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In-Band Full-Duplex Antenna Using Orthogonal U-shaped Slot Antenna

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Abstract

In this paper, a new design is proposed for the in-band full-duplex antenna for 5G communication systems. The proposed two-port in-band full-duplex antenna consists of orthogonally arranged two U-shaped slot sections which are fed by coupled microstrip lines. The microstrip-coupled coplanar waveguide (CPW) is used at both ports to excite the U-shaped stepped-slot sections in the CPW odd mode. The surface currents from the active port interact with the other port in CPW even mode and result in neutral electromagnetic coupling from the stepped slot to the microstrip line. The interport isolation is achieved by CPW odd mode excitation of the individual stepped slot and it is further improved by the orthogonal arrangement of stepped slots. The proposed antenna has a minimum of 39 dB of interport isolation over the entire operational band and a maximum of 47 dB at 3.52 GHz. The -10 dB impedance bandwidth of both ports is 370 MHz and resonates in the 5G band of (3.32-3.69) GHz. The design provides the broadside radiation pattern with cross-polar content of less than -20 dB. The gain of the antenna for port1 and port2 is 3.8 dBi and 4.5 dBi, respectively at 3.52 GHz.

1. Introduction

In recent years, the electromagnetic spectrum for wireless communication has become more crowded, making the remaining deployable bands extremely valuable. The in-band full-duplex or simultaneous transmit and receive (STAR) systems have garnered a great deal of interest as a promising method for optimizing spectrum efficiency. The in-band full-duplex system has twice the spectral efficiency of frequency-division and time-division duplex systems. Various techniques to improve the isolation between transmitting (Tx) and receiving (Rx) antennas have been studied and reported over the past few decades. In general, these designs are classified into several categories: the first one is the spatial diversity category in which the Tx and Rx apertures are physically separated by a large distance, i.e., involving bistatic antennas. This method to enhance isolation is simple but results in a large antenna dimension. The second category involves exploiting the polarization diversity [1] and pattern diversity [2] techniques to achieve high isolation by using different polarizations and radiation patterns, respectively. The third category utilizes near-field cancellation techniques [3] that isolate Tx and Rx antennas with dissimilar radiation patterns by incorporating one antenna in the near-field null of the other antenna. Apart from the mentioned techniques above, between the Tx and Rx antennas, decoupling networks such as electromagnetic bandgap (EBG) structures, resonators, and high-rejection filters [4] are added to reduce the electromagnetic coupling. In [5], an auxiliary port is connected to the Rx aperture of the bistatic antenna so that the interference from the Tx's direct coupling is cancelled at the Rx port by the indirect coupling of the auxiliary port. The reflective terminal controls the magnitude and phase of the indirect coupling signal, causing destructive interference between the direct and indirect coupling signals from the Tx and auxiliary ports, respectively. In [6], the symmetrical antennas are connected by a decoupling network comprised of directional couplers, transmission lines, and a parallel resonant circuit. By superimposing equal and opposite phase coupling signals from the decoupling network and via free space, the employed decoupling network eliminates mutual coupling at the port terminals. In [7], between the two co-linearly polarized patch antennas, the interdigital lines are connected, which are made up of parallel striplines connected to the ground plane through vias. The interdigital lines stimulated by the electric fields at the edge of the active patch (TM_{01} mode) produce orthogonal polarization (TM_{10} mode) on the adjacent patch. This orthogonal mode contributes to the improvement of port isolation. In [8], the Tx and Rx ports are separated by the RF circulator, which is connected to a single antenna via a reconfigurable impedance mismatched terminal (IMT). Due to the impedance mismatch, the reconfigurable IMT reflects the secondary interference signal from the antenna and cancels the primary interference signal from the Tx port to the Rx port via the circulator. IMF can adjust the input impedance variations and fabrication errors of the antenna. The complex antenna structure resulting from the installation of the circulator and reconfigurable IMT is a drawback of the antenna system. In [9], the fence strip resonator (FSR) consists of a metallic vias fence and a strip positioned at the centre of the microstrip antenna at a distance from the ground. This results in co-linear polarization and a symmetrical radiation pattern for the microstrip antenna. When the FSR is resonating in its half-TM_{01} mode with high isolation, the radiating current is concentrated at the centre of the patch. in [10], two shorted $TM_{1/2,0}$ mode patch antennas are co-linearly polarized and fed with gap-coupled quarter wavelength microstrip. The Tx and Rx shorted $TM_{1/2,0}$ mode patch antennas are separated by a defective ground plane, the interport isolation is improved by imparted slots with T-shaped strips, and a patch antenna is located in the weak field region of the other patch antenna due to metallic vias.

