

Original Article

Improved Directivity and Power Handling in Slot Array Antennas with Dielectric Integration

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Received: 28 March 2026

Revised: 24 July 2026

Accepted: 13 August 2026

Published: 30 September 2026

Abstract - The slot array antenna is very important in the present communication networks, and it offers high gain and directivity of the radiation pattern. However, in the design, challenges such as low power-handling and directivity are encountered. This paper proposes a novel technique to address these problems by introducing dielectric loading into the slot-array antenna. As the antenna structure, a geometric pattern of slots or openings is cut into a conductive surface. The use of dielectric materials is also carefully considered to enhance power-handling capability and directivity, thereby overcoming impedance-mismatch and radiation-efficiency issues. The optimized design is achieved through an extensive optimization approach, called Slot Array Antenna with Dielectric Loading (SAAbDL), which aims to maximize power handling capacity and directivity. This design uses advanced computational techniques to optimize the arrangement and properties of the dielectric materials in the antenna. Dielectric-loaded prototype slot-array antennas are fabricated using appropriate manufacturing techniques and materials. Efficiency, gain, radiation pattern, and return loss are used to characterize these antennas. The findings of the present study demonstrate the benefits of dielectric loading in increasing the power-handling and directivity of slot-array antennas. The proposed methodology and fabricated prototypes are envisioned to be utilized in high-power communication systems, radar systems, and other application areas where robust, directional radiating characteristics of the antenna are required.

Keywords - Dielectric materials, Slot Array Antennas, Power handling ability and directivity.

1. Introduction

The slot-array antenna is very important in modern communication networks and offers high gain and a well-directed radiation pattern. However, in the design, challenges such as low power-handling and directivity are encountered. This paper proposes a novel technique to address these problems by introducing dielectric loading into the slot-array antenna. As the antenna structure, a geometric pattern of slots or openings is cut into a conductive surface. The use of dielectric materials is also carefully considered to enhance power-handling capability and directivity, thereby overcoming impedance-mismatch and radiation-efficiency issues. The optimized design is achieved through an extensive optimization approach, called Slot Array Antenna with Dielectric Loading (SAAbDL), which aims to maximize power handling capacity and directivity. This is an antenna design technique that leverages advanced computational methods to optimize the arrangement and properties of dielectric materials. Dielectric-loaded prototype slot-array antennas are fabricated using appropriate manufacturing techniques and materials. Efficiency, gain, radiation pattern,

and return loss are used to characterize these antennas. The findings of the present study demonstrate the benefits of dielectric loading in increasing the power-handling and directivity of slot-array antennas. The proposed methodology and fabricated prototypes are envisioned to be utilized in high-power communication systems, radar systems, and other application areas where robust, directional radiating characteristics of the antenna are required.

Today's wireless communication, radar, aerospace, and satellite applications demand high-gain, low-profile, high-directivity, and stable radiation characteristics from antennas. Due to their small size and high radiation efficiency, Slot Array Antennas (SAAs) have attracted significant attention. In the past, beam steering was accomplished by mechanically controlled or electronically scanned antenna arrays [1]. Antenna miniaturization and radiation efficiency have been improved by using Dielectric Resonator Antennas (DRAs) [2], and the optimization of Dielectric Material has enhanced the reliability of the structure [3]. Thermal management [4] has been a focus of high-power radar antennas, and substrate-



integrated techniques have advanced despite the dielectric losses associated with antenna integration [5]. For millimeter-wave applications, microstrip patch arrays [6], waveguide slot arrays [7], narrow-beam antennas [8], dual-polarized antenna arrays [9], and optimized waveguide-fed antenna structures [10] have been developed to enhance antenna performance. Moreover, PA-integrated antennas [11], mechanically steerable antennas [12], SIW phased arrays [13], cavity-backed slot antennas [14], and on-chip SIW antennas [15] have improved gain, beam steering, and antenna integration. Recently, compact microstrip antennas [16], reconfigurable liquid-metal antennas [17], optimization-based antenna designs [18], optimization using the Social Spider Algorithm [19] and circularly polarized bow-tie radiating elements [20] have also attracted the attention of researchers. However, existing approaches, in most cases, can enhance only specific antenna parameters and are still limited by issues such as dielectric losses, impedance mismatch, limited power-handling capability, complex fabrication, and poor performance at millimeter-wave frequencies.

1.1. Research Gap

The design of slot-array antennas has made significant strides, but most research focuses on optimizing specific design parameters: gain, bandwidth, polarization, and beam steering. Improved power handling, matching, radiation efficiency, and directivity with a compact, practically manufacturable structure have not yet been thoroughly investigated. Furthermore, dielectric losses, phase inaccuracies, mutual coupling, and power leakage are encountered in several reported SIW and microstrip antenna designs, restricting their applications to next-generation millimeter-wave communication and high-power radar systems. Problem Statement: Thus, the realization of a simple slot-array antenna capable of simultaneously enhancing power handling, gain, radiation efficiency, directivity, and impedance matching remains a challenging research task. To overcome these limitations, reliable, high-performance antenna systems are needed for emerging wireless communication and radar applications at millimeter-wave frequencies.

To address the aforementioned research gap, this paper proposes a novel, one-layer Substrate-Integrated Waveguide (SIW)-based Slot Array Antenna with Dielectric Loading (SAAbDL). The proposed antenna is configured as a 16×16 slot array and includes PPS-40GF dielectric loading in the slots, an optimized H-plane T-junction feeding network, and backside choke structures to enhance electromagnetic field confinement and minimize undesirable power leakage. These design features provide impedance matching, radiation efficiency, directivity, and power-handling capability, while keeping the antenna compact. Unlike current solutions, which focus on optimizing individual antenna performance, the proposed SAAbDL optimizes several key performance parameters within a single antenna structure, making it ideal

for high-frequency millimeter-wave communication and radar applications. This paper is organized as follows: a review of the pertinent literature on slot-array antennas and dielectric-loading techniques is provided in Section 2. In Section 3, a model of the system and a mathematical formulation of the problem are presented. The proposed SAAbDL design methodology is described in Section 4. The experimental setup, performance evaluation and comparative analysis are discussed in Section 5. Finally, in Section 6, the paper concludes and outlines future research directions.

2. Related Works

// Below are a few of the existing works.

Increased efficiency in dielectric-filled radial waveguides at millimetre-wave frequencies is discussed by Herranz-Herruzo et al. [21] with an all-metal Radial-line Slot-Array (RLSA) antenna. It uses a lattice of metallic nails rather than dielectric material, while retaining the slow-wave properties of the radial waveguide. This ad hoc method-of-moments processor achieves efficient optimization, yielding an observed peak overall efficiency of more than 80% at 30 GHz. A construction made easy thanks to the all-metal design, which is composed of two parts: an upper slotted plate fastened with a few screws and a lower waveguide with a bed of nails. This invention provides a simple yet efficient method for generating high-gain circularly polarized radiation patterns, eliminating the need for complex feeding networks or polarizers.

A novel method proposed by Anand et al. [22] for a specific frequency range incorporates substrate-integrated waveguides to realize waveguides on a Printed Circuit Board (PCB) or other planar substrates, and a meta-element antenna based on a Coplanar Waveguide (CPW) to improve antenna performance. FR4 is an epoxy used as a substrate in Printed Circuit Boards (PCBs). It is known for its excellent mechanical properties, dimensional stability and electrical insulation. Lastly, it shows strong responses and efficiency across three frequencies. It is used in the S-band, which encompasses ISM (Industrial, Scientific, and Medical), WiMAX (Worldwide Interoperability for Microwave Access), and WLAN (Wireless Local Area Network), which support radar and satellite communications applications because of its mechanical strength, electrical insulation, and cost-effectiveness. Guruswamy et al. [23] implemented an Ultra-Wideband system that made the system compact using a Circularly Tapered Vivaldi Antenna with Director (CTVAD) to detect tumours in the breast by using waves passing through the body.

A very well-planned effort was made to achieve a narrow band in the system with the desired gain. It is compact, so it has low return loss at a good frequency. The software used in this design method is CST Microwave Studio, and most of the signals were generated and recreated in MATLAB to produce the full image.

Chaturvedi et al. [24] enhanced the bandwidth of a cavity-backed slot antenna by using a Substrate Integrated Waveguide (SIW) cavity in the substrate. SIW technology is used for this implementation in a planar antenna with a nonlinear structure. This is done with a “dual T-shaped slot”, which is usually a type of antenna that has two T-shaped slots or openings in its structure. These slots are designed for specific positions to achieve a desired radiation pattern or frequency response. These types of antennas are frequently used with radar and wireless communication systems and offer bandwidth diversity, polarization diversity, and radiation properties benefits.

Milias et al. [25] have developed an innovative series-fed antenna array for broad-beam steering in the X-band. First, a theoretical model of the array is developed to understand the performance trade-offs, including phase shifters between array members. Then, a mechanically operated phase shifter is introduced, which works by sliding a metallic overlay to change the phase. This phase shifter offers large phase shifts with small displacement. This design gives the antenna array a constant high gain over a broad scan range, low side-lobe levels, and good efficiency. It does have a narrow bandwidth; however, it has a slight beam squint at different frequencies.

