Survey on metamaterial antennas

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Abstract: Metamaterials are popular in the antenna research area because of their unusual properties. Metamaterials can be used to surpass disadvantages of conventional microstrip antenna such as larger bandwidth, reduction in size of the antenna, better return loss and improvement in gain, directivity with acceptable amount of input power. The main aim of this paper to analyse the best model required to design a patch antenna with respect to the relevant application.

Keywords: Metamaterials, SRR, CSRR, TSRR, Thin wire, Defected ground plane, Truncation, Super directivity, Multiband Behavior.

1 Introduction:
Microstrip patch antennas is one of the popular and broader-beam antennas. A simple patch antenna uses a patch which is responsible for radiation along with feed and ground is fabricated on the insulating dielectric substrate by placing a metallic sheet on it using PCB technology. There are multiple types of optimization that can be done to get better gain, return loss and performance. Natural metal patches use Right hand materials (RHM). Few new types of artificial materials can be produced which behave opposite the RHM generally called metamaterials or Left-hand materials. These metamaterials reduce refractive index by refusing permeability and permittivity thus causing less dispersion of field, thus giving good directivity. Negative permittivity is achieved with thin wire, SRR (Split ring resonator) along with Thin wire will give DNG (Double negative) while CSRR (complementary split ring resonator) can only be used to achieve negative permittivity.

2 SPLIT RING RESONATOR(SRR)
SRR will help to meet different C - band applications by tuning the geometrical parameters by optimizing mutual coupling between antennas. A combination of Split ring resonator (SRR) and T shaped stub loaded at its four sides, with the resonating structure has its applications in C - band operating applications[1] which is seen in Figure1.a. For the design the bands range from 5.977GHz - 6.984GHz and 12.48GHz - 13.50GHz along with impedance bandwidth obtained at 6.3GHz and 12.9GHz respectively and with peak gain of 8.48dB at 6.3GHz for phy = 0° and theta = 160°. For Satellite and Radar applications which requires a gain greater than 5dB the proposed antenna is suitable for these applications.

In next paper[2], a pair of SRR directors is appended on to a conventional SDP(series fed dipole pair) antenna for dual-band operation which can be seen in Figure.1.b and c. The geometrical parameters of the SRR directors affect reflection coefficient and realized gain of the Series Fed Dipole Pair antenna. Firstly a conventional Series Fed Dipole Antenna which was designed by adjusting the distances of the dipole along with the space between the two presentations that operates in 1.7GHz - 2.7GHz was designed. Next, a couple of SRR was mounted above the top dipole in order to improve antenna performance. The conventional antenna resonates at 1.8GHz with a return loss of -13.192dB and 2.62GHz with a return loss of -29.273dB while the proposed antenna resonates at
1.58GHz with return loss of -31.15dB and 2.6GHz with a return loss of -15.35dB thereby less transmitted power is reflected back.

While in the above paper the proposed design operates at two resonance frequency, a triple band notched ultra - wide band circular microstrip patch antenna with split ring resonator and S- shaped slot loaded in microstrip feed line as seen in Figure.1.d is designed by Sweta Agrawal, Ajay Yadav and R.P. Yadav[3]. Three band stop structures namely, SRR slot cut on the patch, S shape slot in feed for miniaturization and a symmetric pair of electromagnetic coupling SRR with feed line along with small slit on the ground successfully shows triple notch at 3.5GHz - WiMAX, 5.5GHz - WLAN and 7.5GHz - Satellite Communication band with VSWR less than 2 maintaining broadband performance from 3.10GHz to 10.60GHz(UWB).

