FINAL YEAR PROJECT REPORT

Meta-surface Design and Development for Polarization Conversion

By

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Pak/20095036, 95(B) EC

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COLLEGE OF AERONAUTICAL ENGINEERING

PAF Academy, Asghar Khan, Risalpur

February 10, 2024

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Report submitted in partial fulfillment of the requirements for the degree of Bachelors of Engineering in Avionics, (BE Avionics)

In

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Approval

It is certified that the contents and form of the project entitled “Meta-surface Design and Development for Polarization Conversion” submitted by Aviation Cadet Hassaan Shahzad have been found satisfactory for the requirement of the degree.

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Dedication

I want to take this opportunity to express my sincere gratitude to all those who have played a significant role in making this project possible. I would like to extend a special thanks to my loving family and my dedicated advisor, whose unwavering support and guidance have been instrumental in my academic success. Without their encouragement and support, I would not have been able to reach this point. To my parents, in particular, I owe a debt of gratitude for their selfless sacrifices, endless encouragement, and unwavering belief in me. This report is a tribute to them and all those who have contributed to my journey, and I am honored to share this achievement with them.

Acknowledgement

I am profoundly grateful to Allah Almighty for granting me the opportunity to successfully complete this project with utmost dedication and effort. My sincere gratitude extends to my esteemed parents, whose unwavering encouragement, unwavering moral support, and above all, their heartfelt prayers have been the driving force behind my achievements.

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Abstract

An ultra-thin single-layer meta surface manifesting both cross-polarization conversion (CPC) and linear-to-circular polarization (LP-to-CP) conversion in C, X and Ku-band is presented in this research. The designed meta surface not only converts horizontal polarization into vertical and vice versa, but also exhibits linear-to-circular and circular-to-linear polarization conversion. The designed meta surface acts as a multi functional meta surface achieving CPC over a fractional bandwidth of 69.52GHz, 8.37–11.60 GHz and 13.29–16.72 GHz with more than 95is also realized over three frequency bands from 7.42–8.15GHz, 12.25-12.63 and 17.22–18.08 GHz.

Furthermore, the stability of the polarization-transforming capability remains consistent across a broad frequency spectrum, specifically within the range of 5–18 GHz. This stability is maintained even when subjected to wide oblique incidence angles, extending up to 60°. Furthermore, the proposed structure acts as a meta-mirror which preserves handedness of the circular polarization upon refection.The proposed meta surface with simple structure, angular stability and multi functional capability qualifies for many applications in communication and polarization manipulating devices.

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Chapter 1

1 Introduction to the Project

1.1 Project Title

The title of the project is ”Meta-surface Design and Development for Polarization Conversion”.

1.2 Project Description

This project aims to design and fabricate a meta-surface capable of efficient polarization conversion, enabling the transformation between linear and circular polarization. The objective of this project is to explore designing of a unit cell and fabrication techniques by replicating them to achieve high polarization conversion efficiency and angular stability at wide bandwidth.

1.3 Motivation

The motivation behind the project stems from the contemporary need to manipulate electromagnetic (EM) waves effectively. The use of engineered structures known as metasurfaces allows for precise control over the electric and magnetic responses of EM waves. The project specifically addresses the domain of polarization manipulation, where altering the polarization of incident waves is crucial. Existing literature reveals various methods such as isotropic structures and chiral metasurfaces for polarization conversion. However, the project aims to go beyond current limitations by introducing a compact, single-layer asymmetric anisotropic metasurface design.

The motivation is to create a metasurface that not only achieves efficient wideband Circularly Polarized Conversion (CPC) but also enables Linear-to-Circular Polarization (LP-to-CP) conversion in the C, X, and Ku bands. The project’s motivation lies in engineering a metasurface that is not only multifunctional but also performs efficiently even at wide oblique incidence angles, extending up to 60°. This research seeks to contribute to advancements in metasurface technology and its practical applications in communication and radar systems, particularly in the aerospace domain.

1.4 Scope of the Project

The scope of this project is to design and develop a meta-surface that will be able to convert EM waves between linear-to-linear or linear-to-circular polarization or vise-versa. It includes designing and optimizing a unit cell structure for the meta-surface that achieves efficient polarization conversion between linear and circular polarization. The meta-surface design can be operating in either reflection or transmission mode. The project's scope lies in revolutionizing multi-band polarization conversion through a novel metasurface design. The designed metasurface aims for efficiency and stability over a broad frequency spectrum (5–18 GHz) and under wide oblique incidence angles (up to 60°). The research explores the potential of the proposed metasurface for practical applications in communication, radar, aerospace, and beyond.

The scope of the project involves several components:

1- Meta Surface Literature Review: A thorough examination of existing literature on meta surfaces will be undertaken to establish a robust knowledge base. This review will lay the groundwork for understanding meta surface design fundamentals.

2- Evaluation of Reconfigurable Meta Surface Techniques: An in-depth analysis of various techniques employed in the design of reconfigurable meta surfaces will be conducted. This exploration aims to identify and select suitable approaches that align with the project's objectives.

3- Design, Fabrication, Optimization, and EM Simulation of Meta Surface Elements: The project entails the individual design, fabrication, optimization, and electromagnetic (EM) simulation of meta surface elements.

4- Fabrication, VNA, and Anechoic Chamber Testing for Multi-Band Operation: Real-time results will be obtained through the fabrication of the designed meta surface. The project involves conducting Vector Network Analyzer (VNA) measurements and performing tests in an anechoic chamber to validate the multi-band operation and reconfigurable functionality of the meta surface.

Chapter 2

2 Literature Review

2.1 Literature Overview

Conventional techniques for polarization conversion using birefringent anisotropic crystals, Faraday Effect and optical activity of helical molecules suffer from bulky size, narrow bandwidth and incidence angle dependent response. To overcome these limitations, scientists proposed artificial structures called metasurfaces to achieve polarization conversion, featuring subwavelength thickness, large bandwidth and angularly stable response in a compact size with easier fabrication and lesser cost. Polarization conversion can be categorized into two types: firstly cross-polarization conversion and secondly linear to circular or circular to linear polarization conversion. Any form of polarization conversion can either be in reflection mode or transmission mode. In the former, one form of the polarization is transformed into another upon reflection from the metasurface. For example, in cross polarization conversion, an x-polarized wave can be converted into a y-polarized wave upon reflection from the metasurface and vice versa. On the other hand, in transmission mode one type of polarization can be converted into another type, while passing through the metasurface.

Polarization conversion which includes cross-polarization and linear to circular conversion in various bands either in reflection mode or transmission mode is proposed by designing a compact unit cell with angularly stable and high bandwidth response.

2.2 Meta-materials for polarization conversion

Conventional polarization conversion techniques using anisotropic crystals and helical molecules have limitations like bulkiness, narrow bandwidth, and dependence on incidence angles. To address these issues, researchers introduced meta-surfaces. These artificial structures offer compact size, sub-wavelength thickness, wide bandwidth, and angular stability. Meta-surfaces provide an efficient and cost-effective way for achieving polarization conversion with easier fabrication methods. Polarization conversion can be divided into two categories :

- cross-polarization conversion
- linear-to circular or circular-to-linear polarization conversion.

According to a survey of the literature, anisotropic [1] and chiral metasurfaces, which can be endowed with inherent or extrinsic chirality, can be used to rotate the polarization plane. In order to control the polarization of the impinging wave in either transmission [2-3] or refection mode [4–5], researchers have developed metasurface designs.

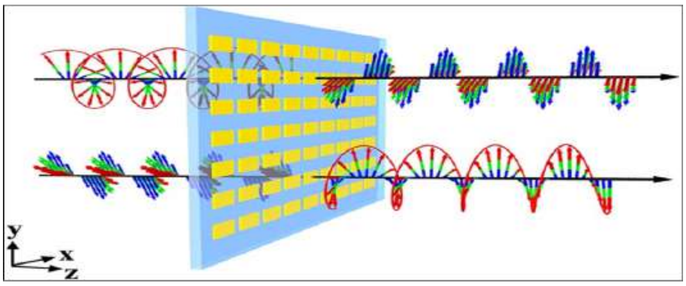

Figure 1: Polarization conversion

2.2.1 Anisotropic Material's

A meta-surface built on an anisotropic unit cell can be used to convert cross-polarization in the reflection mode. Cross-polarization conversion happens because of how the anisotropy in the meta-surface reacts differently to the orthogonal components of the incident linearly polarized wave.As a result, one component is reflected in phase while the other component is reflected out of phase.

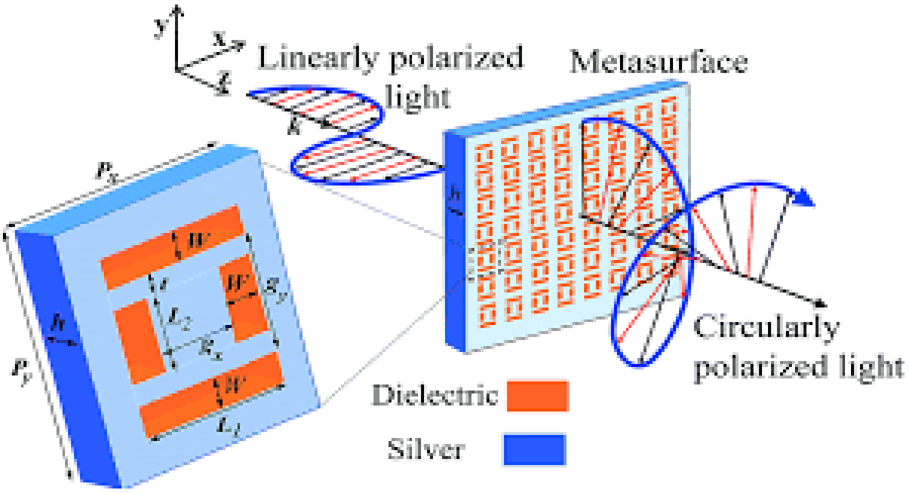

Figure 2: Anisotric Materials

2.2.2 Chiral Material's

Chiral materials in metamaterials play a crucial role in converting linear polarization to circular polarization. These materials' asymmetrical structures cause a phase shift between light's left- and right-handed circular components, which changes the polarization of the light. These materials use this ability to manipulate polarization in various fields, including polarization optics, telecommunications, and sensing.

Chiral metamaterials typically consist of subwavelength helical structures, which can be fabricated using various techniques such as lithography or self-assembly.

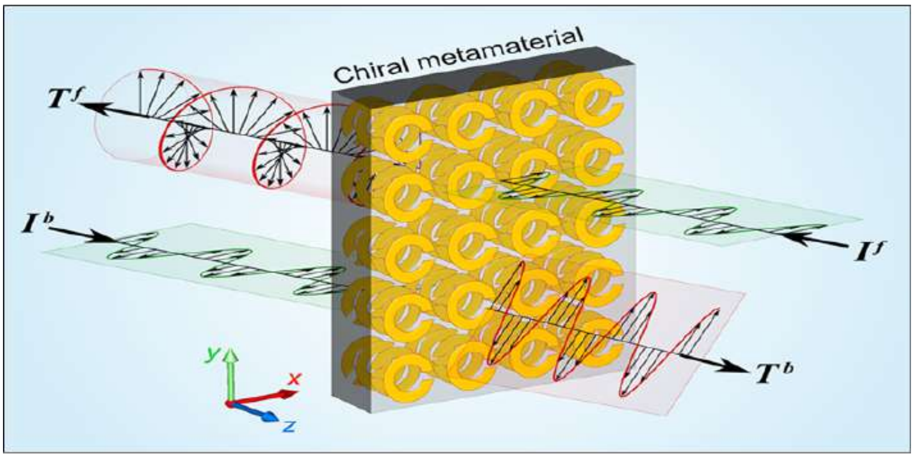

Figure 3: Chiral Materials

2.3 Cross-Polarization Conversion

Cross polarization in metasurfaces refers to the phenomenon where these specially designed surfaces can convert incoming light from one polarization state to its orthogonal (perpendicular) polarization state. By carefully engineering these structures, metasurfaces can selectively manipulate the transmission, reflection, or absorption of light based on its polarization.

- Co-Polarization (Copol): Copol or co-polarization refers to the situation where the transmitting and receiving antennas have the same polarization orientation. In co-polarization, the electric field of the received signal is aligned with the orientation of the receiving antenna.This alignment enhances the overall performance of communication systems by maximizing the reception of signals with matching polarization.

- Cross-Polarization (Xpol): Cross-polarization, or cross-polar, occurs when the transmitting and receiving antennas have orthogonal polarization orientations. In cross-polarization, the electric field of the received signal is perpendicular to the orientation of the receiving antenna.

