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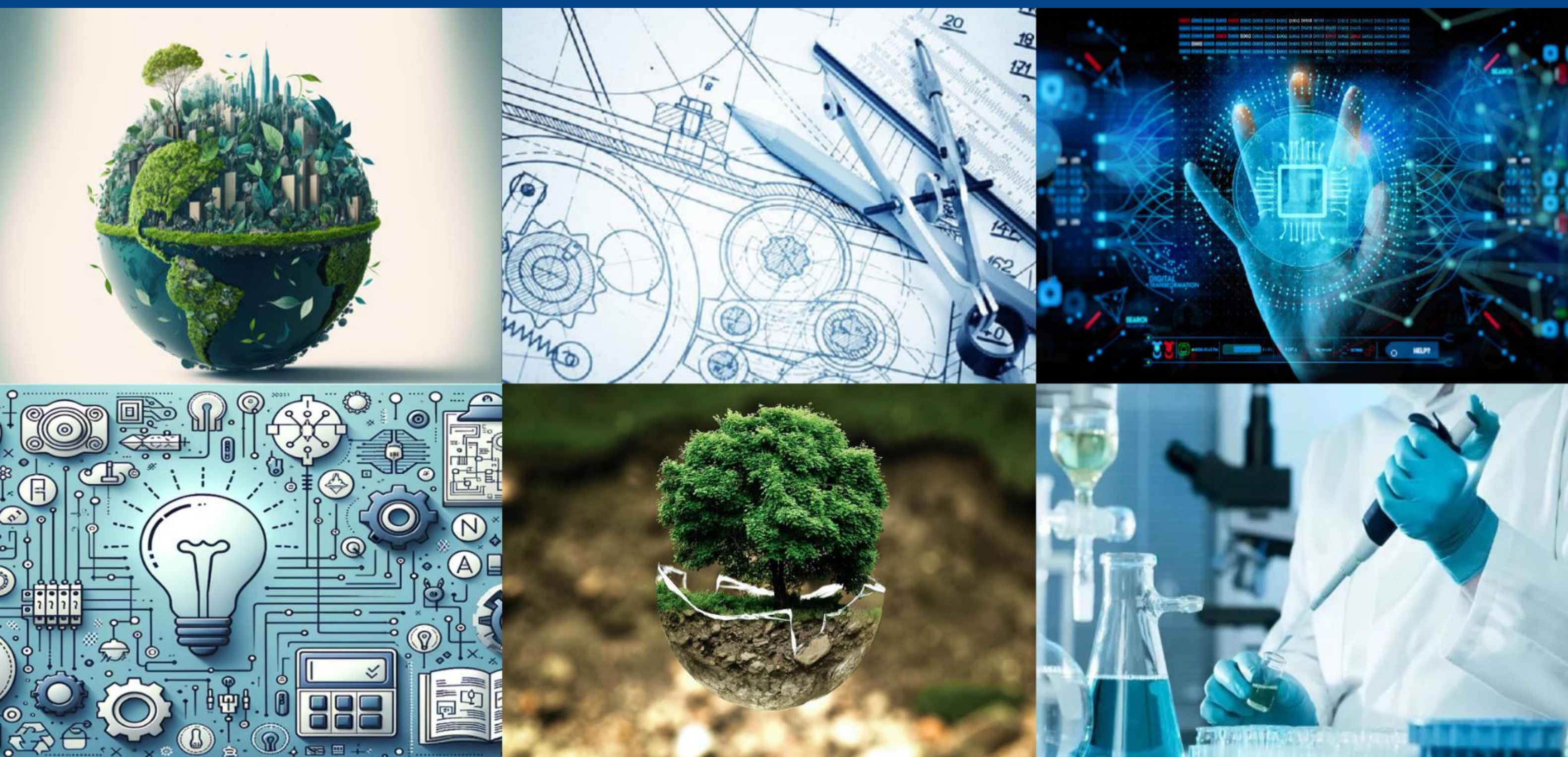

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Substrate Integrated Waveguide (SIW) Based Multiband Antenna for Wireless Applications

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ABSTRACT: This paper presents the design, analysis, and simulation of a Substrate Integrated Waveguide (SIW) based multiband antenna intended for wireless applications including 5G, radar, and satellite communication. The antenna integrates a bowtie slot into the SIW structure to achieve multiple resonances within a compact profile. Using Ansys HFSS, the antenna was simulated to evaluate key parameters including return loss, gain, radiation pattern, and VSWR. The results demonstrate multiband operation with a peak gain of approximately 7 dB and VSWR below 2 across the operating bands, confirming the antenna's suitability for high-performance wireless systems.

