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RESEARCH ARTICLE

A Wideband SIW Cavity Structure Transverse Slot Antenna for 5G communications

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Abstract

This paper presents the design of a wideband cavity-structure transverse slot antenna based on a substrate integrated waveguide (SIW) for fifth-generation (5G) applications. The antenna is specifically engineered to cover the European 5G frequency range (24.25 – 27.5 GHz). By strategically positioning multiple resonant slots on the bottom metal cladding of the SIW cavity, hybrid modes are generated within the desired frequency band. The characteristics of these modes can be adjusted by altering the slot parameters, resulting in the merging of wideband resonance frequencies. Simulation results demonstrate a bandwidth of 3.3 GHz (13.58%), spanning from 23.5 GHz to 26.8 GHz, with a gain of 10.34 dBi across the bandwidth and a cross-polarization level below -35 dB. The proposed antenna is compared to previously reported designs, evaluating its performance in terms of reflection coefficient, bandwidth, gain, optimized parameter values, and radiation pattern. The total volume of the proposed design, including the feedline, is 36.6 mm × 26.7 mm × 1.572 mm.

Keywords: transverse slot Antenna, EM-Field, 5G applications.

1 Introduction

With the rapid demand of fifth-generation (5G) mobile communications in both business and academics, millimeter-wave (mmWave) technology has attracted a lot of attention as wireless communication advances quickly. Among the main 5G technologies, millimeter-wave technology is considered one of the most innovative and effective solutions [1, 2]. According to experimental findings, the 5G mmWave architecture is taking into consideration the frequency spectrum around 28 GHz, 38 GHz, and 73 GHz [3–7]. Antenna topologies must be able to accommodate low-cost manufacturing techniques in the mm Wave band while also offering a substantial working bandwidth in a small footprint, given the demand for user devices like mobile phones. Radar and satellite applications have made substantial use of cavity-backed slot antennas [8]. Their appealing characteristics, including a high back-to-front ratio, unidirectional radiation patterns, high power handling

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capabilities, low profile, good isolation from the feeding network, and low mutual coupling, make them excellent candidates for mmWave applications [9]. Nevertheless, traditional metallic cavity-backed slot antennas are frequently costly and heavy, which prevents them from being integrated with other planar circuits. Substrate Integrated Waveguide (SIW) technology, created by Wu [10], has shown promise as a remedy for these issues. This method converts non-planar rectangular guided-wave structures into planar forms that are compatible with current planar and non-planar processing architectures by arranging metallic posts in regular gaps to produce the lateral walls of a planar waveguide. Due to the high Q factor of the cavity, SIW-based cavity-backed slot antennas have a narrow bandwidth even though they offer high gain and unidirectional radiation. The bandwidth of SIW-based cavity-backed antennas has been increased using a variety of methods [11–16]. A slot antenna with a cavity and substrate removal technique, for instance, was utilized in one study [11] to boost bandwidth by 2.16%; nevertheless, this method increases the structure's complexity and expense. Combining several resonant modes into a single passband is another way to increase bandwidth [12]. In one method [13], a dual-mode resonating SIW cavity was excited by a non-resonant slot, leading to a 6.3% increase in bandwidth. A further design [14] included a bow-tie slit and a cavity-backed antenna. It made the bandwidth 9.4% higher. Other designs [15] included a low-profile cavity antenna with several slots to split a single cavity into sub-cavities [16], increasing the bandwidth to 13.5%, and a broadband SIW cavity antenna with a semi-closed SIW cavity and two radiating slots. Furthermore [17], antennas with numerous resonances were created by inserting shorting vias into the SIW cavity, resulting in bandwidths of 15.2% and 17.5%. Other methods [18] have succeeded in achieving an 11.7% fractional impedance bandwidth, such as paired half-mode SIW CBS antennas. A wideband dual-resonance SIW cavity-backed slot antenna for 5G wireless systems in Europe (24.25–27.5 GHz) is presented in this paper. Wideband resonant slots in the shape of a rectangular complementary split-ring slot are present in the antenna. This stimulates the operating band's hybrid modes. A wide impedance bandwidth is achieved by combining several resonance frequencies through the fine-tuning of these hybrid modes. The antenna's operation is described in detail, and the simulated results show that it is appropriate for 5G applications because it operates in the 23.5 GHz to 26.8 GHz frequency range. Among the many benefits of the suggested antenna are its straightforward design, small size, and simplicity of construction. Additionally, it has outstanding radiation performance, which qualifies it for enhanced mobile communications, biomedical applications, and field sensing. The antenna design is provided and discussed together with simulated and measured findings, such as radiation patterns, antenna gains, and return loss.

