International Journal of Microwave and Wireless Technologies

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Research Paper

Cite this article: Nawaz H, Niazi AU (2022). Stacked patch antenna with wider impedance bandwidth and high interport isolation for 2.4 GHz IBFD transceiver. *International Journal of Microwave and Wireless Technologies* **14**, 590–594. https://doi.org/10.1017/S1759078721000660

Received: 3 November 2020
Revised: 8 April 2021
Accepted: 8 April 2021
First published online: 3 May 2021

Keywords:
Parasitic feeding; differential excitation; in-band full duplex; single antenna; high isolation; self-interference cancellation; dual polarization

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Stacked patch antenna with wider impedance bandwidth and high interport isolation for 2.4 GHz IBFD transceiver

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Abstract

This paper reports a bi-port, wideband, parasitic-fed, single/shared patch antenna with enhanced interport isolation for 2.4 GHz in-band full duplex (IBFD) applications. The employed parasitic feeding provides comparatively the wider impedance bandwidth and better gain for the presented antenna. The improved self-interference cancellation (SIC) levels across the required bandwidth are obtained through differentially-driven receive (R_x) mode operation. The differential R_x operation performs effective cancellation of in-band self-interference (SI) through signal inversion mechanism to achieve the additional isolation on the top of the intrinsic isolation of polarization diversity. The validation model for the presented antenna features ≥88 dB peak isolation between the dual-polarized T_x and R_x ports. In addition, the measured T_x–R_x isolation for prototype is >70 dB across the 10 dB return loss bandwidth of 100 MHz (2.42–2.52 GHz). The measured gain for each mode is better than 7.0 dBi. The novelty of this work is that compared to previously reported designs, the presented antenna offers wider impedance bandwidth and improved SIC levels in addition to superior gain performance. To the best of our knowledge, this is the first single/shared patch antenna which provides better than 70 dB interport isolation across the 10 dB return loss bandwidth of 100 MHz along with 7.0 dBi gain for T_x/R_x modes.

Introduction

The in-band full duplex (IBFD) transceiver integrated with the single or shared antenna for both transmit and receive operations, has the potential of doubling the spectral efficiency (bps/Hz) theoretically through the simultaneous transmit (T_x) and receive (R_x) operations across the overlapping bandwidth or range of frequencies [1, 2]. However, the strong coupling from the local transmitter to its own receiver which is termed as self-interference (SI) is a major impediment to the successful realization of such full-duplex operation [1, 2]. Practically, the resulting improvements in system capacity in terms of spectral efficiency or throughput are primarily dependent on the achieved SI cancellation (SIC) or isolation levels [2]. In fact, an effective SIC operation at local receiver enables it to retrieve very weak (low power) intended R_x signal [2, 3].

In order to achieve the intended isolation levels between T_x and R_x chains of transceiver, excessive SIC levels are required [2,3]. These levels are directly related to the radiated power, bandwidth and the noise figure of the receiver [4]. Such high isolation levels can be obtained through SIC techniques deployed at the receiver's front-end in conjunction with the analog and digital domain SIC topologies [1–4]. However, comparative to the other SIC stages, high SIC levels should be performed at the transceivers front-end to safeguard the dynamic range of the analog to digital converter (ADC) for the signal of interest (SOI) and alleviate the SIC requirements on the other SI suppression stages and topologies [4]. Thus, an antenna with high interport isolation has a key role to achieve intended isolation levels for the required bandwidth [4]. However, achieving the wider impedance and isolation or SIC bandwidths is a very challenging task for such single-element based IBFD antennas [5–7].

At the transceiver's front end, the T_x and R_x signals can be isolated through dual polarization where polarization diversity provides moderate levels of interport isolation through transmitting and receiving radio signals with orthogonal polarization from same antenna element [8]. For example, the radio signals can be transmitted and received with vertical and horizontal polarizations, respectively. The intrinsic isolation characteristics of orthogonal modes will also decouple the both signals in the propagation domain [8]. However, the polarization diversity isolation alone is not enough to realize full-duplex transmission through printed antenna systems. So various SIC techniques are used to achieve additional isolation on the top of polarization isolation for the case of single-patch antenna-based IBFD transceiver. For instance, the addition isolation can be achieved through SIC techniques based on differential feeding

