Defence Science Journal, Vol. 68, No. 2, March 2018, pp. 197-202, DOI : 10.14429/dsj.68.11827

Bandwidth Enhancement of Substrate Integrated Waveguide Cavity-backed Bow-tie-complementary-ring-slot Antenna using a Shorted-via

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ABSTRACT

In this study, a planar cavity-backed bow-tie-complementary-ring-slot antenna is proposed, and a new approach for bandwidth enhancement using a shorted-via is introduced. A shorted-via concept overcomes the narrow impedance bandwidth of a conventional substrate integrated waveguide cavity-backed antenna. By adjusting the location of the shorted-via (placed just above the centroid of the radiating slot), the individual bandwidth of the lower and higher order resonances has been tuned below -10 dB criterion, which results in the broadening of the bandwidth. Finally, the antenna is proficient to operate for an impedance bandwidth of 15.71 per cent, ranging from 12.02~14.07 GHz. The proposed antenna shows a gain of better than 4 dBi within the operating band with less than 0.5 dBi variation. Moreover, the antenna preserves good radiation characteristics, which is similar to that of the conventional metallic counterpart. To validate the simulated results, an antenna is fabricated and tested. The simulated results in terms of the reflection coefficient, gain, and radiation patterns are in good agreement with the measured results.

Keywords: Cavity-backed antenna; Slot antenna; Shorted-via; Substrate integrated waveguide; Wideband

1. INTRODUCTION

A state-of-the-art substrate integrated waveguide (SIW) based cavity-backed slot antennas have been emerging as a popular choice to realise planar cavity-backed antennas. By employing SIW technology, the backed-cavity can be emulated using the chains plated metallic vias which facilitate the features of conventional metallic cavity-backed antennas such as high gain and unidirectional radiation characteristics. Additionally, the backside cavity is very effective to suppress the surface waves, hence increases the antenna efficiency[1–5]. Moreover, SIW cavity-backed antennas have a low manufacturing cost, as entire design is possible to fabricate by means of a low-cost standard printed-circuit-board (PCB) process. However, the limited height of the dielectric substrate critically affects the Q-factor (Quality factor) of the SIW cavity resonator. Thus, in case of SIW cavity-backed antennas, a low profile substrate increases Q of the antenna that leads the narrow bandwidth.

A variety of SIW based cavity-backed antennas reported in the literature[1–11]. However, most of them offer limited operating bandwidth which makes them unfit for many practical applications.

To eradicate this limited bandwidth issue of planar cavity-backed antennas, numerous techniques have been suggested by researcher. Bandwidth enhancement was achieved by exciting the closely spaced hybrid modes simultaneously, as a result, individual bandwidth gets tuned over a wideband[6,7]. Melioration in the bandwidth was achieved by exciting the slots of multi-resonance characteristics simultaneously within the required frequency range[8]. Two resonant slots are employed to generate dual-resonance[9]. By properly tuning these resonances, a wide bandwidth characteristic was realised with uniform gain over the entire operating frequency band. While to reduce the spurious radiation effect of lossy microstrip feedline, radiating SIW cavity was excited indirectly by using an additional SIW structure, in between the cavity and microstrip feedline[10,11]. However, such techniques may require to change the physical size of the slot or antenna. A multilayered structure, removal of the substrate beneath the radiating slot and new feeding mechanism–transition from stripline to SIW was recommended, but these methods may cause the fabrication and design complexity[12-14].

This paper introduces a bandwidth broadening approach for an SIW cavity-backed antenna using a shorted-via. A shorted-via is placed just above the centroid of bow-tie-complementary-ring-slot (BTCRS), etched on the top of an SIW cavity. By adjusting the location of the shorted-via, individual bandwidths at higher and lower resonances get merged, which leads bandwidth enhancement. This method could be suitable to improve the impedance bandwidth of any planar cavity-backed slotted antennas without increasing its original size. Finally, the proposed design is capable to operate for an impedance bandwidth of 15.71 per cent, ranging from 12.02 ~ 14.07 GHz. Moreover, to validate the simulated results, an antenna is fabricated and experimentally tested. The simulated results are in good agreement with the measured results.