At the next, an embedded symmetrical rectangular radiator and Rectangular Split ring resonator (RSRR) viewed in Figure.1.e for 2 high frequencies, one with 26GHz(5G) and 33.2GHz (higher satellite band)[4] is proposed. Main focus is on Millimeter Waves (MMW) of frequency range (20-300GHz). The advantages of this MMW are higher bandwidth (BW), more data rates and less traffic. To check the performance of the antenna operating in 5G and higher satellite ranges they have carried out parametric study in 3 steps:

1. Effect of feed-width on impedance matching : By varying Feed width from 0.25 to 0.75mm, best feed width occur at 0.5mm.
2. Effect of Rectangular SRR split gaps, S and S1 on impedance matching : Metamaterial Rectangular SRR split gaps are altered with different spacing conditions,
   (i) S- closed , S1- closed , impedance matching at satellite band is disturbed and there is shift to 5G band
   (ii) S-closed , S1- open, impedance matching at the satellite band is decreased,
   (iii)S- open , S1- closed, impedance matching at the both the band is decreased.
   (iv)S- open , S1- open, best matching for entire two operating bands.
3. Current distribution : It is been analyzed that for the dual band i.e. 26 GHz and 33.2 GHz the proposed antenna has corresponding resonant paths.

This proposed configuration has S11 < -10dB and bandwidth of about 1600MHz (25.2 - 26.8GHz) and 600MHz (32.9-33.5GHz). The bandwidth obtained can satisfy millimeter 5G and higher satellite band.

In the next, we have a Split Ring Resonator based microstrip patch antenna for X band applications[5] in which four similar SRR slots viewed in Figure.1.f and Figure1.g are used in the patch which is operated under 11.2GHz with return loss of -29.5288dB and VSWR of 1.005. Comparing values of return loss,VSWR of simulated and fabricated, the return loss and resonant frequency of the fabricated antenna is -24.17dB and 11.21GHz and the return loss and resonant frequency of the proposed antenna with SRR is -29.52dB at 11.2GHz. The large difference between fabricated and proposed one is due to SMA connector and fabrication tolerance.

A parametric analysis is done by changing :

A) SRR DIRECTIONS
B) DOWN CIRCLE DIMENSIONS
C) UP CIRCLE DIMENSIONS
D) LEFT CIRCLE DIMENSIONS
E) RIGHT CIRCLE DIMENSIONS
A) The differences of return loss is shown below for all 4 SRR directions as shown in Table 1 with respective directions in Figure 1.h:

Table 1. Difference of return loss for change in SRR direction

| SRR Directions | Resonant Frequency(GHz) | Return Loss(dB) |
|----------------|--------------------------|-----------------|
| Up             | 9.4                      | -11             |
|                | 11.3                     | -25             |
| Down           | 9.5                      | -24             |
|                | 11.2                     | -29             |
| Left           | 9.1                      | -28.05          |
|                | 10.9                     | -11             |
| Right          | 9                        | -2              |
|                | 10.8                     | -3              |

B) The width of inner rings is changed as 0.85mm and 0.8mm and outer rings are changed as 1.25mm and 1.3mm. The variations is shown below in table 2:

Table 2. Comparison of change in width of rings

| Width of SRR rings | Resonant Frequency(GHz) | Return Loss(dB) |
|--------------------|--------------------------|-----------------|
| C1 - 1.25, C2 - 0.85 | 11.2                     | -29             |
| C1 - 1.3, C2 - 0.8  | 10.9                     | -28             |
| C1 - 1.3, C2 - 0.85 | 10.8                     | -24             |
| C1 - 1.25, C2 - 0.8 | 11.3                     | -29             |

C) The return loss and the resonant frequency of the up circle SRR configuration is varying from -24dB to -29dB and 9GHz and 9.8GHz.

D) The return loss is varied from -24dB to -42dB and its resonant frequency is changed from 8.9 to 9.1GHz. When C1=1.3mm and C2 = 0.85mm, the significant improvement of return loss is about -42dB observed at 9GHz.

