International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 10
***Article Received:** 26 August 2023 **Revised:** 14 October 2023 **Accepted:** 26 October 2023*

Design and Performance Evaluation of Cavity-Backed SIW Antenna for Monopulse Applications

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Abstract— The design of a cavity-backed substrate integrated waveguide (SIW) dual-plane antenna for monopulse application is presented in this publication. The primary objective is to create a four-element circularly polarized cavity-backed slot antenna array that is compact and highly efficient. Two antenna subarrays are utilized to develop a complete analysis, design, and implementation of an antenna, and each antenna element can be used as an independent antenna for monopulse applications. The antenna element is made up of two square ring slot antenna components, a power divider, and a feed point. To produce sum and difference signals, the feed point of each antenna element can be connected to one of the input ports on a monopulse comparator. The antenna's performance at 10 GHz was assessed regarding radiation pattern, gain, return loss, bandwidth, axial ratio, and efficiency. A high-frequency structure simulator (HFSS) simulates a complete planar and compact SIW structure with a footprint of 61.6 mm x 58.1 mm. With a permittivity of 3.55 and a thickness of 1.524 mm, an antenna is manufactured using a photo-lithographic process on a single-layer Rogers RO4003 substrate. As per experimental findings, the antenna has a return loss of -40.17 dB, an RL bandwidth of 395 MHz, a gain of 13.11 dB, an axial ratio of 2.97 dB, and an efficiency of 89.85% at a frequency of 9.92 GHz. Experimental findings reveal exceptional performance parameters for the designed antenna, which can be used for monopulse applications at 10 GHz.

Keywords- Circularly polarized, compact, dual plane, high efficiency, monopulse antenna, substrate integrated waveguide (SIW)

I. INTRODUCTION

The rapid advancements in wireless communication and radar systems have led to increasing demand for compact and high-performance antenna arrays for monopulse applications. Monopulse radar systems require accurate and efficient antenna arrays for target detection, tracking, and angle measurement. Cavity-backed substrate integrated waveguide (SIW) antennas have gained significant attention among the various antenna technologies due to their inherent advantages, such as compact size, low profile, and high radiation efficiency. SIW technology combines low cost, like a microstrip line and high performance, like a waveguide, utilizing closely spaced metallic vias to achieve waveguide-like characteristics, resulting in high-quality factors and power handling capability while avoiding radiation leakage.

The System on Substrate (SoS) platform, utilizing SIW technology, enables low-cost, easy-to-fabricate, and high-performance systems by integrating antennas, passive elements, and active elements on the same substrate, allowing for multiple chip sets on the same substrate to minimize losses without the need for transitions between components [1]. The fabrication procedures of various SIW antennas are explained in [2]. The size reduction method for cavity-backed slot antennas involves replacing the solid metal plate around the radiating slot with a specific metallic pattern proposed in [3], but it results in a bulky structure. In [4], a cavity-backed SIW slot antenna is presented with a planar, low-profile, lightweight, and cost-effective design, operating at a frequency of 10 GHz using the RT Duroid 5880 substrate with a permittivity of 2.2. While this antenna demonstrates excellent radiation properties, its bandwidth is limited.

The analysis and discussion of compact and planar SIW antennas with various radiating slots, including square ring, U-shape, Inverted U-shape, C-shape, and Inverted C-shape, are presented and evaluated for X-band applications in [5] and a prototype of a planar and compact inverted C-shape slot antenna with a substrate integrated waveguide (SIW) is fabricated and tested in [6]. The excellent agreement between simulation and experimental results confirms the feasibility of deploying the antenna for ISM band applications. The square ring circularly polarized cavity-backed slot antenna, as presented in [7], can be utilized to design the antenna element required for monopulse applications.

The compact dual-mode monopulse cavity-backed SIW antenna was proposed, and a prototype was fabricated at the centre frequency of 10 GHz [8]. The advantage of this structure is its implementation on a single-layer PCB, allowing for size reduction. In [9], a compact monopulse cavity-backed SIW antenna has been proposed, integrated on a two-layer dielectric with dimensions of 42 mm × 36 mm. A prototype of the antenna was fabricated and tested at the centre frequency of 9.9 GHz, with a gain of 9.2 dBi, which has the potential for further improvement. A compact monopulse antenna array prototype, based on SIW technology and measuring 124 mm x 25 mm, is fabricated and tested [10], demonstrating excellent agreement between measured and simulated results, with an impedance bandwidth of 4% and a null-depth of 22 dB in difference mode. The entire structure can be realized on an SIW platform.