KEYWORDS: Substrate Integrated Waveguide (SIW), Multiband Antenna, Bow-Tie Slot, HFSS, Gain, VSWR, Radiation Pattern.

I. INTRODUCTION

The continuous evolution of wireless communication systems has increased the demand for compact, efficient, and multiband antennas. Devices operating in multiple frequency bands enable seamless connectivity across various standards such as 5G, Wi-Fi, satellite, and radar systems. Designing such antennas requires balancing multiple criteria including bandwidth, gain, impedance matching, and size constraints.

Traditional waveguide antennas, though offering low loss and high performance, are bulky and incompatible with planar integration. Microstrip antennas, while compact and lightweight, suffer from lower efficiency and narrower bandwidth at higher frequencies. Substrate Integrated Waveguide (SIW) technology bridges this gap by combining the low loss of waveguides with the planar integration capability of printed circuit boards (PCBs).

In SIW structures, the sidewalls of a rectangular waveguide are emulated using rows of metallic via holes embedded within a dielectric substrate, confining electromagnetic energy effectively. This work explores an SIW-based multiband antenna incorporating a bow-tie slot etched into the top conductor layer to achieve multiple resonant frequencies. The antenna was designed, simulated, and analyzed using Ansys HFSS, with results showing its viability for high-frequency multiband applications.

II. ANTENNA FUNDAMENTALS

An antenna functions as a transducer between guided electromagnetic energy and radiated waves. Its performance is characterized by parameters such as radiation pattern, gain, directivity, bandwidth, impedance, and polarization.

A. Key Parameters

Radiation Pattern: Describes the variation of the radiated power from the antenna as a function of direction in space.

Directivity: Ratio of the radiation intensity in a given direction to the average radiation intensity.
Gain: Incorporates directivity and antenna efficiency, representing the ability to direct radiated power.

VSWR: Voltage Standing Wave Ratio measures impedance matching ideal antennas VSWRW close to 1.

Bandwidth: Frequency range over which antenna maintains acceptable performance (e.g., S11 ¡ -10 dB).

Impedance Matching: Ensures maximum power transfer between transmission line and antenna, typically targeting 50 Ω.

III. SUBSTRATE INTEGRATED WAVEGUIDE (SIW)

Substrate Integrated Waveguide (SIW) is a planar implementation of a conventional rectangular waveguide achieved by using rows of metallized via holes within a dielectric substrate. SIW supports transverse electric (TE) modes similar to traditional waveguides while enabling integration into planar circuits.

A. Advantages of SIW

SIW offers several advantages over conventional waveguides and microstrip lines:

- Low radiation and conduction losses due to waveguide like confinement.
- High quality factor (Q-factor) and better shielding against interference.
- Planar integration compatible with standard PCB processes.
- Compact and low-profile structure compared to bulky waveguides.
- Reduced spurious radiation and coupling with adjacent circuits.

B. Effective Width

The effective width of an SIW structure is approximated by the equation:

$$a_{eff} = a - \frac{d^2}{0.95p}$$

where:

- a = distance between rows of via holes (center to center).
- d = via diameter.
- p = pitch or spacing between adjacent vias.

The design of SIW must satisfy:

$p < 2d$, $d < 0.1\lambda_g$

to minimize leakage and preserve waveguide behavior,
where λ_g is the guided wavelength.

IV. ANTENNA DESIGN METHODOLOGY

The proposed antenna utilizes an SIW cavity with a bowtie slot etched on the top conductor layer to enable multiband operation. The bow-tie slot introduces multiple current paths by creating varying electrical lengths for resonance.

A. Design Equations

Initial patch dimensions for the dominant mode are estimated using:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}}$$

$$L = \frac{c}{2f_r\sqrt{\epsilon_{eff}}} - 2\Delta L$$

where:

- c = speed of light in vacuum.
- f_r = desired resonant frequency.
- ϵ_r = dielectric constant of substrate.
- ϵ_{eff} = effective dielectric constant.
- ΔL = length extension due to fringing effects.