E) The return loss and the resonant frequency of the right circle SRR configuration is varied -16dB to -20dB and 8.7GHz to 9GHz.
Figure 1. Figures of SRR designed models
2.1 Comparison of the designs:
Comparison of SRR structures is shown in Table 3:

Table 3. Comparison table for SRR

| Ref paper | Design techniques                  | Loss tangent | Return loss (dB)/ Gain(dB) | Frequency (GHz) | Applications                      |
|-----------|-----------------------------------|--------------|---------------------------|-----------------|-----------------------------------|
| 1)        | SRR+T stub loading Thickness (mm): 1.6mm Simulator used: HFSS 13 | 0.02 VSWR<2  | RL-14.8 Gain 8.4          | 6.3GHz          | C band applications                |
| 2)        | Series fed dipoles (SDP) + SRR Thickness (mm): 1.6mm Simulator used: CST microwave studio | 0.025 VSWR<2 | RL-13.19, -29.27, -31.15, -15.35/ Gain 7.75(main band) and 6.49 (second circle) | 1.8, 2.62, 1.58, 2.6 GHz | GPS,WIFI, Wi-MAX                  |
| 3)        | Circular microstrip antenna with SRR + S- shaped slot (feed line) Thickness (mm): 1.6mm Simulator used: Ansoft HFSS 13 | 0.02 VSWR<1.5 | RL-13.98/ Gain 5          | 3.5GHz, 5.5GHz, 7.5 GHz | Wi-MAX, WLAN and Satellite communications |
| 4)        | Symmetric rectangular radiator + Rectangular SRR [RSRR] Thickness (mm): 1.6mm Simulator used: HFSS 13 | 0.02 VSWR<2  | Gain 4.08                 | 26GHz and 33.2GHz | 5G, Higher Satellite bands         |
| 5)        | Microstrip antenna + SRR Thickness (mm): 0.8 mm Simulator used: HFSS 13 | 0.02 VSWR<1.005 | RL-29.5288dB for purposed antenna and 24.17dB for fabricated Antenna | 11.2GHz         | X band applications like Satellite communications |
2.2 Conclusion for SRR:

After referring above 5 papers with different Frequency bands, Return loss, Gain and applications etc., for our application (i.e Satellite Communication) we can use the antenna designed in [3] and [5] for frequency range in X band, but if we need to use higher frequency bands (i.e for 5G bands) we can use the antenna designed in [4]. For a less cost antenna we can prefer the antenna designed in [3]. Comparing the values in the table we will come to know that if return loss is low then bandwidth is wider and also bigger in size for chosen frequency band and structure of antennas. In [5] we will come to know the actual difference between proposed (simulated antenna) and fabricated antenna.

Overall in all the papers they have preferred VSWR < 2, thickness = 1.6mm, loss tangent = 0.02 and HFSS 13 simulator as it has a wide range of applications.

3 COMPLIMENTARY SPLIT RING RESONATOR (CSRR)

To reduce size of patch antennas Complementary Split Ring Resonators (CSRR) on ground plane provide an average reduction of 30% in area. Miniaturization of the square patch antenna[6] can be achieved by a layer of CSRR between patch and the ground. Miniaturized patch antenna contains a metamaterial plane which is sandwiched between two substrates as seen in Figure.2.a. The metamaterial plane acts as a loading element thereby decreasing the electrical size of the antenna. To access the level of miniaturization, a traditional square patch antenna is also implemented without metamaterial plane. It was found that size reduction was for CSRR loaded plane shrinks antenna size by 1/4th compared with traditional antenna without sacrificing the antenna performance significantly. The miniaturization is achieved by concentric CSRR structures between the ground and patch. For a traditional patch of radiation efficiency of 98.6% with a Bandwidth of 2% at a gain of 7.35dBi as compared to miniaturized antenna with a radiation efficiency of 78% with a Bandwidth of 0.4% at gain of 5.72dB with reduction in size by 1/4th for comparable values.

At the next is a microstrip antenna with CSRR loaded ground plane[7] which improves gain and bandwidth. The proposed antenna design is shown in Figure.2.c(front view) and d(back view). Resonant frequency was at 2.78GHz with a bandwidth of 65MHz. Measured results show that antenna has an impedance bandwidth of 100MHz (<210 dB) 2.4–2.5GHz which is slightly greater than that of an unloaded antenna. For good gain and bandwidth CSRR loaded ground plane has slightly higher values compared to that of an unloaded antenna. Studies show that the length, number of CSRR slots and ring width has higher impact on resonance frequency while slit width having less effect on resonant frequency. It was designed for WLAN applications 5GHz operation which has good gain, compact sized and a stable radiation pattern. CSRR etched on ground plane affects the resonant characteristics making it resonate at lower resonant frequency.

