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Design and Implementation of Substrate Integrated Waveguide for 5G Applications

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Abstract

This study analyses Substrate-integrated waveguides (SIW) using design, simulation, and performance evaluation over a frequency range of 26 GHz to 36 GHz. The structural diagram details a rectangular structure with perforations along its longer edges. The S-parameter plot shows good impedance matching at ports with high isolation between them. The VSWR plot indicates moderate to good impedance matching, with values ranging from approximately 1.2 to 3.5. The SIW highest field intensity is observed near the perforations and edges. Simulation results correlate field patterns with performance characteristics. The device demonstrates minimal reflection at the specific frequencies, enhancing transmission efficiency.

Keywords: SIW, VSWR, Impedance Matching, Field Intensity. Rectangular Structure.

1. Introduction

The rapid growth of 5G technology has led to increased demands for high- performance communication systems operating at millimeter-wave (mmWave) frequencies. As 5G networks evolve, they require efficient, compact, and cost-effective components to handle high data rates, low latency, and wide bandwidth. Substrate Integrated Waveguide (SIW) technology has emerged as a promising solution to address these challenges. SIW integrates the advantages of traditional metallic waveguides with the versatility of planar circuits, enabling compact and high-performance structures suitable for mmWave applications. It achieves this by forming waveguide-like structures on printed circuit boards (PCBs) using rows of metallic vias to confine electromagnetic waves. This design is particularly well-suited for 5G systems, which demand components with low loss, high power- handling capability, and easy integration with planar antennas and active devices. Substrate Integrated Waveguide (SIW) technology has

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emerged as a promising solution for 5G applications, offering compact, low-loss, high-performance transmission lines. High frequency and high-data-rate transmission.

1.1 Objective

To develop a compact and high-performance waveguide for 5G that supports millimeter-wave (mmWave) frequency bands (e.g., 24 GHz to 100 GHz). Enable low-loss signal transmission, high power-handling capability, and compact integration into 5G systems. The objective of a Substrate Integrated Waveguide (SIW) for 5G applications is to utilize its unique properties to meet the stringent demands of 5G networks, which include high data rates, low latency, and efficient spectrum utilization.

2. Related Work

This survey delves into the existing body of research to understand the evolution of SIW technology, particularly concerning its application in the millimeter-wave frequencies essential for 5G.

W. Hong et al. [1] in the work specifically tackles the inherent challenges of millimeter wave (mm Wave) frequencies, which, while offering vastly increased bandwidth, suffer from significant path loss and susceptibility to blockage. To address these issues, the researchers focused on designing and prototyping "practically Large-Scale" antenna systems, essentially massive MIMO arrays, crucial for enabling beam-forming capabilities

A. Ghosh, et al. [3] delved into the application of mm Wave frequencies for localized, high-density environments, envisioning their role in future wireless networks beyond just wide-area cellular. K. Wu, D. Deslandes et al. [4], presented a groundbreaking approach for integrating high-frequency electronic and optoelectronic components directly onto a substrate, effectively creating a new paradigm for circuit design. This concept, known as substrate integrated circuits (SICs), aimed to overcome the limitations of traditional circuit fabrication methods, particularly at high frequencies where parasitic effects and interconnection losses become significant.

E. Sandi et al. [5], focused on utilizing substrate integrated waveguide (SIW) technology to enhance antenna performance specifically for 5G mobile communication applications. M. Bozzi et al. [8], proposed a valuable resource, consolidating the growing body of knowledge on substrate integrated waveguide (SIW) technology. By providing a thorough overview, the authors highlighted the versatility and advantages of SIW circuits and antennas for high-frequency applications. F. Xu and K. Wu et al. [9], delved into the fundamental properties of substrate integrated waveguides (SIWs), focusing on how electromagnetic waves propagate within these structures and the potential for signal leakage. By examining these characteristics, the authors provided crucial insights into the behavior of SIWs, which are essential for designing efficient and reliable high-frequency circuits.

