International Journal of Microwave and Wireless Technologies

cambridge.org/mrf

Substrate integrated waveguide differential antenna for full duplex applications

Gunjan Srivastava and Shalini Singh

Department of Electronics and Communication Engineering, Graphics Era (Deemed to be) University, Dehradun, India

Research Paper

Cite this article: Srivastava G, Singh S (2024) Substrate integrated waveguide differential antenna for full duplex applications. *International Journal of Microwave and Wireless Technologies*, 1–7. https://doi.org/10.1017/S1759078724001120

Received: 19 March 2024
Revised: 17 October 2024
Accepted: 24 October 2024

Keywords:
differential; full duplex; SIW; slot antenna (SA)

Corresponding author: Gunjan Srivastava;
Email: gunjansrivastava.ece@geu.ac.in

Abstract

This paper presents a substrate-integrated waveguide (SIW) differential antenna for full duplex applications. The proposed antenna consists of two square SIW cavities named as outer and inner. The inner cavity is nested into the outer cavity. The outer cavity is differentially excited with a pair of coaxial feed lines, while the inner square patch is orthogonally excited with another pair of differential coaxial feed lines. This orthogonal feeding arrangement results in high isolation between the differential ports. The modified hybrid $TE_{130/310}$ mode of the outer cavity radiates through a pair of arc-shaped slots at 9.35 GHz, while the TM_{01} mode of the inner square patch is responsible for the radiations at 8.65 GHz. The proposed antenna prototype is fabricated and measured for validation. Moreover, the designed antenna has a front-to-back ratio better than 22 dB and measured maximum gain values of 6.1 dBi and 7.6 dBi at 8.65 GHz (Port 2 ON) and 9.35 GHz (Port 1 ON), respectively.

Introduction

Differential antennas are preferred over single-ended ones due to their several advantages, such as low cross-polarization, ease of integration with differential circuits, excellent environmental noise immunity, high spectral efficiency, etc [1]. Several three-dimensional differential antennas have been studied in detail [2–5]. However, these antennas occupy a large footprint and have a relatively high profile. To integrate these antennas in the system, low-profile antennas are required. Several low-profile planar differential antennas are also investigated in the literature [6–9]. Nowadays, substrate-integrated waveguide (SIW) is a promising technology that allows the realization of low-profile high-gain differential antennas [10–12].

Moreover, modern wireless communication systems require compact, low-profile, and multiband antennas with high input port isolation. These multiband antennas are connected to multiple transceivers, which suffer from poor port-to-port isolation. A diplexer can be used to enhance the isolation between the ports [13]. However, this requires additional circuit elements, which increases the design complexity and results in a large transverse size. Thus, the full-duplex antenna systems, which do not require extra components for isolation enhancement, can provide an excellent solution to the limitations mentioned above [14–16].

In full-duplex communication systems, the simultaneous transmission and reception of signals takes place. This simultaneous transmission and reception of signals not only double the spectral efficiency but also increase the data throughput [17–19]. Two separate frequencies, one for transmission and another for reception of signals, are used in a dual-band full-duplex system. High isolation between the transmitter and receiver is one of the main requirements of any full-duplex systems. For acceptable performance of full-duplex systems, at least 110 dB of inter-port isolation is essential [20]. This high isolation can be attained in different design stages of the wireless communication systems. Several methodologies are applied in the antenna-stage, analog-stage, and digital-stage to obtain high isolation in each stage. High inter-port isolation in the antenna stage alleviates the requirement for isolation in the subsequent stages.

Two separate operating frequencies are employed in a dual-band full-duplex system, one for the transmission and another for the reception of the RF (Radio Frequency) signals. For the faithful performance of full-duplex systems, high isolation between the transmitter and the receiver is one of the essential requirements. High isolation can be obtained with the usage of different methods such as polarization diversity [21], differential feeding arrangement [22], introduction of defected ground structure [23, 24] etc. between the transmitting and receiving antenna. These aforementioned methods have constraints of inadequate isolation, which is one of the essential requirements for full-duplex systems. Owing to the requirements of high port-to-port isolation with high spectral efficiency, the design of a compact full-duplex antenna, operating in two different frequency bands is a challenging task.

In this article, a full duplex differential antenna with high isolation between the differential ports is presented. The designed antenna consists of two square cavities, named as outer and inner. The inner cavity is one nested into the outer cavity. The modified hybrid $TE_{130/310}$ mode of the outer cavity is differentially excited by a pair of coaxial feed lines, which radiates through a pair of arc-shaped slots at 9.35 GHz. To obtain radiations at 8.65 GHz, a TM_{01} mode of the square patch is differentially excited by another pair of coaxial feed lines. With the simultaneous orthogonal differential excitation of the outer cavity and square patch, high isolation between the differential ports is obtained.

The salient key features of the proposed full-duplex antenna are as follows:

1. The low profile of the proposed full-duplex antenna provides ease of integration with the planar circuits.
2. The combination of differential feeding arrangement along with the dual-polarized radiation characteristics provides high isolation (better than 52 dB) in both the operating bands of the proposed full-duplex antenna.
3. Due to the usage of SIW technology, the designed antenna exhibits high gain in both operating bands.
4. The proposed antenna also exhibits the advantage of independent tunability of each operating band. Thus, the proposed full-duplex antenna has the flexibility to redesign it within X-band frequency spectrum.
5. The proposed antenna provides very good polarization purity, i.e., the designed antenna has very low cross-pol levels (<-30 dB) with respect to co-pol in the broadside direction.