2. ANTENNA DESIGN AND OPERATION

2.1 SIW-based Cavity-backed BTCRS Antenna

The geometry of the proposed planar cavity-backed slot

Received : 31 August 2017, Revised : 20 November 2017
Accepted : 11 December 2017, Online published : 13 March 2018

antenna is depicted in Fig. 1. A BTCRS has etched on the top cladding of the SIW based cavity. An idea to implement BTCRS antenna is instigated by conventional wire bow-tie antenna for broadband applications. The narrow walls of the SIW are modeled by four sequences of metal filled vias. The diameter of a metallic via (d) and pitch distance (p) are optimised in such a manner that it offers minimal leakage of power while the essential conditions[15] are maintained. The original dimensions of the SIW based cavity have been chosen as guidelines suggested[10], by using Eqns. (1) and (2).

$$f_r(TE_{120}) = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{1}{W_{eff}}\right)^2 + \left(\frac{1}{L_{eff}}\right)^2} \quad (1)$$

$$L_{eff} or W_{eff} = L or W - 1.08\frac{d^2}{p} \quad (2)$$

In Eqn. (1), f_r is a resonant frequency of the cavity, c is the speed of light in the free space, and ε_r is relative permittivity of the dielectric substrate. As BTCRS is etched on the top cladding of the SIW cavity, which controls the resonances within the operating frequency band. Thus, the perimeter of the BTCRS should be an integer multiple of a half wavelength at the frequency of interest. Thus, the initial value of the perimeter (P) of the BTCRS could be estimated by Eqn. (3).

$$P_{BTCRS} = N \times \frac{c}{2f_r\sqrt{\frac{1+\varepsilon_r}{2}}} \quad (3)$$

where N must be an integer. The geometrical parameters of the antenna are optimised with the help of CST tool. Moreover, the proposed antenna is fed by means of a 50 Ω microstrip line at the backside of the SIW cavity that owning the merits of planar integration. The one end of the microstrip line is connected to SMA connector. Also, this end is stepped by $0.04\lambda_o$ to attain better impedance matching[8].

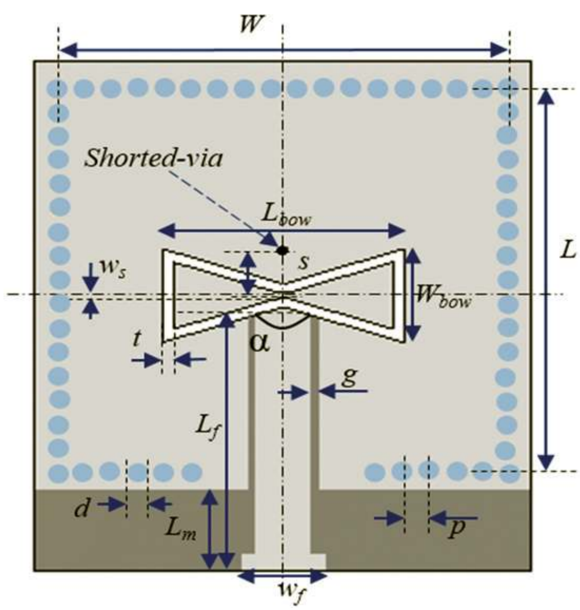

Figure 1. Antenna configuration with W=25.50, L=24, s=2.60, L_{bow}=13.40, W_{bow}=6.25, L_m=5, L_f =15.95, t=0.60, p = 1.50, g=0.4, w_f=4.80, w_s= 0.25, d=1. (All dimensions are in mm).

2.2 Bandwidth Enhancement Using a Shorted-via

As shown in Fig. 1, a shorted-via of a radius 0.25 mm is inserted just above the centroid of the BTCRS. By properly adjusting the location of shorted-via (up and down), the effective length of the slot (BTCRS) varies. Owing to a shorted-via, the individual bandwidth of higher and lower resonances can be tuned below -10 dB criteria. Figure 2 shows the performance comparison of the proposed and reference antenna, which is summarised in Table 1. The impedance bandwidth of the proposed antenna is 2.25 times of the reference antenna.

Table 1. Performance comparison of SIW antennas

Case / Properties	Reference antenna (w/o shorted-via)	Proposed antenna (with shorted-via) (GHz)
Impedance BW	686 MHz, 216 MHz	2.03
Reso. frequencies	11.90 GHz, 12.32 GHz, 13.27 GHz	12.30, 12.74, 13.68

