International Journal of Multidisciplinary Engineering in Current Research - IJMEC
Volume 10, Issue 6, June-2025, http://ijmec.com/, ISSN: 2456-4265

Efficient Design of H-Plane SIW Horn Antenna Array at mm Waves

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ABSTRACT

A H-plane Substrate Integrated Waveguide (SIW) horn antenna with improved performance is designed in this paper. A modified SIW feeding technique and corrugated flare is presented for improvements in the gain, bandwidth, radiation efficiency and cross-polarization reduction. The feeding section of the horn antenna uses stepped transformer for the improvement in the impedance bandwidth. The corrugated horn section is used to enhance the radiation characteristics of the proposed antenna. The center frequency of the proposed SIW horn antenna is 18.48 GHz. It has a gain of 8.69 dBi, impedance bandwidth of 2.82 % and the radiation efficiency of 95.67%.The SIW based horn antennas are gaining attention over the waveguide based traditional horn antenna because its two-dimensional nature making it is easy to integrate with other two- dimensional RF components. Continuous efforts have been made by antenna engineers to improve the performance of SIW based horn antenna.

1-INTRODUCTION

The Substrate Integrated Waveguide (SIW) Corrugated H-Plane Horn Antenna is a next-generation antenna design that combines the benefits of planar circuit technology with the high-performance characteristics of waveguide structures. This design is particularly suited for millimeter-wave (mmWave) applications where compact size, high gain, and efficient radiation characteristics are essential.

In this project, the H-plane horn configuration is selected due to its ability to concentrate radiation in a single plane, resulting in a highly directive beam. The addition of corrugations along the H-plane significantly improves the antenna's performance by:

1. Reducing side-lobe levels, which minimizes interference and enhances signal clarity.
2. Enhancing impedance matching, leading to lower reflection losses and better efficiency.
3. Improving beam symmetry, making the antenna ideal for high-precision radar and communication systems.

The SIW technology plays a crucial role in miniaturizing the antenna, making it compact and lightweight while retaining the low-loss characteristics of traditional waveguides. The fabricated antenna is expected to demonstrate high radiation efficiency, excellent gain, and low return loss, making it suitable for 5G, satellite communication, and automotive radar applications.

2-LITERATURE SURVEY

A literature survey provides an extensive review of previous research and developments in the design and optimization of H-Plane Substrate Integrated Waveguide (SIW) Horn Antenna Arrays. Wireless communication systems continuously demand high-performance antennas capable of supporting increased data rates, low latency, and enhanced spectral efficiency. SIW technology has gained prominence due to its compact design, high directivity, and ability to integrate seamlessly with modern RF circuits.

In recent years, researchers have proposed several innovative techniques to enhance SIW-based antenna performance. Notable advancements include phased array integration, dielectric lens enhancements, beamforming techniques, and low-loss waveguide structures. Additionally, SIW-based feeding modifications, including stepped transformers and corrugated horn structures, have significantly improved gain, impedance bandwidth, and radiation efficiency. This chapter reviews major research contributions in these areas, highlighting key improvements and challenges in mmW communication systems.

Several research methodologies have been explored to improve SIW horn antenna performance. A primary focus has been on increasing gain while mitigating signal attenuation and radiation losses at high frequencies. Among the commonly studied methods, microstrip patch antenna (MPA) arrays have been extensively used to enhance gain, though they come with challenges such as increased complexity and transmission losses. As an alternative, dielectric lenses and corrugated SIW horn designs have been developed to improve directivity while maintaining a compact footprint.

1 Dielectric Lenses and Gain Enhancement: Dielectric lenses have been widely adopted to improve the directivity and gain of SIW horn antennas. Traditional dielectric lenses, however, suffer from high manufacturing costs and bulkiness. Recent advancements have introduced lightweight and cost-effective 3D-printed dielectric lenses, significantly reducing manufacturing complexity. Integrated lens antennas (ILAs) have demonstrated notable improvements in radiation efficiency, gain, and suppression of back- lobe radiation, making them ideal for mmW applications. Studies from IEEE research papers confirm that integrating dielectric lenses with SIW-based antennas enhances beam focusing capabilities, thereby improving network coverage and signal reliability.

2 Phased Array and Beam Steering**:** Phased array antennas play a crucial role in dynamic beam steering, enabling directional signal transmission for efficient point-to-point communication. SIW-based phase shifters provide a cost-effective solution for phased array implementation, allowing real-time beamforming and interference mitigation. Beamforming is essential in next-generation communication systems such as 5G and 6G, where high-speed data transmission and low latency are critical.

