On the effect of S-parameter stability of antenna and coupler on electrical balance duplexing

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ABSTRACT

Electrical Balance Duplexers (EBDs) provide transmit-receive isolation to implement a form of self-interference cancellation to facilitate simultaneous transmission and reception from a single antenna in systems like In-Band Full-duplex (IBFD) transceivers. EBD works by coupling transmitter, receiver, antenna, and balancing impedance using a hybrid coupler. In recent pieces of literature, antenna impedance variations are considered the main factor limiting the EBD isolation bandwidth, while the EBD balancing impedance needs to be equal as much as possible to the antenna impedance to achieve high isolation. But hybrid couplers are also not ideal elements, and their S-parameters are not stable in the frequency domain. In this work, five broadband RF devices (two antennas, two couplers, and a 50-Ohm RF-load) are used to form four EBD set-ups. One of the antennas, designed by the authors, has more impedance stability in the frequency domain than the other one, which is a commercial antenna. Also, one of the couplers, designed by the authors, has more S-parameter stability in Ultra-Wideband (UWB) frequency domain than the other one, which is a commercial UWB coupler. The implemented EBDs show that when both antenna and coupler have strong S-parameter stabilities in the frequency domain, wider isolation bandwidth (UWB 1.5–3.5 GHz range) and higher EBD isolation are obtained.

1. Introduction

In-Band Full-Duplex (IBFD) systems theoretically can double link the capacity of Time Division Duplex (TDD) and Frequency Division Duplex (FDD) systems, thus allowing simultaneous transmission and reception on the same frequency and reducing wireless latency [1–5]. Transmitting and receiving on the same time–frequency resource results in strong co-channel Self-Interference (SI), which can be more powerful than the desired receive signal [2,6]. Any residual SI, due to unsuitable transmit (Tx) to receive (Rx) isolation, will effectively increase the receiver noise floor, therefore, reducing the capacity of the receive channel [7,8].
Figure 1. EBD stage of the IBFD system with adaptive balancing impedance.

Existing IBFD designs [9–11] involve various combinations of analog cancellation, digital cancellation, and antenna-based suppression to provide the required isolation. Digital cancellation [12] cannot properly prevent SI from overloading the receiver. Analog cancellation [11,12] can provide significant isolation and prevent receiver overloading in most cases [11]. Antenna-based suppression and separation methods can provide significant isolation also; however, these designs require additional antennas [12]. Single-antenna full-duplex systems in [11] use circulators to provide some level of Tx-Rx isolation, but these are unattractive options due to their cost, size, and limited bandwidth. New duplexers based on SI Cancellation (SIC) at the receiver have received substantial interest to enable IBFD operation [1,11–14].

Recent results [7,13,15–17] have demonstrated that Electrical Balance Duplexers (EBDs), which is of interest as the first stage of passive Radio Frequency (RF) front-end cancellation in IBFD transceivers, implement a form of SIC to provide transmit to receive isolation, while facilitating simultaneous transmission and reception from a single antenna. EBD could be combined with analog cancellation, digital cancellation, and full-duplex MIMO technology [10]. The analog circuit technique of EBD works by coupling the transmitter, receiver and antenna using a four-port hybrid junction, along with balancing impedance connected to the fourth port Figure 1. Using a suitable hybrid coupler, higher transmit-to-receive isolation is expected in the EBD stage when the balancing impedance is equal to the antenna impedance at all frequencies within the aimed bandwidth. However, in practice, the antenna impedance is not an ideal 50 Ω resistor but has complex impedance having real and imaginary parts. This exhibits variations with respect to frequency, so the bandwidth and value of the Tx-Rx isolation will be limited by impedance mismatching between the antenna and balancing impedance.
Measured real antenna data in [7,14], and results for a prototype EDB in [18], demonstrate that the variation in antenna impedance significantly reduces the isolation bandwidth. Evaluations that include measured antenna data in the EBD in [13,15,17] show isolation over a 20-MHz bandwidth at 1.9 GHz, but the poor performance of wider bandwidths was again shown because of antenna impedance variations. A Micro-ElectroMechanical Systems (MEMS) implementation of tuneable balancing impedance of the EBD is presented in [19], balancing at 800 and 1900 MHz to provide isolation over a 20 MHz bandwidth at each frequency, but introduce non-linear distortion into the system. Consequently, to maintain Tx-Rx isolation, the balancing impedance must be tuneable as it tracks and mimics the antenna impedance as it changes. This requires an adaptive architecture [15,17], Figure 1, using a balancing algorithm that extremely limits the mimic and the isolation bandwidths.

