SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549/ https://doi.org/10.14445/23488549/IJECE-V11I7P101

Volume 11 Issue 7, 1-9, July 2024
© 2024 Seventh Sense Research Group®

Original Article

Design of Self-Duplexed Hybrid Substrate Integrated Waveguide Antenna for Sub-6 and Mm-Wave Application

Chaudhari Neelima K.[1], Rekha P. Labade[1], B.S. Agarkar[1], Sachin Vasant Chaudhari[1]

[1]*PG Research Center in Electronics and Telecommunication Engineering, Sanjivani College of Engineering & Research, SPPU, Maharashtra, India.*

[1]*Corresponding Author : rplabade@gmail.com*

Received: 01 May 2024 Revised: 02 June 2024 Accepted: 01 July 2024 Published: 27 July 2024

Abstract *- The following paper will study the quarter mode and full mode SIW antennas operating at 3.5 GHz for the sub-6 GHz frequency band and 30.5 GHz for the 30 GHz millimeter-wave band. To satisfy the full-size form factor, a new Quarter Mode (QM) is employed for the sub-6 GHz frequency, and a Full Mode (FM) with a millimetre-wave frequency that uses a rectangular slot cavity-backed design is used. The suggested antenna is built on an RT Duroid 5880 substrate, with dimensions of 18.8 × 18.8 × 1.54 mm at 3.5 GHz frequency and 5.16 × 5.16 mm × 1.54 mm at 30.5 GHz frequency, to offer spatial diversity and improve isolation between the two modes. The antenna radiates in a unidirectional manner and has gains between 4.3 and 7.15 dB.*

Keywords *- Hybrid mode, Quarter Mode (QM), Mm-wave, Substrate Integrated Waveguide (SIW), Slot antenna.*

1. Introduction

The SIW technology is becoming very popular today due to its governing advantages of conventional bulky waveguides and its easy interconnection with uni, bi, tri, and multi-planar circuits on printed circuit boards. After first proposed by Luo et al. [1], the SIW cavity back slot antennas are gaining enormous interest among scholars in RF technology, and several designs for multi-frequency, bandwidth enhancement, hybrid mode, linear and circular polarization, antenna array have been proposed in recent years [2-4].

Not limiting SIW technology to designing only an antenna, researchers implemented numerous active and passive microwave components (filters-single mode/multimode, n-way power divider/combiner, multiplexers – diplexer and triplexer) using SIW technology. By being low profile, simple to fabricate, and inexpensive, this research helps overcome traditional devices' drawbacks and become the ideal option for planar integration [5-7]. Considering the ongoing demand for SIW technology, it has been widely deployed in sensor-based applications, such as complex permittivity estimation [8], metal crack detection [9], and characterization of dielectric samples [10].

As technology grows, there is always a demand for miniaturization of devices, circuits, and systems. Considering this necessity, various attempts were made to compact SIW antennas. The structure can be made smaller by making cuts along its imaginary quasi-magnetic wall. Even after cutting the structure, the filed distribution of the original SIW antenna remains the same for the miniaturized structure. A SIW antenna can be further modified by cutting along its center symmetric axis to become a Half-Mode (HMSIW) [11], Quarter-Mode (QMSIW), Eight-Mode (EMSIW), or even more. [12] has studied HMSIW slot array antennas; [13] provides a clear explanation of QMSIW antennas for linear in TE101 and circular polarization in TE202 modes. Further, the mode SIW antenna was well realized by [14] at 2.4GHz.

Since last year, attempts have started combining sub6 and mm-wave frequencies on the same aperture using SIW technology. Gheisanab et al. presented a self-duplexing antenna based on a SIW cavity designed for microwave and millimeter-wave frequencies, specifically targeting 4.8 GHz and 28 GHz, as described in [15]. The same author expanded upon the research in [16], Gheisanab et al., to include a self-quadruplexing antenna for microwave and millimetre-wave frequencies that target 4.8 GHz, 5.4 GHz in sub6 and 28 GHz, and 30.5 GHz in the millimeter range. Both studies used cavity-based SIW technology for antenna realization [15-16]. A similar attempt from the same group was made by PourMohammadi et al. in [17], in which four half-mode cavities with four ports were designed to resonate at 5.8GHz,

This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

7.4GHz, 28GHz, and 38GHz. However, the claim for a half-mode cavity resonator was explained similarly to the cavity back slot antenna.

In this paper, we proposed a detailed and systematic approach toward developing a miniaturized hybrid SIW antenna that works at sub-6 and mm-wave frequencies, respectively. One antenna is designed at 3.5GHz (sub-6), and its miniaturization is achieved by designing it in quarter mode. The same aperture is shared to design the mm antenna to resonate at 30.5GHz (mm-wave) using the cavity back SIW antenna concept. The proposed antenna is linearly polarized at both frequencies, with TE101 as an operating mode. Several benefits come with the suggested design, including a small and simple structure, self-duplexing, high gain, sound isolation, ease of fabrication and integration, and a foundation for array and MIMO antennas. The entire antenna was realized in 18.8mm by 18.8mm on RT-droid 5880 substrate (thickness 1.54mm). Based on the literature survey, this is the most miniature antenna at 3.5GHz and 30.5GHz using the quarter mode technique.

2. Antenna Design

The proposed SIW antenna design is segmented into two distinct parts. First, a quarter-mode SIW antenna was designed for sub-6 frequency at 3.5GHz, and then the same aperture was shared to design a cavity-back SIW antenna for mm-wave applications at 30.5GHz. This paper uses a similar approach to discuss the SIW design.

