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Design and Analysis of Substrate Integrated Waveguide Antenna for Millimeter Wave Applications

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ABSTRACT: For high-frequency communication systems, Substrate Integrated Waveguide (SIW) antennas are small, effective structures. The design and analysis of a cavity-backed SIW antenna for millimeter-wave (mmWave) 5G applications are presented in this study. Recent advancements in circular grooved SIW-based reconfigurable antennas served as inspiration for the concept. Ansys HFSS is used to model and simulate a reduced antenna structure. The antenna exhibits high impedance matching and efficient radiation performance, and it resonates close to 30 GHz. This demonstrates SIW technology's promise for small, powerful antennas in next 5G systems.

KEYWORDS: Substrate Integrated Waveguide, 5G Communication, Impedence Matching, Ansys HFSS Simulation.

I. INTRODUCTION

Millimeter-wave (mmWave) technologies have become a crucial enabler for the fifth-generation (5G) wireless communication systems, offering wide bandwidths and high data rates. However, there are a number of difficulties in designing small, effective, and low-loss antennas at mmWave frequencies, especially when it comes to integrating with planar circuitry and preserving high performance. Substrate Integrated Waveguide (SIW) technology is a potential approach that combines the planar integration capabilities of printed circuit boards with the low-loss properties of waveguides. SIW antennas' compact profile, cheap cost, excellent Q-factor, and ease of integration with other microwave components make them ideal for high-frequency applications. For fixed-frequency mmWave 5G applications, a small cavity-backed SIW antenna has been built and examined in this work.

The suggested design operates close to 30 GHz and emphasizes a simpler, static structure in contrast to reconfigurable SIW antennas that use active components like PIN diodes. Ansys HFSS, a high-frequency electromagnetic simulation tool, is used to carry out the design process, which includes modeling and simulation. This system's goal is to provide a small, effective antenna that is simple to fabricate and incorporate into 5G modules, especially for uses such as user terminals or small cell base stations.

The viability of the suggested design for actual mmWave application is confirmed by its strong impedance matching and efficient radiation performance. The structure of this document is as follows. The relevant literature and current reconfigurable SIW antenna techniques are covered in Section II. The suggested antenna design and simulation configuration are described in depth in Section III. The analysis and performance results are shown in Section IV. The paper's conclusion, Section V, offers suggestions for future improvements.

II. LITERATURE SURVEY

In order to incorporate waveguide performance onto planar circuit boards, the idea of Substrate Integrated Waveguide (SIW) antennas was presented. SIW technology is appropriate for high-frequency applications like 5G and mmWave communication systems because it enables the fabrication of waveguide-like structures on dielectric substrates utilizing arrays of metallic vias or slots. For 5G NR (n258) mmWave communications, the authors of [1] introduced a reconfigurable antenna based on circular grooved SIW. The antenna allowed dual-beam radiation modes and used 20 PIN diodes to perform 360° azimuthal beam scanning. Novel groove patterns and concentric high-impedance surface (HIS) rings were used to provide improved bandwidth and impedance matching. A small cavity-backed SIW antenna with self-multiplexing capabilities for hexa-band operation was shown in the work in [2]. In order to achieve frequency agility while preserving high gain and efficiency, the design made use of a special SIW arrangement.





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A high-gain SIW cavity-backed antenna for Ka-band applications was presented in [3], demonstrating a reduced construction with enhanced radiation efficiency and impedance characteristics, appropriate for mmWave devices with limited space. A miniature SIW cavity-backed slot antenna was created in [4], proving its feasibility for mmWave frequency bands with a small form factor and superior gain performance. With an eye on 60 GHz applications in 5G WLAN/WPAN systems, the authors in [5] investigated reconfigurable SIW antenna arrays with integrated metasurfaces for circular polarization and wideband performance. The possibility of SIW-based antenna arrays for beam-steering and integration into 5G modules was examined in [6]. The benefits of low loss, planar manufacturing, and high efficiency at mmWave frequencies were highlighted in the study. This paper's work is broken down into two phases: 1) Simulation and Design; 2) Performance Evaluation. Ansys HFSS is used to simulate and model the antenna design utilizing a cavity-backed SIW construction. The main goals of simulation are to assess radiation properties, gain, and S-parameters. Performance investigation validates the antenna's suitability for small mmWave 5G communication systems by confirming that it resonates close to 30 GHz with good impedance matching and an efficient radiation pattern.

