High Isolation Novel Interleaved TRX Antenna Array with Defected Ground Structure for In-Band Full-Duplex Applications

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***Abstract*—A compact symmetrical simultaneous transmit and receive antenna with high isolation is one of the main barriers that restricts the in-band full-duplex (IBFD) communication system architecture. To overcome this barrier, a novel interleaved transmit and receive antenna array with plus shaped defected ground structure (DGS) has been developed and presented in this paper. It is designed at 10 GHz, fabricated and validated with the measurements. The proposed interleaved array consists of symmetric 2x1 transmitter (TX) antenna elements and symmetric 2x1 receiver (RX) antenna elements with the spacing of 1λ_0 while the spacing between TX and RX (TRX) antenna elements is 0.5λ_0 similar to a checkerboard pattern. The plus-shaped DGS is applied to reduce self interference (SI) by suppressing the existing surface wave between the TRX antenna elements. The measurement results confirm that this technique increased the isolation from 16.5 dB to 56.5 dB between TRX antenna arrays. In addition, the proposed array and a co-located array without DGS are compared in terms of simulation and measurement to present the benefits of the proposed antenna array. Furthermore, the interleaved antenna arrays with and without DGS are investigated to analyze the isolation characteristics. The analyses indicate that interleaved antenna array structure with DGS enhances the compactness and enables the alternative placement of TX and RX array antennas for better front-end designs towards in-band full-duplex (IBFD) communication systems for 5G and beyond. Simulation and measurement results confirm a close agreement for the proposed antenna array.**

I. Introduction

The ever-increasing demands for higher data rate and higher spectrum efficiency have spawned the development of In-Band Full-Duplex (IBFD) or Simultaneous Transmit and Receive (STAR) systems [1]. IBFD or STAR operation entails wireless terminal/device to transmit and receive signal at the same time over the same frequency band. These systems are promising not only because of their ability to simultaneously transmit and receive but also leading to increased spectral efficiency, theoretically doubled-date rate and requirement of less antenna hardware [1], [2]. Subsequently, IBFD systems have a vital role of implementing joint communication and sensing (JC&S) applications since actual communication and radar systems are currently utilized separately including distinctive hardware, spectrum and waveforms [3]. Hence, these systems will be beneficial for the enhancement of today's limited wireless spectrum while allowing better detection performance [4]. However, self-interference (SI) is one of the main barriers in realizing STAR systems since stronger transmitted signal can suppress the received signal and/or can saturate the receiver chain [1], [2]. In general, there are two approaches to realize a STAR system: Use of two separated antennas and one shared antenna with the circulator as explained in [1].

In fact, SI is a main barrier for both approaches whereas the one shared antenna with circulator have some more deficiencies such as higher power consumption, bigger area. Furthermore, available circulator architectures do not provide sufficient isolation over the operating band [5]. Hence, use of two separate antenna approach is considered in this work. In an attempt to overcome the major impediment of SI, three well-recognized methods that exist in antenna propagation domain, analog-circuit domain, and digital domain are currently being utilized. In this work, antenna propagation domain was considered that can reduce the dynamic range requirements of the receiver and has relatively smaller size as well as lower power consumption [6]. Thus, it provides an easy and low-cost implementation of future 6G JC&S applications [7].

To cancel the self-interference in the antenna propagation domain, a vast number of SI reduction techniques are being proposed so far as given in [8]–[11]. One of the proposed techniques is Defected Ground Structure (DGS) which indicates a defect in ground plane by slotting or etching with various shapes. This slotting or etching on the ground plane affects to disturb the current distribution of antenna and control the coupling between antenna elements. In this paper, one of DGS techniques which are as thoroughly reviewed by [11], has been implemented with the single layer interleaved TRX antenna array. Accordingly, isolation has been achieved higher than 50 dB. The SI reduction is realized by the presented slot structure on the ground plane which is perpendicular to the current on the surface of patches with a center-to-center spacing of 0.5λ_0. Apart from the main limitation of SI, the usage of two separate antennas implementation also have further performance requirements for appropriate simultaneous transmission and reception:

- The TRX structure must be capable of Beamforming.
- The beam reciprocity between TX and RX antennas is required for most of the applications.