In all the above scenarios in the literature, analyses consider the antenna impedance variations as the main factor limiting the SIC when the antenna is connected to a hybrid coupler. But hybrid couplers are also not ideal elements, and their S-parameters are not stable in the frequency domain. The main aim of this work is to investigate how the EBD isolation is affected by the S-parameter stability of coupler and antenna in the Ultra-Wideband (UWB) frequency domain. In Section 2, the Tx-Rx gain function of EBD circuitry is briefly reviewed to assess EBD isolation in generic form. Used broadband RF devices in the experiments of this work (stable impedance antenna, stable S-parameter coupler, commercial antenna, commercial coupler, and balancing load) are introduced in Section 3. Stable impedance (or S-parameter) antenna and stable S-parameter coupler are designed by the authors. In Section 4, Tx-Rx isolations are measured for four different EBD set-ups consisting of four different antenna/coupler pairs introduced in Section 3. The EBD isolation bandwidth is increased (2 GHz UWB bandwidth at 1.5–3.5 GHz range), and the EBD isolation value is optimized when using the designed stable S-parameter coupler and designed stable S-parameter antenna. Finally, a conclusion is given in Section 5.

### 2. Tx-Rx gain of electrical balance duplexers

Tx-Rx gain of a symmetrical EBD is given [16] by

\[
G_{\text{Tx-Rx}}(\omega) = L |\Gamma_{\text{BAL}}(\omega) - \Gamma_{\text{ANT}}(\omega)|^2
\]

(1)

where \( \Gamma_{\text{BAL}} \) and \( \Gamma_{\text{ANT}} \) are the complex reflection coefficients of the balancing impedance and antenna impedance, respectively (see Figure 1), and for an ideal (lossless) hybrid \( L = 1/4 \). As shown in (1), the Tx-Rx gain is theoretically zero when the balancing reflection coefficient and antenna reflection coefficient are equal at the carrier frequency. To obtain maximum (theoretically infinite) Tx-Rx isolation over a given frequency band, the balancing impedance must be equal to the antenna impedance at all frequencies within that band such that \( \Gamma_{\text{BAL}}(\omega) = \Gamma_{\text{ANT}}(\omega) \) for \( \omega_l < \omega < \omega_h \) where \( \omega_l \) and \( \omega_h \) are the lower and upper limits of the band of interest, respectively. Also, coupler characteristic, \( L \), is a determining parameter to calculate the Tx-Rx gain. Abdelhaleem et al. [16] demonstrate that (1) remains valid for non-ideal circuits.
3. Devices

In this section, five broadband RF elements used in the paper experiments are introduced. Firstly, two antennas are introduced: the first one is designed by the authors, and it has more impedance (S-parameter) stability in the frequency domain than the second one, which is a commercial antenna. More details on the design steps of the stable impedance antenna are given in the authors’ other paper in [20] and the coupler effect is investigated briefly in [21]. Moreover, two UWB couplers are introduced: the first one is designed by the authors, and it has more S-parameter stability in the frequency domain than the second one, which is a commercial couple. Also, a wideband 50-ohm RF load is used as the EBD balancing impedance.