3 Low-Loss Hollow Integrated Waveguides (HIW): Minimizing dielectric losses remains a fundamental challenge in SIW technology. Hollow Integrated Waveguides (HIW) have emerged as a potential solution to improve signal integrity and reduce insertion loss. While traditional methods such as low-temperature co-fired ceramic (LTCC) and lithographic fabrication techniques have been employed, their high costs and fabrication complexity limit widespread adoption. Alternative approaches, such as modified SIW feeding techniques with optimized via placements and stepped transformer transitions, have been proposed to improve impedance matching and minimize propagation losses.

4 Millimeter-Wave Wireless Power Transfer (WPT): The rapid expansion of the Internet of Things (IoT) has necessitated the development of efficient wireless power transfer (WPT) solutions. High-gain, low- cost mmW antenna arrays are being designed to facilitate energy harvesting for battery-free IoT sensor nodes. Studies indicate that mmW WPT systems can efficiently power IoT devices over short distances, reducing dependency on battery replacements..

5 Corrugated SIW Horn Antenna Designs: One of the latest advancements in SIW horn antenna research

involves the implementation of structured corrugations at the flared section The IEEE paper reviewed in this study presents a modified SIW feeding technique combined with a corrugated flare, leading to enhanced radiation characteristics and cross-polarization reduction. The proposed SIW corrugated horn achieved a gain of

8.69 dBi, impedance bandwidth of 2.82%, and a radiation efficiency of 95.67%. These findings highlight the effectiveness of integrating corrugations with SIW horn antennas to optimize performance in mmW communication applications.

3-EXISTING SYSTEM

3D printed lens

H-plane SIW Horn Antenna systems are expected to enhance reliability and drastically increase data rates to an ever-growing number of mobile users and Internet-of-Things devices. To address this increase in telecommunication traffic requirements, portions of the underused millimetre-wave spectrum have been offered by regulators and used by service operators worldwide for fixed wireless access . Candidate bands include 28 GHz, 38 GHz, 39 GHz, as well as 26 GHz, recently recommended by the United Kingdom's regulatory body.

However, millimetre-wave communication systems have limited range due to higher path loss and atmospheric attenuation and absorption. This drawback has motivated the research to develop efficient and high-gain antennas, especially in the Ka band for Horn Antenna. Currently, several solutions have been proposed to address this issue of limited range due to higher path loss at millimetre-wave frequencies. A particularly attractive and cost-effective method is gain enhancement using dielectric lenses, placed on top of source antennas such as microstrip patch antennas (MPAs) or substrate integrated waveguide (SIW) slot antennas. These are also known as integrated lens antennas (ILAs).

The dielectric lens increases the directivity of the source antenna by transforming the spherical wave front of the radiated wave into a planar one. MPAs and SIW slot antennas are preferable for source antennas, due to the ease of their fabrication, straightforward integration with other planar circuits, low mass, and low profile.

3D printed lens antennas are already extensively used in the upper millimetre-wave frequency region, as evidenced by recent research. A waveguide fed 3D printed lens antenna for the 60 GHz millimetre-wave Industrial, Scientific and Medical (ISM) band. Industrial poly-jet 3D printing was used to manufacture the hemispherical lens, which provided gain enhancement of the source antenna. Another 3D printed ―meta-lens‖ for gain enhancement at Ka band. The lens provided gain improvement of 7.5 dB at 32.5 GHz.

Recently, a combination of 3D printed dielectric lens and dielectric polarizers have also been reported for polarization conversion, in addition to gain enhancement at millimetre-wave

frequencies. The drawbacks of these polarizers are fabrication complexity, lower gain enhancement, and more losses when compared to a stand-alone dielectric lens. The polarizers also increase the overall footprint of the antenna.

Most of the dielectric lens antennas reported in the literature have high manufacturing cost and excessive weight due to the use of expensive and dense dielectric materials such as quartz, in addition to costly fabrication techniques. Furthermore, gain improvement due to the addition of these lenses is not always quantified and reported in these works.The use of commercially-available 3D printers for the quick and cost- effective prototyping of dielectric lens antennas has recently increased rapidly. However, most reported results use industry- grade printers such as Stratasy or slower and more expensive fabrication techniques such as stereolithography (SLA). Dielectric lenses fabricated through desktop 3D printers using fused deposition modelling (FDM) technology tend to be printed as solid objects (100% infill density), which increases the cost and weight of ILAs and decreases the radiation efficiency due to the high dielectric losses of FDM materials.

