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Dielectric Resonator Antenna Mode Excitation using Substrate Integrated Waveguide Feed with L-Slot

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Abstract: In this study, a substrate integrated waveguide dielectric resonator antenna excited by an L-slot is proposed, and the design is operated within the frequency range of 24.25 to 29.5 GHz bandwidth for 5G-NR applications. Rogers 5880 is used as a substrate with a permittivity of 2.2; in contrast, the dielectric resonator antenna has a permittivity of 10. The antenna demonstrates a simulated impedance bandwidth of 25.2 to 30.5 GHz, and a high gain of 8.7 dBi is observed due to the excitation of the DRA higher-order TE_{113} mode, whereas the design exhibits over 98% radiation efficiency, attributed to minimal copper losses at resonant frequencies. These results highlight the antenna's suitability for broadband, high-efficiency, high-gain applications in the millimeter-wave 5G-NR frequency bands.

Keywords: Cubical Dielectric resonator antenna (Cub DRA), higher-order mode, millimeter (mm) wave band, substrate integrated waveguide (SIW), L-slot, fifth generation New Radio (5G-NR)

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1. INTRODUCTION

Dielectric resonator antennas (DRAs) [1] have emerged as a prominent choice in the realm of microwave and millimeter-wave communications, captivating the attention of researchers and engineers. DRA has a wide bandwidth, excellent efficiency, gain, and negligible conductor loss. One of the key challenges in the antenna design is the effective coupling of the energy from the feeding network to the dielectric resonator. Substrate-integrated waveguide (SIW) technology has proven to be a promising solution offering a low-cost, compact, and high-efficiency approach to feed antennas. The SIW [2] is a planar version of a standard rectangular waveguide, realized by embedding rows of metallic vias within a dielectric substrate. This configuration enables the realization of waveguide-based circuits and components in a planar form, seamlessly integrating with other microwave and millimeter-wave systems on a single substrate making it well-suited for a wide range of applications, including wireless communications, radar, and satellite systems.

The mm-wave band is now being established and used for 5G users [3], which necessitates the usage of high-gain antennas with wide bandwidths and directional features to meet the demands of long-distance mm-wave communication. Cub DRA is employed in the proposed antenna to make it low profile, with the size of the DRA proportional to $\lambda o/\sqrt{\varepsilon_r}$ and bandwidth is inversely proportional to the permittivity of DRA. An L-shaped cut at the top metal ground in the SIW center excites the Cub DRA. The design is suggested to have a larger bandwidth, less losses, more efficiency, and greater gain for 5G applications.

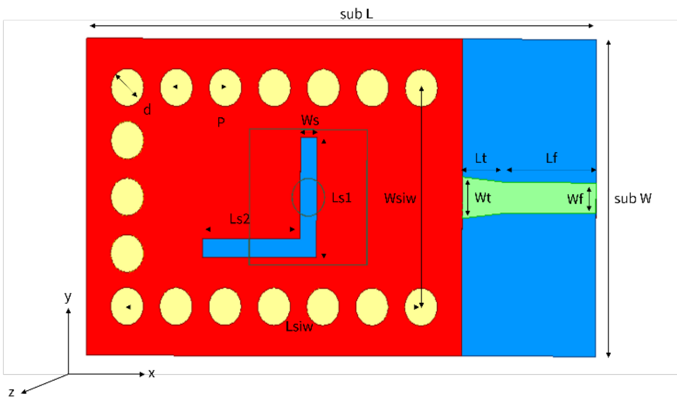


Figure 1. Single SIW DRA antenna with L-slot excitation

2. ANTENNA DESIGN

2.1 Substrate Integrated Waveguide

The propagation and dispersion [4] characteristics of substrate-integrated waveguides are comparable to rectangular waveguides. SIW structures do not allow Transverse magnetic (TM) modes because the metallic posts conductively connect the surface currents between the top and bottom planes, therefore, only Transverse electric TE_{n0} modes exist. These posts set the boundary conditions for electromagnetic waves. SIW design parameters are the width of SIW 'Wsiw', metalized via diameter 'd', and distance between two vias 'p', 'W' is the width of rectangular waveguide (RWG), and 'Wd' is the width of dielectric-filled waveguide (DFW). The design equations for SIW are [5].