However, the above-mentioned duplex antenna systems have one or more disadvantages like multiple substrate layers, complex design, large dimensions, costly substrate material, and insufficient interport isolation for full-duplex operation.

This article proposes a new design approach for in-band full-duplex antenna to achieve a good interport isolation using the microstrip coupled CPW exciting in odd mode. Compared to the isolation techniques discussed in the above references, the proposed design provides a good interport isolation with the following contributions.

(a). The U-shaped stepped slot is excited using the microstrip forming microstrip coupled coplanar waveguide (CPW) in the odd mode of excitation. This feeding provides the closed surface currents around the stepped slot.

(b). The coupling surface currents from the excited port flow parallel to the non-excited stepped slot and results in neutral coupling with the microstrip. Due to the neutral coupling with the microstrip from the stepped slot, the interport isolation is improved.

(c). The orthogonal arrangement of the stepped slots will further enhance the interport isolation due to the orthogonal surface current distributions from the active port interacting with the other port.

(d). The proposed in-band full-duplex antenna with orthogonal U-shaped stepped slots fed by microstrip coupled CPW odd mode excitation achieves the minimum interport isolation of 39 dB over the entire operational band.

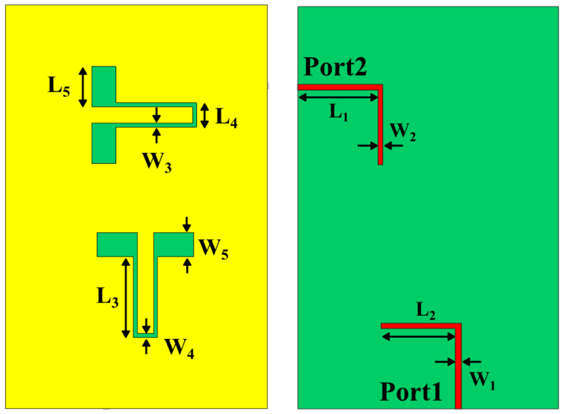
2. Proposed In-band Full-duplex Antenna

A. Antenna Configuration

In this section, the proposed in-band full-duplex antenna is examined and elaborated on in detail. The antenna system consists of two stepped-width L-shaped microstrip feedlines on the bottom layer of the substrate. The L-shaped microstrip feedline is coupled to the U-shaped stepped slot on the top layer of the substrate. The stepped slots are positioned orthogonal and close to each other to reduce the overall volume of the antenna. The proposed dual-band full-duplex antenna, as shown in Figure1(a)-(b), is realized on an FR-4 lossy substrate with a thickness of h = 0.8 mm, relative permittivity $\varepsilon_r = 4.4$, and loss tangent of $\delta = 0.02$ with the overall size of 100 mm × 65 mm × 0.8 mm. The parameters of the proposed antenna are varied to obtain the optimized results and the final optimized dimensions (unit: mm) are as: L_1=20, L_2=18.50, L_3=20, L_4=6, L_5=10, W_1=1.5, W_2=1.2, W_3=1, W_4=1, W_5=6.

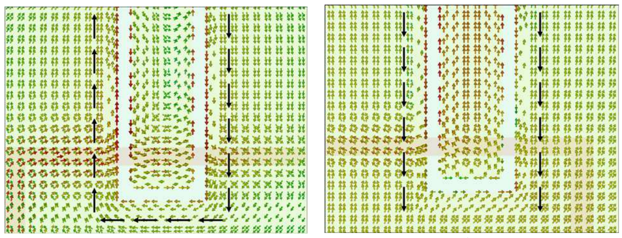
B. Operating Principle of Antenna

The proposed in-band full-duplex antenna is realized by using the technique of microstrip coupled CPW exciting in odd mode or otherwise called coplanar mode. This method of feeding provides a particular surface current distribution on the stepped slot line. Firstly, the microstrip feedline that



(a) (b)

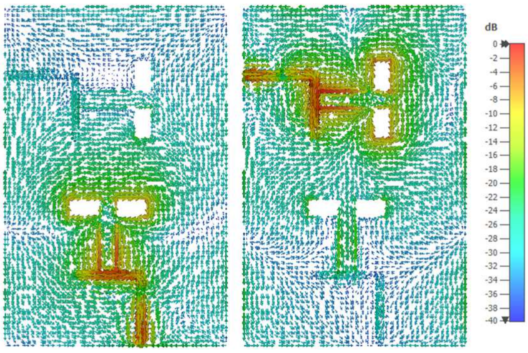
Figure 1. Proposed Full-Duplex antenna. (a) Front view and (b) Back view