In this chapter, the design and implementation of low-cost, low-loss, easy to fabricate and integrate dielectric lens antennas at 28 GHz are reported. The fabrication process features commercially available desktop 3D printer, CEL Robox RBX02-DM, using standard FDM process. The ILAs were fabricated with a reduced infill percentage of 50%, which speeds up prototyping time, and simultaneously decreases dielectric loss, manufacturing cost and weight. At the same time, the lens antennas provide considerable gain enhancement of 6 dB, for two different types of source antennas - a 2x1 MPA array and a SIW slot antenna array. These were jointly designed and optimized to operate over the cluster of H-Plane candidate bands around 28 GHz. A parametric analysis on infill density and infill pattern of dielectric lenses and free space dielectric characterization of Polylactic Acid (PLA) with reduced infill densities have also been experimentally verified and are presented.

Dielectric Characterization of PLA Having Different Infill Densities

The dielectric constant and loss tangent of PLA filament given in supplier‘s datasheet is εr = 2.7 and tanδ=0.01 at 1 GHz. To accurately design and simulate the 3D printed dielectric lens antennas with reduced infill density, the effect on the complex relative permittivity of the 3D printed samples needs to be quantified for mmW frequency band. For this purpose, three PLA samples with dimensions of 50 x 50 x 25 mm3 were fabricated using 25%, 50%, and 75%
infill density. The resulting fabrication parameters of these samples are summarized in Table 3.1.

The Keysight Technologies 85071E free-space measurement software was used to measure the dielectric properties of the PLA samples having different infill densities over the frequency range of 26 - 32 GHz. Figure
3.1 shows the measurement setup for the complex relative permittivity, with results from the free-space measurements. A network analyser and two standard gain horn antennas facing each other with sample them were used for transmission and reception of signals through PLA samples for dielectric measurements. Keysight 85071E software converts the transmission and reflection coefficients to dielectric properties i.e. εr and tanδ. Gated Reflect Line (GRL) technique was used to calibrate the system before starting actual dielectric characterization measurements. Further details on GRL calibration are given in Appendix C. Each sample was measured 3-4 times from different sides and using different distances, i.e. 25-40 cm, between the antennas to minimize the measurement error due to the anisotropic nature of PLA samples.

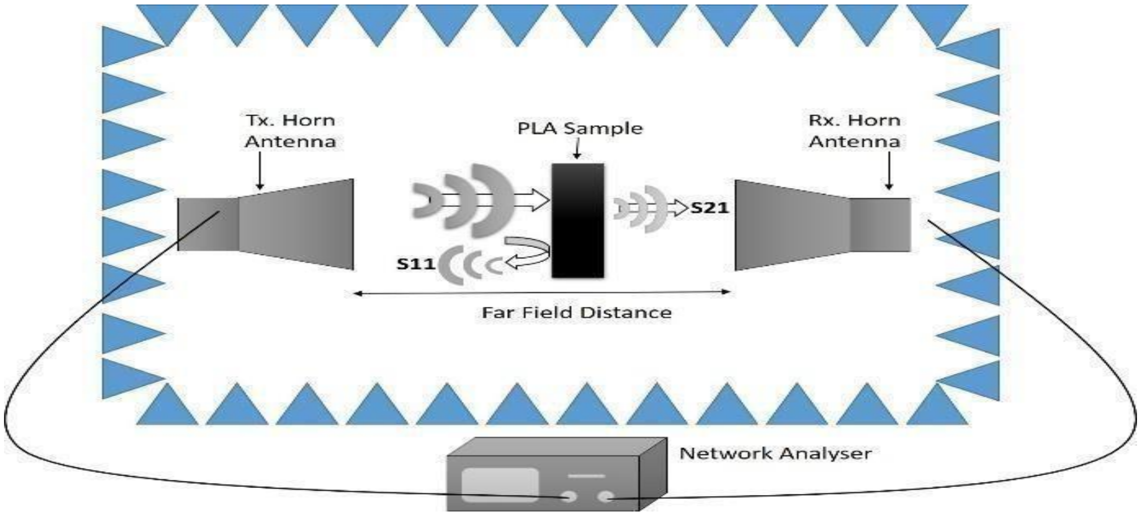

Fig 3.1: Free space measurement setup for dielectric characterization of PLA samples having different infill densities.

Measured results show that the relative permittivity and dielectric loss linearly decrease with a reduction in the infill density of PLA samples from 100% to 25%. The values of dielectric constant and loss tangent for different infill densities at 28 GHz are given in Table 3.1. Reduction of infill density also shows a clear impact on the fabrication time, weight and production cost, as summarized in Table 3.1.