B. Design Workflow

The antenna was designed following these steps:

Selected substrate: Rogers RT/Duroid 5880 with $\epsilon_r = 2.2$ and thickness h =0.787 mm.

- Calculated SIW dimensions from waveguide cutoff frequency.

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- Arranged via holes along parallel rows to form SIW sidewalls.
- Integrated a bow-tie slot at the center of the SIW cavity to introduce multiple resonances.
- Designed a tapered microstrip-to-SIW transition to excite the TE_{10} mode efficiently.
  - Modeled and simulated the complete structure in Ansys HFSS.
  - Performed parametric optimization to achieve targeted resonant frequencies and impedance matching.

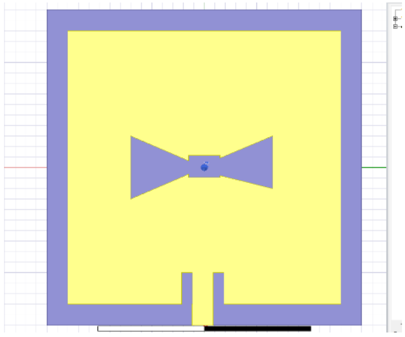

Fig. 1. Simulated SIW-based multiband antenna in HFSS.

V. SIMULATION RESULTS

The designed antenna was simulated in Ansys HFSS to evaluate return loss (S11), gain, VSWR, and surface current distribution

A. Return Loss (S11)

The return loss plot is presented in Fig. 2. The antenna achieves multiple resonances at 6.88 GHz, 14.68 GHz, 17.23 GHz, 20.07 GHz, and 25 GHz. Each resonance achieves S11 below -10 dB, confirming effective impedance matching and multiband operation. Return loss in an antenna is a measure of the power reflected back from the antenna's input port due to an impedance mismatch between the antenna and the transmission line. It indicates show efficiently power is transferred from the source to the antenna. A higher return loss (expressed in decibels, dB) signifies better impedance matching, meaning less power is reflected and more is delivered to the antenna.

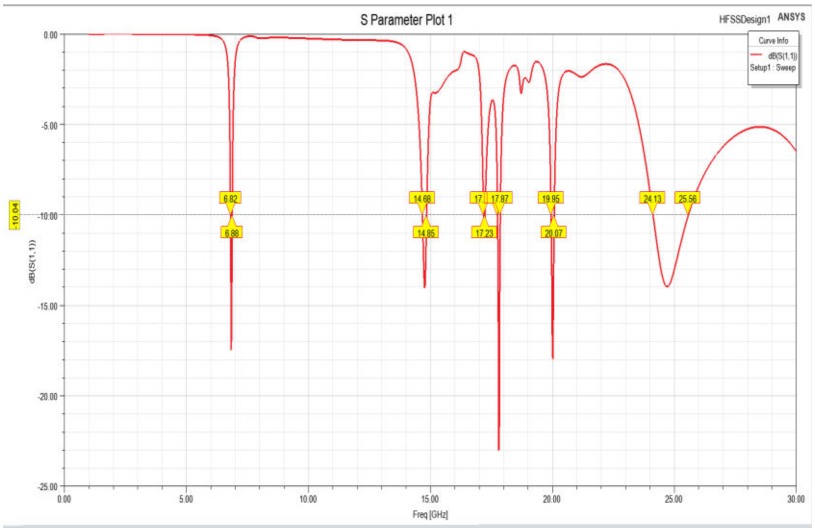

Fig. 2. Simulated return loss (S11).

B. Gain and Radiation Pattern.

The 3D gain pattern is shown in Fig. 3. The antenna achieves a peak gain of approximately 6 dB at 14.68 GHz, indicating moderate directivity and efficient radiation towards the broadside direction of the substrate. The gain remains stable across other resonant frequencies, making the antenna suitable for multiband wireless applications where consistent performance is required

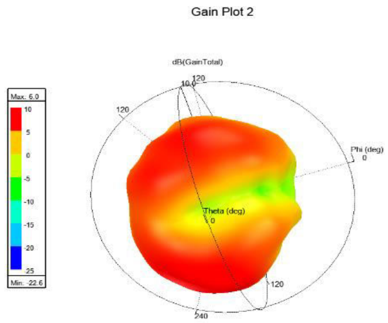

Fig. 3. 3D gain pattern of the proposed antenna.

