ISSN: 2229-6948(ONLINE)
DOI: 10.21917/ijct.2025.0519

LOW PROFILE DIELECTRIC RESONATOR ANTENNA BACKED BY SUBSTRATE INTEGRATED WAVEGUIDE CAVITY

Manoj Joseph, S. Femina Beegum, K. Ashok, H. Sreemoolanadhan, Saji Joyas and J. Girija
Vikram Sarabhai Space Centre, Indian Space Research Organization, Thiruvananthapuram, India

Abstract
A low-profile dielectric resonator antenna backed by substrate integrated waveguide cavity is proposed in this paper. A novel feeding mechanism is used to excite a low-profile dielectric resonator antenna backed by substrate integrated waveguide cavity. Instead of a single slot, a 2x2 array of 2mm x 2mm slots is used to excite the dielectric resonator antenna. With this feeding technique, an antenna working in X band frequencies is designed by combining substrate integrated waveguide cavity and dielectric resonator antenna resonant modes. The paper compares the conventional single slot excited dielectric resonator antenna and the proposed 2x2 slot array excited dielectric resonator antenna. The proposed antenna is linearly polarized with a 2:1 VSWR bandwidth of 5.3% and a peak gain of 6.5dBi. Overall dimension of the antenna is 30mm x 30mm x 0.78mm.

Keywords:
Substrate Integrated Waveguide, Low Profile Dielectric Resonator Antenna, Cavity Backed, Slot Array

1. INTRODUCTION

Substrate integrated waveguide (SIW) is the newly developed technology that enables high-frequency transmission in planar circuits without much radiation losses. SIW-based antennas find relevance in future wireless communication systems due to the easy integration with high-frequency circuits with low power losses. Several papers have been reported on SIW cavity-backed antennas. A low-profile planar slot antenna backed by substrate integrated waveguide cavity was reported [1], which utilizes the TE120 mode of the cavity to achieve radiation at 10 GHz with 1.7% bandwidth. This slot antenna configuration had a very narrow bandwidth. Numerous techniques are applied to SIW cavity-backed antenna for achieving wide bandwidth.

Bandwidth enhancement is achieved by simultaneously exciting two modes, TE110 and TE120, in the SIW-backed cavity and merging them within the required frequency range [2]. With this technique, 6.3% bandwidth was achieved. In another research work [3], a via-hole above the slot was used to create the second resonance and enhance the bandwidth. SIW cavity-fed dielectric resonator antennas (DRA) are suitable choices for wideband applications. Designing the DRA resonant frequency near the SIW cavity mode can give wide bandwidth by merging these modes (Cavity mode and DRA mode). Dielectric resonator antennas have many advantages like compactness, lightweight, low cost, and high radiation efficiency due to the absence of conductor loss. SIW cavities fed DRAs are reported for high-frequency applications [4]-[6]. However, very few studies are reported on SIW-fed low aspect ratios (Low profile) DRAs, which are highly useful in much low profile planar applications. In the case of aerospace applications, which are susceptible to higher levels of vibration, low profiles DRAs are preferred to conventional DRAs. Designing low-profile dielectric-resonator antennas is a challenge. When the height of a DRA is significantly reduced, the field distribution in the dielectric resonator becomes more sensitive to coupling apertures and feeds. Also, it becomes challenging to achieve good input matching [7].

A commonly used method of exciting a DRA is using a transverse slot on SIW. Depending on the dimension and dielectric constant, an offset between slot and DRA may be required for proper excitation and impedance matching. For example, Low profile aperture coupled DRA [8] has an offset from the slot center to the DRA center to achieve optimum coupling between the microstrip feed and the high-permittivity DRA. This kind of offset introduces an asymmetry in the geometry and causes a tilt in the radiation pattern depending upon the offset direction, dielectric constant, and dimension of the DRA. Hence, to retain the symmetry in the geometry and the radiation pattern, a novel feeding technique is described in the proposed work. Instead of a single slot, a 2x2 array of 2mm x 2mm slots is used to excite DRA. In this method, slots and DRA are placed symmetrically, and hence radiation pattern is undisturbed. A detailed analysis is presented in subsequent sections. Section 2 describes the conventional feeding method with slots and the role of offset. Section 3 explains the proposed new method with periodic slots and its optimization.