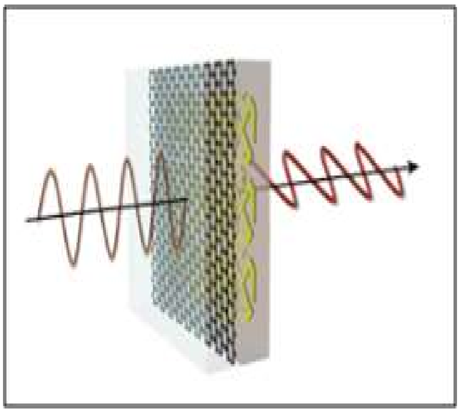

Figure 4: Cross Polarization conversion

2.4 Linear-to-Circular Polarization Conversion

Similar to the cross-polarization conversion in section 2.3, anisotropic and chiral unit cell designs can be used to convert linear to circular polarization.

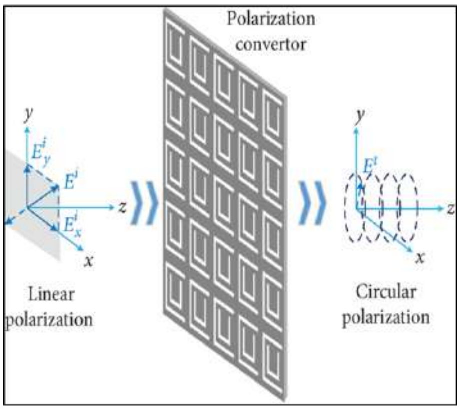

Figure 5: Linear-to-Circular Polarization conversion

- Anisotropic materials, which exhibit different physical properties along different axes, can demonstrate the conversion of linear polarization to circular polarization. This phenomenon occurs due to the inherent birefringence present in anisotropic materials, which causes a phase difference between the two orthogonal polarization components.When linearly polarized light interacts with an anisotropic material, it experiences different refractive indices along different directions.

•linear to circular polarization can also be accomplished by adjusting the optical activity of the chiral meta-surfaces. The lack of mirror symmetry causes chiral meta-materials to have strong chirality around resonance and produce significant cross-coupling between electric and magnetic fields at resonance EM waves.

2.5 Existing Techniques in developing meta-surfaces

There are several existing techniques for developing meta-surfaces, which are artificial structures engineered to manipulate electromagnetic waves with unique properties. Some of the commonly used techniques include

2.5.1 Ultra-wideband cross-polarization conversion metasurface

A generalized overview of the designed cross polarization conversion metasurface is illustrated. It consists of a 2-D periodic array of metallic coupled split ring resonators (SRR’s) placed on the top of the dielectric, which is backed by a metallic plane. The unit cell consists of two coupled SRR’s with two splits in each of the SRR placed within the perpendicular sides. The dielectric used is FR4 with a relative permittivity of 4.4 and a loss tangent of 0.02, while the material used for both SRR’s and the ground-plane is copper. A broad 3 dB bandwidth of 5.8 GHz (5–10.8 GHz) is achieved with a fractional bandwidth of 73 percent. Resonances occur at 5.3, 7.8, and 10.3 GHz. The proposed meta-surface converts an x-polarized wave into a y-polarized wave and vice versa over a broad frequency ranges of 5.3–10.8 GHz. [6]

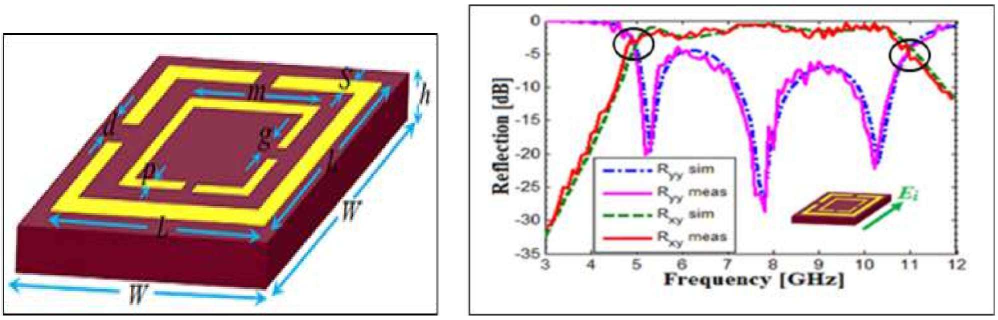

Figure 6: Unit cell and reflection coefficient of ultra-wideband meta-surface

2.5.2 Angularly stable dual-broadband anisotropic metasurface

In this article, an electrically thin and dual-broadband reflective cross polarization-conversion anisotropic meta-surface which works not only for normal incidence but also for oblique incidence is proposed. The unit cell of the proposed meta-surface consists of a two-slit rectangular split ring resonator inside of which a metallic cross element is placed. Excellent CPC is achieved in two wide frequency bands from 5 to 9.7 GHz (4.7 GHz bandwidth) and from 11.2 to 15 GHz (3.8 GHz bandwidth) for both normal and oblique incidences. The wide CPC bandwidth is due to the plasmonic resonances occurring at three distinct frequencies. The dielectric used is FR4 with the relative permittivity of 4.4 and the loss tangent of 0.02.[7]

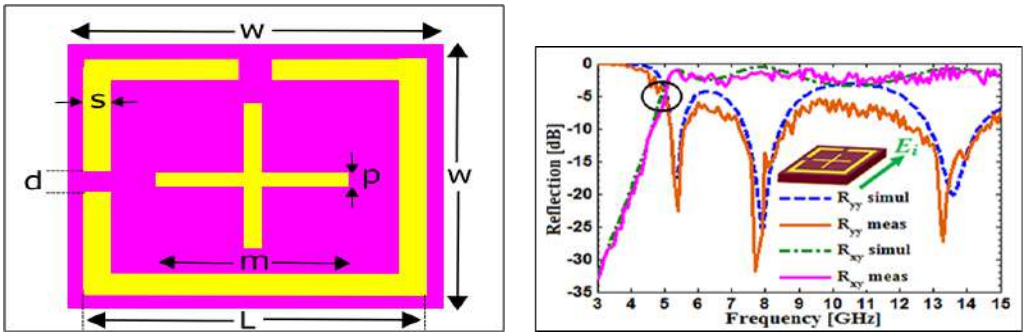

Figure 7: Unit cell and reflection coefficient of f dual-broadband meta-surface

2.5.3 Quarter-Wave plate and half Mirror Operation using flexible meta-surface

A quarter-wave plate is an optical component that changes an EM wave from linear to circular polarization.It comprises of a periodic two-dimensional metallic structure array printed on top of a flexible substrate with a 0.06 mm thickness. Half of the linearly polarized electromagnetic waves that are impinging on the proposed meta-surface are reflected as circularly polarized waves, and the other half is transmitted as circularly polarized waves at the resonance frequency. Similarly, a circularly polarized incident wave is reflected and transmitted as linearly polarized wave with equal half power in the operating band (24- 25.6 GHz).[8]

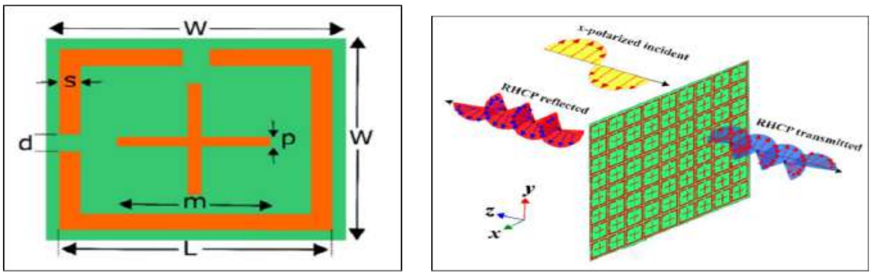

Figure 8: Unit cell and Schematic diagram of the proposed meta-surface

2.5.4 LP to CP conversion in X-band using anisotropic meta-surface

An ultrathin single-layer meta-surface manifesting both linear cross-polarization conversion (CPC) and linear-to-circular polarization (LP-to-CP) conversion in X-band is presented in this research. The designed meta-surface acts as a multi functional meta-surface achieving cross polarization conversion over a fractional bandwidth of 31.6 percent (8–11GHz) with more than 95percent efficiency while linear-to-circular polarization conversion is realized over two frequency bands from 7.5–7.7GHz and 11.5–11.9GHz.[9] In this study, a unique unit cell with a fish-like structure is described, which can be used to create a compact, single layer mirror-symmetric anisotropic meta-surface.A steady response for oblique incidence angles up to 45° is achieved by the unit cell's overall optimized construction for both transverse-electric and transverse-magnetic polarization.The dielectric used in the unit cell is FR4 with relative permittivity 4.4 and loss tangent 0.02 while the material used for metallic part is copper with conductivity 5.8×107 S/m.

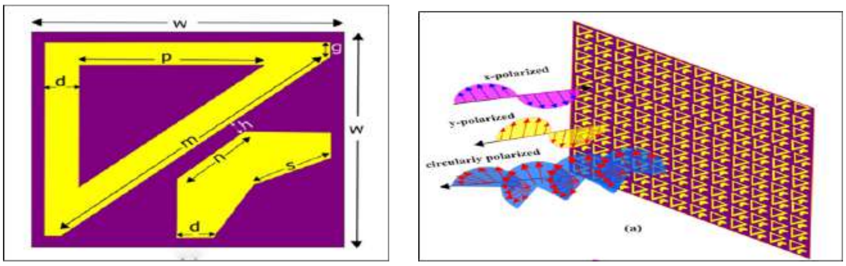

Figure 9: Unit cell and Schematic diagram of the proposed meta-surface

Chapter 3

3 Preliminaries

3.1 Meta-material

Meta-materials are specially designed materials that have unique properties not found in nature.[4-5]Khan They are created by arranging and manipulating elements on a small scale, much smaller than the wavelength of the waves they interact with, such as light or sound.These elements, known as meta-atoms or meta-molecules, are carefully structured to have specific electromagnetic or acoustic properties. The concept of meta-materials emerged in the early 2000s and has since revolutionized various fields, including optics, electro-magnetics, acoustics, and microwave engineering. The properties of meta-materials are derived from the collective behavior of their sub wavelength structures, known as meta-atoms.

These meta-atoms can be tailored to exhibit specific electromagnetic responses by carefully designing their geometry, size, and arrangement. By controlling these parameters, researchers have achieved unprecedented control over wave propagation, polarization, phase, and dispersion, opening up new possibilities for manipulating light and other electromagnetic waves.[10-12]

The negative refractive index of the metamaterials causes unusual electromagnetic properties which include negative refraction [13-16], negative Doppler effect [17], reversal of Cherenkov radiation [18], perfect lensing [19-21], electromagnetic cloaking [22-27] etc. Besides these outlandish properties, metamaterials have also been applied in applications where conventional materials were previously used such as electromagnetic absorbers [28-31], polarization converters [32-34], antennas [35-37], magnetic resonance imaging [38-39] and sensors [40-43]. Moreover, metamaterials have been predicted to enable potential applications in nonlinear domain including magnetic nonlinear response, backward phase matching, second harmonic generation, solitons and nonlinear mirror [44-48].

3.2 Metasurfaces

Meta-surfaces, a class of ultra-thin artificially structured materials, have garnered significant attention in recent years due to their ability to manipulate electromagnetic waves with unparalleled precision and efficiency. Among the various functionalities they offer, linear-to-circular polarization conversion has emerged as a crucial area of research with applications in telecommunications, imaging systems, and polarization-sensitive devices. Meta-surfaces are planar meta-materials with sub wavelength thickness. A meta-surface is a special type of surface engineered to manipulate light or other electromagnetic waves in unique ways. Unlike traditional materials, which interact with light based on their chemical composition, meta-surfaces are designed with tiny structures or elements that are smaller than the wavelength of light. These structures, known as meta atoms or meta-elements, are arranged in a precise pattern on the surface.

3.3 Polarization of Electromagnetic Waves

polarization refers to the trace covered by the tip of the electric field at a fixed location in space. Polarization is a very important characteristic of electromagnetic waves and it plays an important role in numerous applications including optical imaging, contrast imaging, molecular biotechnology, optical sensing and telecommunication [2]Khan. For example in telecommunication, radio and microwave antennas used for transmitting or receiving are intrinsically polarized. They transmit in (or receive signals from) a particular polarization, being totally insensitive to the opposite polarization. For instance, if one attempts to use a horizontally polarized antenna to receive a vertically polarized transmission, the signal strength will be substantially reduced. The signal must be brought to the desired polarized for maximum reception through the antenna. Similarly, polarization is used in satellite television in order to double the channel capacity over a fixed frequency band. The same frequency channel can be used for two signals broadcast in orthogonal polarization. By adjusting the receiving antenna for one or the other polarization, either signal can be selected without interference from the other. There are three types of polarization.

