Cross Polarization Discrimination Enhancement of a Dual Linear Polarization Antenna Using Metamaterials

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***Abstract* — This paper presents a novel approach to enhance the cross polarization discrimination in a dual linear polarization microstrip patch antenna at the frequency of 5.5 GHz. Two different designs of a dual linear polarization antenna using metamaterials are considered. In the first design, microstrip patch antenna is loaded with two pairs of spiral ring resonators, and in the second design, two orthogonal microstrip feed lines are loaded with pairs of split ring resonators. The addition of metamaterial inclusions to the antenna structure allow compensation for an asymmetric current distribution flow on the patch antenna and thus result in symmetrical current distribution on it. This compensation leads to a significant improvement in the cross polarization discrimination in comparison to the conventional dual linear polarized antenna. As compared to the conventional antenna, the proposed designes improve the cross polarization pattern by 12 dB and 6.6 dB for the first and second design, respectively.**

Keywords-component; Dual linear polarization antenna; Metamaterials; Band stop filter

I. INTRODUCTION

Dual linear polarization antenna configurations are popular and ideally suited for high performance satellites, wireless communications, and radar applications. It can provide two communication channels. Therefore, it can double the capacity of communication systems [1] [2] [3]. However, it suffers from two main drawbacks: cross-polarization pattern and higher mutual coupling between two input ports [4], these drawbacks are due to several reasons: such as an asymmetrical current distribution on the patch antenna that will lead to a higher inter-coupling and generates cross polarization pattern. The reason of an asymmetrical current distribution is to the design natural of two orthogonal feeds placed on nearest two edges, while remaining other two edges are without excitation [5]. The propagation of electromagnetic waves through a microstrip patch antenna and microstrip feed lines can be manipulated and controlled by spiral ring resonator (S-RR), and split ring resonator (SRR) inclusions. Hence, the metamaterials are used to compensate the current distribution on the patch antenna which leads to enhancement in the cross polarization discrimination (XPD) and to a reduction of mutual coupling between the two microstrip feed lines. According to this aforementioned discussion, an S-RR, and SRR-based on band-reject filter concepts have been designed.

Metamaterials (MTM) [6] have been used to develop antennas and microwave circuits with unusual properties [7], and this study is based on use of metamaterials in forms of S-RR, and SRR structures to represent single-negative medium and exhibited a band stop filter. This paper is divided into two scenarios; the first scenario is based on the use of S-RR metamaterial in the near environment of the rectangular patch antenna. By employing a with pair of S-RRs, the XPD of the antenna system is improved, and the simulation displays an improvement of 12 dB in XPD as compared to the conventional antenna in E-and H planes. The second scenario is based on loading the microstrip feed lines with pairs of SRR. The XPD of the antenna system is improved and the simulation displays an improvement of 6.6 dB, in XPD as compared to the conventional antenna in E, H, and ± 45 planes. The structure has been simulated using a full wave electromagnetic simulation is performed by using finite element method (FEM)-based on High-Frequency Structure Simulator (HFSS) software. The paper is includes the following: the dual linear polarization antenna using S-RR design is presented in section II. Section III is devoted to a dual linear polarization antenna using SRR design. Finally, section IV gives the conclusions.

II. DESIGN OF A DUAL LINEAR POLARIZATION ANTENNA USING SPIRAL RING RESONATOR (S-RR)

A. Design and Characterization of Spiral Ring Resonator as Band Stop Filter

The proposed structure of spiral ring resonator and its equivalent circuit are shown in Fig. 1(a), which consists of two S-RR connected with a line of length (ℓ_1) and width (w). The dimensions of S-RR unit cell were optimized as (a = 4.5 mm, b= 3.25 mm, g= 0.2 mm, w= 0.3 mm, ℓ_1= 1.6 mm). Fig. 1(b) shows transmission and reflection coefficients of unit cell, it is noticed that S-RR provides stop band (S_{21}=-31 dB) at center frequency of 5.5 GHz. Fig. 1(c) represents the real values of permittivity, and permeability; it is noticed that the real values of permeability are purely negative and positive values of permittivity, this means that the unit cell metamaterial works in a single negative medium which leads to a stop band in this region.