A millimetre-wave filter system utilizing a monopulse antenna array based on SIW technology is presented in [11]. The maximum measured gain of the sum beam at the centre operating frequency was reported as 8.1 dBi, offering the potential for improvement, and the system is expandable to larger array designs with additional antenna units. A planar substrate integrated waveguide monopulse slot array antenna design incorporating an 8×8 slot array and a distinct structure for the sum-difference comparator, resulting in a low profile and high aperture efficiency, is presented in [12]. Round corners are used for the feeding network design. The entire structure can be realized on the SIW platform.

The primary objective of this research is to develop a compact and circularly-polarized antenna array that exhibits excellent performance characteristics. A comprehensive design methodology was employed to achieve the research objective. It includes theoretical analysis, electromagnetic simulations, and optimization techniques. The design process will involve careful consideration of parameters such as gain, radiation pattern, bandwidth, axial ratio, and efficiency, which are crucial for successful monopulse operation. Moreover, the proposed antenna array will be fabricated using state-of-the-art manufacturing techniques to ensure accuracy and reproducibility.

The array design comprises four antenna elements with a square-ring cavity-backed slot antenna, offering compactness and circular polarization for enhanced performance. These antenna elements achieve the desired functionality, each serving as an independent antenna for monopulse applications. These are composed of two antenna components, a power divider and a feed point, which allow the production of sum and difference signals for accurate angle measurement.

The performance evaluation of the compact cavity-backed SIW dual-plane antenna array was conducted through rigorous experimental measurements and comparisons with theoretical and simulated results. A high-frequency structure simulator (HFSS) simulates the complete planar and compact SIW structure with a footprint of 61.6 mm x 58.1 mm. Furthermore, an antenna is manufactured using a photo-lithographic process on a single-layer Rogers RO4003 substrate, with a permittivity of 3.55 and a thickness of 1.524 mm. Based on simulation and experimental results, the antenna has outstanding performance parameters and can be used for monopulse applications at 9.92 GHz.

This article first provides a comprehensive overview of the design procedure and simulation of the critical components of the dual-plane antenna. Through detailed analysis and optimization, the design aims to achieve high precision, enhanced angular resolution, and superior performance characteristics. The subsequent sections of the research paper will further delve into the implementation, experimental evaluation, and performance analysis of the dual plane antenna for various applications in radar, satellite communication, and autonomous cruise control.

II. ANTENNA DESIGN PROCEDURE

A. Design of an Antenna Element

The design procedure for the cavity-backed SIW dual-plane antenna begins with the design and optimization of the antenna element. The antenna element is crucial in capturing and radiating electromagnetic signals. A thorough antenna element simulation and analysis were conducted to ensure its efficiency and suitability for mono-pulse tracking applications. The design parameters, such as the dimensions and materials, are carefully selected to achieve the desired performance characteristics. The antenna element is designed by two square rings, circularly polarized cavity-backed slot antenna as presented in [7]. The square ring slot is etched on the SIW top wall for radiation, which is shorted by the strip at one end. A shorting via shortens the metal area of a square ring slot with the bottom wall of SIW. The right-hand circularly polarized (RHCP) wave is generated by combining strip and shorting via. Circular polarization results from the electromagnetic fields being perturbed just near the shorting. The SIW cavity is realized by four rows of vias, which operate in the fundamental mode TE_{10}. The antenna element comprises two configurations of an antenna component, a power divider, and a feed point, as shown in Fig. 1. As shown, the SIW power divider is used to divide the power equally.