Cutoff frequency, fc= c/2W (1)

DFW width, Wd= W/ $\sqrt{\varepsilon_r}$ (2)

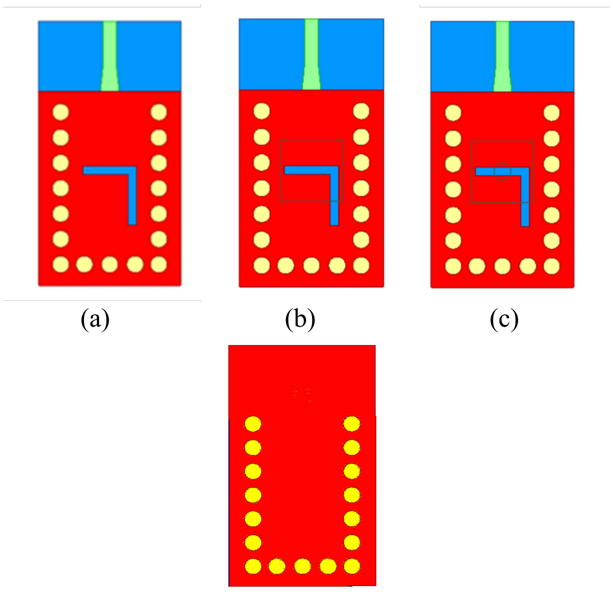
SIW width, Wsiw= Wd + d2/0.95p (3)

The conditions required for SIW are:

$p \leq 2d$ (4)

$d < \lambda g/5$ (5)

Guided wavelength, $\lambda gsiw = \frac{\lambda_o}{\sqrt{\varepsilon_r[1-\left(\frac{fc}{fo}\right)^2]}}$ (6)



(a) (b) (c)

(d)

Figure 2. Antenna Design Evolution: Top view, (a) Stage1, (b) Stage 2, (c) Stage 3, (d) Bottom

2.2 Dielectric Resonator Antenna

The resonant frequency of the DRA is estimated through the dielectric waveguide model (DWM) [6].

$$k_y \tan(k_y W_d/2) = \sqrt{(\varepsilon_{rd} - 1)k_o^2 - k_y^2} \quad (7)$$

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_{rd}\, k_o^2 \quad (8)$$

$$k_x = \frac{\pi}{L_d};\; k_z = \frac{\pi}{2H_d};\; k_o = \frac{2\pi fo}{c} \quad (9)$$

k_x, k_y, and k_z are the wave numbers along the x, y, and z directions, respectively. W_d is the width of the DRA, L_d is the length of the DRA, H_d is the height of the DRA, f_o is the resonant frequency, ε_{rd} is the relative permittivity of the dielectric material, and k_o is the free space wave number. DRA modes are checked using the eigenmode analysis in HFSS.

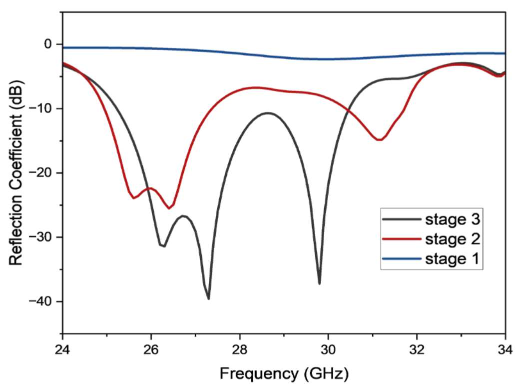
2.3 Design of Single SIW Cub DRA

The single port SIW fed DRA is shown in Figure 1. A Rogers 5880 substrate with a permittivity of 2.2, a loss tangent of 0.0009, and a thickness of 0.254 mm is used, whereas DRA has a permittivity of 10 and a loss tangent of 0.002 in this work. The step-by-step design process is shown in Figure 2, where SIW and microstrip transition design parameters are computed by [6]. The dimensions for Cub DRA are 3.6x3.6x3.6 mm^3 resonant at 26 GHz and are calculated using [7]. At stage 1, only the L-slot is cut, and the reflection coefficient shows no slot excitation. At stage 2, DRA is excited in higher mode TE_{113} by L slot cut, located in the top metallic wall of SIW operating in TE_{10} mode, presenting good results as gain and bandwidth. The third stage is the final one, a hole of 0.5mm radius is drilled at the center of the DRA and is placed at the middle of the L-slot [8] to get maximum radiation. The slot length is chosen to be half of the guided wavelength to avoid slot resonance, whereas the slot width is below λg/10 to avoid high cross-polarization. The diameter of the vias is 1 mm, and the distance between the two consecutive vias is 1.5 mm. The optimized dimensions of the proposed design are in Table 1.