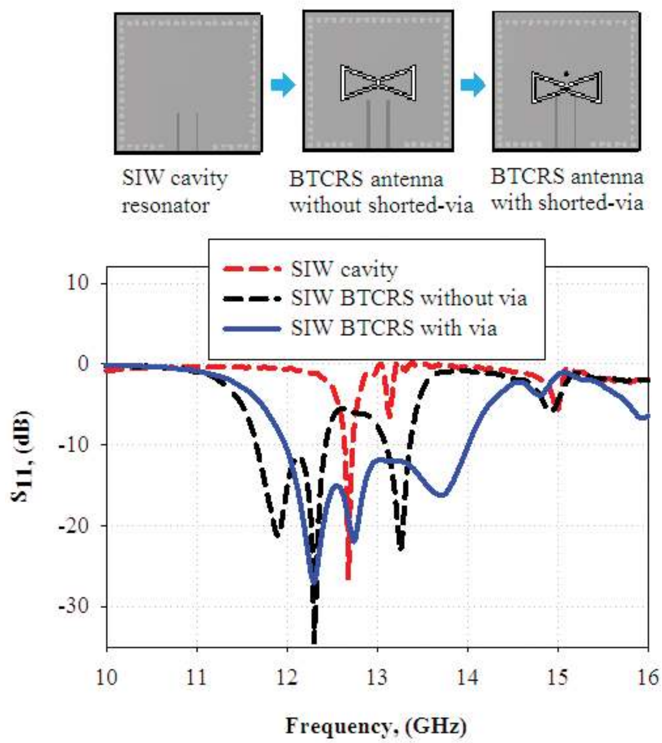

Figure 2 Reflection coefficients of different prototypes.

2.3 Current Distribution

To understand the radiation behaviour of the BTCRS at different resonant frequencies, respective current distributions with and without shorted-via are represented in Fig. 3. The shorted-via electrically connects the top and bottom cladding of the SIW cavity. As aforementioned, the location of the shorted-via changes the effective length of the slot. Thus, it controls the flow of the current along the lateral sides of the BTCRS. After introducing a shorted-via, it can be observed that the current path length predominantly increases and changes at

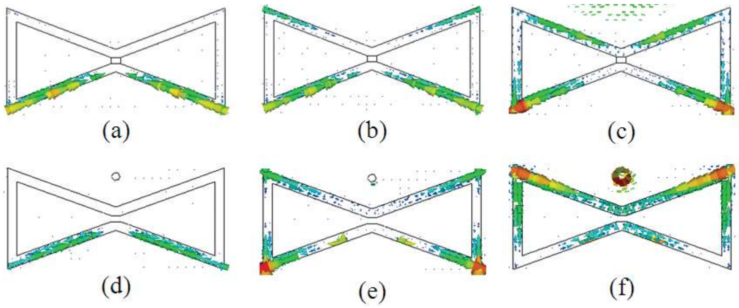

Figure 3. Simulated surface current distribution at different resonant frequencies: BTCRS without shorted-via (reference antenna) (a) 11.90 GHz, (b) 12.32 GHz, and (c) 13.20 GHz. BTCRS with shorted-via (proposed antenna) (d)12.30 GHz, (e) 12.74 GHz, and (f) 13.68 GHz.

the higher resonance (Fig. 3 (f)), and has a slight impact on lower resonances. By virtue of this, individual bandwidths get tuned below -10 dB criterion.

3. PARAMETRIC ANALYSIS

To comprehend the antenna performance, an extensive parametric study of its critical parameters has been executed. As explained above, the location of a shorted-via plays a vital role in tuning the resonant frequencies. With the variation of parameter s, the higher and lower order resonances can be moved as confirmed by Fig. 4. Eventually, at the optimum location, a wideband response is realised. Also, effects of the shorted-via on radiation efficiency and the input impedance $\mathrm{Re}(Z_{11})$ of the antenna is demonstrated in Fig. 5. The length of the parameter s for the proposed design is chosen to be 2.6 mm in order to maximise the bandwidth of 2.03 GHz. Also, the antenna shows around 80 per cent efficiency and a wide input impedance matching characteristics over the entire operating frequency band.

The length of BTCRS (L_{bow}) is much higher than a half wavelength at the centre frequency and a parametric variation of L_{bow} is shown in Fig. 6. By appropriately tuning a feed length (L_f), a broadband impedance bandwidth has been achieved. Similarly, Fig. 7 shows a variation in the reflection