1. Linear Polarization: In linearly polarized light, the electric field vector oscillates in a fixed direction along a straight line. This orientation can be horizontal, vertical, or at any angle in between. When the electric field vector remains constant over time, it is called linear polarization with a specific angle. When the electric field vector changes direction periodically, it is referred to as linearly polarized light with a changing angle, known as linearly polarized light in an arbitrary direction.

Linear polarization is accomplished if the field vector (electric or magnetic) has either:

a. Only one component

b. Two orthogonal linear components which are either in phase (0° phase difference) or out of phase (180°phase difference)

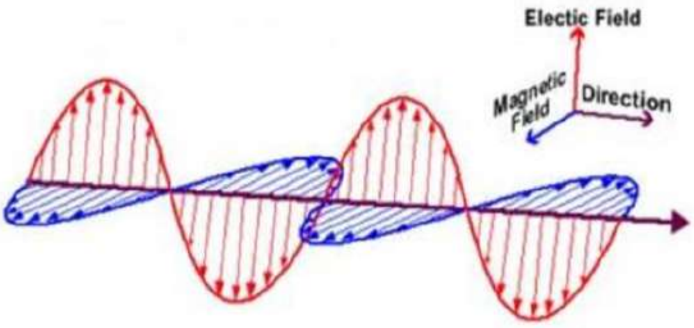

Figure 10: Linear Polarization

2. Circular Polarization:The electric field vector rotates in a circular pattern as the wave travels, which is a defining characteristic of circularly polarized light. It has two possible rotational directions: clockwise (right-handed) and counterclockwise (left-handed). Circular polarization is achieved when the horizontal and vertical components of the electric field vector have identical amplitudes and a 90 degree phase difference, circular polarization results. The necessary conditions to achieve circular polarization are:

a. The field must have two orthogonal linear components with same magnitude and a phase difference that is an odd multiple of 90°.

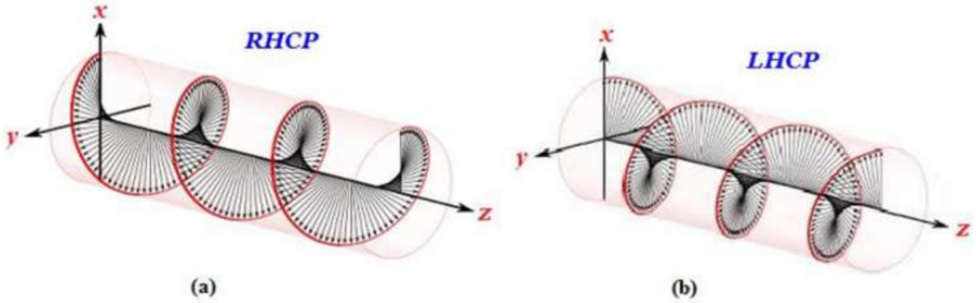

Figure 11: Circular Polarization

3. Elliptical Polarization: Elliptically polarized light occurs when the electric field vector traces out an ellipse as the wave propagates. This state includes both circular and linear polarization as special cases. Depending on the relative amplitudes and phase differences between the horizontal and vertical components, the ellipse can be elongated or squashed, and its major axis can be aligned at any angle.

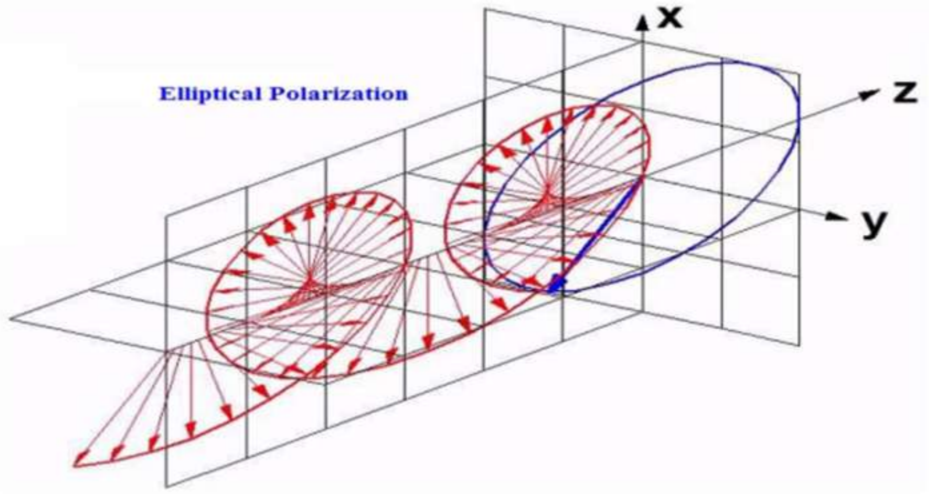

Figure 12: Elliptical Polarization

3.4 Birefringence

Birefringence refers to the property of certain materials that causes light to split into two different polarizations when passing through them. These materials are said to be birefringent or exhibit double refraction. When an electromagnetic wave enters a birefringent material, it splits into two orthogonal polarizations known as the ordinary and extraordinary rays. To understand birefringence, imagine a material that has a preferred direction or orientation for its molecular structure. Birefringence is commonly observed in materials like crystals, certain plastics, and biological tissues. It has practical applications in various fields, such as optics and telecommunications. For example, birefringent materials can be used to create optical devices like wave plates, polarizers, and retardation plates, which manipulate the polarization and phase of light waves.

Light whose polarization is perpendicular to the optic axis is governed by a refractive index called ordinary refractive index (no) whereas the EM wave polarized along the direction of the optic axis sees an optical index called extraordinary refractive index (ne) and the difference between the two is quantified as birefringence:

$$\Delta n = n_0 - n_e \tag{1}$$

The difference in the refractive index cause orthogonal components to travel with different speeds which causes phase difference resulting in the polarization conversion of emanating waves. All polarization conversion types can be achieved depending upon the phase difference accumulated while traveling tin the optically anisotropic material.

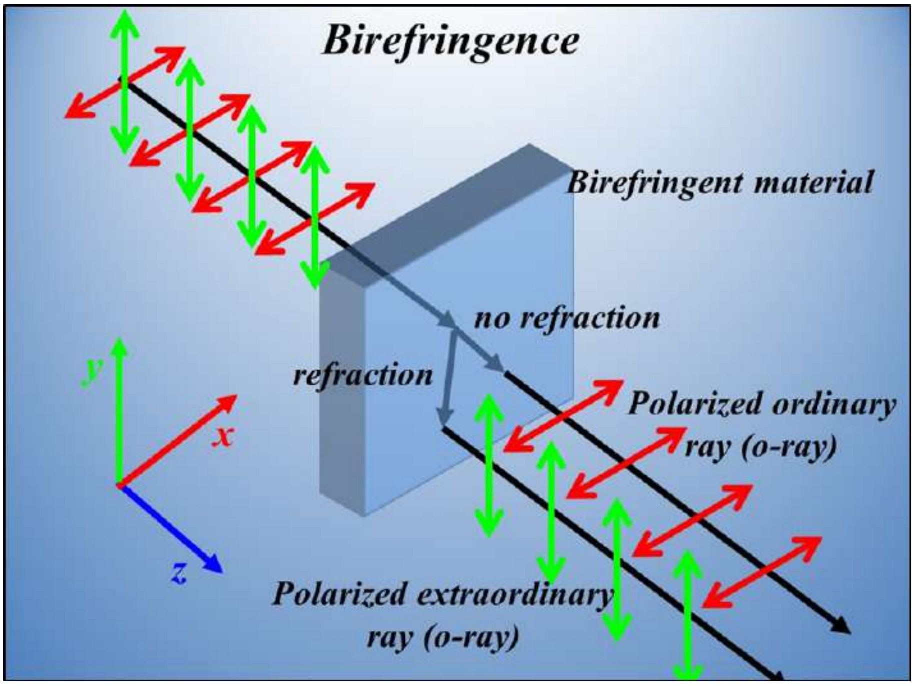

Figure 13: Birefringence

3.5 Manipulating Polarization of Electromagnetic waves

Polarization manipulation of electromagnetic waves cite to the ability to control and alter the orientation of the electric field vector as the waves propagate. To modify the polarization of electromagnetic waves, various techniques can be employed:

1. Polarizers: Polarizers are materials that selectively transmit light waves with a specific polarization while blocking or absorbing waves with other polarizations. They work based on the principle of polarization by absorption or polarization by reflection.

2. Wave plates or retarders: Wave plates are birefringent materials that introduce a phase delay between different polarization components of an incident wave.

3. Quarter-wave plates and half-wave plates: These are specific types of wave plates that introduce a phase delay of a quarter wavelength or half-wavelength, respectively.

4. Liquid crystals: Liquid crystals are materials that can change their molecular orientation in response to an applied electric field.

5. Meta-materials: Meta-materials are artificially engineered materials that exhibit properties not found in naturally occurring substances. They can be designed to manipulate the behavior of electromagnetic waves.

By carefully engineering the geometry, orientation, and arrangement of these meta-atoms, it is possible to control the behavior of light at subwavelength scales.

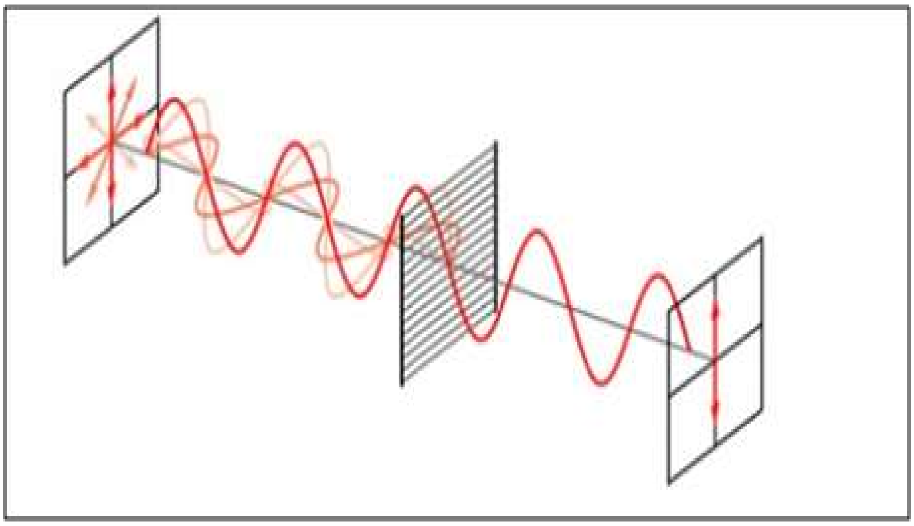

Figure 14: Manipulating Polarization

3.6 Software Environments for Meta surface Design

High Frequency Structure Simulator HFSS

HFSS is a software used for solving Electromagnetic Structure using finite element method.Electronic products which operate at high frequency used for communication systems,cellular communication,satellite communication and in radar ssystem are designed in HFSS. It simulates structures in 3D and can also change the properties of materials to observe their effect.

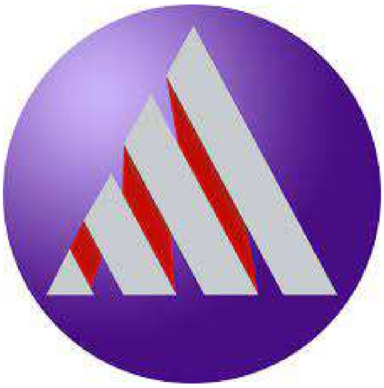

Figure 15: High Frequency Structure Simulator HFSS

CST Software

CST is software package developed by simulation used to design, analyze and optimize electromagnetic structures. It contains many solvers all interfaced in a single user interface.CST is used to simulate both high and low frequency structures.CST software is a powerful tool for simulating and testing meta-surfaces designed to convert linear polarization to circular polarization. CST offers a range of specialized tools and modules for different applications, including high-frequency and low frequency simulations, antenna design, RF and microwave circuits and signal integrity analysis.

Figure 16: CST Software

Origin Pro

Origin Pro is a powerful data analysis and graphing software widely used in scientific and engineering research. Known for its user-friendly interface and versatile functionalities, Origin Pro offers comprehensive tools for data visualization, statistical analysis, and graph creation. With support for a wide range of file formats and extensive customization options, users can easily import, analyze, and present their data. Additionally, Origin Pro provides advanced features like 3D surface fitting, peak analysis, and batch processing, making it a preferred choice for professionals and researchers in various fields.

