna loaded with two ring SRR superstrate and substrate is shown by red and green dash line. Red dash line result is for small gap between the two rings. Green dash line result is for large gap between the two rings.

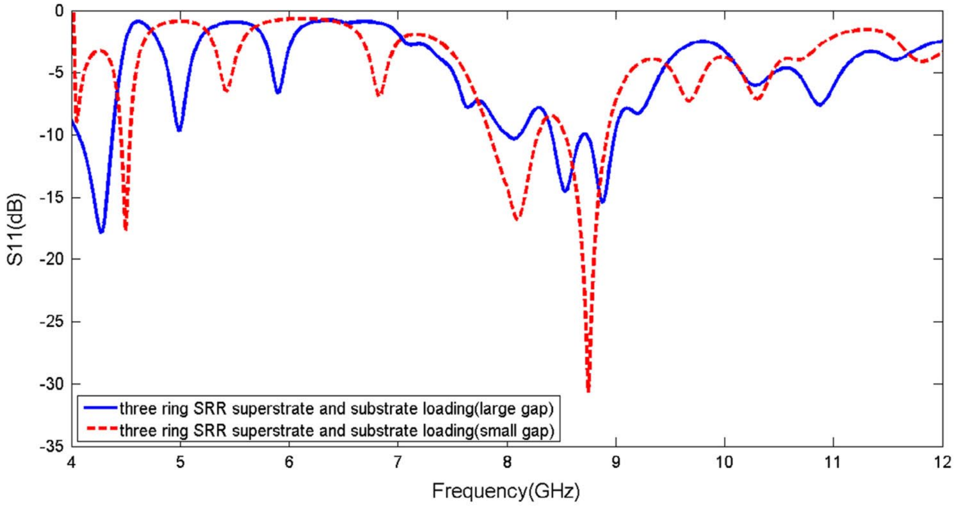

Figure 7. Comparison of three-ring SRR superstrate and substrate loading for small and large gap. Blue line is for large gap between the corresponding rings and red dash line is for small gap.

The design results of four-ring SRR superstrate and substrate loading for different gap spacing is shown in Figure 8. The maximum bandwidth is achieved for small gap design with 590 MHz. The comparison of all the designs (simple patch, superstrate, and substrate-loaded designs) with previously published design [7,20,24] is presented in Table 2. From the comparison, it is clear that the design with two-ring SRR superstrate and substrate loading (small gap) has the maximum bandwidth of 980 MHz.

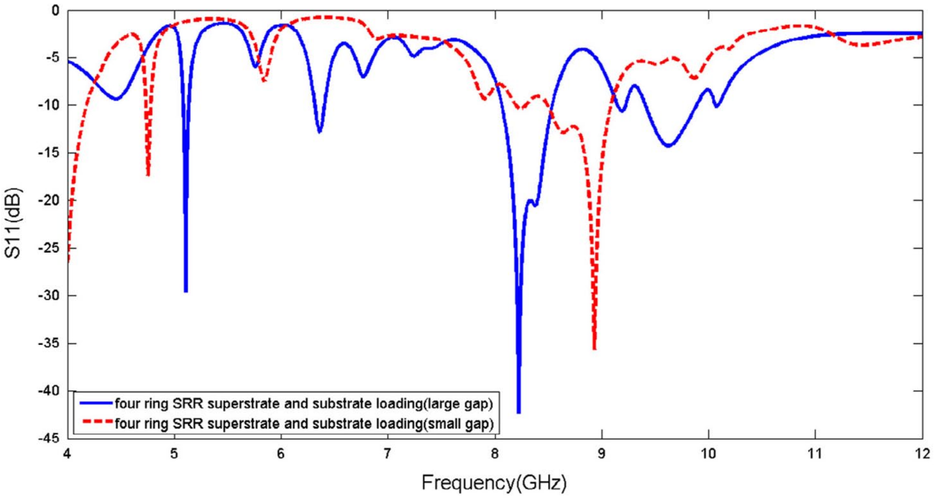

Figure 8. Comparison of four-ring SRR superstrate and substrate loading for small and large gap. Blue line is for large gap between the corresponding rings and red dash line is for small gap.

Table 1. Comparison of simple patch antenna design with SRR superstrate and substrate loading with different gap spacing.

Design	Frequency (GHz)	Minimum S_{11}(dB)	Maximum bandwidth (MHz)
Simple patch	8.50	−15	360
Two-ring SRR superstrate and substrate loaded (small gap)	8.60	−32	980
Two-ring SRR superstrate and substrate loaded (large gap)	8.60	−35	450

Table 2. Comparison of all the designs for bandwidth and S_{11}.

Design	Frequency (GHz)	Minimum S_{11}(dB)	Maximum bandwidth (MHz)
Simple patch	8.5	−15	360
Two-ring SRR superstrate and substrate loaded (small gap)	8.6	−32	980
Two-ring SRR superstrate and substrate loaded (large gap)	8.6	−35	450
Three-ring SRR superstrate and substrate loaded (small gap)	8.7	−30	400
Three-ring SRR superstrate and substrate loaded (large gap)	8.5	−15	280
Four-ring SRR superstrate and substrate loaded (small gap)	8.8	−37	590
Four-ring SRR superstrate and substrate loaded (large gap)	8.3	−35	470
Two-ring superstrate design from Ref. [7]	7.8	−16	440
Superstrate metasurface design from Ref. [20]	2.6	−40	320
Superstrate and Substrate design from Ref. [21]	1.2	−25	70
Superstrate design from Ref. [24]	2.4	−16	100

The gain of an antenna is equally important parameter while designing any antenna. We have simulated the gain polar plot of the SRR loaded substrate and superstrate patch antenna and simple patch antenna. The design results have been shown in Figures 9 and 10 for SRR loaded patch and simple patch antenna, respectively. It is clear that by introducing SRR loading in the simple patch the gain of antenna is enhanced from 1.9 to 3.4 dB. There is 75% increase in gain in SRR loaded patch antenna compared to simple patch antenna.