2.1. Design of Square Cavity (Full Mode SIW)

The first step in implementing a quarter-mode antenna is designing a square SIW cavity. The resonant frequency of a square cavity, also known as a Full Mode (FMSIW) cavity, can be determined using the following formulas [18].

$$f_{mnl} = \frac{C}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{L_{eff}}\right)^2 + \left(\frac{n\pi}{H}\right)^2 + \left(\frac{l\pi}{W_{eff}}\right)^2} \tag{1}$$

The half-wavelength variation (guided electromagnetic wave) along the length, height, and width of the SIW cavity resonator is denoted by the values m, n, and l, respectively. The speed of light in a vacuum is represented by C. The substrate's permeability and permittivity are represented by μ_r andε_r, respectively.

The effective width and length of the SIW cavity resonator can be determined using the equations mentioned below [19],

$$L_{eff} = L_{sub} - \frac{d^2}{0.95 \times S} \tag{2}$$

$$Weff = W_{sub} - \frac{d^2}{0.95 \times S} \tag{3}$$

Where the dielectric substrate's length (L_{sub}) and width (W_{sub}) are given. The values are the via hole's diameter (d) and the distance between neighboring vias (S).

Rogers RT5880 (er = 2.2, loss tangent = 0.0011) and a thickness of 1.54 mm are selected for the SIW antenna. There are no restrictions on the substrate's height. It can take any value as per availability and requirement, but for wideband applications, the designer can go for a thicker dielectric height, which is one of the common practices for increasing the bandwidth of the antenna.

The variation of an electromagnetic wave along height diminishes, which results in TE_{m0l} modes to propagate due to its smaller height compared with the other dimensions. As its square cavity, length (m) and width (l) values are the same and can be interchanged. When applying Equation (1) and taking into account the resonate frequency for sub 6 application at 3.5GHz for dominating mode TE101, the SIW cavity resonator's effective length and width come to 40.86mm. Deslandes and Wu [20] provide a clear statement of the SIW design equations that maintain the electromagnetic field inside the cavity. This indicates the following relationship between the via diameter (d) and the space between them (S):

$$d < \frac{\lambda_g}{5} \text{ and } S \leq 4d \tag{4}$$

Which combines results in,

$$\frac{d}{S} \leq 0.5 \tag{5}$$

The diameter of the via holes (d = 1 mm) and the spacing between adjacent vias (S = 2 mm) are chosen according to the specified constraint. Through simulation, it has also been observed that two rows of via holes can be used, but the results will not be significantly improved. So, only a single row of vias is used, which is sufficient to retain the EM field inside the cavity.

2.1.1. Eigenmode Analysis

The mathematical dimensions obtained from the equations mentioned above for square cavity resonator were further analyzed in electromagnetic simulation software Ansys HFSS V21 under eigenmode analysis. For eigenmode analysis, the cavity has to be fully closed in all directions; otherwise, mode analysis will throw errors or provide improper results. Figure 1 shows that the SIW cavity resonates well at 3.5GHz for TE101 mode (half wavelength variation of the electric field along width and length). Similarly, Figure 2 confirms that the SIW cavity is capable of TE202 mode at 7 GHz. This also motivates this FMSIW to be divided into HMSIW and further QMSIW by cutting at the fictitious magnetic wall present at the symmetric plane, as shown in Figure 1.

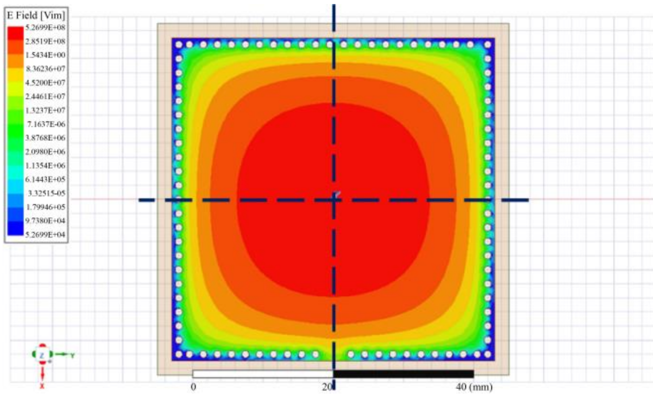

Fig. 1 Eigenmode analysis for TE101 mode at 3.5GHz

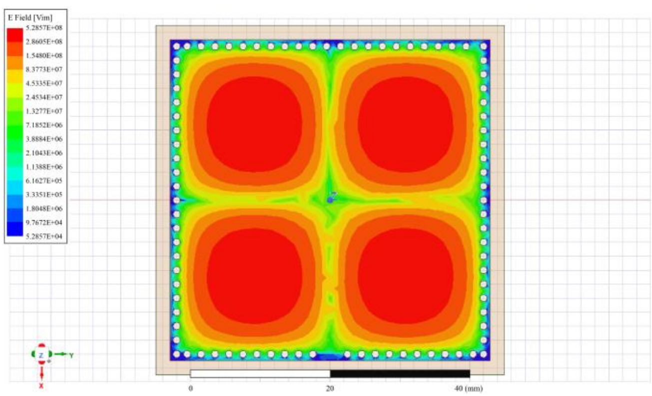

Fig. 2 Eigenmode analysis for TE202 mode at 7GHz

For the excitation of the SIW cavity, we need to provide proper feed. Here, the coplanar waveguide-based insect feed is used with waveport excitation in simulation software. The Feed width(F_w), Gap width (G_w) and Insect cut length (C_l) were calculated for 50ohm impedance port matching and further optimized based on the formulae stated in [21].

The final dimensions of square SIW cavity resonators are as mentioned here: Sub_L = Sub_W = 50mm. Patch_L = Patch, W = 43mm, Leff = Weff = 40 mm, d = 1mm, S = 2mm, F_w = 4.8mm, G_w = 0.5mm, C_l = 1mm.