Nicolson-Ross-Wier approach was used to extract the permittivity and permeability (ε and μ). The S-parameters of this system can be written as [8].

$$S_{11}=\frac{R_{01}\left(1-e^{j2n\beta h}\right)}{1-R_{01}^{2}e^{j2n\beta h}} \quad (1)$$

$$S_{21}=\frac{\left(1-R_{01}^{2}\right)e^{j2n\beta h}}{1-R_{01}^{2}e^{j2n\beta h}} \quad (2)$$

$$z=\pm\sqrt{\frac{(1+S_{11})^{2}-S_{21}^{2}}{(1-S_{11})^{2}-S_{21}^{2}}} \quad (3)$$

$$e^{jn\beta h}=\frac{S_{21}}{1-S_{11}\frac{z-1}{z+1}} \quad (4)$$

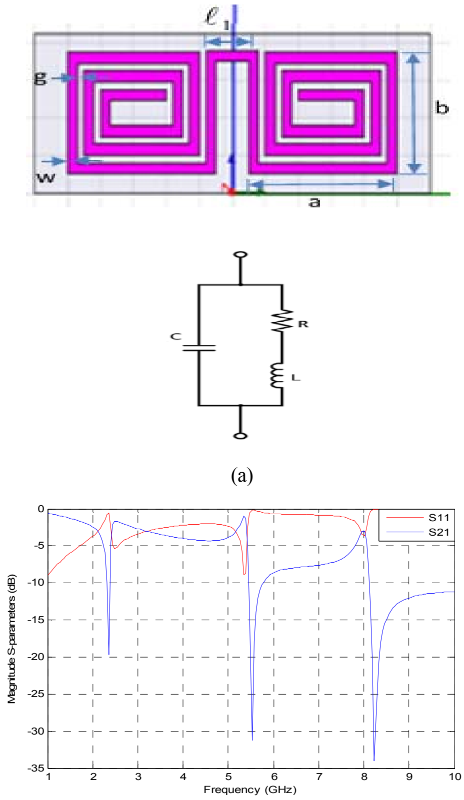
$$n=\frac{1}{\beta h}\left[\left\{\left[\ln\left(e^{jn\beta h}\right)\right]'+2m\pi\right\}-j\left[\ln\left(e^{jn\beta h}\right)\right]''\right] \quad (5)$$

where (.)′ represents the real component and (.)″ represents the complex component of the complex number; S_{21} and S_{11} are transmission and reflection coefficients, respectively; n is the refractive index; β is the phase constant; R_{01} is (z-1)/(z+1); z is the impedance; h is the thickness of substrate material; m is the branch due to the periodicity of the sinusoidal function. The permittivity (ε) and permeability (μ) can be calculated by the following expressions [9]:

$$\varepsilon=n/z \quad (6)$$

$$\mu=nz \quad (7)$$

S-parameters are extracted using HFSS, the permittivity and permeability curves are calculated using MATLAB script.



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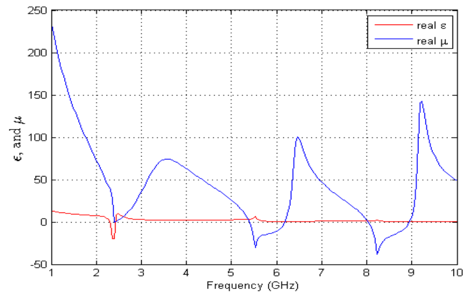


(c)

Figure 1. Spiral ring resonator a) 2D geometry of spiral ring resonator and its equivalent circuit b) S-parameters of unit cell c) real values of permittivity, and permeability.