In the next paper, a compact microstrip patch antenna is proposed for Wi-Fi and WiMAX[8]. CSRR is etched on the patch to obtain dual operating band. SRR acts as a magnetic dipole which can be easily excited by applying an external magnetic field. The antenna occupies 25% less by volume compared to an existing antenna which is due to metamaterials and fractal. Equivalent figures can be viewed in Figure.2.e for SRR and Figure.2.f for CSRR. Fractal curves are used in designing compact sized antennas which are space filling and self repetitive curves. The fractal concepts are introduced along the edges of the patch to improve return loss bandwidth and axial ratio bandwidth at upper band. Change in bandwidth is shown in Table 4. Since the proposed antenna is compact it can be used in portable devices for Wi-Fi and WiMAX applications.
Table 4. Comparison of bandwidth for various designs

| Antenna | 10dB return loss (left hand band) | Bandwidth (patch mode band) |
|---------|----------------------------------|-----------------------------|
| Ant 1   | ---                              | 9.27% (3.29 - 3.61 GHz)     |
| Ant 2   | ---                              | 15.06% (3.07 - 3.57 GHz)    |
| Ant 3   | Resonance at 2.4GHz              | 5.66% (3.09 - 3.27 GHz)     |
| Ant 4   | Resonance at 2.4GHz              | 8.22% (3.03 - 3.29 GHz)     |

In the next paper [9], a compact 2×1 MIMO antenna system has been presented which operates in the LTE band 7 (2.5-2.57 GHz). To improve efficiency of radio spectrum LTE uses MIMO technology. The proposed antenna designed is viewed in Figure 2.g and h. In normal operating mode the resonance frequency is found to be 5 GHz. In order to reduce resonant frequency, a single CSRR was loaded at its center of the ground plane, which brings down the resonant frequency to 2.5 GHz. CSRR changes characteristics of the antenna cavity and hence the resonant frequency is shifted. It is also found that size reduction of 72% is obtained compared to conventional antenna after inclusion of CSRR in ground plane. At 2.5 GHz resonant frequency return loss was observed to be -26.5 dB during simulation, whereas at measurement it was found to have resonant frequency of 2.7 GHz with a return loss of -38 dB. For better characterization of MIMO antenna systems, parameters such as Total Active Reflection Coefficient (TARC) and Correlation Coefficient are measured along with other parameters. Hence the designed antenna is useful in wireless portable devices operating in 2.5 - 2.57 GHz LTE band 7 operation.

In next paper [10], investigation on microstrip filters with various CSRR defective ground structures (low insertion loss in pass band and high rejection in stop band) has been proposed. For different configurations of CSRR - Defective Ground Structure, parameters such as roll off rate, bandwidth, effective inductance and capacitance have been studied.
After analysis of various parameters, Triangular CSRR - Defective Ground Structure was used in designing dual band, band pass and low pass filters because of high Q factor, better roll off rate, and higher selectivity. First resonator resonates at a frequency of 3.5GHz and the second resonator at a frequency of 5.7GHz. The structure is composed of two concentric metallic slot rings which are interrupted by a small gap at its opposite sides. The gap decreases the resonant frequency of the structure that makes the size of CSRR only tenth of resonant wavelength. The widening of bandwidth is due to the thickness of the gap. The simulated results show high rejection at resonant frequencies i.e at 3.8GHz and 5.7GHz where the return loss is more than 40dB. The 3dB bandwidth of band stop filter for dual bands are 1.4GHz and 1.6GHz. The simulated and measured return loss and resonant frequencies are in acceptable limits. Method used to achieve Low Pass characteristics is Stepped Impedance method and that for a High Pass characteristics is Slot Gap method and the combination of both giving Band Pass characteristics. The an-isotropic property of CSRR is used in obtaining dual band characteristics and the dumbbell shaped triangular CSRR - DGS for size reduction.