The designed antenna can be used for X-band radar applications including dual-polarized synthetic aperture radar for weather monitoring, air traffic control, maritime vessel traffic control [25–27].

Antenna configuration

Figure 1 shows the proposed differential full duplex antenna. The differential antenna is designed on RT/duroid 5880 substrate with dielectric constant 2.2, loss tangent 0.0009, and thickness of 0.508 mm. In the present design, there are two SIW cavities, named as outer and inner. The inner cavity is nested into the outer cavity. The side walls of cavities are obtained by introducing a series of metallic vias of diameter d with separation p. The values of d and p are chosen in such a way that there is confinement of electromagnetic energy within the SIW cavities. The outer cavity is excited by the differential Port 1 through a pair of coaxial feed lines. The diff. Port 1 comprises of coax Port 1+ and Port 1−. A square ring slot of dimension b and width w_i is introduced on the top surface of the inner cavity to obtain a square patch radiator of dimensions $a \times a$. This square patch radiator is differentially excited through another pair of coaxial feed lines, which is designated as differential Port 2. The differential Port 2 consists of coax Port 2+ and Port 2−.

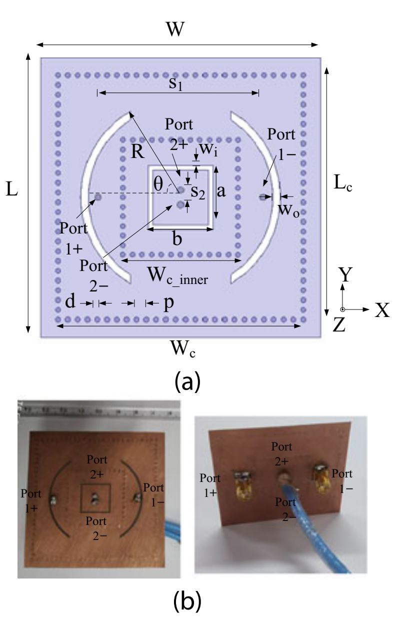

Figure 1. (a) Geometry of the proposed differential full duplex antenna (b) Photograph of fabricated prototype.

The terminals of the differential Port 1 are placed along the x-axis, while the terminals of the differential Port 2 are placed along the y-axis to obtain the orthogonal placement of the feeds. This orthogonal placement of the feeds is responsible for the high isolation between the differential ports. The design parameter s_1 is the center-to-center distance between the terminals (Port 1+, Port 1−) of the differential Port 1, while s_2 is the center-to-center distance between the terminals of the differential Port 2 (Port 2+, Port 2−). A pair of arc shaped slots of radius R, and subtended angle 2θ are etched on the top surface of the outer cavity to facilitate radiations at 9.35 GHz under differential Port 1 excitation. While the square patch radiator is responsible for the radiations at 8.65 GHz, under Port 2 excitation.

Operational mechanism

Square SIW cavity

The resonant frequency for TE_{mn0} mode of the cavity is

$$f_{mn0} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a_{eff}}\right)^2 + \left(\frac{n\pi}{b_{eff}}\right)^2} \quad (1)$$

where μ and ε are permeability and permittivity of the dielectric material, a_{eff} and b_{eff} are effective dimensions of the cavity [28]. For the square cavity, $a_{\text{eff}} = b_{\text{eff}}$, $m \neq n$, several pairs of degenerate modes are excited simultaneously inside SIW cavity, e.g. TE_{130} and TE_{310} modes can form one degenerate modal pair and the corresponding electric field distributions inside the square cavity are shown in Fig. 2(a), where positive sign indicates the upward direction and negative sign indicates the downward direction of the fields. Since they are degenerate modes, their fields will superimpose each other and resulting in hybrid $TE_{130/310}$ mode and the corresponding field distribution shown in Fig. 2(a). When the inner square cavity is introduced inside the outer cavity, the resonant frequency of hybrid $TE_{130/310}$ mode will shift from 6.65 GHz to 9.55 GHz and fields of the modified hybrid $TE_{130/310}$ mode will be confined between the outer and inner cavities as shown in Fig. 2(b). With the coaxial differential feeding, Port 1+ is fed with positive signal and Port 1− with negative signal of equal amplitude. With this feeding arrangement, the E-fields inside SIW cavity will modify accordingly. The vector electric fields for this differential feeding arrangement is shown in Fig. 2(b).

