# Design and Development of Polarization Agile Frequency Selective Surfaces (FSS) for C, X and Ku bands


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# Dedication

*I dedicate this work to my Parents, my batch fellows, my supervisor Dr. Nosherwan Shoaib and to all those whohave helped me throughout my thesis.*

# Acknowledgement

First of all, I am very thankful to almighty ALLAH the most merciful and the most beneficent who gave me the strength, wisdom and enlightened me to complete this research work.

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# Abstract

In this thesis, to realize the concept of Co-Cross(LP-LP) and Cross-Circular(LP-CP) polarization of the reflected wave, a multi-band polarization agile frequency selective surface (FSS) for C, X and Ku bands is presented. It consists of a periodic single-layered split circular ring with rectangular slot and small split inscribed circle shaped metasurface is designed by introducing the split circular structure. It consists of diagonal strip that surrounds the half solid circular strips that behaves like a capacitor. The bottom layer consists of full copper ground structure that makes it as a perfect reflector. The proposed metasurface is able to adds the Co-Cross(LP-LP) and Cross-Circular(LP-CP) capability. There are three LP-LP Polarization bands are achieved from 7.3-7.7 GHz, 9.0-9.3 GHz and 15.3-17 GHz. Similarly, for LP-CP, a mature band of 9.8-13 GHz having a fractional bandwidth of 28% is achieved. Furthermore, multiple useful operating bands and miniaturized single layer profile makes the proposed structure of metasurface a good candidate for polarization conversion useful applications.

# CHAPTER 1

# Introduction

In this chapter, the background and the motivation to this thesis work is presented. The importance of Polarization Agile Frequency Selective Surface(FSS) has also been highlighted. With the rapid development in polarization agility, the researchers are more interested in metasurfaces. Metasurfaces are the two-dimensional artifically synthesized 2D structures used to control and change the behavior of EM waves. The polarization control metasurfaces are used in many applications includes reflect array structures, the polarization delicate devices and reduction in radar cross section (RCS). Many Conventional phenomena's such as the Faraday's law and optical theory of crystals is used to change the performance of EM wave. Therefore, such phenomena are not practical in nature which results in slightly narrow response of frequency, the bulk size of the used applied structures and the reliant response of incident angle. Recently, these techniques can't be recommended to fabricate the planar reduced polarization agile devices. In recent literatures, a lot of designs on the polarization agile metasurfaces have been published [1]-[3]. There are alternate structures, e.g double-headed arrows structure [4], V-shaped structure patches [5], inverted L-shaped structure in diagonal [6] and the square structure along with the diagonal [7] and also already designed to find the broadband polarization agility. A split-ring resonator(SRR) are broadband polarization conversion has been achieved using multi-layer structure [8]. However, those multilayer structures are not good and compatible with current planar polarization controllable devices.

## 1.1 Background:

Electromagnetism is the phenomena that studies the relationship between electric and the magnetic fields. It is a fundamental type of force that plays a vital role in many aspects of our daily usage things [3], from the operation of electrical appliances to the behavior of subatomic particles. Key concepts and principles in electromagnetism include:

**Electric Field (E):** The electric fields are generated by the presence of electric charges. They exert the forces on the other charges placed within the field. The direction of electric field is a point where the direction at which the positive charge will move if placed at that point.

Magnetic Field (B): Magnetic fields are generated by the movement of the electric charges, such as currents. They exert forces on other moving charges and on magnetic materials [4]. The magnetic field lines form a closed loop that do not have isolated magnetic monopoles.

$$E = \frac{F}{Qtest} = k|Q|/r_2$$

**Coulomb's Law:** This law states that the force is directly proportional to the product of the charges and the inversely proportional to the square of their distance between both of them [16].

$$F = kq_1q_2/r2$$

**Gauss's Law:** This law states that the electric flux through the closed surface to the charge enclosed within the surface. It's a fundamental principle of electrostatics.

$$\varphi = q/\varepsilon_0$$

**Ampere's Law:** This law states that magnetic field around any closed loop to the electric current passing through the loop.

**Faraday's Law of Electromagnetic Induction:** This law states that a changing of magnetic field induces an electromotive force (EMF) in a conductor [5], leading to the generation of the current. This phenomenon is the basis for generators and transformers.

$$E = -N\Delta\varphi/\Delta t$$

**Maxwell's Equations**: The Maxwell's equations are the set of basic four fundamental equations that describes the behavior of electric and the magnetic fields. These equations unify the theories of electricity and magnetism and are essential for understanding the behavior of electromagnetic waves.

$$\nabla.E = \frac{\rho}{\varepsilon_0}$$

$$\nabla.B = 0$$

$$\nabla \text{ X E} = -\frac{\partial B}{\partial t}$$

$$\nabla X B = u_0(J + \varepsilon_0 \frac{\partial E}{\partial t})$$

In wireless communication, electric field vector in the electromagnetic waves is manipulated and controlled for the numerous applications at terahertz and microwave frequency regimes [12]. Traditional techniques that were previously deployed for the manipulation of EM waves are given below:

- Faraday Effect
- Birefringence in anisotropic materials

Faraday Effect (also known as Faraday rotation) works on the magneto-optical phenomenon; i.e. the inter-action between the electromagnetic wave and magnetic field in the medium. For the polarization conversion of the EM waves benefiting from Faraday Effect, external magnetic biasing is required to excite the magnetic field [2]. On the other hand, birefringence effect is an optical characteristic of materials that have refractive indices which depends on the propagation and polarization direction of EM waves [1]. The birefringent materials have also the capability to transform the polarization states of EM waves by establishing a phase difference among the two components with different handedness. A linearly-polarized wave can also be dissolved into two circular-polarized components of same magnitude along with opposite handedness [9].

Some of the inherent limitations of these conventional techniques are given below:

- External batteries are needed for the excitation of magnetic field in Faraday rotation
- Complex structure and bulky volume
- Narrow operating frequency band
- Incompatible with miniaturized polarization control devices
- Polarization manipulation is sensitive to the oblique angles

To overcome these limitations, researchers have come up with artificial structures known as metamaterials or metasurfaces, that have an ability to change the polarization state of EM waves [11]. Recently, different structures of metamaterials were designed to succeed the polarization conversion, beam-splitting and many other manipulations. Metamaterials have the advantage of ultra-thin profile [5], high efficiency, multi-functional operation, broadband operating frequency bands, angular stability and ease of fabrication. Next section will provide insight to the importance of metamaterials in detail.

## 1.2 Metamaterials:

Metamaterials are the artificial synthesized materials that engineered to have properties which not found in nature. They are designed at a microscale, altering the performance of electromagnetic waves [18], or other physical phenomena in unique ways. Metamaterials have added vital role in the field of science and engineering due to their potential to enable a broad range of applications [2], including cloaking devices, super lenses, and improved antennas. Here are some key characteristics and applications of metamaterials:

**Cloaking Devices:** Metamaterials have been used to develop cloaking devices that can makes the object to invisible in certain wavelengths of electromagnetic radiation. By manipulating the path of light or other waves [1], these materials can conceal objects from detection.

**Seismic and Vibration Dampening**: Metamaterials can be used to create structures that can dissipate or redirect seismic waves, potentially enhancing earthquake resistance [27]. They can also be used to dampen vibrations in mechanical systems.

**Chiral Metamaterials:** Chiral metamaterials have asymmetrical structures that interact differently with left- hand and the right-hand circularly polarized waves [15]. They find applications in polarization manipulation, beam steering, and optical communication.

**Thermal Metamaterials**: Some metamaterials are designed to manipulate the flow of heat, allowing for applications in thermal management [24], such as in thermoelectric devices or heat shields.

Medical Imaging: Metamaterials have been explored for improving the performance of medical imaging equipment, such as MRI and ultrasound [30].

**Energy Harvesting:** Metamaterials can be used in energy harvesting systems to capture energy from specific wavelengths or sources [34], such as solar cells that can absorb more light due to their unique properties.

It's important to note that the development and practical application of metamaterials are still evolving, and there are ongoing research efforts to explore new possibilities and overcome practical challenges in manufacturing and scalability [38]. The field of metamaterials holds excessive potential for a wide range of technological innovations.

## 1.3 Metasurface:

A metasurface is a two-dimensional subwavelength-structured element, often referred to as a meta-atoms or meta-elements, designed to manipulate electromagnetic waves in unique and controllable ways [2]. Metasurfaces are a class of the metamaterials, which are engineered materials with properties not found in naturally occurring substances. Metamaterials [10], including metasurfaces, have gained significant attention for the capability to control and change the behavior of electromagnetic waves [5], making them applicable in various fields such as optics, electronics, and telecommunications.

Metasurfaces are typically thin and flat structures that are designed to take a variety of functions, including:

Wavefront Manipulation: Metasurfaces are designed to control the phase, the amplitude, and the polarization of electromagnetic waves [1], enabling them to shape wavefronts in ways not achievable with conventional optics. This is useful in applications like lenses, beam steering, and holography.

Polarization Control: Metasurfaces can be used to change the polarization of light [2], making them valuable in the polarization control devices, such as polarizers and wave plates.

Anomalous Refraction and Diffraction: By carefully designing the subwavelength structures, metasurfaces can exhibit anomalous refraction and diffraction behaviors, allowing for the creation of flat lenses and other optical components [53].