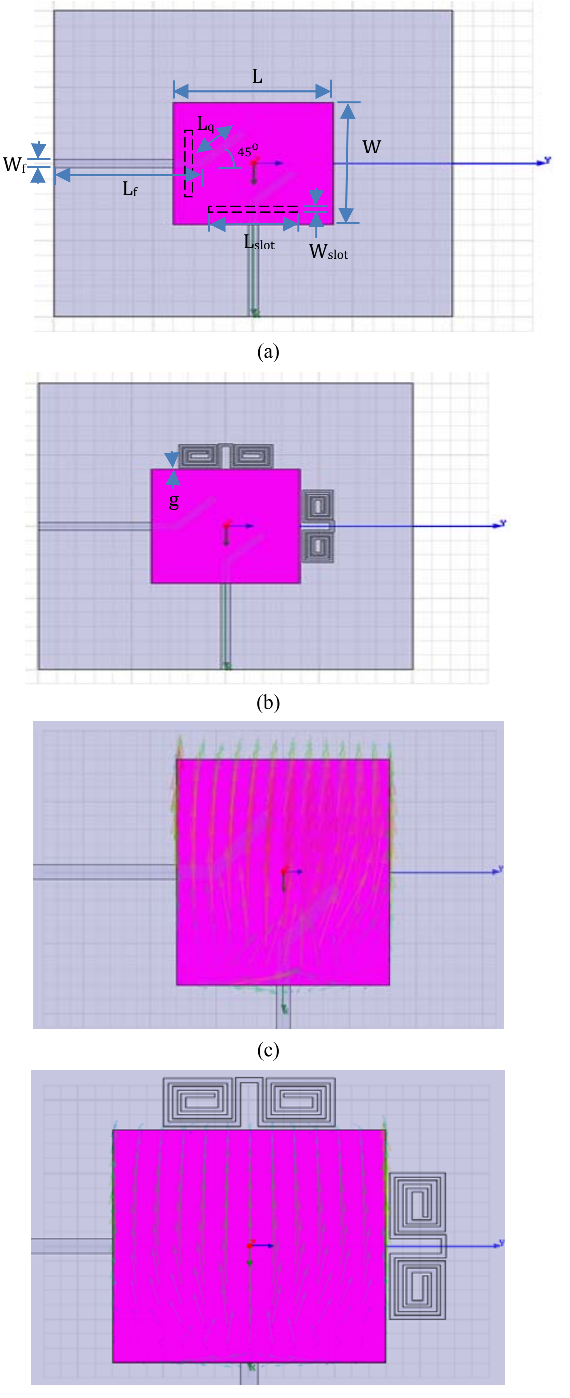
B. *Design of a dual linear polarization antenna using spiral ring resonator (S-RR)*

The basic configuration, 2D geometry of the proposed microstrip patch antenna for exciting a dual linear polarization at a single frequency of 5.5 GHz is depicted in Figs. 2 (a and b) before and after the addition of the two unit cells respectively. The antenna consists of a rectangular microstrip patch antenna with dimensions (W*L), which is supported on the first substrate layer made-up of Roger RT/duroid 5880 substrate with thickness of 1.575 mm and relative permittivity of 2.2. The feeding networks consist of two orthogonal aperture microstrip feed lines, which are printed on the bottom of the second substrate layer that uses Rogers RO4350 substrate with a thickness of 0.508 mm and relative permittivity of 3.38. The implementation of the feed network on a high dielectric substrate while at the same time allowing for a low dielectric patch substrate.

Determination of the current distribution along the proposed structure gives a good prediction for the cross-polarization discrimination. And it is noticed that the current distribution becomes more symmetric after adding the two unit cells as shown in Figs. 2(c, and d), which represent the current distribution before and after the addition of S-RR due to vertical port, respectively. Via such a scenario, the cross polarization discrimination can be improved.

Figs. 3(a, b, c, and d) show the linear co-cross polarization radiation patterns in E, H, and ± 45 planes for two antennas (conventional dual linear polarized and proposed antennas). Co-polarization patterns in two cases are compact and are not affected by the addition of the metamaterial spiral resonator. On the other hand, we get a significant improvement in cross polarization discrimination in comparison to the conventional dual linear polarized antenna. The simulation shows an improvement of 12 dB in cross polarization discrimination as compared to the conventional antenna. Fig. (4) shows the reflection and mutual coupling coefficients between two orthogonal input ports with and without S-RR inclusions. It is noticed that the mutual coupling becomes worse by 2 dB, and the reflection coefficients for two input ports are S_{11}=-28.4 dB, and S_{22}=-

30.3 dB at the center frequency. Table (I) lists the dimensions of a dual linear polarization antenna system.