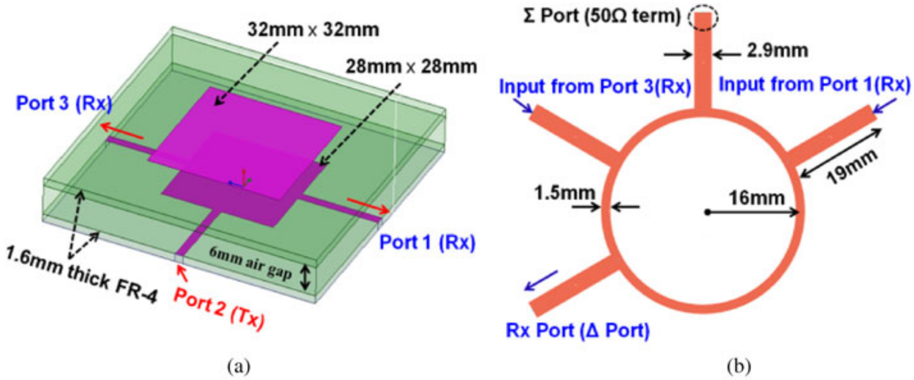

Fig. 1. The layouts of proposed dual polarized, patch antenna (a) three-port parasitic-fed stacked antenna and (b) 2.4 GHz ring hybrid coupler.

employed at T_x or R_x ports [9–13], by using impedance mismatched terminal circuit for inherent SI suppression [14] or through double differential feeding at both ports for effective SIC [15]. The differential feeding is a near-filed SIC technique to provide very high interport isolation levels for such antennas [9–13, 15].

The achievable isolation levels through differential feeding are highly dependent on the proximity and symmetry of R_x ports with respect to T_x port(s) and response of differential circuit. For instance, the achievable interport isolation levels for the differentially-excited dual-polarized antenna reported in [16] are limited by the strong coupling between the T_x port and the pair of R_x ports. Moreover, the impedance bandwidths of T_x and R_x ports, the achievable SIC levels and SIC bandwidth are considered as the main design parameters for differential-fed patch antennas. The achievable SIC levels and the SIC bandwidths are dependent on the performance of employed differential-feeding network while the impedance bandwidth is related to design topology of the patch. The patch antenna provides very narrow impedance bandwidth due to its inherent resonating nature. However, the stacked patch antenna with parasitic feeding provides comparatively wider impedance bandwidth. The dual polarization can provide initial interport isolation levels over the entire impedance bandwidths of T_x and R_x ports and differential feeding through well-balanced differential circuit can provide improved isolation through effective SIC operation.

This paper presents a dual port, stacked patch antenna with parasitic feeding for wider impedance bandwidth and excellent port-to-port isolation through differential receive (R_x) mode operation for 2.4 GHz IBFDtransceiver. The inherent isolation of cross-polarization is superimposed by additional isolation achieved through the differential R_x mode operation. Consequently, very high interport isolation levels are obtained across the concerned impedance bandwidth for both T_x and R_x ports of antenna.

The rest of the paper is organized as follows: "Differentially-driven parasitic-fed stacked patch antenna" section describes the differentially-driven R_x mode-based SIC operation for three ports, stacked patch antenna which employs the parasitic feeding for improved impedance bandwidth. The design details of 3 dB/180^o ring hybrid coupler (SIC circuit) are also presented in this section. The prototype of antenna and SIC circuits are presented in "Experimental results for antenna interfaced with ring hybrid coupler" section. The measured and simulated reflection coefficients, interport isolation, co-polarization and cross-polarization results for three-port antenna interfaced with SIC circuit are also given in "Experimental results for antenna interfaced with ring hybrid coupler" section. "Conclusion" section concludes the paper.

Differentially-driven parasitic-fed stacked patch antenna

The layouts and optimized dimensions of the three-port parasitic-fed antenna are shown in Fig. 1. The presented antenna is composed of a parasitic radiating patch (32 mm × 32 mm) which is excited by a three-port driven patch (28 mm × 28 mm). The driven patch is composed of a T_x and two R_x ports. The ground-plane on the back of driven patch is used to obtain the unidirectional radiation patterns for both T_x and R_x modes. Both patches are placed on 1.6 mm thick FR-4 substrate with $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$ and two substrate layers are separated by a 6 mm thick air gap. Each port feeds the driven patch through corresponding feed-lines to excite the parasitic patch electromagnetically. The feeding lines are placed at center of respective edges of driven patch to obtain optimum interport isolation between each pair of dual-polarized ports for desired resonance frequency [5]. The symmetry of three-port antenna results in the same levels of leakage or SI from T_x to each of R_x ports. The differentially-driven R_x mode can be excited by a 3 dB ring hybrid coupler connected to R_x ports of antenna with its difference (Δ) port as an output R_x port. The employed coupler is also designed on 1.6 mm thick FR-4 dielectric with $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$. It is important to mention here that the FR-4 substrate was duly characterized through free-space measurement method [17] in order to measure its dielectric constant and loss tangent values. Based on such measurements, the values of $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$ were used for simulations of proposed antenna in order to avoid the deviations of measured results from the simulations.