4-SIW PHASE SHIFTER

components and devices implemented in Substrate Integrated Waveguide (SIW) technology are emerging as a promising candidate for microwave and millimetre-wave transmission. SIW technology is widely used for the design and implementation of RF and microwave components such as phase shifters, filters and antennas arrays because of its low profile, high Q-factor, low-cost fabrication and straightforward integration with other circuits. SIW is a more competitive technology as compared to other planar technologies such as microstrip line transmission or coplanar waveguide (CPW) due to lower loss transmission and higher power handling capability. The drawbacks of a microstrip line transmission and CPW include undesired radiation and high insertion and propagation loss at millimetre-wave and terahertz frequencies, which can significantly degrade the efficiency of the components. The conventional metallic rectangular waveguides despite having low loss and high Q-factor are not suitable for the design of low cost, light weight applications due to their bulky size, relatively high cost and their difficult integration with microwave and millimetre-waves planar circuits.

Electronically controllable SIW phase shifter

Phase shifters, which are circuits that change the phase of a signal with minimum insertion loss, are fundamental to the operation of electronically steerable phased array antennas at microwave and millimetre-wave frequencies . Components and devices implemented in SIW technology are emerging as a promising candidate for high Q-factor circuits and low loss antenna feeding networks, due to the reduced amount of conduction loss . SIW phase shifters are widely used because of their low profile, high Q-factor, low-cost fabrication and straightforward integration with other circuits . Conventionally, these circuits use fixed metal posts to perturb the propagating electromagnetic field in order to provide a fixed value of phase shift between their input and output.

However, there are only a handful of reports on electronically controllable SIW phase shifters. A circuit using a design approach similar to the one reported in this work has previously been , of the SIW circuits.

Block Diagram for initial design of antenna

demonstrated over the X-band frequency range , achieving a maximum phase difference of 450 using4 PIN diodes; however the diodes used were housed in large ceramic packages, which in

turn imposed a limit on the minimum size, and hence maximum frequency

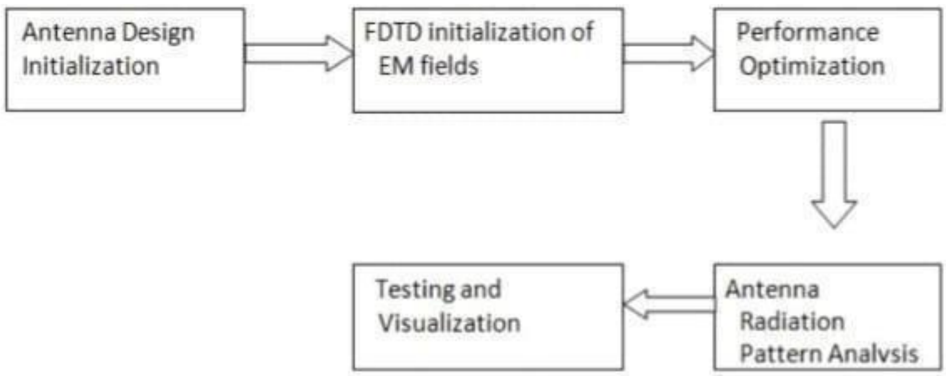

Fig 4.1: Block Diagram for initial design of the antenna

Antenna Design Initialization : This is the foundational phase of the antenna development process, where the basic parameters of the antenna are defined. In this step, engineers select the type of antenna based on the application, such as a patch antenna, dipole antenna, or horn antenna. Key characteristics like the physical dimensions, materials (substrate and conductor), and operating frequency range are also established. This phase may involve theoretical calculations or initial modeling using computer-aided design (CAD) tools. The goal is to create a preliminary antenna structure that meets the intended specifications before moving into simulation.

FDTD Initialization of Electromagnetic Fields : After the antenna design is initialized, the next step involves simulating the behavior of electromagnetic (EM) fields using the Finite- Difference Time-Domain (FDTD) method. FDTD is a numerical analysis technique used to solve Maxwell‘s equations in the time domain. This step requires setting up a computational grid over the design space, applying boundary conditions like Perfectly Matched Layers (PML) to absorb outgoing waves, and defining signal sources for excitation. This simulation provides a time-based visualization of how EM waves propagate through and around the antenna structure, helping identify issues such as reflections or mismatches.

Performance Optimization : Once the initial EM field behavior is understood through FDTD simulation, the next step is performance optimization. This involves modifying the antenna design to improve key performance metrics such as

ISSN: 2456-4265
IJMEC 2025

return loss gain, bandwidth, efficiency, and VSWR (Voltage Standing Wave Ratio). Engineers may iteratively tweak dimensions, change materials, or adjust the feeding technique based on simulation results. The optimization phase ensures that the antenna performs reliably within its intended frequency range and delivers strong, efficient signal transmission or reception.

Antenna Radiation Pattern Analysis : Following performance optimization, the focus shifts to analyzing the antenna's radiation pattern. This pattern shows how the antenna radiates energy in space and helps determine its directionality. A radiation pattern may be omnidirectional, directional, or highly focused depending on the antenna type. This step involves plotting 2D or 3D radiation diagrams that depict the intensity of the radiated EM fields in various directions. Key parameters such as main lobe direction, side lobe levels, and beam width are evaluated to ensure the antenna meets directional performance requirements.