K. Mahant et al. [10], explored the design and implementation of antennas utilizing logarithmic slot patterns integrated within substrate integrated waveguide (SIW) structures. By combining these two techniques, the authors aimed to achieve improved antenna performance, particularly in terms of bandwidth and gain. The objective of the work is to develop a compact and high-performance waveguide for 5G that supports millimeter-wave (mm Wave) frequency bands (e.g., 24 GHz to 100 GHz). To Enable low-loss signal transmission, high power-handling capability, and compact integration into 5G systems. K. Harini and T.R. Ganesh Babu, et al. [11]. Stated their investigation that involved loading this coupler with a resonance-type metal material. This approach suggests an exploration into enhancing the performance or reducing the size of the hybrid coupler by leveraging the specific electromagnetic properties of the loaded material.

S. Leo Pauline and T.R. Ganeshbabu, et al. [14]. aimed to achieve a compact and efficient antenna system that provides filtering capabilities, operating within the X and Ku microwave frequency ranges, which are commonly used in various communication and radar applications. This research by Z. U. Khan et al. [19] explores the development of an Empty Substrate Integrated Waveguide (ESIW) slot antenna array, specifically designed for 5G applications. The authors focus on utilizing ESIW technology, which offers advantages in terms of reduced losses and improved performance at millimeter-wave frequencies, a key aspect for 5G communication.

C. Yu and W. Hong et al. [20] presented the design and development of a substrate integrated filtenna operating in the 37-38 GHz frequency range, targeting wireless communication applications. Rahali, B. and Feham, M. et al. [13]. explored the integration of multiple microwave components – a coupler, a circulator, and a power divider – all based on the SIW technology, operating within the K-band frequency range. The study likely aims to develop compact and integrated solutions for microwave systems by utilizing the advantages of SIW structures for these essential passive components.

Vivek Singh Kushwah and G.S. Tomar et al. [18] investigated the method for reducing the size of microstrip patch antennas, an essential aspect of integrating these antennas into compact electronic devices. The authors explore the use of Defected Microstrip Structures (DMS) as a technique to achieve this size reduction. DMS involves intentionally etching patterns or slots into the microstrip structure, which alters the current distribution and effectively lowers the resonant frequency of the antenna. This allows the antenna to operate at the desired frequency with a smaller physical footprint. Khajeim et al. [16] addresses the challenges of integrating efficient and compact antennas into 5G mobile handsets. Recognizing the space constraints inherent in modern mobile devices, the authors propose a novel antenna design based on a slotted Substrate Integrated Waveguide (SIW) array. This design focuses on achieving end-fire radiation, a characteristic that allows for directional signal transmission from the edge of the device.

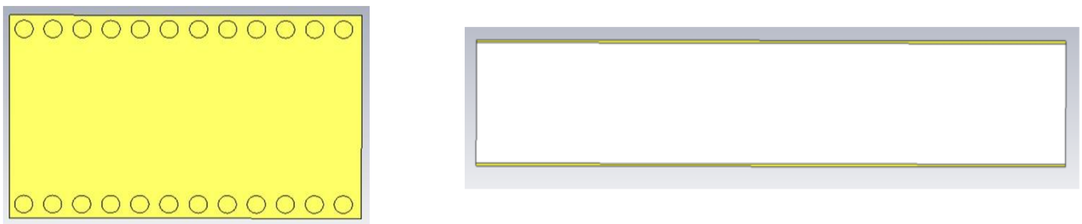
Nasir et al. [17] presented a compact and cost-effective antenna array designed for 5G applications operating at 28 GHz. The core of their design is a Substrate Integrated Waveguide (SIW) fed slot antenna array, which aims to achieve high isolation between antenna elements. A key focus of the research is the implementation of beamforming and beam scanning techniques, essential for directing and optimizing signal transmission in 5G networks. T. Djerafi et al. [6], delves into the specifics of substrate integrated waveguide (SIW) antennas, a technology that has become increasingly important for high-frequency applications, particularly in the millimeter-wave (mm Wave) domain.

K.Z. Hu, et al. [15]. specifically aim to achieve a physically small and thin antenna design while also improving its operational bandwidth. This research contributes to the field of antenna design by exploring advancements in integrated microwave components for applications where size and performance are critical. T. S. Rappaport et al. [2], suggests a foundational piece in the development of 5G, directly addressing the skepticism surrounding the practical application of mm Wave frequencies. The authors tackled the perceived limitations of mm Wave, such as high path loss and sensitivity to obstacles, by providing empirical data and analysis that supported its feasibility.