Figure 4 illustrates the return loss. The plot reveals that the cavity resonates at the intended frequency of 3.5 GHz. Although the return loss value is relatively low, it verifies the cavity's resonance. This can be attributed to the abrupt impedance transition from the microstrip line to the SIW cavity.

2.2. Design of HMSIW

According to the Eigenmode analysis, the electric field is symmetrical in the azimuth plane, with its center containing the electric field maxima (Figure 1). The height of the substrate is quite small in relation to its width and length; as a result, the magnetic field on the symmetric axis is nearly zero (Figure 1, black dotted line). That is why these axes can be treated as quasi-magnetic walls (H=0), and the structure can be further divided into two parts and each half can be treated as a separate half-mode cavity. As one side of the cavity is open now, the open edges will start radiating on applying source excitation. Due to the radiation from open edges, this structure lost its cavity nature and now can be called an antenna. Figure 5 shows the HMSIW antenna structure along with its fringing fields from the open edge, and Figure 6 illustrates the return loss against the frequency of the HMSIW antenna.

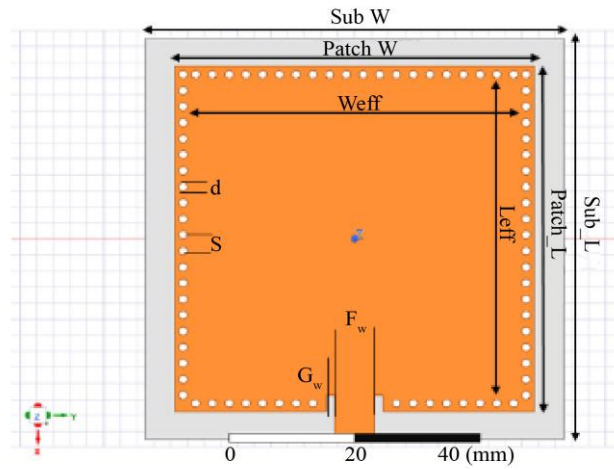

Fig. 3 The final substrate integrated waveguide square cavity with insect feed

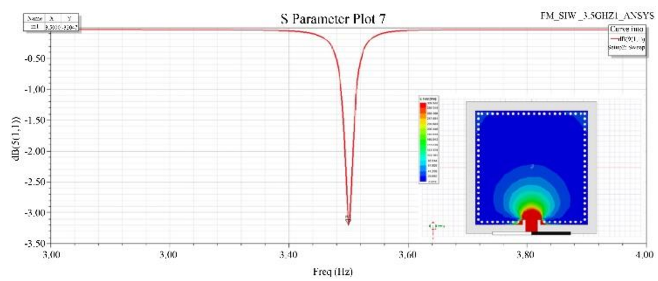

Fig. 4 Frequency-dependent return loss and TE101 mode electric field. Distribution for FMSIW cavity resonator

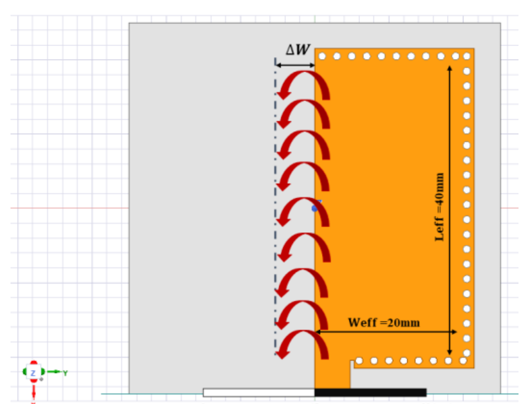

Fig. 5 HMSIW antenna with fringing fields emanating from the open edge

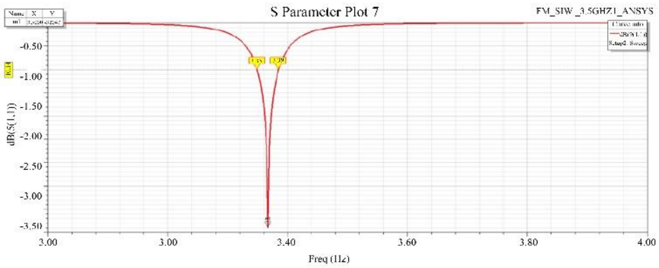

Fig. 6 Frequency-dependent return loss of HMSIW antenna in TE101 mode

The HMSIW antenna's reflection coefficient shows that the TE101 mode resonates at 3.3675GHz, 132.5MHz lower than the intended 3.5GHz frequency. This happens because of the fringing field at the open edge of the HMSIW, which increases the equivalent width and decreases the resonant frequency. Since the primary goal of this work is to compact the antenna to quarter mode further, no more studies have been performed on this structure, nor has it been optimized to resonate at 3.5GHz. If the researcher is interested in optimizing the HMSIW antenna, then they have to decrease the width further and, with that, need to optimize the feed width to maintain the 50ohm impedance.

2.3. Design of QMSIW

Because of the HMSIW structure's symmetry, it is possible to cut the structure deeper along its symmetric axes, as seen in Figure 1, where a quasi-magnetic wall with zero net magnetic field results. To achieve quarter mode, the HMSIW antenna is chopped one more along its quasi-magnetic wall. Using EM simulation software, this QMSIW antenna is examined in more detail. This construction now has two open edges, which increases radiation when compared to the HMSIW antenna. Figure 7 shows the quarter mode structure along with its fringing field. Due to the fringing field from both open edges, the equivalent size is increased from both edges, and hence resultant resonant frequency is further decreased to 3.19GHz from 3.5GHz. So, there is a drift of 310MHz from the desired resonance in frequency can be explained by mathematical relation.