Testing and Visualization : The final step in the antenna design process is testing and visualization. This phase involves visualizing the EM field distribution, current flow on the antenna surface, and observing performance parameters like gain and impedance across the frequency band. Advanced simulation tools offer powerful visualization capabilities to inspect the internal and external field behavior. This stage may also include comparing simulation results with real-world measurements if a physical prototype is built. The goal is to validate the design before deployment or production, ensuring it functions as intended under real operating conditions.

5-RESULT AND DISCUSSIONS

This project focuses on the realization and analysis of a corrugated Substrate Integrated Waveguide (SIW) H- plane horn antenna using the Finite Difference Time Domain (FDTD) method and advanced beam synthesis techniques. The simulation and numerical modeling are implemented in MATLAB to investigate the electromagnetic behaviour of the antenna and to synthesize the radiation characteristics of slot arrays.

Analysis

The MATLAB project is implementing a Finite-Difference Time-Domain (FDTD) simulation for a Horn Antenna, specifically dealing with electromagnetic wave propagation. The code is divided into two major components:

FDTD-Based Time-Domain Electromagnetic Simulation

This section of the code implements a 2D FDTD method to analyse the propagation of the electric field (Ez) through the SIW horn antenna structure:

Grid Size: A 200×200 computational domain is defined (ie=je=200).

Material Properties: Permittivity (epsilon), permeability (mu_0), and conductivity (sigma) are specified for different regions to simulate wave propagation through dielectric and metallic structures.

Source Excitation: A Gaussian pulse is injected at the feed point (ez(150,100)) to excite the structure and simulate the time-varying response of the antenna.

Perfectly Matched Layer (PML): PML boundary conditions are implemented to absorb outgoing waves and prevent reflections at the edges of the domain.

Horn Geometry: The horn flare is modelled by adjusting the permittivity and conductivity of specific grid points, creating a corrugated structure.

Field Visualization: A time-evolving 2D plot of the Ez field is generated, showing how energy propagates through the horn and radiates outward.

This simulation offers insight into wave behaviour, efficiency, directionality, and interaction with horn geometry, crucial for validating the electromagnetic performance of the antenna.

ISSN: 2456-4265
IJMEC 2025

Beam Synthesis and Radiation Pattern Analysis

The second section analyses the radiation characteristics of linear slot arrays based on three amplitude tapering techniques:

1. Dolph–Chebyshev Synthesis
2. Taylor One-Parameter Synthesis
3. Taylor Line Source Synthesis

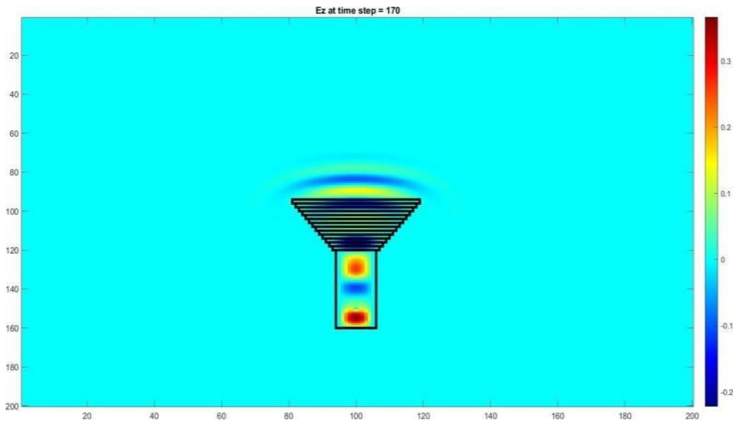

Fig 1 SIW Based H-Plane Horn Antenna Design

Ez Field Visualization (FDTD Simulation Output)

The output consists of a series of 2D color plots displaying the Ez field values at each time step during an FDTD (Finite-Difference Time-Domain) simulation, typically generated using imagesc(ez). These plots are used to visualize the dynamic propagation of electromagnetic waves through the horn antenna structure. The simulation reveals strong field confinement within the waveguide, indicating effective mode excitation, and shows a well- formed directional beam emerging from the horn's aperture. The presence of corrugated steps along the horn enhances the shaping of the radiated wavefront and helps minimize back lobes. The smooth transition of the field from the waveguide to the horn aperture highlights good impedance matching, while the formation of a focused, directional beam suggests low cross- polarization and efficient gain performance, affirming the antenna‘s effectiveness in radiating energy forward with minimal losses.

