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Single Layer, Dual Polarized, 2.4 GHz Patch Antenna with Very High RF Isolation between DC Isolated Tx-Rx Ports for Full Duplex Radio

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Abstract—This paper presents a single layer, dual polarized 2.4 GHz microstrip patch antenna based on monostatic radiator. Microstrip-T (MS-T) feeds have been used for DC isolated Tx-Rx ports. It deploys differential feeding for receive mode operation to achieve high interport RF isolation. The differential feeding acts as a signal inversion technique to suppress the in-band self interference (SI) for simultaneous transmit and receive (STAR) operation at same frequency. The implemented single layer, dual polarized, compact patch antenna provides better than 78 dB isolation between DC isolated Tx-Rx ports at centre frequency of 2.393 GHz. Moreover, the implemented antenna achieves better than 64 dB interport isolation for 10 dB-return loss bandwidth of 50 MHz (2.37 GHz to 2.42 GHz). The measured interport RF isolation is around 70 dB for 25 MHz bandwidth (2.385 GHz to 2.41 GHz). To the best of our knowledge, these are the highest levels of RF isolation reported for single layer, dual polarized microstrip patch antenna with DC isolated ports.

1. INTRODUCTION

IN band full duplex (IBFD) or single channel full duplex (SCFD) wireless node can substantially improve the spectral efficiency of wireless networks. This improvement results through simultaneous transmit and receive (STAR) operation at same carrier frequency [1–3]. However, in order to achieve all potential gains of IBFD wireless operation, the transceiver should suppress the self interference (SI) on receive side [2, 3]. For example, for a receiver with 50 MHz bandwidth (BW) and typical noise figure (NF) of 17 dB, the received noise power (P_n) is given as [3]:

$$P_n = -174\,\text{dBm} + 10\log(\text{BW}) + \text{NF} = -174\,\text{dBm} + 77 + 17 = -80\,\text{dBm} \tag{1}$$

As sketched in Fig. 1, the total intended amount of self interference cancellation (SIC) for such a node with 20 dBm transmit power (P_t) will be 20 dBm − (−80 dBm) = 100 dB. This will render the self interference negligible; otherwise, the residual SI will degrade the signal to noise (SNR) of transceiver [2, 3]. In addition, the nonlinear SI and transmitter noise as depicted in Fig. 1 should also be suppressed to at least noise power level (P_n) to avoid the SNR degradation [2, 4]. The required amount of SIC can be reduced by decreasing the transmit power to force the radio to operate in reduced coverage area.

Normally, the above mentioned high amount of required SIC is achieved by combination of SIC techniques deployed at antenna, analog (RF), and digital baseband stages [1–3] as shown in Fig. 1, where a large amount of SIC at antenna stage is required in order to prevent the saturation of radio receiver by strongest RF leakage or SI from its own transmitter [1–3]. Mostly, for IBFD transceiver based on shared or monostatic antenna architecture, 100 dB SIC is achieved through 30 dB SIC at each of analog (RF) and digital SIC stage. The additional 40 dB interport RF isolation is achieved with dual port,

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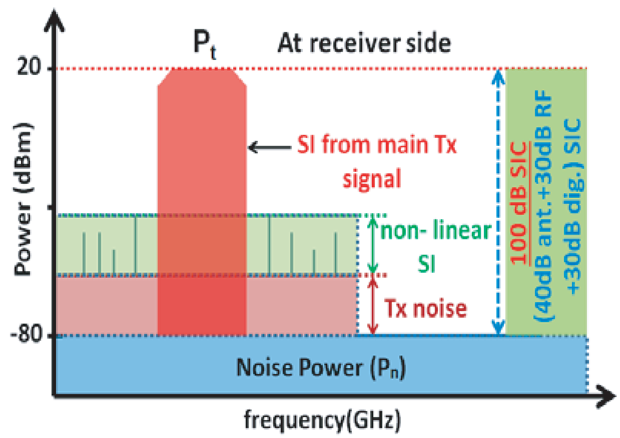

Figure 1. Various components of SI and around 100 dB self interference cancellation (SIC) across IBFD transceiver using single antenna with SIC techniques used at analog (RF) and digital baseband stages.

single antenna as shown in Fig. 1. However, if $\sim$ 70 dB SIC is achieved at antenna stage, only 30 dB SIC at digital stage is required. The 100 dB SIC for above case will realize successful STAR wireless operation at the same carrier frequency without using complex analog (RF) domain SIC techniques.