**Sensing:** Metasurfaces can be used as sensors to detect changes in the local environment. Changes in the properties of the metasurface [52] due to external factors (e.g., temperature, pressure, or the presence of specific molecules) can be used for sensing purposes.

Terahertz and Infrared Devices: Metasurfaces have applications in terahertz and infrared regions, such as terahertz imaging [59] and spectroscopy.

**Figure 1.1:** Metasurfaces Structures [3]

Metasurfaces have found practical applications in fields like imaging, communication systems, and optical design. They are particularly valuable for their ability to replace the bulky optical devices with compact [62], lightweight, and easily tunable structures.

The design and fabrication of metasurfaces often involve techniques such as lithography, plasmonics, and nanofabrication, allowing for precise control over the subwavelength structures that make up the metasurface [55]. These structures can be made from various materials, including metals and dielectrics, depending on the desired functionality.

**1.4 Frequency Selective Surface(FSS):** A frequency selective surface is a type of structure or material that selectively allows certain frequencies of electromagnetic waves to pass through while reflecting or attenuating others [49]. FSS is used in various applications in the field of electromagnetics, including antennas, radomes, and electromagnetic shielding.

Here are some key characteristics and uses of Frequency Selective Surfaces:

**Frequency Filtering:** FSS operates on the principle of resonance. It is designed to transmit or reflect specific frequencies of electromagnetic waves while suppressing others. It can be engineered to allow certain microwave or radio frequencies to pass through, which makes it useful for applications like frequency-selective filters [57].

**Radomes:** FSS is employed in radome construction to protect antennas from environmental factors such as wind, rain, and ice, while still allowing the transmission and reception of electromagnetic waves. It offers a transparent cover for the antenna while permitting the passage of radar or communication signals.

**Stealth Technology:** In military applications, FSS can be used to design stealth technology that reduces the radar cross-section of aircraft or vehicles. By coating surfaces with FSS, it's possible to scatter radar waves away from the source, making the object less detectable by radar.

**Electromagnetic Shielding:** FSS can be used to construct screens or enclosures that prevent certain electromagnetic frequencies from passing through. This can be useful in applications where electromagnetic interference (EMI) or electromagnetic compatibility (EMC) is a concern [43].

In summary, Frequency Selective Surfaces are engineered structures used in various applications to control the passage of electromagnetic waves, allowing specific frequencies to pass through while reflecting or attenuating others [27]. They play a crucial role in the design of different types of antennas, radome structures, stealth technology, and electromagnetic shielding.

## 1.5 Polarization in EM waves

By understanding of electromagnetic (EM) waves has always been the keen interest for scientists and engineers. Electromagnetic waves are produced due to the accelerated charged particles or time-varying electric current [58]. Electromagnetic (EM) waves can exhibit polarization, that refers the orientation/angle of the electric field vector with respect to the propagation direction of the wave. Polarization is an important property of EM waves and plays a major role in the various applications, such as in optics, telecommunications, and radar [1]. There three types of polarization, including linear polarization, circular polarization, and elliptical polarization:

**Linear Polarization(LP):**

In the linearly polarized EM waves, the electric field propagates in a single plane perpendicular to the propagation direction of the wave [5]. Linear polarization can be oriented in any direction with respect to the wave's direction. If the electric field always stays in the same plane, it's considered linear polarization.

**Circular Polarization(CP):**

In circular polarized EM waves, the electric field vector rotates in a circular pattern as the wave propagates [5]. There are two types of circular polarization: right-handed circularly polarized(RHCP) and left-handed circularly polarized(LHCP). As the right-handed circular polarization(RHCP), the vector of electric field rotates in clockwise when viewed in the propagation direction, and in left-handed circular polarization(LHCP), it rotates counterclockwise.

**Elliptical Polarization(EP):**

In elliptically polarized EM wave, there is such a combination of the linear and the circular polarization occurs. The electric field vector traces out an elliptical path as the wave propagates. The elliptical shape and the orientation of its major and minor axes determines the specific polarization state. Polarization can have important practical implications in various useful applications. For instance: In optics [5], polarizing filters are used to selectively block or transmit light waves with specific polarization orientations, allowing for the control of glare and enhancing contrast in photography or displays. In telecommunications, the use of polarized antennas can help reduce interference and enhance signal quality by transmitting and receiving EM waves with a particular polarization.

Radar systems use polarization to distinguish between different types of targets or to minimize interference from unwanted reflections [51]. Polarization is also used in 3D cinema systems, where two images with different linear polarizations are projected and then viewed through glasses with corresponding polarized filters to create a 3D effect.

In summary, polarization in Electromagnetic wave raises to the orientation of electric field as the wave propagates. The polarizations are linear, circular, or elliptical and it has a broad scope of applications in many fields of science and technology [62].

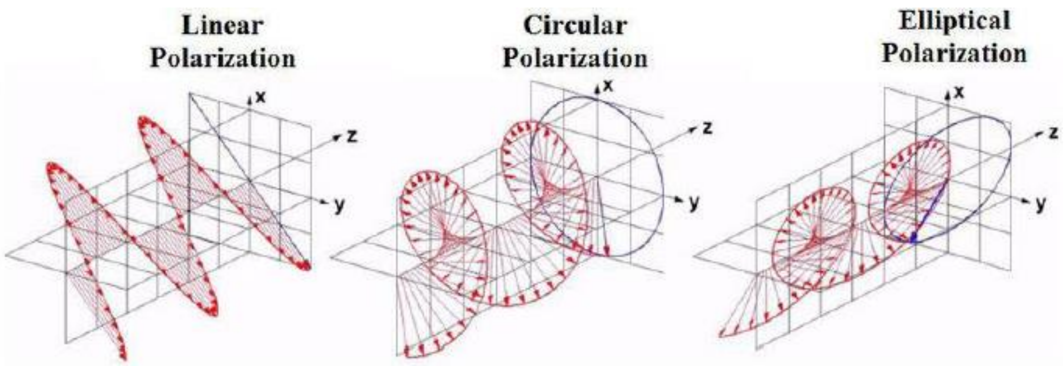



**Figure 1.2**: Types of Polarization Conversions [7]

## 1.6 Applications:

Metasurfaces offers the huge advantages such as, having a low profile, on-chip integration and ease of operation. Therefore, the metasurfaces are used in applications like antenna radiation broadened, the scattering suppression, the radar cross-section reduction and focusing lens for the gains enhancement [44]–[46]. There are some striking applications such as, polarization beam splitting and the beam deflection were also discussed in [47] and [48] respectively. In optical and telecommunications, the phenomena of plasmonic metasurfaces can also be used in the high-technology communications, the real-time holograms technology and adaptive optics [49]. The additional applications of the metasurfaces are polarization tuning at terahertz frequency regime, [50] the suggested novel design to dynamically control the functionalities of metasurface. The metasurfaces were also used for radio frequency energy harvesting applications [51]. For improvement in confidentiality, polarization modulation techniques are explored in information and telecommunication regime [52].


**Figure 1.3:** Applications of Polarization Conversion in Communication and Medical fields [8]

## 1.7 Problem Statement:

In the last few decades, a lot of advancement in the field of metasurfaces has been observed in the field of science and technology. Metasurfaces have become attracts the researchers for their wide range of applications like cloaking, beam splitting, quarter-wave operation, etc. Metasurfaces have many advantages such as miniaturized in size, efficiency, multi-functional operation, angular stability and easy fabrication. In the literature, a very few amount of work on multiband FSS polarization conversion has been reported using single layered metasurfaces to produce broadband results. Now, researchers have directed their attention towards achieving wide band in polarization. It has been realized that the designs for polarization conversion surfaces that is either a lower efficiency, that operates only at resonance frequencies with the narrow bandwidth, or operates at normal angle of the incidence. In this context of polarization, an achieving efficient wideband polarization conversion metasurface along with the high polarization conversion ratio(PCR).

## 1.8 Thesis Objectives:

The main objective of this research work is to achieve a linear-to-linear (Co-pol to Cross-Pol) and also a linear to circular polarization(LP-CP) conversion (Polarization conversion frequency selective metasurface) using single layered metasurface. The aim is also to fabricate, test and analyze the performance of this polarization conversion metasurface.

The following points were considered as key objectives for polarization conversion metasurface:

- To design single layer metasurface.
- To design for co-polarization to cross polarization in (C, X and Ku band) response.
- To design for co-polarization to circular polarization in (Ku band) response.
- To fabricate the miniaturized metasurface on low cost FR-4 substrate.
- To test and verify results of the designed Metasurface

# CHAPTER 2

# Literature Review

In this chapter, the different polarization techniques have been discussed in passive metasurface structures. Firstly, a passive metasurfaces structures are discussed to understand the phenomena of cross and circular polarization techniques that has been used. The comparison of the state of art reconfigurable metasurfaces and the motivation to design a novel miniaturized multiband metasurface is discussed. Several polarization converting metasurfaces are also categorized based on their operations.