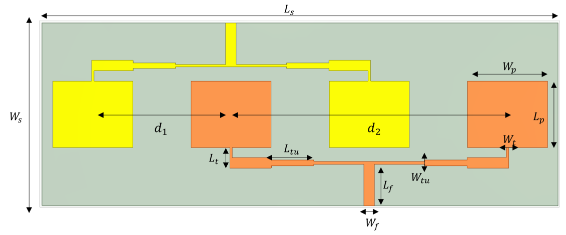


Fig. 1: Dimensions of Interleaved TRX antenna array model without DGS

- The channel reciprocity is also an important requirement for certain use cases.

A novelty of proposed interleaved array antenna is consisting of TX and RX with symmetric 2x1 antenna elements, thus enables the multi-element front-end design with alternative receiver and transmitter placement. This alternation of TRX placement is beneficial in particular for 5G and 6G communications [12]. It's because 5G does not solely support smart phones services but also various novel services such as boundless XR, green network and further use cases which hinge the capability of 5G [12]. Due to high wireless data traffic, the up-link and down-link does not match. Thus, this proposed antenna array provides better beam and channel reciprocity for multiple communication system architecture.

This paper is organized as follow: the comparison of co-located and interleaved antenna arrays with the simulation results without DGS are analyzed in section II. The design concept as well as the simulation and measurement results of proposed interleaved antenna array with DGS are illustrated in section III. The conclusion and future work of paper are given in section IV.

II. Interleaved TRX and Co-located TRX Antenna Array without DGS

The proposed interleaved TRX antenna array without DGS is presented in Figure 1. The interleaved TRX array consists of two symmetric 2x1 antennas working at 10 GHz. The total size of interleaved TRX is 60 mm x 19.9 mm. The substrate of interleaved TRX array is Rogers 4003C with the permittivity of 3.55 and tanδ of 0.0027. The thickness h of the substrate is chosen to be 1.52 mm. The center-to-center spacing between TX and RX antenna is d_1=15 mm (0.5λ_0), where λ_0 is the free-space wavelength at 10 GHz. However, it should be noticed that the antenna elements of either the TX or RX antennas are separated with d_1=30mm (λ_0). The arrays are fed by 50 Ω microstrip transmission lines and they share a common ground plane. On the other hand, co-located antenna array is designed with the same design parameters such as operating frequency, substrate permittivity and thickness. The geometry of those antenna arrays are illustrated in Figure 1 - 2 and the dimensions are tabulated in Table I.

Simulations are carried out using ANSYS High-Frequency Structure Simulator (HFSS) software to observe the behaviour of these antenna arrays. Figure 3 illustrates the simulated results in terms of isolation (S_{21}/S_{12}) and return loss (S_{11}/S_{22})

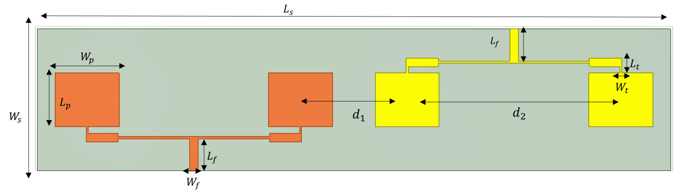


Fig. 2: Dimensions of Co-located TRX antenna array model without DGS

TABLE I: Dimensions of Interleaved and Co-located TRX antenna array

Parameters [mm]	Interleaved array	Co-located-array
L_s	19.9	19.9
W_s	60	89
L_p	7.21	7.21
W_p	9	9
L_f	4.51	4.51
W_f	1.2	1.2
L_t	1.1	0.89
W_t	0.28	0.28
d_1	15	15
d_2	30	30
h	1.52	1.52

of co-located and interleaved antenna arrays. The achieved isolation of interleaved array is slightly less than the co-located array since it has larger overlapping radiation field of individual elements. However, interleaved array is more compact than the co-located array even with the same spacing between individual TX and RX antenna elements. In addition, performance parameters of both arrays are almost the same although interleaved array is designed with smaller aperture area. The simulated maximum realized gain values with respect to frequency of interleaved and co-located antenna arrays are given in Figure 4.