A simple dual polarized patch antenna uses two orthogonal feeds with a square radiating patch to excite horizontal and vertical polarization modes. It provides $\sim$ 35–40 dB interport isolation through polarization diversity, whereas some antennas use different feeding mechanisms with multilayered structures to obtain additional interport isolation [5]. For example, one polarization mode is excited through direct feed while the second polarization can be excited through slot coupled port. It can improve port to port isolation $\sim$ 20 dB as reported in [5]. As demonstrated in [6], an improvement of $\sim$ 20 dB interport isolation has been obtained for a dual polarized patch antenna with a defected ground structure (DGS).

A single layer antenna with two orthogonal feeds along with external circuitry is also used to cancel the RF leakage from transmit to receive port. This technique is based on the signal inversion technique to obtain $\sim$ 25 dB interport isolation improvement at centre operating frequency [7]. However, the amount of SIC obtained by such techniques is highly dependent on the accuracy of signal inversion path. Moreover, the SIC is achieved within very narrow bandwidth for the presented antenna as discussed and reported in [7].

Some dual-polarized patch antennas also utilize two different feed networks to excite two orthogonal modes of square radiating patch. Then, a balanced feed network is added to achieve high interport isolation and low cross polarization levels. But such configurations mostly use complex feeding networks with multi-layered antenna structures [8]. A two-port antenna in [9] deploys ring mono-radiator and uses extra signal path to cancel out interport RF leakage in order to achieve around 20 dB isolation in 1.85–2.62 GHz bandwidth. Previously presented antennas for active integrated antenna technology [10] and to implement retrodirective [11] or amplifying-reflect antenna arrays [12] utilize electromagnetic coupled ports for single layer implementation [5]. Some antennas have utilized multilayered structures for interport DC and high RF isolation [8]. Such antennas will avoid the requirement of additional DC blocking capacitors in RF paths. The dual-polarized antennas are also very useful in mobile applications at GSM and LTE bands to mitigate fading [13].

In this work, a single square radiating patch with three microstrip-T (MS-T) feeds for DC isolated ports is used. The patch is differentially excited through two anti-parallel MS-T feeds. A simple 180° ring hybrid coupler is used for receive (Rx) mode to suppress the RF coupling from antenna's orthogonal transmit (Tx) port. Such differential feeding mechanism provides more than 35 dB improvement for interport RF isolation between DC isolated ports. It also cancels the nonlinear SI from transmit chain. The compact antenna has been implemented by etching a three ports antenna and ring hybrid coupler on a single 1.6 mm thick FR-4 substrate. The implemented antenna with DC isolated ports provides very high interport RF isolation at centre frequency. In addition, the self interference is well suppressed within antenna's 10 dB-return loss impedance bandwidth of 50 MHz. This results from nice amplitude and phase-balance response of 180° ring hybrid coupler which acts as SIC circuit.

The rest of the paper is organized as follows. Section 2 describes the self interference suppression mechanism for a single layer, three ports antenna with MS-T feeds using differential Rx operation. The implementation details for a compact, single layer, differential antenna by using 180° ring hybrid coupler as SIC circuit are also presented. Test and measurement results for compact implemented antenna system have been presented and discussed in Section 3. Section 4 concludes the paper.

2. SINGLE LAYER, DUAL POLARIZED DIFFERENTIAL FED MICROSTRIP PATCH ANTENNA WITH MS-T FEEDS

The electromagnetic (EM) model for the proposed square patch antenna with three MS-T feeds is shown in Fig. 2, where Port 1 is for Tx mode, and Port 2 and Port 3 will be used for differential Rx operation. The optimized dimensions of antenna structure are also depicted in Fig. 2. The square patch resonates at the same Tx and Rx frequencies with orthogonal polarization when being excited through Port 1 and Port 2 using symmetrical MS-T feeds [5]. Same is the case for Port 1 and Port 3. Keysight ADS momentum is used for antenna's simulation, and simulated S-parameters results for three port antenna with MS-T feeds are shown in Fig. 3. The antenna is designed by using a 1.6 mm thick FR-4 substrate with $\varepsilon_r = 4.4$ & $\tan\delta = 0.02$. Due to symmetrical dimensions of radiating patch, equal amount of coupling results from Tx port (Port 1) to both Port 2 and Port 3 is observed as depicted in Fig. 3.