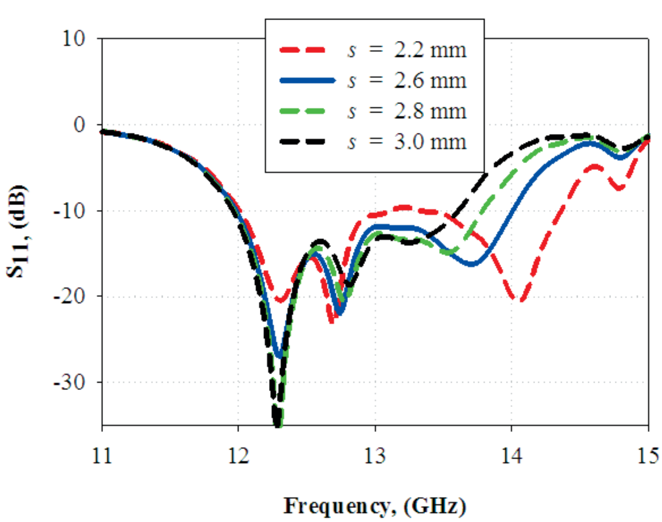

Figure 4. Variation of the S_{11} with change in parameter s.

coefficients with a change in flare-width (W_{bow}). It can be observed clearly that the matching of impedance bandwidth can be improved by tuning a parameter W_{bow}. Similarly, Fig. 8 shows the variation in reflection coefficients for different bow-angle α (symbolised in Fig. 1). Finally, by the process of optimisation, L_{bow} and W_{bow} are adjusted to 13.4 mm and 6.25 mm respectively. Figure 9 shows the effect on S_{11} for different values of shorted-via diameter, and optimally it has been chosen as 0.5 mm.

4. FABRICATION AND MEASUREMENTS

As shown in Fig. 10, the proposed SIW-BTCRS antenna was fabricated on Rogers RT-Duroid 5880 (1.575 mm thickness) sheet of a dielectric constant of 2.2.

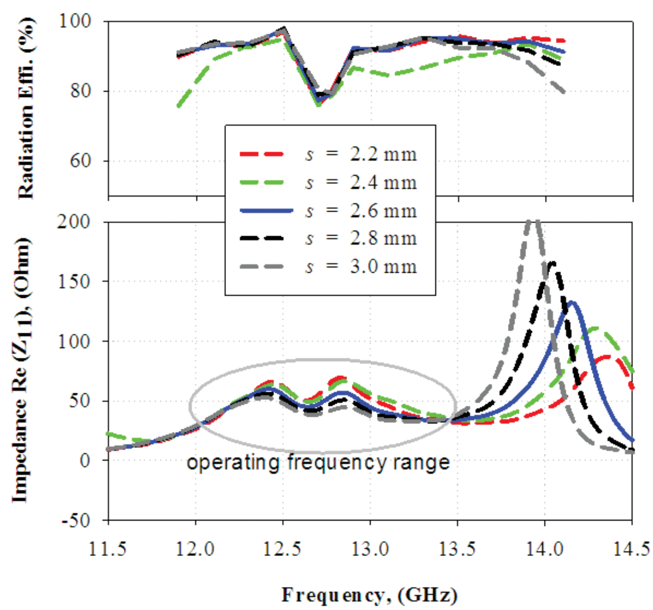

Figure 5. Effect of shorted-via on radiation efficiency and input impedance Re (Z_{11}) of antenna with change in parameter s.

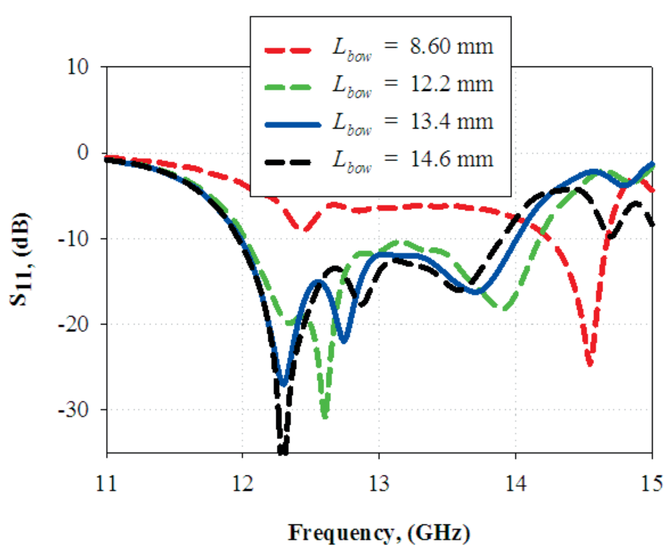

Figure 6. Variation of the S_{11} with change in parameter L_{bow}.