3. Proposed Work

The substrate-integrated waveguide (SIW) is a type of planar rectangular waveguide created by forming electrical side walls using a series of metallic vias. The basic structure of the SIW front and side views are depicted in Figure 1 The design parameters of the Substrate Integrated Waveguide (SIW) are as follows: The spacing between the via holes is 0.8 mm, and the substrate thickness is 0.6 mm, providing the necessary height for the waveguide. The substrate material has a relative permittivity (εr) of 4.4, which affects the wave propagation and dimensions of the waveguide. The radius of each via hole is 0.25 mm, which is crucial for maintaining efficient energy transmission and minimizing losses. The overall length of the waveguide is 17 mm, and the width is 8 mm, which defines the waveguide's dimensions and determines its cutoff frequency and operating bandwidth. The material used is Rogers 5880, a high-performance substrate commonly used for microwave and millimeter-wave applications due to its low loss and stable dielectric properties at high frequencies. These parameters collectively enable the SIW to operate effectively within a specific frequency range with low loss and high efficiency. Figure 2 shows the design parameters and dimensions of SIW. Table 1 shows the design parameter of SIW.

Based on the design the cutoff frequency is approximately 2.14 GHz, which is the frequency below which the waveguide cannot propagate the signal in its fundamental mode. The loss tangent of the Rogers 5880 substrate is very low, approximately 0.002, indicating minimal dielectric losses and making it suitable for high-frequency applications with low attenuation. The characteristic impedance of the waveguide is estimated to be around 50Ω, which is typical for microwave and millimeter-wave circuits and allows for efficient energy transmission.



(a) (b)

Figure 1. Simulated Structure of the SIW (a) Front View (b) Side View

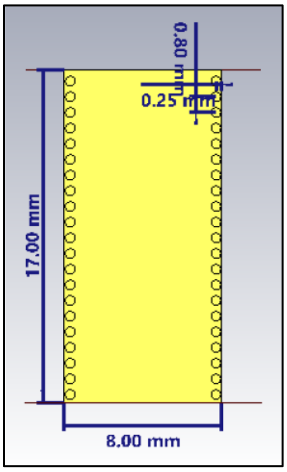


Figure 2. Design Parameter and Dimensions of SIW

Table 1. SIW Design Parameters

S.No	Parameters	Dimension in (mm)
1	Pitch	0.8
2	Thickness	0.6
3	Relative permittivity (εr) constant value	4.4
4	Material	Roggers 5880
5	Radius of Via	0.25
6	Length	17
7	Width	8

4. Results and Discussion

4.1 S-Parameter

The Figure 3 S-parameter analysis in the 26–36 GHz range reveals that the reflection coefficients, S11 and S22, remain relatively constant at approximately -2 dB, indicating good impedance matching and minimal reflection at both ports. In contrast, the transmission coefficients, S21 and S12, fluctuate between -12 dB and -18 dB, exhibiting dips and peaks across the frequency range. This variation suggests frequency-dependent transmission characteristics, likely due to resonances or other effects within the measured device. The similar behavior of S21 and S12 indicates reciprocity in the system.

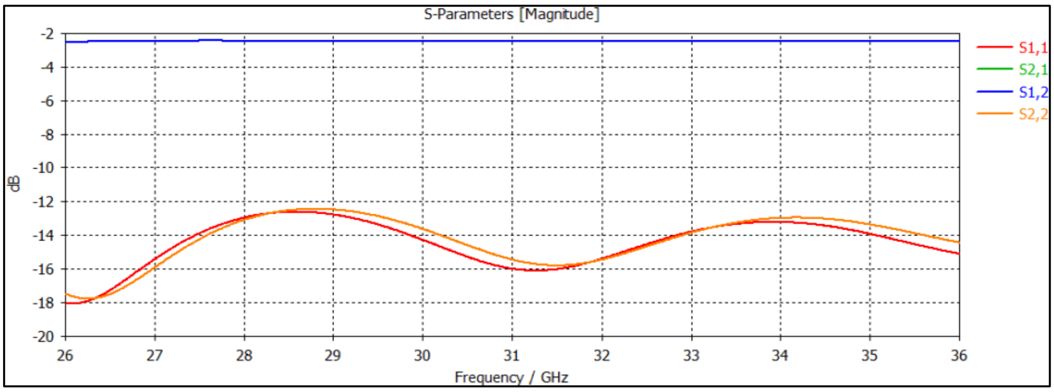


Figure 3. S-parameter of Proposed SIW Design

The high reflection coefficients (S11 and S22) hovering around -2 dB across the frequency band signify a substantial mismatch between the impedance of the device under test and the characteristic impedance of the measurement system (typically 50 ohms). This impedance mismatch causes a significant portion of the incident power to be reflected back at both ports instead of being transmitted through the device. Consequently, the poor impedance matching is the primary reason for the observed high reflection coefficients, indicating that the device is not effectively absorbing or transmitting power across the measured frequency range.