Figure 17: Origin Pro

Chapter 4

4 PROJECT APPROACH

4.1 Expected Deliverables

The Expected deliverables of the project are as follows

1. Design of unit cell using CST software.
2. Fabrication of Meta-Surface by replicating unit cells over it. Meta-surface is to be designed either in reflection mode or transmission mode.
3. Testing and Verification of Meta-Surface using VNA (Vector Network Analyzer) in an anechoic chamber.

4.2 Project Approach

4.2.1 Sequence of Project

The sequence of the project is as flashed through a flow chart:

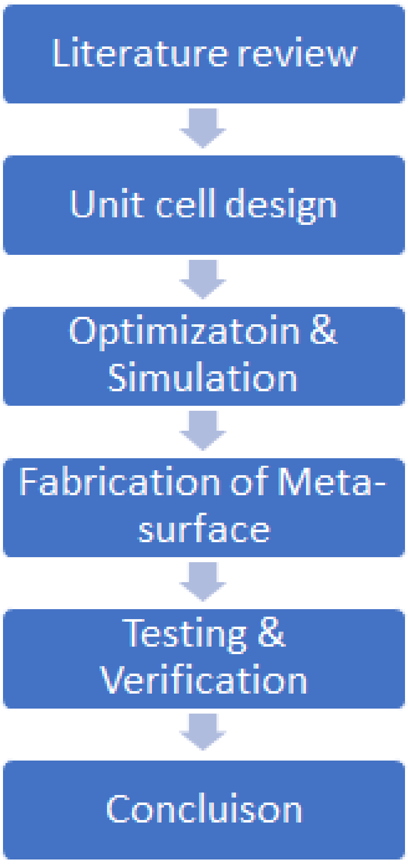

Figure 18: Flow chart of methodology

4.2.2 Project Approach

This project will be divided into the phases listed below.

- Review of the literature and instruction in the use of software CST
- Design of unit cell, optimization of the unit cell
- Simulation of unit cell and replicating it on the fabricated material
- fabrication of meta surface
- Testing of meta-surface via VNA in anechoic chamber having two horn antennas
- Preparation of documentation

Details of the phases are given below.

4.2.3 Phase 1 : Review of the literature and instruction in the use of software CST

In the initial phase literature review will be studied focusing on the aspects following project covers. Studying the literature review is an essential initial phase when researching the design techniques of meta-surfaces for transforming linear polarization to circular polarization. Conducting a literature review involves reviewing and analyzing existing scholarly articles, research papers, and relevant publications that explore the existing techniques for designing meta surface.

4.2.4 Phase 2 : Design of unit cell, optimization of the unit cell

In second phase, a unit cell will be designed first on CST either in the transmission or reflection mode.The unit cell is then replicated on the fabricated sheet and optimize the unit cell parameters to enhance its performance. This can involve adjusting dimensions, modifying material properties, or altering the unit cell's geometry to achieve desired functionalities or optimize specific characteristics like polarization conversion, frequency response, or phase manipulation.

4.2.5 Phase 3 : Simulation of unit cell and replicating it on the fabricated material

Simulation plays a crucial role in designing meta-surfaces and understanding the behavior of unit cells within them.Select an appropriate electromagnetic simulation method based on the characteristics of the unit cell and the desired analysis. Create a simulation environment that accurately represents the metasurface system.Execute the simulation based on the defined parameters.Based on the analysis, refine the unit cell design if necessary. Adjust parameters such as dimensions, material properties, or geometric configuration to optimize the unit cell's behavior or achieve desired functionalities.

4.2.6 Phase 4 : fabrication of meta surface

In this phase, meta-surface is fabricated on FR-4 sheet having unit cells replicating on it and the other side will be plane.Meta-surface is designed based on the requirements either capable of linear to circular polarization conversion in transmission or reflection mode.

4.2.7 Phase 5 : Testing of meta-surface via VNA in anechoic chamber having two horn antennas

In the last phase, Testing the fabricated metasurface in an anechoic chamber using two horn antennas and a VNA involves the following steps: 1. Set up the anechoic chamber with proper electromagnetic absorbing materials.

2. Connect one horn antenna to the transmitter port (Tx) and the other to the receiver port (Rx) of the VNA.

3. Calibrate the VNA using calibration standards to eliminate systematic errors.

4. Define the measurement parameters such as frequency range and sweep time on the VNA.

5. Perform measurements using the VNA to analyze the metasurface's scattering parameters, S-parameters, or other relevant characteristics.

6. Analyze and interpret the measurement results to understand the metasurface performance.

4.3 Software

The software required for the project includes:

- CST Studio Suite
- ANSYS hfss
- Origin Pro

4.4 Selection of substrate

The selection of the FR-4 substrate for this project is strategically grounded in its specific attributes that align perfectly with the project's requirements:

Cost-Effectiveness: FR-4 offers a cost-effective solution, ensuring the project stays within budget constraints while maintaining optimal performance.

Optimal Thickness: The chosen thickness of 1.6 mm provides the necessary mechanical stability for microwave applications, facilitating ease of fabrication.

Dielectric Constant (ε_r)**:** FR-4 boasts a moderate dielectric constant of 4.4, striking a balance between signal integrity and cost-effectiveness.

Signal Loss and Dispersion Effects: The dielectric properties of FR-4 contribute to lower signal loss and reduced dispersion effects, critical for maintaining signal integrity within the desired frequency range.

Electrical Properties: Recognized for good electrical properties, including a low loss tangent and high thermal stability, FR-4 ensures reliable performance even under varying environmental conditions.

In summary, the project's preference for FR-4 with a thickness of 1.6 mm and a dielectric constant of 4.4 is based on its cost-effectiveness, mechanical stability, moderate dielectric constant, and favorable electrical properties. This substrate provides a practical and reliable solution for achieving project goals without the need for a more expensive alternative.

Chapter 4

5 Methodology

5.1 Evolution of Unit Cell Design

The principle of polarization conversion is completely based on anisotropy of the unit cell of meta surface structure. The final optimized unit cell geometry with desired level of anisotropy has been achieved step by step through comprehensive parametric analysis. The design evolution of the proposed meta surface is depicted through four major design steps of the unit cell.

Stage 1:

As a first step, we opt for a square ring that is segmented to maintain an-isotropic behavior. It can be seen from fig. 19(a) that co-polarized reflection coefficient Rxx is resonating at 6.4 GHz and around 10 GHz while cross polarized reflection coefficient Rxy is resonating at same frequencies, thus at 8.74 GHz and at 11.51 GHz Rxx = Rxy $\approx$ 1.

Stage 2:

The anisotropy is further improved in fig. 19(b) by adding a circular ring, thus co and cross polarized reflection coefficients are crossing each other more number of times.This very structure introduced in fig. 19(b) draws inspiration from the pioneering work done in [14], who first explored this framework in 2019.

Stage 3:

In fig.19(c) due to the addition of another split ring in the structure, cross polarized reflection coefficients have started showing resonance after 14 GHz.

Stage 4:

As shown in final design fig. 19(d) when the width of both of split ring resonators have increased, the co and cross polarized reflection coefficients are dramatically enhanced in the frequency regime 14-18 GHz.

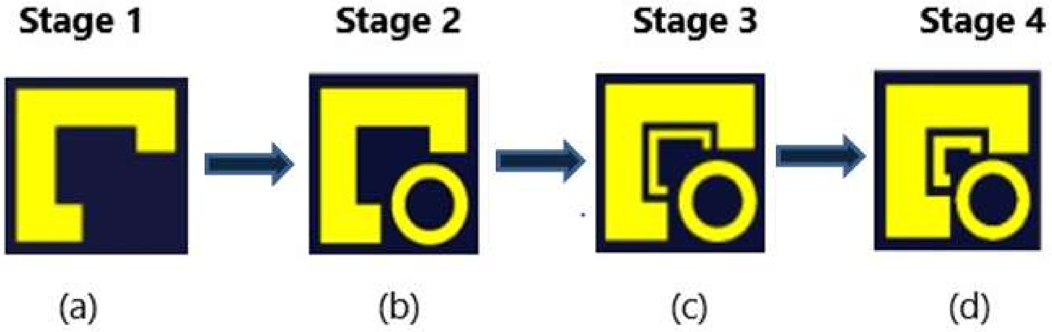

Figure 19: Evolution of proposed unit cells (a) split ring unit cell (b) split ring with a circular ring unit cell (c) Two split rings with a circular ring unit cell (d) Increased width of two split rings with a circular ring unit cell

The provided image illustrates the reflection coefficients of various unit cell designs, each contributing to the development of the final unit cell configuration. It offers a visual representation of the co-polarized (co-pol) and cross-polarized (cross-pol) reflection coefficients associated with different stages of the unit cell evolution. The distinctive patterns in these coefficients depict the gradual refinement and enhancement of the unit cell's anisotropic behavior, crucial for achieving efficient polarization conversion.

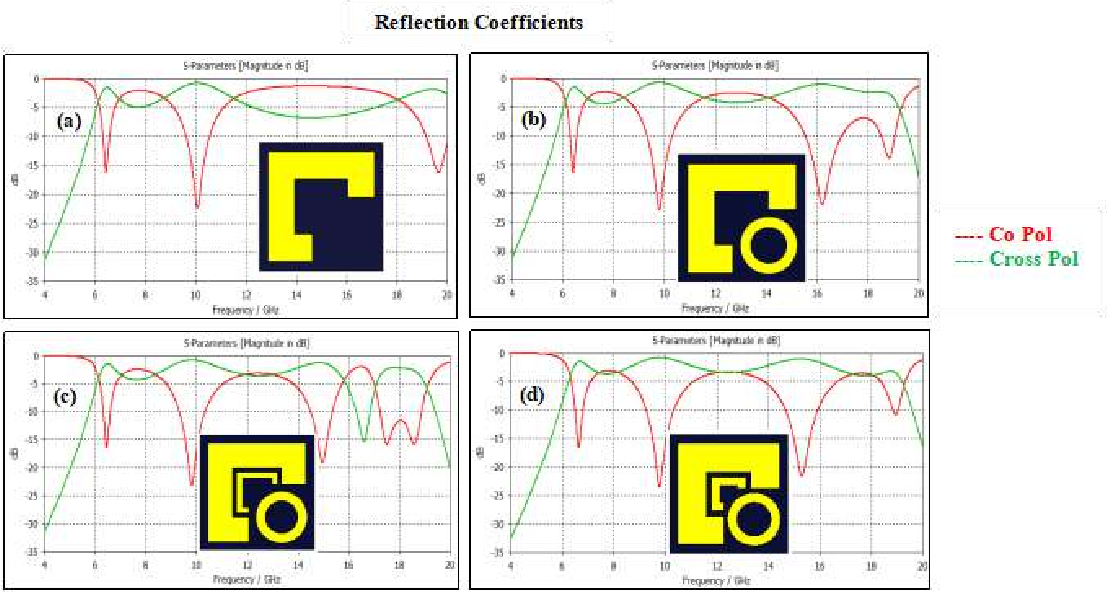

Figure 20: Reflection coefficients of proposed unit cells

5.2 Proposed meta surface unit cell

Each element of the metallic array on the top of the meta surface is composed of two split ring resonators with a circular-ring at the corner, as shown in figure. 20(a). A 3D schematic of the unit cell is presented in figure. 20(b). The physical dimensions of the unit cell in millimeter are: a = 6mm, s = 2.5mm, m = 1.5mm, b = 0.58mm, p= 1mm, z = 7mm, h = 1.6mm, d = 2mm. The FR4 substrate backed with ground plane was used to model the meta surface with relative permittivity 4.4 and loss tangent 0.02, while the material used for split rings loops with circular ring and the ground plane is copper with a conductivity of 5.8×107 S/m. The thickness of the dielectric substrate is 1.6mm. The unit cell is replicated with periodicity of 7mm along both x- and y-axis for fabrication with 30×30×1.6mm3.