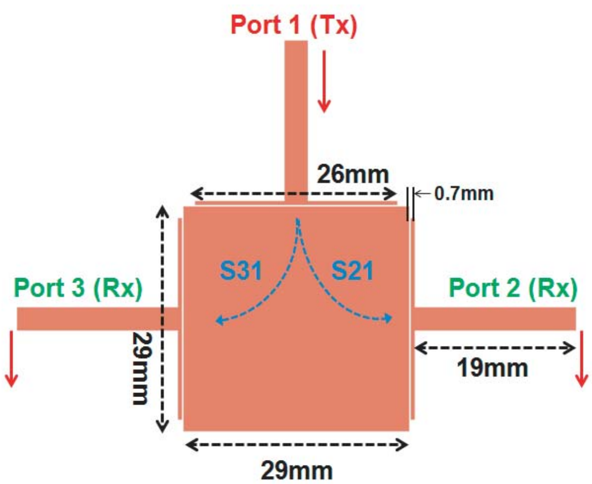

Figure 2. EM model for patch antenna with one Tx port and two Rx ports for differential receive mode using MS-T feeds for all ports.

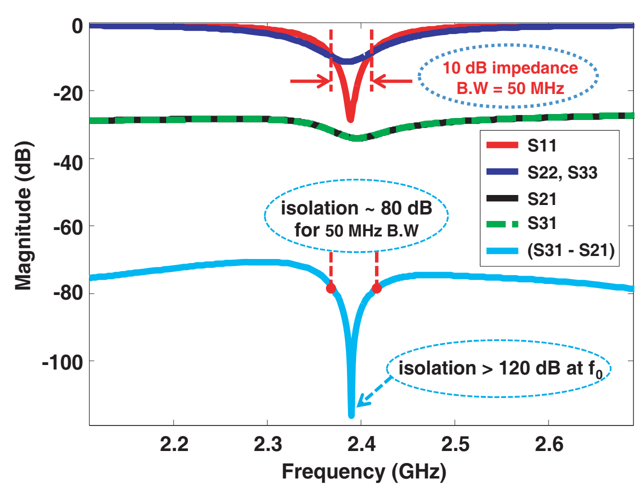

Figure 3. Simulated port matching (S_{11}, S_{22}, S_{33}) and RF interport isolation $\{(S_{21}, S_{31}), (S_{31} - S_{21})\}$ for three ports antenna shown in Fig. 2.

Both Port 2 and Port 3 are orthogonally polarized with respect to Port 1, and polarization diversity provides ~ 35 dB RF isolation (S_{21}) between Port 1 and Port 2 at centre frequency. Same is the case for Port 3 and Port 1 (S_{31}) as shown in Fig. 3. In addition, each pair of ports is DC isolated due to MS-T feeds [5]. The differential feeding of proposed square patch through Port 2 and Port 3 effectively suppresses the RF coupling at Rx port resulting from transmit port (Port 1) through ($S_{31} - S_{21}$) operation as clearly shown in Fig. 3. The differential feeding also improves the port to port RF isolation with reduced cross polarization levels by suppressing the excited higher order modes. The square patch is enabled to operate with fundamental modes [14] only in this case. The ideal differential mechanism provides > 85 dB additional interport RF isolation, and the proposed antenna structure achieves > 120 dB interport isolation at centre frequency. Moreover, there is ~ 80 dB RF isolation between Tx and Rx ports for 50 MHz bandwidth (2.37 GHz–2.42 GHz) as clearly shown in Fig. 3. Although the SIC mechanism for three ports has been explained with Port 1 designated as Tx port and Port 2 and Port 3 for differential Rx operation, Tx and Rx ports can be interchanged. This can be done without affecting the interport isolation performance of implemented patch antenna.