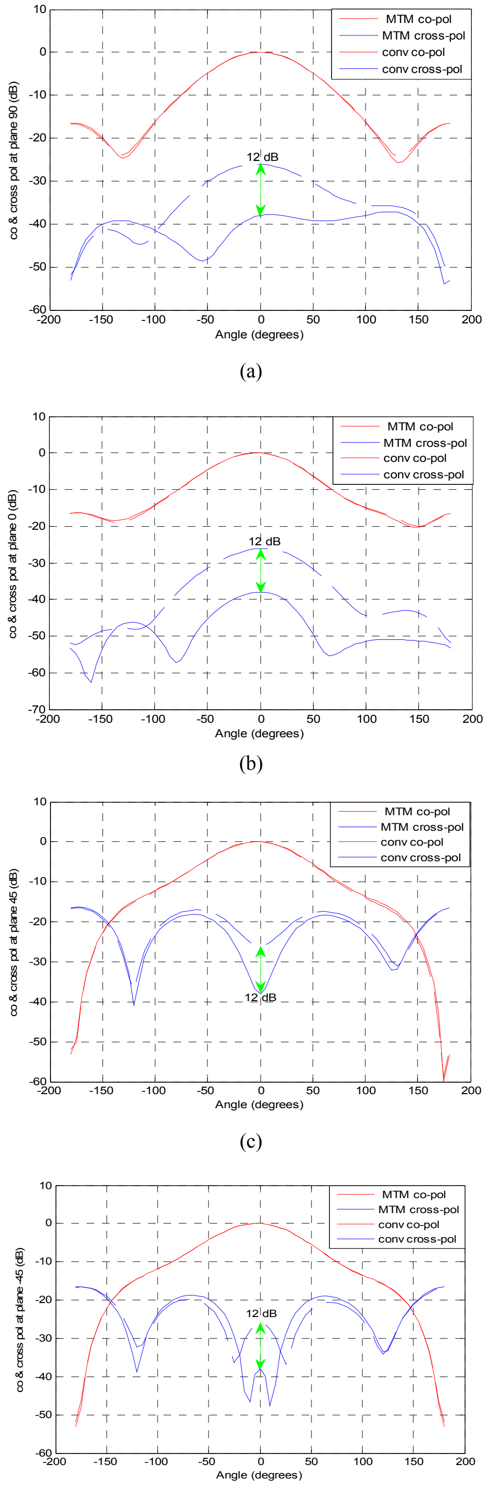
(a)

(b)

(c)

(d)

Figure 2. Dual linear polarization antenna a) 2D geometry of conventional dual linear polarization antenna b) 2D geometry of proposed antenna c) current distribution due to vertical port before adding S-RR d) current distribution due to vertical port after adding S-RR.



(a)

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Figure 3. Linear co-cross polarizations radiation patterns in a) E b) H c) +45 d) -45 planes, for dual linear polarization antenna with and without S-RR unit cells

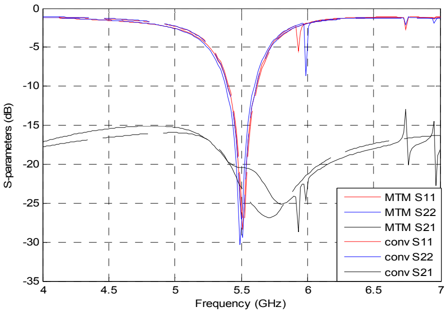


Figure 4. Reflection and mutual coupling between two orthogonal input ports with and without S-RR unit cells.

TABLE I. DIMENSIONS OF DUAL LINEAR POLARIZATION ANTENNA (ALL DIMENSIONS IN MM).