Figure 2. Figures of CSRR designed models
### 3.1 Comparison of the designs:

Comparison of CSRR structures is shown in Table 5:

| Paper reference | Design techniques | Material used | Antenna parameters | Freq (GHz) | Applications |
|-----------------|-------------------|---------------|--------------------|------------|--------------|
| 6)              | Miniaturization of CSRR where 2 substrates are used | Rogers RT/Duroid 6002 | Loss tangent 0.002 Return Loss-28dB Gain (dBi) 5.72 | 2.78 | Since the antenna size is reduced by 1/4 it can be used in many application |
| 7)              | CSRR loaded ground plane for gain enhancement | FR-4 Thickness in mm:1.6 | Loss tangent 0.02 Return Loss<-10dB Gain (dBi) 5.93 | 2.4-2.5 | Instruments, scientific and measurement (ISM) band applications |
| 8)              | CSRR and SRR loaded Microstrip Patch Antenna Simulator Used: HFFS | Rogers RT/Duroid 5880 Thickness in mm: 3.175 | Loss tangent 0.002 Return Loss--25dB | 2.4 | WLAN, Wi-Fi and WiMAX |
| 9)              | CSRR Loaded 2×1 Triangular MIMO Antenna Simulator Used: HFFS | FR-4 Thickness in mm :0.8 | Loss tangent 0.02 Return Loss At 2.5GHz -26.5dB and at 2.7GHz -38dB | 2.5 | LTE band 7 operations |
| 10)             | Microstrip Filters with CSRR Defected Ground Structure | FR-4 Thickness in mm: 1.524 | Loss tangent 0.002 Return Loss At 3.8GHz -16dB and at 5.7GHz -14dB | 3.5 and 5.7 | Amplifiers |
3.2 Conclusion for CSRR:

After referring to papers it can be observed that for similar output values of the patch antenna, CSRR produced a much compact size as compared to that of the values obtained for other designing of antennas and has applications in various fields. Miniaturation[6] turns out to be one the main aspects of the future evolving antenna designing. ISM [7] band equipments have applications in scientific, medical, domestic by using local RF energy. As observed[8][9], evolving wireless communication requires a better design of antenna parameters with a minimal space occupancy.

4 THIN WIRE

To optimize patch dimensions, a technique used is the usage of Thin Wire(TW) and SRR MTM. MSA is designed using TW, SRR and air substrate with Duroid $\varepsilon_r = 2.2$ is inserted below the patch as seen in Figure.3.a. The proposed antenna is simulated using HFSS - 9. The simulated results and the experimental results show that the miniaturization factor is almost 65%. Gain improved is by 6 dB to 6.37 dB impedance remained to be same, resonant frequency changed to 1.87GHz from 6 GHz by using TW MTM. Beam width deduced by $3^0$. SRR was used for negative permeability. They also fabricated the the antenna with and without TW and got good comparison between theoretical and experimental results.

In the next paper[12], in order to improve microstrip patch antenna performance, LH - MTM Figure.3.b which has a negative refractive index is been used. Using Nicolson Ross Weir (NRW) Algorithm effective MTM parameters are extracted using the S parameter. For patch antenna operating a 303GHz, results demonstrate an improve in gain by $1.1$dB, bandwidth by 14.73GHz, return loss by 12.62dB on comparing with the one without MTM lens with a slight reduction in beam size. After trying different combinations of arrangements of MTM, gain, return loss and bandwidth has an improvement by 1.5dB, 2dB and 10.15MHz with a minimal change in antenna beam width.

In the next paper[13], the author touches into multiple aspects of aspects of using MTM in different ways Figure.3.c and their consequences by categorizing MTM into single negative(with SRR or TW) or double negative (both SRR and TW) and shows its demonstration. Paper also explains how using S parameters, $\mu,\varepsilon$ and refractive index can be found. The paper later explains how MTM can be applied to antennas and how dimensions can be optimized. Paper also further explains the inclusion of metamaterials in the patch antenna design is an popular method not only to reduce return loss and size of the antenna, enhance the gain, increase the bandwidth, but also to design multiple band antennas.

