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Introduction

1.1 METAMATERIALS AND METASURFACES: A BRIEF OVERVIEW

Historically, the progress of mankind is linked with its ability to utilize and control the material properties efficiently. The development of new technologies and devices is inherently dependent on the development of new materials. Materials having specific properties are required for particular applications. These days microwaves materials are extensively needed due to their numerous applications ranging from communication to health care. The emergence of a new kind of engineered materials, named metamaterials, which provide unprecedented ability to control the specific electromagnetic properties paved the way for realizing advanced microwave devices.

The electromagnetic properties of a material are majorly characterized by its permittivity ε and permeability μ. The values of ε and μ for a naturally occurring material are fixed, and therefore, for specific applications, it is difficult to find materials with desired values of ε and μ. Metamaterials comprised of artificially structured inclusions have the ability to tune the values of ε and μ to desired values. The field is actively researched in the past decades and has attracted the interest of various researchers. The detailed discussions and up to date collection of references can be found in [Engheta and Ziolkowski, 2006; Lapine and Tretyakov, 2007; Steshenko and Capolino, 2009].

The metamaterial is an amalgamation of two words: 'meta' and 'material'. 'Meta' is a Greek word that symbolizes alteration or advancement to the term it is annexed. The metamaterial is a synthetically engineered composite material having sub-wavelength sized inclusions and exhibits exotic electromagnetic properties not found in natural materials [Cui *et al.*, 2010]. Due to the sub-wavelength size of the inclusions, metamaterials can be considered as homogeneous materials, and their properties are given by effective material parameters ε_{eff} and μ_{eff}. The electromagnetic properties can be controlled by varying the structural unit cells which facilitates the engineers to design materials having any desired values of ε_{eff} and μ_{eff}. The unit cell inclusions are scalable, making it possible to achieve the desired electromagnetic (EM) properties across the electromagnetic spectrum.

With further advancement in the field of metamaterials a new research branch emerged known as metasurfaces. Metasurface is a two-dimensional (2D) array of sub-wavelength unit cells arranged in a periodic, quasi-periodic or aperiodic manner and having thickness much smaller than the operating wavelength. They are capable of generating abrupt interfacial phase changes thus allowing complete manipulation of the local wavefront of the electromagnetic wave. The conceptual difference between metamaterials and metasurfaces is that the metamaterials are characterized by bulk effective parameters such as effective permittivity ε_{eff} and permeability μ_{eff} whereas metasurfaces are characterized by induced (electric and magnetic) surface currents. Metasurfaces have gained extensive research interest in the past few years due to low insertion losses, small volume and easy fabrication.

Metamaterials and metasurfaces with the ability to control the electromagnetic properties have produced a substantial impact on the development of the advanced microwave devices such as absorbers, filters, antennas, lenses, cloaking devices.

1.2 MOTIVATION AND OBJECTIVES

The present research work is mainly focused on applications of metamaterial and metasurface based structures for stealth technology. Stealth is an inevitable part of any military platform and with rapid development of detection technologies, advanced stealth features are required. The primary goal of stealth technology is to significantly reduce the radar cross section (RCS) of the object under surveillance such as missile, aircraft etc. RCS of a object is defined as the area intercepting that amount of power which, when scattered isotropically, produces an echo equal to that received from the object [Bole *et al.*, 2005]. A larger RCS indicates that an object is more easily detected. RCS reduction is basically achieved in four ways:

- **Shaping:** Altering the features of the target to reduce the back scattered field towards the source direction. But this could destroy the aerodynamic layout and results in increased design complexity.
- **Absorption:** Use of radar absorbing materials to convert the incident electromagnetic energy into heat. However, low-profile planar broadband absorbers are difficult to achieve.
- **Cloaking:** The incoming electromagnetic waves are smoothly bent around the target, thus reducing backscattering. The cloaks demonstrated so far have high losses, extremely narrow operational bandwidth, and large volume thus limiting their practical application.
- **Phase Cancellation:** Opposite phase cancellation for suppressing the backscattered waves, which is achieved using artificial designed surfaces; however, these surfaces have narrow operational bandwidth.

This Thesis address two different approaches of RCS reduction i.e. absorption and phase cancellation employing metamaterial and metasurface based structures.

For stealth applications, there are mainly two crucial performance parameters, i.e., absorption bandwidth and oblique incidence response, as the frequency and the direction of the incoming radar wave are unpredictable. Planar absorbers that are low profile, lightweight, and flexible along with wide absorption bandwidth and stable oblique incidence response are thus required for stealth applications. The earliest reported radar absorbers are Salisbury Screen [Salisbury, 1952], Jaumann [Chambers and Tennant, 1994], and Dallenbach absorbers [Dallenbach and Kleinsteuber, 1938] closely followed by ferrite tiles [Naito and Suetake, 1971] and carbon nano-tube loaded epoxy composite absorbers [Baek *et al.*, 2011]. However, they have narrow absorption bandwidth, fragile nature, and bulky structures, respectively limiting their practical applications. With the emergence of the metamaterial field, a new kind of absorbers, i.e., metamaterial-based absorbers were introduced [Landy *et al.*, 2008]. These absorbers are much thinner than their conventional counterparts and have improved absorption response along with the ability to tune the operational frequency across the EM spectrum.

