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A Compact Dual-Band Linearly Co-Polarized Antenna Array System for In-Band Full-Duplex (IBFD) Applications

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ABSTRACT

This paper presents a compact, linearly co-polarized in-band full-duplex (IBFD) antenna system for dual-band applications. The antenna system comprises two identical and closely spaced two-element arrays of quarter-wavelength shorted microstrip patch antennas (MPAs). A C-shaped slot is precisely etched near the shorted edge of each individual Microstrip Patch Antenna (MPA) to facilitate dual-band characteristics. At 2.4 GHz, the MPAs operate in the $TM_{1/2,0}$ mode, with efficient radiation characteristics. At 3.5 GHz, these antennas switch to the $TM_{1/2,2}$ mode, to maintain optimal performance and reliability in a second operational band. The $|S_{11}| \leq -10$ dB bandwidth for each MPA is 2.5 % at 2.4 GHz and 2 % at 3.5 GHz, with inter-port isolations exceeding 20 dB and 45 dB at 2.4 GHz and 3.5 GHz, respectively. Additionally, the antenna arrays achieve a broadside gain of 8.3 dBi at 2.4 GHz and 9.4 dBi at 3.5 GHz.

Keywords: Co-polarized antenna array; High inter-port isolation; In-band full-duplex (IBFD); Microstrip patch antenna

1. INTRODUCTION

As the development of 5G technology advances beyond traditional mobile broadband, it presents exciting opportunities across various specialized applications. These applications include industrial uses, enterprise solutions, extended reality, vehicle-to-everything (V2X) communications, the metaverse, and high-speed fixed wireless access, all of which require high data rates and low latency for optimal performance. One effective method to enhance the utilization of the available spectrum is the implementation of In-band Full-Duplex (IBFD) systems[1,2,3]. IBFD systems allow for the simultaneous transmission (Tx) and reception (Rx) of signals on the same carrier frequency, effectively doubling spectral efficiency compared to conventional half-duplex systems. However, while the ability for concurrent transmission and reception represents a significant advancement, it also brings notable challenges. Interference between the Tx and Rx terminals is a major concern that must be carefully addressed. A strong transmitted signal can disrupt a weaker received signal, complicating the accurate detection of the intended incoming signal. To overcome this challenge, it is essential to focus on strategies that effectively suppress strong interfering signals, ensuring the reliable operation of the IBFD antenna system.

Bui[4], *et al.* described a dual-polarized In-Band Full Duplex (IBFD) transceiver antenna system that incorporates a slot-patch antenna designed for dual-band applications, operating at 2.4 GHz and 5.2 GHz. Similarly, Kumari et al. presented an alternative dual-polarized IBFD transceiver antenna system using a monopole antenna[5]. Researchers[6] showcased another dual-polarized IBFD transceiver antenna system that utilizes printed dipoles, offering a wide beamwidth suitable for dual-band applications. These antenna systems primarily employ orthogonal feeding techniques and diverse antenna orientations to achieve high isolation, a fundamental requirement for IBFD transceiver systems[7,8]. However, despite these advancements, all the systems are dual-polarized, have limited gain, and do not adequately meet the requirements of the rapidly evolving 5G linearly co-polarized IBFD communication systems. Therefore, designing a compact linearly co-polarized IBFD antenna system with high gain remains a significant challenge.

This paper presents the design and development of a dual-band linearly co-polarized antenna system for In-Band Full Duplex (IBFD) applications. The antenna system operates within the frequency bands of 2.4 GHz and 3.5 GHz, utilizing the $TM_{1/2,0}$ and $TM_{1/2,2}$ modes of the microstrip patch antenna for dual-band functionality. The system consists of two closely spaced identical two-element arrays of quarter-wavelength shorted modified microstrip patch antennas (m-MPAs). A series of metallic vias is employed to short one of the radiating edges of the m-MPA, which functions as a unit element in the IBFD antenna system. Additionally, the microstrip patch features a C-shaped slot etched near the shorted edge on its top surface, which provides capacitive loading to the $TM_{1/2,2}$ mode and effectively lowers its resonant frequency. In contrast, the resonant frequency of the $TM_{1/2,0}$ mode remains unchanged. To

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enhance gain, a two-element array is designed using m-MPAs. Finally, to achieve the IBFD antenna system, two m-MPA arrays are positioned side by side, ensuring high isolation between them. This isolation is achieved due to the confinement of the electromagnetic field within each individual m-MPA. The resulting low-profile, compact IBFD antenna system shows great potential for wireless communication applications utilizing the 2.4 GHz and 3.5 GHz frequency bands.