III. METHODOLOGY

For millimeter-wave (mmWave) 5G applications, a small cavity-backed Substrate Integrated Waveguide (SIW) antenna is intended. The Ansys HFSS electromagnetic simulation software is used in the design, modeling, and analysis of the antenna as part of the technique. Utilizing a dielectric substrate with rows of metallized vias serving as waveguide sidewalls, the SIW structure efficiently directs electromagnetic waves while preserving a compact and flat shape. The antenna is intended to function at a fixed frequency in the vicinity of 30 GHz. In order to get the best impedance matching and radiation characteristics, the simulation procedure starts with modeling the SIW cavity structure. Geometric factors like substrate thickness, via diameter, via spacing, and patch size are carefully chosen. For excitation, a feed mechanism is included, usually a coaxial or microstrip feed.

Electromagnetic modeling and algorithmic design aid in improving the antenna construction to reduce return loss and increase gain. This guarantees that the finished design will function well enough to be included into 5G networks.

IV. EXPERIMENTAL RESULTS

The simulation results of the SIW antenna design using Ansys HFSS are displayed in the figures. The antenna's performance analysis at various design and validation phases is shown in Figs. 2, 3, and 4. The 3D model of the antenna with the cavity-backed SIW construction is displayed in Fig. 2(a). For mmWave 5G applications, the antenna was made to resonate close to 30 GHz.







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Parameter	Value	Description
Operating Frequency	30 GHz	Target resonance frequency
Substrate Material	Rogers RT/Duroid 5880	$\epsilon r = 2.2, tan \delta \approx 0.0009$
Substrate Thickness (h)	0.508 mm	For mmWave efficiency
Patch Type	Rectangular/Cavity-backed	Compact radiating element
Via Diameter (d)	0.4 mm	For forming SIW side walls
Via Pitch (p)	0.8 mm	Center-to-center spacing of vias
Number of Vias per Side	14	Adjusted based on cavity perimeter
Via Metal	PEC / Copper	Perfect conductor assumption
Ground Plane Material	Copper	Standard for SIW structures
Feed Type	Microstrip Line	50-ohm matched feed
Feed Line Width	1.2 mm	Adjusted for 50 Ω on 0.508 mm substrate
Slot Dimensions	Breadth: 4.8mm; Height: 0.1mm	Adjusted to obtain the required freq.
	(d)	(e)

The return loss (S11) characteristics of the antenna are shown in Fig. 2(b), which confirms resonance at about 30 GHz with a return loss of less than -10 dB, showing satisfactory impedance matching. The 3D radiation pattern is depicted in Fig. 2(c), which provides adequate gain and directional radiation performance for 5G systems.



(d)

(e)

To further understand the gain and radiation efficiency, more investigation was done. The 2D polar plot of the radiation pattern at 30 GHz is displayed in Fig. 3(a). The gain plot over a frequency sweep is shown in Fig. 3(b), demonstrating steady gain across the working range. The highest gain that was recorded was around 7.5 dBi.





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The distribution of the electric field across the SIW cavity structure is shown in Fig. 4. Effective mode propagation and low leakage are crucial features of SIW-based antennas, and they are confirmed by the field confinement and propagation inside the cavity.

The simulation also assessed characteristics like bandwidth and VSWR to guarantee correct performance. The antenna's suitability for mmWave communication was confirmed by the VSWR staying below 2 in the working band.

V. CONCLUSION

For millimeter-wave (mmWave) 5G applications, we have deployed a small cavity-backed Substrate Integrated Waveguide (SIW) antenna. Ansys HFSS was used to effectively simulate our design, which shows effective radiation performance close to 30 GHz and strong impedance matching. The antenna structure provides a low-profile, small solution that can be integrated into contemporary 5G systems. Through a variety of simulations, we assessed the design and discovered that it satisfies the mmWave operating criteria, hence validating its appropriateness for applications involving next-generation wireless communication.

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