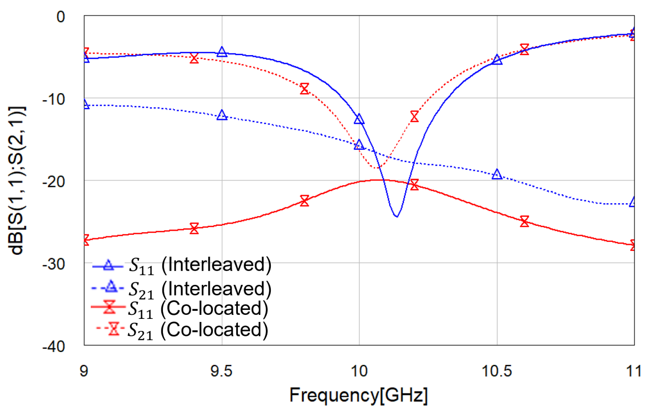
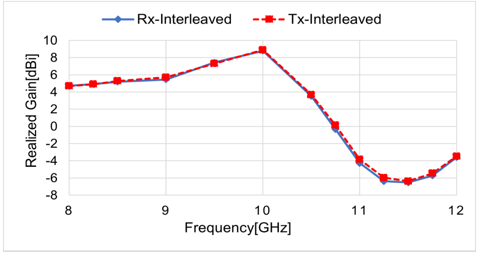
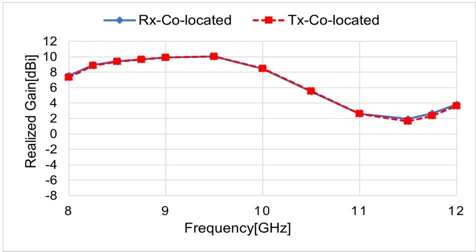


Fig. 3: Comparison of Isolation and Return loss parameters of Co-located and Interleaved Antenna Arrays

Furthermore, the interleaved array enables multi-element front-end design with an alternative receiver and transmitter placement thus providing better channel and beam reciprocity of the TX and RX channels. Table V provides the comparison

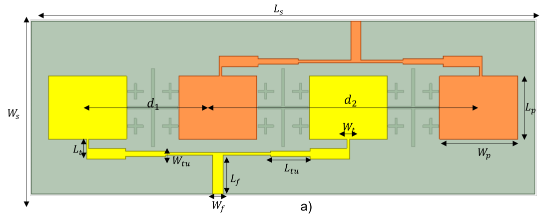


a)

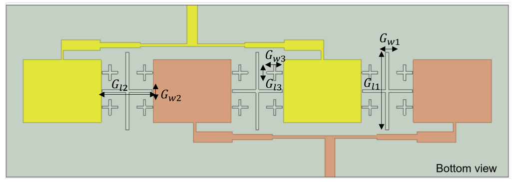


b)

Fig. 4: Simulated maximum realized gain values with respect to different frequencies a) Interleaved array b) Co-located array



a)



b)

Fig. 5: Geometry of interleaved antenna array with DGS a) Top view b) Bottom view

of antenna performance parameters for co-located and interleaved antenna arrays.

TABLE II: Performance comparison of co-located and interleaved arrays with respect to the simulation results

Parameters	Co-located array	Interleaved array
Bandwidth [MHz]	410	387.5
Maximum Gain [dBi]	9.2	9
Isolation [dB]	20.1	16.5

III. Interleaved TRX antenna arrays with DGS

In the previous section II, it is observed that SI is an undesired phenomenon that distorts the behavior of radiating elements in an antenna array. Each element affects others by propagating surface currents through the ground plane or radiating over the air. Accordingly, radiation characteristic of such antennas tends to degrade due to strong self interference. Therefore, an antenna cancellation technique of DGS is presented with novel shaped interleaved antenna array structure in this section. DGSs are realized by etching or slotting on the ground plane of microwave circuit with various shapes as given in [11]. The working principle of DGS can be summarized as follows: the compact well-optimized geometrical shape is etched off on the ground plane. Depending on the shape and the dimensions of the defect, the current distribution on the ground plane is disturbed. As a result, disturbed current controls the excitation and propagation of electromagnetic waves through substrate layer. This allows the suppression of the surface wave of the substrate which eventually increases the isolation and bandwidth.

In an attempt to reduce the self-interference in the proposed interleaved array, the plus shaped DGS is implemented in between the transmitting and receiving antenna elements. During the design, the locations of the slots are optimized since they play a significant role in the performance of DGS structures. The proposed interleaved array is designed and fabricated on low cost Rogers substrate RO4003 with the permittivity and the thickness of 3.55 and of 1.52 mm, respectively. The equipment used for fabrication of the interleaved array is LPKF ProtoMat which follows the process of 3D printing technology and standard PCB manufacturing. The geometrical layout of interleaved array with DGS is shown in Figure 5. The optimized dimensions of interleaved array are given in Table III.