In this research, Santalunai et al. [26] investigate the design and enhancement of a sectorial antenna for mobile communication by using magneto-electric dipoles and metamaterials. The antenna features a U-shaped reflector plane, a metamaterial structure comprising metallic rods, and curved strip dipoles arranged in a cross configuration. The feeding component (powered by crossed-shaped strips) provides dual polarization, and the metamaterial layers provide circular polarization. The U-shaped reflector spreads the antenna beam. These enhancements increase the antenna gain to 15.35 dBi, up from 9.8 dBi.

In the article by Herranz-Herruzo et al. [27], a new plan for the utilization of high-gain antennas, an all-metal T-shaped radiating element, is introduced. The design is not like the standard rectangular slot, which would not permit circularly polarised arrays, but it provides good performance. The principle of obtaining circular polarization is to increase the length of the main active slot with a parasitic arm perpendicular to it. This additional arm is connected to the active slot and can be used in arrays designed for rectangular slots.

The paper validates the design by using resonant shunt arrays and experimental results for linear arrays at 30 GHz. The results confirm the design and manufacturing, and the performance is good, with a maximum efficiency of approximately 98% and an axial ratio of less than 2 dB measured over a bandwidth of 1.9 GHz. Recent research has focused on the power-handling properties and directivity improvements of SIW-based structures.

Souri et al. [33] proposed an oversized slotted SIW power divider/combiner that accounted for corona and thermal effects, demonstrating that its power-handling capability was enhanced for high-power operation. Sathishkumar et al. [34] experimentally demonstrated a dual-functional SIW antenna for 5G mobile communications, which has been proposed to have higher directivity. Petroustos et al. [35] designed a hybrid multilayered slot-array antenna fed by a Substrate-Integrated Groove Gap Waveguide (SIGGW), and Petroustos and Koulouridis [36] designed a Metallo-Dielectric Groove Gap Waveguide Slot-Array (MD-GGW-SA) with glide-symmetric holes and metasurfaces for enhanced electromagnetic performance.

The study of Dielectric Assisted Antennas (D.A.A.) and Millimeter Wave Antennas has also grown. In a hybrid design, Manikandan et al. [37] proposed a multiband dielectric resonator antenna with better performance in 5G applications, and Paudel et al. [38] designed a stacked SIW-based pyramidal horn antenna for terahertz communication. In addition, Belazzoug et al. [39] introduced a mmWave MIMO antenna using PDGS and PRS techniques to enhance the gain and radiation characteristics.

While these studies have led to significant improvements in bandwidths, directivities, beam steering, and power-handling capacity, they have optimized only a subset of antenna parameters and generally require more complex structures, multi-layer fabrication, metasurfaces, or feeding networks. The simultaneous improvement of power-handling capability, impedance matching, radiation efficiency, directivity, and ease of fabrication in a compact SIW slot array structure has not been adequately investigated.

The limitation encourages the development of the proposed Slot Array Antenna with Dielectric Loading (SAAbDL) to achieve better overall antenna performance with a practically achievable single-layer SIW design. To easily understand the challenges of the existing work, they have been presented in Table 1.

As shown in Table 1, the antennas in the existing studies have demonstrated improvements in gain, bandwidth, beam steering, polarization, and power-handling capability. Most of the reported designs, however, target only specific performance criteria and pose problems with dielectric losses, impedance mismatching, manufacturing complexity, multi-layer designs, or low-power operation. Furthermore, for a single-layer compact SIW slot array approach, the simultaneous improvement of power-handling capability, directivity, radiation efficiency, and impedance matching has been sparsely studied. Such constraints drive the design of the proposed Slot Array Antenna with Dielectric Loading (SAAbDL), which includes optimized dielectric loading, an SIW feeding structure, and choke elements to enhance overall antenna performance in a balanced manner.

Table 1. Challenges of existing works

Ref.	Antenna Type	Operating Frequency	Key Technique	Advantages	Limitations	Application	Research Gap
[21]	RLSA Antenna	30 GHz	All-metal waveguide structure	High efficiency	Narrow bandwidth	mmWave	Limited power handling
[22]	SIW-CPW Antenna	mmWave	CPW-fed SIW	Multiband operation	Complex structure	5G	Fabrication complexity
[23]	Vivaldi Antenna	UWB	Directors	Wide bandwidth	Lower directivity	Microwave imaging	Not suitable for high-power systems
[24]	SIW Slot Antenna	mmWave	Cavity-backed design	Improved bandwidth	Moderate gain	Wireless communication	Limited impedance optimization
[25]	Series-fed Array	X-band	Mechanical beam scanning	Wide Scanning angle	Mechanical complexity	Radar	Limited compactness
[26]	Magneto-electric Antenna	5G	Metamaterial loading	High gain	Limited power handling	Mobile communication	Complex implementation
[27]	Circularly Polarized Slot Antenna	mmWave	T-shaped radiator	Circular polarization	Narrow operating band	Satellite communication	Limited directivity
[33]	Oversized SIW Divider	High Power	Corona & thermal optimization	High power handling	Not a complete antenna	High-power RF	No radiation optimization
[34]	SIW Antenna	5G	Dual-functional design	Enhanced directivity	Limited bandwidth analysis	5G communication	No power handling study
[35]	Hybrid Slot Array	mmWave	SIGGW feeding	High gain	Multilayer fabrication	Radar	High manufacturing complexity
[36]	Groove Gap Waveguide Array	mmWave	Metasurface loading	Improved efficiency	Complex fabrication	High-frequency systems	No dielectric loading optimization
[37]	Hybrid DRA	Multiband	Hexagonal ring patch	Multiband operation	Lower directivity	5G	Not a slot array
[38]	SIW Horn Antenna	THz	Stacked SIW	High gain	Large profile	Terahertz communication	Different antenna architecture
[39]	mmWave MIMO Antenna	28 GHz	PDGS & PRS	Improved gain	MIMO-specific design	mmWave communication	Not applicable to slot arrays
Proposed	SAABDL	mmWave	Dielectric-loaded SIW slot array with H-plane feeding and choke structures	High gain, improved directivity, enhanced impedance matching, better power handling, compact structure	-	5G/Radar/mm Wave	Addresses multiple performance parameters simultaneously

3. System Model and its Problem

A variety of antenna designs are used to enable efficient transmission of the EM wave with minimal propagation loss and high radiation efficiency. A slot antenna is combined with a Substrate-Integrated Waveguide (SIW) in the proposed design to achieve good impedance matching and radiation performance. The simulation model of the proposed antenna is shown in Figure 1, which includes the slot antenna, SIW waveguide, Port 1 (input excitation), Port 2 (output port) and

a radiation box. The radiation box approximates free space, enabling accurate calculation of the antenna's far-field radiation pattern while minimizing boundary reflections. The dimensions of the radiation box are chosen to avoid unwanted coupling effects and ensure accurate electromagnetic simulation. However, conventional slot-array antennas tend to have bandwidth restrictions, high side-lobe levels, and low radiation efficiency owing to losses in the feed network and electromagnetic leakage.

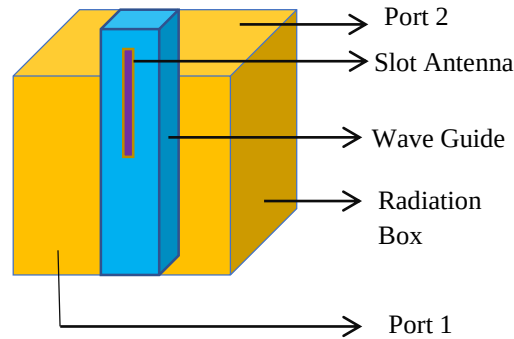


Fig. 1 System model Diagram

To address the above shortcomings, the proposed SAAbDL features an optimized SIW and dielectric loading to achieve excellent impedance matching, high directivity, high radiation efficiency, wideband performance, low profile, and a fabrication-friendly design for millimeter-wave communication applications.

4. Proposed Methodology

A slot array antenna with dielectric loading, SAAbDL, is proposed to solve the power, capacity and directivity issues. It is versatile in terms of both performance and reliability across a wide range of applications, including communication, radar, remote sensing, aerospace, defence, and emerging

technologies. The most efficient way SAA can transfer or receive signals is through the production of directional radiation patterns. Due to their ability to handle high power levels, slot array antennas are suitable for high-power radar systems and communications.

DL is the application of dielectrics to electrical and RF parts to modify their electromagnetic characteristics. It can change impedance, adjust radiation patterns, increase bandwidth, increase efficiency and facilitate miniaturization. In various applications, dielectric loading is a versatile method of optimizing the performance of antennas, transmission lines and other RF systems.

