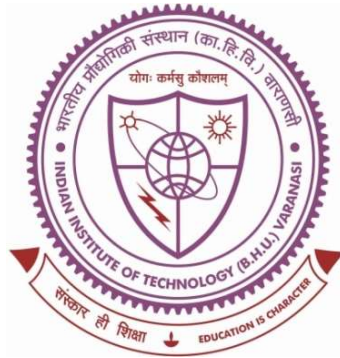


Design, Development, and Analysis of the Spoof Surface Plasmon Polaritons-based Antennas



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

Doctor of Philosophy

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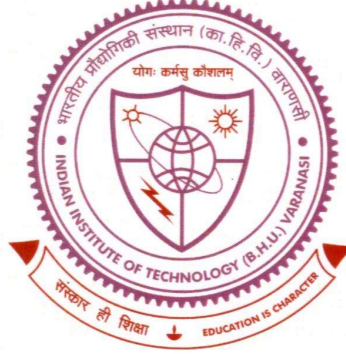
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I, **Rajkumar Jatav**, hereby declare that the work contained in the dissertation entitled "**Design, Development, and Analysis of the Spoof Surface Plasmon Polaritons-based Antennas**" is an authentic record of my own work carried out at the Department 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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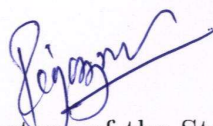
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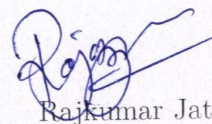
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Date: 14/11/2024


Rajkumar Jatav

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...

CONTENTS

List of Figures	v
List of Tables	xi
Nomenclature	xiii
1 Introduction	1
1.1 Surface Plasmons	2
1.2 Surface Plasmon Polaritons (SPPs)	3
1.3 Spoof Surface Plasmon Polaritons (SSPPs)	6
1.4 SSPPs-based Devices	8
1.4.1 SSPPs-based leaky wave antennas (LWAs)	13
1.4.2 SSPPs-based endfire antennas	15
1.5 Multiple Input Multiple Output (MIMO) System Implementation using SSPPs-based Endfire Antennas	17
1.5.1 The MIMO system performance metrics	20
1.6 Reflectarray System Design using SSPPs-based Endfire MIMO feed	22
1.6.1 The operational principle	23
1.6.2 Methods of phase tuning	25
1.6.3 Beam scanning reflectarray	26
1.7 Motivation	27

1.8	Organization of this Thesis	28
2	Realization of Leaky-Wave Antenna Based on Variable-Width Strip Dipole	31
2.1	Introduction	32
2.2	Working Principle and Designed Description	34
2.2.1	Dispersion characteristics	34
2.2.2	Working principle	35
2.2.3	Two-port antenna design	36
2.2.4	Single-port antenna design	39
2.3	Results and Discussion	41
2.4	Conclusion	50
3	A Low-profile High-isolation Endfire MIMO Antenna	51
3.1	Introduction	52
3.2	The Unit Cell Characteristics and Antenna Design	53
3.2.1	The unit cell characteristics	53
3.2.2	Antenna design discussion	54
3.3	Simulation and Experimental Results	60
3.3.1	Discussion on reflection, coupling coefficients, surface current, and near E-field distribution	60
3.3.2	Radiation characteristics	64
3.3.3	Diversity performances	67
3.4	Conclusion	68
4	Beam-Scanning Reflectarray Antenna Stimulated Using a Low-profile Endfire MIMO Antenna	71
4.1	Introduction	72
4.2	Design and Working Principle of Reflectarray (RA)	74
4.2.1	The RA design discussion	74
4.2.2	RA working principle	76

4.2.3	MIMO feed antenna	79
4.3	Simulation and Experimental Results	80
4.4	Conclusion	87
5	Conclusion and Future Scope	89
5.1	Conclusion	90
5.2	Future Scope	92
	References	95
	Publications	117