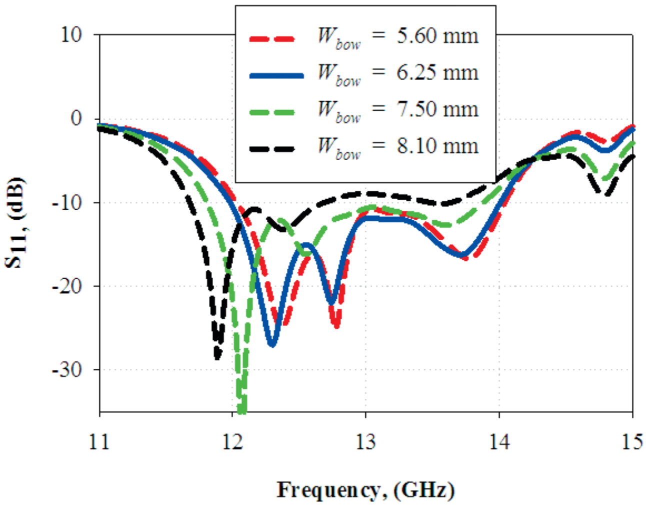

Figure 7. Variation of the S_{11} with change in parameter 'W_{bow}'.

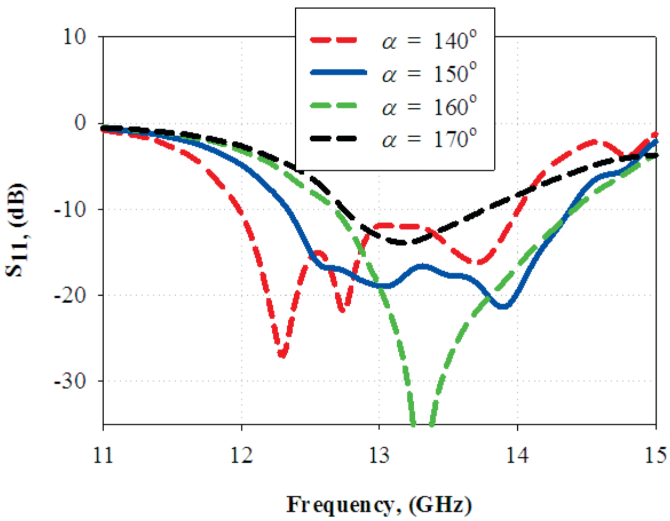

Figure 8. Variation of the S_{11} with change in bow-angle 'α'.

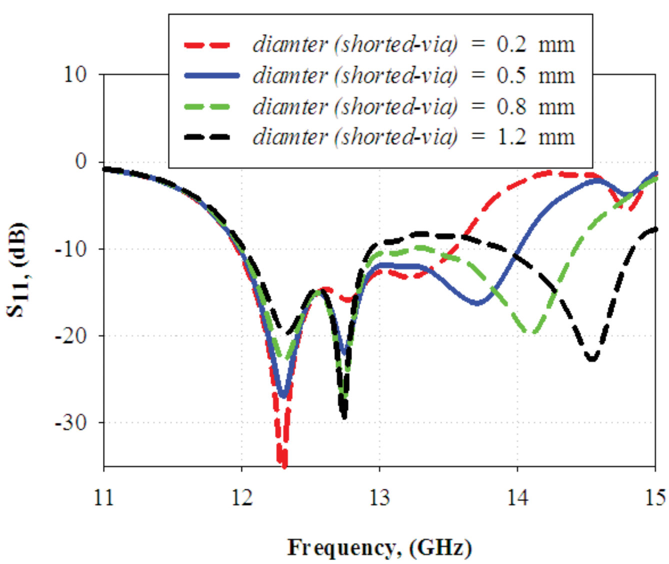

Figure 9. Effect on S_{11} for different values of a shorted-via diameters.

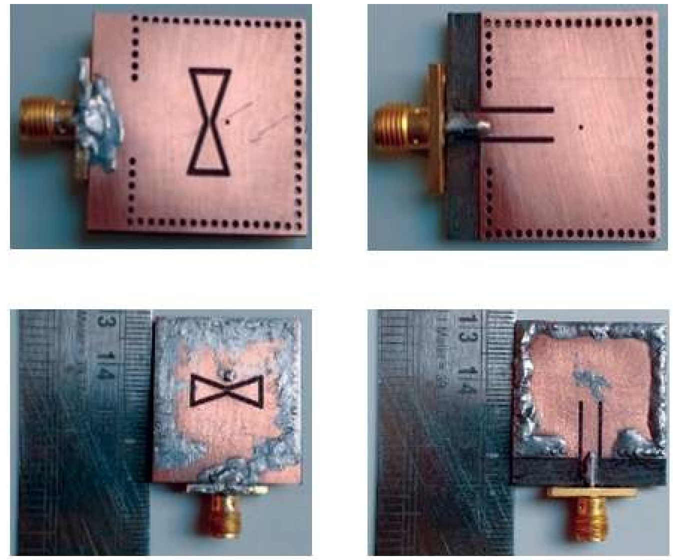

Figure 10. Fabricated proposed SIW-BTCRS antenna: (a) with empty vias and (b) vias filled with copper.