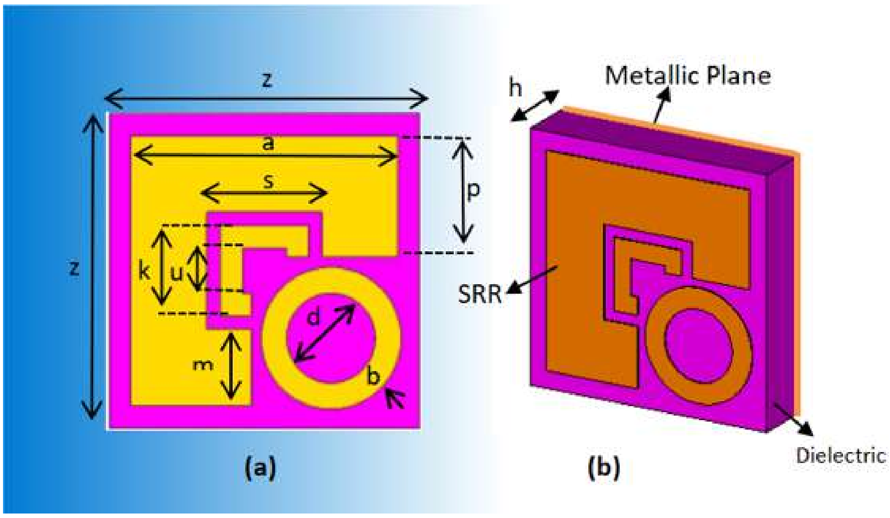

Figure 21: An artistic rendering of the proposed meta surface.(a) Unit cell of the proposed meta surface (b) 3D view of unit cell

5.3 Schematic View of the proposed Meta Surface

This groundbreaking design features a two-dimensional array of carefully crafted metallic patterns arranged on top of a dielectric substrate. The specific layout of these metallic patterns creates a structured pattern, strategically designed to elicit targeted electromagnetic responses. Through the manipulation of how incident electromagnetic waves interact with the metasurface, it achieves notable functionalities like cross-polarization conversion and linear-to-circular polarization conversion.

The arrangement and shape of the metallic patterns are crucial in customizing the metasurface response across a wide frequency range. With thoughtful design considerations, the metasurface is fine-tuned to deliver outstanding performance in cross-polarization conversion efficiency and stability, even when facing challenges such as wide oblique incidence angles, up to 60 degrees.

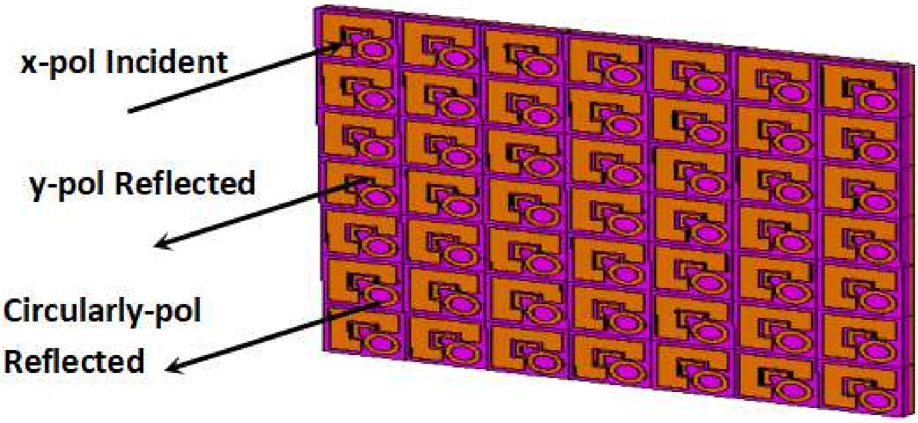

Figure 22: Schematic Depiction of proposed unit cell design

Chapter 5

6 Results

6.1 Co- and cross-polarized refection coefficients

As the meta surface is backed by a metallic plane, therefore, all the transmission coefficients are zero.Thus, we have to evaluate only the refection coefficients of the meta surface. The reflected fields;$[ErxEry]^T$, are related to fields, $[EixEiy]^T$, through Jones matrix in Cartesian coordinate system :

$$(E_{rx}E_{ry}) = \frac{R_{xx}R_{xy}}{R_{yx}R_{yy}} (E_{ix}E_{iy}) \tag{2}$$

where the refection matrix has complex elements, possessing both magnitude and phase.

Figure 23 show the magnitude of the co- and cross polarized reflection coefficients,$|R_{xx}|$ and $|R_{yx}|$, when the incident wave is x-polarized. The cross polarization reflection coefficient is greater than 0.8 in three frequency bands (6.39-7.21GHz, 8.37-11.60, and 13.295-16.720), which leads to the combined fractional band width of 69.52%.

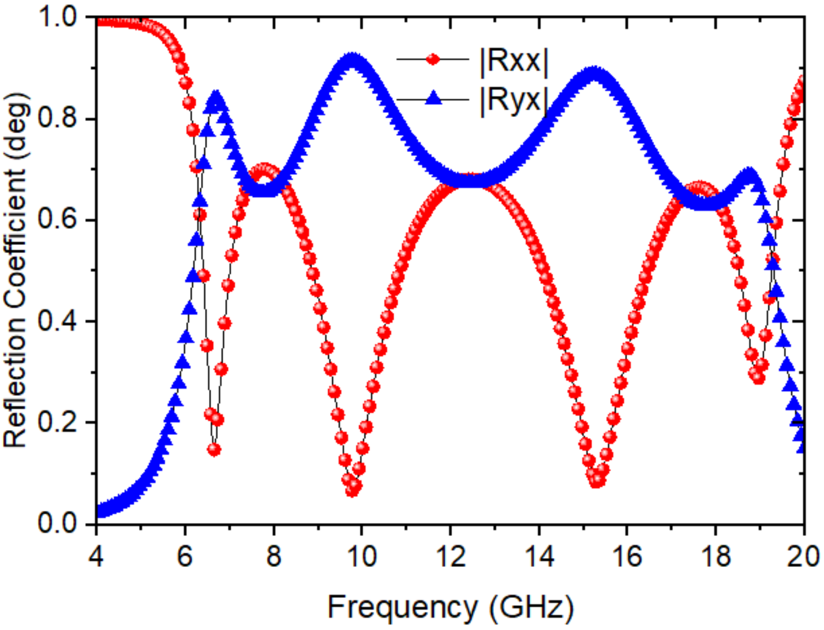

Figure 23: Co- and cross-polarized refection coefficients

6.2 Phase of Co and cross reflection coefficients

In addition to CPC, another interesting feature of the proposed design is its ability to achieve linear to circular polarization conversion. In order to achieve LP-to-CP conversion, the magnitude of co- and cross-polarized reflection coefficient must be the same and equal to 0.7, $|R_{xx}| = |R_{yx}| \approx 0.7$ while their phase difference,$\Delta\phi_{yx} = \phi_{xx} - \phi_{yx}$ must be an odd multiple of 90°[15]. Ideally, the amplitude ratio $\frac{|R_{xx}|}{|R_{yx}|}$ must be 1, however, LP-to-CP conversion is still achieved if the amplitude ratio lies within (0.85–1.15) and the phase difference satisfies $(n_{90^\circ} - 5^\circ) \leq \Delta\phi_{yx} \leq (n_{90^\circ} + 5^\circ)$ where n is an odd integer.

From fig 24, it can be seen that the LP-to-CP conversion criteria for the amplitude ratio $0.85 \leq \frac{|Rxx|}{|Ryx|} \leq 1$ and phase difference $(n_{90^\circ} - 5^\circ) \leq \Delta\phi_{yx} \leq (n_{90^\circ} + 5^\circ)$ are satisfied over three frequency bands: 7.42–8.14 GHz, 12.16–12.72 GHz, 17.27–18.05 GHz.

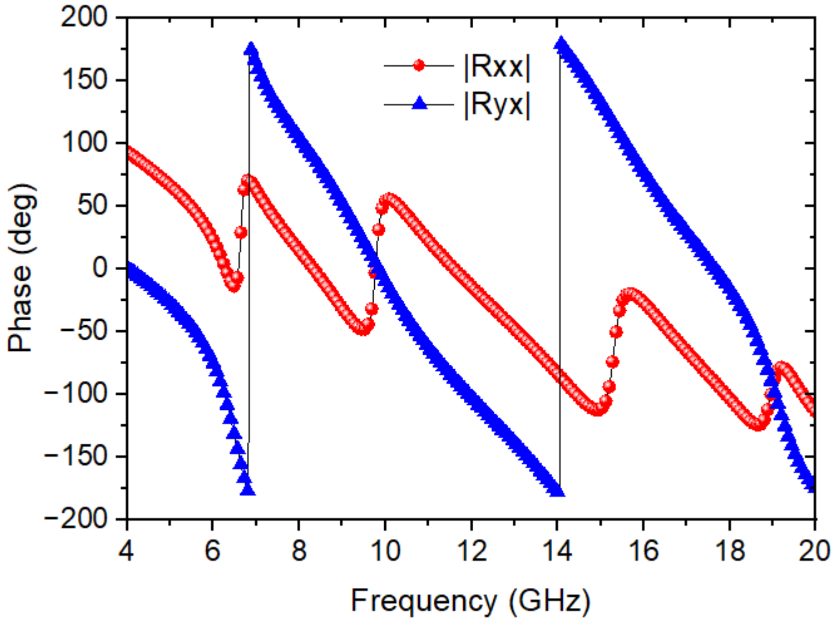

Figure 24: phase

6.3 Polarization Conversion Ratio (PCR)

A good measure of the efficiency of the cross-polarization transformation capability of a structure is the polarization conversion ratio (PCR). It is defined as the ratio of the power reflected in cross polarized field of the EM wave to the total reflected power.

Mathematically:

$$PCR = \frac{|Ryx|^2}{|Ryx|^2 + |Rxx|^2} \tag{3}$$

The polarization conversion ratio of the proposed design when the incident wave is x-polarized is shown in figure 4. It can be seen from figure 5 that PCR reaches almost 100% at three resonance frequencies: 6.6 GHz, 9.8 GHz, 15.2 GHz and 18.7 GHz, while it is more than 80% in the frequency bands 6.5–6.9 GHz, 9–10.5 GHz, 14.4–16.1 and 18.5-19.2 GHz. The PCR can be further improved with low loss dielectrics such as Rogers; however, it is much more expensive compared to FR4.

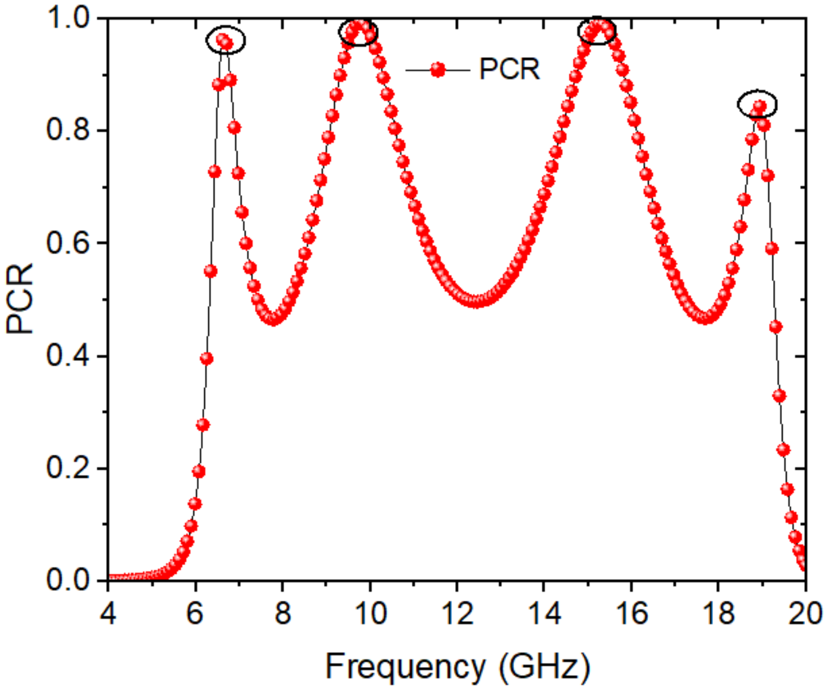

Figure 25: Polarization conversion ratio when the incident wave is x-polarized

6.4 Phase difference rxy-rxx

The phase difference, denoted as $\Delta\phi_{yx} = \phi_{xx} - \phi_{yx}$, between the co-polarized (R_{xx}) and cross-polarized (R_{yx}) reflection coefficients is a critical parameter in polarization conversion. In polarization conversion applications, such as linear-to-circular polarization conversion, achieving a phase difference within the range of 85 to 95 degrees is essential for optimal performance. This phase difference ensures efficient conversion between different polarization states. Additionally, it's crucial for the phase difference to be an odd multiple of 90 degrees to maintain the desired polarization transformation. This condition ensures that the converted polarization state is orthogonal to the original state, facilitating effective manipulation of electromagnetic waves

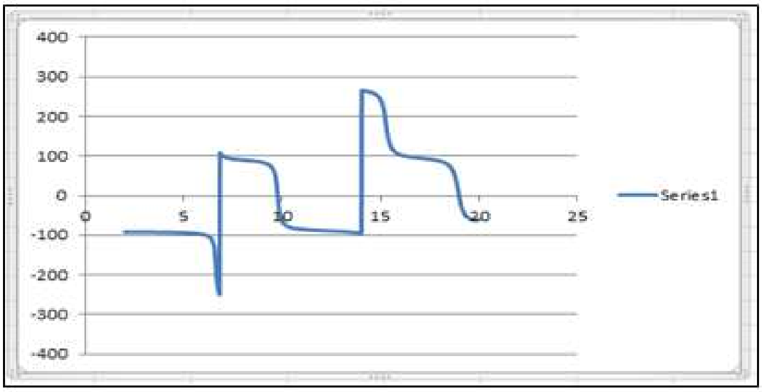

Figure 26: Phase difference rxy-rxx

6.5 Incident angle up to 60 °

The proposed meta surface must maintain its polarization conversion capabilities for oblique incidence angles in order to be useful in a variety of applications. To check this, simulations were carried out and the results are shown in figure 26. The proposed design achieves angularly stable CPC operation up to 60° in both $|R_{xx}|$ and $|R_{yx}|$ referred as co and cross polarization coefficients of the designed unit cell as shown in fig. 26.