The dual-polarized characteristics of the proposed stacked patch antenna are obvious from Fig. 2 as illustrated through simulated surface currents distributions and 3D gain patterns for T_x and differentially-excited R_x modes. The excitation of port 2 generates y-directed polarization for T_x mode and differentially-excited R_x mode is polarized along with the x-axis. These simulation results have been obtained through full-wave simulations by using frequency-domain electromagnetic HFSS solver. The simulated gain patterns are based on spherical theta (θ) and phi (Φ) co-ordinates for variations of theta (θ)-dimensions having fixed values of $\Phi = 90^o$ and $\Phi = 0^o$ for T_x and differentially-excited R_x modes, respectively. Moreover, due to the unidirectional radiation characteristics of presented antenna, the theta (θ)-variations of -90^o to 90^o (upper hemisphere) are recorded only for gain patterns of intended T_x and R_x polarizations as clear from simulation results in Fig. 2.

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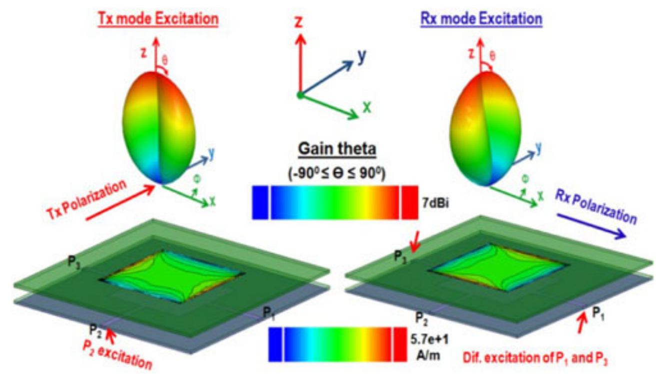

Fig. 2. The simulated surface current distributions and 3D gain patterns (θ-direction) for T_x mode and differentially-driven R_x mode at f = 2.46 GHz.

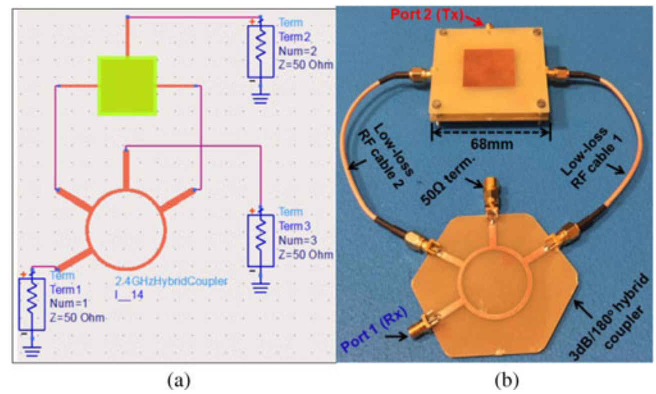

Fig. 4. Keysight ADS simulation schematic and validation model (prototype) of presented antenna for simulated and measured results.

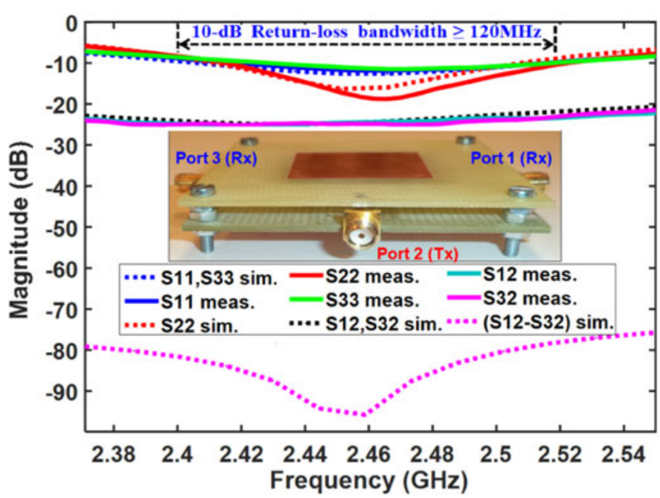

Fig. 3. The simulated and measured S_{11}, S_{22}, S_{33}, and interport coupling (S_{12}, S_{32}), (S_{12}–S_{32}) results for three-port parasitic-fed stacked patch antenna.