2. DESIGN CONFIGURATION

The proposed IBFD antenna system is illustrated in Fig. 1. It is designed on an FR-4 substrate with a height of 0.8 mm, a relative permittivity (ε_r) of 4.3, and a loss tangent (tan δ) of 0.025. The substrate dimensions are $L_a \times W_a$ (120 mm × 64 mm). The antenna system consists of two identical two-element antenna arrays placed face-to-face, with one array functioning as the transmitter (Tx) array and the other as the receiver (Rx) array, while the roles can be interchangeable.

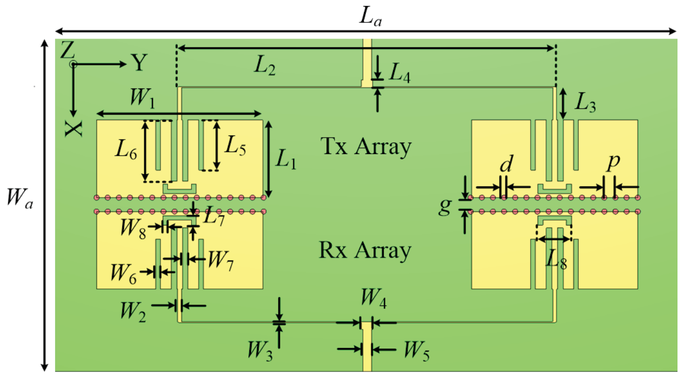


Figure 1. Top view of the proposed IBFD antenna array system.

Table 1. Dimensions of the proposed IBFD antenna system

Parameter	Value (mm)	Parameter	Value (mm)
L_a, W_a	120, 64	d, p, g	1, 2.14, 1.5
L_1, L_2	14.91, 72.85	W_1, W_2	31.92, 0.77
L_3, L_4	6.2, 1.3	W_3, W_4	0.2, 2.17
L_5, L_6	9.61, 11.75	W_5, W_6	1.67, 0.89
L_7, L_8	1.79, 6.41	W_7, W_8	1.07, 0.94

The adjacent radiating edges of the microstrip patch antennas (m-MPAs) are shorted using an array of metallic vias with a diameter of *d*, and the separation between the vias is *p*. The ratio of *d* to *p* is approximately 0.48, which helps confine the electromagnetic fields within the MPAs. An edge-to-edge distance, g, separates the patches. The width (W_1) and length (L_1) of the m-MPA are specifically chosen to ensure that the antenna operates in the $TM_{1/2,0}$ mode at a frequency of 2.4 GHz. A C-shaped slot is engraved in the MPAs to generate electromagnetic radiation at 3.5 GHz. This slot is located approximately 1 mm from the shorted edges of the m-MPAs and provides capacitive loading, effectively shifting the resonating frequency of the $TM_{1/2,2}$ mode from 5.2 GHz to 3.5 GHz. Open-ended slots have been introduced near the microstrip feedlines to improve impedance matching at both operating frequencies. All simulations for this design were conducted using CST Microwave Studio.