## 2.1 A Metasurface for Cross Polarization Conversion

The phenomena of polarization are an important part of EM waves, which can be changed the properties by artificially synthesized two dimensional planar periodic structures which is called as metasurface. The polarization conversion metasurfaces is also used in a broad range of advanced applications that includes the reflect arrays, the polarization sensitive devices and the RCS (radar cross section) reduction. Those conventional methods such as the known method Faraday Effect and the optical states of crystals are used to control polarization of EM wave. However, due to narrow frequency response, those techniques are not very useful (bulk structure and the dependence of incident angle). As according to this, those techniques are not very useful nowadays to fabricate or synthesize the planar the lessened the size of polarization control structures. In recent literature, a lot of designs on the method of polarization conversion metasurfaces has been published such as the double-headed arrow structure [4], the V-shape patches structure [5], the inverted L-shape structure in a diagonal [6] and the square patches structure along the diagonal [7] was designed to achieve the broadband polarization conversion. The split ring resonators(SRR) that based broadband polarization conversion is achieved using the multilayer structure [8]. As, the multilayer structures are not usually compatible with the modern planar polarization control devices.

In this literature, the broadband polarization converter that is composed of circular split ring resonator (C-SRR) as described in Figure. 2.1 which is composed of the circular ring in the middle is designed on the low cost FR4 dielectric substrate. The designed structure is a broadband polarization converter at the normal angle of incidence on a fabricated single layer. The simulated response of the composed metasurface remains the same for both the x-axis and the y-axis because both are polarized incident wave faces the same split and non-split sides of the circular split ring resonator.

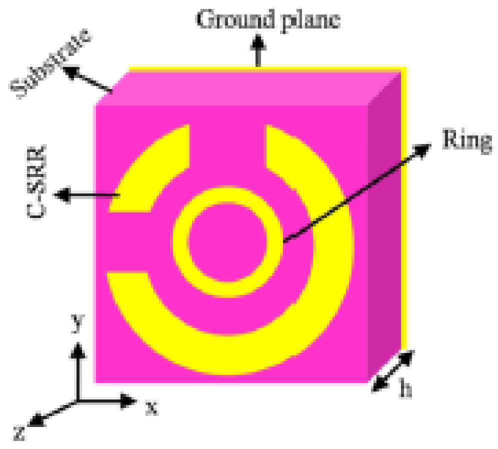



**Figure 2.1:** Three-dimensional (3D) view [10]

The ground plane of structure is fully copper as a bottom of the substrate that shows the design is perfectly reflector. The substrate used for fabrication is low cost FR-4 having dielectric constant 4.3 and the loss tangent 0.02. The circular split ring, and the inner circular ring and the ground plane are modeled with copper having thickness of 35 microns.

## 2.2 Results and Discussion

The designed metasurface structure acts as a cross-polarizer in the reflection mode that converts an x-polarize wave into y-polarize wave and vice versa. Similarly, if incident wave has right-hand circular polarization(RHCP), it is converted into left-hand circular polarization(LHCP) and vice versa upon the reflection from the metasurface. The designed structure of unit cell as shown in Fig.2.2 is modeled in the software CST Microwave Studio with unit cell boundary conditions along x- and y-axis and open (add space) boundary conditions in z-axis. The optimized physical dimensions of the unit cell RO=4.8mm, RI=2mm, W=1.8mm, L=0.8mm, g=2.4mm, h=3mm and P=10mm.

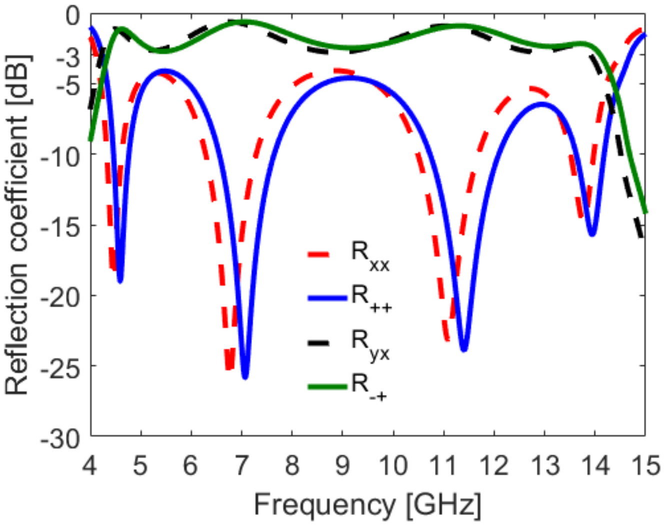



**Figure 2.2:** Simulated reflection coefficient for x-polarized and right-hand [10]

The simulated results of the cross-pol are shown in Figure. 2.2 and Figure. 2.3. The designed structure of metasurface is an anisotropic as it is not symmetric when splits along the x-axis and y-axis. The anisotropy phenomena of the unit cell which results in a cross-polarization reflection for the linearly and circularly polarized waves. The reflection component (Rxx and Ryx) are the co-pol and cross-polarized reflection coefficients respectively. When x-polarized wave strikes the metasurface. Similarly, Rxx and Ryx are the co-pol and cross-polarized reflection coefficients respectively for right-hand circularly polarized(RHCP) incident wave. It is evident from Fig.2.3 that co-polarized (Ryy and Rxx) reflection coefficients are very small while the cross-polarize reflection coefficients (Ryx and Rxy) are above the -3dB criterion (70% polarization conversion efficiency) within the operating band of about 4.2-13.9 GHz.

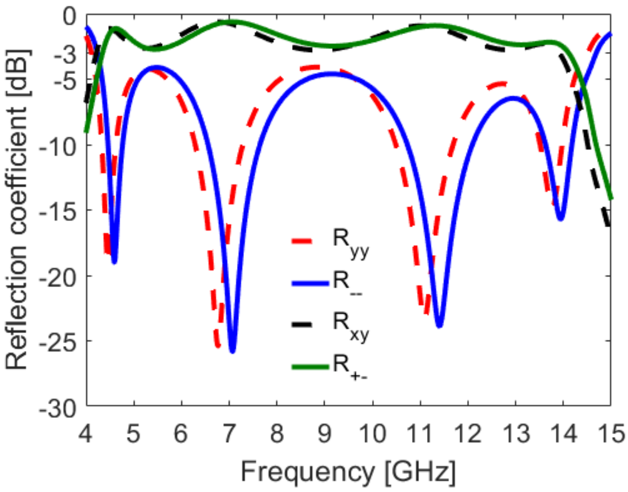



Figure 2.3: Simulated result of reflection coefficient for y-polarized and left-hand circularly [10]

The reflection component (Ryy and Rxy) have shown in Fig. 2.3, are the co-pol and cross polarized reflection coefficients respectively. When y-polarized wave strikes the metasurface. As results, Rxx and Rxy are the co-pol and cross-polarized reflection coefficients respectively for left-hand circularly polarized(LHCP) incident wave. As it is clear from Fig. 2.3, that cross-pol efficiency is around 90% at four resonance frequencies. The unit cell of the designed metasurface has the symmetry along the x-axis and y-axis that results in the same response for x-axis and y-axis polarization.

In this article, a broadband cross-polarizer that consists of a circular split ring resonator is presented. This design is a single layered design that can efficiently transform the linearly-polarized or circularly-polarized wave into its orthogonal components and vice versa. The metasurface has 3dB fractional bandwidth of 107% from 4.2-13.9GHz at the normal incidence. The cross-polarizer can also be used for various applications and polarization control devices.

## 2.3 A Broadband Linear polarization converter based on anisotropic metasurface

In this design a metamaterial absorber(MA) it has been attracting a great interest due to its advantage of ultrathin thickness and scalable property. In the past few years, great effort has also been made to improve the performances of Metamaterial Absorber, as especially in the expanding of the absorption band [2–11]. The broadband property is also required in the many other applications, such as metasurface holograms [12,13]. To achieve, the broadband absorption, one approach is to utilize the multi-resonance by using the multiple resonators within one-unit cell [2–5], the other approach is to utilize the multilayer structure [6–11]. Since the typical metamaterial absorber that is a periodic array of metal-dielectric-metal (MIM) resonate structures units, its absorptivity is the reflection coefficients for the co-polarization and cross-polarization, respectively. Here, a y-polarized plane wave illumination is considered, which is the same as the x-polarized plane wave illumination occurred due to the symmetric of the unit cell along the diagonal direction. Recently, by using a relatively simple structure is to achieve the broadband absorption has been reported, which is also actually poor absorber when the cross-polarized reflection is considered [14–20].

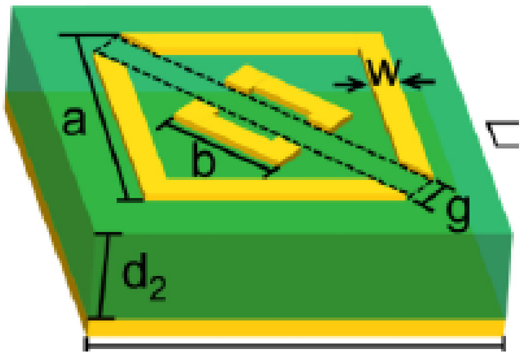



**Figure 2.4:** A unit cell of the proposed absorber [14]

Here, a proposed an ultra-broadband high-efficiency linear polarization(LP) convertor that consists of an asymmetric double ring resonators. As, compared with the previously reported reflective structure of cross-polarization convertor [23–27], the proposed polarization convertor shows much more advance in the bandwidth. The broadband transformation effect is attributed to overlap of four polarization rotation resonances that is generated in an asymmetric double ring resonate structure.