In this paper[14] they used CSRR and TW pairs and even conducted experiments to rotate the orientation of metamaterial to get the best angle for max advantage. The proposed antenna Figure.3.d operating at 10 GHz is fabricated, the practical results show that gain of the antenna is improved by 4.6dB. Experimented with different combinations of no of CSRR/TW structures to observe the refractive index changes, it is observed that the measured bandwidths of the fabricated antenna with and without MTM are the same, around 400 MHz. But the return loss of the 10 GHz proposed antenna included with MTM lens placed on the patch is improved from -13 dB to -30 dB. The main idea here is to address two issues namely mechanical stability and large size where are explained in detailed.

At the next[15] the microstrip patch antenna designed using thin wires made of different metamaterial (Sea water/ Fresh/Distilled) are placed in the layers of radome Figure.3.e and f). MTM is constructed with water tubes and its S parameters are compared giving improvement of 6.5 dB gain. It shows how the water made TW MTM is influencing the radiation properties and how it will help gain. Experiment with 3 different kinds of water and given their result and effects of different
materials are compared in the paper. They concluded that antenna with metamaterial thin circular wires has the highest bandwidth of 26.25 GHz and antenna with multilayer radome with sea water metamaterial thin wires has the highest reflection coefficient ($S_{11}$) of -39.65 dB and antenna with multilayer radome with sea water metamaterial thin circular wires has the highest gain of 8.31 dB.

Figure 3. Figures of CSRR designed models
### 4.1 Comparison of Thin Wire:
Comparison of Thin Wire structures is shown in Table 6:

**Table 6. Comparison table for Thin Wire**

| Paper ref | Novelty                                   | MTM combination | Gain improved By | Operating frequency | Other improvements                                                                 |
|-----------|-------------------------------------------|-----------------|------------------|---------------------|-----------------------------------------------------------------------------------|
| [11]      | Minaturization factor by 5%               | SRR/TW          | 0.36dB           | 6 GHz               | Beam width reduced by 3’                                                            |
| [12]      | Did for 10GHz and extended to 303GHz(heart rate sensor) | SRR/TW          | 1.5dB            | 10GHz and 303 GHz   | antenna gain, bandwidth, and return loss have improved by 1.5 dB, 10.15 MHz, and 2 dB. |
| [13]      | Extended to Gsm principle antenna         | SRR/TW          | 2dB              | 2GHz                | Gain ≥2 dB, Bandwidth ≥100%, Reduce size ≥50% or to create additional frequency bands for multi communication systems operated antennas. |
| [14]      | Experimented rotating plane of axis of MTM | CSRR/TW         | 4dB              | 10GHz               | Handelled mechanical stability and large size issues.                                |
| [15]      | TW Metamaterial made of Fresh/Distilled/Sea water | TW made of circular water tubes | 6.5dB            | 15.5GHz             | Max BW 24 GHz and compared various possibilities                                     |
4.2 Conclusion for Thin Wire:

In the above 5 papers Thin wire metamaterial was used to increase 0.36 to 6.5 db based on what different combinations and methods were used. Generally TW MTM is used with SRR or CSRR as together it can enhance permittivity and permeability thus together increasing negative refractive index hence allowing more directionality of the field. These papers have different operating frequencies based on construction and application of antennas. 5th paper is a unique recent paper where water is used as the main material of thin wire MTM and has given good increase in gain compared to other paper. TW MTM reduces the effective size of the antenna thus improving microstrip antenna further.

5 Conclusion:

SRR antenna designs have its applications in various fields where in it can be used for a particular frequency range suitable for the application whereas CSRR helps in an overall size reduction of the antenna without compromising with the antenna parameters which are normally operated at lower frequency compared to that of SRR also has a better value for gain having its applications in fields depending on the frequency of operation. Thin Wire antenna has a better values of gain and also has a reduction in size of the antenna and along with SRR or CSRR help in better values of gain and bandwidth of the antenna.

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