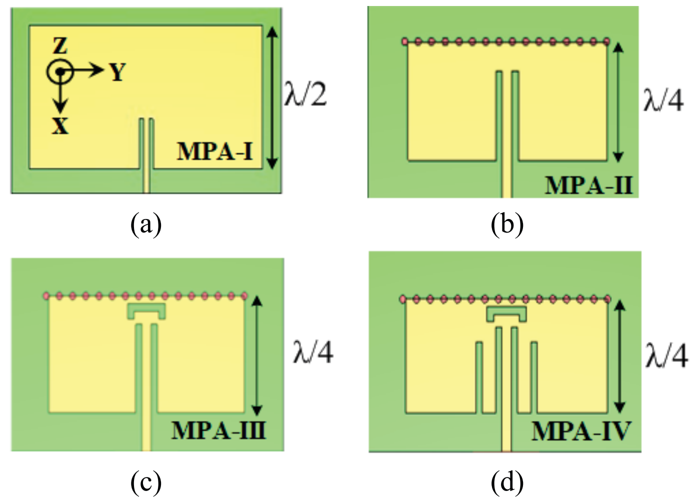


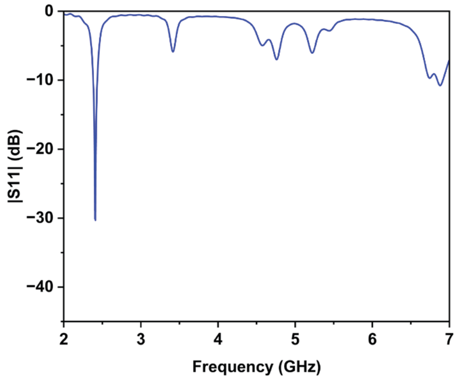
Figure 2. Evolution stages of the unit element of the proposed IBFD antenna system i.e., m-MPA (a) MPA-I, (b) MPA-II, (c) MPA-III, and (d) MPA-IV.

2.1 Unit Element Evolution

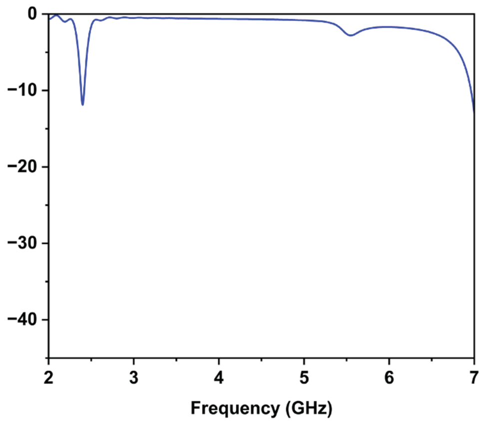
Figure 2 illustrates the evolution stages of the m-MPA unit element, along with their corresponding simulated S-parameters. Initially, a rectangular microstrip patch antenna (MPA-I) is designed to operate at 2.4 GHz, as shown in Fig. 2(a). This MPA-I utilizes the $TM_{1,0}$ mode to operate at 2.4 GHz. Higher-order modes, such as $TM_{0,2}$, $TM_{2,2}$, $TM_{1,2}$, and $TM_{3,0}$ may also be excited, as depicted in Fig. 3(a). An array of grounded metallic vias is introduced at the null location of the electric field for the MPA-I operating in the $TM_{1,0}$ mode, and half of the patch is removed to enable the MPA to function in the $TM_{1/2,0}$ mode, resulting in MPA-II. The MPA-II operates at 2.4 GHz in the $TM_{1/2,0}$ mode, with the subsequent higher-order mode being $TM_{1/2,2}$ at 5.2 GHz. In this configuration, the structure does not support additional higher-order modes such as $TM_{0,2}$, $TM_{2,2}$, $TM_{1,2}$, and $TM_{3,0}$. Afterward, a C-shaped slot is introduced at the null location of the E-field of the TM1/2,0 mode to create the MPA-III structure (see Fig. 2(c)). This C-slot does not affect the TM1/2,0 mode; however, it provides capacitive loading to the TM1/2,2 mode. As a result, the operating frequency shifts from 5.2 GHz to 3.5 GHz, which is evident from the S-parameter of MPA-III (refer to Fig. 3(c)). The figure shows that MPA-III does not achieve adequate impedance matching at 2.4 GHz and 3.5 GHz. To improve the impedance matching at both operating frequencies, two identical slots are etched along the length of MPA-III, resulting in the modified microstrip patch antenna designated as MPA-IV (see Fig. 2(d)). This m-MPA serves as the unit element for the design of co-polarized IBFD systems. The S-para meter for the m-MPA is plotted in Fig. 3(d), demonstrating that the m-MPA antenna operates effectively at 2.4 GHz and 3.5 GHz.