TABLE III: Dimensions of Interleaved TRX antenna array with DGSs

Parameters [mm]	Interleaved Antenna Array
L_s	23
W_s	60
L_p	7
W_p	9
L_f	4.51
W_f	1.14
L_t	4.7
W_t	0.27
G_{w1}	0.35
G_{l_1}	9
G_{w2}	0.35
G_{l_2}	5.75
G_{w3}	0.27
G_{l_3}	2
h	1.52

The antenna performance parameters comparison with and without DGS is provided in Table IV.

TABLE IV: Performance comparison of TX and RX antenna board with and without DGS according to the simulation results

Parameters	Without DGS	With DGS
f_r [GHz]	10.1	10.25
Return loss [dB]	-25.4	-18.63
Bandwidth [MHz]	387.5	487.5
Maximum Gain [dBi]	9	6.6
Isolation [dB]	16.5	63.2

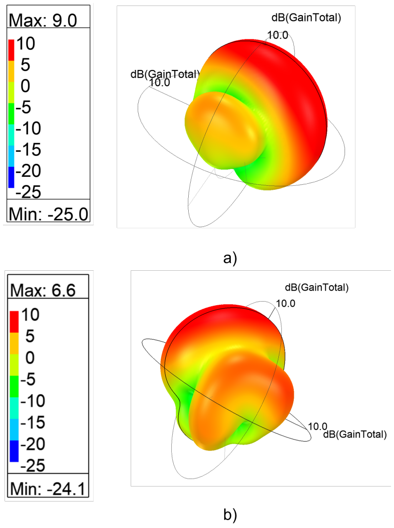


Fig. 6: 3D Gain pattern comparison a) without DGS b) with DGS

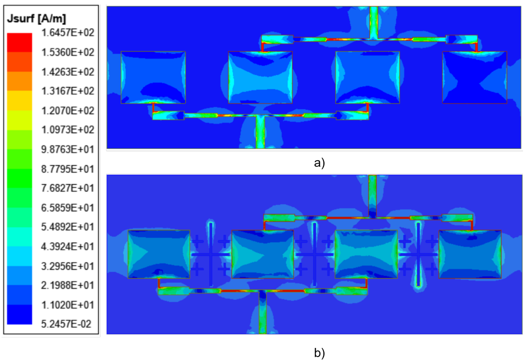


Fig. 7: Simulated current distribution on the ground plane a) without DGS b) with DGS

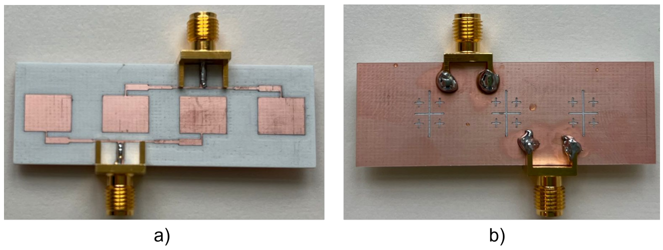


Fig. 8: Fabricated interleaved antenna array with DGS a) Top view b) Bottom view

According to the simulation results, resonance frequency of the interleaved antenna array with DGS is shifted up from 10 GHz to 10.2 GHz due to increase of inductance effect of the slot. The interleaved antenna array with DGS has more bandwidth than the antenna array without DGS. This bandwidth enhancement is observed since the DGS on the ground increases fringing field, leading to an increase of the parasitic capacitance. The interleaved antenna array without DGS shows a very strong coupling, with isolation value of 16.5 dB due to surface wave excitation. On the other hand, the interleaved structure with DGS has suppressed surface waves. As a result, surface waves are suppressed and simulations show that isolation increases to 63.2 dB which is 46.7 dB higher than the without DGS counterpart. The maximum gain of the antenna with and without DGS is decreased from 9 dB to 6.6 dB as illustrated in Figure 6. Figure 7 demonstrates the current distribution on the ground plane of the interleaved antenna array with and without DGS at the resonate frequency of 10 GHz. As evident from this figure, the surface current is highly distributed on the interleaved with DGS than without DGS due to the increase in the inductance and capacitance effect.

To verify the simulation results, the interleaved antenna array with DGS is fabricated and measured as shown in Figure 8. Two identical SMA connectors are soldered at feeding ports of each realized TX and RX array for the measurement. The fabricated interleaved antenna array is measured using KEYSIGHT (PNA) Network Analyzer model N5224B, which has the frequency range from 10 MHz to 43.5 GHz.