C. VSWR Performance

The Voltage Standing Wave Ratio (VSWR) was simulated across the frequency range of interest. As shown in Fig. 4, the VSWR remains below 2 across all operating bands, confirming acceptable impedance matching and minimal reflected power.

A low VSWR is critical to ensure efficient power transfer from the feed line to the antenna, reducing insertion losses and maintaining stable operation over the desired frequency bands.

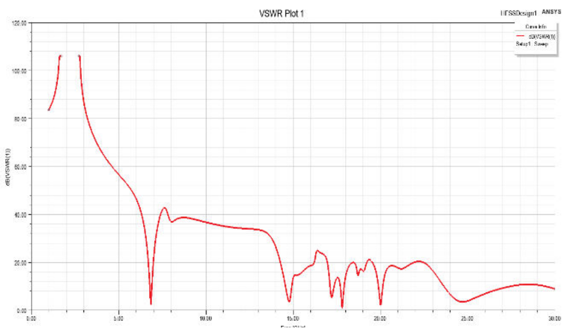

Fig. 4. VSWR of the proposed antenna across operating bands

D. Surface Current Distribution

The surface current distribution at 14.68 GHz is illustrated in Fig. 5. The current is concentrated along the edges of the bow-tie slot, validating its role in introducing multiband operation by enabling multiple resonant current paths within the SIW cavity.The current distribution also confirms that the bow-tie slot effectively perturbs the cavity mode to generate multiple resonances without requiring additional radiating elements or structural complexity.

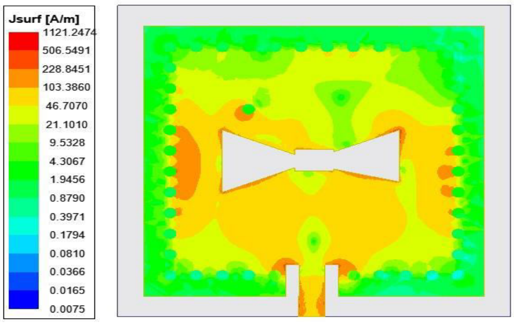

Fig. 5. Surface current distribution at 14.68 GHz.

VI. DISCUSSION

The integration of a bow-tie slot into an SIW cavity successfully enables multiband operation without compromising antenna size or complexity.
frequencies spanning from 6.88 GHz to 25 GHz while maintaining low return loss and VSWR.

Key advantages observed include:

- Compact Design: The antenna achieves multiband operation within a compact planar structure, suitable for integration in space-constrained systems.
- Low Loss: SIW confinement reduces dielectric and radiation leakage compared to traditional microstrip lines.
- Planar Fabrication: The antenna can be fabricated using standard PCB manufacturing techniques, reducing production cost.
- Directional Radiation: The antenna exhibits broadside radiation with peak gain of 7 dB, making it suitable for point-to-point communication.

Compared to conventional microstrip patch antennas, the proposed design offers improved performance at high frequencies due to reduced spurious radiation and better confinement of electromagnetic fields.
The simulated results demonstrate that the bow-tie slot effectively introduces additional resonant modes without requiring multiple feed networks or stacked structures. This simplicity enhances reliability and eases fabrication.
Additionally, the antenna shows stable performance across multiple bands, making it a strong candidate for systems requiring operation in different frequency regimes such as C-band, Ku-band, and Ka-band applications.

VII. CONCLUSION

A Substrate Integrated Waveguide (SIW) based multiband antenna incorporating a bow-tie slot was designed, simulated, and analyzed using Ansys HFSS. The antenna achieved resonant frequencies at 6.88 GHz, 14.68 GHz, 17.23 GHz, 20.07 GHz, and 25 GHz, with return loss (S11) below -10 dB and VSWR under 2 across all bands.

A peak gain of approximately 7 dB was achieved with broadside radiation pattern, making the antenna suitable for wireless applications such as 5G, radar, and satellite communications requiring compactness, multiband capability, and planar integration.

The proposed design successfully demonstrates how SIW technology can be utilized to realize efficient, low-profile, multiband antennas without requiring complex multilayer or stacked configurations. Future work may explore physical fabrication and experimental validation, as well as bandwidth enhancement techniques using advanced slot geometries or metamaterial loading.

Overall, the results confirm that SIW technology, when combined with smart slot design like the bow-tie aperture, can produce compact, high-performance multiband antennas suitable for modern RF applications.

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