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I, Diptiranjan Samantaray, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of Dr. Somak Bhattacharyya from "25/07/2017" to “15/02/2022”, at the Department of Electronics Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports, dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

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Diptiranjan Samantaray

This thesis is dedicated to

[My Beloved Parents]

CONTENTS

Chapter 2: A Modified Slotted Patch Antenna with Defected Ground using Metasurface for Dual-band Applications

Chapter 3: A Gain-Enhanced Slotted Patch Antenna Using Metasurface as Superstrate Configuration

Chapter 4: Efficient High-Performance Modified Slotted Patch Antenna using Metasurface for Dual-band Applications

Chapter 5: A Planar Low-Profile Gain-Enhanced CPW-Fed Slotted Patch Antenna Using AMC Surface

Chapter 6: Conclusion and Future Scope

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Full Form
EM	Electromagnetic
GHz	Gigahertz
TE	Transverse Electric
TM	Transverse Magnetic
PCB	Printed Circuit Board
HFSS	High Frequency Simulation Software
CST	Computer Simulation Technology
ADS	Advanced Design Systems
MS	Metasurface
MTM	Metamaterial
MSA	Metasurface Antenna
2D	Two-Dimensional
3D	Three-Dimensional
AMC	Artificial Magnetic Conductor
EBG	Electromagnetic Band Gap
FSS	Frequency Selective Surface
HIS	High Impedance Surface
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
DPS	Double Positive
ENG	Epsilon Negative

Abbreviation	Full Form
MNG	Mu-Negative
DNG	Double-Negative
ENZ	Epsilon-near-zero
MNZ	Mu-near-zero
ZIM	Zero-Index Materials
CPW	Coplanar Waveguide
FP	Fabry-Perot
CSR	Complementary Spiral Ring Resonator
EHL	Embedded Hilbert Line
MED-WG-MTM	Magneto-electro-dielectric waveguided MTM
PRS	Partially Reflected Surface
AIS	Artificial Impedance Surface
RCS	Radar Cross Section
CAMS	Checkerboard-organized Metamaterial Superstrate
VNA	Vector Network Analyzer
SLL	Side Lobe Level
SRR	Split Ring Resonator
Tx	Transmitter
Rx	Receiver

LIST OF SYMBOLS

Symbol	Details
N	Numbers of cells
P	Periodicity
β_{SW}	Propagation constant of surface wave resonances
L_{MS}	The overall length of the MS structure
β_{TM}	Propagation constants of TM-wave
β_{TE}	Propagation constants of TE-wave
η	Intrinsic Impedance
ε_0	Permittivity in free space
ε_r	Relative permittivity
μ_0	Permeability of free space
μ_r	Relative permeability
β	Phase change experienced by the wave
k_0	Wavenumber
n	Refractive index
E	Electric field
H	Magnetic field
J	Surface current density
c	Speed of light in air
λ_0	Free-space wavelength

Symbol	Details
Z	Equivalent Impedance
θ	Angle of Incidence
E_i	Resultant of the reflected field vectors
i	Transmitted wave index
E_0	Amplitude of the electromagnetic wave
f	Frequency
z	Normalized Impedance
h	Bottom and top layer distance
d	Maximum length of the unit cell
W	Width of the Microstripline
t	Thickness of the substrate
S_{11}	Reflection coefficient
S_{21}	Transmission coefficient
v	Normal incidence angle
Ω	Ohm
L	Inductance
C	Capacitance
L_p	Equivalent Inductance of the patch
C_p	Equivalent Capacitance of the patch
C_g	Ground Capacitance
L_{eq}	Effective Inductance
C_{eq}	Effective Capacitance

Symbol	Details
φ_s	Reflection phases of MS Layer
φ_g	Reflection phases of the ground layer
R_m	Radiation resistance of the metasurface resonator
L_m	Inductance values of the MS slot resonator
C_m	Capacitance values of the MS slot resonator
C_{cm1}	Coupling capacitance along the vertical directions of the MS layer
C_{cm2}	Coupling capacitance along the horizontal directions of the MS layer

PREFACE

Modern communication has expanded significantly in recent years across multiple frequency bands due to wide impedance bandwidths, high device density, low latency, and the growth of transceiver antennas. As a result, the antenna designers have faced a substantial challenge in miniaturization without compromising the performance. Due to the rapid growth of existing wireless communication networks, the antenna designers have begun to put significant emphasis on the realization of compact and inexpensive multiband antennas due to their frequency reusability and increased channel capacity. Metasurface antennas (MSAs) are more versatile in comparison to the conventional antennas in meeting a variety of requirements for wireless communications applications. Additionally, by placing MSAs, the constraint on the relative position of transmitting and receiving antennas can be reduced, hence decreasing the possibility of inconsistent wireless network disturbances. The metasurface is a two-dimensional periodic structure in which the lattice spacing is too minimal to scatter electromagnetic waves. Additionally, MS structures exhibit flexible reflection characteristics and controlled dispersion properties in various applications, including absorbers, polarisation converters, antennas, and filters. MSA designs have the ability to generate highly directed radiation patterns with far-field characteristics.

The metasurface is used in the development of high-performance antennas, which include a variety of radiating elements such as patch antennas, slot antennas, and coplanar waveguide-fed antennas (CPW-fed) antennas. Planar technology is used to study and implement all the structures. The MS is placed on top or at the bottom, or both are taken together, depending on the application. Planar antennas are frequently conformable, low-profile, simple to integrate, and inexpensive to manufacture.

However, they have low directivity and generate surface waves, which is incompatible with the system's requirements. The use of electromagnetic band-gap materials, artificial magnetic conductors (AMCs), resonant layers, fabry-perot (FP) cavities, and metasurfaces can improve the performance of planar antennas. On the other hand, monopole antennas have a restricted bandwidth and a low gain. Thus, radiating elements with MS can enhance the performance of antennas to a certain point.

The author, from time to time, has reported the present work part-wise at national and international conferences as well as in reputed journals, namely, International Journal of RF and Microwave Computer-Aided Engineering, IEEE Transactions on Antennas and Propagation, Radio Science, and IEEE Antenna Wireless Propagation Letters.

The author will consider his modest effort a success if it proves to be useful in the modern era of wireless communication systems with multi-standard operations.

Chapter 1

Introduction

In recent days, modern communication has ushered in a paradigm shift in terms of frequency allocation diversity, characterized by vast impedance bandwidths, high device densities, low latency, and a massive number of transceiver antennas [1]-[5]. The exponential growth of wireless communication devices necessitates the development of low-profile antennas with enhanced bandwidth and gain [1]-[5]. Earlier, numerous techniques such as coplanar parasitic patches, stacked patches, dielectric resonators, and the incorporation of various types of slots were used to design and develop broadband antennas [4]-[7]. However, these antennas were large, complicated to design, along with a limited bandwidth [4]-[7]. As a result, the substantial design and development of dual-band antennas have conveyed numerous challenges to the advancement of modern communication systems hence, introducing various operating frequency ranges and numerous wireless standards [8]-[14].

This chapter discusses the theoretical backgrounds of two-dimensional (2D) metasurfaces, which are the surface representations of metamaterials [15]-[17]. Later in this chapter, typical metasurface antennas are studied, and their inherent limitations emphasize the advantage of integrating metasurface (MS) with the radiating element [18]-[31]. The MS can significantly improve the antenna performance in terms of impedance bandwidth, gain, and efficiency for