## 2.4 Results and Discussions

As far as design results is concerned, both numerical simulations and the experimental results that shows the polarization conversion ratio (PCR) of the proposed polarization convertor is above the 90% in the frequency range from 6.67-17.1 GHz. The bandwidth reaches upto the 87.7%. Recently, the topology of this design method [28] and the multi-layer structure [29] have also been proposed to expand the operating bandwidth of polarization converter. However, they are limited by complicated fabrication or the PCR is under the 90% at the several frequencies of the operating bands.

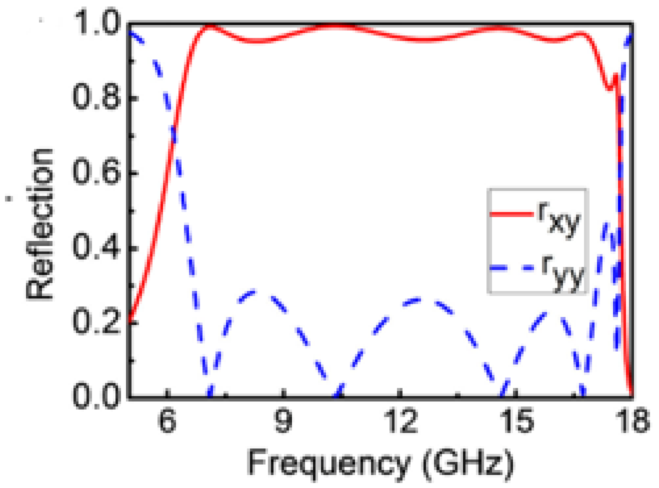
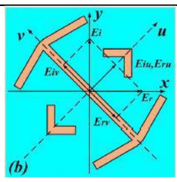
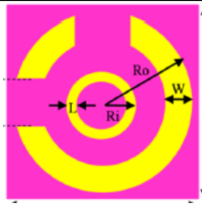
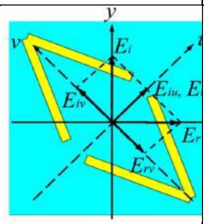
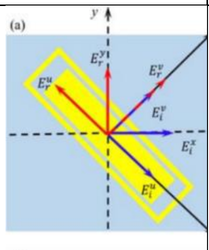
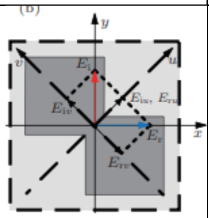
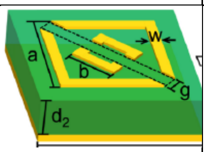
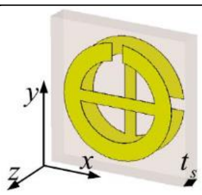



**Figure 2.5:** Simulation results of the polarization converter [14]

The measurement of Polarization conversion ratio(PCR) is an often used to evaluate the performance of a polarization convertor, which is defined as the PCR = Rxy2/ (Rxy2 + Ryy2) [22]. As, we consider a resonant unit cell consists of a single inner split-ring, the single outer split-ring, and the double split-rings, the simulated PCR of the design is as shown in Fig. 2.5. Obviously, a single inner split ring and a single outer split-ring can't achieve an effective polarization conversion. However, when they are combined with this, an ultra-broadband and high-efficiency polarization converter is obtained. The Polarization conversion ratio(PCR) is above 90% in the frequency range from 6.68-17.1 GHz and the relative bandwidth is up to 87.8% (PCR>90%).

In summary of this article, an ultra-wideband and the high-efficiency cross-polarization convertor are achieved by breaking the symmetry of the resonator structure of a perfect absorb. We have to design a linear polarization convertor that consists of asymmetric double-ring resonators. Both the numerical simulation and measurement results shows that the PCR of the proposed metasurface is above 90% in the frequency range from 6.68-17.1 GHz and the relative bandwidth reaches 87.8%. The significant bandwidth is attributed to four EM resonances that generates in a double-ring resonator. The proposed method, which also be extended to the terahertz band. The potential applications in the microwave communications, remote sensors, and the optical devices. In addition to this, the proposed method may have some inspiration in the designing switchable multifunctional device [30], which also acts as an absorber in one state and as a polarization converter in another state.

**Table 1: Comparison of Polarization converting metasurfaces based on their operations and limitations**

| Research Paper | Unit Cell | Operation | Frequency bands | Substrate layers |
|---|---|---|---|---|
| An ultra-wideband and the broad-angle linear polarization conversion metasurface JAP 2017 [72] |  | Cross polarizer Passive | 18 GHz, 42.6 GHz | Single F4B |
| A Broadband Metasurface for Cross Polarization Conversion Applications ICCEM 2019 [70] |  | Cross Polarizer Passive | 10.1-15.1 GHz | Double FR4 |
| An UWB and High efficiency Linear Polarization Converter based on Double V-Shaped Metasurface TAP (2015) [68] |  | Cross Polarizer Passive | 12.4-27.9 GHz | Triple FR4 |
| An Ultrathin Dual-Band Metasurface Polarization Converter TAP (2019) [88] |  | Cross Polarizer Passive | 4.4–5.3 9.45–13.6 GHz | Triple FR4 |
| An Ultra-wideband reflective polarization converter based on anisotropic metasurface Chinese Physics B [73] |  | Cross Polarizer Passive | 7.5-20 GHz | Single F4B |
| An Ultra-broadband linear polarization converter based on anisotropic metasurface Optics Express (2018) [89] |  | Circular polarizer Passive | 6.7-17.1 GHz | Single - |
| A multi-functional polarization convertor based on chiral metamaterial for terahertz waves |  | Circular Polarizer Passive | 1.14 THz, 1.34 THz | Double - |

| | | | | |
|---|---|---|---|---|
| Optics Comm. (2019)<br>[90] | | | | |

## 2.5 Summary

In this summary, the state-of-the-art polarization conversion passive metasurfaces have been discussed earlier in this chapter along with their multiple functions. It is clear that the mentioned planar structures are configured to obtain one or two major operations i.e., linear -linear conversion(LP-LP) or linear to circular(LP-CP) polarization conversion. In the literature, but it is observed that most of the single layered metasurface structures operates on single band and the multiple layered structures operates on multiband which are fabricated on FR-4 low-cost substrate. However, no single layered metasurface has been reported in literature that operates on the multiband dual polarization wide bandwidth behavior using single layer of substrate. Some of the main challenges examined through the literature are discussed below that laid the foundation of this thesis.

- Most of the fabricated design work for multi layers.
- Performance is generally limited to narrow band for single layers.
- Most of the designs work for lower frequency band.

# CHAPTER 3

# Design Methodology

In this chapter, the design evolution is presented to achieve a reconfigurable polarization converter using multiple approaches through active metasurface.

## 3.1 Introduction

The main goal is to design the multiband polarization conversion frequency selective surface(FSS), that operates in microwave frequency regime which can also perform reflected linear polarization in three bands and circular polarization in one band. Considering, the linear polarization bands explains the performance of the design, the co-polarization reflection coefficient ($R_{xx}$) and the cross-polarization reflection coefficient ($R_{xy}$) shall be analyzed. The co-polarize component indicates the wave reflects along the x-axis and cross polarize component indicates the wave reflects along the perpendicular (orthogonal) y-axis, when the incident wave was also impinging along the x-axis.

For validation of circular polarization, the axial ratio (AR) should be less than 3dB and for further confirmation polarization extinction ratio(PER) should be greater than +20dB or lesser than -20Db. The cross component should be less than -10 dB keeping co- component of reflected wave as closer to 0 dB, for maximum polarization conversion ratio up to 90%.

## 3.2 Design Evolution

Before designing of a unit cell for proposed specifications, after a broad literature review on geometrical configuration has been done with different polarization capabilities. Afterwards, results of selective published works were reproduced to ensure working principal of circular polarizers and cross polarizers. The maximum implemented designs from literature were under millimeter wave regime. It is observed that the reported designs for reconfigurable polarizers, have narrow band width and those with higher bandwidth uses multilayer approach. Furthermore, they dose not perform the polarization conversion on multiband.

## 3.3 Diagonally Circular Split Ring

After brief literature review on the specifications and design requirements, the design process of unit cell is initiated. A multiband cross polarizer and circular polarizer is designed as described in Fig. 4.1. The size of unit cell design and the thickness of substrate used is a key parameter for designing wide band polarizer within any frequency range. To keep cross polarizer wide band thickness is chosen carefully as 1.6mm with periodicity of 8 mm. The substrate used is FR-4 with permittivity of 4.3 to work within microwave frequency regime.

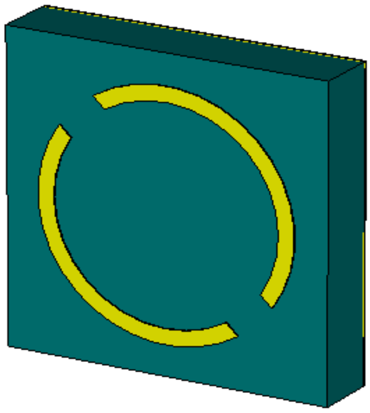


**Figure 3.1:** Diagonally Split Circular FSS

For polarization conversion, the structure must be anisotropic. hence if the structure is symmetric along X- or Y-axis then there would be no conversion possible. To further analyze the response of the structure a circular patch is introduced with etched center over the I-shaped structure. Due to increased inductance from a circular patch, frequency is shifted toward lower frequency.

$$f=12\pi\sqrt{LC}$$

### 3.3.1 S-Parameter Analysis

Following equation is used to understand frequency shifting phenomena under required frequency band. In this simulation from the band of 5GHz to 20 GHz. There is one frequency band of co and cross component is achieved at 11.5GHz with the narrow bandwidth of 11.35-11.67GHz. This shows that the diagonally circular split ring resonates at single band with narrow bandwidth. A circular split ring is a metallic structure with a split or gap in the ring, and it can exhibit resonant behavior at specific frequencies. The geometry of split-ring determines the resonance frequency, and it can be tailored to interact with incoming electromagnetic waves in a desired manner.