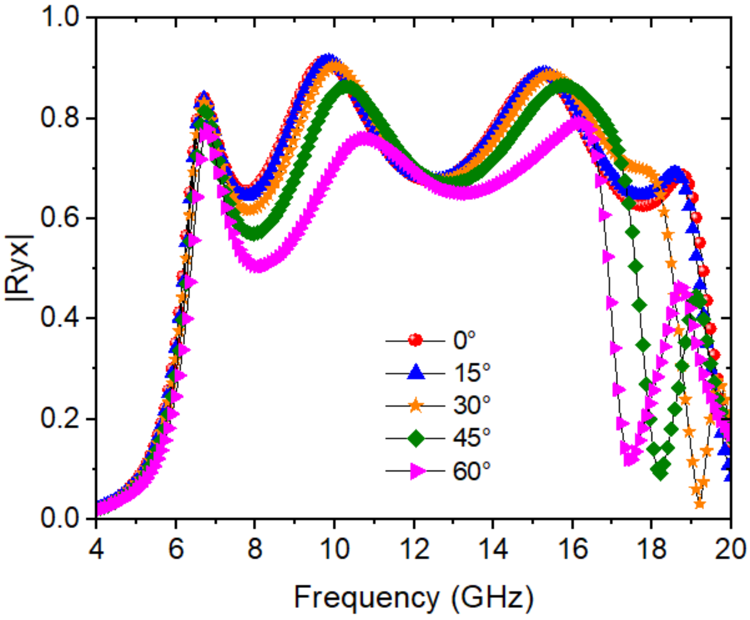

Figure 27: $|R_{yx}|$

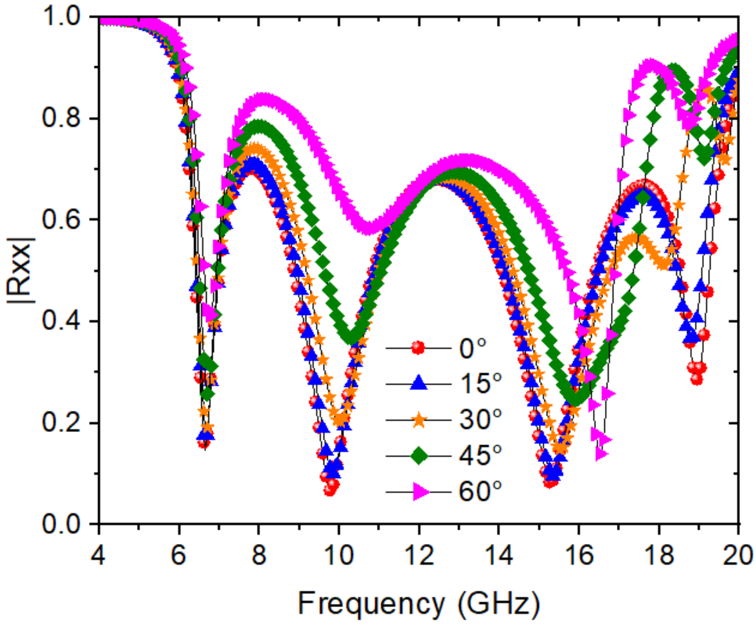

Figure 28: $|R_{xx}|$

6.6 Ellipticity

By determining the positive or negative values of the e-value, the rotation direction of circular polarization can be obtained. In this paper, when the e-value is close to 1, the linearly polarized wave in the y direction is converted into right-handed circularly polarized wave, and when the e-value is close to -1, the linearly polarized wave in the y direction is converted into left-handed circularly polarized wave. The above discussion was carried out under the assumption of the co-polarization being Y-polarization.As this paper focuses on the conversion between linear polarization and circular polarization in the C,X and Ku band through calculations of its ellipticity value (e-value or e):

$$e = \frac{2|\mathrm{rxy}| \cdot |\mathrm{ryy}| \sin \Delta\phi}{|\mathrm{rxy}|^2 + |\mathrm{ryy}|^2} \tag{4}$$

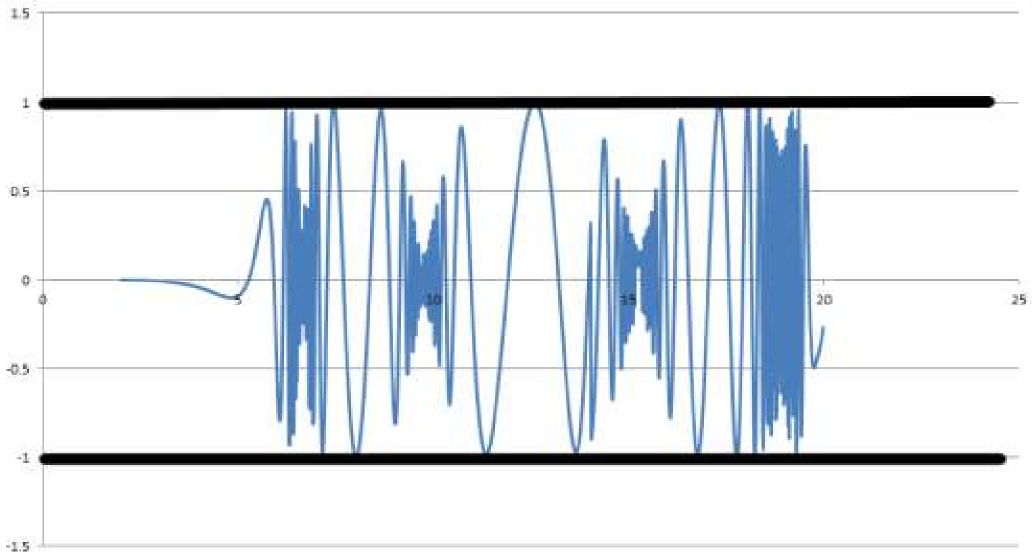

Figure 29: e-value

Chapter 6

7 Fabricated of Meta Surface

7.1 Fabricated Meta surface

Meta surface is fabricated on FR-4 having thickness of 1.6mm and is replicated by 20x20 unit cells. The above shown image is a fabricated meta surface:

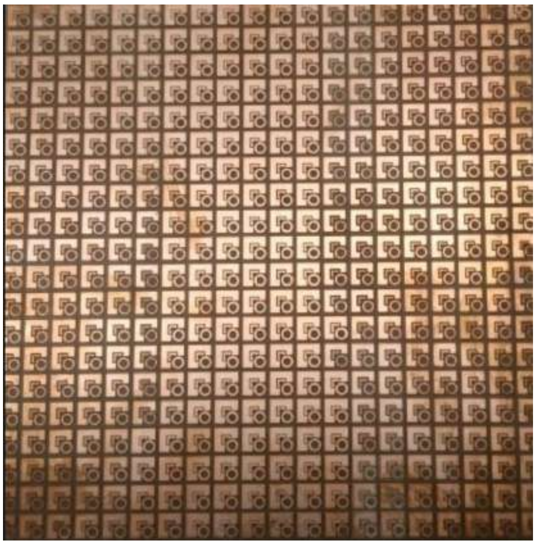

Figure 30: Meta Surface

7.2 Measurement Setup

A setup is installed on a smaller scale using two horn antennas and a Vector Network Analyser (VNA).

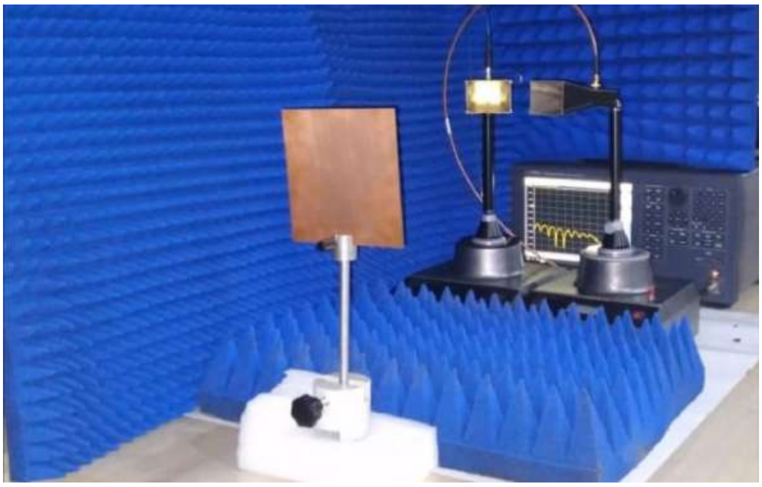

Figure 31: Measurement Setup

Chapter 7

8 Measurement Results

For measuring co- and cross-polarized reflection coefficients, the prototype is placed in front of two horn antennas, one acting as a transmitting while the other as receiving antenna. The orientation of the horn openings is the same for measuring co-polarized reflection while it is perpendicular for cross-polarized reflection coefficients. The antennas are placed tilted at 4° with the major lobe pointing towards the metasurface. The obtained results are calibrated by comparing with measurement results for a simple copper plate of the same dimensions as the fabricated metasurface. All the measurements are performed in an anechoic chamber. The measurement setup is shown in figure 31.

8.1 Measurement in C-band

8.1.1 Reflection Coefficients in C-band

The measurements conducted in the C band reveal a notable phenomenon in cross-polarization at 7.35 GHz, where a distinct pattern emerges. Interestingly, this pattern demonstrates a consistent maintenance of equal magnitude within the frequency range of 7.6 to 8 GHz.

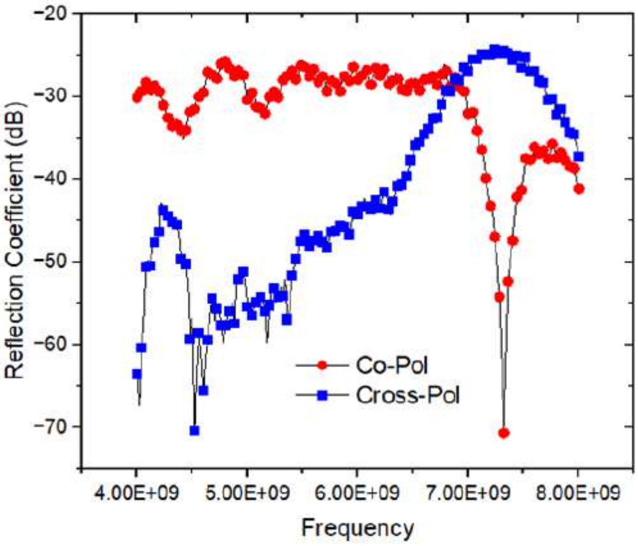

Figure 32: Co and Cross polarized Reflection Coefficient

8.1.2 Phase of Reflection Coefficients

The phase difference remains consistently at 90° within the frequency band of 7.5 to 8 GHz, where the ratio of amplitude falls within the range of 0.85 to 1.15. This observation indicates a precise and stable alignment between the co-polarized and cross-polarized components of the electromagnetic waves. The maintenance of this phase difference is critical for achieving effective linear-to-circular polarization conversion, ensuring the fidelity and reliability of the polarization transformation process within the specified frequency range.