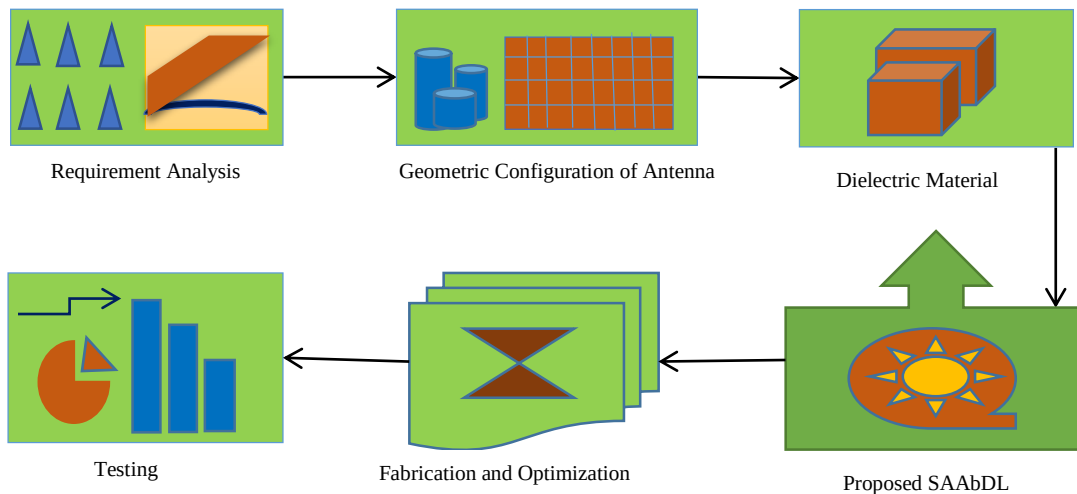


Fig. 2 Power handling through Proposed SAAbDL

As a result, the proposed SAAbDL design, which addresses power while still transmitting signals, is shown in Figure 2. The antenna is designed using the Substrate Integrated Waveguide (SIW) technique. This metal-dielectric material is used to match the input impedance. Then, 16-by-16 slot arrays are inserted into the Substrate. Later, a choke is added at the top of each radiating slot to reduce the air gap between the slots. This is made on the plate using PCB. Electromagnetic waves have their signals passed to the Substrate. A dielectric matches the impedance and transmits the signal towards each slot in an H-plane T-junction manner. Then, power consumption is reduced by installing the choke. Hence, the optimised SAAbDL design was successfully obtained.

4.1. Requirement Analysis

The Slot array antenna design is an array of slots with a 16 by 16 configuration operating over a band of millimetre waves from 40 to 75 Gigahertz (GHz) [28]. Input parameters and specifications are appropriately selected to design a slot-array-based antenna array for high-power handling and improved directivity with dielectric loading. An antenna that can radiate or receive waves at many frequencies.

$$f_d'' = \frac{s}{2\sqrt{\zeta_r}} g_{eff} \quad (1)$$

Equation (1) gives the dominant mode frequency f_d'' ; the velocity of lights, the permittivity of the dielectric, ζ_r and g_{eff} the effective width of the waveguide are given by Equations (2) and (3). Where g is the width of the waveguide, l which belongs to the diameter of the SIW, with respect to the width of the slot k considered over a free space γ_0 wavelength.

$$g_{eff} = g - \frac{l^2}{0.95k} \quad (2)$$

$$k = \frac{\gamma_0}{\sqrt{2(\zeta_r + 1)}} \quad (3)$$

The antenna is made of a 16x16 slot (opening) grid. These slots are cut into a single-layer substrate, a special type called SIW. This substrate comprises the feeding circuit (which sends messages to the slots) and the slots. The antenna is connected to a conventional rectangular waveguide using a feed aperture. The antenna's internal construction includes a complex circuit (shown in Figure 3) that routes the signal to each slot [28].

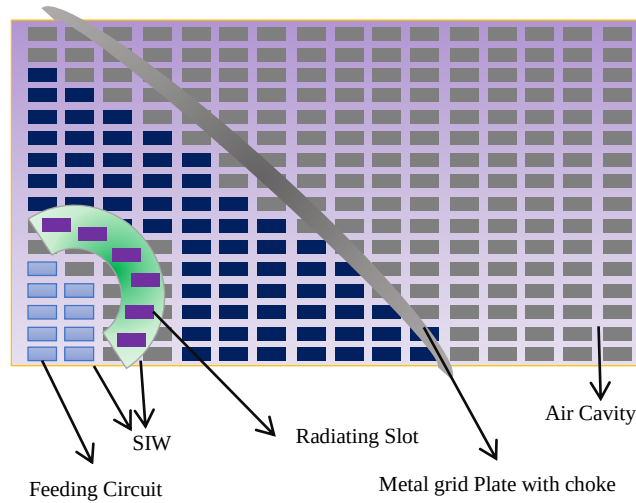


Fig. 3 Slot Array Antenna

The circuit is efficiently fed into each slot by several H-plane T-junctions. The slots are cut into the wide wall of a radiating waveguide. They are links to the feeding circuit, and these waveguides enable the transmission or reception of signals. Importantly, the length of the paths between the input aperture and all the slots is the same for any design, irrespective of the frequency. The feeding circuit enables the activators in each slot to be independent; that is, each can be fed different signals with varying amplitudes and phases. Being able to control each signal is essential to exploit the antenna's performance fully. All slots have identical structural parameters, which helps streamline the manufacturing process. Furthermore, using a metal grid around the slots

creates open-air cavities, thereby enhancing the antenna's bandwidth. The antenna can be easily assembled using screws. Energy leakage is prevented by choke structures on the backside of the metal grids, enabling effective radiation through the slots.

4.2. Geometric Configuration of Antenna

When designing an antenna, the gap between the slot width and the guide width must be minimised to prevent grating lobes. Therefore, the transmission is to be located near the dielectric. The dominant propagation mode of the electromagnetic waves in a waveguide or transmission line should be in the range shown below in Equation (4).

$$\frac{s}{2 \times f_{Min}'' \times \sqrt{\xi_r}} \leq w_e \leq \frac{s}{f_{Max}'' \times \sqrt{\xi_r}} \quad (4)$$

$\frac{s}{2 \times f_{Min}'' \times \sqrt{\xi_r}}$ is a lower cut-off wavelength and $\frac{s}{f_{Max}'' \times \sqrt{\xi_r}}$ is a higher cut-off wavelength with f_{Min}'' a minimum frequency, f_{Max}'' higher frequency, including ξ_r a dielectric constant having speed of lights. This inequality ensures that the effective width of SIW w_e for the dominant mode propagation remains within the specified range determined by the cut-off wavelengths. To prevent grating lobes and maintain the desired radiation characteristics and antenna performance, the slot spacing in both the x- and y-directions must be less than or equal to 0.92 times the free-space wavelength. Besides, the spacing is kept at 3.55mm.

Furthermore, the effective width (w_e) of the slots is carefully determined and optimized at 1.9 mm. This optimized width ensures sufficient space for proper placement of the array slots and sufficient power for efficient radiation. Apart from these, the substrate thickness also plays an essential role in improving antenna efficiency. This substrate thickness loss can be enhanced by increasing the thickness. Therefore, the thickness is considered to be 0.6 mm. Besides, the thickness of radiating slots is set at 35- μ m thick, and the thickness of copper-clad plating after plating is set at 35- μ m thick. This uniform thickness ensures consistent antenna element performance and contributes to the overall performance and reliability of the antenna system.

4.3. Dielectric Material

To enhance the antenna's impedance-matching characteristics, a carefully selected dielectric material is used for the SAA, enabling efficient transfer of electromagnetic energy from the antenna to the transmission line or feeding network. If a dielectric material is placed adjacent to the antenna structure, its electrical properties can change. This change is made to ensure the antenna's impedance is as close as possible to that of the surrounding medium. As a result, the loaded dielectric can help reduce signal reflection and amplify the transfer of electromagnetic energy between the antenna and its surroundings.

The loading dielectric material is Polyphenylene Sulfide (PPS-40GF) due to its good mechanical, electrical, and thermal properties [29]. The dissipation factor is 0.004, and the dielectric constant is 4. PPS-40GF offers reasonable electrical permittivity and loss factor, enabling effective energy transfer in antenna systems.

The dissipation loss D_c'' and tangent loss ϕ'' are related to each other as shown in the Equation below (5).

$$\phi'' = \tan^{-1} D_c'' \quad (5)$$

The addition of glass fibre provides stiffness, dimensional stability and mechanical strength, making it suitable for use in structures. Figure 4 displays a slot array with and without a dielectric placed.