2. DIELECTRIC RESONATOR ANTENNA EXCITED BY SINGLE SLOT ON SIW CAVITY

The configuration of the dielectric resonator antenna excited by the SIW cavity is shown in Fig.1. The SIW cavity is designed on a single PCB of height h, where the walls of the cavity are realized by placing plated through holes (PTH) along the edges of the substrate. Rogers RT/duroid 5880 substrate ($\varepsilon r = 2.2$) of thickness 0.76mm is used as the dielectric due to its features like low losses, less relative permittivity, etc. The PTH diameter (d) and pitch (s) is suitably chosen to meet the criteria $d/s \geq 0.5$ and $d/\lambda 0 \leq 0.1$, where $\lambda 0$ is the free-space wavelength. When these criteria are met, leakage between two adjacent PTH is negligible [9]-[11].

The dimensions of the SIW cavity can be approximately determined from equation given in [12]. A 50Ω microstrip line section is tapered at the end for exciting the SIW. As shown in the figure, a transverse slot is etched on the ground plane with an offset of 2mm from the center. A cylindrical dielectric resonator (DRA) of 6mm diameter and 2mm height is placed at the center of the SIW structure, as shown in the figure. DRA has a dielectric constant of 24 and a loss tangent of 0.0012. DRA was sliced from a thick disc of Ba ($Mg_{1/3}Ta_{2/3})O_3$ ceramic that had an εr 24.6, Qu 20,000 at 11.45GHz [13].

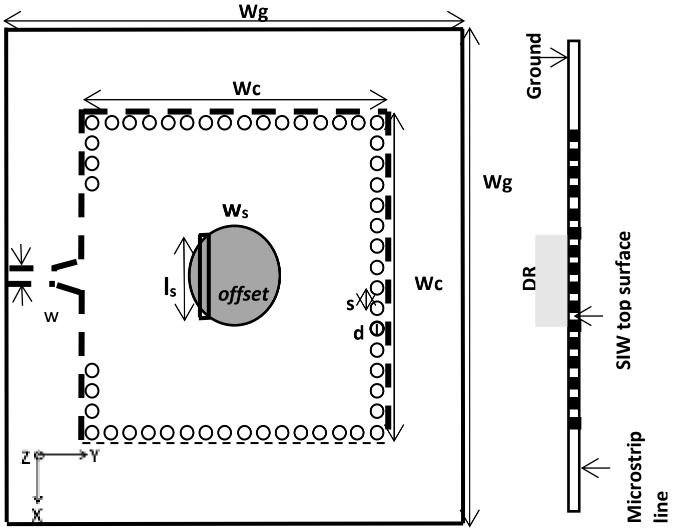


Fig.1. Configuration of DRA excited by SIW cavity with slot (Wg=30mm, Wc=20mm, w=1mm,s=1.25mm, d=0.8mm, ls=5mm, ws=0.5mm, offset=2mm)

The simulated return loss characteristic of the SIW cavity-backed DRA excited using a transverse slot is shown in Fig.2. Simulation is carried out using Ansys HFSS software. When the slot and DRA are placed symmetrically, DRA does not get excited, and the resonance seen at 10.5GHz in the return loss curve is due to the TE120 mode of the cavity. From equation (1) calculated value for TE120 mode is 11.9GHz without DRA loading. Reduction in the simulated resonant frequency is attributed to the DRA loading. With an offset of 2mm in the slot position to DRA, dual resonance is generated, as shown in the figure. In this case, the antenna is resonating at 10.75GHz and 11.13GHz. The first resonance is the SIW cavity TE120 mode, and the second one is due to the HEM11δ mode of the DRA. The equation for the HEM11δ mode is given below [14].

$$f_{\mathrm{HEM11}\delta} = \frac{c}{2\pi r_d \sqrt{\varepsilon_r}} \sqrt{1.71 + \frac{r_d}{h_d} + 0.1578\left(\frac{r_d}{h_d}\right)^2} \qquad (1)$$

where ε_r is the dielectric constant of the DRA, r_d and h_d are the radius and height of the cylindrical DRA. In this case, the calculated value is 11.58GHz, nearly matching the measured value at 11.13GHz.