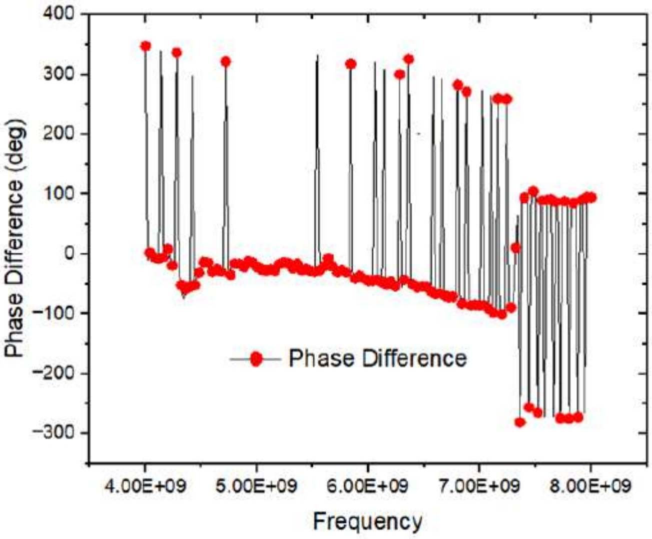

Figure 33: Co and Cross polarized Reflection Coefficient

8.2 Measurement in X-band

8.2.1 Reflection Coefficients in X-band

The cross polarization exhibits a consistent magnitude at 11.2 GHz, maintaining equal amplitude levels within the frequency band of 9.3 to 10.3 GHz. This observation suggests robust performance and stability in the conversion of polarization states across the specified frequency range. The consistent magnitude of the cross-polarized component ensures reliable and efficient transmission or reception of electromagnetic signals with orthogonal polarization orientations.

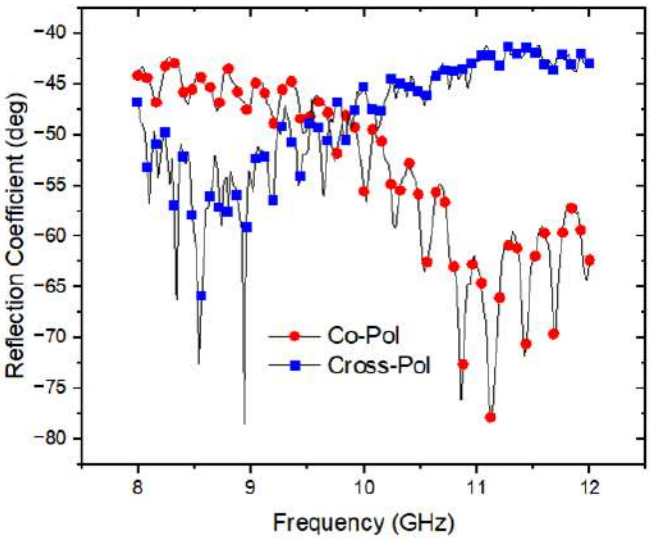

Figure 34: Co and Cross polarized Reflection Coefficient

8.2.2 Phase of Reflection Coefficients

The observed phenomenon of maintaining a consistent 90° phase difference at specific frequencies, namely 9.36, 9.38, 9.40, and 9.46 GHz, where the ratio of amplitude falls within the range of 0.85 to 1.15, underscores the precision and stability of the polarization conversion process. This finding highlights the capability of the system to effectively modulate the amplitude and phase of electromagnetic waves within the desired frequency band, ensuring optimal performance and reliability in communication systems and related applications.

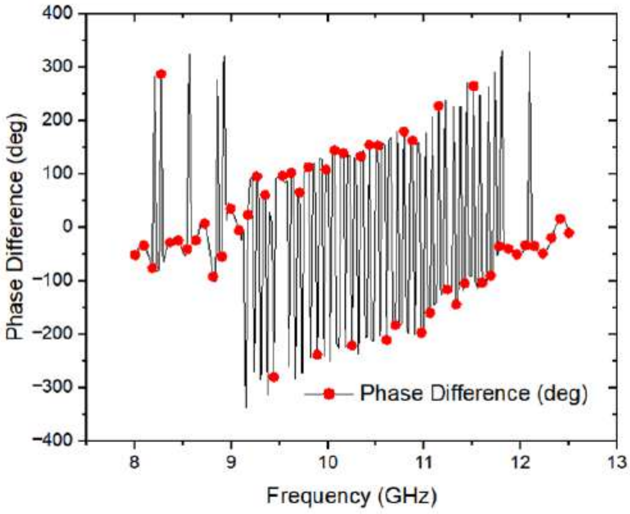

Figure 35: Co and Cross polarized Reflection Coefficient

8.3 Measurement in Ku-band

8.3.1 Reflection Coefficients in Ku-band

In the Ku-band spectrum, the reflection coefficient analysis highlights a significant observation at 17.5 GHz, where the cross-polarization exhibits consistent magnitude across a frequency range spanning from 14.5 to 16 GHz. This remarkable stability underscores the efficacy of the polarization conversion process within the Ku-band frequency spectrum. The uniformity in cross-polarization magnitude within this frequency range ensures reliable and consistent performance, making it suitable for various communication and radar applications operating in the Ku-band.

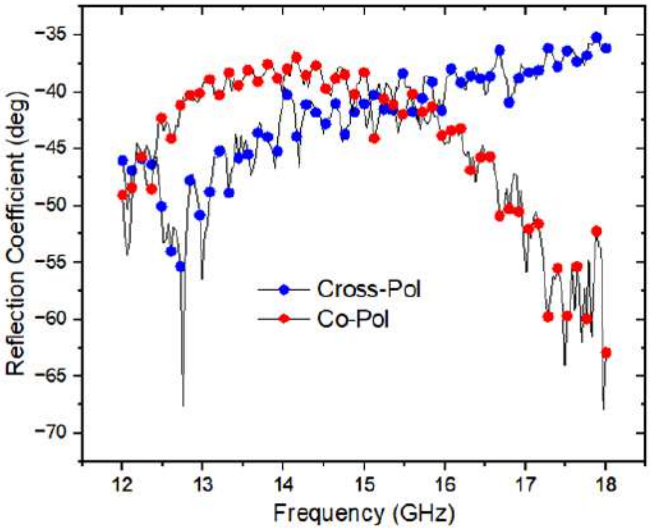

Figure 36: Co and Cross polarized Reflection Coefficient

8.3.2 Phase of Reflection Coefficients

The phase difference remains stable, consistently at 90°, at specific frequencies where the ratio of amplitude falls within the range of 0.85 to 1.15. Notably, this behavior is observed at frequencies of 14.82 GHz, 15.84 GHz, and 15.87 GHz. Such precise control over phase characteristics is essential for ensuring accurate polarization conversion in communication and radar applications, particularly in the Ku-band spectrum.

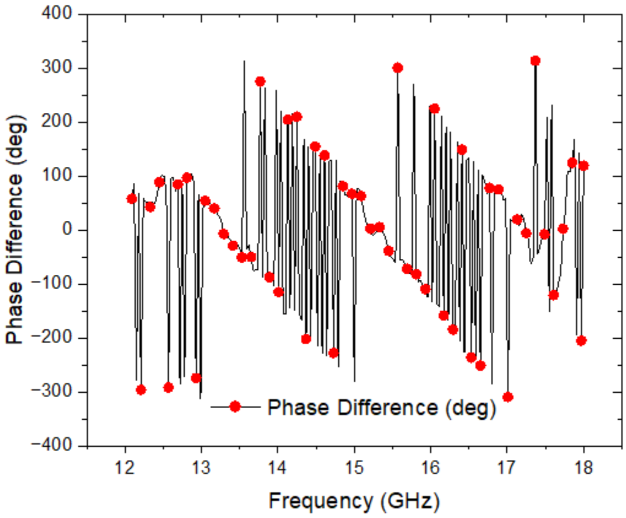

Figure 37: Co and Cross polarized Reflection Coefficient

8.4 Ellipticity

By determining the positive or negative values of the e-value, the rotation direction of circular polarization can be obtained. In this paper, when the e-value is close to 1, the linearly polarized wave in the y direction is converted into right-handed circularly polarized wave, and when the e-value is close to -1, the linearly polarized wave in the y direction is converted into left-handed circularly polarized wave. Ellipticity is checked in C-band (measured through horn antennas and VNA).

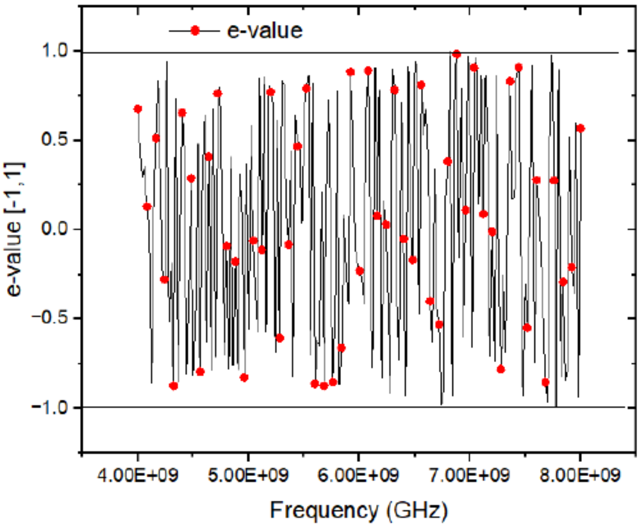

Figure 38: Ellipiticity

Chapter 8

9 Challenges

Designing a meta surface posed several intricate challenges, most of which are related to the fabrication and testing of meta surface. All of them are methodically addressed:

- **Outdated Equipment Compatibility:**

  The LPKF M60 machine's compatibility with Windows XP posed a significant challenge during fabrication. As modern design software and operating systems evolve, compatibility issues with older equipment become more pronounced. This hindered the fabrication process as it limited the software capabilities needed for uploading design files.

  Additionally, the inability to upload files with unit cells exceeding 20x20 constrained the size of the meta surface design. This limitation impacted the overall efficiency of the fabricated meta surface by restricting its complexity and resolution.

- **Efficiency Compromise:**

  The equipment constraints led to an inability to fabricate larger meta surfaces, such as those with 40x40 unit cells. This compromise in size directly affected the efficiency of the meta surface design. With size limitations in place, the fabricated meta surface's efficiency was compromised, potentially leading to sub optimal performance compared to what could have been achieved with larger dimensions.

- **Testing Equipment Availability:**

  The absence of appropriate horn antennas for testing across C, X, and Ku bands posed a significant hurdle. Without access to the necessary equipment, comprehensive testing across multiple frequency bands becomes impractical, limiting the thorough evaluation of the meta surface's performance.

  Moreover, the lack of broadband antennas further restricted testing capabilities. Broadband antennas are essential for assessing the meta surface's functionality across a wide range of frequencies. Without them, the testing process becomes incomplete, potentially overlooking important performance characteristics.

- **Manual Adjustments and Precision:** The need for manual rotation of horn antennas by 90 degrees introduced variability and limitations in obtaining accurate results. Manual adjustments are prone to human error and may not achieve the precise positioning required for reliable testing.

  This manual process not only compromises the precision of measurements but also introduces inconsistencies between test configurations, impacting the reliability and repeatability of the results obtained.

- **Bandwidth Constraints:**

  Limited availability of broadband antennas imposed constraints on the range of frequencies that could be tested. Meta surfaces designed for wide band applications require testing across various frequency ranges to assess their effectiveness across different communication or sensing scenarios.

  Without access to broadband antennas, the evaluation of the meta surface's performance may be confined to a narrower frequency range, limiting its potential applications and real-world usability.

- **Calibration Challenges:**

  Difficulty in calibrating equipment for precise measurements across different bands adds another layer of complexity to the testing process. Accurate calibration is essential for ensuring the reliability and accuracy of measurement results.

  Calibration challenges can arise due to equipment limitations, environmental factors, or inconsistencies in measurement setups. Addressing these challenges is crucial for obtaining trustworthy data and meaningful insights into the meta surface's performance across different frequency bands.

Chapter 9

10 Applications

Meta Surface have vast applications in today's world because of their agility to operate in multiple frequency bands. Polization Conversion Meta surfaces are also used in various applications some of them are listed below :

1. **Radar Systems:** Meta-surfaces are integral to radar systems utilized for military surveillance, target detection, and tracking. Circularly polarized radar signals offer distinct advantages over linearly polarized ones, including enhanced target discrimination, reduced clutter interference, and improved performance in adverse weather conditions.

2. **Communication Systems:** Circularly polarized antennas, facilitated by meta-surfaces, are extensively deployed in military communication systems. They offer superior signal reception in challenging environments characterized by multipath propagation and electromagnetic interference, thereby ensuring reliable and secure communication channels for military operations.

3. **Stealth Technology:** Meta-surfaces play a pivotal role in advancing stealth technology by enabling the conversion of linearly polarized radar waves to circular polarization. This conversion reduces the radar cross-section of military assets, making them less detectable by enemy radar systems and enhancing their survivability on the battlefield.

4. **Imaging and Sensing:** Meta-surfaces designed for linear to circular polarization conversion contribute to military imaging and sensing systems. These systems leverage circular polarization to enhance imaging resolution, mitigate signal distortion, and improve target identification and tracking capabilities, thereby enhancing situational awareness and mission effectiveness.