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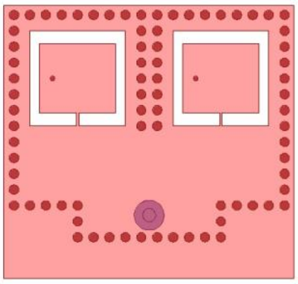

Figure 1: Antenna Element

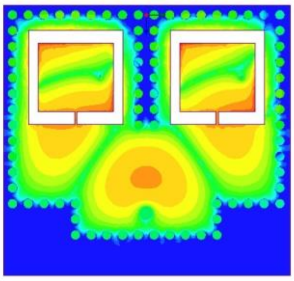

Figure 2: Current Distribution

The design approaches presented in this section focus on achieving the specified performance criteria for an antenna. The critical factor in the design process revolves around carefully selecting frequency and substrate parameters. These parameters play a crucial role in determining the overall performance and characteristics of the antenna. By considering the appropriate frequency range and substrate properties, such as dielectric constant and loss tangent, the design of an antenna can be optimized to meet the desired performance criteria. Hence, the frequency 10 GHz is selected along with the substrate Rogers RO4003, which has permittivity (ϵ_r) of 3.55, loss tangent ($tan\delta$) of 0.0027, and thickness (h) of 1.524 mm.

Minimizing losses is a critical consideration in the design of SIW structures. Parameters such as the diameter of the metal vias (*d*), transverse spacing (*Lsiw*), and longitudinal spacing (*dp*) play a significant role in achieving low losses. To minimize radiation losses, it is essential to maintain a *dp/d* ratio of less than 2.5, with the recommended value being 2. As the spacing *dp* decreases, the diameter *d* of the metal vias should increase to approach a continuous metal wall condition and minimize radiation leakage. Consequently, keeping the gap between the metal vias small is necessary. This design selects the SIW parameters as d = 1 mm and dp = 1.5 mm to optimize performance and minimize losses.

The lengths and widths of SIW cavities are determined by employing the equation of modes TE_{101}, which utilizes specific values of *m* and *n*. The TE modes of the electric field distribution within the cavities are calculated using the given equation,

$$F_{m0n} = \frac{c}{2\sqrt{\epsilon r \mu r}} \sqrt{\left(\frac{m}{aeff}\right)^2 + \left(\frac{n}{beff}\right)^2} \quad (1)$$

The dimensions of SIW cavities can be determined by employing the equation corresponding to the TE_{101} mode of the electric field. In this mode, both the values of *m* and *n* are set to one, resulting in equal lengths (a_{eff}) and widths (b_{eff}) of the cavity, forming a square SIW cavity. This calculation allows for precise determination of the dimensions required for the square SIW cavity design. At 10 GHz frequency, the calculated width value for the SIW cavity is 11.25 mm.

To facilitate radiation, square ring slots are etched on the top wall of the SIW, and a strip of length *Lst* shorts these slots. The geometrical parameters of the slot are carefully chosen to achieve high radiation performance. To enhance the bandwidth performance, the length of the slot and the effective width of the SIW are maintained at approximately equal values. Expressly, the slot length is set to one-third of the wavelength, enabling improved performance and increased bandwidth for the SIW structure. At the resonant frequency of 10 GHz, the slot lengths are determined to be 10 mm on each side.

$$Lslot = \lambda/3 \quad (2)$$

The shorting vias connect the metal area of square ring slots with the bottom wall of the SIW. These vias are positioned at a distance of *Ls*/2 from the edge of the square ring slots and a distance of *Lv* from the SIW axis. Combining the strip and shorting vias enables the generation of a right-hand circularly polarized (RHCP) wave. Conversely, by mirroring the shorting vias concerning the SIW axis, a left-hand circularly polarized (LHCP) wave can be obtained. This arrangement allows for generating and controlling circularly polarized waves within the SIW structure.

The optimized dimensions for the antenna element are summarized in Table I, considering various parameters. The axial ratio bandwidth of the antenna can be controlled by adjusting the distance between the shorting vias (*Lv*) and their diameter (*dv*). The width of the slot (*Ws*) and the length of the short (*Lst*) play a role in the impedance matching of the antenna, although their influence is limited. However, the impedance matching is improved due to the effect of the coax-to-SIW transition. Additionally, the operating frequency depends on the slot's outer dimensions (*Ls*). These dimensions and parameters collectively determine the performance and characteristics of the antenna element.