2 Antenna Design

The proposed slot antenna is designed to operate within the 23.5–26.8 GHz frequency range on a Rogers RT/Duroid 5880 copper-laminated substrate. The substrate has a height of 1.572 mm, a dielectric constant of 2.2, and a loss tangent $(\tan\delta)$ of 0.0009. Figures 1 and 2 depict the antenna arrangement and the manufactured antenna design, respectively, while Figure 3 displays the matching reflection coefficient. According to the simulated results, the slots are crucial in increasing the impedance bandwidth. The slot configuration not only broadens bandwidth but also exhibits filtering properties similar to those reported in SIW filtennas [29], improving out-of-band rejection. This ensures resonance, maximizing radiation efficiency and impedance matching. Altering the length or width shifts the resonant frequency and bandwidth.

Metal posts that mimic the cavity's sidewalls are incorporated into the substrate to construct the SIW cavity. The requisite conditions to make the SIW cavity identical to conventional metallic cavity are $d/s \geq 0.5$ and $d/\lambda_0 \leq 0.1$. In order to avoid the bandgap effect, $d < s \leq 2d$ must be satisfied. To provide the mechanical stability, s/λ_c must be greater than 0.05. To guarantee ideal SIW performance, there should be no more than 20 vias per wavelength.

To keep the SIW cavity compatible with planar circuits, it is excited by a 50 Ω GCPW feedline. Slots are etched into the SIW cavity's lower metal covering to reduce parasitic radiation from the microstrip feedline. The resonant frequency of the associated rectangular waveguide cavity can be used to compute the cavity's primary dimensions.

$$fr = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{w_{ef}}\right)^2 + \left(\frac{n}{L_{ef}}\right)^2} \tag{1}$$

Now, the effective width and effective length of the SIW can be determined by the equation in (2) & (3)

respectively as:

$$L_{ef} = L - \frac{4d^2}{0.95s} \tag{2}$$

$$W_{ef} = W - \frac{4d^2}{0.95s} \tag{3}$$

$$d \leq \frac{\lambda_g}{5} \tag{4}$$

$$d < s < 2 * d \tag{5}$$

where f_r represents the resonant frequency of the SIW cavity, c is the speed of light, and ε_r is the relative permittivity of the dielectric substrate. Equations (4) and (5) describe some of the limits of the SIW architecture. Because of the dielectric substrate, the SIW has a narrower width than a typical waveguide, but its planar shape keeps the waveguide height constant. Equation (5) must be met in order to prevent the bandgap effect. Table 1 lists the optimal geometric parameters for the suggested construction.

The current distribution of the higher-order mode (TE_{120}) is disturbed by inserting a rectangular split-ring-shaped slot into the SIW cavity, positioned side-by-side [13], improving the bandwidth and radiation properties by more than 50%. The cavity's overall performance is improved by etching the inner rectangular complementary-split ring slots, which introduces many hybrid modes without changing the lower-order mode's resonant frequency. The rectangular slot shape antenna design is simple and also affects the current distribution and mode excitation. The number of slots is increased to 11, and the optimization procedure is repeated.

Based on the simulation results, the reflection at PORT1 can be made better than -45 dB by increasing the number of slots. The step-by-step optimization process of the proposed antenna is shown in Figure 1.