The simulated 2D radiation pattern of the antenna is shown in Fig.3. Co polarization patterns at the two principal planes E–plane (YZ plane, Φ=900) and H-plane (XZ plane, Φ=00) for both the resonances are plotted in the figure. The antenna is linearly polarized along the Y direction for both frequencies. A tilt of nearly 30 degrees is observed in the radiation pattern of DRA, which is shown in Fig.3b. It may be due to the offset between the slot and the DRA. The HFSS simulated Electric field distributions at two resonances are plotted in Fig.4. The E field plot shows that the first resonance 10.75GHz is solely due to the TE120 mode of the SIW cavity. When the cavity is resonating in TE120 mode, the electric field on either side of the slot has an opposite phase, and there is a transverse field across the slot [1]. A slight asymmetry in the filed distribution is due to the offset position of the slot, in the case of second resonance, which is primarily due to the DRA; asymmetric field distribution is observed due to the offset in the slot position. This asymmetry introduces tilt in the radiation pattern, as shown in Fig.3b.

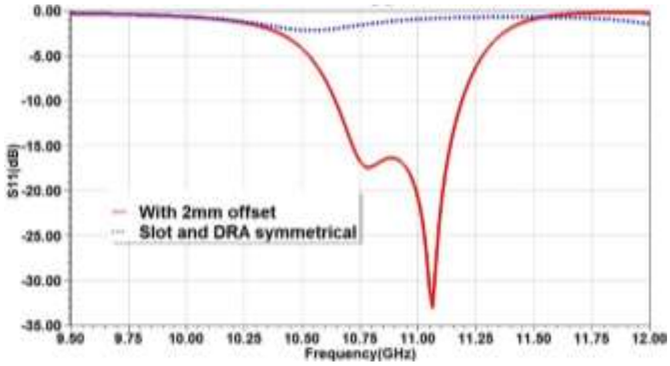
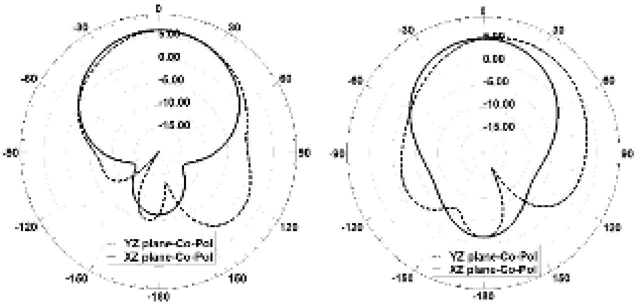


Fig.2. Return loss characteristics of the SIW cavity backed DRA excited using transverse slot



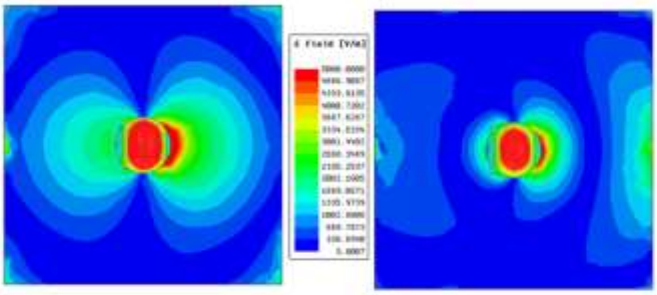
(a) 10.75GHz (b) 11.13GHz

Fig.3. Simulated radiation pattern of the SIW cavity backed DRA excited using offset slot

To avoid the tilt in the radiation pattern and retain the symmetry in the geometry, a novel feeding technique and a novel antenna configuration are designed, as explained in section 3.