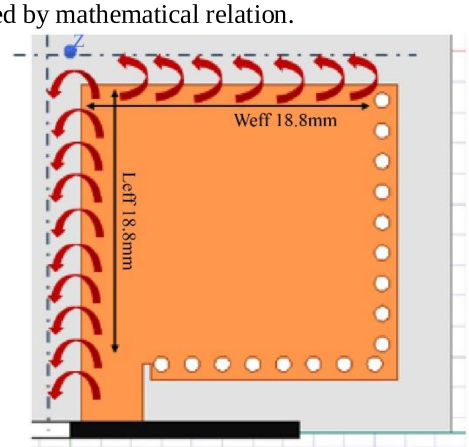

Fig. 7 QMSIW waveguide antenna with fringing fields from both open edges

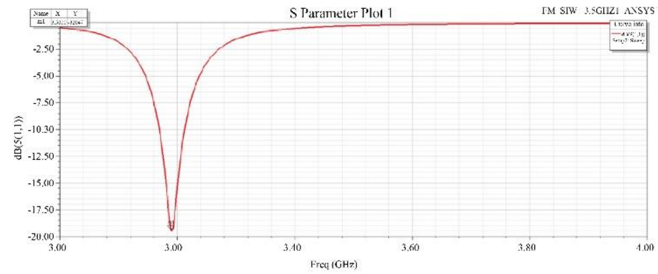

Fig. 8(a) Frequency-dependent return loss for default quarter mode SIW antenna

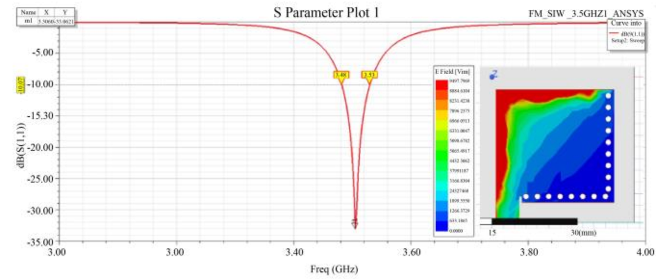

Fig. 8(b) Frequency-dependent return loss for optimized quarter mode SIW antenna with TE101 mode electric field distribution

To make the resonance happen at the desired 3.5GHz, parametric optimization was done on the QMSIW antenna, and size was further decreased from initial dimensions Leff = Weff = 20mm to optimized dimensions as Leff = Weff = 18.8mm. The optimized QMSIW antenna and its simulated return loss are displayed in Figures 8(a) and 8(b). This return loss shows that the 3.5GHz radiation from the QMSIW antenna is good. Figure 8(b) also illustrates the electric field distribution along the QMSIW antenna patch. It is crucial to remember that splitting the FMSIW in half also splits the feed width, increasing the feed line's characteristic port impedance from 50 ohm to 77 ohm. Hence, feed width also needs to remain the same as FMSIW, i.e. Fw = 4.8mm, to keep port impedance equal to 50 ohm.

From the electric field distribution plot, it is observed that the electric fields from both open edges are equal in magnitude with zero-degree phases between them, which results in linear polarization at dominant mode TE101. It is also observed from the literature [13] that circular polarization can also be possible if we go for a higher mode like TE202 mode.

2.4. Cavity Back SIW Antenna for mm Range

Upon analyzing the electric field distribution on the antenna patch, it was found that a small area of the aperture near the closed end could be utilized to create another cavity for millimeter-wave applications without disturbing the required field distribution. With this motivation, a closed square cavity is designed for 30.5GHz, which falls under an extremely high-frequency band. The initial dimensions are calculated using the formula in Equation (1) for dominant mode TE101, which were further optimized in EM simulation software for desired results. The optimized final dimensions for mm SIW cavity are Leff = Weff = 5.16mm. The diameter of the via hole and the spacing between adjacent vias are maintained as previously specified, in accordance with the criteria outlined in Equation (4). The coplanar waveguided feed line dimensions are calculated from the formula mentioned [21], ensuring 50ohm impedance matching at the second port. The insect feed width was found to be Fw = 4.8mm, gap width Gw = 0.5mm, and insect cut length C_l = 1.5mm. Figure 9 shows the final realized square SIW cavity for the mm range at 30.5GHz.

Before going for open slot cutting on the patch, the closed cavity was analyzed again by eigenmode analysis using EM solution software Ansys HFSS and further return loss to ensure its resonance at 30.5 GHz, as stated in section A. Once confirmed, the open slot was cut with a length equal to half of the guided wavelength at 30.5 GHz. It is vital to remember that the length of the open slot radiator in the cavity back slot SIW antenna must equal half of the guided wavelength in order to achieve optimal radiation efficiency [1].

This principle came from a slot antenna being equivalent to a complementary dipole antenna; hence, the guided wavelength becomes responsible for maximum radiation. Considering the major impact of slot length, which is also inversely proportional to the resonant frequency, an accurate slot length at an extremely high frequency is required. Keeping this in mind, the length of the slot was kept precisely as Ls = 3.37 mm. Later, the parametric optimization was also done and presented in the result and discussion section. The slot width has almost no impact on resonance frequency, but it slightly impacts impedance bandwidth [1]. The parametric optimization was done to realize the location and width of the slot; based on that result, the slot width was fixed to Ws = 1mm. Figure 10 shows the frequency response and electric field distribution of the cavity back SIW antenna. This return loss of 17.50 dB at 30.5 GHz confirms that the antenna is resonating at the desired frequency.