Two adjacent frequencies are created by adding transverse and longitudinal slots to the rectangular slot antenna, which effectively broadens the bandwidth. This design is partially supported by the field distribution inside the waveguide, where the magnetic field direction is parallel to the conductor surface and perpendicular to the sides, and the electric field of the dominant SIW mode is perpendicular to both the ground and the surface. Only in these circumstances can the Complementary Split-Ring Resonator (CSRR), which acts like an electric dipole and needs axial electrical excitation, be efficiently excited. The broadband antenna's impedance matching sensitivity is greatly influenced by the slot [19–23]. The impedance bandwidth is greatly increased by adding a rectangular slit to the cavity's bottom metal covering, which excites an extra resonance at 26.1 GHz. The antenna's overall performance is improved by the slot's multi-resonance feature, which results in the highest resonance band. Top and bottom view of fabricated designed of proposed antenna is shown in Figure 2.

Table 1. Optimized parameters of the proposed antenna.

Parameter	Value(mm)	Parameter	Value(mm)
L	36.6	b	22
W	26.7	L_1	16
L_f	7.93	W_1	2.16
W_f	1.3	g	0.5
a	21.6	S	2.0

3 Results

The finite element method (FEM) technology is used by the High Frequency Structure Simulator (HFSS) to improve the antenna size. Figure 3 displays the optimized reflection coefficient (S_{11}) for the suggested wideband resonance SIW slot antenna. The antenna's return loss (S_{11}), as determined by measurements and modelling, aids in the antenna design's completion. With a -47 dB return loss bandwidth of 3.3 GHz, the simulation spans a frequency range of 23 to 27 GHz. It is clear from the Figure 3 that wideband matching is guaranteed by two resonances. $S_{11} < -10$ dB has a fractional bandwidth of 13.58%, which spans the working frequency band from 23.5 GHz to 26.8 GHz, as shown in Figure 3. At the resonance of 24.2 GHz, -47 dB was the reflection coefficient attained.

In terms of co-polarization, the cross-polarization level is below -35 dB in the E-plane and below -29 dB in the H-plane as shown in Figure 5. The multi-resonant slots in the suggested structure are responsible for the simulated gain of 10.34 dBi at 25.2 GHz across the broad range, which is confirmed by measured gain also with co and cross polarization results. Table 2 summarizes the performance of the suggested antenna in comparison to similar antennas found in the literature. When compared to previously published designs, the suggested antenna performs better in terms of cross-polarization, peak gain, and impedance bandwidth. The antenna is a good contender for 5G applications in both the USA and Europe due to its straightforward construction, lightweight design, and small size.