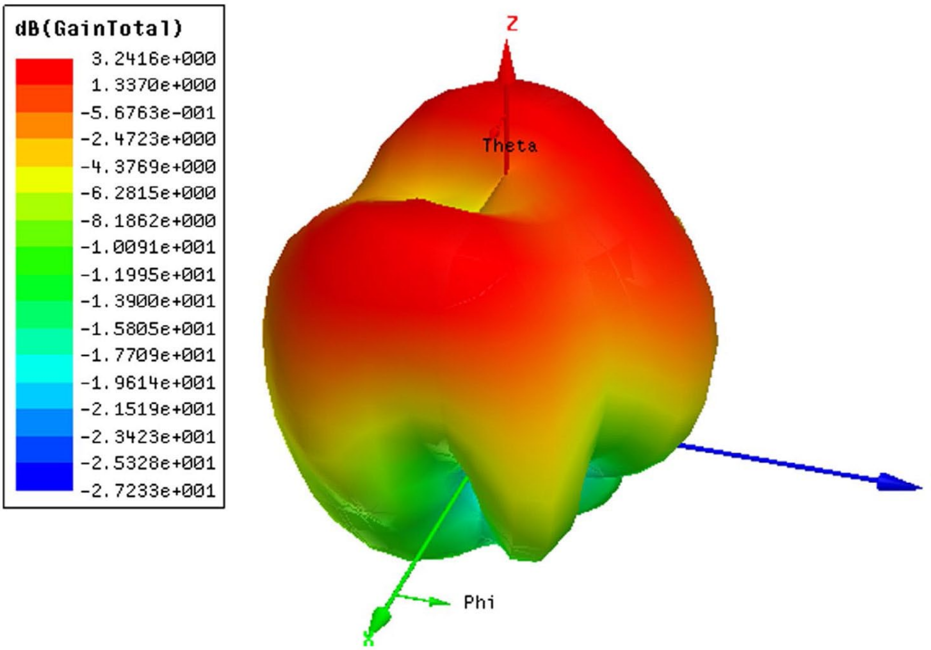

Figure 9. Gain polar plot of two-ring SRR superstrate and substrate-loaded microstrip patch antenna.

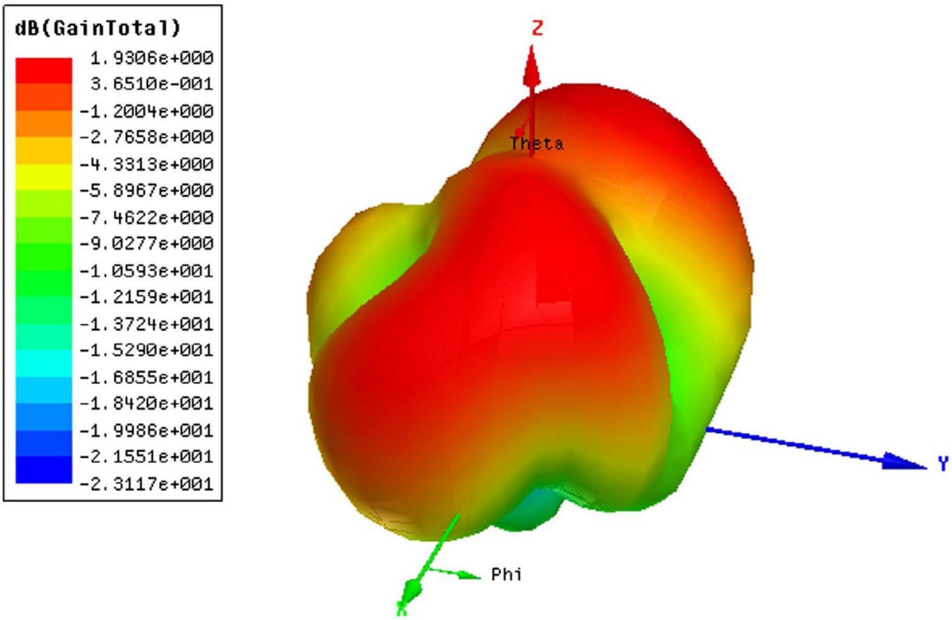

Figure 10. Gain polar plot of two-ring simple microstrip patch antenna.

4. Conclusion

We conclude that loading of multiple split ring resonator in superstrate and substrate improve the bandwidth of the simple microstrip patch antenna. The results of the design also change with variation in gap size of the multiple split ring resonator. The small gap design gives better performance compared to the large gap design. The design results are also compared with the previously published designs from [7,20,24]. The current superstrate and substrate-loaded designs have better performance compared to all old designs. The bandwidth is enhanced from 360 to 980 MHz. Reflection coefficient is also improved from −15 to −32 dB. There is still further chance of improvement in the results by adding more superstrate layers. The current antenna design can be fabricated by etching the copper multiple split ring resonators in the superstrate and substrate.

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