LIST OF FIGURES

- 1.1 (a) The EM field at the interface between a metal and a dielectric, and
 (b) the decay length in the dielectric and metal [19]. 3
- 1.2 Dispersion curve of SPPs at the metal-dielectric interface [20]. 5
- 1.3 (a) The 3-D structure to implement the Spoof SPPs, and (b) spoof
 surface plasmon dispersion relation on a structural surface [24]. 7
- 1.4 A set of spoof SPPs structures (a) the experimental sample shows the
 square brass tubes and cylindrical rods [25], (b) E-field superfocusing
 on a corrugated cone [27], (c) a square lattice of square holes [30], and
 (d) metallic wedge with a recurring pattern of grooves [31]. 8
- 1.5 A set of spoof SPPs waveguides (a) the metallic grates that have a
 finite thickness (L) [33], (b) the complementary plasmonic waveguide
 with four different shapes of grooves [35], (c) the primary corrugated
 strips as slots aligned parallel to one another [39], (d) the conformal
 surface plasmons waveguide on a flexible dielectric film [34], (e) the
 SW-TL where SSP structure connected to the microstrip line [37], and
 (f) meander slow wave transmission line [38]. 10
- 1.6 The broadband band-pass filter [45]. 11

1.7	(a) a schematic and manufactured prototype of the bandwidth reconfigurable BPF based on a T-shaped SSPP resonator [44], and (b) a schematic and fabricated prototype of the spoof SPP-based varactor-loaded tunable filter [46].	11
1.8	(a) the plasmonic Y-splitter of H-shaped and composite H-shaped structure [47], and (b) the ultrathin frequency splitter in microwave frequencies [55].	12
1.9	The manufactured prototype to amplify SSPPs (a) the rear view, and (b) the front view and its magnified perspective [56].	12
1.10	A broad view of the spoof SPP emitter [59].	13
1.11	An illustration of a plasmonic waveguide with sinusoidal modulation utilizing a corrugated metal strip [60].	14
1.12	Schematic of the tilting unit-based LWA [75].	14
1.13	A set of SSPPs based LWAs (a) configuration of the periodically loaded patches based LWA [76], (b) a frequency-controlled beam-scanning antenna fed by the standing wave of SSPPs [77], (c) wide-angle beam scanning LWA [78], (d) single-beam LWA with lateral scanning [79], (e) continuous scanning LWA based on second-mode [80], and (f) broadband circularly polarized (CP) LWA [81]	15
1.14	A set of SSPPs based endfire antennas (a) a metamaterial-based endfire antenna [83], (b) low-profile traveling wave endfire antenna [84], (c) broadband frequency scanning endfire antenna [85], (d) a vertically polarized endfire antenna [86], (e) a single layer high gain endfire antenna [87], and (f) a planar low-profile endfire antenna [88].	16
1.15	MIMO system with $(M \times N)$ antenna elements.	17
1.16	Electromagnetic coupling between two antennas (a) patches with common ground on the same substrate, (b) patches with partial ground on a distinct substrate, (c) patches on a partial substrate with common ground, and (d) separate antennas.	19

1.17	The experimental setup of the first waveguide-based reflectarray [103].	23
1.18	The basic architecture of a planar reflectarray antenna [105].	23
1.19	MIMO feed reflectarray configuration.	24
1.20	Phase tuning approaches for reflectarray (a) patches with varying lengths of phase delay lines, (b) patches of varied sizes, and (c) split rings with different degrees of rotation.	26
1.21	Organization of thesis work.	30
2.1	Configuration of the unit cell.	34
2.2	Dispersion characteristics.	35
2.3	Configuration of the two-port antenna structure.	37
2.4	Parametric study of the inclined angles of strip dipoles.	38
2.5	Configuration of the proposed single-port antenna structure.	40
2.6	Analysis of the offset distance parametrically.	40
2.7	Parametric study of the strip dipole separation.	40
2.8	Simulated S-parameters of the two-port antenna.	41
2.9	Normalized attenuation constant (α) versus frequency plot.	42
2.10	Simulated E-field distribution at different frequencies in the XZ and XY-planes.	42
2.11	The three-dimensional radiation pattern of the two-port antenna at different frequencies.	43
2.12	Fabricated prototype of the proposed SSPPs-based leaky wave antenna.	44
2.13	Simulated and measured S-parameters of the single-port antenna. . .	44
2.14	Simulated E-field distribution at different frequencies in the XZ and XY-planes.	45
2.15	Beamwidth comparison between the two-port and single-port antennas.	46
2.16	Side lobe level comparison among different styles.	46
2.17	The three-dimensional radiation pattern of the single-port antenna at different frequencies.	47