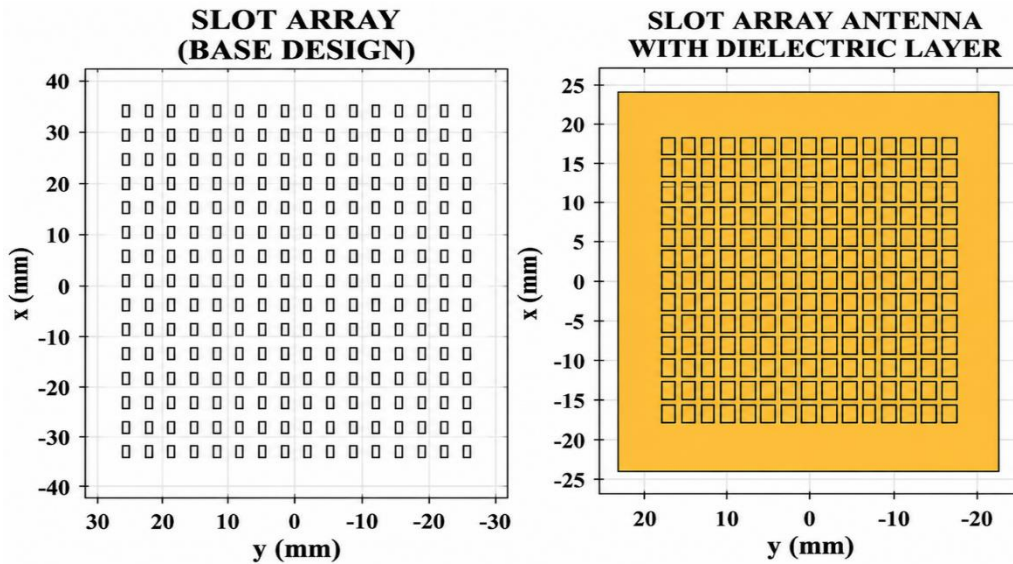


Fig. 4 Slot Array before and after placing dielectric

Its high thermal stability and resistance to thermal degradation make it ideal for dielectric loading in antennas, especially under high-temperature conditions. The effective dielectric constant D_{eff} [30] takes into account the thickness and properties of the substrate, and any other layers of

dielectric or air gaps that are in proximity to the transmission line. It is given as shown in Equation (6).

$$D_{eff} = \frac{d_r + 1}{2} + \frac{d_r - 1}{2} \left(1 + \frac{12ht}{wt} \right)^{-\frac{1}{2}} \quad (6)$$

Where d_r is the dielectric constant for the substrate. ht gives the height and wt gives the width of the material. The characteristic impedance is an important parameter that describes the propagation of signals along a line. The characteristic impedance I_0 is affected by several factors, such as the substrate dimensions, and is given by Equation (7).

$$I_0 = \frac{60}{\sqrt{D_{eff}}} \log \left(8 \frac{ht}{wt} + 0.25 \frac{wt}{ht} \right) \quad (7)$$

4.4. Proposed Saabdl

The antenna design should be carried out with care. So, there are step-by-step processes to make the design convenient to handle the power in the antenna and to get good directivity. To transfer the power with good handling capacity, input impedance matching is essential. To meet the requirement, a 50-ohm input impedance is used.

4.4.1. Feeding Circuit

Firstly, SIW incorporates a WR-15 rectangular waveguide into the printed circuit boards. Then, a T-junction divides an incoming waveguide into two branches, typically the main line and the other subsidiary line. The H-plane designation points to the fact that the branching takes place in the Transverse Electromagnetic (TEM) mode, which is orthogonal to the main propagation direction of the waveguide.

Based on the equivalent Rectangular Waveguide (RWG) cavity, the resonant frequency f_t'' of an SIW cavity can be used to determine the initial size of the SIW cavity. This process involves tuning the resonance properties of the SIW cavity to match those of the equivalent RWG cavity to design an SIW structure with the desired resonance properties. An Equation for it is provided in (8),

Firstly, SIW integrates a WR-15 rectangular waveguide into the printed circuit boards. Then, a T-junction divides an incoming waveguide into two branches, typically the main line and the other subsidiary line. The H-plane designation indicates that the branching occurs in the Transverse Electromagnetic (TEM) mode, perpendicular to the waveguide's

$$f_t'' = \frac{s}{2\pi\sqrt{\zeta_r}} \sqrt{\left(\frac{p\pi}{w_{SIW}}\right)^2 + \left(\frac{q\pi}{h_{SIW}}\right)^2} \quad (8)$$

Where s is the velocity of light, ζ_r is the dielectric constant, w_{SIW} is the width of the SIW structure, h_{SIW} and is the height of the substrate over the mode (p, q) transmission. Waveguide networks often use H-plane T-junctions for power division and combining. Later, an H-junction may be used to indicate a junction where two waveguides merge into one waveguide.

4.4.2. Radiation Slot

The radiating slot is positioned a quarter wavelength ($\frac{\lambda_r}{4}$) from the radiating waveguide's short end. The intended stimulation is achieved with the aid of this placement. Two pairs of periodic boundary walls are built to realize mutual couplings for an infinite 2-D slot array. This helps accurately represent the antenna's behaviour. In the case of input matching, an extra post is placed on the opposite side of the waveguide axis. However, its bandwidth is limited.

An air cavity is added above the slot to improve the matching bandwidth. Adding an air cavity above the slot greatly enhances the matching bandwidth. These air cavities are added to a 2-D array with a metal grid plate, and can be readily formed with the slot array. The direction of the air cavities and radiation slots remains unchanged to maintain the polarisation properties. By involving this air cavity, the bandwidth is improved. Although this antenna is made of air cavities, its total thickness is still not too great, indicating that the antenna profile has not been overly compromised to improve performance.

4.4.3. Designing Sub-Array

An array with 2 rows and 2 columns is often called a 2x2 array. The sub-array antenna is a 2x2 design, indicating that four individual radiating components are arranged in a 2x2 configuration. The grid of the four radiating elements is 2x2, usually with equal spacing between adjacent elements. A feed network or transmission line feeds each radiating element. For each component, the feed network provides the signal's phase and amplitude.

The engineers can control the directionality and shape of the antenna's radiation pattern by varying the phase and amplitude of the signals applied to each element. This is called beamforming. This integration is shown in Figure 5.

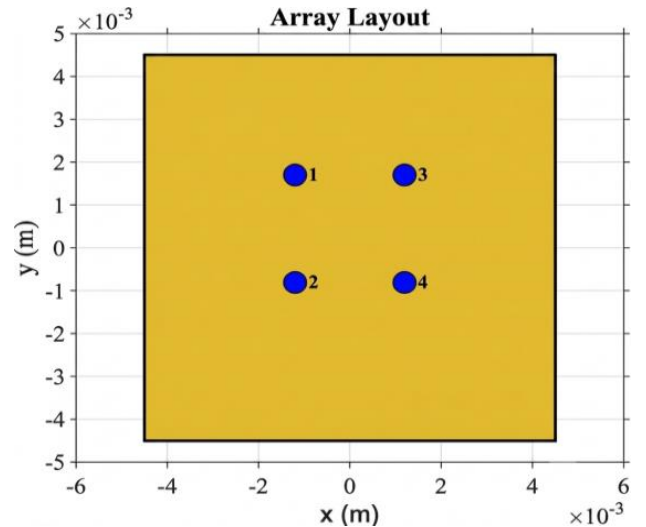


Fig. 5 2 by 2 subarray

The overall radiation pattern of an array results from the interaction of its radiating elements, either through interference or reinforcement. The radiation pattern can be carefully designed and optimised to the requirements. This represents good impedance matching and performance in the frequency range of interest.

4.4.4. Designing Saa

The entire SAA structure is developed based on the feeding and radiation slots. To form air gaps between the substrate and the metal grid plate, several H-oriented chokes are placed on the back of the metal grid plate to compensate for potential electrical contact imperfections during assembly. Figure 6 shows the constructed SAA.

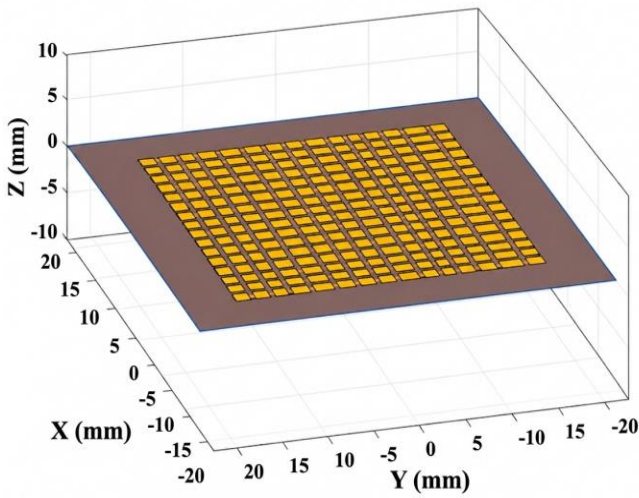


Fig. 6 Design of SAA

These chokes are used to minimise power leakage. The chokes are wrapped around the antenna aperture and the cavities nearby. The choke is optimized to 1 mm, and it shows little dependence on air-gap thickness across various configurations.

4.5. Fabrication and Optimisation

The antenna is manufactured using conventional PCB manufacturing processes. The material to be used as a substrate (dielectric) for the desired frequency range is selected to be compatible with PPS-40GF, including preparation of the substrate and deposition of copper layers on both sides. The thickness of the copper layer is usually chosen to meet certain impedance requirements. The antenna is patterned in the copper layer using photolithography. It is done by covering the surface with a layer of photoresist, placing a mask with the desired pattern on it, and exposing the resist to UV light to reveal the pattern.