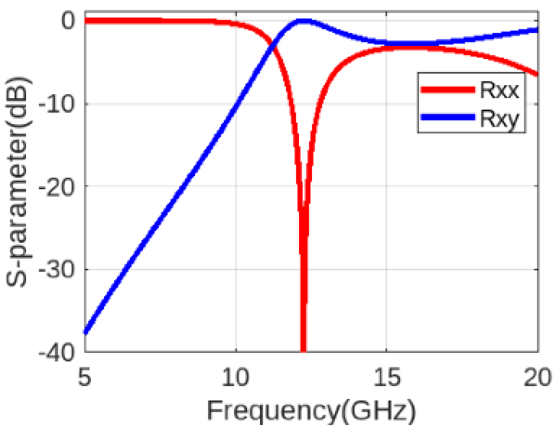



Figure 3.2: S-Parameter of Split Circular Ring.

## 3.4 Split ring with rectangular slot

For achieving a desired result, some changes in the design could made that a rectangular slot can be added diagonally between the split circular ring. The parameters of the slot are length=10mm and the width= 0.4mm. The slot creates more capacitance between the split circular ring.

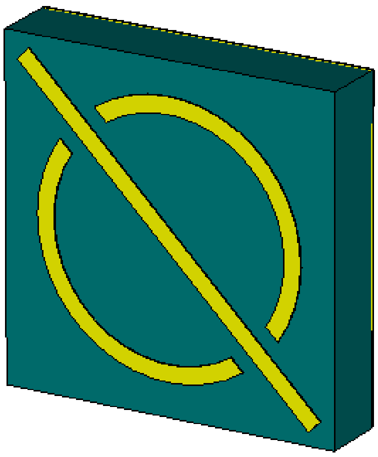


Figure 3.3 Split ring with rectangular slot

### 3.4.1 S-Parameter Analysis

This results that it resonates co and cross polarization on two frequency bands at 10GHz and 13.2GHz respectively. But it doesn't give the circular polarization band. The polarization components (co-polarization reflection coefficient (Rxx) and the cross-polarization reflection coefficient (Rxy)) shall be analyzed. The co-polarize component indicates the wave reflects along the x-axis and cross polarize component indicates the wave reflects along the perpendicular (orthogonal) y-axis when the incident wave was impinging along the x-axis. The orientation of the unit cell geometry provides the anisotropic behavior that results in the Linear Polarization (LP) conversion for incident waves along the x-axis.

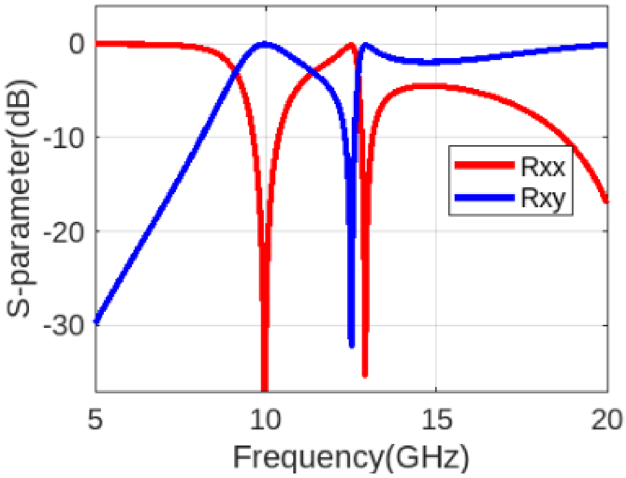



**Figure 3.4** S-Parameter of split circular ring with rectangular slot

## 3.5 Split circular ring with rectangular slot and small split circular patch

For achieving a desired result, some more changes could be made that a two halves of the split circular patches with the rectangular slots that behaves like a capacitor plates. This creates more capacitance with the rectangular slot. The radius of the inner circle is r1= 1.5mm with a spacing of s=0.2mm with the rectangular slot.

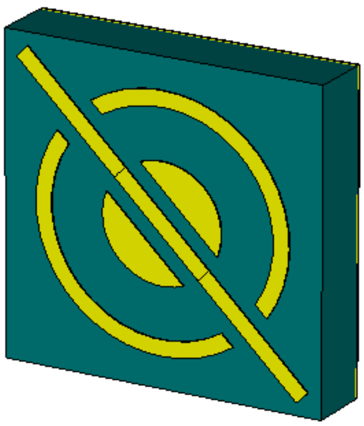


**Figure 3.5** S-Parameter of split circular ring with rectangular slot and small split circular patch

### 3.5.1 S-Parameter Analysis

After the simulation of the modified design, this gives the result that, it resonates co and cross polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band. The polarization components (co-polarization reflection coefficient (Rxx) and the cross-polarization reflection coefficient (Rxy)) shall be analyzed The co-polarize component indicates the wave reflects along x-axis and the cross polarize component indicates the wave reflects along the perpendicular (orthogonal) y-axis. When the incident-wave is impinging along x-axis. The orientation of the unit cell geometry provides the anisotropic behavior that results in the Linear Polarization (LP) conversion for incident waves along the x-axis. Thus the circular polarization occurs, when the electric field vector of wave that rotates it in a circular motion as the wave propagates through space. This rotation can be clockwise (right-handed) or counterclockwise (left-handed). Circular polarization is often described using the terms right-handed circular polarization (RHCP) and left-hand circular polarization (LHCP).

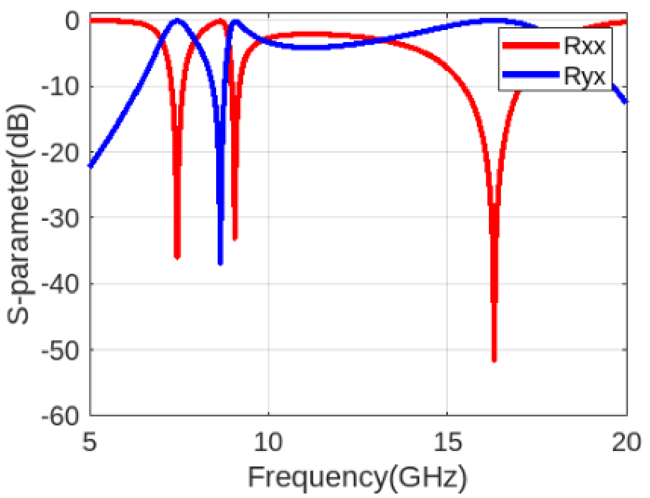



**Figure 3.6** S-Parameter of split circular ring with rectangular slot and split circular patches

# CHAPTER 4

# Polarization Agile Frequency Selective Surface(FSS) for C, X and Ku bands

## 4.1 Introduction

In this chapter, a multiband polarization frequency selective metasurface is discussed. A circular split ring resonator (SRR) with 45-degree rectangular slot that also cuts the inner circle into two halves. The top layer and bottom layer of the dielectric substrate have the same design this gives the result that, it resonates co and cross polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB. The CPS metasurface, operating in C-, X- and Ku-bands, is suitable for numerous applications in polarization controlled devices. For achieving a desired result, some more changes could be made that a two halves of the split circular patches with the rectangular slots that behaves like a capacitor plates. This creates more capacitance with the rectangular slot. The radius of the inner circle is r1= 1.5mm with a spacing of s=0.2mm with the rectangular slot.

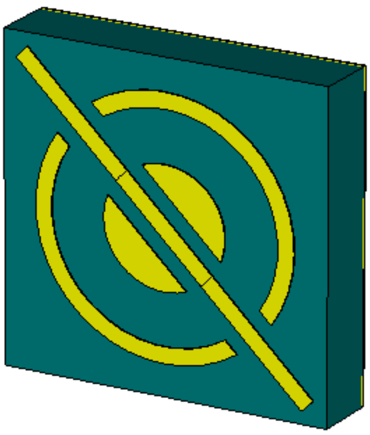


Figure 4.1 Proposed structure of Multifunctional Reconfigurable Metasurface

## 4.2 Geometrical Configuration

After brief literature review on the specifications and design requirements, the design process of unit cell is initiated. A multiband cross polarizer and circular polarizer is designed using 450 tilted slot structure backed with complete ground for maximum reflections as described in Fig. 4.1. The size of unit cell and the thickness of substrate is a key parameter for designing wide band polarizer within any frequency range. To keep cross polarizer wide band thickness is chosen carefully as 1.6mm with periodicity of 8 mm. FR-4 substrate is used with permittivity of 4.3 to work within microwave frequency regime.