A radiation pattern, also known as an antenna

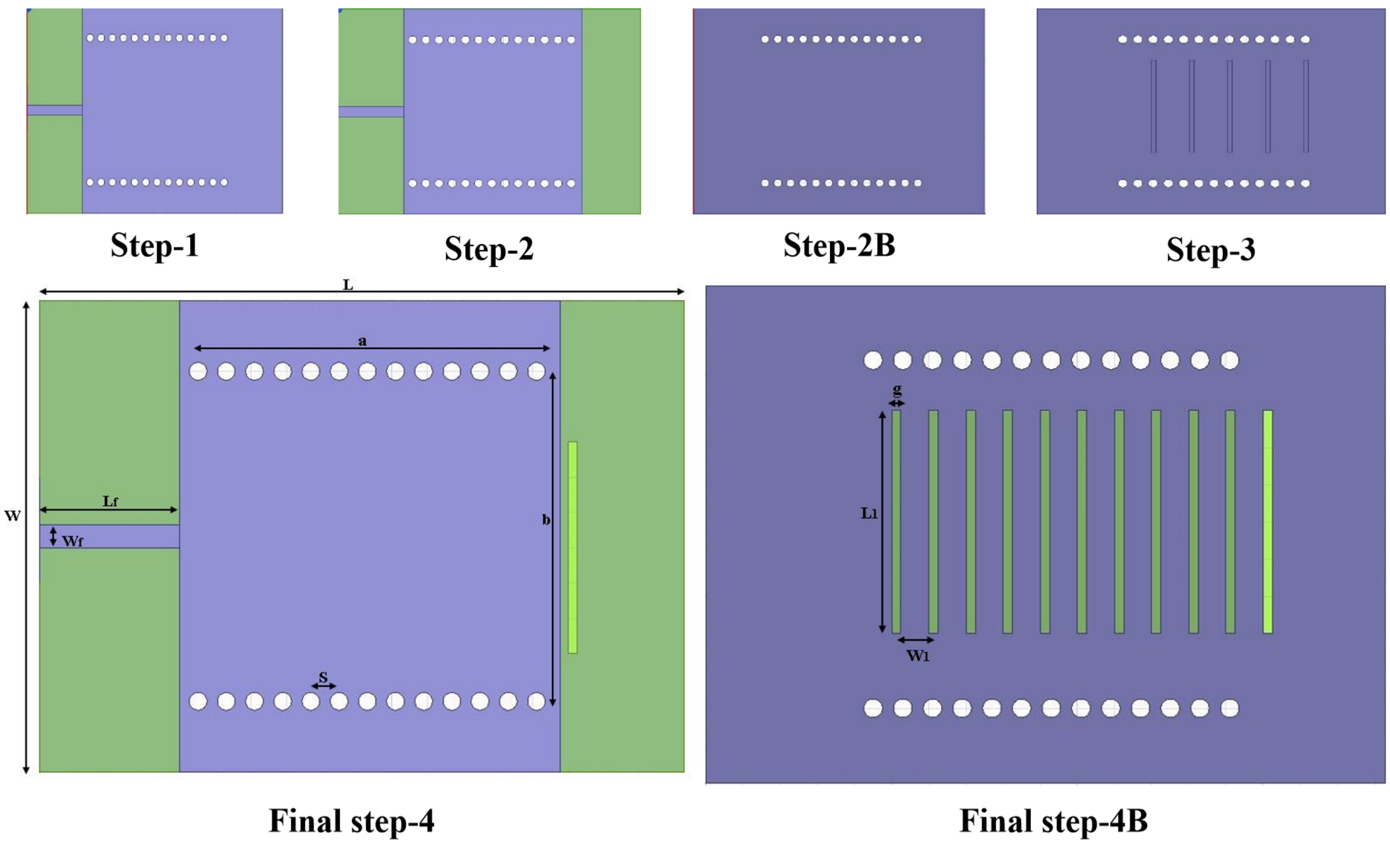
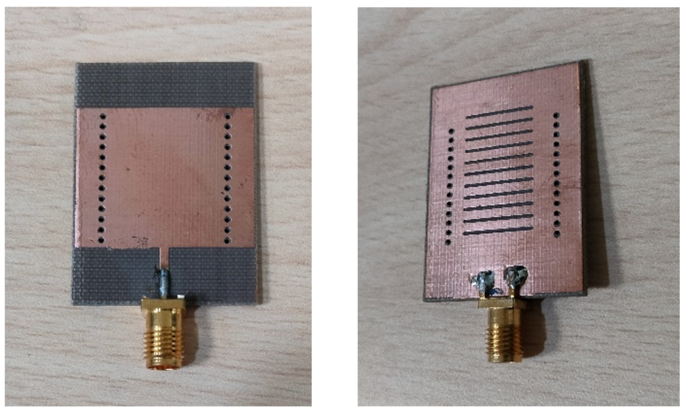


Figure 1. The geometrical configuration of the step-by-step optimization including proposed antenna. (a) Top view. (b) Bottom view.



(a) Top view (b) Bottom view

Figure 2. fabricated Antenna configuration of the proposed antenna. (a) Top view. (b) Bottom view.