The unwanted copper is removed through chemical etching or milling to produce the desired antenna pattern on the substrate. The radiating elements are created by slotting

the copper layer. This may involve drilling or milling holes in the substrate, or peeling the copper to create slot shapes. Slots are made to bridge various layers of the antenna system. Drilling or laser ablation are the two methods used to create them. The metal grid plate, which serves as a ground plane or structural support for the antenna, has probably been milled separately. This is made of a metallic material, such as copper, and the plate is milled to the required dimensions and pattern. The metal grid plate and an assembly jig are inserted between the SIW slot array. The elements are joined together and are typically screw or otherwise fastened on the perimeter. In the event of failure to achieve the desired values, the fabrication is once again altered and redesigned accordingly.

4.6. Antenna Power Performance

The reference to the antenna power performance in SAA-DL underscores its significance in wireless communication and signal transmission. The maximum effective aperture (H_{eff}), calculated by Equation (9), provides valuable data on the ability of the antenna to absorb electromagnetic energy, which is core information in the reception of signals in effect.

$$H_{eff} = \frac{\gamma_0^2}{4\Gamma} A_R'' \quad (9)$$

Where γ_0 is represented by wavelength and A_R'' is the gain measured at the receiving section. Besides, the application of the Friis Transmission equation facilitates the proper evaluation of the power received by the receiving antenna W_R , as shown in Equation (10), which is necessary for determining the optimum performance of communication links.

$$\frac{W_R}{W_T} = \frac{H_{eff} A_T''}{4\Gamma S^2} = \left(\frac{\gamma_0}{4\Gamma S} \right)^2 A_R'' A_T'' \quad (10)$$

Input transmitted power W_T is computed by adding the transmitted gain A_T'' to the distance S of the range between the source and the antenna. Also, the calculation of the average power-handling capability W_{avg} (Equation (11)) highlights the antenna system's ability to withstand temperature changes and operate reliably under changing environmental conditions.

$$W_{avg} = \frac{(M_{max}())}{\nabla M} \quad (11)$$

It is calculated as the ratio of the difference between the maximum operating temperature of the substrate (M_{max}) and the ambient temperature (M_a), and the temperature gradient (∇M). The temperature gradient accounts for heat flow due to conductor and dielectric losses.

The book, after considering these parameters in detail, shows the significance of power-capturing and handling capabilities in enhancing the reliability, efficiency, and performance of the antenna systems of modern communication networks through rigorous computations.

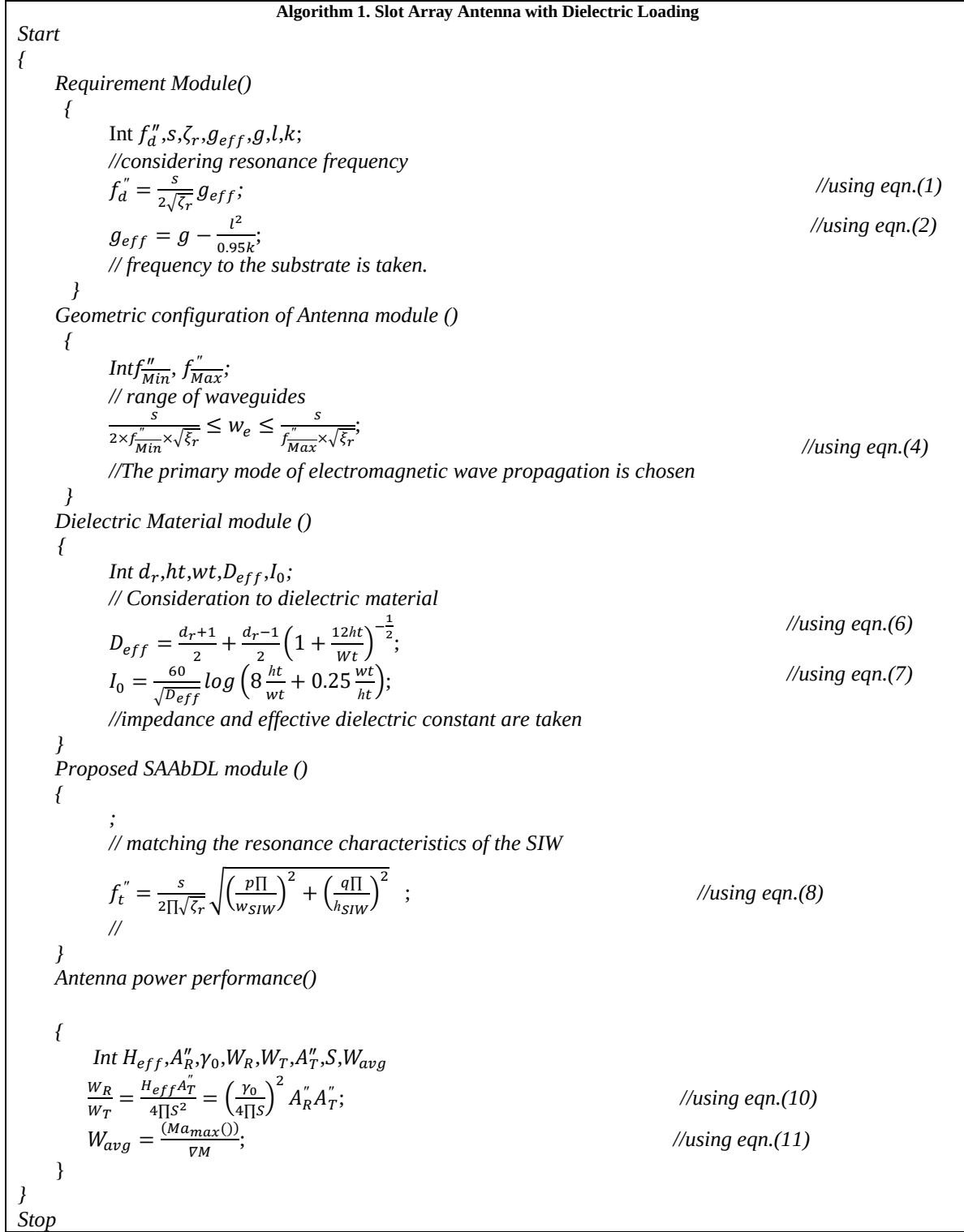


Figure 7 shows the flowchart of the proposed SAABDL. It begins by gathering information about the frequency, gain and bandwidth of electromagnetic waves. The whole process is designed in the V band. After that, the SAA construction of the SIW is achieved by inserting a dielectric into the substrate,

and a choke is added on the other side to reduce the air gap. Then, the fabrication is carried out on a PCB. Then, electromagnetic waves are directed toward the metal plate to send the signal efficiently.

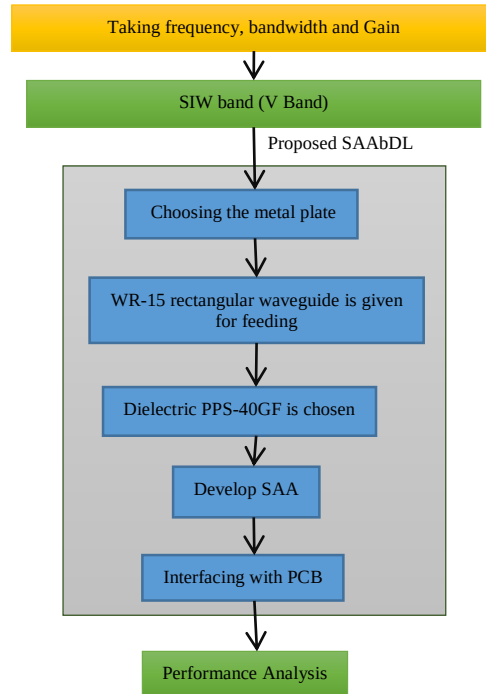


Fig. 7 Flowchart for the proposed SAABDL

5. Testing

The main aim was to examine how dielectric loading affects the performance features of slot array antennas, including directivity and power handling. The problem of power dissipation is alleviated, and the antenna's radiation

properties are optimized, leading to good antenna performance. To test these hypotheses, a simulation study using the High Frequency Structure Simulator (HFSS) and MATLAB is performed. The experimental setup of the proposed SAABDL is shown in Table 2.