Proposed geometry

The proposed differential full duplex antenna is realized by inserting a pair of arc-shaped slots inside the outer cavity and a square ring-shaped slot inside the inner cavity. These slots are inserted

https://doi.org/10.1017/S1759078724001120 Published online by Cambridge University Press

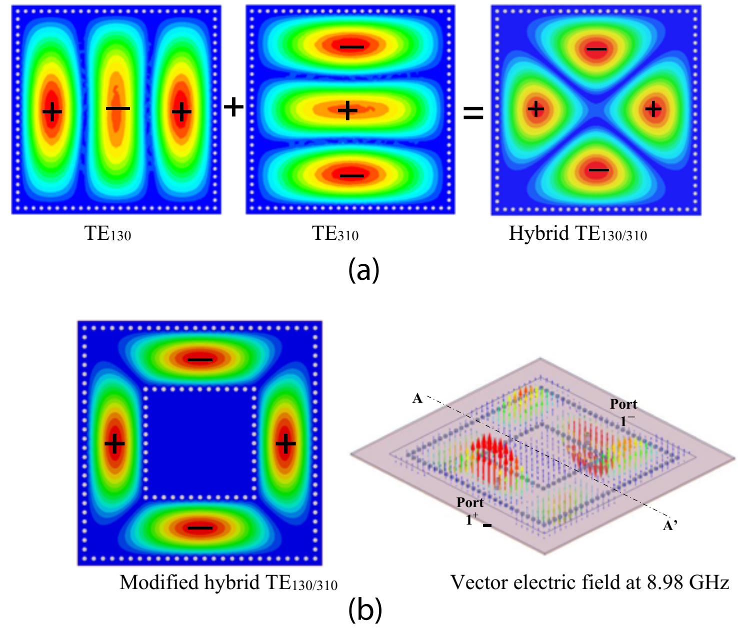

Figure 2. (a) E-fields for TE_{130} mode, TE_{310} mode and hybrid $TE_{130/310}$ mode (b) E-fields inside the cavity for modified hybrid $TE_{130/310}$ mode and vector E-field at 8.98 GHz under Port 1 excitation.

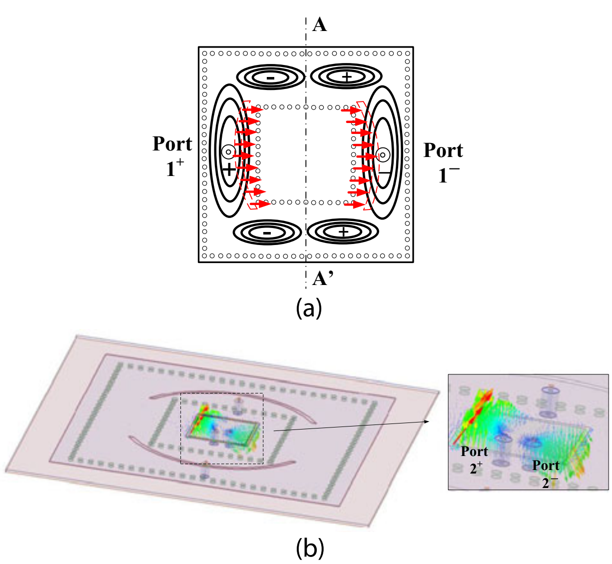

Figure 3. (a) Electric-field isolines for modified hybrid $TE_{130/310}$ mode under differential Port 1 excitation (b) Vector electric field at 8.65 GHz under Port 2 excitation.

at the top-surfaces of the cavities. With the placement of the arc-shaped slots, the resonant frequency of the modified hybrid $TE_{130/310}$ mode shifts to the lower value i.e. from 9.55 GHz to 9.35 GHz. This lowering is due to the strong reactive loading effect of these slots. This phenomenon can be better explained by plotting the contour of the electric field distribution in the outer cavity with Port 1 excitation [Fig. 3(a)]. When the arc-shaped slots are energized by the Port 1, it perturbs the fields of the modified hybrid $TE_{130/310}$ mode and results in x-polarized radiations at 9.35 GHz. Furthermore, the locations and lengths of these arc-shaped slots are fine adjusted for the better radiation characteristics.

On the other hand, the other radiating frequency of the differential full duplex antenna is obtained by inserting a square ring slot of dimensions (b, w_i) on the top surface of the inner cavity. This square ring slot separates the inner cavity from the inner conductor and forms a floating square microstrip patch of dimensions $a \times a$. When this square microstrip patch is differentially fed with a pair of coaxial feed lines, designated as Port 2+ and Port 2−, it will excite the odd order resonant modes such as TM_{01}, TM_{21}, TM_{03}, etc. and the remaining even order modes such as TM_{02}, TM_{12}, etc. will be suppressed. According to the cavity model of microstrip patch antenna [29], the resonant frequency f_{mn} of TM_{mn} mode of the differentially excited patch is given as

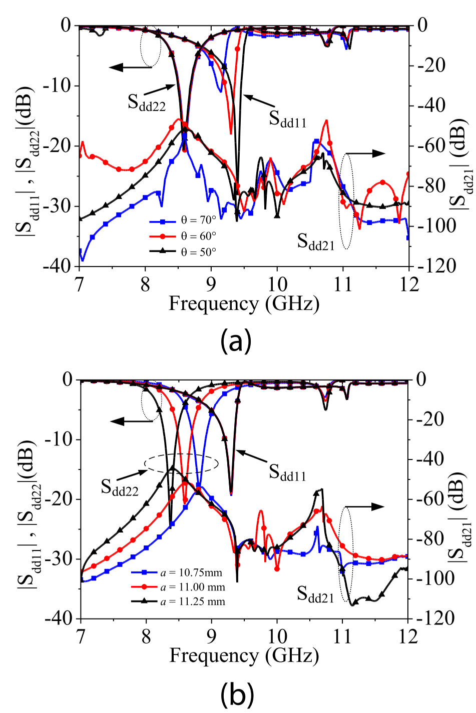

Figure 4. (a) Simulated S-parameters of the proposed differential full duplex antenna for different values of θ (b) Simulated S-parameters of the proposed differential full duplex antenna for different sizes of inner square patch.