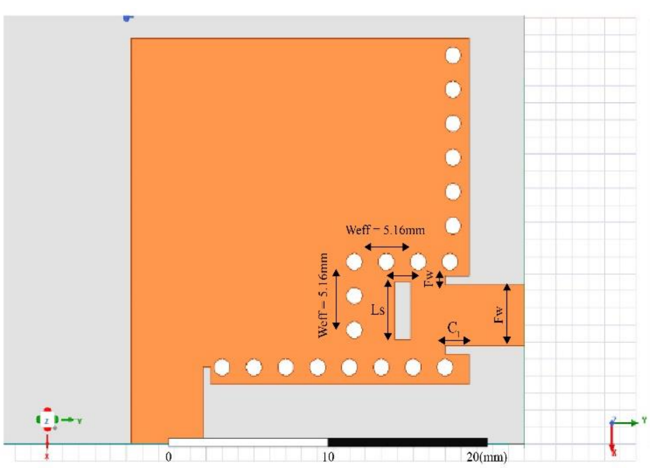

Fig. 9 Final realization of cavity back SIW antenna for mm-wave at 30.5GHz

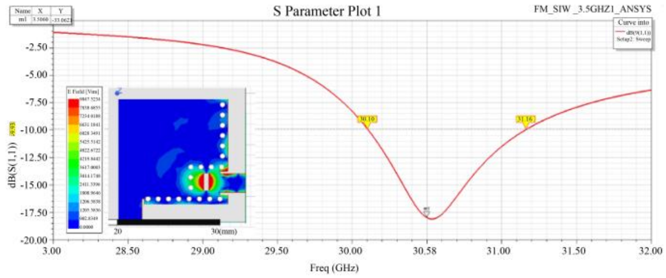

Fig. 10 Return loss and electric field distribution of cavity-backed SIW antenna designed at mm frequency

3. Results and Discussion

Figure 11 shows the fabricated proposed hybrid SIW antenna based on the dimensions discussed in the design sections. The measurement setup for radiation pattern and gain measurement in an anechoic chamber with a reference antenna as a horn antenna and test antenna as a proposed SIW antenna is shown in Figure 12. The simulation and measured return losses are compared for both QMSIW antenna and cavity-backed antenna and are shown in Figures 13 and 14. It indicates that the antenna's resonance is at 3.5GHz and 30.5GHz, as expected, with satisfactory return loss much lower than 10dB, corresponding to 90+% of the energy transmitted from source to load. There is a slight delta between simulation and measured results, which includes losses due to fabrication, connector soldering, etc. The measured bandwidth over return loss of the optimized QMSIW antenna is 50MHz, and the cavity-backed antenna is 1.02GHz, which is near the simulation bandwidth. The effect of variation of slot length is shown in Figure 15. As we decrease the length by 0.2mm, resonance frequency increases drastically. Hence, it is essential to take the correct slot length in fabrication at mm frequency. It has also been observed from the literature that offsite feeding can be used for higher bandwidth performance [22]. We used spatial diversity to isolate significantly between both ports.

A comparison of Figures 16 and 17 shows that the isolation level between the two ports is more than 30 dB. Apart from the modeling analysis, anechoic chamber measurements are made of each antenna's radiating properties. Using a double-rigged rectangular horn antenna as the reference, the proposed SIW antenna acts as the test antenna in this configuration. The cavity-backed antenna and the improved QMSIW antenna's radiation field patterns at 3.5 GHz and 30.5 GHz, respectively, are shown in Figures 18 and 19. In the comparison between the simulated data and the experimental findings, differences may be minimized by making changes like fixing manufacturing flaws and making sure connections are soldered correctly. The findings demonstrate that both antennas' cross-polarization in the mm-wave and sub-6 bands is greater than -20 dB in the broadside direction. The optimized QMSIW antenna's measured Front-to-Back Ratio (FBR) is 20.32 dB, whereas the cavity-backed mm-wave antenna's FBR is 32 dB.