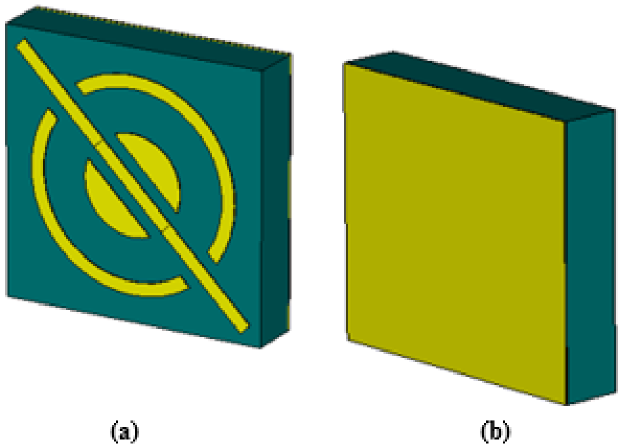



**Figure 4.2**: Unit cell design for Multifunctional Reconfigurable Metasurface
(a) Top layer (b) Bottom layer

**Table 2:** Optimized Parameters for multifunctional controllable Metasurface (mm)

| Outer Circle Radius | Inner Circle Radius | Diagonal Slot Length | Diagonal slot Width | Substrate Height | Substrate (LXW) | Ground Thickness |
|---|---|---|---|---|---|---|
| R | r1 | z | w | h | p | g |
| 3.2 | 1.5 | 10 | 0.4 | 1.6 | 8 | 0.035 |

## 4.3 Simulated Results

To simulate and to analyze the proposed metasurface, a full EM numerical solver software, CST Studio Suite is used with a periodic and open boundary conditions along x-axis and y-axis directions and the floquet ports along z-axis.

### 4.3.1: S-Parameter Analysis

After the simulation of the modified design, this gives the result that, it resonates co-pol-cross pol and cross pol to co-pol on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band. The polarization components (co-polarization reflection coefficient (Rxx) and the cross-polarization reflection coefficient (Rxy)) shall be analyzed. The co-polarize component indicates the wave reflects along the x-axis and the cross polarize component indicates the wave reflects along the perpendicular (orthogonal) y-axis when the incident wave was impinging along the x-axis. The orientation of the unit cell geometry provides the anisotropic behavior that results in the Linear Polarization (LP) conversion for incident waves along the x-axis.

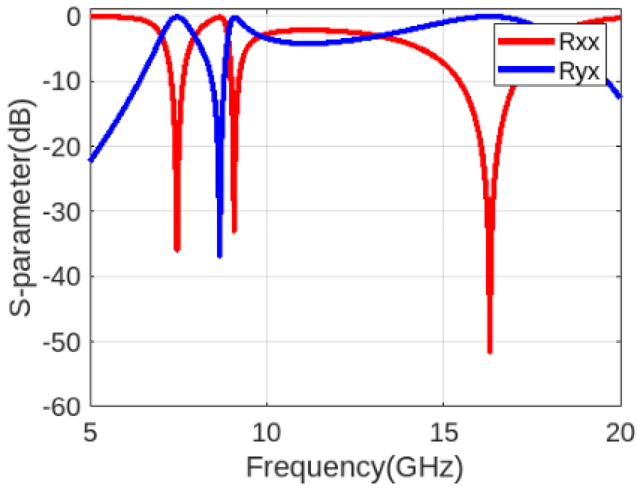



Figure 4.3 Simulated S-Parameter Analysis

### 4.3.2 Axial Ratio

Axial ratio (AR) is another criterion to demonstrate the circular polarization selectivity in a healthier way. The value of axial ratio (in dB) must be minimum to acquire pure circularly polarized wave. Although, the desired criterion of circular polarization is 3 dB axial ratio. To achieve circularly polarized wave in this present work, less than 2 dB axial ratio criterion is chosen across all the claimed frequency bands as displayed in Fig. 4.4 for both y-axis and x-axis polarizations. The equation used to calculate axial ratio is given below:

$$AR = [|Tyy|^2+|Txy|^2+\sqrt{a}\ |Tyy|^2+|Txy|^2-\sqrt{a}]\ ^{1/2} \quad (4.9)$$

Where

$$a = |T_{yy}|^4 + |T_{xy}|^4 + 2|T_{yy}|^2|T_{xy}|^2 * \cos(2\Delta\emptyset) \quad (4.10)$$

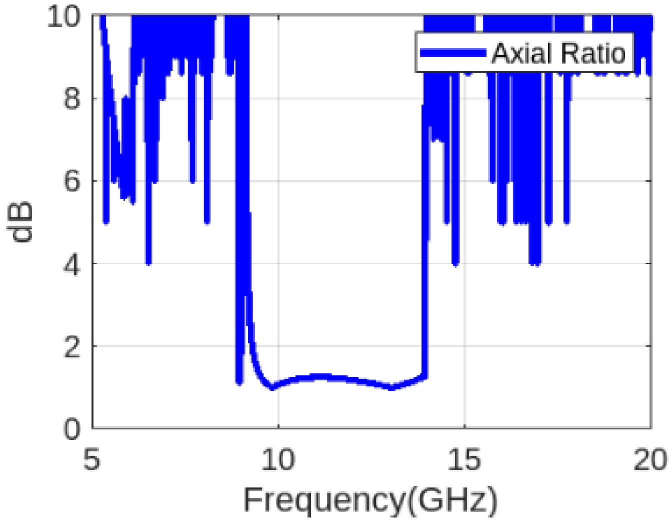



**Figure. 4.4**: Axial Ratio of the simulated unit cell

In this result of axial ratio, as far as simulated design of the unit cell is concerned, it resonates co-polarization to cross polarization and cross polarization to co-polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands with the Axial Ratio greater than 3dB as in Figure. 4.4. It shows that those resonating bands occur co and cross polarization. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band as the axial ratio throughout the band is less than 3dB as in Figure. 4.4.

### 4.3.3 Polarization Conversion Ratio(PCR)

Polarization conversion ratio(PCR) basically refers to the efficiency with which a designed structure that can convert the polarization state of the EM wave. In the context of EM, a wave is often described by its polarization, which refers to the orientation of the electric field vector. The polarization conversion ratio (PCR) is the efficiency with which a wave is converted from one form to another. In this proposed design, when an incident wave strikes a unit cell, the $R_{xx}$ component indicates the wave's reflection along the x-axis, and the $R_{xy}$ component indicates the wave's reflection along the y-axis. It transforms the incident wave into its orthogonal components.

$$PCR = \frac{{R^2}_{xy}}{{R^2}_{xy} + {R^2}_{xx}}$$

A PCR of 100% indicates perfect conversion, meaning all incident light has been converted to the desired polarization state. In practical applications, achieving 100% conversion is often challenging due to factors such as material properties, device design, and experimental conditions.

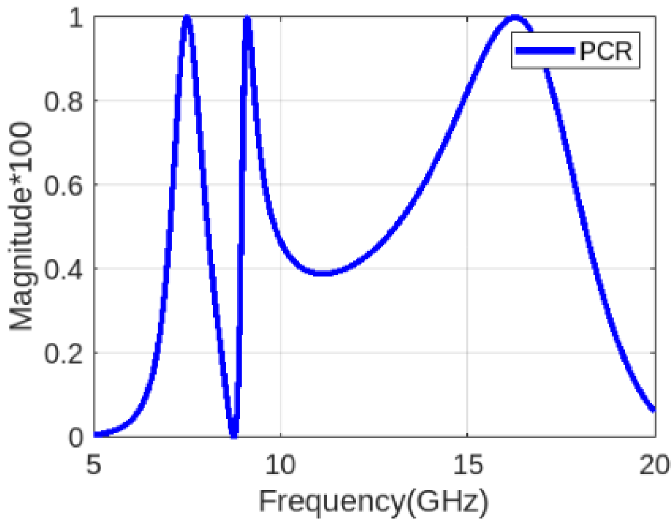



**Figure 4.5:** Polarization Conversion Ratio(PCR) of the proposed unit cell

In this Figure 4.5, the polarization conversion ratio(PCR) of the proposed unit cell structure, it resonates co-polarization to cross polarization and cross polarization to co-polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands with the Polarization Conversion ratio of more than 90%. That means the 90% of the total incident wave is polarized from co-polarization to cross polarization, and same for cross polarization to co-polarization. Along with the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band, thus the polarization conversion ratio in thus wideband is more than 50% that means the more than 50% of the incident wave is circularly polarized.

### 4.3.4 Polarization Extinction Ratio(PER)

The polarization extinction ratio(PER) refers to the ratio of the power of the desired polarization to the power of the undesired polarization in a signal. It is a measure of how good a system maintains the polarization state of the transmitted signal.

As the polarization refers to the orientation of the electric field vector in an electromagnetic wave. In RF systems, signals may be polarized in a particular direction, and it's desirable to maintain this polarization throughout the transmission to ensure optimal signal strength and quality.

The polarization extinction ratio is expressed in decibels (dB) and is calculated using the following formula:

$$\text{PER (dB)} = 10 \cdot \log10(P \text{ undesired} / P \text{ desired})$$

Where:

- $P$ desired is the power of the desired polarization.
- $P$ undesired is the power of the undesired polarization.

The higher value of PER indicates the better polarization preservation, means that the system is effectively maintaining the desired polarization and minimizing the impact of undesired polarization. To maintain the higher PER is important in applications where the polarization is critical, such as in satellite communications, radar systems, and wireless communication systems. In those applications, minimizing cross-polarization interference and maintaining the integrity of the transmitted signal's polarization can improve overall system performance. In the Figure 4.6, the polarization extinction ratio of the wave from the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band is greater than +20dB. That shows that, the circular polarized wave is Right Handed Circularly Polarized(RHCP) clockwise, based on the direction of rotation when viewed in the direction of propagation.