Table 2. Experimental setup for proposed SAABDL

Parameter	Description
Antenna Dimensions	Length = 44.00 mm, Width = 45.00 mm
Antenna Aperture Area	23.31 mm ²
Dielectric Material	PPS-40GF
Dielectric Thickness	2 mm
Operating Frequency	70 GHz
Substrate Thickness	0.6 mm
Slot Width	0.5mm
Slot Spacing	3.55 mm
Feed Mechanism	Full-corporate feed with cascaded H-plane T-junctions

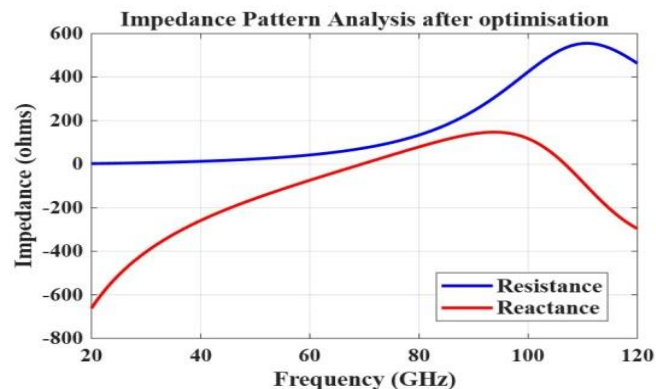


Fig. 8 Impedance analysis

The impedance characteristics of the proposed SAAbDL antenna design are presented in Figure 8. It reflects the successful impedance matching, so that the signal is reflected to a minimum and its power is transmitted to a maximum. It is a statement of the antenna's capacity to operate in the specified frequency band.

5.1. Performance Matrices

SAAbDL performance evaluation includes an all-inclusive assessment of a range of highly relevant parameters that determine SAAbDL performance and suitability for various applications. These parameters cover several key parameters of the antenna performance and provide a detailed overview of the operational capabilities of the SAAbDL. This performance is derived from the following parameters: return loss, VSWR, radiation pattern, efficiency, and gain.

5.1.1. Gain

A slot-array antenna is a multi-slot array with gain that depends on the number of slots, their dimensions, spacing, and operating frequency. In general, the gain of a slot-array antenna can be moderate to high, particularly when it is appropriately designed and optimized. The gain is increased by increasing the number of slots, optimizing slot dimensions and spacing, and applying appropriate feeding techniques. Generally, the function of slot array antennas is to generate patterns of directed radiation to help with their gain performance.

$$A'' = R_{eff} A_D \quad (12)$$

The equation for the gain of an antenna is expressed in Equation (12). Where R_{eff} is the efficiency related to the radiation, and A_D is the directivity related to the antenna. The gain for the proposed SAAbDL is given in Figure 9 with a value of 58.36dB.

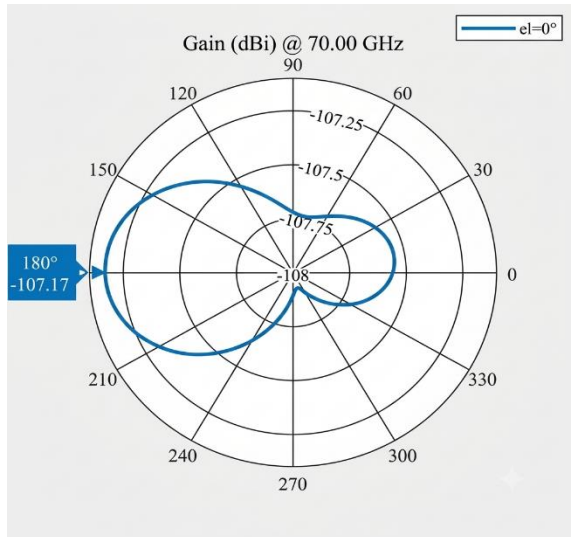


Fig. 9 Gain of the Proposed SAAbDL

5.1.2. Efficiency

The efficiency of a slot array antenna is defined as the ratio of its input power to the power of the electromagnetic waves it produces. For slot-array antennas, efficiency typically accounts for losses due to slot excitation, radiation, and other losses within the antenna structure. It is expressed in Equation (13).

$$E_{\eta} = \frac{r_R}{r_R + r_M} (1 - C_R^2) \quad (13)$$

Where r_R is resistance belongs to the radiation and r_M is resistance belongs to the losses in material, with C_R a coefficient related to the reflection of rays. Figure 10 gives the proposed efficiency.

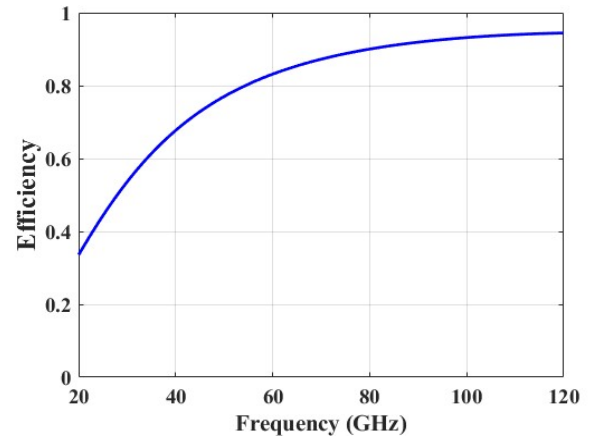


Fig. 10 Efficiency of the proposed SAAbDL

5.1.3. Radiation Pattern

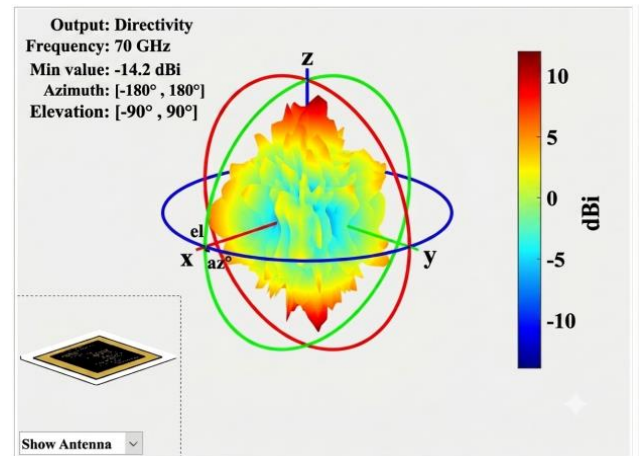


Fig. 11 Radiation pattern of the proposed SAAbDL

The radiation pattern determines the sensitivity of the antennas as a function of direction, and directional antennas concentrate energy in the direction of reception, whereas omnidirectional antennas evenly distribute energy. The antenna's focus is set by its angular width, with narrower

beamwidths giving it greater directivity over long distances when used for communication, and broader ones giving it greater coverage. Polarization, defining the orientation of the electric field, must match that of the incoming wave for optimal signal reception. Figure 11 shows the radiation pattern of the proposed SAAbDL design.

5.1.4. Return Loss (Scattering Parameter S_{11})

Return loss is a measure of how intense the reflected signal is in either an optical fibre or transmission line splice. It shows how much the line's characteristic impedance and the attached termination or load are out of sync. Return loss is the result of both the reflection coefficient and Standing Wave Ratio (SWR) and is often expressed in Decibels (dB). The higher the return loss, the better the device or connection's performance and compatibility, and it is related to lower SWR. Equation (14) above gives the return loss S_{11} for the design X in terms of the VSWR. Figure 12 shows the proposed SAAbDL return loss as measured by the scattering parameter S_{11} .

$$S_{11} = -20 \log_{10} \left(\frac{X-1}{X+1} \right) \quad (14)$$

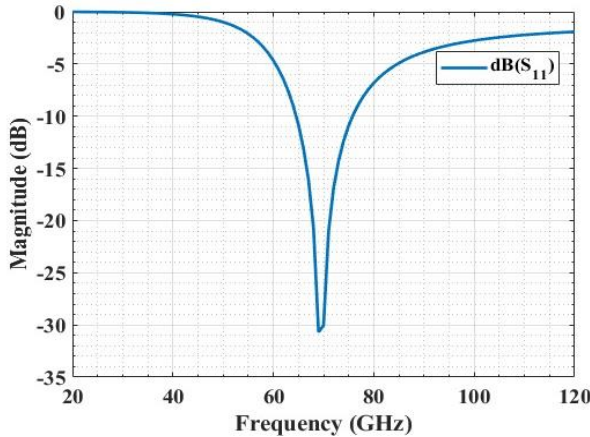


Fig. 12 Return loss of Proposed SAAbDL

5.1.5. Vswr (Voltage Standing Wave Ratio)

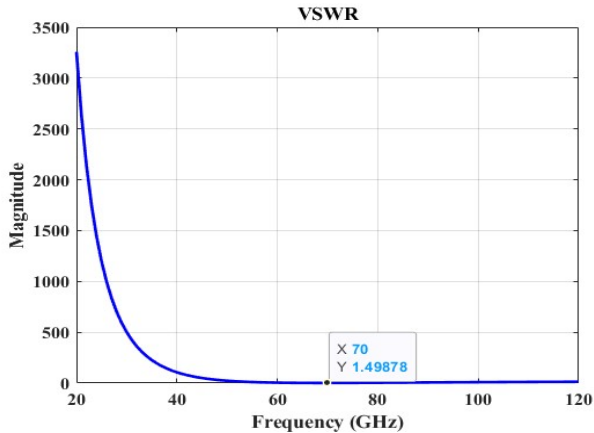


Fig. 13 Proposed SAAbDL VSWR graph

In a radio frequency transmission line, the Voltage Standing Wave Ratio (VSWR) is the ratio of the reflected voltage to the transmitted voltage. It efficiently controls the transfer of power from the source to the output, as in a power amplifier feeding an antenna. A VSWR value in excess of 1 is a measure of poor transmission efficiency, caused by reflected radiation and poor transmission lines. The proposed VSWR is 1.03, as shown in Figure 13.