Chapter 10

11 Conclusion and Recommendations

11.1 Conclusion

In summary, we have realized a multi band polarization converting meta surface that efficiently converts linearly polarized to circularly polarized waves. Simulation results show that efficient cross-polarization conversion is achieved over three frequency bands: 6.39–7.21 GHz, 8.37–11.60 GHz and 13.29–16.72 GHz, which leads to the combined fractional band width of 69.52%. Similarly, linear-to-circular polarization conversion and vice versa is demonstrated in following frequency bands: 6–6.1 GHz, 7.42–8.14 GHz, 12.16–12.72 GHz and 17.27-18.05 GHz.The proposed design is based on dual rectangular split-ring resonators which gets multiple resonances enabling the meta surface to achieve polarization transformation across a broad frequency range (5–37 GHz), covering X, C, and Ku bands. The proposed meta-surface demonstrates robust performance up to 60°.

11.2 Recommendations

The recommendations with respect to future need of polarization converting meta surface is as flashed :

1. **Advanced Radar Systems:** Develop meta surface polarization conversion technologies optimized for next-generation radar systems used by the Air Force. These systems require enhanced capabilities for target detection, tracking, and identification in various operational scenarios.
2. **Multi-Band Operation:** Design meta surfaces capable of operating across multiple frequency bands relevant to Air Force radar applications, such as X-band, Ku-band, and Ka-band. This versatility enables flexibility in radar deployment and ensures compatibility with existing and future radar systems.

3. **Stealth and Countermeasures:** Focus on meta surface designs that contribute to stealth technology by reducing the radar cross-section of military assets. Implement polarization conversion techniques to mitigate radar detection and enhance survivability on the battlefield against adversaries equipped with advanced radar systems.
4. **Adaptive and Reconfigurable Systems:** Incorporate adaptive and reconfigurable meta surface technologies that can dynamically adjust polarization conversion characteristics based on evolving operational requirements and environmental conditions. This adaptability enhances the agility and effectiveness of Air Force radar systems in response to changing threats and mission objectives.
5. **Interference Mitigation:** Develop meta surface solutions capable of mitigating electromagnetic interference and clutter in radar environments, particularly in contested or congested electromagnetic spectra. Implement polarization manipulation techniques to improve signal-to-noise ratios and enhance target detection capabilities in challenging electromagnetic environments.
6. **Collaborative Research and Development:** Foster collaboration between academia, industry, and government agencies to advance research and development efforts in meta surface polarization conversion technology. Leverage interdisciplinary expertise to address complex challenges and accelerate the transition of innovative concepts from the laboratory to operational deployment.
7. **Validation and Testing:** Conduct comprehensive validation and testing of meta surface polarization conversion technologies in realistic operational environments, including field trials and exercises with Air Force radar systems. Gather empirical data to assess performance, reliability, and scalability, ensuring that the developed solutions meet the stringent requirements of Air Force missions.

Chapter 5

12 Bibliography

[1] Khan, M. I. et al. Multiband linear and circular polarization converting anisotropic metasurface for wide incidence angles. J. Phys. D Appl. Phys. 53(9), 095005 (2019).

[2] Fahad, A. K. et al. triple-wide-band Ultra- thin Meta sheet for transmission polarization conversion. Sci. Rep. 10(1), 1–12 (2020)

[3]Khan, M.I., Hu, B., Amanat, A., Ullah, N., Khan, M.J.I. and Khalid, A.U.R., Efcient asymmetric transmission for wide incidence angles using bi-layered chiral metasurface. J. Phys. D Appl. Phys. 53(30), 305004 (2020).

[4] Khan, M. I., Fraz, Q. Tahir, F. A. Ultra-wideband cross polarization conversion metasurface insensitive to incidence angle. J. Appl. Phys 121, 045103 (2017).

[5] Khan, M. I., Fraz, Q. Tahir, F. A. Ultra-wideband cross polarization conversion metasurface insensitive to incidence angle. J. Appl. Phys 121, 045103 (2017).

[6] M. I. Khan, Q. Fraz, and F. A. Tahir, ”Ultra-wideband cross polarization conversion metasurface insensitive to incidence angle,” Journal of Applied Physics, vol. 121, no. 4, p. 045103, 2017. DOI: 10.1063/1.4974849.

[7] M. I. Khan and F. A. Tahir, ”An angularly stable dual-broadband anisotropic cross-polarization conversion metasurface,” Journal of Applied Physics, vol. 122, no. 5, p. 053103, 2017. DOI: 10.1063/1.4997456.

[8] M. I. Khan and F. A. Tahir, ”Simultaneous quarter-wave plate and half-mirror operation through a highly flexible single layer anisotropic metasurface,” Scientific

Reports, vol. 7, no. 1, p. 16059, 2017. DOI: 10.1038/s41598- 017-15279-8.

[9] M. I. Khan, Z. Khalid, and F. A. Tahir, ”Linear and circular-polarization conversion in X-band using anisotropic metasurface,” Scientific Reports, vol. 9, no. 1, p. 4552, 2019. DOI: 10.1038/s41598-019-40793-2.

[10] Khan M I, Khalid Z and Tahir F A 2019 Linear and circularpolarization conversion in X-band using anisotropic metasurface Sci. Rep. 9 4552

[11] Pfeiffer C and Grbic A 2014 Bianisotropic metasurfaces for optimal polarization control: analysis and synthesis Phys. Rev. Appl. 2 044011

[12] Xia R, Jing X, Gui X, Tian Y and Hong Z 2017 Broadband terahertz half-wave plate based on anisotropic polarization conversion metamaterials Opt. Mater. Express 7 977–88

[13] Lezec, H.J., Dionne, J.A. and Atwater, H.A., 2007. Negative refraction at visible frequencies. Science, 316(5823), pp.430-432.

[14] Fleury, R., Sounas, D.L. and Alu, A., 2014. Negative refraction and planar focusing based on parity-time symmetric metasurfaces. Physical review letters, 113(2), p.023903.

[15] Ziemkiewicz, D. and Zielińska-Raczyńska, S., 2015. Complex Doppler effect in left-handed metamaterials. JOSA B, 32(3), pp.363-369.

[16] Ziemkiewicz, D. and Zielińska-Raczyńska, S., 2015. Cherenkov radiation combined with the complex Doppler effect in left-handed metamaterials. JOSA B, 32(8), pp.1637-1644.

[17] Pendry J 2000 Negative refraction makes a perfect lens Physical Review Letters 85 3966–3969

[18] Fang N, Lee H, Sun C and Zhang X 2005 Sub-diffraction limited optical imaging with a silver superlens Science 308 534–537

[19] Lee, H., Xiong, Y., Fang, N., Srituravanich, W., Durant, S., Ambati, M., Sun, C. and Zhang, X., 2005. Realization of optical superlens imaging below the diffraction limit. New Journal of Physics, 7(1), p.255

[20] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 Metamaterial electromagnetic cloak at microwave frequencies Science 314 977–980

[21] Alu, A. and Engheta, N., 2008. Plasmonic and metamaterial cloaking: physical mechanisms ane potentials. Journal of Optics A: Pure and Applied Optics, 10(9), p.093002

[22] Liu, R., Ji, C., Mock, J.J., Chin, J.Y., Cui, T.J. and Smith, D.R., 2009. Broadband ground- plane cloak. Science, 323(5912), pp.366-369

[23] Alù, A. and Engheta, N., 2008. Multifrequency optical invisibility cloak with layered plasmonic shells. Physical review letters, 100(11), p.113901

[24] Kanté, B., Germain, D. and de Lustrac, A., 2009. Experimental demonstration of a nonmagnetic metamaterial cloak at microwave frequencies. Physical Review B, 80(20), p.201104

[25] Edwards, B., Alù, A., Silveirinha, M.G. and Engheta, N., 2009. Experimental verification of plasmonic cloaking at microwave frequencies with metamaterials. Physical Review Letters, 103(15), p.153901

[26] Hao, J., Wang, J., Liu, X., Padilla, W.J., Zhou, L. and Qiu, M., 2010. High performance optical absorber based on a plasmonic metamaterial. Applied Physics Letters, 96(25), p.251104

[27] Shrekenhamer, D., Chen, W.C. and Padilla, W.J., 2013. Liquid crystal tunable metamaterial absorber. Physical review letters, 110(17), p.177403

[28] Wang, B.X., Wang, L.L., Wang, G.Z., Huang, W.Q., Li, X.F. and Zhai, X., 2014. Frequency continuous tunable terahertz metamaterial absorber. Journal of Lightwave Technology, 32(6), pp.1183-1189

[29] Bossard, J.A., Lin, L., Yun, S., Liu, L., Werner, D.H. and Mayer, T.S., 2014. Near-ideal optical metamaterial absorbers with super-octave bandwidth. ACS nano, 8(2), pp.1517-1524

[30] Grady, N.K., Heyes, J.E., Chowdhury, D.R., Zeng, Y., Reiten, M.T., Azad, A.K., Taylor, A.J., Dalvit, D.A. and Chen, H.T., 2013. Terahertz metamaterials for linear polarization conversion and anomalous refraction. Science, 340(6138), pp.1304-1307

[31] Li, Y., Zhang, J., Qu, S., Wang, J., Chen, H., Xu, Z. and Zhang, A., 2014. Wideband selective polarization conversion mediated by three-dimensional metamaterials. Journal of Applied Physics, 115(23), p.234506

[32] Zheng, X.X., Xiao, Z.Y. and Ling, X.Y., 2016. Broadband and efficient reflective polarization converter based on a three-dimensional metamaterial. Optical and Quantum

Electronics, 48(10), p.461

[33] Valagiannopoulos, C.A., Mirmoosa, M.S., Nefedov, I.S., Tretyakov, S.A. and Simovski, C.R., 2014. Hyperbolic-metamaterial antennas for broadband enhancement of dipole emission to free space. Journal of Applied Physics, 116(16), p.163106

[34] Islam, M.M., Islam, M.T., Samsuzzaman, M. and Faruque, M.R.I., 2015. Compact metamaterial antenna for UWB applications. Electronics Letters, 51(16), pp.1222-1224

[35] Antoniades, M.A. and Eleftheriades, G.V., 2008. A folded-monopole model for electrically small NRI-TL metamaterial antennas. IEEE Antennas and Wireless Propagation Letters, 7, pp.425-428

[36] Freire, M.J., Marques, R. and Jelinek, L., 2008. Experimental demonstration of a $\mu = 1$ metamaterial lens for magnetic resonance imaging. Applied Physics Letters, 93(23), p.231108

[37] Algarin, J.M., Freire, M.J., Lopez, M.A., Lapine, M., Jakob, P.M., Behr, V.C. and Marqués, R., 2011. Analysis of the resolution of split-ring metamaterial lenses with application in parallel magnetic resonance imaging. Applied Physics Letters, 98(1), p.014105

[38] Melik, R., Unal, E., Perkgoz, N.K., Puttlitz, C. and Demir, H.V., 2009. Metamaterial-based wireless strain sensors. Applied Physics Letters, 95(1), p.011106

[39] Withayachumnankul, W., Jaruwongrungsee, K., Tuantranont, A., Fumeaux, C. and Abbott, D., 2013. Metamaterial-based microfluidic sensor for dielectric characterization. Sensors and Actuators A: Physical, 189, pp.233-237

[40] O'Hara, J.F., Singh, R., Brener, I., Smirnova, E., Han, J., Taylor, A.J. and Zhang, W., 2008. Thin-film sensing with planar terahertz metamaterials: sensitivity and limitations. Optics Express, 16(3), pp.1786-1795

[41] Karaaslan, M. and Bakir, M., 2014. Chiral metamaterial based multifunctional sensor applications. Progress In Electromagnetics Research, 149, pp.55-67

[42] W. Cai, V. M. Shalaev, Optical Metamaterials: Fundamentals and Applications(Springer, 2010)

[43] Lapine, M., Shadrivov, I.V. and Kivshar, Y.S., 2014. Colloquium: nonlinear metamaterials. Reviews of Modern Physics, 86(3), p.1093

[44] Litchinitser, N.M. and Sun, J., 2015. Optical meta-atoms: Going nonlinear. Science, 350(6264), pp.1033-1034

[45] Hsiao, H.H., Abass, A., Fischer, J., Alaee, R., Wickberg, A., Wegener, M. and Rockstuhl, C., 2016. Enhancement of second-harmonic generation in nonlinear nanolaminate metamaterials by nanophotonic resonances. Optics express, 24(9), pp.9651-9659

[46] Kozyrev, A.B., Shadrivov, I.V. and Kivshar, Y.S., 2014. Soliton generation in active nonlinear metamaterials. Applied Physics Letters, 104(8), p.084105

[47] Xia R, Jing X, Gui X, Tian Y and Hong Z 2017 Broadband terahertz half-wave plate based on anisotropic polarization conversion metamaterials Opt. Mater. Express 7 977–88

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