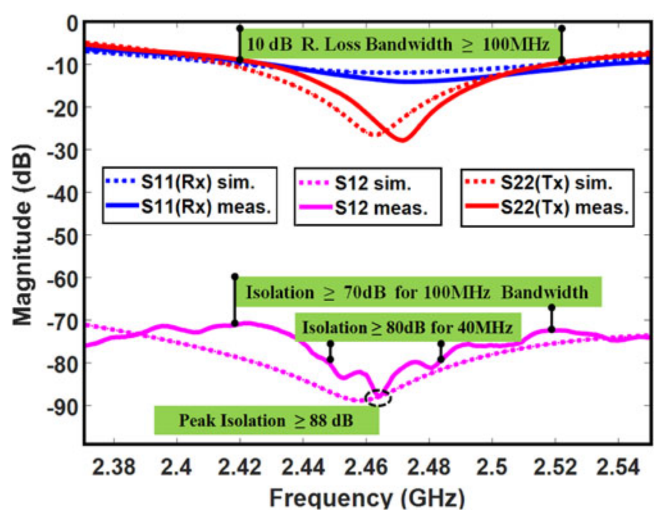

Fig. 5. The simulated and measured S-parameters results (S_{11}, S_{22}, and S_{12}) for dual polarized, parasitic-fed stacked IBFD patch antenna.

The simulated and measured S-parameters for the implemented prototype of three-port parasitic-fed antenna are given in Fig. 3. The measured 10 dB return-loss bandwidth for each port ≥120 MHz as clearly marked in Fig. 3. The cross-polarization features ~ 24 dB interport isolation across the 100 MHz bandwidth for each pair of dual-polarized T_x–R_x ports. The differentially-driven R_x mode through ports 1 and 3 of stacked patch can provide effective SIC operation (S_{12}–S_{32}) based on interport currents decoupling ratio (I_{Tx} and I_{Rx} are currents for T_x and R_x ports, respectively):

$$\frac{I_{Tx}}{I_{Rx}} = \frac{\sqrt{2}}{(S_{12} - S_{32})} \tag{1}$$

As obvious from (1), the achievable SIC levels are defined by polarization diversity decoupling (S_{12} and S_{32}) and characteristics of the employed differential circuit. For instance, an ideal differential circuit can offer ≥55 dB SIC levels on the top of initial isolation to achieve ~ 80 dB isolation between T_x and differentially-driven R_x port of patch antenna. However, the achieved SIC levels will be degraded when the practical differential circuit is used for differential excitation of R_x mode due to its non-ideal characteristics [7].

Experimental results for antenna interfaced with ring hybrid coupler

For experimental characterization, the implemented validation model or prototype for the three-port parasitic-fed stacked antenna was interfaced with the prototype of 3 dB/180° ring hybrid coupler (differential circuit) in order to record measurement results. The interconnections are shown in Fig. 4b with designated T_x and R_x ports. The simulation results for comparison purpose were obtained through Keysight advance Design System (ADS) schematic for co-simulation of SIC circuit and three-port antenna as shown in Fig. 4a.

The simulated and measured reflection coefficients (S_{11} and S_{22}) and interport coupling results (S_{12}) for complete antenna structure (Fig. 4b) are presented in Fig. 5. These measurements were performed inside the anechoic chamber to suppress the propagation domain SI resulting from the environmental reflections. As clear from Fig. 5, the antenna prototype demonstrates 10 dB return-loss impedance of better than 100 MHz spanning over 2.42–2.52 GHz

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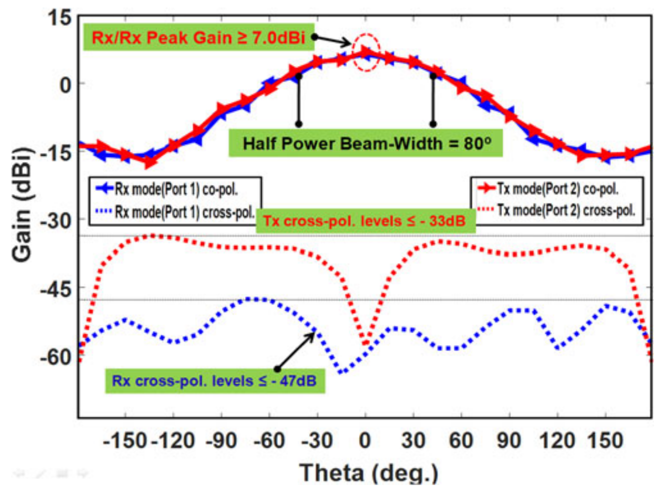