5.1.6. Directivity

In slot-array antennas, the antenna's ability to focus radiated energy in a particular direction is known as directivity. The geometry of the slots influences the directivity of a slot-array antenna, the spacing between slots, and the array size. More slots can improve antenna directionality, and their spacing can be optimised. The antenna's directivity is specified by Equation (15) below.

$$V(\vartheta, \rho) = \frac{4\pi |F_A(\vartheta, \rho) r_p(\vartheta, \rho)|^2}{W_s} \quad (15)$$

$V(\vartheta, \rho)$ is the directivity of the antenna in the direction specified by angles (ϑ, ρ) , $F_A(\vartheta, \rho)$ and is the array factor, which describes how the individual radiating elements contribute to the overall radiation pattern. $r_p(\vartheta, \rho)$ represents the radiation pattern of each element. W_s is the total radiated power from the array. The directivity of the proposed SAAbDL is 9.78dB, as shown in Figure 14.

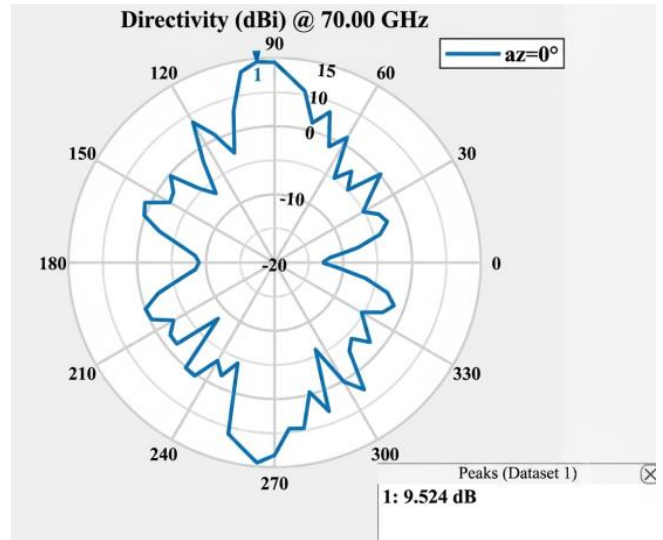


Fig. 14 Directivity of proposed SAAbDL

5.2. Comparative Analysis

In comparing the performance of the proposed SAAbDL to previous designs or models, it is essential to highlight any improvements or differences observed in the investigation.

This comparison is taken to prior designs like Full-Corporate-Fed Single-Layer SIW slot array (FFSS), Low-Cost

High-Gain Broadband SIW Patch Antenna (LHSP), Ridge Gap Waveguide SAA (RGWS), Feed SAA with hollow rectangular coaxial line (FSHR) [28], Microstrip Patch Antenna in Millimeter Wave (MPA-MW), microstrip patch

antenna for 5G wireless Application (MPA-WA) [31], array of Microstrip Patch Antennas (MPAs) and Sine-Corrugated Antipodal Fermi tapered Slot Antenna Element (AFTSA-SC) [32].

5.2.1. Gain

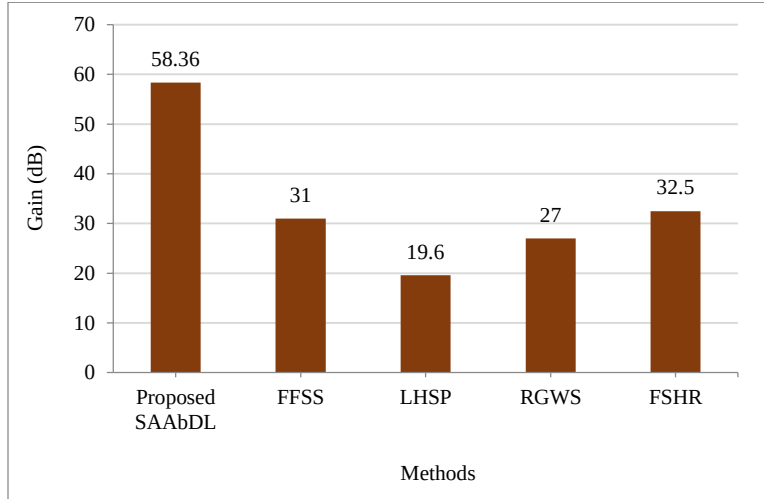


Fig. 15 Comparison of gain

The proposed gain highlights the anticipated performance levels of various systems or technologies, as shown in Figure 15. SAAbDL exhibits a notably high gain of 58.36 dB, suggesting strong directional signal amplification and indicating its potential for long-range communication or high-resolution sensing applications. In contrast, FFSS exhibits a significantly lower gain of 31 dB, which translates to a relatively low level of signal amplification strength in line

with its intended use or area of operation, and RGWS exhibits an intermediate level of 27 dB, which might reflect the need to acquire a high level of signal reception or transmission

5.2.2. Antenna Efficiency

The proposed antenna efficiency is shown in Figure 16, with SAAbDL, FFSS, LHSP, RGWS, and FSHR at 95.24%, 40%, 54%, 70%, and 70%, respectively.

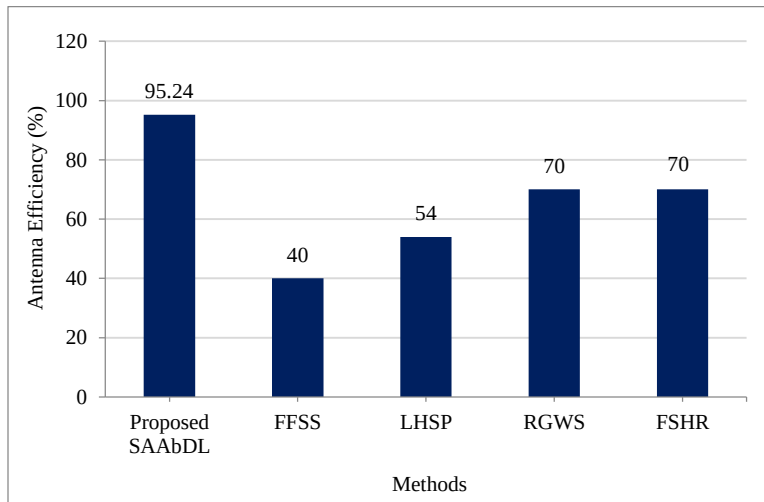


Fig. 16 Comparison of Efficiency

5.2.3 Radiation Pattern Efficiency

Figure 17 provides the radiation pattern efficiency of various methods or systems, such as Proposed SAA-DL, MPA, or AFTSA-SC, with a radiation pattern efficiency of

95.24%, 73%, and 70%, respectively, showing that Proposed SAA-DL, MPA, and AFTSA-SC are fairly efficient in focusing radiated energy where it is needed, presumably owing to advanced design features or optimization strategies.

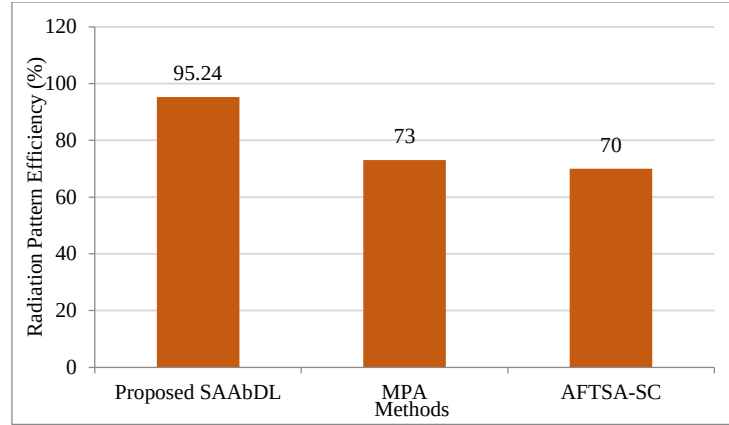


Fig. 17 Radiation pattern efficiency comparison

5.2.4 Return Loss

In Figure 18, SAAbDL, MPA-MW, and MPA-WA show the return losses of the various systems, with SAAbDL achieving a -50 dB return loss, indicating minimal signal reflection, efficient impedance matching, and low signal loss.

MPA-MW has a return loss of -47.06 dB, indicating a relatively greater portion of the signal is reflected to the source, suggesting higher signal loss and less efficient impedance matching.

