Design, Development, and Analysis of the Spoof Surface Plasmon Polaritons-based Antennas

Thesis Submitted in Partial Fulfillment for the
Award of the Degree of

Doctor of Philosophy

By

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It is certified that the work contained in the thesis entitled **"Design, Development, and Analysis of the Spoof Surface Plasmon Polaritons-based Antennas"** by **Mr. Rajkumar Jatav (Roll No. 18091504)** has been carried out under my supervision, and this work has not been submitted elsewhere for a degree.

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I, **Rajkumar Jatav**, hereby declare that the work contained in the dissertation entitled **"Design, Development, and Analysis of the Spoof Surface Plasmon Polaritons-based Antennas"** is an authentic record of my own work carried out at the Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi, India, as the requirement for the award of the degree of Doctor of Philosophy in Electronics Engineering, submitted in the Indian Institute of Technology (Banaras Hindu University) Varanasi for the session 2024-25 under the supervision of **Prof. Manoj Kumar Meshram**, Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi, India.

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Acknowledgements

I am profoundly thankful to God ALMIGHTY; this study would not have been possible without His grace and blessings. It is a privilege and an honor to extend my appreciation to everyone who contributed substantially to this academic journey.

First and foremost, I express my deepest gratitude to my supervisor, Prof. Manoj Kumar Meshram, for allowing me to work under his supervision in this prestigious institution. I immensely thank him for his unwavering support, encouragement, suggestions, and discussion. This dissertation was completed thanks to his direction, inspiration, and critical assessment of my work at every level. I could not have imagined having a better advisor and mentor for my doctoral studies. I want to express my appreciation to the members of my research performance evaluation committee (RPEC), Dr.Smrity Dwivedi, Department of Electronics Engineering, and Prof. Devender Singh, Department of Electrical Engineering, for their wise advice and perceptive remarks during my progress presentations, which were extremely helpful in steadily directing me toward my research. My profound gratitude goes out to Professor S. P. Singh for his insightful advice and valuable time.

I would also like to acknowledge Prof. S.P. Singh, Prof. K.P. Singh, Prof. M.K. Meshram, and Dr. Amit Kumar Singh for teaching informative and interesting subjects during my coursework that immensely helped my research. I am thankful to the Department of Electronics Engineering, IIT (BHU), Varanasi faculty members, who have contributed directly or indirectly through their discussion and suggestions at some point in my research. I want to express my gratitude and sincere thanks to the entire staff of the Department of Electronics Engineering, with special mention to Mr. Jayram, Technical Superintendent of the Microwave Laboratory, for his assistance during my research work and Mr. Gyan Chand Vishwakarma, Senior Technician of the Device Laboratory, for his cooperative efforts that contributed to the success of my antenna prototypes.

I am also thankful to my seniors, Dr. Situ Rani Patre, Dr. Arun Kumar Saurabh, *Dr. Akanksha Singh, Dr. Saurabh Kumar Srivastava, and Dr.Rahul Dubey, for their friendly behavior and academic support. My most profound appreciation is extended to my co-authors, Mr. Praveen Singh Rathore and Mr. Ravi Mali, with whom I have shared many tense and joyful moments, and they always cared well for me. Special mention goes to my near and dear junior, Mr. Ravi Mali, for his unconditional support. We had a lot of discussions over tea, solving problems together. Your companionship will never be forgotten. I owe you my heartfelt gratitude. I would like to share special thanks to my labmates and fellow Dr. Abhishek Saroj, Mr. Ajitesh, Mrs. Rupam Bharati, Miss. Urvashi Singh, Dr. Joginder Singh Rana, and Dr. Varun Kumar Singh for their cooperation, interesting discussions, inspiration, and support.*

Last but not least, I cannot express enough how grateful and indebted I am to my late mother, Mrs. Kashi Devi, and my father, Mr. Narayan Lal, for their unwavering support and sacrifices of their happiness for me. Without their unwavering love, care, guidance, and encouragement, I would not be who I am today. My utmost respect goes to my elder brother, Mr. Krishna Murari, for his sacrifices, care, love, and belief in me. I am also thankful to all my family members, sisters, sister-in-law, nephews, and nieces, who have always been with me on this journey and made it joyful, although they are miles away.

My acknowledgment would only be complete with mentioning my wife. No words can describe my love and sincere gratitude to my loving wife, Khushi; you kept me going through the most challenging times and cared for me at the cost of your health and happiness. I appreciate your love and trust and the fact that you are my pillar of support and source of happiness.

Finally, I am extremely grateful to the merciful Kashi Vishwanath for providing me with the opportunity, strength, knowledge, and ability to complete this research study satisfactorily in the holy city of Varanasi.