(a) (b)

Figure 2. Surface Current distributions on the proposed antenna. (a) CPW odd mode excitation and (b) Coupling Surface Currents on non-excited slot.

couples with the stepped slot with the port are optimized with stepped width L-shaped line. The stepped width L-shaped feedline is chosen to obtain better impedance matching with the U-shaped stepped slot and improve the bandwidth of the antenna. The L-shaped feedline not only has better impedance matching but also reduces the dimensions of the antenna and optimizes the overall volume of the structure. The active microstrip feedline interacts with the slot in the top layer of the substrate and the energy transition occurs between the feedline and the stepped slot by coupling electromagnetic fields. The microstrip line crosses the U-shape slot orthogonally at two positions and the transition of the fields from the feedline to the slot occurs at these two positions. The fields between the feedline and the ground plane transit to the slot section at the two positions of the feedline crossing the stepped slot. The transmitted fields induce the surface currents around the slot and form the closed surface current distribution, as shown in Figure 2(a), around the slot. This feeding system is microstrip coupled CPW in the odd mode of excitation. The odd mode, otherwise called coplanar mode, excitation technique is used to obtain the interport isolation. The leaked surface currents from the active U-shaped stepped slot reaches the orthogonally positioned other U-shaped stepped slot which has dimensions identical to that of the active slot. The coupled surface currents flow in the same direction along the edges of the



(a) (b)

Figure 3. Surface current distribution at $f = 3.52$ GHz : (a) port1 and (b) port2.

U-shaped slot, as shown in Figure 2(b). This in-phase coupled surface current distribution, particularly at the coupling points where the feedline and the slot line cross perpendicularly, transits the countering fields from the slot line to the microstrip feedline. The contradicting or out-of-phase fields nullify each other at the centre of the two coupling positions and result in minimum induced surface current on the microstrip feedline. The dimensions of the proposed in-band full-duplex antenna are optimized to obtain a good interport isolation without affecting the radiation pattern. The isolation is further improved due to the orthogonal arrangement of stepped slots. As seen in Figure 3, the coupled surface currents which are in phase at the slot edges have a weak coupling with the microstrip feedline due to the nullify fields. It is also observed the surface currents are perpendicular to the feedline structure and causes minimum induced current to the port.

C. Results and Analysis

The designed antenna structure resonates in the 5G communication band of (3.3-3.6) GHz with the return losses of -24 and -26 dB at port1 and port2, respectively. The S-parameters of the proposed antenna are shown in Figure.4. It attains the minimum interport isolation of 39 dB for the entire bandwidth of 370 MHz and the maximum interport isolation of 47 dB occurs at the centre frequency of 3.52 GHz for both ports. The antenna with good interport isolation offers broadside radiation, as shown in Figure 5, and seen that both ports have very similar radiation patterns. The antenna provides a broadside radiation pattern due to the stepped slots and the radiation patterns of both ports at 3.52 GHz are almost similar for E and H planes. The cross-polarization is less than 20 dB in the broadside direction of the radiation pattern for both ports in both planes at centre frequency $f = 3.52$ GHz. The antenna attains the gain of 3.8 and 4.5 dBi at the centre frequency of port1 and port2, respectively.

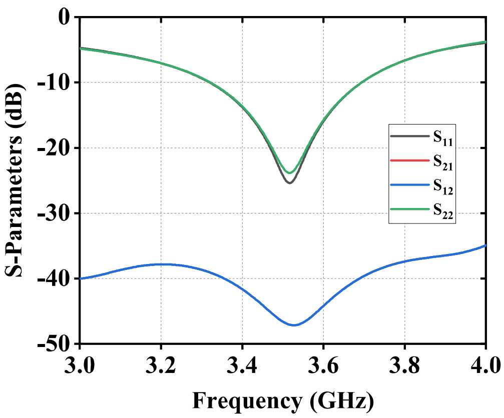


Figure 4. Scattering parameters of proposed antenna.