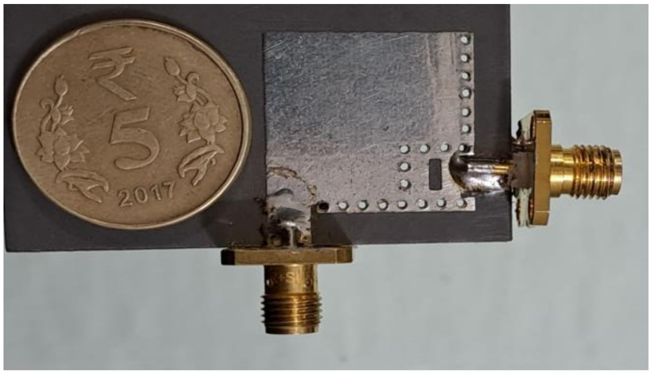

Fig. 11 Fabricated proposed hybrid SIW antenna

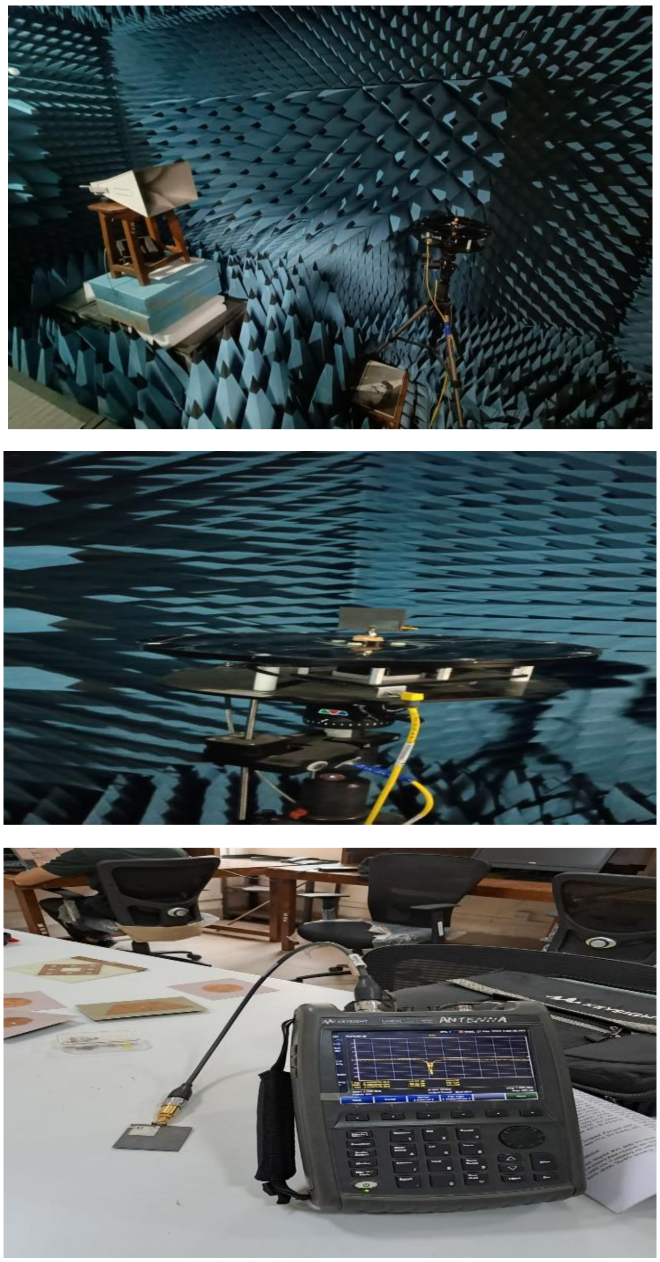

Fig. 12 Measurement setup for radiation pattern measurement at D.I.A.T. Pune

Table 1 compares the suggested hybrid SIW antenna's performance with current antennas. This demonstrates that the suggested antenna performs optimally thanks to its most compact and straightforward construction, maximum isolation, and distinctive design, which combines the quarter-mode and cavity-backed SIW design methodologies.

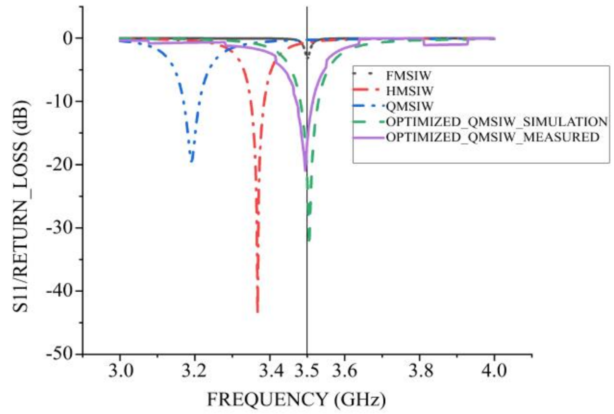

Fig. 13 Return loss of optimized QMSIW antenna compared with FMSIW and HMSIW antennas

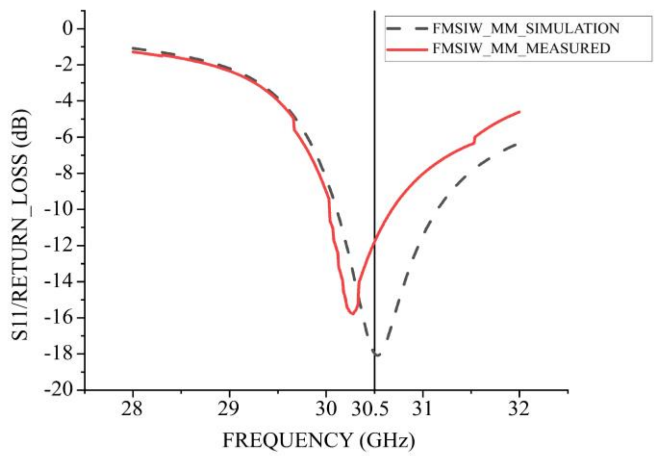

Fig. 14 Return loss of mm-wave antenna at 30.5GHz

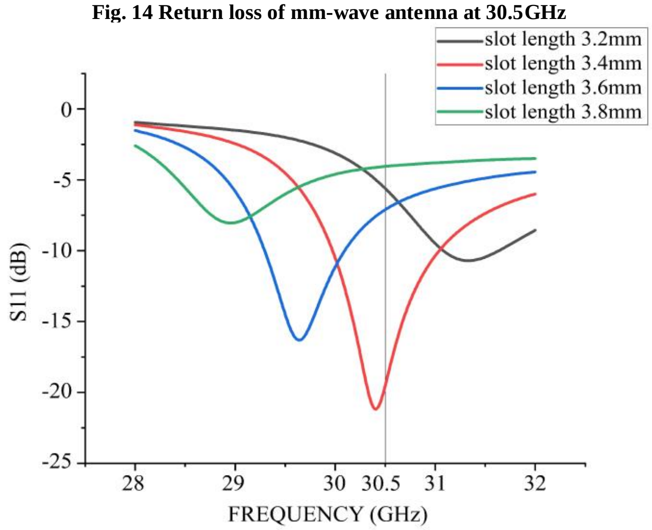

Fig. 15 Effect of variation of slot length on the resonance frequency of cavity-backed mm wave SIW antenna

Table 1. Comparison of proposed hybrid SIW antenna performance with existing antennas