Fig. 6. The experimental co-polarization and cross-polarization *E*-plane gain patterns at 2.46 GHz for implemented parasitic-fed patch antenna.

for both T_x and R_x ports. The experimentally characterized isolation levels between dual-polarized T_x and R_x ports are higher than 70 dB over the 100 MHz bandwidth. Moreover, the measured isolation ≥ 80 dB for 40 MHz (from 2.445 to 2.485 GHz) bandwidth. In addition, the recorded peak isolation levels exceed 88 dB as indicated in Fig. 5. Consequently, the differentially-driven R_x operation contributes ≥ 45 dB isolation on top of the polarization diversity isolation.

The measured T_x and R_x modes *E*-plane gain patterns (co. and cross-polarization levels) at $f = 2.46$ GHz for presented antenna structure (Fig. 4b) are given in Fig. 6. The *E*-plane gain patterns for implemented antenna were measured in an anechoic chamber through far-field calibrated measurement setup based on 3D spherical dimensions. The implemented antenna or antenna under test (AUT) was used as receiving antenna and a standard horn antenna with known gain was used as transmitting antenna. The AUT was aligned at $\Phi = 90^o$ and $\Phi = 0^o$ and θ was varied from -90^o to 90^o to record the intercepted power through AUT for intended T_x and R_x polarizations, respectively. The gains for both polarizations were determined through comparison method to plot the results. These measurements demonstrate peak gain levels of better than 7.0 dBi for both modes. The comparative improved gain performance of presented antenna is due to employed parasitic feeding for both T_x and R_x modes. The cross-polarization levels are below −33 and −47 dB for T_x and R_x ports, respectively.

The performance comparison of presented differentially-fed stacked patch antenna with previously reported 2.4 GHz IBFD antennas is presented in Table 1. This comparison table provides the comparison of 10 dB return-loss bandwidth, peak (highest) isolation levels, isolation levels versus isolation bandwidth, and maximum T_x/R_x gain for reported dual-polarized IBFD antenna designs. As clear from Table 1, the presented antenna provides wider impedance bandwidth (100 MHz), very high peak isolation (88 dB), and improved isolation levels versus isolation bandwidth (70 dB over 100 MHz bandwidth) performance along with the superior gain performance as compared to previously reported antennas. The contributions of this work are the realization of a single-element based antenna with wider impedance bandwidth and high gains for both T_x and R_x polarizations along with the characteristics of high interport isolation over a wider bandwidth.

Conclusion

A dual polarized, stacked antenna with parasitic feeding is presented to demonstrate wider impedance bandwidth, high gain and excellent interport isolation through differential R_x operation. The presented antenna features wider impedance bandwidth, improved interport isolation characteristics and superior gain performance compared to previously reported antennas. The measured peak radiation efficiency for presented antenna was better than 75%. More compact antenna structure can be realized through placement of ring coupler (SIC circuit) on the backside of the driven patch with via-interconnections to both R_x ports. The implemented antenna can be used for 2.4 GHz transceiver to realize full-duplex operation over the 100 MHz bandwidth without additional and complex analog domain SIC topologies.

Table 1. The performance comparison of presented differential-fed stacked patch antenna with other IBFD antennas.

Ref.	Bandwidth (RL ≤10 dB), MHz	Peak isolation, dB	Isolation levels (dB)/isolation BW (MHz)	Max. gain (T_x/R_x), dBi
[4]-1	50	67	62/50	4.3
[4]-2	50	90	70/50	4.1
[5]	90	30	25/90	6.5
[6]	90	60	50/90	5.0
[7]	90	87	60/90	4.5
[10]	50	85	65/50	7.0
[12]	45	95	85/45	3.8
[15]	50	98	80/40	4.0
[16]	50	57	40/50	3.7
[18]	100	Not mentioned	47/100	5.06
[19]	200	55	30/200	Not mentioned
This work	**100**	**88**	**70/100**	**7.0**

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