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TABLE I. GEOMETRICAL PARAMETERS OF ANTENNA ELEMENT

Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	30	*h*	1.524
W	15.6	*Xsh*	2
Ls	10.2	*Lst*	0.25
d	1	*Lv*	2.689
dp	1.7	*dv*	0.5
Wsiw	13.6	*Lp*	8.155
Lamda	30	*Wp*	7.384

Simulation results of the antenna element are shown in Fig. 2 to 7. It shows at 10.02 GHz frequency RL as -22.1307 dB with a bandwidth of 270 MHz. Gain 7.7792 dB and above 6 dB for a total range of 9.7 to 10.5 GHz. It gives an axial ratio of 1.9807 dB. It provides a radiation efficiency of 90.21%, above 80%, for a total range of 9.5 to 10.5 GHz.

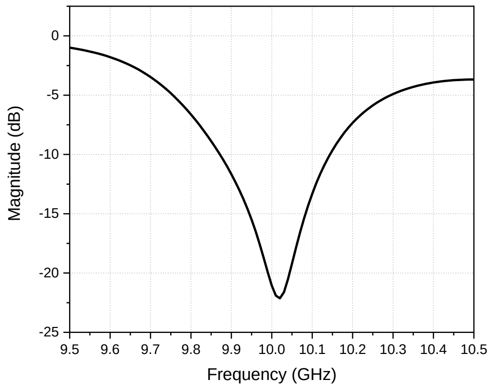

Figure 3: S-Parameters

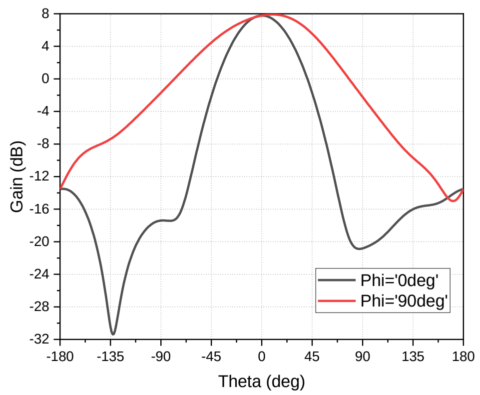

Figure 4: Radiation Pattern

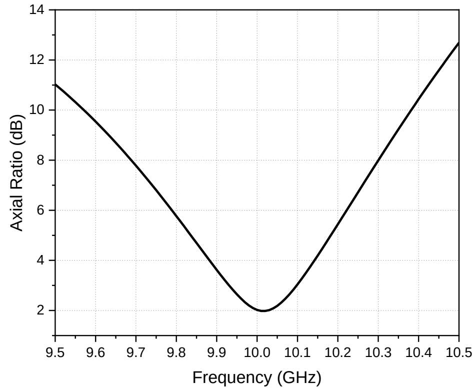

Figure 5: Axial Ratio Vs Frequency Plot

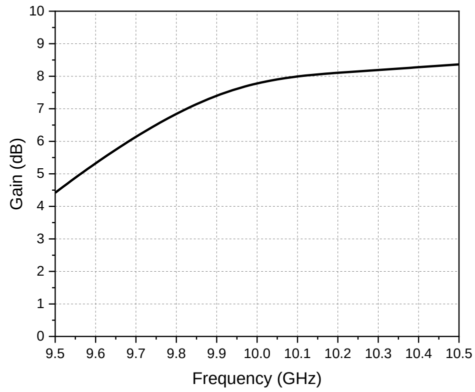

Figure 6: Gain Vs Frequency Plot

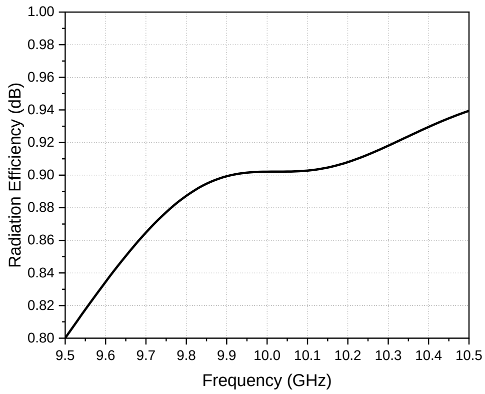

Figure 7: Radiation Efficiency Vs Frequency Plot

B. Development of Antenna Subarray and Dual Plane Antenna

The antenna subarray is designed, which involves the arrangement and interconnection of antenna elements. The subarray enhances the overall performance of the antenna by providing increased gain and improved radiation pattern control. The optimization of the subarray configuration is crucial to achieve the desired beam width and side lobe levels. Various techniques, such as amplitude tapering and phase shifting, may be employed to enhance performance further. The design and fabricated antenna subarray are shown in Fig. 8 and 9, respectively. It is realized using two antenna elements.

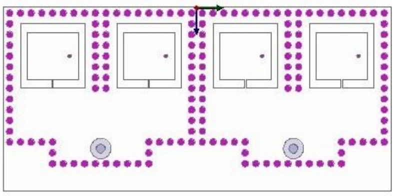