parameters	L	W	L_f	W_f	L_{slot}	W_{slot}	L_q	g
	15.89	15.9	15	1	10	0.4	6	0.25

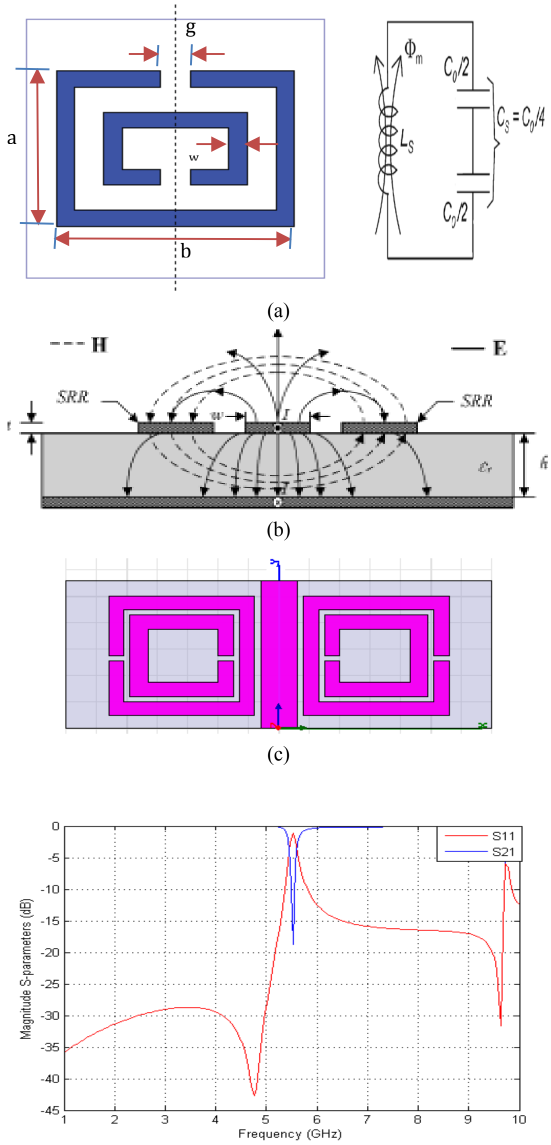
III. DESIGN OF A DUAL LINEAR POLARIZATION ANTENNA USING SPLIT RING RESONATOR (SRR)

This part deals with the design of dual linear polarization microstrip patch antenna with two microstrip feed lines that are loaded with a pair of SRR inclusions on both sides of the feed system. This feature permits to build a microstrip band stop filters and thus absorb the fields that are radiated on both sides of two microstrip feed lines.

A. *Design and Characterization of SRR as Band Stop Filter*

Recently, there has been an increasing interest in using the split-ring resonator (SRR) as a constituent inclusions for the design of antennas or novel planar microwave components, in particular, with either negative permeability ($\mu < 0$) or permittivity ($\varepsilon < 0$) or double-negative with both parameters ($\mu < 0$, and $\varepsilon < 0$) which lead to band-stop or band-pass filters respectively [10][11]. This type of resonator is characterized by being significantly smaller size than the conventional resonator structures (optimally less than or equal to one-tenth of the free space wavelength), which facilitates the design of very compact filters [12].

Fig. 5(a) shows the 2D geometry of SRR and its equivalent circuit. A microstrip feed line generates magnetic field lines that are encircle around the feed line as shown in Fig. 5(b). If a pair of SRRs is placed closely at both sides of the microstrip feed line as shown in Fig. 5(c), a significant portion of the magnetic field lines is induced by the line which are expected to cross the SRRs with the desired polarization giving rise to a negative-μ effect over a narrow band around the resonant frequency of the individual SRRs. Therefore, suppression of signal propagation over the region around the feed line can be achieved [12]. Based on this idea, SRRs have been designed as band stop microstrip filter, as shown in Fig. 5(d), and they absorb the surface waves radiated from two microstrip feed lines, where two pairs of SRR (i.e., 4 SRRs) have been employed. The width of the microstrip feed line is set to 1 mm to make the line's characteristics impedance approximately 50 Ω. The filter has been implemented on a RO4350C high-frequency laminate (ε_r = 3.38, substrate height of 0.508 mm and metal thickness copper cladding of 35 μm). The parameters of this filter are: a = 4.8 mm, b =4.5, g= s=0.2 mm, w =0.5 mm. Fig. 5(d) shows transmission and reflection coefficients of unit cell, it is noticed that SRR offers stop band (S_{21}=-19 dB) at center frequency of 5.5 GHz. The real values of permittivity and permeability are shown in Fig. 5(e), and it may be noticed that the real values of permeability are purely negative and this leads to a stop band in this region.