3. DIELECTRIC RESONATOR ANTENNA EXCITED BY PERIODIC SLOTS ON SIW CAVITY

The configuration of the dielectric resonator antenna excited by periodic slots on the SIW cavity is shown in Fig.5. Instead of a single transverse slot, a periodic array of 2x2 slots are etched on the bottom ground plane of the SIW cavity. The bottom surface is used to avoid the radiation from the feed, which distorts the antenna's radiation pattern. Slots are square with dimension Ws = 2mm, and the gap between the slots is g=1mm. The dimension of the slots and gap is optimized to achieve better impedance matching. The slots and DRA are placed symmetrically at the center of the SIW cavity, as shown in the figure. The SIW cavity's and DRA's parameters are kept the same as in the previous case mentioned in section 2. Simulated and measured return loss characteristics of the antenna are shown in Fig.6. The antenna resonates at 10.31GHz and 10.54 GHz with a 2:1 VSWR bandwidth of 5.3%. Simulated results are closely matching with the measured response. The simulated VSWR bandwidth is 5.02%, with resonances at 10.23GHz and 10.49GHz. The first resonance is due to the TE120 mode of the SIW cavity and the second one is due to the excitation of the DRA. Both the nearby resonances merged to give a wide bandwidth. A slight decrease in the cavity mode compared to the earlier case mentioned in section 2 may be due to the loading of the slots entirely by DRA. In the earlier case slot was partly loaded due to the offset. In the case of DRA mode, 2x2 slot excitation causes a lower shift in the resonance. It may be due to the variation in coupling as compared to the single slot case since the effect of coupling aperture is significant on low-profile DRAs.



(a) 10.75GHz (b) 11.13GHz

Fig.4. E field plots of the SIW cavity backed DRA excited using offset slot

The effect of slot width Ws on antenna performance has been studied by varying from 1.5mm to 3.5mm, keeping the gap between the slots constant. The antenna exhibits better impedance matching for Ws=2mm. As the slot dimension increases, cavity mode frequency decreases, keeping resonance due to DRA remains less affected. For smaller Ws, DRA is not resonating, and for larger values, the separation between the two resonances is more. So in order to merge both the resonances and to achieve better impedance bandwidth Ws=2mm is the optimized width.

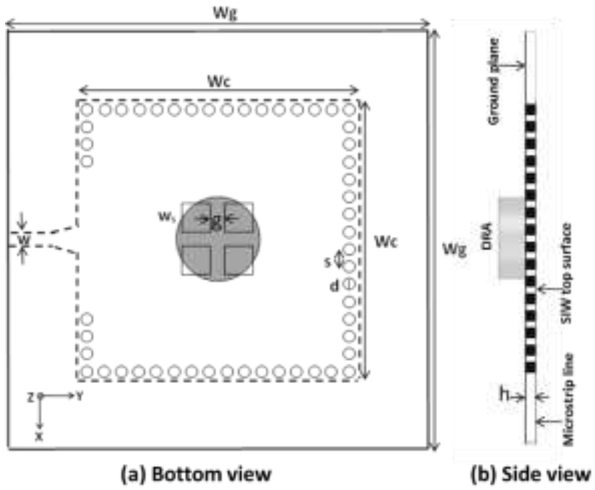


Fig. 5. Configuration of DRA excited by periodic slots on SIW cavity (Wg=30mm, Wc=20mm, w=1mm, s=1.25mm, d=0.8mm, Ws=2mm, g=1mm)

Similarly, for analyzing the effect of gap ‘g’ between the slots, parametric analysis is carried out by varying ‘g’ from 0.25mm to 2mm for slot width Ws=2mm. For g =1mm antenna shows better impedance bandwidth. In the case of larger spacing, slots are moved beyond the DRA geometry, hence reducing coupling. For smaller gaps, impedance matching is poor even though DRA gets excited. Different slot array combinations such as 1x2, 2x2, 3x3, and 4x4 are also explored as feed. 2x2 slot arrays give better impedance bandwidth compared to other slot arrays. The optimized 2x2 array of slots acts as a differential feed for exciting DRA since the cavity is resonating in TE120 mode, the electric field on either side of the center of the cavity has an opposite phase. This field distribution forces differential excitation on DRA as the slots on either side of the DRA are opposite in phase as shown in Fig.7.