The earlier reported metamaterial-based absorbers have narrow absorption bandwidth, as they operate near the vicinity of structural resonances. Various new design concepts were introduced, such as multi-scale [Bhattacharyya *et al.*, 2013a], multi-layer [Ding *et al.*, 2012], lumped component loaded [Yang and Shen, 2007] metamaterial absorbers. However, the practical implication of these structures is limited by increased design complexity, large thickness, and high fabrication cost.

There has been significant progress hitherto in the field of broadband metamaterial-based absorbers; still, the field is expanding. In the first part of this Thesis, broadband polarization-insensitive absorbers with a stable oblique incidence response based on disordered metamaterials are proposed. The disordered metamaterials are less explored compared to their periodic counterparts as periodicity simplifies both design and analysis process. The proposed absorbers are quite thin and have very simple geometric features.

For the absorption-based technique of RCS reduction, the incident EM energy is converted into heat, which leads to the rise in the temperature resulting in a strong thermal signature that could be detected by the infrared detectors. To mitigate this issue another RCS reduction technique i.e., Phase Cancellation is explored in the subsequent part of the Thesis. The idea is to combine structures having 180^o phase difference among corresponding reflection coefficient, resulting in complete phase cancellation in backward scattering direction. Various RCS reducing surfaces were demonstrated in literature so far; however they have limited bandwidth as well as high design complexity. The two distinct metasurfaces are proposed having simple geometry, low thickness and wideband RCS reduction bandwidth.

1.3 CONTRIBUTION OF THE THESIS

Contributions of this Thesis can be listed as follows

- Simple broadband metamaterial absorbers based on disordered metamaterial structure are proposed and analyzed. The effect of position disorder on the initial periodic metamaterial-based absorbers are investigated from order to disorder transition. The disordered metamaterial-based absorber is further analyzed for the effect of increased filling fraction and oblique incidences. The effect of the shape of the patch resonators on the absorption characteristics of the disordered metamaterial absorbers is also explored. It is observed that disorder, rather than being an unwanted parameter, can be used as a tool in enhancing the absorption properties of the otherwise periodic metamaterial absorbers.

- The proposed disordered patch resonator-based metamaterial absorbers are fabricated and experimentally characterized. Different disordered configurations are considered, i.e., overlapping and non-overlapping resonators. The effect of increasing filling fraction and oblique incidences is also investigated experimentally. A good degree of agreement is there between the experimental and the simulated results. It is observed that the absorption properties are mainly dependent on the coupling among the neighboring resonators.

- Two different metasurfaces based on two different design concepts i.e., array antenna theory and generalized Snell's Descartes law are proposed for RCS reduction. The proposed metasurfaces have a simple geometry, small thickness and broadband polarization independent RCS reduction bandwidth.

List of Publications

Journal Papers:

1. Shraddha Choudhary and Kirankumar R. Hiremath, "Numerical Investigation of Disordered Patch Resonator Absorbers" Applied Physics A, 125.9: 603, (2019).

2. Shraddha Choudhary and Kirankumar R. Hiremath, "Experimental Studies of Absorption Bandwidth Enhancement in Random Metamaterials" Applied Physics A, 124.12: 829, (2018).

Conference Papers:

1. Shraddha Choudhary and Kirankumar R. Hiremath, "Random phase gradient metasurface for broadband RCS reduction" in IEEE TENCON 2019, Kochi, India, October, 2019.

2. Shraddha Choudhary and Kirankumar R. Hiremath, "Random checkerboard metasurface for wideband RCS reduction" in 13th International Congress on Artificial Materials for Novel Wave Phenomena -Metamaterials 2019, Rome, Italy, September, 2019.

3. Shraddha Choudhary and Kirankumar R. Hiremath, "Effect of Position Randomness on Absorption Bandwidth of Disordered Metamaterials" in IEEE Indian Conference on Antennas and Propagation (InCAP), Hyderabad, India, Decemeber,2018.

4. Shraddha Choudhary and Kirankumar R. Hiremath, "Bandwidth Enhancement in Random Metamaterials" in 12th International Conference on Microwaves, Antenna, Propagation and Remote Sensing (ICMARS), Jodhpur, India, February, 2017.

1.4 OUTLINE OF THE THESIS

This Thesis is divided into six chapters. **Chapter 1** gives a brief introduction of the field, motivation and objective along with the contribution and outline of the Thesis.

Chapter 2 contains the literature review of the metamaterial field. Various earlier reported metamaterials and metasurfaces based structures are discussed. A brief overview of the absorption and phase cancellation RCS reduction techniques is provided.

In **Chapter 3** a disordered patch resonator based metamaterial absorbers are proposed. The proposed absorbers has wide absorption bandwidth along with stable oblique incidence response. It is demonstrated that the disorder can be used as a tool for enhancing the absorption bandwidth of a otherwise narrow band periodic absorber structure.

In **Chapter 4** the proposed disordered patch resonator based metamaterial absorbers are experimentally characterized. Different disorder configuration are investigated experimentally. The fabricated random metamaterial based absorber has wide absorption bandwidth and stable oblique incidence responses. A good degree of agreement is observed between the simulated and experimental results.

In **Chapter 5** wideband RCS reducing metasurfaces based on phase cancellation effect are demonstrated. Two different design concepts are used and two metasurfaces are proposed. The proposed metasurfaces has ultra wideband RCS reduction bandwidth along with polarization-insensitivity.

Chapter 6 concludes the Thesis along with the future scope of the work.

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