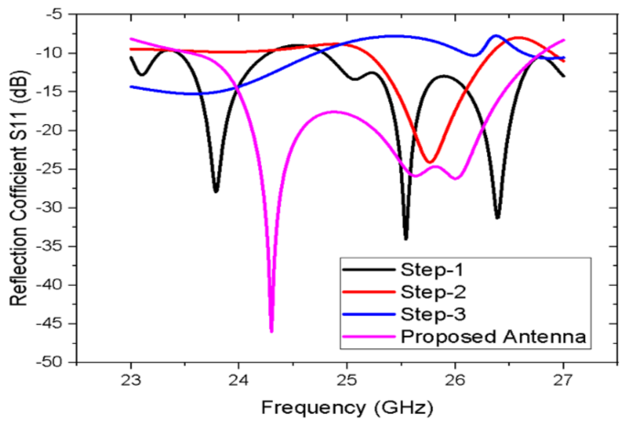
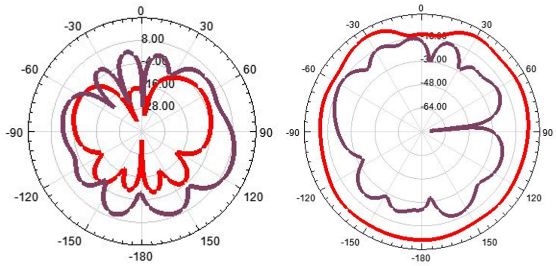


Figure 3. Return loss S11 of optimized proposed Antenna.

pattern, is a graphic representation of the radiation characteristics of an antenna as a function of geographical coordinates. It displays the power distribution of an antenna in the immediate vicinity. Centered placement of slots is ensuring symmetrical radiation patterns. The results of the radiation pattern simulation are shown in polar coordinates in Figure 4. The radiation pattern is shown in the θ-plane, or vertical plane, in Figure 4(a), and in the ϕ-plane, or horizontal plane, in Figure 4(b).

4 Measurement Setup

Figure 5 depicts the experimental configuration used to assess the SIW patch antenna's gain and radiation pattern. For the purpose of measuring the radiation pattern at 24.2 GHz, port 1 of the VNA is linked to a standard horn antenna (the antenna's name and gain) of the 23–27 GHz band. The ultra-wide band SIW patch antenna is linked to port 1 VNA. In this case, a



(a) H-field pattern (b) E-Field pattern

Figure 4. Co and cross radiation pattern at 24.2 GHz. (a) H-field pattern (b) E-Field pattern.

Table 2. Qualitative comparison of the reported antennas with respect to proposed antenna.

Ref.	Frequency band (GHz)	B.W. (%)	Gain (dBi)	Cross-Pol (dB)	Feed Type	Substrate h(mm)
[11]	28	4.6	7.5	-	GCPW Microstrip line	1.57
[24]	X, Ku	1.4,5.7	4.8,6.7	-15	Microstrip line	1.57
[25]	Ku	11.8,11	6,8.03	-20	SIW Microstrip line	1.57
[26]	28	1.4	6.9	-	Microstrip line	0.5
[27]	28	3.5	7.05	-	Microstrip line	0.78
[28]	28	4.8	9.05	-	Microstrip line	1.6
[30]	28	1.9	4.7,8	-	SIW	1.57
This Work	23-27	13.58	10.34	-35	GCPW Microstrip line	1.57

patch antenna attached to port 1 serves as a receiver and a horn antenna attached to port 2 as a transmitter. Both antennas are positioned within line of sight of one another, approximately one meter apart.

S_{12} is measured in increments of 10 degrees from $-90°$ to $+90°$ while the patch antenna is positioned on the rotating stage. The simulated and measured gain values were in agreement. The patch antenna's gain in dBi at each measurement frequency is determined by the linear magnitude values in the line-of-sight direction, or at 0 degrees. Figure 5 below depicts the experimental setup for radiation pattern measurements.

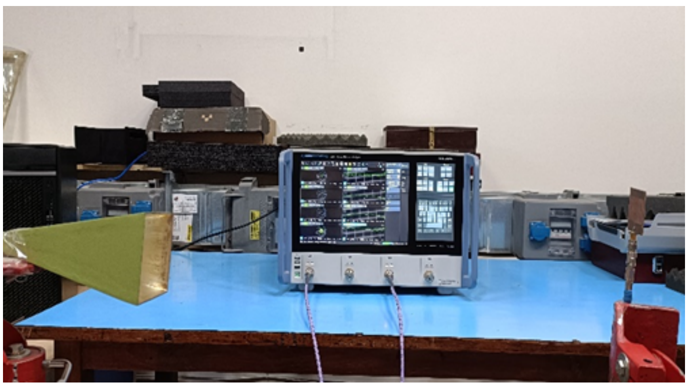


Figure 5. Measurement setup of proposed Antenna.