https://doi.org/10.1017/S1759078724001120 Published online by Cambridge University Press

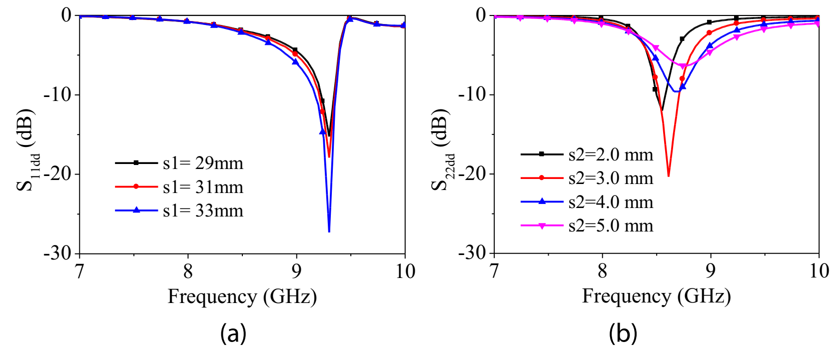

Figure 5. S-parameters of the proposed full-duplex antenna
(a) $|S_{11dd}|$-parameters for different values of s_1
(b) $|S_{22dd}|$-parameters for different values of s_2.

$$f_{mn} = \frac{c}{2\sqrt{\varepsilon_{eff}}}\sqrt{\left(\frac{m}{W_P}\right)^2 + \left(\frac{n}{L_P}\right)^2} \tag{2}$$

where c represents the speed of light, ε_{eff} is the effective dielectric constant of the substrate, W_{p} and L_{p} indicates the patch width and patch length, respectively. For the square microstrip patch, $W_{\text{P}} = L_{\text{P}}$. The dimensions of the square microstrip patch $a \times a$ are chosen in such a way that it operates at 8.65 GHz. The electric field distribution of the square microstrip patch under differential Port 2 excitation in TM_{01} mode results in y-polarized electromagnetic wave [Fig. 3(b)]. Figure 3 clearly demonstrates the dual polarized behavior of the proposed full-duplex antenna.

To minimize the mutual coupling of the fields between the outer cavity and square microstrip patch, the patch is differentially excited through differential Port 2, which is orthogonally placed w.r.t. to differential Port 1 of the outer cavity. Thus, high isolation is obtained between the differential ports, which facilitates the full duplex characteristics of the designed antenna.

Parametric analysis

To investigate the effect of different varying parameters on the radiating frequencies of the differential full duplex antenna, a parametric study is performed using Ansys HFSS 2020. The variations of the radiating frequencies for different slot and patch dimensions are presented in this section. During the parametric analysis, only one design parameter is varied, while the others are kept constant. By varying the angle θ of arc-shaped slots, only the first radiating frequencies of the differential full duplex antenna can be changed, while the other radiating frequency remains unchanged. The first radiating frequency can be independently tuned in the frequency range from 9.1–9.45 GHz by varying the value of θ from 70° to 50°mm, as shown in Fig. 4(a). The second radiating frequency of the differential full duplex antenna can be changed by varying the dimension a of the square microstrip patch. It can be tuned from 8.3 to 8.8 GHz, by changing the value of a from 11.25 to 10.75 mm, as depicted in Fig. 4(b). It is clear from Fig. 4 that during these variations, one of the radiating frequency bands changes while the other remains unaltered. Thus, it can be concluded that both the frequency bands of the proposed differential full duplex antenna can be controlled independently. Due to the orthogonal arrangement of the differential ports, excellent isolation, better than 50 dB, is also maintained.

To have better understanding about feed locations, parametric analysis for the design parameters s_1 and s_2 are also performed and their results are plotted. Figure 5 shows the simulated S-parameters for different values of s_1 and s_2 for differential Port 1 and Port 2, respectively. As the value of s_1 increases, impedance bandwidth

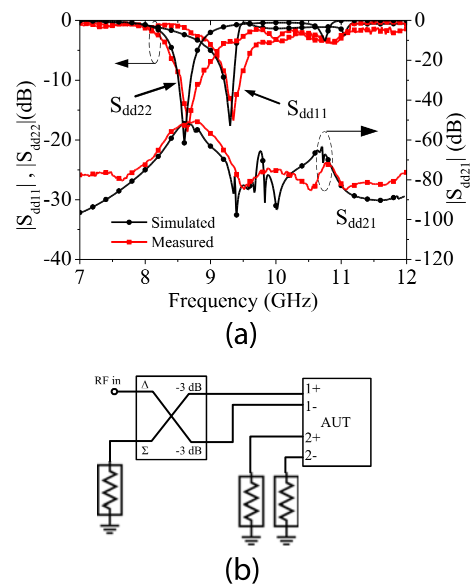

Figure 6. (a) Simulated and measured S-parameters of the designed full duplex differential antenna (b) Experimental set-up for antenna radiation pattern measurements.

enhancement is observed. However, the value of s_1 cannot be increased beyond $s_1 = 33$ mm due to the presence of arc-shaped slots. Thus, $s_1 = 33$ mm, provides optimum feed location which is nearest to the radiating arc-shaped slots. Figure 5(b) shows simulated S-parameters for different values of s_2. It can be observed from the figure that designed antenna has good impedance match for the center-to-center distance $s_2 = 3.0$ mm of the differential Port 2.