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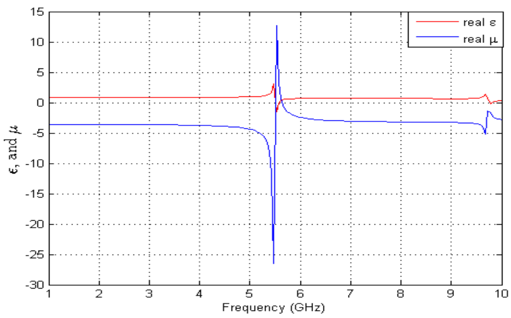
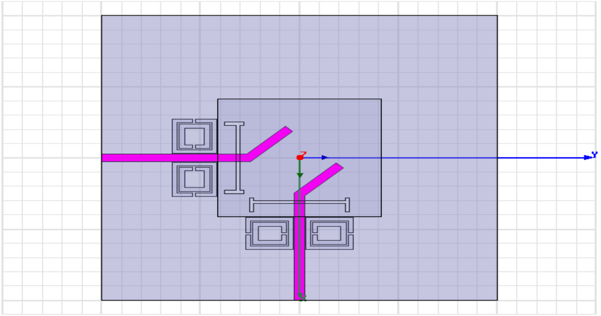


(e)

Figure 5. Split ring resonator a) 2D geometry of single SRR and its equivalent circuit b) electric and magnetic fields around microstrip feed lines electric and magnetic fields around microstrip feed lines c) electric and magnetic fields around microstrip feed lines d) S-parameters of unit cell (S_{11}, S_{21}) e) real values of permittivity and permeability.

B. *Design of a dual linear polarization antenna using two pairs of split ring resonators (SRR)*

Fig. 6(a) shows the 2D geometry of a dual linear polarization antenna using two pairs of the unit cells. The two pairs of unit cell are placed on both sides of each microstrip feed line at the same level. The distance between SRRs and microstrip feed line is 0.2 mm. Fig. 6(b) shows the current distribution after adding of SRR in the vertical port branch. More symmetry in the current distribution is noticed after adding of the two pairs of unit cells. Fig. 7(a, and b) show the linear co-cross polarization radiation patterns in E, H, and ±45 planes, we get a significant improvement in cross polarization discrimination in comparison to the conventional dual linear polarized antenna. The simulation shows an improvement of 6 dB in cross polarization discrimination as compared to the conventional antenna. Fig. 8 shows the reflection and mutual coupling coefficients between two orthogonal input ports with two pairs of SRR inclusions. It is noticed that the mutual coupling becomes better by 3 dB (S_{21}=-26 dB), and reflection coefficients for the two input ports are S_{11} =-33.5 dB, and S_{22}=-29.5 dB at the center frequency as demonstrated in the table (II).



(a)

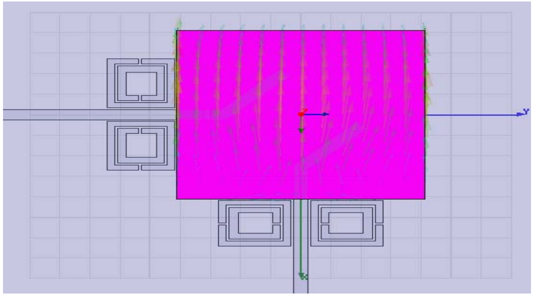


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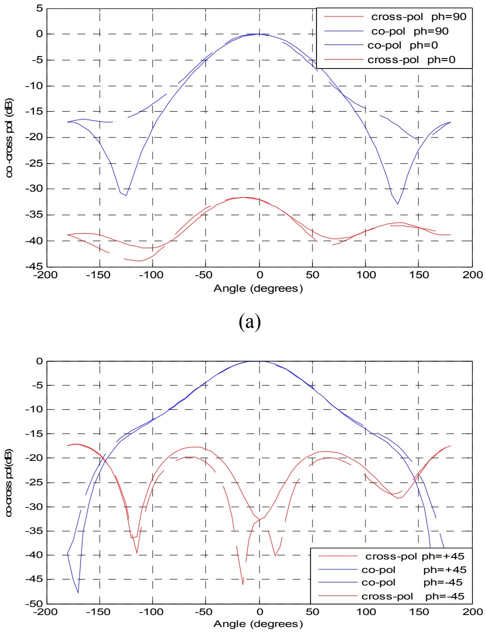
Figure 6. Dual linear polarization antenna a) 2D geometry of a dual linear polarization antenna using two pairs of unit cells b) current distribution after the addition of SRR due to vertical port.



(a)

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Figure 7. Linear co-cross polarizations radiation patterns in a) E and H planes, b) ± 45 planes for dual linear polarization with two pairs of SRRs unit cells.