The fabrication of the antenna was done with the help of a low-cost PCB process and empty vias are filled with copper rivets.

The volume engaged by the proposed design is 28 mm x 30 mm x 1,57 mm, including microstrip feed line. To verify design speculations, the antenna was examined experimentally in terms of reflection coefficients (S_{11}), gain and radiation characteristics. Figure 11 demonstrates the comparison of the simulated and measured S_{11}. The measured S_{11} of the proposed BTCRS antenna is below -10 dB criterion for 11.88~14.12 GHz (17.23 per cent), while simulated one is 12.02~14.07 GHz (15.71 per cent). Due to multi-resonance characteristics of BTCRS, the antenna shows three resonant frequencies at 12.15 GHz, 12.59 GHz, and 13.86 GHz within the operating bandwidth. The measured gain at each of resonant frequency is 3.80 dBi, 4.03 dBi, and 4.90 dBi, respectively. However, a slight discrepancy is observed between the measured and simulated data, which may be attributed to imperfections in soldering and fabrication errors.

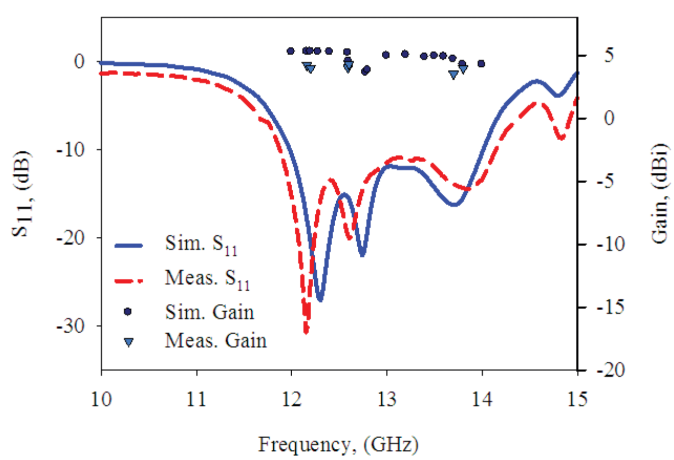

Figure 11. Comparison of simulated and measured S_{11} and gain of the proposed antenna.

The measured and simulated radiation patterns (co-polar and cross-polar) in the plane $\phi = 90^o$ (E-plane) and $\phi = 0^o$ (H-plane) at three frequencies (12.10 GHz, 12.59 GHz, and 13.86 GHz) are shown in Fig. 12. The radiation patterns of the proposed antenna are relatively wider than the conventional SIW rectangular slot antenna[4]. As a result, the directivity of the antenna decreases in bore sight-direction. The proposed antenna possesses stabilised, symmetrical and unidirectional radiation patterns at different resonant frequencies. Thus, this antenna design can be a promising candidate for the modern wireless communication systems, operating in K_u-band, particularly for broadband applications.

The performance comparison of the proposed design with previously reported antennas is listed in Table 2. It is observed that the proposed design has the advantages of the wide operating frequency band while other properties are comparable.

5. CONCLUSIONS

A new bandwidth enhancement technique for SIW cavity-backed antenna using a shorted-via is presented in this article. A shorted-via is inserted just above the centroid of bow-tie-complementary-ring-slot (BTCRS) of the antenna, that helps in merging the individual impedance bandwidths of the lower and higher resonant frequencies. As a result, the proposed antenna exhibits a simulated (measured) impedance bandwidth of 15.71 per cent (17.23 per cent), ranging from 12.02 GHz to 14.07 GHz (11.88 GHz to 14.12 GHz) with stabilised gain and radiation patterns. The impedance bandwidth of the proposed design is improved up to 2.25 times of the reference antenna. The experimental results reveal a good agreement with simulated one. Moreover, the proposed technique can be a reasonably useful to meliorate the impedance bandwidth of the planar cavity-backed antennas.