The design parameters of the full duplex antenna are: $L = 56$ mm, $W = 56$ mm, $W_c = 49$ mm, $W_{c\_inner} = 23$ mm, $R = 19$ mm, $a = 11$ mm, $b = 12$ mm, $s_1 = 33$ mm, $s_2 = 3$ mm, $d = 1$ mm, $p = 2$ mm, $w_i = 0.5$ mm, $w_o = 0.8$ mm, $\theta = 60$.

Design guidelines

Based on the aforementioned simulation studies, the design guidelines can be summarized as:

1) Calculate the initial dimensions ($L_c \times W_c$) of the outer cavity using (1) for the degenerate modes TE_{130} and TE_{310} modal pair.
2) Place the nested inner cavity inside the outer cavity such that frequency of modified hybrid $TE_{130/310}$ mode lies in the X-band (8–12 GHz).

https://doi.org/10.1017/S1759078724001120 Published online by Cambridge University Press

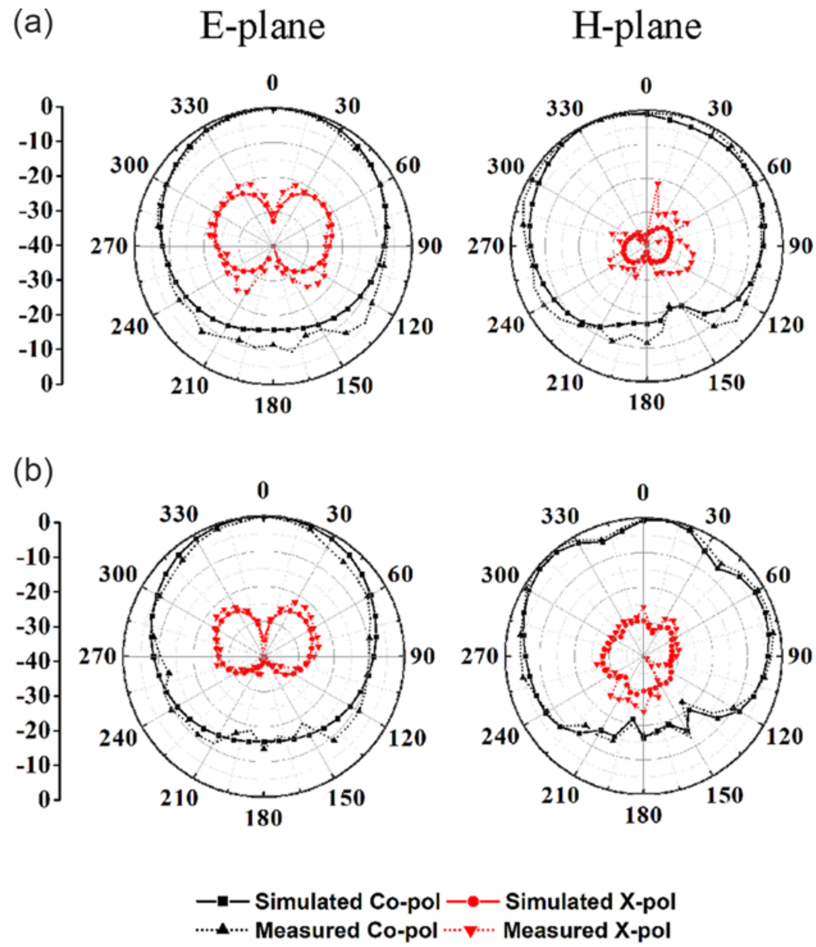

Figure 7. Simulated and measured far field radiation patterns at (a) 8.65 GHz (diff. Port 2 ON) (b) 9.35 GHz (diff. Port 1 ON).

3) Apply the differential coaxial feed lines (Port 1+ and Port 1−) to the outer cavity.
4) Place a pair of arc-shaped slots in the outer cavity such it radiates in X-band. Tune the slot dimensions and location for better radiation characteristics.
5) Insert a square ring slot of dimension b and width w_i in the nested inner cavity to obtain the floating microstrip patch of dimension $a \times a$. Tune the dimensions such that TM_{01} mode of the square patch lies in the X-band.
6) Apply the differential coax feed lines (Port 2+ and Port 2−) to the microstrip patch along the orthogonal axes w.r.t. differential Port 1 to minimize the mutual coupling of the electric fields of the modified outer cavity and microstrip patch.
7) Finally, the cavity and/or slot dimensions can be fine-tuned to adjust the frequency bands.