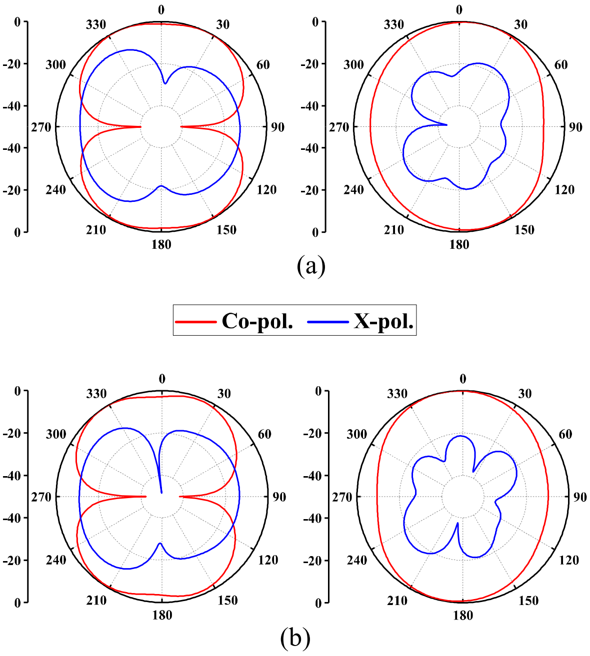


Figure 5. Polar plots of radiation patterns in E and H planes at f=3.52 GHz: (a) port1 and (b) port2.

3. Comparison with Related Work

The proposed in-band full-duplex antenna is compared with the other state-of-the-art works, as shown in Table.I. As seen, the antennas in [5] and [8] have 40 dB minimum interport isolation which is 1 dB greater than that of the proposed antenna, but the operational bandwidth of the proposed antenna is approximately double that of the antennas in [5] and [8]. In [6], [7], and [9], the antenna structures are more complex than the proposed antenna and

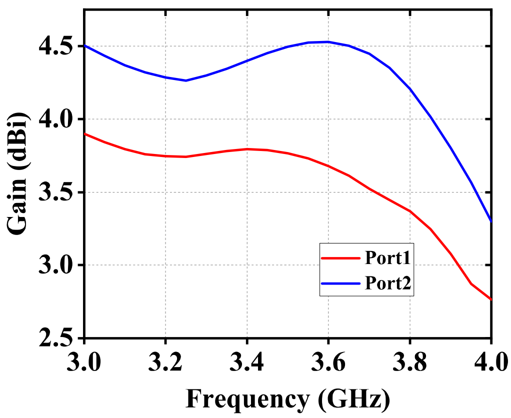


Figure 6. Gain Vs Frequency of proposed antenna.

require additional components to achieve considerable interport isolation. From the comparison table, it is seen that the proposed in-band full-duplex antenna has better performance in terms of interport isolation and maximum bandwidth with a bidirectional radiation pattern.

Table. I. Comparison with Related Work

Ref	Centre Freq.	Isolation Technique	Isolation (dB)/B. W (MHz)	Dimension in λ_0
[5]	2.5	Polarization diversity	40/220	$(1.1\times0.7\times0.05)\ \lambda_0$
[6]	2.45	Analog SIC	30/300	$(1.2\times0.8\times0.03)\ \lambda_0$
[7]	5.80	Inter-digital lines	20/270	$(0.9\times0.58\times0.08)\ \lambda_0$
[8]	2.45	Analog SIC	40/65	-
[9]	2.46	Fence Strip Resonator	23/120	$(0.25\times0.25\times0.04)\ \lambda_0$
[10]	2.47	DGS	25/140	$(0.7\times0.7\times0.012)\ \lambda_0$
This Work	3.52	CPW Odd Mode	39/370	$(0.82\times0.53\times0.006)\ \lambda_0$

Note: λ_0 is the free-space wavelength at the frequency of 2.45 GHz.

4. Conclusion

The in-band full-duplex antenna with U-shaped stepped slots is designed to obtain good interport isolation for both ports in the operational band with a broadside radiation pattern. In this design, a good degree of interport isolation is achieved by utilizing the technique of CPW odd mode excitation. The microstrip feedline coupled to the stepped slot is least interacted with the leaked parallel surface current distribution around the slot and improves the interport isolation. Compared to the state-of-the-art research, the proposed antenna exhibits the highest interport isolation of 47 dB at a centre frequency of $f = 3.52$ GHz and a minimum of 39 dB over the entire operational band for both ports. It exhibits maximum radiation in the broadside direction with cross-polar less than 20 dB in both E- and H-planes for both ports at the centre frequency. The antenna achieves the gains of 3.8 dBi and 4.5 dBi at the centre frequency for port1 and port2, respectively.

5. References

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