2.18	Simulated and measured normalized radiation pattern at different frequencies.	48
2.19	Beam scanning variation.	48
2.20	Simulated and measured realized gain and efficiency.	49
3.1	Unit cell design and its dispersion characteristics.	54
3.2	Layout of the proposed MIMO configuration.	54
3.3	(a) An endfire antenna configuration [88], and (b) taper length L_1 parametric study.	55
3.4	(a) Unit cell equivalent circuit model, (b) unit cell current distribution, and (c) schematic of proposed antenna system.	57
3.5	(a) Equivalent circuit of the radiator section, (b) equivalent circuit and the full-wave simulation S_{11} comparison, and (c) impact of matched grooves heights on impedance bandwidth.	58
3.6	Fabricated prototype of the proposed MIMO configuration.	60
3.7	Simulated and measured S-parameters of the MIMO configuration.	61
3.8	Surface current distribution at 10.4 GHz (a) O.C. when $S_p = 11.25$ mm, (b) O.C. when $S_p = 6.25$ mm, (c) O.C. when $S_p = 1.25$ mm, (d) interacting structures (I.S.), (e) interacting ground (I.G.), and (f) S-parameter comparison of different MIMO configurations.	62
3.9	Surface current distribution at 10.4 GHz when (a) Ant 1 is stimulated, (b) Ant 2 is stimulated, and (c) Ant 3 is stimulated.	63
3.10	Simulated near E-field distribution in the XY-plane at 10.4 GHz when (a) Ant 1 is stimulated, (b) Ant 2 is stimulated, and (c) Ant 3 is stimulated.	63
3.11	Simulated 3-D radiation pattern of the proposed MIMO configuration.	64
3.12	Simulated and measured 2-D radiation pattern in xz and xy planes.	65
3.13	3-dB beamwidth variation with frequency of the of the proposed MIMO configuration.	66

3.14 (a) Realized gain and efficiency variation in the operating band, and (b) the FBR curve.	66
3.15 The proposed MIMO system performances characteristics (a) ECC extracted by S-parameters, (b) ECC extracted by 3D field, (c) TARC, and (d) CCL.	68
4.1 Schematic of the application scenario.	73
4.2 Unit cell design of the proposed RA.	74
4.3 Unit cell (a) length (L) optimization, (b) width (W) optimization, (c) reflection magnitude, (d) reflection phase, (e) incidence angle effect on magnitude, and (f) incidence angle effect on phase.	76
4.4 Proposed RA (a) front view, (b) rear view, and (c) edge taper.	77
4.5 MIMO feed reflectarray configuration.	78
4.6 Phase distribution on the RA aperture.	78
4.7 Aperture blockage in the case of conventional pyramidal horn feed.	79
4.8 (a) Endfire MIMO source [168], (b) MIMO s-parameters [168], (c) sim- ulated xz -plane radiation pattern, and (d) simulated yz -plane radiation pattern.	80
4.9 Fabricated prototype (a) frontal view, (b) back view, and (c) measure- ment setup in anechoic environment.	81
4.10 The reflection coefficient of the MIMO source with RA.	81
4.11 Simulated E-field distribution at 10.4 GHz (a) left element port 2 (P_2) excited, (b) center element port 1 (P_1) excited, and (c) right element port 3 (P_3) excited.	82
4.12 (a) Simulated 3-D patterns of the proposed RA at 10.4 GHz, and (b) corresponding wv -patterns.	83
4.13 Simulated and measured 2-D radiation patterns in the yz -plane at 10.4 GHz (a) left element port 2 (P_2) excited, (b) center element port 1 (P_1) excited, and (c) right element port 3 (P_3) excited.	84
4.14 The simulated and measured xz -plane pattern when port 1 (P_1) excited.	84

4.15 Simulated 2-D beam scanning radiation pattern in the yz -plane. . . .	85
4.16 Realized gain of the proposed RA and the MIMO feed.	86
4.17 Radiation and aperture efficiencies of the proposed RA.	86

LIST OF TABLES

2.1 Comparison with the other reported planar leaky wave antennas . . . 49

3.1 Comparison with the other low-profile endfire antennas 59

3.2 Comparison study with the reported MIMO antennas 68

4.1 Comparison study of the proposed RA and the similar planar feed RA
antennas 87

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 permittivity
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**.