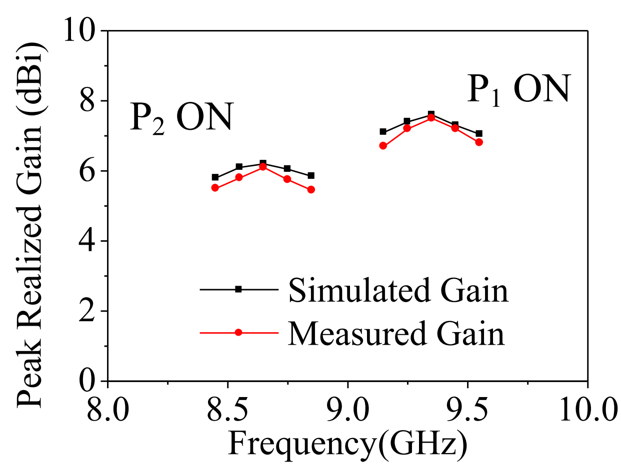

Figure 8. Peak realized gain of the proposed full-duplex differential antenna.

Results and discussion

To validate the proposed concept, the designed differential full duplex antenna is fabricated on RT/Duriod 5880 substrate and tested. The photograph of the fabricated prototype is shown in Fig. 1(b). The S-parameters of the fabricated antenna are measured using Agilent 5071C VNA, whereas radiation patterns and gains are measured inside the anechoic chamber. The differential S-parameters are evaluated as follows [1]:

$$S_{11dd} = \frac{1}{2}\left(S_{1^+1^+} - S_{1^+1^-} - S_{1^-1^+} + S_{1^-1^-}\right)$$

$$S_{22dd} = \frac{1}{2}\left(S_{2^+2^+} - S_{2^+2^-} - S_{2^-2^+} + S_{2^-2^-}\right)$$

$$S_{21dd} = \frac{1}{2}\left(S_{2^+1^+} - S_{2^+1^-} - S_{2^-1^+} + S_{2^-1^-}\right)$$

Figure 6(a) shows the simulated and measured S-parameters of the designed differential full duplex antenna. The measured results are found to be good agreement with the simulated

https://doi.org/10.1017/S1759078724001120 Published online by Cambridge University Press

Table 1. Comparison with other full duplex antennas

Ref	Feeding arrangement	Size (λ_g^3)	Freq.(GHz)	Pol.	Min. iso. (dB)	Gain (dBi)
[4]	Single	1.08 × 1.89 × 0.03	4.1, 4.9	Dual	32	4.36, 4.83
[5]	Diff.	0.86 × 0.86 × 0.28	3.5, 4.95	Dual	20	7.6, 7.92
[6]	Diff.	0.80 × 0.33 × 0.012	2.4, 5.8	Single	18	5.45, 8.5
[32]	Diff.	1.50 × 1.50 × 0.07	2, 2.44	Single	36	5.86, 6.67
[33]	Diff.	1.79 × 1.79 × 0.017	3.22, 4.1	Dual	51	2.5, 2.5
Prop.	Diff.	1.8 × 1.8 × 0.019	8.65, 9.35	Dual	52	6.1, 7.6

λ_g is the wavelength at the lowest operating frequency,.

results. The fabricated full duplex differential antenna radiates at 9.35 GHz (9.25–9.45 GHz) under Port 1 excitation and at 8.65 GHz (8.55–8.85 GHz) under differential Port 2 excitation. An isolation better than 52 dB is observed between the differential ports. In terms of bandwidth, our designed full duplex antenna has the narrow bandwidth, an inherent characteristic of SIW-cavity-based antennas. However, the bandwidth provided by our antenna is more than sufficient for radar applications including dual-polarized synthetic aperture radar. Though, there are various methods that can be adopted to improve the impedance bandwidth. From cavity-backed antenna theory, it is well known that impedance bandwidth is directly proportional to cavity depth [30, 31]. The impedance bandwidth of the proposed antenna can be improved by increasing substrate thickness.

Figure 6(b) shows the setup for the measurement. To measure the far field radiation pattern and gain of the fabricated differential full duplex antenna, a wideband 180° coupler is utilized to generate differential signals. The hybrid coupler has the difference (Δ) and the summation (Σ) ports. The first one is connected to the signal source whereas the latter one is connected to 50Ω matched load. During the measurement of radiation pattern with Port 1 excitation, the outputs of the hybrid coupler are connected to Port 1− and Port 1+ of the differential antenna, while the other ports (Port 2− and Port 2+) are terminated with 50 matched Ω loads. In the similar fashion, with Port 2 excitation, the outputs of the hybrid coupler are connected to Port 2− and Port 2+.

The simulated and measured radiation pattern of the designed differential full duplex antenna at 9.3 GHz (under diff. Port 1 excitation) and 8.65 GHz (under diff. Port 2 excitation) in both the principal planes are plotted in Fig. 7. The designed antenna has broadside radiation characteristics with high front-to-back ratio of 22 dB in the operating bands. The peak realized gains of full duplex differential antenna are plotted in Fig. 8 and are 7.6 dBi (under diff. Port 1 excitation at 9.35 GHz) and 6.1 dBi (under diff. Port 2 excitation at 8.65 GHz), respectively. The radiation efficiencies better than 80% are also observed.