2.2 Proposed IBFD Antenna System

The gain of the m-MPA decreases when the size of the radiator is reduced by half. To improve the gain, a two-element array of the m-MPA is designed. The two m-MPAs



(a)



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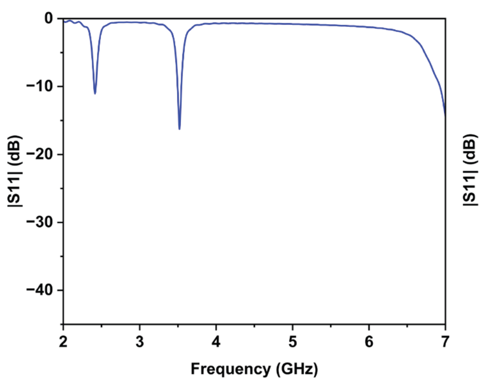

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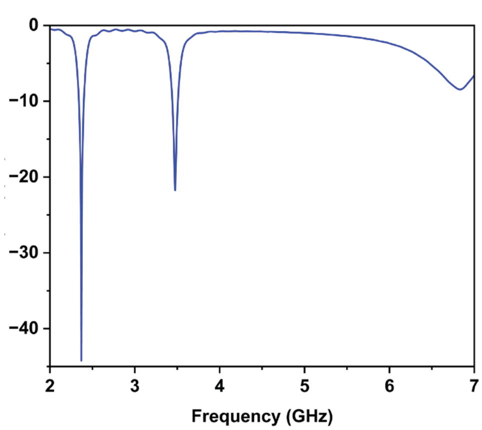
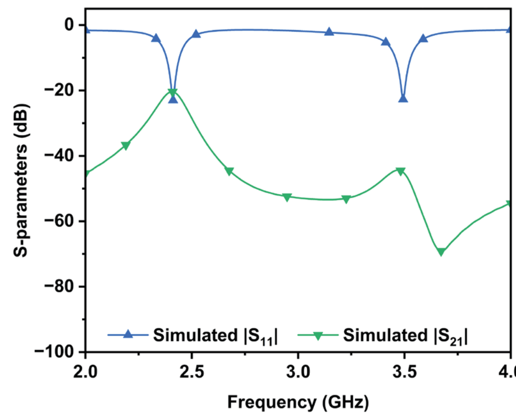


(d)

Figure 3. S-parameters of different stages of unit element shown in Fig. 2 (a) MPA-I, (b) MPA-II, (c) MPA-III, and (d) MPA-IV.

are initially positioned 14.9 mm apart, and a T-junction power divider is created to feed both elements. In this design, a 50-Ω transmission line is divided into two symmetric feed lines using a quarter-wave transformer, with each arm feeding one element of the antenna array. Two two-element m-MPA antenna arrays are placed side by side to design the IBFD antenna systems, as shown in Fig. 1. Due to the strategic placement of these two-element m-MPA antenna arrays, the electromagnetic fields of each array are contained within themselves, resulting in high port-to-port isolation. The designed antennas operate within two frequency bands: 2.4 GHz (with a bandwidth of 60 MHz) and 3.5 GHz (with a bandwidth of 70 MHz), as illustrated in Fig. 4 (a). The inter-port isolation exceeds 20 dB in the first operating band and 45 dB in the second operating band. Additionally, this isolation can be further enhanced by increasing the separation between the m-MPAs. The $|S_{21}|$ parameter for the proposed IBFD transceiver's antenna system, with varying values of *g* (gap between the m-MPAs) is depicted in Fig. 4 (b). As the *g* value increases, the inter-port isolation also increases; however, this improvement comes at the expense of a larger footprint for the IBFD antenna system. Fig. 5 and Fig. 6 shows the simulated 3-D gain of the proposed IBFD antenna system under Tx port excitation at 2.4 GHz and 3.5 GHz respectively. At 2.4 GHz the antenna array attains a peak gain of 8.2 dBi, while at 3.5 GHz, a gain of 10.8 dBi is realized.



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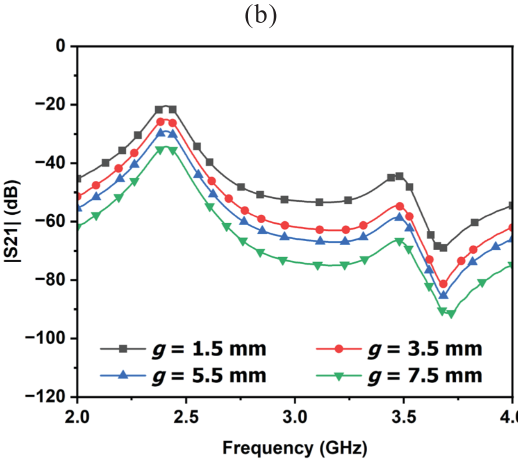


(b)

Figure 4. (a) Simulated S-parameters of the designed dual band IBFD antenna array system, (b) $|S_{21}|$ of the proposed IBFD antenna system for different values of design parameter gap *g*.