4.2 VSWR Analysis

The Figure 4 illustrates the numerical analysis of the VSWR graph over the 26–36 GHz range. It shows that both VSWR1 and VSWR2 fluctuate between 1.28 and 1.63, indicating variations in impedance matching. At 26 GHz, the VSWR is close to 1.0, suggesting good impedance matching. As the frequency increases, a peak occurs around 29 GHz, where VSWR reaches approximately 1.63, indicating a mismatch. The VSWR then decreases to a minimum of about 1.28 near 31.5 GHz, representing improved matching. Another peak of 1.63 is observed around 34.5 GHz, followed by a decline toward the upper end of the frequency range. These variations suggest frequency-dependent impedance changes, likely due to resonances, affecting the efficiency of power transfer.

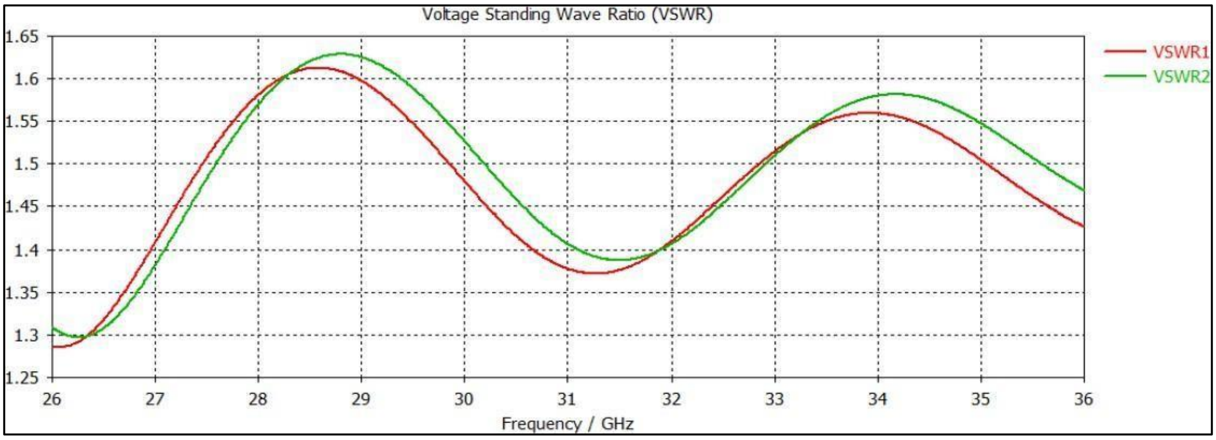


Figure 4. VSWR Plot of Proposed System

The provided VSWR plot, depicting VSWR1 (red) and VSWR2 (green) between 26 GHz and 36 GHz, shows fluctuations between approximately 1.28 and 1.63, with prominent peaks around 29 GHz and 34.5 GHz. These peaks indicate significant impedance mismatch at these frequencies, causing increased power reflection and the formation of stronger standing waves on the transmission line, while the lower VSWR values at other frequencies suggest a better, though not perfect, impedance match.

4.3 Electric and Magnetic Field Analysis

Figures 5 and 6 show the electric field and magnetic field of proposed systems. This pattern shows distinct, concentrated areas of high field intensity, suggesting resonant modes within the cavity. These areas are arranged in a regular, symmetrical pattern, indicating a standing wave formation.