The designed full-duplex antenna system is compared with other state-of-the-art works reported in the literature. The comparison is performed in terms of size, polarization, gain, and port-to-port isolation and is depicted in Table 1. It is clear from the table that the performance of the designed antenna is comparable with the other antennas w.r.t. size, operating frequency, port-to-port isolation, and gain. Moreover, the designed antenna has high gain and excellent isolation along with good polarization purity that makes it a potential candidate for the full duplex systems operating in X-band.

Conclusion

A low-profile differential, full-duplex antenna is designed in this paper. The proposed antenna is fed by two pairs of differential coaxial feed lines. It radiates at 9.35 and 8.65 GHz, along with an isolation better than 52 dB between the differential ports. The operating bands of the designed differential antenna can be independently adjusted as per the requirements. The designed differential antenna eliminates the requirements of additional circuitry that provides high isolation between the differential ports. The proposed antenna provides excellent polarization purity, i.e., the designed antenna has very low cross-pol levels (<-30 dB) with respect to co-pol in the broadside direction. The designed antenna can be used for X-band radar applications, including dual-polarized synthetic aperture radar for weather monitoring, air traffic control, and maritime vessel traffic control.

Author contributions. "G.S. gave the concept and performed the simulations. G.S. and S.S. contributed equally to analysing data and reaching conclusions, and in writing the paper."

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. **Eisenstadt WR, Stengel B and Thompson BM** (2006) *Microwave. Differential Circuit Design Using Mixed-Mode S-Parameters*. Boston, MA: Artech House.
2. **Tang H, Chen J, Yang W, Zhou L and Li W** (2017) Differential dual-band dual-polarized dielectric resonator antenna. *IEEE Transaction on Antennas and Propagation* **65**, 855–860.
3. **Tang H, Chen J, Zhan Y and Li J** (2015) Differential dual polarization dielectric resonator antenna with higher mode suppression, high isolation and low cross-polarization. In *2015 Asia-Pacific Microwave Conference Nanjing*, 1–3.
4. **Hu KZ, Tang MC, Wang Y, Li D and Li M** (2021) Compact, vertically integrated duplex filtenna with common feeding and radiating SIW cavities. *IEEE Transactions on Antennas and Propagation* **69**, 502–507.
5. **Han L, Zhang W, Chen X, Han G and Ma R** (2020) Design of compact differential dual-frequency antenna with stacked patches. *IEEE Transaction on Antennas and Propagation* **58**, 1387–1392.
6. **Li D, Tang MC, Wang Y, Hu KZ and Ziolkowski RW** (2021) Compact differential diplex filtenna with common-mode suppression for highly integrated radio frequency front-ends. *IEEE Transaction on Antennas and Propagation* **69**, 7935–7940.
7. **Li J, Hu P, Chen J, Xu KD, Mao CX and Zhang XY** (2022) Dual-polarized duplex base-station antenna with a duplexer-integrated balun. *IEEE Antennas and Wireless Propagation Letters* **21**, 317–321.