For differential Rx operation, a 3-dB ring hybrid coupler has been used which performs as SIC circuit when difference port (Δ port) of 180° ring hybrid coupler is used. It acts as a 3-dB power divider with a phase difference of 180° to perform ($S_{31} - S_{21}$) operation at Rx port. The detailed optimized design parameters for ring hybrid coupler are shown in Fig. 4.

As shown in Fig. 5, the compact antenna for full duplex radio is realized by inter-connecting the three ports antenna and 180° ring hybrid coupler through 50 Ω microstrip transmission lines. The compact single layer differential fed patch antenna is linearly vertically polarized when being excited from Tx port (Port 1) and linearly horizontal polarized with delta port of ring hybrid coupler used as Rx port (Port 2 in Fig. 5). This fact is illustrated through simulated surface currents shown in Fig. 5 for Tx and Rx modes, respectively. It is important to mention here that using Port 3 of the proposed antenna will also excite the horizontal polarization. However, this polarization mode will result in degradation in Rx mode performance. This degradation results from destructive interference of two current components flowing in opposite directions on antenna surface. Moreover, the effective SIC will

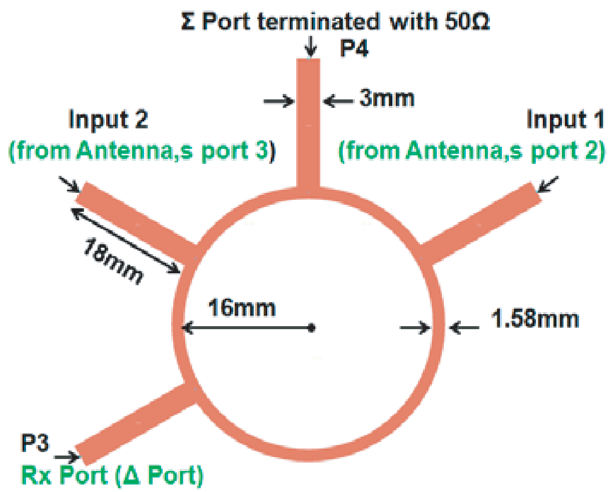

Figure 4. EM model for 180° ring hybrid coupler (designed using 1.6 mm thick FR-4 substrate with $\varepsilon_r = 4.4$ & $\tan\delta = 0.02$).

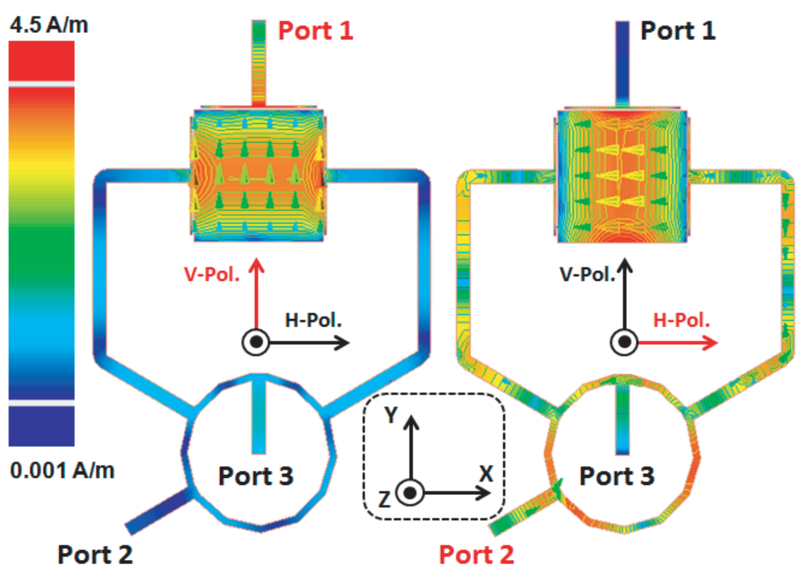

Figure 5. The ADS momentum simulated current distributions for Tx (Port 1) and Rx (Port 2) for compact single layer, differential fed patch antenna.

not be performed at Port 3 as two components of Tx power will be added at Port 3. The analytical details and analysis of differential feeding based SIC (without radiation performance degradation) are presented in [15].