EM Wave Distribution

The simulation uses the FDTD method to model the TEz mode propagation in a 2D horn antenna, where the electric field Ez radiates from a Gaussian source placed inside a waveguide structure and expands through a flared horn into free space. The image captures the wavefront at a specific time step, showing clear directional radiation, while PML boundaries absorb reflections to mimic open space.

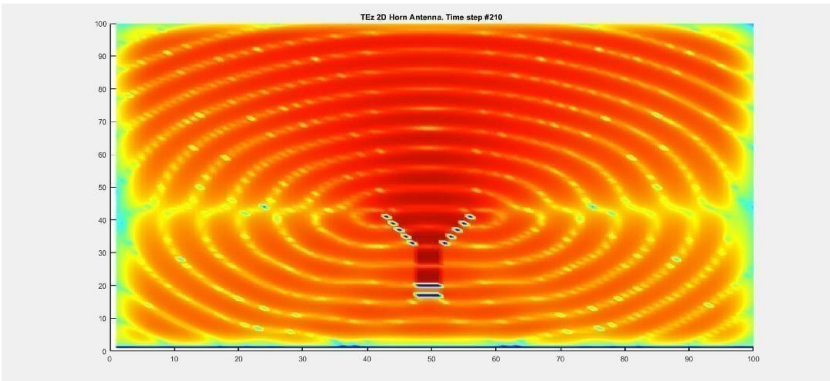

Fig 2: Electromagnetic Field Distribution of a Horn Antenna

The MATLAB code includes both the FDTD simulation and array synthesis using Dolph–Chebyshev and Taylor line source techniques to optimize the slot distribution, amplitude tapering, and offset, enabling control over the radiation pattern, sidelobe levels, and directivity. This combination allows for effective visualization and design of a high-gain, low-sidelobe horn antenna.

Case 1: Dolph- Chebyshev Synthesis

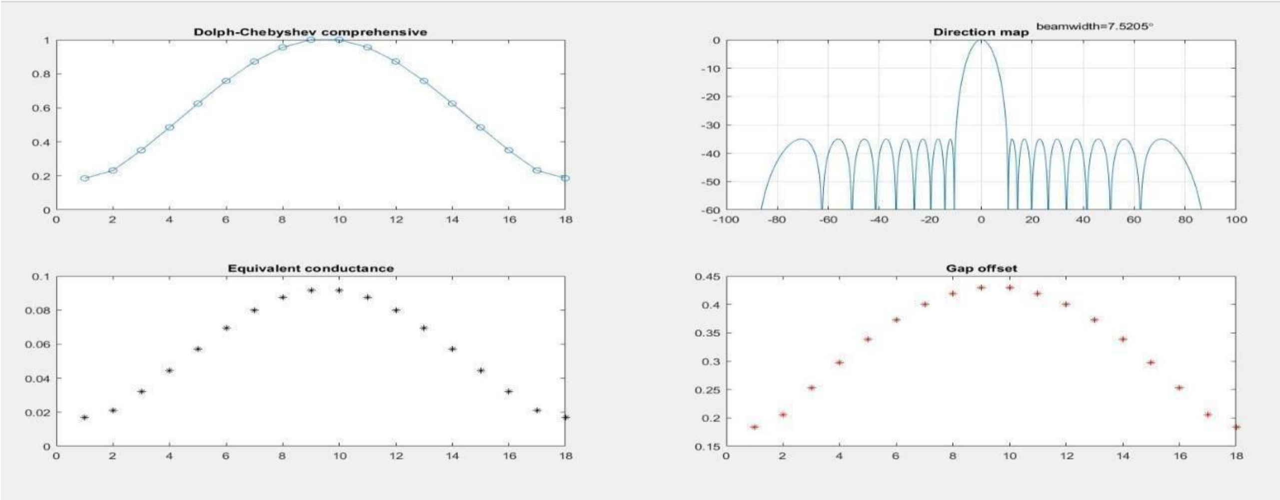

Fig 3: Dolph- Chebyshev Synthesis, Direction map, Equivalent conductance, Gap offset The two radiation pattern plots show differences in beamwidth, sidelobe levels, and overall performance. The fig displays a narrower main lobe, lower sidelobe and backlobe levels, and smoother, more symmetrical radiation, indicating higher directivity and better overall antenna performance. In contrast, the second image has a wider main lobe, more pronounced sidelobes and backlobes, and slightly less symmetry, suggesting reduced directivity and potentially less efficient radiation control. Overall, the first pattern is better suited for applications requiring focused beams and minimal interference, such as radar or directional communication systems.