3. RESULTS AND DISCUSSION

A prototype of the designed antenna system is developed to validate the design methodology of the proposed IBFD antenna system. An (Agilent N5247A PNA-X) Vector Network Analyzer (VNA) is used to measure the S-parameters. Figure 7 presents a photograph of the fabricated prototype.

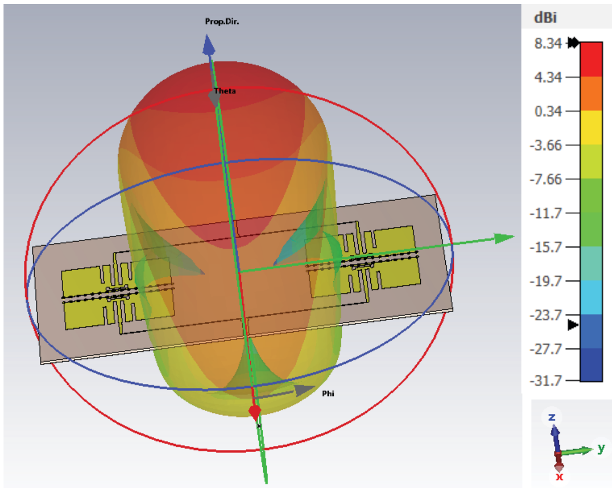


Figure 5. 3-D gain of the proposed IBFD antenna system under Tx port excitation, while the Rx port is terminated with 50 Ω matched load at 2.4 GHz.

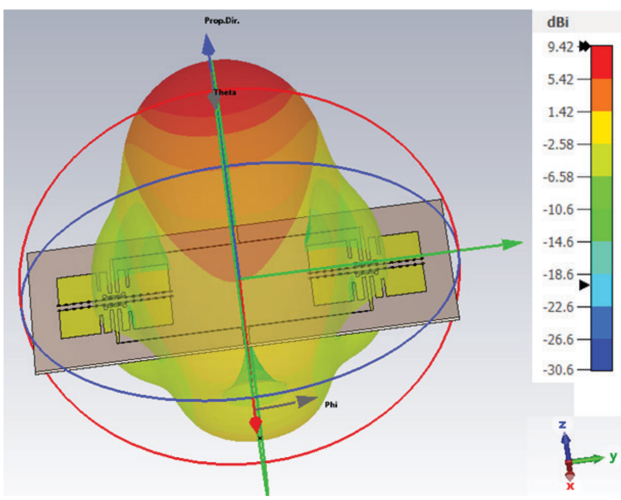


Figure 6. 3-D gain of the proposed IBFD antenna system under Tx port excitation, while the Rx port is terminated with 50 Ω matched load at 3.5 GHz.

The measured S-parameters are depicted in Fig. 8, demonstrating a close correlation between the measured and simulated results. The first operating band of the designed antenna encompasses a frequency range from 2.27 GHz to 2.33 GHz, with a bandwidth of 60 MHz and an isolation level of 20 dB. The second operating band ranges from 3.24 GHz to 3.32 GHz, exhibiting a bandwidth of 80 MHz and an isolation level of 45 dB. Notably, some discrepancies are observed between the simulated and measured results as seen from Fig. 8, which may arise from factors such as fabrication tolerances, connector losses, soldering practices, and variations in the measurement environment.

Furthermore, the 2-D far-field radiation pattern of the proposed IBFD antenna system under Tx port excitation at 2.4 GHz and 3.5 GHz is presented in Fig. 9 and Fig. 10 respectively. Given that both unit elements yield nearly identical radiation patterns, this document focuses solely on the radiation pattern achieved during Tx port excitation. It is evident from the Fig. 9 and Fig. 10 that the cross-polarization (x-pol) level at both operating frequencies is below -40 dB with respect to the co-polarization (co-pol) level, indicating that the x-pol levels are exceptionally low in the broadside direction.

A comparison of the proposed antenna system for the IBFD transceiver with other documented works is provided in Table 2. Our antenna system's performance is comparable to, or superior to, that of previously reported systems. To the best of our knowledge, this study represents the first documentation in the literature of a dual-band, linearly co-polarized IBFD antenna array system.