3.1. Antenna with stable impedance – designed

A single-arm Archimedean Spiral (AS) is backed by a cavity Figure 2, to have an antenna with a unidirectional beam. The AS is formed as a conducting spiral strip arm of width \( w = 2 \text{ mm} \) on the bottom of a disc-shaped Rogers RT 5880 substrate – the so-called DIEL1 – of radius \( A_C = 62 \text{ mm} \) with a dielectric constant of \( \varepsilon_r = 2.2 \), loss tangent of \( 0.0009 \), \( h = 0.79 \text{-mm thickness} \) plus a 9 \( \mu \text{m} \) copper coating. DIEL1 has no copper on the top. The centreline of the spiral arm is defined by the function of \( r = K \Phi \), where \( K \) is a constant and \( \Phi \) is the winding angle, ranging from starting angle \( \Phi_S = 0.07 \pi \text{ Rad} \) to ending angle \( \Phi_E = 28 \pi \text{ Rad} \). The antenna circumference \( C \) is defined by \( C = 2\pi R_{\text{max}} \) with \( R_{\text{max}} = K \Phi_E \) where \( K = 0.64 \text{ mm/rad} \), \( R_{\text{max}} = 56 \text{ mm} \). The cavity radius, \( A_C \), has 6 mm distance from the arm end to the cavity wall as \( A_C = 62 \text{ mm} = 0.31 \lambda_L \), while \( \lambda_L \) is the wavelength at the lowest design frequency of 1.5 GHz. The distance between the bottom of the cavity and the spiral on the bottom of DIEL1 substrate is \( H_C = 6.9 \text{ mm} = 0.035 \lambda_L \). The height of the copper case wall is \( H_C + 2h \) to surround the DIEL1 disc substrate, while the case has a 1 mm uniform thickness of copper.

Reflected fields from the bottom of the case are attenuated in the designed antenna using electromagnetic absorbers (EMAs) made up of model UD-14518 of ARC Technology to make the antenna impedance more stable in a UWB frequency range. The UD-14518 is specified by relative permittivity of \( \varepsilon_r = \varepsilon' - j\varepsilon'' \sim 22 + 3j \) and relative permeability of \( \mu_r = \mu' - j\mu'' \sim 4.5 + 2j \) at the aimed bandwidth [22]. As shown in Figure 2, a ring-shaped Electromagnetic Absorber (EMA) strip – the so-called EMA1 – of optimized width 11 mm and with the same height of copper case \( H_c = 6.9 \text{ mm} \) is placed under the antenna arms. Also, a second EMA, the so-called EMA2, is added to above the DIEL1 substrate to more improve impedance stability. EMA2 has an optimized thickness of \( 2h = 1.6 \text{ mm} \), while its outer radius is equal to the cavity diameter of \( A_C \), and its inner radius is \( A_C - 17 \text{ mm} = 45 \text{ mm} \).

A capacitive impedance matching using two concentric planar copper rings, Figure 2, is also used to improve impedance stability. The maximum bandwidth for a stable impedance is achieved when air with a dielectric constant of \( \varepsilon_r = 1 \) is considered between the copper and the spiral rings. As seen, the two concentric planar copper rings are considered on the top surface of a disc-shaped dielectric material, the so-called DIEL2, with a distance of \( h = 0.79 \text{ mm} \) between the copper rings and the spiral body. DIEL2 with a thickness of \( h \) is made up of the same material as Rogers RT 5880. DIEL2 has a small hole with \( R_i = 1.7 \)
mm radius in the centre for passing the coaxial cable, while the outer radius of DIEL2 is 41 mm. Also, a planar dielectric ring, the so-called DIEL3, with the same thickness and the same material with DIEL2 is used as a spacer between DIEL2 and DIEL1. DIEL3 has a hole with a radius of \( R_H = 35 \) mm in the centre, while its outer radius is equal to the outer radius of DIEL2. The internal copper ring has an inner radius of \( R_i = 1.7 \) mm and an outer radius of \( R_O = 5.5 \) mm, while the external ring has an inner radius of \( R_{ii} = 8 \) mm and an outer radius of \( R_{oo} = 11 \) mm. To hold the substrates and spiral a cylindrical ring is 3D printed on Acrylic material with a dielectric constant of \( \varepsilon_{r(ACR)} = 3.5 \), an internal radius of \( R_{IA} = 41 \) mm, an outer radius of \( R_{OA} = 51 \) mm and height of \( H_{CC} = H_C - 2h = 5.3 \) mm. The antenna is fed by a 50 \( \Omega \) coaxial cable, whereas the inner conductor of the cable is connected to the AS at its starting angle, and the outer ground conductor of the cable is connected to the inner radius of the internal capacitive ring at the top surface of DIEL3.