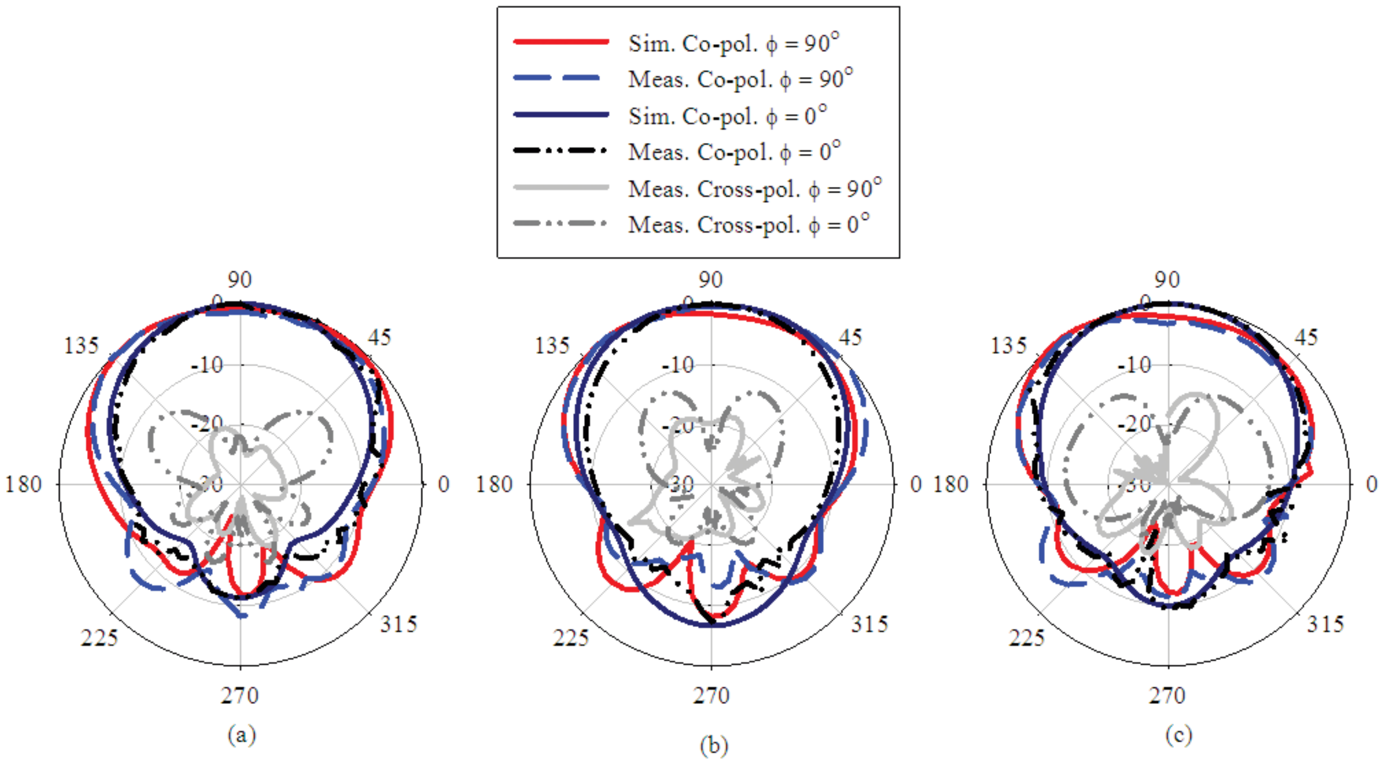

Figure 12. Comparison of simulated and measured radiation patterns at resonant frequencies of (a) 12.10 GHz, (b) 12.59 GHz, and (c) 13.86 GHz.

Table 2. Comparison among proposed and reported SIW cavity-backed antennas

Properties	Operating frequency band	Substrate thickness ($\varepsilon_r = 2.2$)	-10 dB, (S_{11}) BW (per cent)	Peak gain (dBi)	Feed-techniques
[6]	X	0.78	6.3	6.0	Microstrip line
[7]	X	0.78	9.4	3.8	Microstrip line
[8]	K_u	1.57	11.0	8.0	Microstrip line
[9]	X	0.5	1.8	5.3	Microstrip line
[10]	X, K_u	1.57	1.4,5.7	4.8, 6.1	Siw, microstrip line
[11]	K_u	1.57	23	7.0	Siw, microstrip line
[12]	X	1.016	10.9	7.7	Stripline, microstrip line
[14]	X	2.7 ($\varepsilon_r = 2.2$)	25.6	5.2	Stripline
Proposed design	K_u	1.57	17.23	4.9	Microstrip line

ACKNOWLEDGMENTS

Arvind Kumar thanks the Ministry of Electronics and Information Technology (MeitY), India for providing financial funding in the form of fellowship and contingency grant. Also, the authors would like to thank the Rogers Corporation (USA) for providing sample substrates.