The simulated radiation pattern of the antenna at two resonant frequencies is shown in Fig.8. Two principal plane patterns are symmetrical without any tilt in the beam, particularly in the case of DRA resonance, where a tilt of 30 degrees was observed in the conventional slot feed discussed in section 2. Half power beamwidth observed in both the planes are 980 for 10.23GHz and 940 for 10.49 GHz. The antenna is linearly polarized along the Y direction in both frequencies. Cross-polar levels better than 23dB are observed for both resonances.

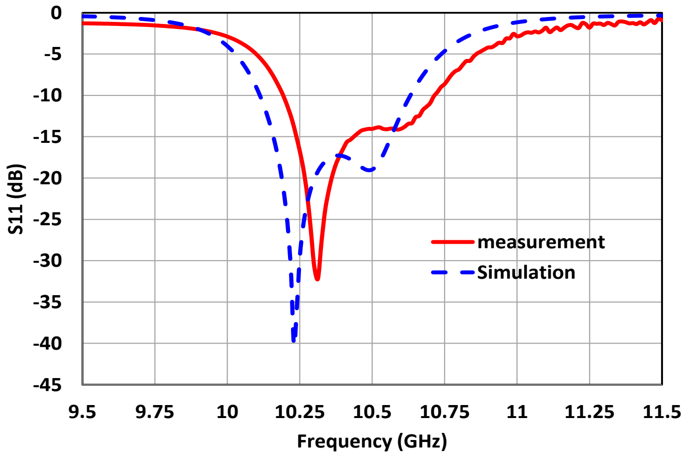


Fig.6. Return loss characteristics of the SIW cavity backed DRA excited using 2x2 array of slots (Wg=30mm, Wc=20mm, w=1mm, s=1.25mm, d=0.8mm, Ws=2mm, g=1mm)

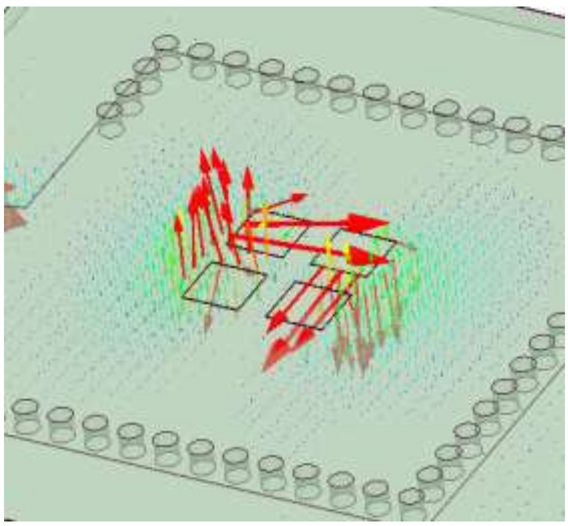
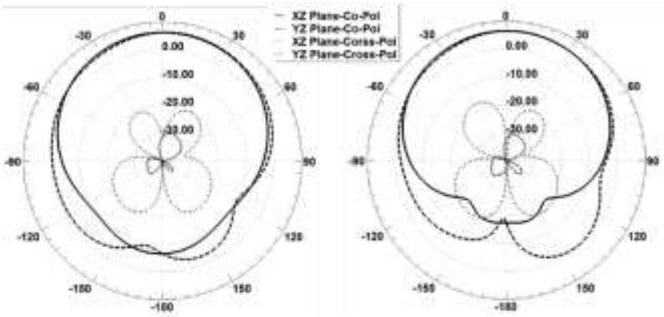
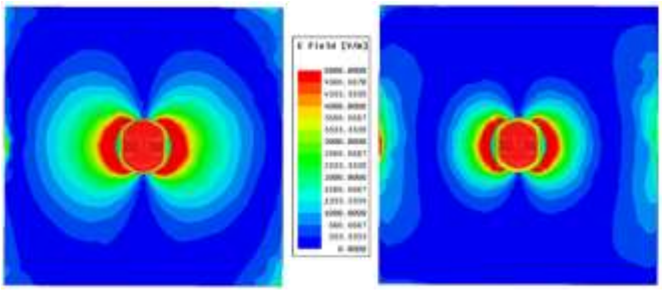