The Finite Integration Technique (FIT) with high meshing in CST MICROWAVE STUDIO [23] software is used for simulations. Measured and simulated antenna’s stable impedances at 1.5–3.5 GHz range are shown in Figure 3, with an average variation of about 15 \( \Omega \) for the measured imaginary and real impedance. Also, the measured directivity pattern of the antenna and its measured gain/efficiency vs. frequency plots are shown in Figures 4 and 5, respectively. Because the spiral length is near the wavelength of lower frequencies, antenna gain drops after around 2.5 GHz. The antenna impedance is very near
to a 50-ohm load, so the radiation efficiency could also be used as total efficiency, considering \( \text{Total Efficiency} = \text{Radiation Efficiency} \times \text{Mismatch Efficiency} \). We measured efficiency and gain at the University of Bristol chamber room. The antenna has a measured Axial Ratio (AR) below 3 dB, indicating a circular polarization over 1.6 GHz (AR plot is not shown here). The above results indicate good impedance stability at the 1.5–3.5 GHz range for the designed antenna, while the antenna also has a suitable radiation performance at this UWB bandwidth. More details about the designed antenna in steps are given in the authors’ other papers in [20] and [24]. S-parameter plot of the designed antenna is given with the commercial antenna characteristics in Section 3.2 for comparison. The fabricated antenna is shown in Section 4 set-ups.

### 3.2. Commercial broadband antenna (Taoglas PAD710)

Taoglas PAD710 is a broadband commercial antenna [18]. Measured antenna impedance at 1–5 GHz range is shown in Figure 6, and measured gain/efficiency plots are shown in Figure 7. Also, measured S\(_{11}\) values of both the Taoglas PAD710 antenna and the stable impedance antenna (Section 3.1) are compared in Figure 8. Figures 6 and 8 show that the Taoglas antenna impedance and S-parameter in the frequency domain are less stable than the designed antenna in Section 3.1. More details about the Taoglas PAD710 antenna and its radiation patterns are given in [25]. The antenna is shown in Section 4 set-ups.

### 3.3. 3-dB UWB coupler with stable S parameters – designed

The proposed miniaturized coupler capable of providing tight coupling over a UWB band is shown in Figure 9(a), where its coupling mechanism is similar to [26] and [27]. The
Figure 4. Measured directivity pattern of the antenna in Figure 2.

differences for the proposed model concern the shaping factor of the broadside coupled strips, the slot, electrical size and most importantly, the operation frequency in the ultra-high frequency band. This coupler consists of three-conductor copper layers interleaved by two dielectric substrates. The top copper layer includes ports 1 and 2. The bottom copper layer is similar to the top layer, but the ports here are ports 3 and 4. Ports 3 and 4 are on opposite sides of the substrate compared to ports 1 and 2. The two layers are coupled via a slot, which is made in the copper layer supporting the top and bottom dielectrics. As shown in Figure 9, the two microstrip conductors and the slot are elliptical. The 50 Ω microstrip lines are included to make connections to SMA ports. The structure features double symmetry with respect to horizontal and vertical plans.
The analysis starts similarly to the ones described in [28] for the equivalent rectangular microstrips. If the characteristic impedance of the microstrip ports of the coupler is $Z_0 = 50 \, \Omega$ and the coupling factor is $C_{dB} = 3 \, \text{dB}$, the values of even mode characteristic impedance $Z_{ev}$ and odd mode characteristic impedance $Z_{od}$ are 175.5 and 14.2 $\Omega$, respectively.
Figure 8. Measured $S_{11}$ parameters of the Taoglas PAD710 antenna (Section 3.2) and designed stable impedance antenna (Section 3.3).