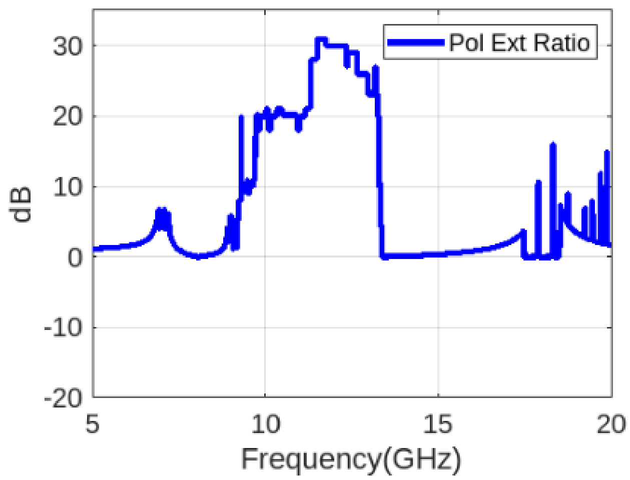



**Figure 4.6**: Polarization Extinction Ratio(PER)

In this case of right-handed circularly polarized (RHCP) wave, if you looking directly into the direction of wave propagation, the electric field vector would appear to rotate in a clockwise direction. This rotation can be observed in various applications, including satellite communication, where RHCP is commonly used to minimize interference and maximize signal quality.

## 4.4 Experimental Results and Discussion

In validation of the simulated results, the proposed design of FSS was fabricated on low cost and easily available FR-4 substrate. The fabricated sample (having cross-section of 232 × 288 x 1.6 mm3) consists of 29 × 36 unit cells as displayed in Fig. 4.7.

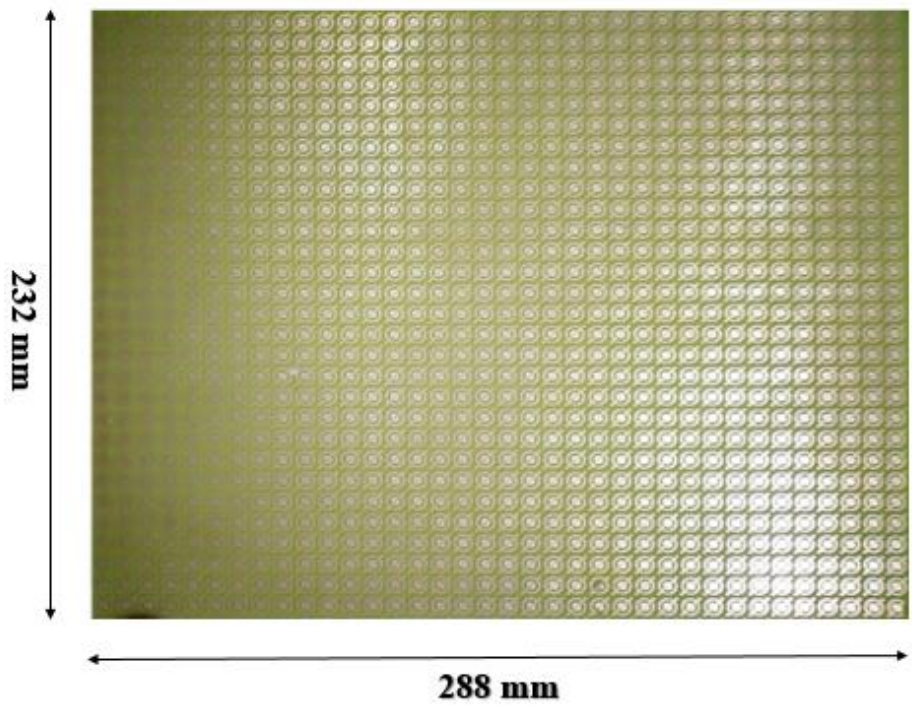



**Figure 4.7**: Photograph of the fabricated circular polarization selective metasurface

All the measurements were taken out in an anechoic chamber lab after de-embedding process while the FR-4 fabricated design was placed in front of both horn antennas as presented in Fig. 4.7.

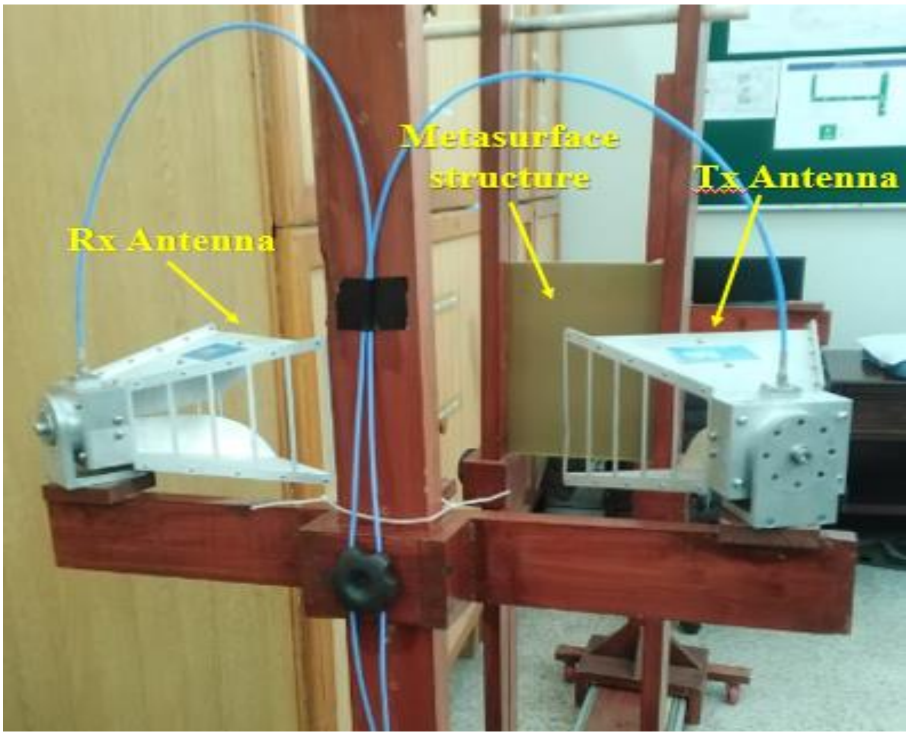



**Figure 4.8**: Experimental measurement setup for the FSS metasurface

These antennas were attached to the Anritsu-MS46122B (vector network analyzer) via coaxial cables. In order to achieve co-polarized transmission (Tyy or Txx), both transmitting and receiving antennas were placed co-polarized, either vertical (for Tyy) or horizontal (for Txx). To measure cross-polarized transmission, the two antennas were placed orthogonal to each other, i.e., the transmitting antenna was vertically while the receiving antenna was placed horizontally.

For the measurements of the transmission components, the free space method was used through the following expression [63]. The de-embedding process is also carried out in measurements of the design:

$$S21(samplecalibration)=S21(sample)-S21(metal)/S21(air)-S21(metal)*e-j(w/c)d$$

Where w, c and d represent the angular frequency, speed of light and thickness of the sample, respectively.

## 4.5 Experimental Results:

### 4.5.1 S-Parameter

After the experimental testings of the fabricated design, this gives the result that, it resonates co-polarization to cross polarization and cross polarization to co-polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band. The co- polarization reflection coefficient (Rxx) and the cross-polarization reflection coefficient (Rxy) shall be analyzed. The co-polarize component indicates the wave reflects along the x-axis and the cross polarize component indicates the wave reflects along the perpendicular (orthogonal) y-axis when the incident wave was impinging along the x-axis. The orientation of the unit cell geometry provides the anisotropic behavior that results in the Linear Polarization (LP) conversion for incident waves along the x-axis. Thus the circular polarization occurs when the electric field vector of a wave rotates in a circular motion as the wave propagates through space. This rotation can be clockwise (right-handed) or counterclockwise (left-handed). Circular polarization is often described using the terms "right-hand circular polarization" (RHCP) and "left-hand circular polarization" (LHCP).

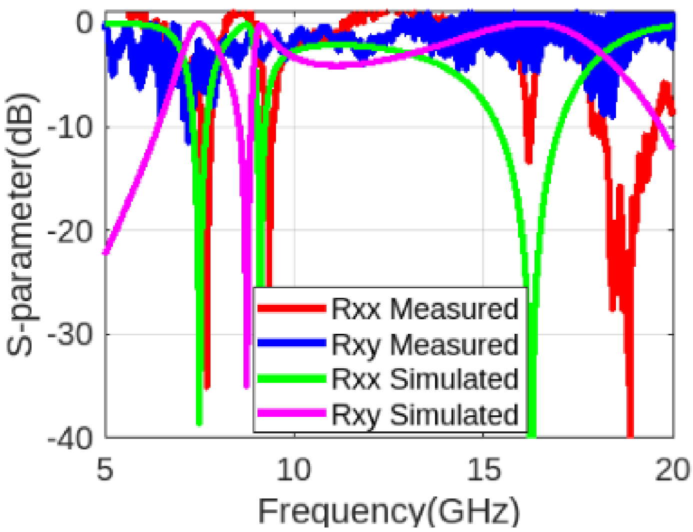



**Figure 4.9:** Simulated and measured results for (a) TE wave (b) TM wave

Small discrepancies between simulated and measured results may be attributed to slight misplacement of antennas, finite size of fabricated sample and permittivity tolerances. These discrepancies can be minimized by using dielectric lens as it has the ability to focus the incident wave onto the circular polarization selective metasurface.