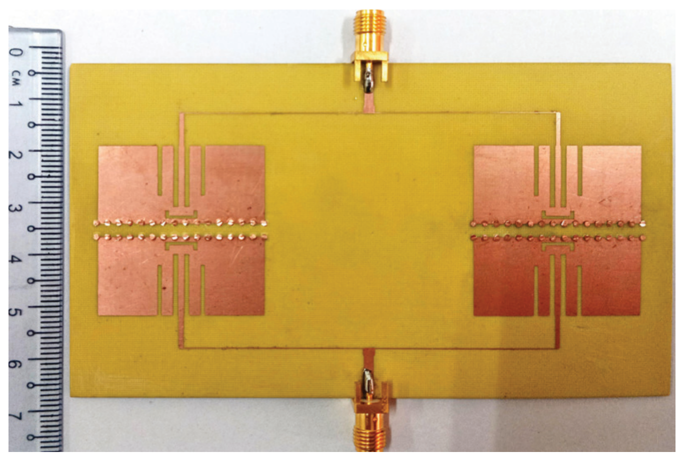
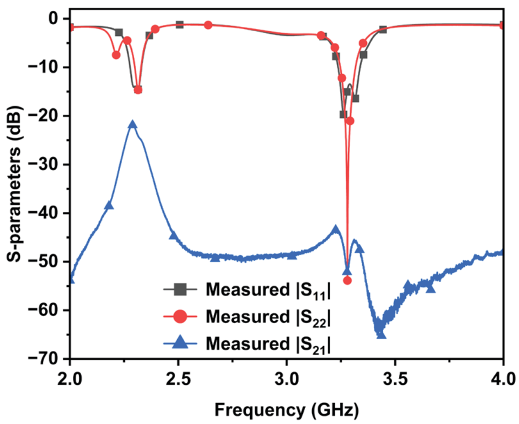


Figure 7. Fabricated prototype of the proposed IBFD antenna array system.

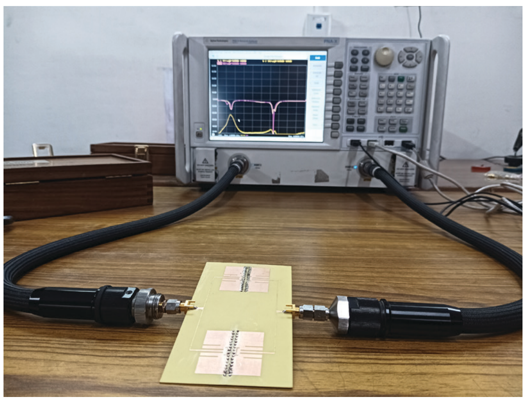
Table 2. Comparative analysis with other documented IBFD antenna systems

References	5	4	6	**This work**
Overall size (λ_L)	0.0045	0.1681	0.0486	0.003
Radiating element	03 multi-branch monopole	02 printed dipoles	Single slotted patch	Double slotted patches
Operating band (GHz)	2.35–2.5 / 5.15– 5.35	2.35–2.53 / 5.64–6.02	2.4–2.52 / 5.09–5.41	2.37–2.43 / 3.46–3.53
Iso. (dB)	40 / 40	50 / 43	44 / 41	20 / 45
Gain (dBi)	2.8 / 6.3	6.2 / 4.6	8.5/ 9.2	8.3 / 9.4
Polarization	Dual-polarized	Dual-polarized	Dual-polarized	Co-polarized

Note: λ_L is the free space wavelength corresponding to the lower frequency



(a)



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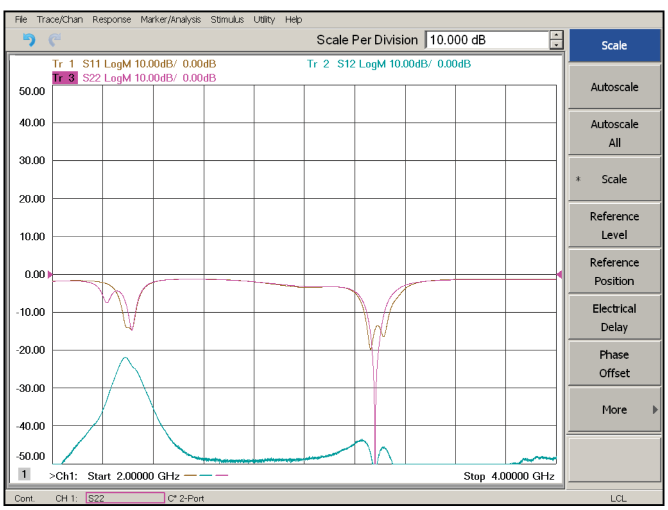
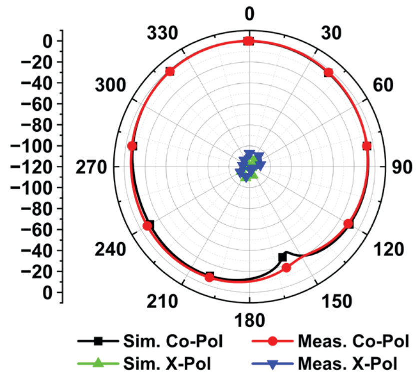