The validity of the presented design is tested in the 1.5–3.2 GHz frequency band, where the centre frequency of operation is 2.35 GHz. A Rogers RO4350B substrate with a dielectric constant of 3.48 and a loss tangent of 0.0037, $h = 0.51$ mm thickness, plus 35-μm-thick conductive copper is used for the coupler development. The elliptical body length is as $20.5 \text{ mm} \sim \lambda/6 \sim \lambda_e/4$ where $\lambda_e$ is the effective wavelength, and $\lambda$ is the free space wavelength at the central frequency of 2.35 GHz. The return loss, coupling, and isolation of the designed coupler are first verified by running high mesh FIT in the CST software, and the final obtained dimensions are shown in Figure 9(a).

Four phase shifters, each with a length of $L_L = 33 \text{ mm} = 0.4 \lambda_e$, are added to the terminals of elliptical bodies to adjust the output phase difference to 90°, needed for a suitable quadrature hybrid coupler, Figure 9(a). To maintain a compact size, phase shifters are formed as curved microstrip lines. Simulations do not show considerable differences in results when the curve angle are not smaller than 75 degrees. A combination of impedance matching techniques and structural modifications also has been employed to optimize the coupler results. The impedance matching is carried out in similarly for all four ports by narrowing the width of tracks that connect the ports to the elliptical body, as shown in Figure 9(a). Also, two narrow slots have been etched on each elliptical body, as shown in the same figure.

Simulated electric current distribution at the top and bottom layers at 2.4 GHz and also magnetic current distribution in the middle layer at 2.4 GHz are given in Figure 9(b,c), respectively. Measurement results by Vector Network Analyzer (VNA) are given in Figures 10 and 11. As shown, the coupler features measured UWB characteristics with a coupling of $3 \pm 1 \text{ dB}$ at the aimed 1.5–3.2 GHz band. Also, smooth isolation in the order of better than 25 dB and return loss in the order of better than 17 dB is achieved as there are non-dense variations around 10 dB for isolation and 9 dB for return loss at the 1–3.5 GHz range. It is shown that the S-parameters for the designed coupler have less variation density and more stability in the frequency domain compared to the commercial Krytar 1831 in Section 3.4. Figure 11 shows that the measured phase difference between ports 2 and 3 is about 90° over the target band. The fabricated coupler is shown in Section 4 set-ups. These results indicate that this compact coupler with $35 \text{ mm} \times 30 \text{ mm} \times 1.1 \text{ mm} (0.27\lambda \times 23\lambda \times 0.009\lambda)$ dimension operates as a backward wave quadrature coupler.
3.4. Commercial 3-dB UWB coupler (Krytar Model 1831)

Krytar coupler model 1831 is a UWB commercially available coupler [29]. Measurement results of the coupler by VNA are given in Figures 12 and 13. As shown, this commercial coupler features UWB characteristics with the coupling of $3 \pm 1$ dB at 1–5 GHz bandwidth. Also, isolation in the order of better than 30 dB and return loss in the order of better than 20 dB are measured. The measured S-parameters are not very stable in the frequency domain as there are dense variations around 15 dB for isolation and 25 dB for return loss at the
Figure 10. Measured S parameters of designed 3-dB coupler with stable S parameter in Figure 9 (Section 3.3).

Figure 11. Measured phase characteristic of the designed 3-dB coupler with stable S parameter shown in Figure 9 (Section 3.3).

Figure 12. Measured S-parameters of the 3-dB commercial Krytar1831 coupler (Section 3.4). The coupler is shown in Section 4 set-ups.

1–3.5 GHz range. Figure 13 shows that the measured phase difference between output ports is dominantly around 90° over the bandwidth needed for a suitable quadrature hybrid coupler. The coupler is shown in Section 4 set-ups.
3.5. **UWB 50-ohm RF load**

A UWB commercial 50-ohm RF load – which has the nearest commercially available impedance to both antenna impedances – is used in the experiments.