3. MEASUREMENT RESULTS FOR SINGLE LAYER COMPACT DIFFERENTIAL FED PATCH ANTENNA

The implemented compact, dual port, dual polarized single layer differential patch antenna with detailed dimensions is shown in Fig. 6. The antenna is fabricated by etching the antenna and 180° coupler on single FR4 substrate ($\varepsilon_r = 4.4$, tangent loss = 0.02, and thickness (h) = 1.6 mm). As shown in Fig. 6, the Tx and Rx ports are also designated to deploy this implemented antenna for IBFD radio transceiver below and can be interchanged as discussed earlier.

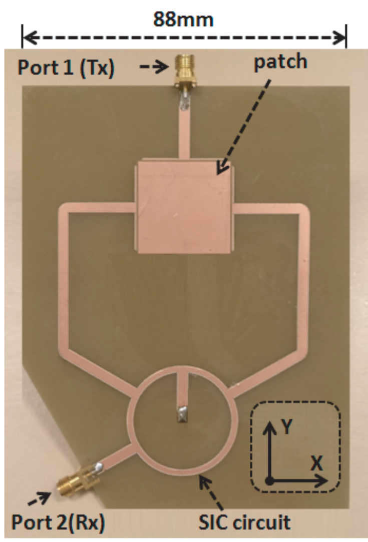

Figure 6. The implemented prototype of compact, single layer, dual port and dual polarized differential patch antenna with MS-T feeds.

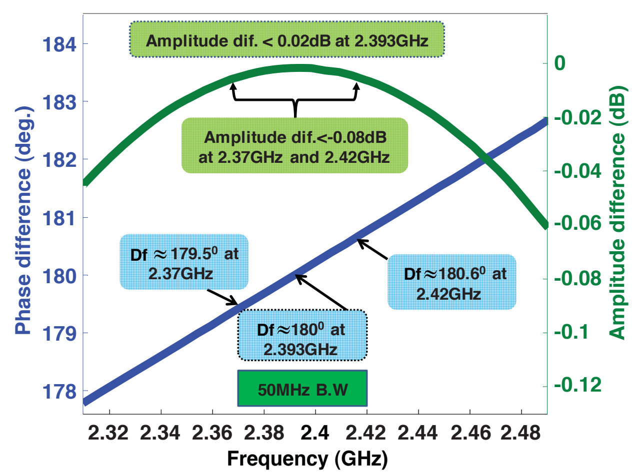

Figure 7. Magnitude & phase response of 180° ring hybrid coupler (SIC circuit).

The measured and simulated return loss (S_{11}, S_{22}) and inter-port isolation (S_{12}) results for implemented compact dual polarized differential patch antenna are shown in Fig. 8. The third port of implemented antenna (sum port of hybrid coupler) is terminated in 50 Ω load during measurement process. The measured port to port RF isolation between DC isolated ports is better than 78 dB at centre frequency of 2.392 GHz. In addition, more than 64 dB interport RF isolation is recorded within 10 dB-return loss bandwidth of 50 MHz (2.37 GHz to 2.42 GHz) as clearly indicated in Fig. 8. Moreover, as shown in Fig. 8, the implemented IBFD antenna achieves around 70 dB RF isolation for 25 MHz bandwidth (2.385 GHz to 2.41 GHz) between DC isolated Tx-Rx ports. As given in Fig. 7, the excellent amplitude and out-of-phase phase balance response of 180° ring coupler (amplitude dif. < -0.008 dB and phase dif. $< \pm 0.5$ degrees for 50 MHz) provides nice SIC in 50 MHz as clear from measured results in Fig. 8. The interport isolation ~ 40 dB is provided by the polarization diversity [5]. The differential feeding provides > 35 dB and 30 dB additional isolation at centre frequency (2.392 GHz) and for both 20 MHz and 50 MHz bandwidths, respectively. As observed in Fig. 8, there is a nice agreement between simulated and measured results for the compact patch antenna.