Case 2: Taylor One- Parameter synthesis

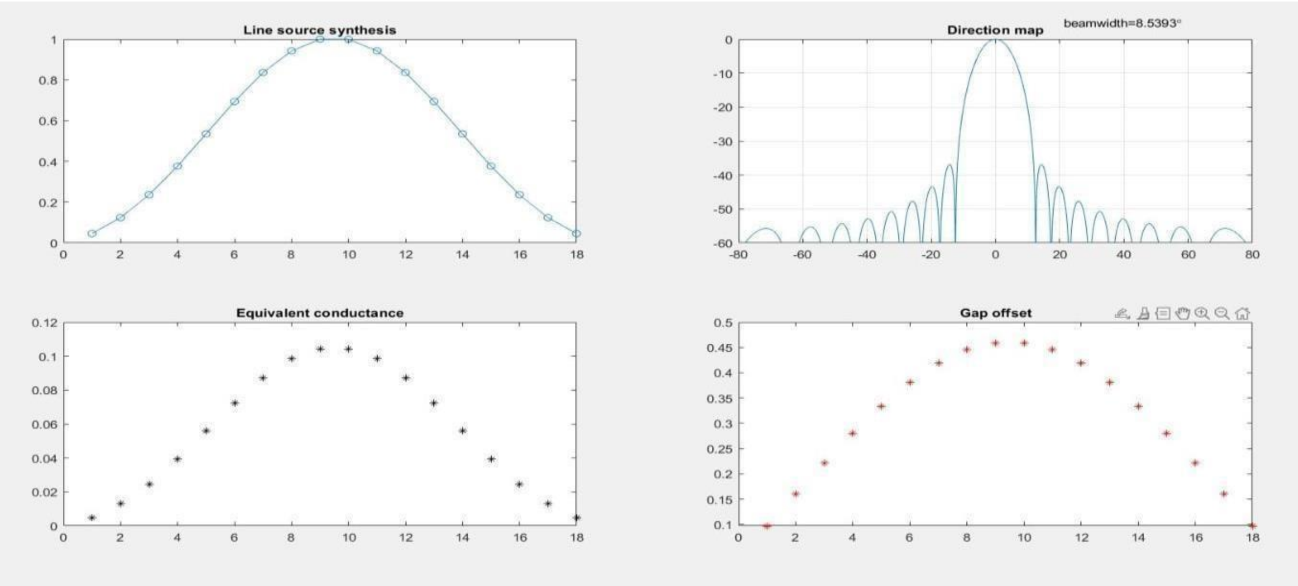

Fig 7.4: Taylor One- Parameter synthesis, Direction map, Equivalent conductance, Gap offset

Taylor One-Parameter Synthesis is a method used in antenna array design to achieve a desired sidelobe level by shaping the array's amplitude distribution with a single adjustable parameter. It modifies the uniform amplitude taper to produce a pattern with controlled sidelobe levels while maintaining a narrow main beam. This synthesis balances beamwidth and sidelobe suppression by using a Taylor weighting function, which approximates an optimal distribution for practical antenna arrays, making it especially useful in radar and communication systems where sidelobe control is critical to reduce interference.

Case 3: Taylor Line-Source Synthesis

Taylor Line Source Synthesis is a technique used in antenna array design to create a radiation pattern with a controlled sidelobe level and a narrow main beam by shaping the current distribution along a linear antenna array.