By using a rectangular slot and a circular slot on each side, the upper surfaces of the patch are carefully positioned on the E-plane of the proposed antenna. Field Concentration in the Slot Confirms proper excitation and resonance of the slot, ensuring effective radiation. The center of the patch can be used to couple resonant currents, allowing for frequency tuning of the antenna. Electric field plot as shown in Figure 6. The analysis of current distributions on the top surface with the slot reveals an enhanced electromagnetic conduction in the proposed antenna. Current path analysis shows how current flows through parasitic elements or multi-slot arrangements are useful for broadband 5G antennas. As shown in Figure 7, the current distribution is concentrated strongly directed towards the center of the patch, indicating efficient current flow and improved performance.

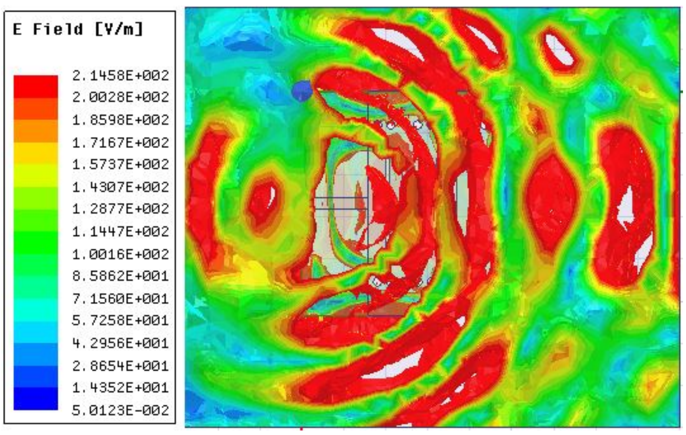


Figure 6. Electric field plots.

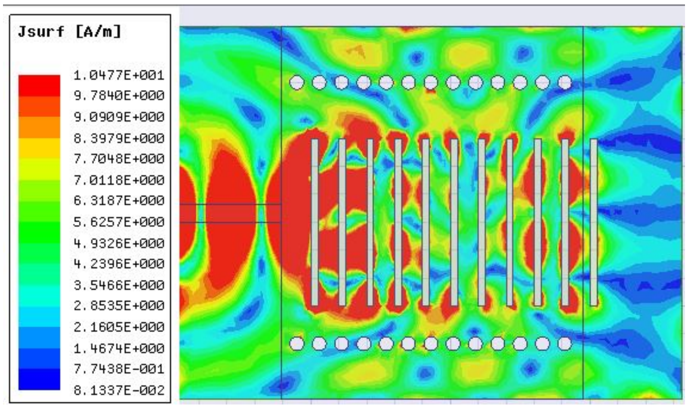


Figure 7. Surface current density.

On the other hand, the full wavelength corresponding to the resonance frequency can be supported by the highly concentrated vector current of 104.7 A/m. This concentrated current leads to the excitation of the TE_{11} mode.

5 Conclusion

A wideband resonance SIW cavity-backed slot antenna has been proposed to increase bandwidth. Strategically placing rectangular complementary split-ring slots allows for a broad bandwidth. These slots excite hybrid modes, which increase the antenna's bandwidth by about 3.3 GHz, from 23.5 GHz to 26.8 GHz. In comparison to earlier published designs, the developed antenna exhibits similar or higher gain and bandwidth performance while keeping a smaller size and a more straightforward topology, which makes it a perfect fit for 5G communications. The antenna efficiently covers the 23.5–26.8 GHz spectrum for 5G applications, according to the simulated findings. The antenna's single-layer structure also provides wideband resonance characteristics over a large impedance bandwidth and flexibility in resonance frequency.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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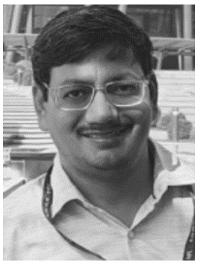

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