The measured E-plane co-polarization and cross-polarization gain patterns for the single layer, compact differential fed dual polarized patch antenna are shown in Fig. 9. As clear from Fig. 9, the implemented antenna provides ~ 4.5 dBi gain for both Tx and Rx ports. The measured cross-polarization levels for both ports are below -45 dB from respective co-polarization levels on bore-sight in

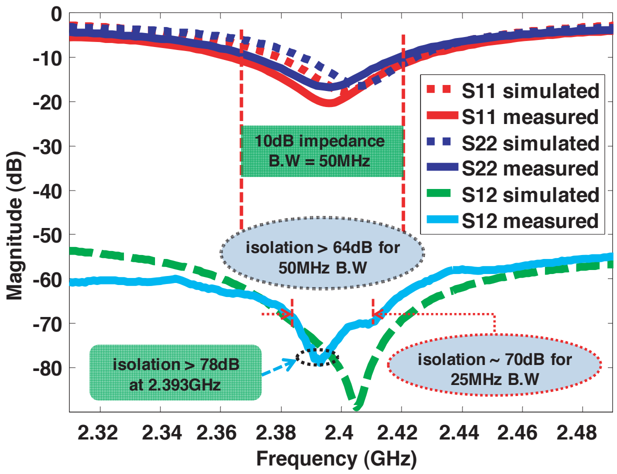

Figure 8. Simulated and measured port matching (S_{11}, S_{22}) and RF interport isolation (S_{12}) results for compact dual polarized differential antenna.

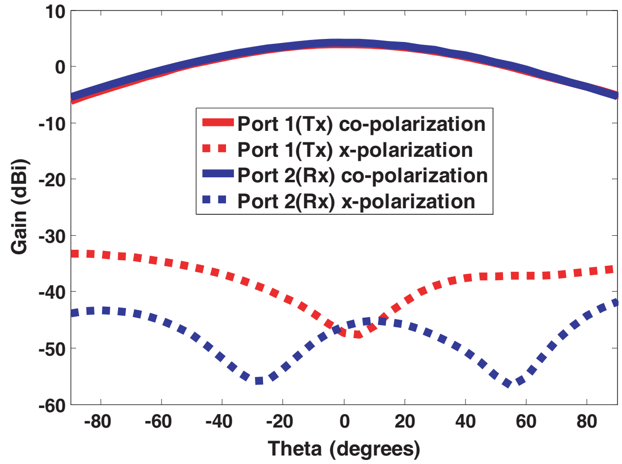

Figure 9. Measured co-polarization & cross polarization gain patterns for compact dual polarized differential patch antenna.

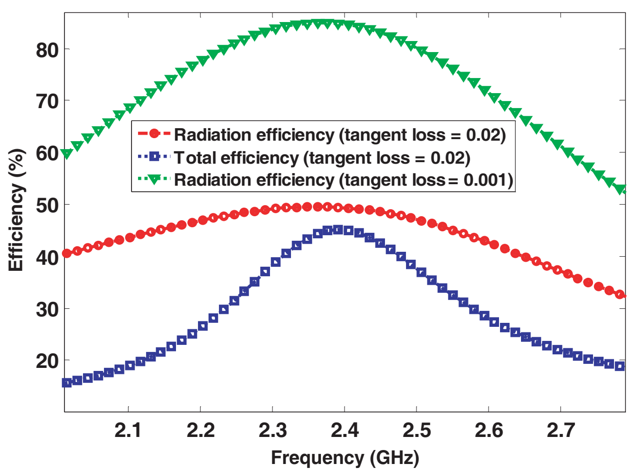

Figure 10. The simulated radiation efficiencies ($\tan\delta = 0.02$ & $\tan\delta = 0.001$) and total efficiency ($\tan\delta = 0.02$) for proposed antenna (P_2 excitation).

E-plane. Thus, implemented antenna has very nice polarization purity due to very low cross polarization levels for both transmit and receive ports.

The gain of proposed antenna can be increased significantly if a low loss substrate is used. Using low loss substrate will achieve improved radiation efficiency to enhance the gain of proposed antenna [16]. For instance, as reported in [16], the radiation efficiency will be increased from 50% to 88% when $\tan\delta = 0.001$ is used instead of $\tan\delta = 0.02$. This will result in around 3 dB improvement in antenna gain. However, low loss substrate will cause minor reduction in impedance bandwidth of proposed antenna. The proposed antenna is simulated by using $\tan\delta = 0.001$ for FR-4 substrate (dielectric constant and thickness of FR-4 were not changed). The maximum simulated radiation efficiency $\geq 85\%$ as clear from Fig. 10, whereas the 10 dB return loss impedance bandwidth of around 45 MHz is observed from simulations. These simulated results are not presented here for brevity. The total efficiency of proposed antenna (which includes both of radiation and matching efficiency) is around 45% as clear from simulated results in Fig. 10 for FR-4 with $\tan\delta = 0.02$.