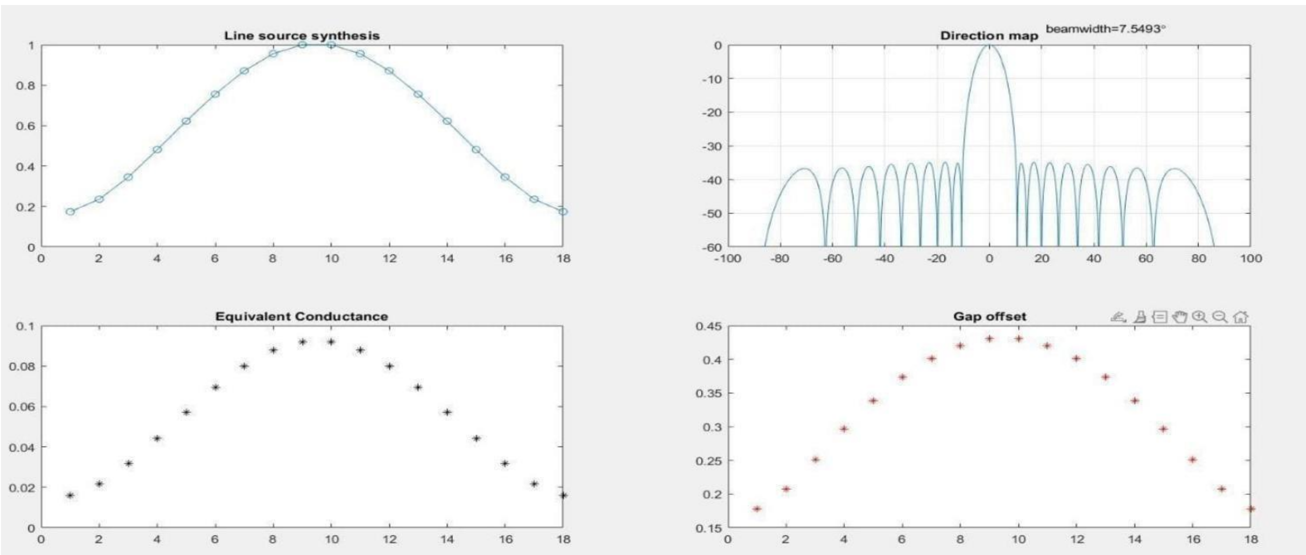

Fig 5: Taylor Line-Source Synthesis, Direction map, Equivalent conductance, Gap offset

It extends the Taylor method, originally developed for continuous line sources, by defining the amplitude taper of the array elements based on a set of parameters that control sidelobe levels and beamwidth. The synthesis uses a specific weighting function derived from the Taylor distribution to achieve an optimal balance between reducing sidelobes and maintaining directivity, making it especially effective for linear arrays in applications like radar and communication systems where minimizing interference from sidelobes is important.

3D Radiation Pattern

The plot displays the 3D radiation pattern of the antenna, generated using far-field analysis from a full- wave electromagnetic simulation, commonly performed in software like CST, HFSS, or MATLAB Antenna Toolbox. It provides a complete spatial visualization of how the antenna radiates energy in all directions. The plot reveals a highly directive main lobe with minimal backlobes and sidelobes, indicating that the antenna is focusing most of its energy in a preferred direction — a hallmark of directional antennas like horn or reflector types. This kind of analysis is crucial for applications like radar, satellite communication, or point-to-point wireless links, where focused radiation is essential for efficiency.

2D Polar Radiation Pattern

The plot displays the polar plot is a 2D representation of the antenna‘s radiation pattern in either the E- plane (electric field) or H-plane (magnetic field). It is derived from far-field simulation data, typically by slicing the 3D radiation pattern along a specific plane. The sharpness and narrowness of the main lobe represent high directivity and a narrow beamwidth. This kind of 2D analysis is useful for calculating Half- Power Beamwidth (HPBW) and identifying the angular extent of effective radiation. The sidelobe levels and angular nulls are also clearly visible, helping in understanding the antenna‘s performance in minimizing interference and unwanted radiation.

Gain vs. Angle/Frequency Plot

This plot presents the gain of the antenna, which is a measure of how well it converts input power into radio waves in a particular direction. The data is extracted from far-field analysis and can either be a gain vs. angle plot (at a fixed frequency) or gain vs. frequency plot (at a specific angle, usually boresight). The peak gain, reaching around 15 dB, indicates strong directivity and high radiative efficiency. Such analysis is critical in evaluating how the antenna performs over its operating range and helps determine its suitability for high-gain applications. Gain plots also reveal the antenna's angular consistency and operational bandwidth.

S11 (Reflection Coefficient) Plot

The S11 parameter plot shows how much power is reflected back from the antenna input port due to impedance mismatch, based on frequency-domain analysis using a network analyzer simulation. A dip in S11 below -10 dB across a frequency range signifies that the antenna is well-matched to its feedline and radiates most of the input power. The frequency at which the lowest S11 value occurs is typically the antenna's resonant frequency. This analysis helps in defining the operational bandwidth of the antenna and is vital to ensure efficient power transfer and minimal standing wave formation on the feedline.

VSWR Computation from S-Parameters

This graph shows the **VSWR**, which is a function of the S11 parameter and indicates how well the antenna is impedance matched. The plot is derived from the same S-parameter analysis but presented in terms more familiar to RF engineers. A VSWR value close to 1 over a frequency range confirms that the antenna is efficiently matched and minimizes power loss due to reflections. Typically, a VSWR below 2 is considered acceptable for most applications. This analysis complements the S11 plot and provides an intuitive understanding of the antenna‗s matching characteristics across frequencies.

6-CONCLUSION

In this study, a Substrate Integrated Waveguide (SIW) based H-plane horn antenna was designed with a modified feeding mechanism and a corrugated flare to enhance performance. The proposed structure demonstrated significant improvements in key antenna parameters including impedance bandwidth, gain, radiation efficiency, and cross-polarization suppression. The simulation results showed a gain of 8.69 dBi, an impedance bandwidth of 2.82%, and a high radiation efficiency of 95.67%. These outcomes confirm that the integration of stepped transformers and corrugated horn geometry effectively improves the antenna‗s operational characteristics compared to conventional designs.

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