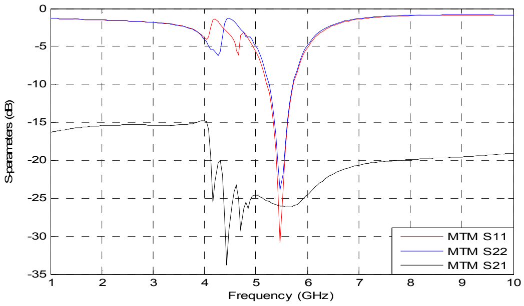
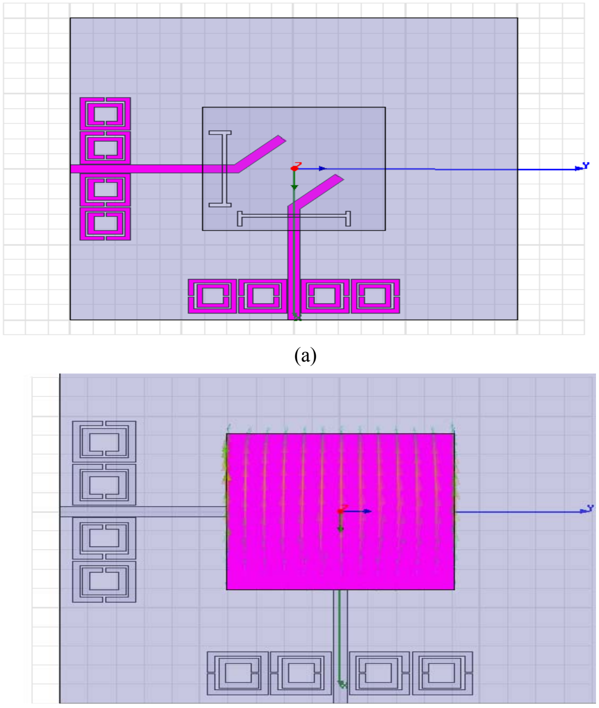


Figure 8. Reflection and mutual coupling coefficients between two orthogonal input ports with two pairs of SRR inclusions.

C. *Design of a dual linear polarization antenna using four pairs of split ring resonators (SRR)*

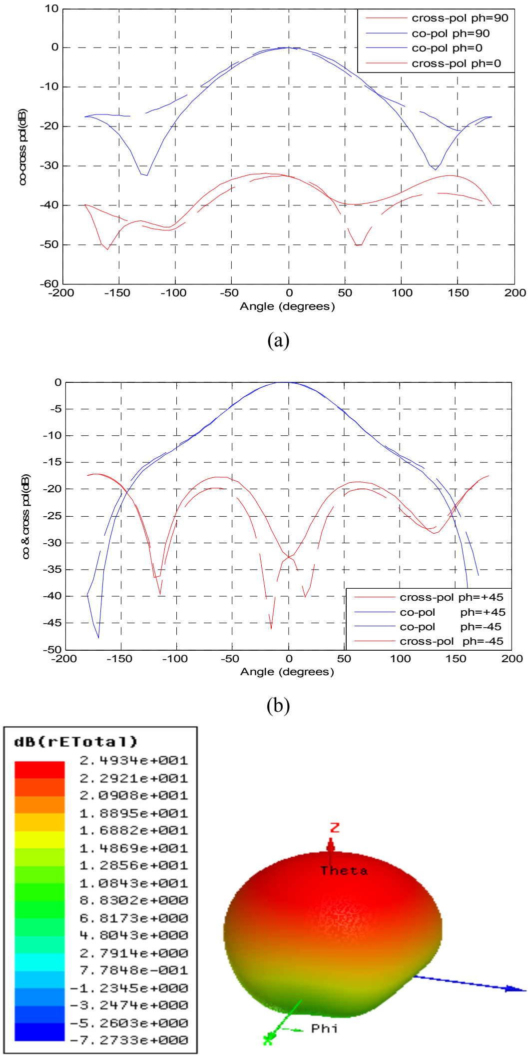
Fig. 9(a) shows the 2D geometry of a dual linear polarization antenna using four pairs of unit cells. Each two pairs of the unit cell are placed on both sides of each microstrip feed line at the same level. Fig. 9(b) shows the current distribution after adding of SRR due to vertical port, and it is noticed that the current distribution becomes more symmetric after the addition four pairs of unit cells. Fig. 10(a, and b) show the linear co-cross polarization radiation patterns in E, H, and ± 45-planes. We get a significant improvement in cross polarization discrimination in comparison to the conventional dual linear polarized antenna. The simulation shows an improvement of 6.6 dB in cross polarization discrimination as compared the conventional antenna. In addition to co-cross polarization pattern in E and H planes, co-cross polarization pattern in ± 45 planes is displayed to provide complete and real performance of antenna system after the adding metamaterial inclusions. Fig. 10(c) shows 3D co-polarization pattern for a dual linear polarization antenna after adding Metamaterials, It is noticed that the 3D co-polarization pattern is the similar for three cases in the shape but there is a very small difference in the magnitude.