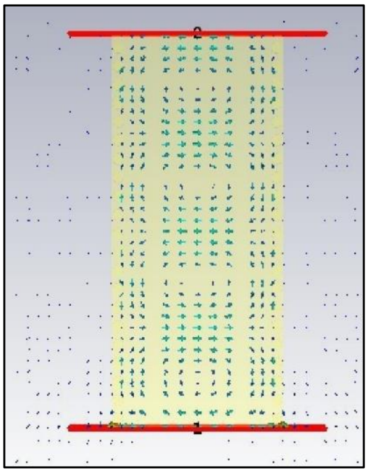


Figure 5. Electric Field

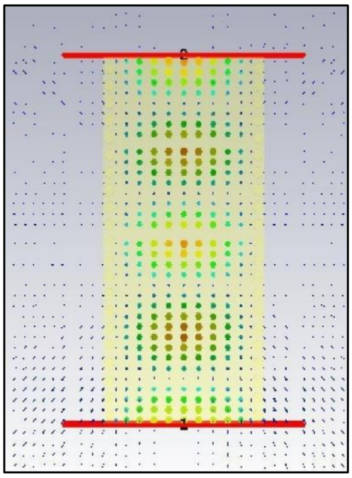


Figure 6. Magnetic Field

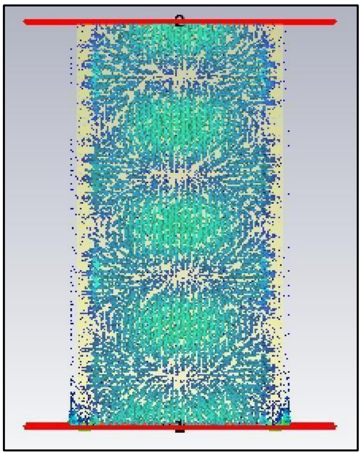


Figure 7. Surface Current Distribution

Figure 7 shows a visual representation of a complex field pattern, likely electromagnetic, within a rectangular enclosure. This pattern suggests a standing wave formation, indicating the presence of resonant modes within the structure. The distribution of dots shows distinct areas of high field intensity concentrated in the center and along the vertical axis, with lower intensity towards the edges. Based on the provided electric field distribution diagram of the SIW, we can infer aspects of its bandwidth and efficiency. The presence of a seemingly well-confined electric field primarily within the SIW structure (indicated by the concentration of colored dots between the top and bottom boundaries) suggests relatively low leakage and thus contributes to higher efficiency within the observed mode. The multiple distinct regions of concentrated field intensity along the length of the SIW likely indicate a standing wave pattern or the presence of a specific guided mode at the simulated frequency. If this pattern remains consistent and well-defined over a range of frequencies (which isn't directly shown in this static image but would be observed in a frequency sweep simulation), it would imply a wider bandwidth of operation for this particular mode.

Table 2. Comparative Analysis

S.no	Type of Antenna	Frequency (GHz)	Gain (dBi)	Return loss (dB)	Bandwidth (GHz)
1.	Compact Slotted SIW antenna [16]	28	5	< -10	N/A
2.	High isolation SIW slot 5-element antenna array [17]	28	10	N/A	3.685
3.	Double-sided 4X4 SIW slot array antenna [18]	28	8	< -10	2

4.	Empty SIW antenna array for 5G [19]	28	11.6	N/A	N/A
5.	SIW filtenna for millimeter wave communication system [20]	28	6.76	< -10	2.01
6	Proposed Design	36	5.2	< -10	N/A

Table 2 provides a comparative analysis of several millimeter-wave antennas, most of which employ SIW technology and operate near 28 GHz, with the exception of the proposed 36 GHz design. These antennas demonstrate a range of gains (5-11.6 dBi), where array configurations typically achieve higher values, and exhibit good return loss (< -10 dB) when reported, signifying effective power transmission. Furthermore, the designs show varying bandwidths (approximately 2-3.685 GHz), indicating customized performance for different applications, while the proposed antenna investigates characteristics at a slightly elevated frequency with a gain of 5.2 dbi.

5. Conclusion

The study concludes that the designed Substrate Integrated Waveguide (SIW) structure exhibits efficient performance over the 26 GHz to 36 GHz frequency range. The perforated rectangular structure contributes to good impedance matching, as indicated by the S-parameter and VSWR plots. High isolation between ports and minimal reflection at specific frequencies enhance transmission efficiency. The highest field intensity near the perforations and edges further supports the observed performance characteristics. The simulation results validate the design's effectiveness in maintaining low reflection and high transmission efficiency, making it suitable for high-frequency applications.

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