4. **Tx-Rx isolation of EBDs and comparisons**

In this section Tx-Rx isolations are investigated. The measured results by VNA are compared when the broadband RF devices, introduced in Section 3, are used to form four EBDs. The antenna and coupler are optimized individually, as given in previous sections. The designed stable impedance antenna (Section 3.1) and the commercial Taoglas PAD710 antenna (Section 3.2) are connected to the designed stable S-parameter coupler (Section 3.3) and the commercial Krytar 1831 hybrid coupler (Section 3.4) in separate set-ups to form EBDs. The 50 Ω wideband 50-ohm RF load (Section 3.5) is also connected as a balancing impedance to the couplers in all experiments. The experiment set-ups and measured Tx-Rx EBD isolations are shown in Figure 14.

Figures 6 and 8 show that the measured impedance and S-parameter of the commercial Taoglas PAD710 antenna are not stable in the frequency domain at the 1.5–3.5 GHz range. There are average real/imaginary impedance variations around 80 Ω and maximum return loss variations around 18 dB for the Taoglas antenna. Less impedance and S-parameter variations are seen for the designed stable impedance antenna from Figures 3 and 8 with an average 15 Ω variation for the measured imaginary/real impedance and a maximum of 7 dB variation for return loss at the same bandwidth.

For the commercial UWB Krytar 1831 coupler from Figure 12, it is already seen that the measured S-parameters are not stable in the frequency domain at 1.5–3.5 GHz range as there are dense isolation variations around 15 dB and return loss variations around 25 dB, while for the designed UWB coupler (Figure 10) fewer variations are seen with the isolation variations around 10 dB and return loss variations around 9 dB.

Figure 14 shows when using the commercial Taoglas PAD710 antenna, average Tx-Rx isolation of 11 and 16 dB is measured, for EBD with the commercial Krytar 1831 coupler and EBD with the designed stable S-parameter coupler, respectively at the 1.5–3.5 GHz range. Also, when using the designed stable impedance antenna, average Tx-Rx isolation of 20 and 29 dB is measured, for EBD with the commercial Krytar 1831 coupler and EBD with the designed stable S-parameter coupler, respectively at the same UWB bandwidth.
Figure 14. Measured Tx-Rx EBD isolation and EBD set-ups for the experiments in Section 4.

| Scenario                        | Commercial Taoglas PAD710 antenna | Designed stable impedance antenna |
|---------------------------------|-----------------------------------|-----------------------------------|
| Commercial Krytar 1831 coupler  | 11 dB                             | 20 dB                             |
| Designed stable S-parameter coupler | 16 dB                             | 29 dB                             |

(Table 1). While all four EBDs use the same 50 Ω RF load, it is seen that the widest UWB bandwidth and highest isolation are achieved when using the designed stable impedance (or S-parameter) antenna and the designed stable S-parameter coupler.

The first limitations still seen in the obtained optimized UWB isolation could be the small inherent impedance variations of the designed coupler and the designed antenna. The second reason could be the impedance mismatch between the antenna and 50 Ω balancing the load.

5. Conclusions

Electrical Balance Duplexers (EBDs) in systems like In-Band Full-Duplex (IBFD) transceivers isolate transmit and receive signals to implement a form of self-interference cancellation to facilitate simultaneous communication from a single antenna. EBD works by coupling transmitter, receiver, antenna, and balancing impedance using a hybrid
coupler. Antenna impedance variations are considered the main factor limiting the EBD isolation bandwidth in the literature. But hybrid couplers are also not ideal elements, and their S-parameters are variable in the frequency domain. Some UWB RF devices (two antennas, two couplers, and a 50-Ohm RF load) are used in the experiments to form four separate EBD set-ups. One of the antennas, designed by the authors, has more impedance stability in the frequency domain than the other one, which is a commercial UWB Taoglas PAD710 antenna. Also, one of the couplers, designed by the authors, has more S-parameter stability in the frequency domain than the other one, which is a commercial UWB Krytar 1831 coupler. The results of EBDs show that the widest Tx-Rx isolation bandwidth (UWB 1.5–3.5 GHz range) and the highest isolation amount are obtained when the antenna and coupler have strong S-parameter stabilities in the frequency domain.

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Data availability statement

The data that support the findings of this study are available from the authors upon request.

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