(a)

(b)

Figure 9. Dual linear polarization antenna a) 2D geometry of a dual linear polarization antenna using four pairs of unit cells b) current distribution after the addition of SRR due to vertical port.



(a)

(b)

(c)

Figure 10. Linear co-cross polarizations radiation patterns in a) E and H planes, b) ± 45 planes, c) 3D radiation pattern for a dual linear polarization with four pairs of SRRs unit cells.

Fig. 11 shows the reflection and mutual coupling coefficients between two orthogonal input ports with four pairs of SRR inclusions. It is noticed that the mutual coupling becomes better by 5 dB (S_{21} =-28 dB), and reflection coefficients for two ports are S_{11} =-34 dB, and S_{22}=-23 dB. Finally, table (II) shows the comparison between the conventional dual linear polarization and the proposed antenna using metamaterials (S-RR, and SRR) by three different examples with respect to S-parameters, XPD, gain (G), and bandwidth (BW) for two input ports. From table (II), it is noticed that there is a good enhancement in XPD and a little enhancement in mutual coupling especially in the second and third examples. On the other hand, there are no a significant change in other characteristics such as gain (G), Bandwidth, and matching for two ports (S_{11}, and S_{22}).

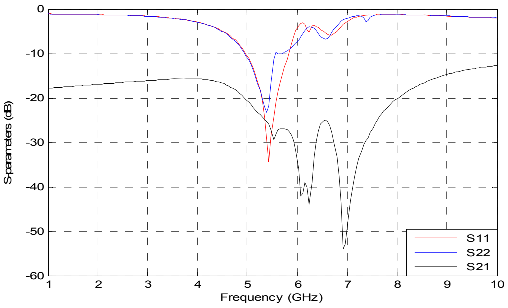


Figure 11. Reflection and mutual coupling coefficients between two orthogonal input ports with two four of SRR inclusions.

TABLE II. COMPARISON BETWEEN THE CONVENTIONAL DUAL LINEAR POLARIZATION AND THE PROPOSED ANTENNA USING MTM WITH DIFFERENT THREE EXAMPLES WITH RESPECT TO S-PARAMETERS, XPD, BW FOR TWO PORTS.

	Conventional Dual pol. antenna	Proposed antenna example1	Proposed antenna example2	Proposed antenna example3
S_{11} (dB)	-27.7	-28.4	-30.8	-34
S_{22} (dB)	-29.3	-30.3	-24	-23
S_{21} (dB)	-23	-21	-26	-28
XPD (dB)	26	38	32	32.6
G (dB)	7.34	7.3	7.37	7.14
BW_1(GHz)	0.215	0.215	0.185	0.288
BW_2 (GHz)	0.216	0.218	0.182	0.204

IV. CONCLUSION

In this paper, a new technique (using metamaterials S-RR, and SRR) is employed to improve the cross polarization discrimination for a dual linear polarization microstrip patch antenna with a frequency of 5.5 GHz. This improvement is achieved by placing two spiral ring resonators nearest from the microstrip patch antenna and placing pairs of split ring resonators on both sides for each microstrip feed line. An improvement in cross polarization discrimination by 12 dB as compared to the conventional dual linear polarized antenna is observed. Further analyzing co-cross polarization pattern in four planes (E, H, and ±45) is achieved after the adding the metamaterial inclusions, in order to show the real antenna performance. The antenna system has several features including simple structure, and metamaterial inclusions occupied very small area, which makes the proposed metamaterial (S-RR, and SRR) more useful for the design of a dual linear polarization antennas. In summary, the resulting antenna is very compact (as compared to a conventional of a dual linear polarization antenna), and with the desired enhanced characteristics.

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