Figure. 8: Antenna subarray

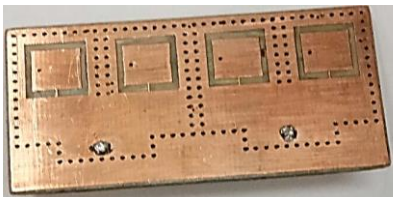

Figure 9: Fabricated Antenna subarray

The dual-plane antenna is an integral part of the monopulse antenna. It allows for accurate tracking and measurement of the target's position and movement. The design and simulation of the dual-plane antenna consider factors such as spacing between the planes, polarization, and radiation pattern requirements. It also considered the performance of the mono-pulse comparator, which processes the signals received by the antenna system to achieve accurate target tracking. The design and fabricated dual-plane antenna are shown in Fig. 10 and 11, respectively. Four antenna elements are used to realize it.

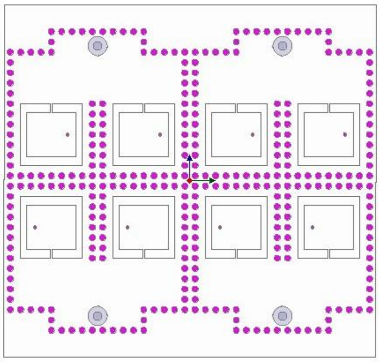

Figure 10: Dual Plane Antenna

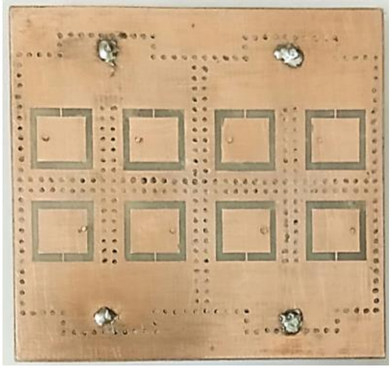

Figure 11: Fabricated Dual Plane Antenna

III. RESULTS & DISCUSSION

The antenna subarray and dual plane antenna are tested for reflection parameters using a vector network analyzer (VNA), Agilent N5247A model and for radiation parameters in an anechoic chamber by Rohde & Schwarz R&S. The experimental setup is as shown in Fig. 12 and 13. TRL technique is used to calibrate the VNA.

Figure 12: VNA Setup

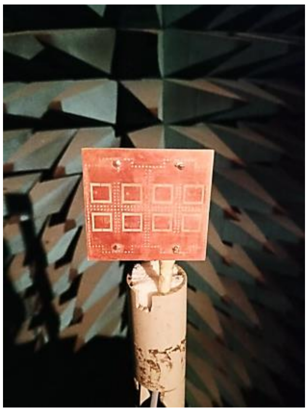

Figure 13: Anechoic chamber Setup

The measured results of the antenna subarray are shown in Fig. 14 and 15. It shows at 9.8 GHz frequency RL as -43.3263 dB with a bandwidth of 382 MHz. The gain is 10.7768 dB and above 7.5 dB for the 9.5 to 10.5 GHz range. It gives an axial ratio

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of 2.3491 dB. It provides a radiation efficiency of 89.67%, above 80%, for the 9.5 to 10.5 GHz range.