The measurement and simulation results comparison are demonstrated in Figure 9. Additionally, gain measurements of the proposed antenna array is performed by a Diamonds Engineering positioner in the anechoic chamber as illustrated in Figure 10. From the results, it is observed that the validation agrees well with the simulated results. However, there is a slight shift in the operation frequency due to fabrication tolerances and environment effect. From this experimental demonstration, it can be concluded that the DGS can be utilized to reduce the antenna self interference between array elements.

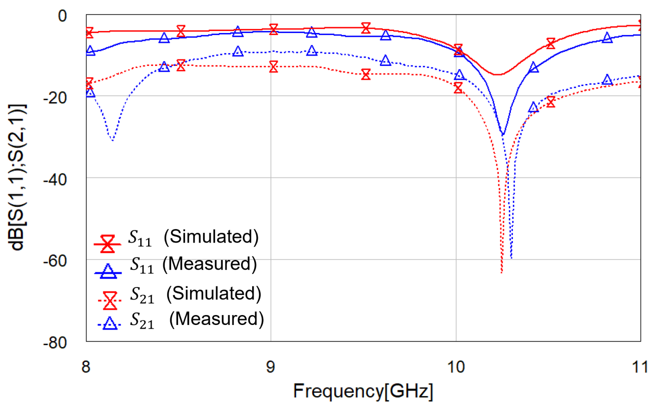


Fig. 9: Comparison of simulated and measured results of interleaved antenna array with DGS

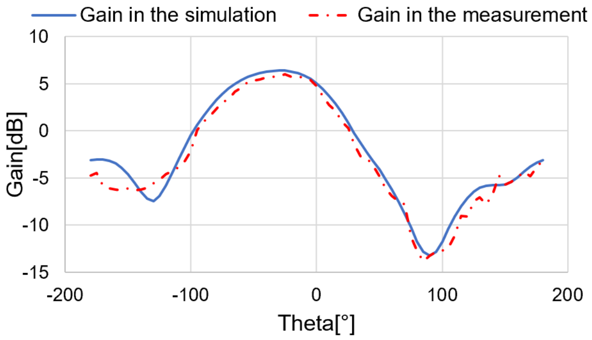


Fig. 10: Comparison of simulated and measured results interleaved antenna array with DGS

TABLE V: Performance comparison of simulated and measured interleaved antenna array with DGS

Parameters	Simulation	Measurement
Bandwidth [MHz]	487.5	500
Maximum Gain [dB]	6.6	6.23
Isolation [dB]	63.2	56.5

Table VI illustrates the comparison of simulation results between proposed antenna array and reference antennas. In contrast to the same SI reduction technique, the proposed antenna uses four radiating element with higher isolation. In addition, the proposed antenna array achieves relatively high gain and bandwidth compared to the references.

TABLE VI: DGS structures of antennas in references compared with the proposed antenna

Source	SI Reduction Technique	Center-to Center spacing	NOE for TRX	Operating Frequency [GHz]	Structure	Improvement in Isolation[dB]	Gain [dB]	Bandwidth [MHz]
[13]	DGS	0.5	2	5.24	Co-located	12.152	6.181	235.1
[14]	DGS	0.61	2	5.64	Co-located	27.11	6.6	78.4
[15]	DGS	0.22	2	2.45	Co-located	18	5.5	-
[16]	DGS	0.75	2	5.3	Co-located	12	-	-
[17]	DGS	0.56	2	6	Co-located	15.1	-	-
[18]	DGS	0.115	2	2.305	Co-located	13	2.69	-
Proposed	DGS	0.5	4	10.25	Interleaved	46.7	6.6	487.5
Note: SI: Self-Interference, NOE: Number of Element, DGS: Defected Ground Structure								

IV. Conclusions

This work demonstrates a novel shaped antenna array structure for in-band full-duplex applications taking into account the placement of transmitter and receiver, an important aspect for channel and beam reciprocity. Accordingly, the design of interleaved TRX antenna array providing high isolation with plus-shaped DGS is proposed. DGS is etched on the ground plane of the antenna array to prevent the propagating surface waves, and thereby, a 40 dB improvement of isolation between transmitter and receiver is experimentally confirmed (16.5 dB to 56.5 dB). Furthermore, the developed co-located and interleaved antenna arrays are compared in terms of performance parameters. In addition, interleaved antenna array with a plus-shaped has been compared to the interleaved antenna array without DGS. In future work, the target will be to investigate the multi-layer interleaved antenna arrays with relatively higher isolation and larger array structures, required by future beam-forming networks.

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