8. **Nawaz H, Niazi AU, Basit MA, Shaukat F and Usman M** (2020) Dual-polarized, monostatic antenna array with improved Tx–Rx isolation for 2.4 GHz in-band full duplex applications. *International Journal of Microwave and Wireless Technologies* **12**, 398–408.
9. **Nawaz H, Basit MA and Niazi AU** (2021) A compact, dual-polarized patch antenna with improved Tx–Rx isolation for 2.4 GHz single frequency full-duplex applications. *International Journal of Microwave and Wireless Technologies* **13**, 266–273.
10. **Srivastava G and Mohan A** (2018) High gain SIW cavity backed differential slot antenna for X-band applications. *IET Electronics Letters* **54**, 1361–1362.
11. **Srivastava G, Mohan A and Bhattacharya A** (2022) Triple-band dual-polarized SIW cavity-backed differential slot antenna. *IEEE Antennas and Wireless Propagation Letters* **21**, 858–862.
12. **Srivastava G and Mohan A** (2019) A differential dual-polarized SIW cavity-backed slot antenna. *IEEE Transactions on Antennas and Propagation* **67**, 3450–3454.
13. **Strassner B and Cheng K** (2001) Wide-band low-loss high-isolation microstrip periodic-stub diplexer for multiple-frequency applications. *IEEE Transactions on Microwave Theory and Techniques* **49**, 1818–1820.
14. **Mukherjee S and Biswas A** (2016) Design of self-diplexing substrate integrated waveguide cavity-backed slot antenna. *IEEE Antennas and Wireless Propagation Letters* **15**, 1775–1778.
15. **Nandi S and Mohan A** (2018) SIW-based cavity-backed self-diplexing antenna with plus-shaped slot. *Microwave and Optical Technology Letters* **60**, 827–834.
16. **Chaturvedi D, Kumar A and Raghavan S** (2019) A nested SIW cavity-backing antenna for Wi-Fi/ISM band applications. *IEEE Transaction on Antennas and Propagation* **67**, 2775–2780.
17. **Sabharwal A, Schniter P, Guo D, Bliss DW, Rangarajan S and Wichman R** (2014) In-band full-duplex wireless: Challenges and opportunities. *IEEE Journal on Selected Areas in Communications* **32**, 1637–1652.
18. **Liu G, Yu FR, Ji H, Leung VCM and Li X** (2015) In-band full-duplex relaying: A survey, research issues and challenges. *IEEE Communications Surveys and Tutorials* **17**, 500–524.
19. **Elmansouri MA and Filipovic DS** (2016) Realization of ultra-wideband bistatic simultaneous transmit and receive antenna system. In *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*. 2115–2116.
20. **Debaillie B, van den Broek DJ, Lavin C, van Liempd B, Klumperink EA, Palacios C, Craninckx J, Nauta B and Pärssinen A** (2014) Analog/RF solutions enabling compact full-duplex radios. *IEEE Journal on Selected Areas in Communications* **32**, 1662–1673.
21. **Heino M, Korpi D, Huusari T, Antonio-Rodriguez E, Venkatasubramanian S, Riihonen T, Anttila L, Icheln C, Haneda K, Wichman R and Valkama M** (2015) Recent advances in antenna design and interference cancellation algorithms for in-band full-duplex relays. *IEEE Communications Magazine* **53**, 91–101.
22. **Gong Q, Jiao Y and Gong S** (2011) Compact MIMO antennas using a ring hybrid for WLAN applications. *Journal of Electromagnetic Waves and Applications* **25**, 431–441.
23. **Makar G, Tran N and Karacolak T** (2017) A high-isolation monopole array with ring hybrid feeding structure for in-band full-duplex systems. *IEEE Antennas and Wireless Propagation Letters* **16**, 356–359.
24. **Wu T, Fang S and Wong K** (2015) Printed diversity monopole antenna for WLAN operation. *Electronics Letters* **38**, 1625–1626.
25. **Qin F, Gao SS, Luo Q, Mao CX, Gu C, Wei G, Xu J, Li J, Wu C, Zheng K and Zheng S** (2016) A simple low-cost shared-aperture dual-band dual-polarized high-gain antenna for synthetic aperture radars. *IEEE Transactions on Antennas and Propagation* **64**, 2914–2922.
26. **Anim K, Shin G-H and Jung Y-B** (2021) Dual-resonant stacked linear array of cross-slotted patches for small SAR satellites. *IEEE Transactions on Antennas and Propagation* **69**, 3584–3587.
27. **Kuo FY and Hwang RB** (2014) High-isolation X-band marine radar antenna design. *IEEE Transactions on Antennas and Propagation* **62**, 2331–2337.
28. **Bozzi M, Georgiadis A and Wu K** (2011) Review of substrate-integrated waveguide circuits and antennas. *IET Microwaves, Antennas and Propagation* **5**, 909–920.
29. **Balanis CA** (2005) *Antenna Theory: Analysis and Design*, 3rd edn. New York: Wiley.
30. **Luo GQ, Hu ZF, Liang Y, Yu LY and Sun LL** (2009) Development of low-profile cavity backed crossed slot antennas for planar integration. *IEEE Transactions on Antennas and Propagation* **57**, 2972–2979.
31. **Luo GQ, Hu ZF, Li WJ, Zhang XH, Sun LL and Zheng JF** (2012) Bandwidth-enhanced low-profile cavity-backed slot antenna by using hybrid SIW cavity modes. *IEEE Transactions on Antennas and Propagation* **60**, 1698–1704.
32. **Wu ZK and Xie ZM** (2020) A differential duplex filtering antenna with low cross-polarization. In *2020 IEEE MTT-S International Wireless Symposium (IWS)*, Shanghai, China, 1–3
33. **Prasad DVS, Singh HV, Tripathi S and Paltani PP** (2023) Dual-band full-duplex antenna with high isolation using differential fed and dual-polarization. *Microwave and Optical Technology Letters* **65**, 192–203.

Dr. Gunjan Srivastava received her Ph.D. degree from the Indian Institute of Technology (Indian School of Mines), Dhanbad, India in Microwave Engineering in 2016. At present, she is working as Associate Professor in the Department of Electronics and Communication Engineering at Graphic Era (Deemed to be) University, Dehradun. Earlier, she was associated with Department of E&ECE at Indian Institute of Technology Kharagpur as a capacity of Women Scientist. She has authored or coauthored over 29 peer-reviewed international journal and conference papers. Her main research interests are design of ultra-wideband, reconfigurable, SIW, MIMO and self-multiplexing antennas.

Dr. Shalini Singh is working as Professor in Department of Electronics & Communication Engineering in Graphic Era Deemed to be University, Dehradun, India. She had received B. Tech. and M. Tech. degrees in Electronics and Communication Technology from the University of Allahabad, India in the years 1999 and 2001 respectively. She has completed her Ph.D in the year 2016, from Motilal Nehru National Institute of Technology, Allahabad, India. Her doctorate thesis work is in the area of Mobile Adhoc networks and Hybrid networks. Her research interests include Mobile Ad hoc networks and Hybrid networks, Signal Processing and Fading channels. She has published several research papers in reputed Journals, Conferences and Books.