As summarized in Table 1, the interport isolation performance of our implemented in this work is compared to some previously published works on dual polarized antennas. The reported antenna in [7]

Table 1. Isolation performance comparison of implemented antenna with previously published works [5, 7, 16].

Ref. Antenna	Peak isolation	10 dB R.L.B.W.	Isolation/B.W.	DC isol.
[5]	60 dB	50 MHz	55 dB/50 MHz	Yes
[7]	73.5 dB	24 MHz	40 dB/24 MHz	No
[16]-1	67 dB	50 MHz	62 dB/50 MHz	No
[16]-2	90 dB	50 MHz	70 dB/50 MHz	Yes
This work	78 dB	50 MHz	64 dB/50 MHz 70 dB/25 MHz	Yes

and antenna-1 in [16] are based on single-layered printed circuit board (PCB). These two antennas offer interport isolation performance comparable to that of our presented antenna here. However, the Tx and Rx ports are not DC isolated for both of these antennas. The third antennas reported in [5] achieves almost comparable RF interport isolation performance again, and the second antenna in [16] offers even better interport isolation performance. However, multi-layered PCB structures are deployed for these antennas which increase the implementation complexity. As compared to these published works [5, 7, 16], our proposed antenna presented in this work is based on single-layered PCB and achieves almost same interport RF isolation performance along with DC isolated Tx and Rx ports.

The implemented dual polarized antenna can be used with IBFD transceiver based on single (monostatic) antenna architecture. However, for bidirectional or two-way wireless communication, the forward and reverse links will be dual polarized to achieve propagation domain isolation. For example, as illustrated in Fig. 11, if transceiver-A uses vertical polarization for Tx mode, then transceiver-B should use vertical polarization for Rx mode in order to align polarization for intended link. Similarly, transceiver-B will use horizontal polarization for Tx operation, and transceiver-A will receive with horizontal polarization. Consequently, one link will use one polarization; the other uses the other polarization for such bidirectional or two-way wireless communication.

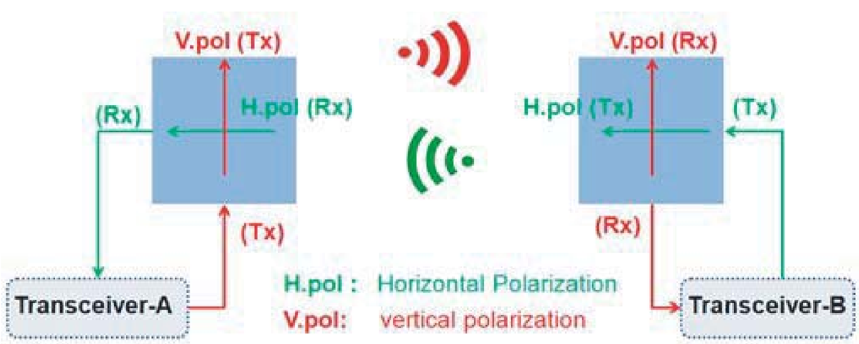

Figure 11. Illustration of an application scenario to deploy the implemented antenna for bi-directional IBFD wireless communication.

4. CONCLUSION

A dual polarized, single layer, 2.4 GHz microstrip patch antenna has been presented which uses MS-T feeds for DC interport isolation. It achieves very high interport RF and low cross polarization levels by suppressing RF leakage from Tx port and higher modes of patch by using a simple 180° hybrid coupler as SIC circuit. The implemented antenna also has the ability to suppress the in-band nonlinear SI from transmitter due to differential feeding as it effectively works as signal inversion mechanism for SIC. The implemented antenna with very high Tx-Rx isolation can effectively provide an antenna plus digital SIC solution to realize low power 2.4 GHz IBFD wireless operation by using single antenna without deploying complex analog (RF) domain SIC techniques. It can also be used for active antenna applications without using additional capacitors neither at Tx nor at Rx port of antenna.

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