The measured results of the dual-plane antenna are shown in Fig. 16 and 17. It shows at 9.92 GHz frequency RL as -40.1740 dB with a bandwidth of 395 MHz. The gain is 13.1090 dB and above 8 dB for the 9.5 to 10.5 GHz range. It gives an axial ratio of 2.9705 dB. It provides a radiation efficiency of 89.85%, above 80% for the 9.6 to 10.5 GHz range.

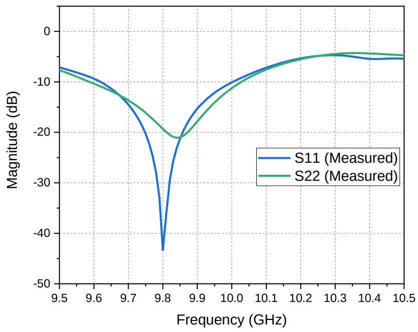

Figure 14: S-Parameters of antenna subarray

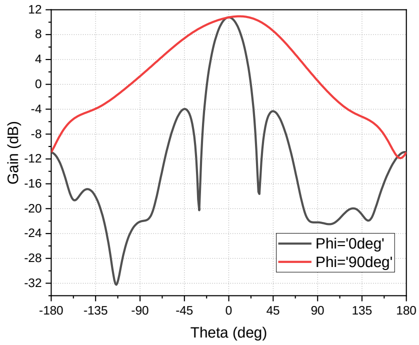

Figure 15: Radiation Pattern of antenna subarray

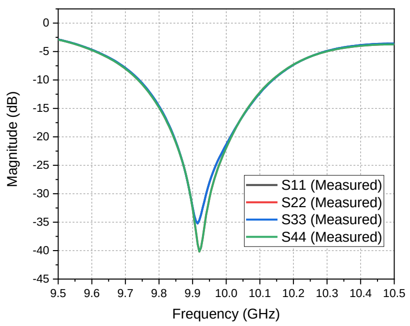

Figure 16: S-Parameters of dual-plane antenna

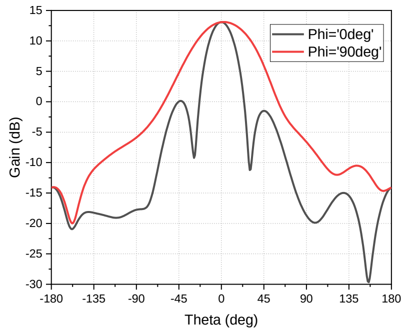

Figure 17: Radiation Pattern of dual-plane antenna

The development of results is summarized in Table II. Gain increases as the antenna develops from a single-element to a dual-plane antenna. Return loss for all antennas is below -10 dB. The axial ratio is below 3 dB for antenna subarray, single-plane, and dual-plane antennas. The efficiency of all antennas is greater than 89%.

TABLE II. RESULT TABLE

	Frequency (GHz)	Gain (dB)	Return Loss (dB)	RL BW (MHz)	Axial Ratio (dB)	Efficiency (%)
Antenna Element	10.02	7.78	-22.13	270	1.98	90.21
Single Plane Antenna	9.80	10.78	-43.33	382	2.35	89.67
Dual Plane Antenna	9.92	13.11	-40.17	395	2.97	89.85

IV. CONCLUSION

This publication presents the design and performance evaluation of a compact and highly efficient cavity-backed SIW dual-plane antenna for monopulse applications. The focus is creating a four-element circularly polarized cavity-backed slot antenna array that offers independent functionality for each antenna element. The antenna's performance at 10 GHz is assessed, considering radiation pattern, gain, return loss, bandwidth, axial ratio, and efficiency. The HFSS simulation is conducted, and a physical antenna is manufactured using a photo-lithographic process on a single-layer Rogers RO4003 substrate. Experimental results show impressive performance parameters, including a return loss of -40.17 dB, an RL bandwidth of 395 MHz, a gain of 13.10 dB, an axial ratio of 2.97 dB, and an efficiency of 89.85%. With its exceptional performance and suitability for monopulse applications at 9.92 GHz, this antenna is valuable to antenna design and monopulse systems.

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