(c)

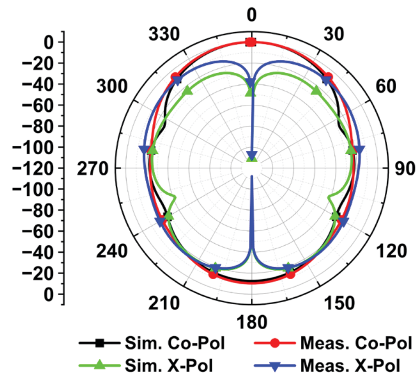
Figure 8. (a) Measured S-parameters of the designed dual band IBFD antenna array system, (b) Measurement of prototype using VNA (c) Snap of VNA screen.

4. CONCLUSIONS

This paper introduces a cutting-edge, compact, linearly co-polarized in-band full-duplex (IBFD) antenna system engineered explicitly for dual-band applications. The system comprises two identical and closely spaced two-element arrays of quarter-wavelength shorted microstrip patch antennas (MPAs). To achieve dual-band characteristics, a precisely crafted C-shaped slot is etched near the shorted edge of each MPA. At 2.4 GHz, the MPAs operate in the $TM_{1/2,0}$ mode, delivering outstanding radiation characteristics. At 3.5 GHz,

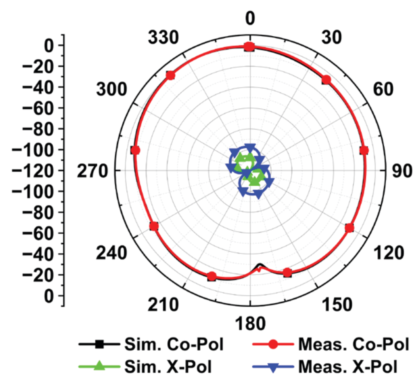


(a)

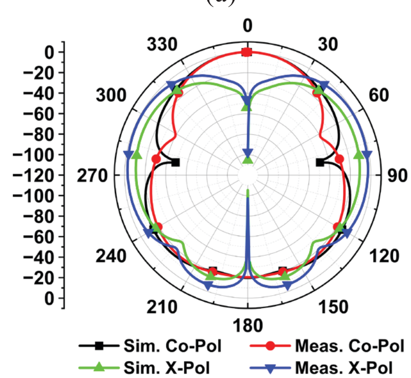


(b)

Figure 9. Far-field radiation pattern of the proposed IBFD antenna under Tx port excitation, while the Rx port is terminated with 50 Ω matched load at 2.4 GHz in (a) xoz-plane (b) yoz-plane.



(a)



(b)

Figure 10. Far-field radiation pattern of the proposed IBFD antenna under Tx port excitation, while the Rx port is terminated with 50 Ω matched load at 3.5 GHz in (a) xoz-plane (b) yoz-plane.

these antennas transition to the $TM_{1/2,2}$ mode, ensures optimal performance and reliability in the second operational band. The $|S_{11}| \leq$ -10 dB bandwidth for each MPA is 3.33% at 2.4 GHz and 2% at 3.5 GHz, with inter-port isolations surpassing 20 dB at 2.4 GHz and 40 dB at 3.5 GHz. Furthermore, the antenna arrays achieve broadside gains of 8.2 dBi at 2.4 GHz and 9.8 dBi at 3.5 GHz while maintaining isolations well above 20 dB across both operating bands. This innovative, low-profile, compact IBFD transceiver antenna system can be a leading solution for wireless communication systems operating within the 2.4 GHz and 3.5 GHz frequency bands.

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He has contributed as conceptualization and manuscript-editing.