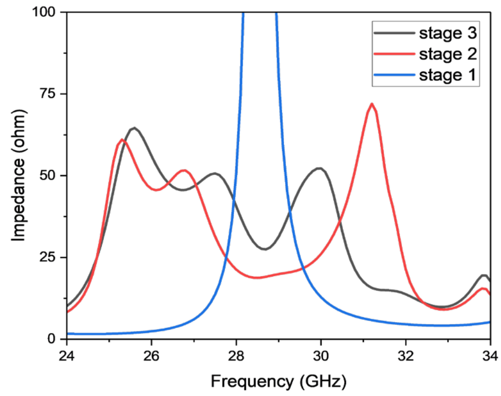
Table 1. Dimensions of Antenna Design

Dimension in mm			
Parameter	Length	Width	Height
Substrate (sub L, sub W, sub H)	15.2	8.4	0.254
DRA (L_d, W_d, H_d)	3.6	3.6	3.6
SIW (W_{SIW}, L_{SIW}, H_{SIW})	9	5.8	0.254
Feed	2.7	0.7	0.035
Taper	1	1	0.035
Slot	3, 3.2	0.5	

3. SIMULATION RESULTS OF SIW RDRA



(a)



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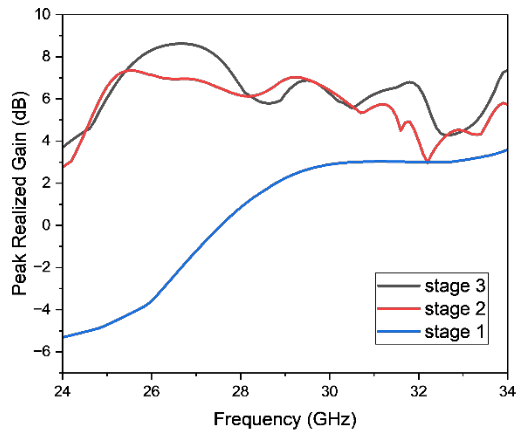
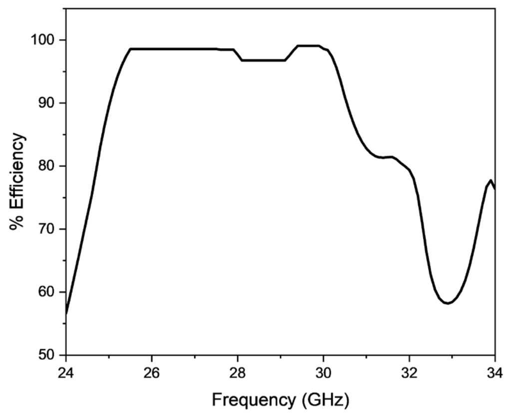


(c)



(d)

Figure 3. Simulated response for different geometry (a) Reflection coefficient, (b) Impedance plot, (c)Realized Gain, (d) Radiation efficiency

The simulated response for the reflection coefficient, impedance plot, realized gain, and efficiency is indicated in Figure 3. In Figure 3a, at stage 1, no excitation occurs due to no DRA. At stage 2, a dual band can be seen however, at stage 3, the design results in a wide band. It can be noticed that when using a slot with DRA, S_{11} is less than 10 dB. In addition, DRA with a hole has good impedance matching and wide bandwidth compared to DRA without a hole for resonant frequencies at 26.1, 27.3, and 29.8 GHz as illustrated in Figure 3b. Figure 3c demonstrates stage 3 has a higher gain than the previous stages. Table 2 displays the simulated results for bandwidth, gain, and efficiency. Figure 4 depicts radiation patterns for the E plane, phi 0, and H plane, phi 90.