Ref No.	Year	Technology/ Mode	Substrate	Dimensions (w×l×th) mm/	Resonance Frequency GHz	Gain (dBi)	Isolation (dB)	mm Operation	Hybrid Structure
[13]	2013	QM	Roger RT5880	35×40×1.57	5.2, 11	4.12, 7.13	NA	No	No
[14]	2016	EM	FR4	40×60×3.3	2.4	5	NA	No	No
[23]	2021	Shielded QM	Roger RT5880	22×22 × 0.787	3.5, 5.	5.36, 5.6	NA	No	No
[24]	2021	Cavity backed	FR4	30×30×1.6	2.21, 3.45, 5.21	3.53,5.14, 5.76	NA	No	No
[16]	2022	HM	Roger 4350	24×24×0.5/ 0.51	4.8,5.4,28,30	5.4, 5.2, 8, 8.7	>20	Yes	No
[15]	2023	HM	Roger 4350	40×40×0.5	4.8,28	5.3, 8	>30	Yes	No
[17]	2023	HM	Roger 4350	13.5×14×0.5	5.8,7.4,28,38	4.1,5.2,6.1,8.3	>26	Yes	No
This work 2024		QM + Cavity backed	Roger RT5880	18.8×18.8× 1.54	3.5, 30.5	4.3, 7.15	>30	Yes	Yes

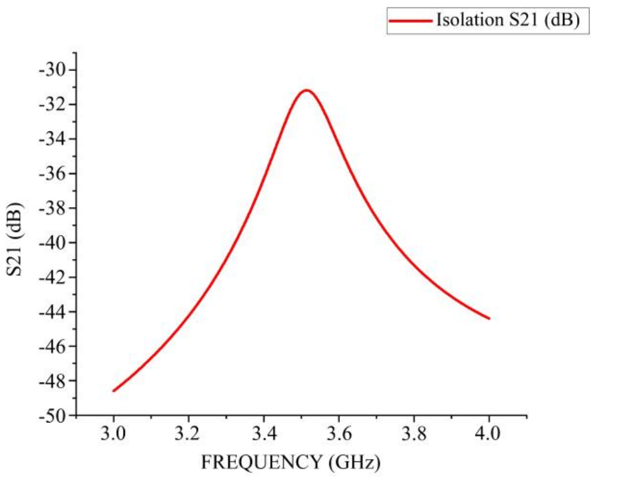

Fig. 16 Isolation S21(dB) between sub6 and mm-wave SIW antenna at 3.5GHz

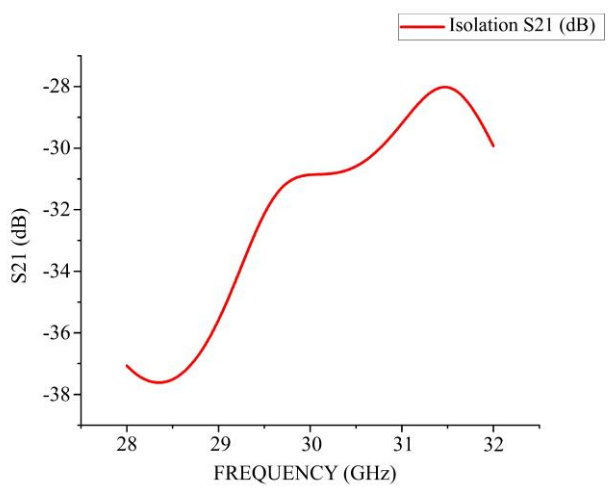

Fig. 17 Isolation S21(dB) between sub6 and mm wave SIW antenna at 30.5GHz

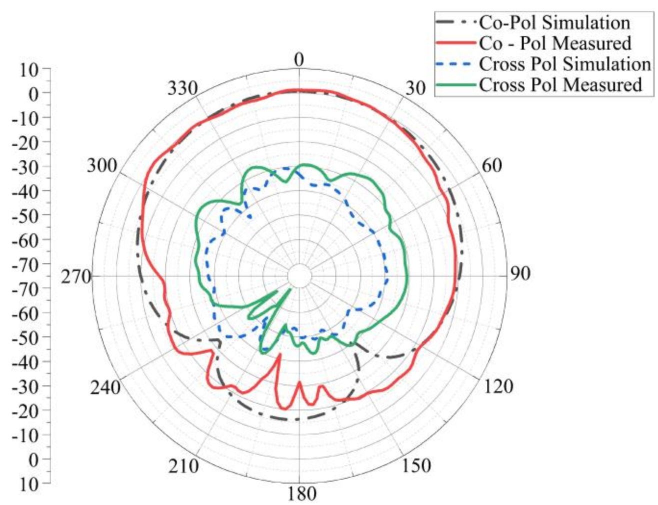

Fig. 18 Radiation pattern at the frequency of 3.5GHz

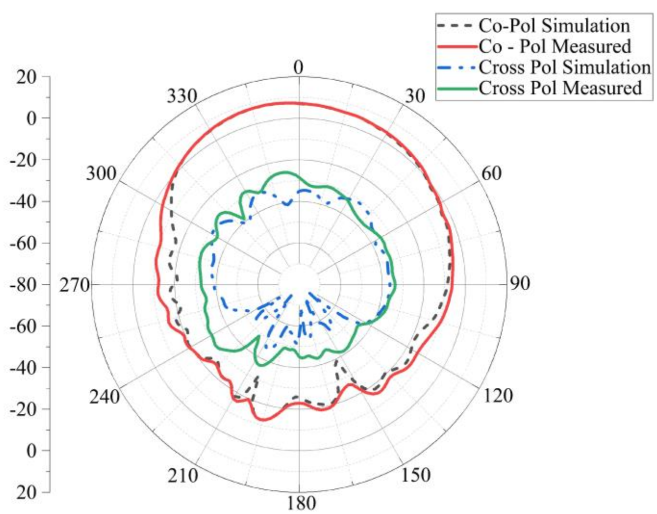

Fig. 19 Radiation pattern at a frequency of 30.5GHz

4. Conclusion

A detailed analysis of the development of quarter mode and cavity back slot substrate integrated waveguide antenna for both sub6 and mm-wave ranges has been proposed in this paper. The design is implemented on RT-Duroid 5880 substrate and it operates at 3.5GHz and 30.5GHz frequency. The simulated and measured results are well presented in this paper, and the results are comparable. The proposed antenna finds its applications in commercial 5G mobile and IoT communication and Non-Terrestrial-Network (NTN) as 30.5GHz has been gaining interest among telecommunication industries since 2023. We are working on extending the current research in designing array and MIMO applications for further gain and isolation enhancement using this as a unit cell.