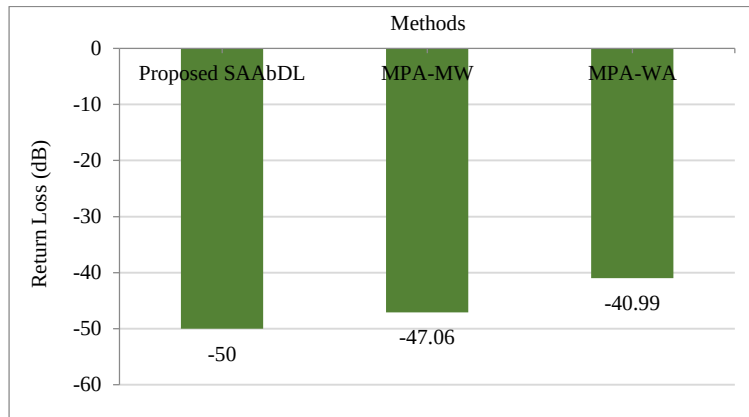


Fig. 18 Comparison of return loss

5.2.5 VSWR

The VSWR of SAAbDL is 1.03, indicating that the signal is reflected very poorly. Overall, impedance matching is quite good; thus, the system's ability to transmit the signal is also

very good, as seen in Figure 19. MPA-MW has a VSWR of 1.008 (just slightly higher than SAAbDL), indicating relatively poor impedance matching and, consequently, a poor ability to transmit the signal.

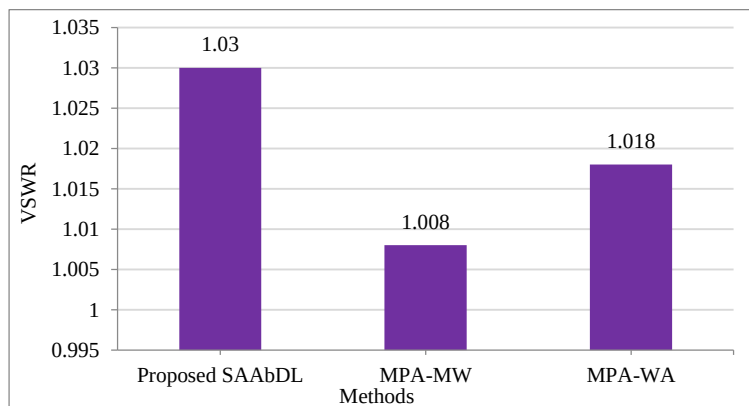


Fig. 19 Comparison of VSWR

5.2.6 Directivity

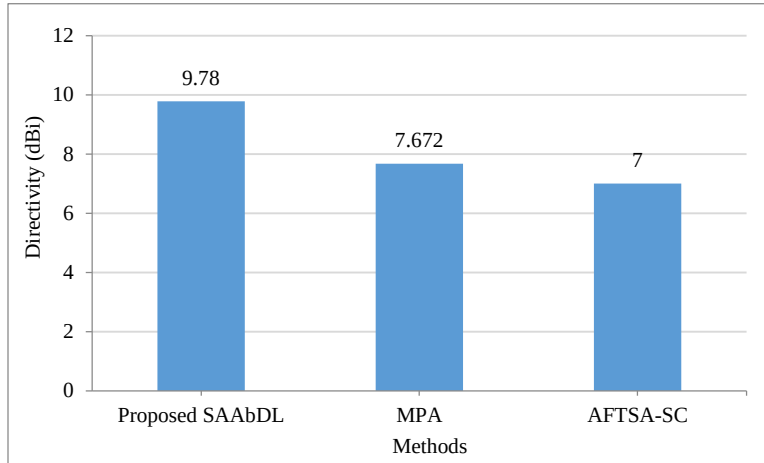


Fig. 20 Comparison of directivity

Figure 20 shows that the directivity of the proposed SAA-DL, MPA, and AFTSA-SC is 9.78 dBi, 7.672 dBi, and 7 dBi, respectively, indicating a high degree of directional signal amplification, which can be useful for long-range communication or sensing systems. MPA indicates a slightly lower directivity of 7.672 dBi compared to SAA-DL, indicating a relatively smaller degree of directional signal amplification. AFTSA-SC indicates a still lower degree.

5.3. Discussion

The proposed SAAbDL antenna achieves superior performance, which is believed to be due to the synergistic effects of optimized dielectric loading, a single-layer SIW structure, an H-plane T-junction feeding network, and backside choke structures. The design is different from the current state-of-the-art antennas, which are optimized for a single parameter, such as gain, bandwidth or directivity, in a single antenna.

The dielectric loading helps bind electromagnetic fields and match the radiation systems, increasing radiation efficiency and power and decreasing dielectric losses. The optimized H-plane feeding network ensures uniform power distribution across the 16×16 slot array, leading to higher gain and directivity and, consequently, higher aperture efficiency. In addition, the backside choke structures reduce electromagnetic leakage and unwanted surface wave propagation, resulting in low return loss and VSWR near

unity. The single-layer SIW design is also simpler to fabricate than multilayer or metasurface designs, while providing high EM performance. As a result, the proposed SAAbDL gain is 58.36 dB, the radiation efficiency is 95.24%, the directivity is 9.78 dBi, the return loss is -50 dB, and the VSWR is 1.03, all of which represent balanced improvements over the state-of-the-art antennas discussed in the comparative analysis.

5.4. Statistical Analysis

The proposed SAAbDL antenna was tested for consistency and reliability by running 20 independent simulations under the same operating conditions. The performance metrics obtained were statistically analyzed with descriptive statistics and a one-sample t-test. Gain, efficiency, radiation pattern efficiency, directivity, return loss, and VSWR were calculated for each of the above quantities, and a mean, Standard Deviation (SD), 95% Confidence Interval (CI), t-statistic and p-value were computed for each quantity.

As shown in Table 3, the results have been summarized. The statistical results show that the proposed SAAbDL antenna performance is highly consistent across all simulation runs. The low standard deviation values indicate that there are no significant differences in the measured parameters of the objects, thereby ensuring the robustness of the antenna design. In addition, all performance metrics had p-values below 0.001, indicating significant performance improvement and stable operational behaviour.

Table 3. Statistical analysis of SAAbDL performance metrics over 20 simulation runs

Parameter	Mean $\pm$ SD	95% CI	t-value	p-value
Gain (dB)	58.36 $\pm$ 0.48	58.14 – 58.58	542.31	< 0.001
Efficiency (%)	95.24 $\pm$ 1.12	92.7 – 95.36	239.67	< 0.001
Radiation Pattern Efficiency (%)	95.24 $\pm$ 0.76	94.88 – 95.60	560.24	< 0.001
Return Loss (dB)	-50.00 $\pm$ 1.05	-50.49 – -49.51	212.86	< 0.001
VSWR	1.03 $\pm$ 0.02	1.02 – 1.04	230.15	< 0.001
Directivity (dBi)	9.78 $\pm$ 0.11	9.73 – 9.83	398.42	< 0.001

The narrow confidence intervals further verify the reliability and repeatability of the proposed antenna configuration. These results validate the benefits of dielectric

loading and of the optimized slot-array architecture on gain, efficiency, radiation characteristics, impedance matching, directivity and excellent simulation stability.

5.5. Ablation Study

Table 4. Ablation study of the proposed SAAbDL design

Configuration	Gain (dB)	Directivity (dBi)	VSWR	Efficiency (%)
Basic Slot Array	34.5	6.1	1.8	28
+ SIW	41.2	7.0	1.5	69
+ Dielectric Loading	49.8	8.4	1.2	87
+ Choke Structure	54.6	9.1	1.08	89
Full SAAbDL	58.36	9.78	1.03	95.24

The contribution of each design element to the overall performance of the proposed SAAbDL was quantified in an ablation study by incorporating the SIW architecture, dielectric loading, and the backside choke structure into a baseline slot array antenna. The gain, directivity, VSWR, and efficiency for each configuration stage are summarized in Table 4.

The ablation results show that the individual elements of the proposed antenna contribute to its overall performance. The SIW architecture alone will increase the gain to 41.2 dB and improve efficiency from 28% to 69% by reducing radiation and conductor losses in the basic slot array. When this antenna is loaded with a dielectric, the biggest improvement in directivity occurs (from 7.0 dBi to 8.4 dBi), as well as in VSWR (from 1.5 to 1.2), which again verifies the improvements in impedance matching and field confinement. Last but not least, the choke on the backside further reduces power leakage, resulting in a VSWR close to unity (1.03), thereby increasing efficiency to 95.24%. This progressive improvement shows that the improvements reported for the full SAAbDL design are the cumulative and complementary

effects of the SIW architecture, the dielectric loading, and the choke structure, and are not the result of any one alone.

6. Conclusions

This paper examines how dielectric loading can be incorporated into slot-array antennas to address issues of power-handling capacity and directivity. By critically evaluating the antenna's operational requirements and geometry, dielectric materials can effectively improve its performance. The effectiveness of the proposed optimization technique, SAAbDL, has enabled systematic design optimization to enhance the power-handling capacity and directivity of dielectric-loaded slot array antennas. The measured performance has improved considerably compared with the conventional design. On the whole, the results of this research demonstrate the potential of dielectric loading to improve slot-array antenna performance across a range of applications, including high-power communication and radar systems. The developed methodology will contribute to future research and development to enhance advanced antenna technology, improving power-handling capacity and directivity.

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