REFERENCES

1. Jaroslav, L. Circularly polarized SIW square ring-slot antenna for X-band applications. *Microwave Opt. Technol. Lett.,* 2015, **54** (11), 2590–94. doi: 10.1002/mop.27113
2. Bozzi, M.; Georgiadis, A. & Wu, K. Review of substrate integrated waveguide circuits and antennas. *IET Microwave Antennas Propag.,* 2011, **5**(8), 909–20. doi: 10.1049/iet-map.2010.0463
3. Kumar, A. & Raghavan, S. Broadband dual-circularly polarised SIW cavity antenna using a stacked structure. *Electronics Lett.*, 2017, **53**(17), 1171–2. doi: 10.1049/el.2017.2407.
4. Luo, G.Q.; Hu, Z.F.; Dong, L.X. & Sun, L.L. Planar slot antenna backed by substrate integrated waveguide cavity. *IEEE Antennas Wireless Propag. Lett.,* 2008, **7**, 236–9. doi: 10.1109/LAWP.2008.923023
5. Lacik, J.; Mikulasek, T.; Raida, Z. & Urbanec, T. Substrate integrated waveguide monopolar ring-slot antenna. *Microwave Opt. Technol. Lett.,* 2014, **56**(8), 1865–9. doi: 10.1002/mop.28465
6. Luo, G.Q.; Hu, Z.F.; Li, W.J.; Zhang, X.H.; Sun, L.L. & Zheng., J.F. Bandwidth-enhanced low-profile cavity-backed slot antenna by using hybrid SIW cavity modes. *IEEE Trans. Antennas Propag.,* 2012, **60**(4), 1698–04. doi: 10.1109/TAP.2012.2186226
7. Mukherjee, S.; Biswas, A. & Srivastava, K.V. Broadband substrate integrated waveguide cavity-backed bow-tie slot antenna. *IEEE Antennas Wireless Propag Lett.,* 2014 **13**, 1152–5. doi: 10.1109/LAWP.2014.2330743
8. Kumar, A. & Raghavan, S. Wideband slotted substrate integrated waveguide cavity-backed antenna for Ku–band application. *Microwave Opt Technol. Lett.,* 2017, **59**(7), 1613–9. doi: 10.1002/mop.30594
9. Luo, G.Q.; Hu, Z.F.; Liang,Y.; Yu, L.Y. & Sun, L.L. Development of low profile cavity backed crossed slot antennas for planar integration, *IEEE Trans. Antennas Propag.,* 2009, 57(10), 2972–9. doi: 10.1109/TAP.2009.2028602
10. Zhang, T.; Hong, W.; Zhang, Y. & Wu, K. Design and analysis of SIW cavity backed dual-band antennas with a dual-mode triangular ring slot. *IEEE Trans. Antennas Propag.,* 2014, **62**(10), 5007–16. doi: 10.1109/TAP.2014.2345581
11. Kim, D.Y.; Lee, J.W.; Lee, T.K. & Cho, C.S. Design of SIW cavity backed circular-polarized antennas using two different feeding transitions. *IEEE Trans. Antennas Propag.,* 2011, **59**(4), 1398–403. doi: 10.1109/TAP.2011.2109675.
12. Yang, W. & Zhou, J. Wideband low profile substrate integrated waveguide cavity backed E-shaped patch antenna. *IEEE Antennas Wireless Propag. Lett.,* 2013, **12**, 143–46. doi: 10.1109/LAWP.2013.2241011
13. Yun, S.; Kim, D.Y. & Nam, S. Bandwidth and efficiency enhancement of cavity-backed slot antenna using a substrate removal. *IEEE Antennas Wireless Propag. Lett.,* 2012, **11**, 1458–61. doi: 10.1109/LAWP.2012.2230392
14. Gao, F.; Zhang, F.; Lu, L. & Jiao, Y.C. Wideband circularly polarized SIW antenna. *Microwave Opt. Technol. Lett.,* 2014, **56** (11), 2539–42. doi: 10.1002/mop.28633
15. Xu, F. & Wu, K. Guided-wave and leakage characteristics of substrate integrated waveguide. *IEEE Trans. Microwave Theory Tech.,* 2005, **53**(1), 66–73. doi: 10.1109/TMTT.2004.839303

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His contribution in the present work is to arrange measurement facility and overall guidance required to accomplish the task.