Rajkumar Jatav

Date: 14/11/2024

This thesis is dedicated to

My mother, *the late Smt. Kashi Devi*,

as a token of my deep, heartfelt love and respect for her

Without her blessings, eternal love, and tremendous support,

I could never have this much optimism for life and enthusiasm

for my work…

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NOMENCLATURE

List of Abbreviations

CPW	Coplanar Waveguide
SP	Surface Plasmon
SPP	Surface Plasmon Polariton
SSPPs	Spoof Surface Plasmon Polaritons
EM	Electromagnetic
LWAs	Leaky-Wave Antennas
SIW	Substrate Integrated Waveguide
CST	Computer Simulation Technology
TEM	Transverse Electro-Magnetic
3-D	Three Dimensional
2-D	Two Dimensional
1-D	One Dimensional
MIMO	Multiple-Input-Multiple-Output
TL	Transmission Line
ECC	Envelope Correlation Coefficient
TARC	Total Active Reflection Coefficient
CCL	Channel Capacity Loss
THz	Terahertz

EBG	Electromagnetic Band-Gap
MS	Metasurface
LPDA	Log-Periodic Dipole Array
ADS	Advanced Design Software
FBR	Front-to-Back Ratio
RA	Reflectarray
GBW	Gain Bandwidth
SPD	Spatial Phase Delay
TA	Transmit Arrays
AE	Aperture Efficiency
BS	Beam Scanning
FBW	Fractional Bandwidth,
PCB	Printed Circuit Board
UWB	Ultra-wideband
BPF	Band-pass Filter
SNR	Signal-to-noise Ratio
UV	Ultraviolet

List of Symbols

dB	Decibel
ϵ	Permittivity
ϵ_{eff}	Effective permittivity
ϵ_r	Relative permittvity
ϵ_h	Hole's permittivity
μ_h	Hole's permeability
c	Speed of light
ψ^R	Correlation matrix of the receiving antenna
k_0	Free space wave number
k_{sspp}	SSPPs wave number
k_x	X-direction wave number
$k_{\|\|}$	Transverse wave number
K	Complete elliptic integral of the first kind
ω_p	Plasma frequency
ϕ_{spd}	Spatial phase delay
ϕ_{sp}	Successive phase
ϕ_{RA}	Phase shift on the reflectarray aperture
λ_0	Free space wavelength
λ_g	Guided wavelength
β_n	n^{th} harmonic wave number
β_{sspp}	SSPPs wave number
α	Attenuation constant
S_i	Separation between the feed antenna and the i^{th} element
$\hat{s}_0$	Beam direction
$tan\delta$	Loss tangent
Γ_a^t	Total active reflection coefficient

Preface

Surface plasmon polaritons (SPPs) are unique surface waves that exist at the metal (a conductive material) and dielectric (a non-conductive material) interface and occur in the optical frequency range. These waves propagate along the side of the interface and exponentially diminish in the direction perpendicular to the interface. When the frequency is dropped to the microwave region, the metals behave more like perfect conductors than plasmas with negative permittivity. As a result, surface plasmon polaritons lose their properties. So, plasmonic metamaterials (or engineered SPPs or spoof SSPs) have been proposed to accomplish SPPs at low frequencies. The spoof surface plasmon polaritons (SSPPs)-based devices are trending nowadays because of their very attractive features, such as depressed mutual coupling, low profile, less complexity, and high signal integrity. Moreover, the SSPPs-based structures can concentrate electromagnetic (EM) waves into subwavelength scales, which is a boon in miniaturizing advanced circuits and systems. The SSPPs can play a vital role as an alternative platform for the next generation of electronic circuits and systems because of their high field confinement, enabling them to overcome the compactness limits of traditional circuits. In recent years, numerous devices have been developed based on SSPPs concepts, such as antennas, filters, couplers, power splitters etc. In antennas, leaky-wave antennas (LWAs) and endfire antennas have received considerable interest because of their benefits of easy feeding, low profile, and ease of design and fabrication using the spoof SPP-based waveguides. In this thesis, leaky-wave antennas (LWAs) and endfire antennas are designed based on the same SSPPs waveguide. To explore the inherent features of the SSPPs, a novel application, an endfire MIMO antenna, is designed and discussed. A novel application of the endfire MIMO antenna to stimulate the reflectarray has also been designed and investigated for beam scanning applications.

This thesis begins with a historical overview of the natural surface plasmons and their characteristics to the spoof surface plasmon polaritons (SSPPs) at lower frequency regimes. An overview of the different devices based on SSPPs is included, along with a review of the relevant literature. A brief overview of MIMO antennas, their features, and their diverse performances is discussed. A quick history of the reflectarray antenna, including its operation principle and methods of phase tuning, is also included in this chapter. The motivation and organization of the thesis are also outlined in the **Chapter 1**.

A variable-width strip dipole-based leaky-wave antenna using spoof surface plasmon polaritons is proposed. It is a single-port, miniaturized, and high-gain frequency beam-scanning leaky-wave antenna with 55° beam-scanning capability in the operating region. The second port of the highly efficient antenna is eliminated to shorten its physical length. The designed antenna is intended to be used as a low-profile antenna for radar and wireless communications, which is discussed in **Chapter 2**.

A novel application, a three-element, low-profile, coplanar endfire multiple-input-multiple-output (MIMO) antenna, is designed and discussed to investigate the intrinsic properties of the SSPPs. This work achieves high isolation without any decoupling structure. The measured isolation has been observed to be well below −35 dB. Wider beam widths for ample azimuth and elevation coverage with a stable pattern in the endfire direction are achieved in the operating band, as presented in **Chapter 3**.

A novel application of the endfire MIMO antenna to stimulate the single-layer, low-profile beam scanning reflectarray (RA) has been designed and investigated. The SSPPs-based endfire MIMO antenna mitigates the aperture blockage, achieves high isolation between the feed elements, and accomplishes continuous one-dimensional (1-D) beam scanning. The proposed RA benefits nano-satellite applications, as explored in **Chapter 4**.

Finally, this thesis encapsulates the research and observations that were carried out. It merely points out the conclusions and suggests directions for future investigations, as stated in **Chapter 5**.