Fig.7. E field plots along 2x2 array of slots for 10.49GHz (Wg=30mm, Wc=20mm, w=1mm, s=1.25mm, d=0.8mm, Ws=2mm, g=1mm)



(a) 10.23GHz (b) 10.49GHz

Fig.8. Simulated radiation pattern of the SIW cavity backed DRA excited using 2x2 array of slots



(a) 10.23GHz (b) 10.49GHz

Fig.9. E field plots of the SIW cavity backed DRA excited using 2x2 array of slots

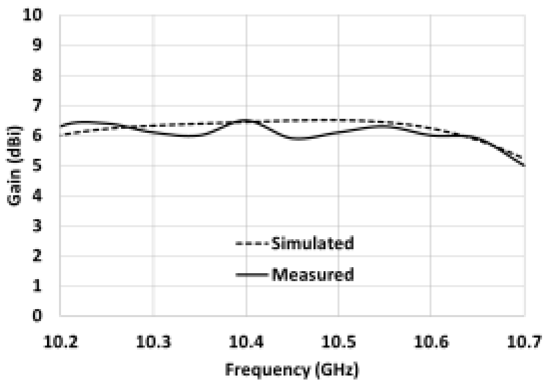


Fig. 10. Gain of the SIW cavity backed DRA excited using 2x2 array of slots (Wg=30mm, Wc=20mm, w=1mm, s=1.25mm, d=0.8mm, Ws=2mm, g=1mm)

The electric field distributions for both resonances are shown in Fig.9. For the first resonance, field distribution is significant on SIW cavity surfaces, indicating the TE120 mode radiation. Whereas for the second resonance, field distribution indicates the primary radiator is DRA. HEM11δ mode of the DRA is excited during this feeding technique.

The gain of the antenna measured at the bore sight is compared with the simulated gain and shown in Fig.10. The antenna has a peak gain of 6.5dBi and an average gain of 6dBi within the band. Photographs of the fabricated antenna are shown in Fig.11.

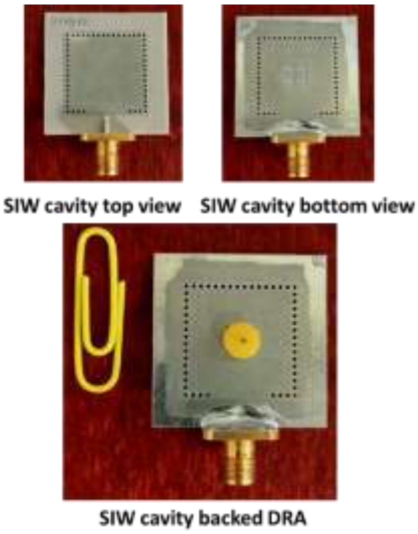


Fig.11. Photograph of the SIW cavity backed DRA excited using 2x2 array of slots (Wg=30mm, Wc=20mm, w=1mm, s=1.25mm, d=0.8mm, Ws=2mm, g=1mm)

4. CONCLUSION

A novel method for feeding the SIW cavity-backed DRA is established in this work. The newly proven SIW cavity with a 2x2 slot array can feed the low profile DRA symmetrically and give undistorted radiation patterns. The concept has been compared with the offset slot fed DRA. The antenna has been fabricated, and the measured results agree with the simulated results. The proposed antenna can be used in high-frequency SIW-based circuits due to its low profile and compact nature..

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