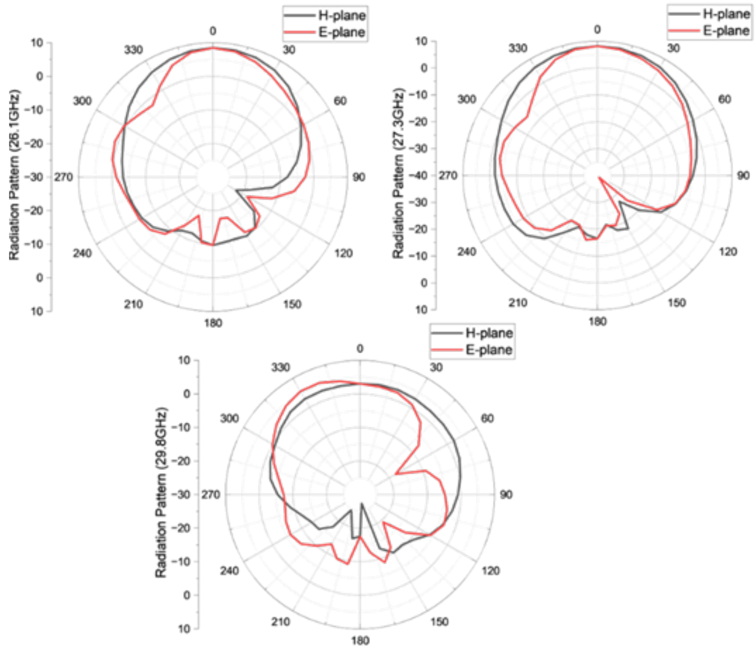


Figure 4. Radiation pattern E plane and H plane at resonant frequencies of 26.1, 27.3, and 29.8 GHz

Table 2. Simulated gain and bandwidth of SIW DRA

Simulated results of SIW Cub DRA		
Bandwidth (GHz)	**Gain (dBi)**	**Efficiency**
25.2 - 30.5 = 5.3 (19.06%)	8.5 @ 26.1, 8.3 @ 27.4, 6.6 @ 29.8	> 98%

4. DISCUSSION

The proposed antenna is designed for the frequency range 24.25 to 29.5 (5.25 GHz), nevertheless, the design achieves a simulated impedance bandwidth of 25.2 to 30.5 (5.3 GHz), where the reflection coefficient is less than -35 dB within the desired band. A hole is drilled at the center of DRA to decrease the effective permittivity, hence increasing the bandwidth. The high gain is due to the excitation of DRA in higher order TE_{113} mode, and the design has radiation efficiency above 98% due to lower copper losses at resonant frequencies. The simulated radiation patterns of the E-plane and H-plane for each resonant frequency showing E plane (XZ) is plotted for Ø = 0 while the H plane (YZ) is plotted for Ø = 90, resulting in broadside radiation.

Table 3 compares the proposed structure with the recently reported antenna. In [9], patch is employed as a resonating element along with slots and SIW feed, however, in [10], hybrid resonators and SIW are used for 5G, besides, microstrip feed has been used in [11] with patch and U slot. The proposed antenna incorporates DRA as a resonating element with an L-slot and SIW feed, which outperforms others in terms of bandwidth, gain, and efficiency.

Table 3. Comparison of the proposed antenna with recently reported literature

Ref	Bandwidth %	Gain dBi	Efficiency %	Feeding
[9]	14.4% 25.10-29	7.5 dBi	90	SIW
[10]	14.11% 26.41–30.42 12.56% 36.05–40.88	6.8 dBi 6.4 dBi	NM	SIW
[11]	19.1% 24.71-29.93	5.28 dBi	NM	Microstrip
Proposed	19.06% 25.2-30.5	8.7 dBi	98	SIW

5. CONCLUSION

This paper analyzes the performance of the SIW dielectric resonator antenna specifically covering the 5G-NR, 26 GHz, and 28 GHz bands for 5G applications. The antenna achieves a percentage bandwidth of 19.06%, attributed to multiple resonant frequencies of DRA modes. A peak gain of 8.7 dBi is observed at 26.6 GHz and efficiency above 98% throughout the band of interest. These findings emphasize the antenna's suitability for low loss, broadband, high-efficiency, and high-gain applications in the millimeter-wave 5G-NR frequency bands.

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