Acknowledgements

The author thanks D.I.A.T., Pune, and GMRT Khodad for providing the antenna testing facility.

References

[1] Guo Qing Luo et al., "Planar Slot Antenna Backed by Substrate Integrated Waveguide Cavity," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 236-239, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[2] Li Yan et al., "Simulation and Experiment on SIW Slot Array Antennas," *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 9, pp. 446-448, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[3] Qi Wu et al., "Broadband Planar SIW Cavity-Backed Slot Antennas Aided by Unbalanced Shorting Vias," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 2, pp. 363-367, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[4] Muftah Asaadi, and Abdelrazik Sebak, "High-Gain Low-Profile Circularly Polarized Slotted SIW Cavity Antenna for MMW Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 752-755, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[5] Xiao-Ping Chen, and Ke Wu, "Substrate Integrated Waveguide Filter: Practical Aspects and Design Considerations," *IEEE Microwave Magazine*, vol. 15, pp. 75-83, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[6] Kaijun Song et al., "High-Isolation Diplexer with High Frequency Selectivity using Substrate Integrated Waveguide Dual-Mode Resonator," *IEEE Access*, vol. 7, pp. 116676-116683, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[7] Shahriar Hasan Shehab, Nemai Chandra Karmakar, and Jeffrey Walker, "Substrate-Integrated-Waveguide Power Dividers: An Overview of the Current Technology," *IEEE Antennas and Propagation Magazine*, vol. 62, pp. 27-38, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Humberto Lobato-Morales et al., "Complex Permittivity Measurements Using Cavity Perturbation Technique with Substrate Integrated Waveguide Cavities," *Review of Scientific Instruments*, vol. 81, pp. 1-4, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[9] Taehwa Yun, and Sungjoon Lim, "High-Q and Miniaturized Complementary Split Ring Resonator-Loaded Substrate Integrated Waveguide Microwave Sensor for Crack Detection in Metallic Materials," *Sensors and Actuators A: Physical*, vol. 214, pp. 25-30, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[10] Prashant Kumar Varshney, Nilesh Kumar Tiwari, and M. Jaleel Akhtar, "SIW Cavity Based Compact RF Sensor for Testing of Dielectrics and Composites," *Proceedings of the IEEE MTT-S International Microwave Symposium (IMS) Digest*, New Delhi, India, pp. 1-4, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[11] Junfeng Xu et al., "Half-Modesubstrate Integrated Waveguide (HMSIW) Leaky-Wave Antenna for Millimeter-Wave Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 85-88, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[12] Qing Hua Lai et al., "Half-Mode Substrate Integrated Waveguide Transverse Slot Array Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 1064-1072, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[13] Cheng Jin et al., "Quarter-Mode Substrate Integrated Waveguide and Its Application to Antennas Design," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 6, pp. 2921-2928, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[14] Manisha Mujumdar, and A. Alphones, "Eighth-Mode Substrate Integrated Resonator Antenna at 2.4 GHz," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 853-856, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[15] Hassan Naseri Gheisanab et al., "Self-Diplexing Antenna Operating at Sub-6 Ghz and Millimeter-Wave Frequency Bands," *17th European Conference on Antennas and Propagation (EuCAP)*, Florence, Italy, pp. 1-3, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Hassan Naseri et al., "SIW-Based Self-Quadruplexing Antenna for Microwave and mm-Wave Frequencies," *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 7, pp. 1482-1486, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Peyman PourMohammadi et al., "Compact SIW-Based Self-Quadruplexing Antenna for Microwave and Mm-Wave Communications," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 70, no. 9, pp. 3368-3372, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[18] David M. Pozar, *Microwave Engineering*, 3rd ed., USA, New York: Wiley, 2004. [Google Scholar] [Publisher Link]

[19] Feng Xu, and Ke Wu, "Guided-Wave and Leakage Characteristics of Substrate Integrated Waveguide," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 1, pp. 66-73, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[20] D. Deslandes, and K. Wu, "Integrated Microstrip and Rectangular Waveguide in Planar Form," *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 2, pp. 68-70, 2001. [CrossRef] [Google Scholar] [Publisher Link]

[21] Brian C. Wadell, *Transmission Line Design Handbook*, Artech House, pp. 1-510, 1991. [Google Scholar] [Publisher Link]

[22] Soumava Mukherjee, Animesh Biswas, and Kumar Vaibhav Srivastava, "Bandwidth Enhancement of Substrate Integrated Waveguide Cavity Backed Slot Antenna by Offset Feeding Technique," *IEEE Applied Electromagnetics Conference*, Bhubaneswar, India, pp. 1-2, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[23] Rusan Kumar Barik et al., "Highly Miniaturized Self-Diplexed U-Shaped Slot Antenna Based on Shielded QMSIW," *IEEE Access*, vol. 9, pp. 158926-158935, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[24] R. Samson Daniel, "Planar SIW Cavity-Backed Antenna Loaded With Slots for Multiband Operations," *Applied Physics A*, vol. 127, 2021. [CrossRef] [Google Scholar] [Publisher Link