From Fig. 4.9, it can be seen that the simulated and measured components (i.e., $R_{yy}$, $R_{xy}$, $R_{xx}$,

$R_{xy}$) can also help to calculate simulated and measured co-cross polarization and circular polarization conversion is achieved.

### 4.5.2 Axial Ratio:

Axial ratio (AR) is another criterion to demonstrate the circular polarization selectivity in a healthier way. The value of axial ratio (in dB) must be minimum to acquire pure circularly polarized wave. Although, the desired criterion of circular polarization is 3 dB axial ratio. To achieve circularly polarized wave in this present work, less than 2 dB axial ratio criterion is chosen across all the claimed frequency bands.

In this simulated and measured result of axial ratio, as far as simulated design of the unit cell is concerned, it resonates co-polarization to cross polarization and cross polarization to co-polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands with the Axial Ratio greater than 3dB as in Figure. 4.11. It shows that those resonating bands occur co and cross polarization. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band as the axial ratio throughout the band is less than 3dB as in Figure. 4.10

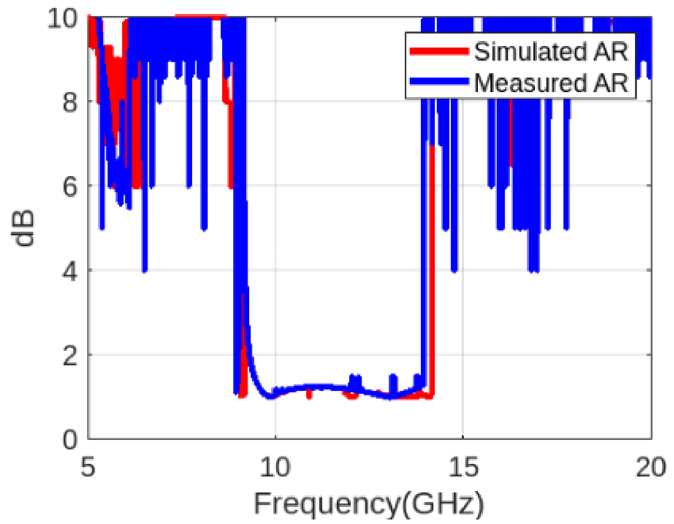



Figure 4.10 Simulated and Measured Axial Ratio(AR)

### 4.5.4 Polarization Extinction Ratio(PER):

As the polarization refers to the orientation of the electric field vector in an electromagnetic wave. In RF systems, signals may be polarized in a particular direction, and it's desirable to maintain this polarization throughout the transmission to ensure optimal signal strength and quality. The higher value of PER indicates the better polarization preservation, means that the system is effectively maintaining the desired polarization and minimizing the impact of undesired polarization. To maintain the higher PER is important in applications where the polarization is critical, such as in satellite communications, radar systems, and wireless communication systems. In those applications, minimizing cross-polarization interference and maintaining the integrity of the transmitted signal's polarization can improve overall system performance.

In this simulated and measured result of Polarization Extinction Ratio(PER) as shown in Figure 4.11, the polarization extinction ratio of the wave from the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band is greater than +20dB. That shows that, the circular polarized wave is Right-Handed Circularly Polarized (RHCP) clockwise, based on the direction of rotation when viewed in the direction of propagation.

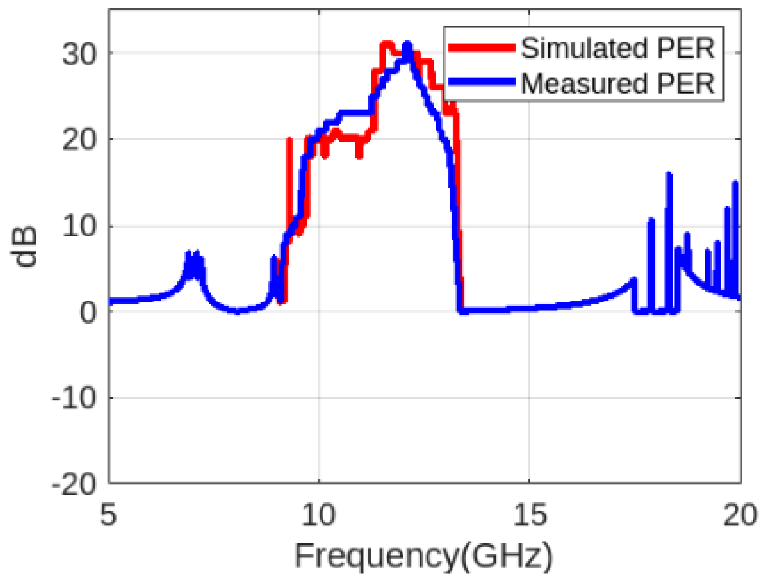



**Figure 4.11:** Simulated and measured Polarization Extinction Ratio(PER)

As the small discrepancies between simulated and measured results may be attributed to slight misplacement of antennas, finite size of fabricated sample and permittivity tolerances. These discrepancies can be minimized by using dielectric lens as it has the ability to focus the incident wave onto the circular polarization selective metasurface.

**Table 3:** Comparison of the State-of-the-art CPS metasurfaces

| Ref. | Journal (Year) | Maximum PER [dB] | No. of Bands | No. of Layers | Thickness [mm] |
|---|---|---|---|---|---|
| [52] | Optics Comm. (2019) | -30.1 | 2 | 2 | 0.008 |
| [54] | Prog. Electrom. Res. (2014) | 30.1 | 4 | 3 | 1.1 |
| [53] | Int. J. RF Microw.Comp. Eng. (2019) | 21.45 | 3 | 3 | 1.2 |
| [55] | Appl. Phys. A (2014) | < 10 | 1 | 2 | 1.5 |
| [56] | Prog. Electrom. Res. (2014) | -21.1 | 2 | 2 | 1.5 |
| [58] | Int. J. RF Microw.Comp. Eng. (2019) | 20.74 | 2 | 2 | 1.5 |
| [59] | IEEE Access (2019) | 31.2 | 1 | 2 | 1.524 |
| **This work** | — | **37.3** | **4** | **1** | **1.6** |

# CHAPTER 5

# Conclusion and Future Recommendations

## 5.1 Conclusion

This thesis presents a linear-to-linear(co-cross) and linear to circular(LP-CP) polarization conversion frequency selective metasurface(FSS) using low-cost and easily available FR-4 single layered metasurface. The aim is also to fabricate, test and analyze the performance of this polarization conversion metasurface. After the simulation of the modified design, this gives the result that, it resonates co-polarization to cross polarization and cross polarization to co-polarization on three frequency bands at 7.3GHz-7.7GHz at 7.5GHz with -38.5 dB and 9GHz-9.3GHz at 9.11GHz with -30 dB and 15.3GHz-17GHz at 16.2GHz with -62 dB respectively in C, X and Ku bands. Along but the major achievement that it gives also the wideband circular polarization band from 9.8GHz-13GHz with a bandwidth of 3.2GHz at -3 dB in Ku-band. The co- polarization reflection coefficient (Rxx) and the cross-polarization reflection coefficient (Rxy) shall be analyzed. The co-polarize component indicates the wave reflects along the x-axis and the cross polarize component indicates the wave reflects along the perpendicular (orthogonal) y-axis when the incident wave was impinging along the x-axis. The orientation of the unit cell geometry provides the anisotropic behavior that results in the Linear Polarization (LP) conversion for incident waves along the x-axis. Thus the circular polarization occurs when the electric field vector of a wave rotates in a circular motion as the wave propagates through space. This rotation can be clockwise (right-handed) or counterclockwise (left-handed). Circular polarization is often described using the terms "right-hand circular polarization" (RHCP) and "left-hand circular polarization" (LHCP).

## 5.2 Future Recommendations

This thesis fulfills the requirement of efficient, multiband design using single layered FSS. However, optimization of this design can further lead to be improvement in the efficiency. Some of the critical aspects for future recommendations are given as: This Polarization conversion FSS works reflection mode, however, using the concept of polarization conversion, metasurface operating in both reflection and transmission modes can be implemented in future. As there is no essential condition to rotate the bottom layer of the FSS at an angle of 90o with respect to the top layer. Bottom layer at any other angle, FSS operating bands can be achieved in both reflection and transmission modes at different frequencies. This design can be implemented on

Rogers substrate in future for more improvement due to good Epsilon and also flexible substrates like denim after examining critical parameters. Improvement in circular polarization(CP) requires parametric analysis of geometrical configuration, periodicity and thickness of the substrate.

# APPENDIX A

## Abbreviations & Acronyms

**Table 4:** Abbreviations and their Acronyms

| | |
|---|---|
| FSS | Frequency Selective Surface |
| LTC | Linear to circular |
| PER | Polarization extinction ratio |
| CPS | Circular polarization selective |
| LCP | Left-hand circular polarization |
| RCP | Right-hand circular polarization |
| AR | Axial Ratio |

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