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Integrated Antenna Technique for Cancelling the Self-Interference Signal in Full-Duplex Communication

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Abstract—In this paper, a novel passive antenna cancellation technique for a full-duplex system is presented. This includes three patch antennas with a developed coupler that are constructed and integrated with the feed network to reduce the self-interference signal without the need for other components, thus achieving a complete antenna cancellation method. Computer Simulation Technology (CST) microwave studio is utilized to simulate the design model. A prototype was fabricated and tested practically to validate the proposed design. The computed results are compared with measurements. The proposed technique provides up to 68 dB cancellation at the operating frequency 2.45 GHz, and this decreases to 40 dB at 70 MHz bandwidth, and to 36 dB at 100 MHz bandwidth.

1. INTRODUCTION

Full-duplex communication is a new concept that is promising to enhance the spectral efficiency of current wireless systems. These systems use the same assigned radio resources (time and frequency) for the same channel. The crucial issue of achieving full-duplex in practice is to suppress the self-interference signal. Current wireless networks cannot meet the demand for high data rate radio service, which has been increasing dramatically, in addition to the sharp growth in wireless devices that are connected to these networks. This deficiency attributes to the limitation of the allocated spectrum for wireless networks, and this limitation prevents increasing the bandwidth of current networks or building new wireless systems. For this reason, researchers have been looking for a solution to overcome this significant issue [1–4].

Full-duplex communication is considered as one of the remarkable techniques that could help to solve the problem. By implementing full-duplex in current wireless networks, systems will be able to transmit and receive at the same time and same frequency. Consequently, it is not required to divide the bandwidth of a system to uplink and downlink as compared to current Time Division Duplex (TDD) and Frequency Division Duplex (FDD) techniques. As a result, it can theoretically double the data rate of current wireless networks without increasing the bandwidth of that system, or keeping the same throughput and releasing half of the spectrum to build a new network [2].

Old presumption states that sending and receiving using the same frequency at the same time is not possible, due to the self-interference signal. Nevertheless, much recent research [5–7] have been concentrating on full-duplex with cancelling the self-interference signal, and have challenged the old claims with a significant full-duplex radio system that could lead to implementing a real full-duplex in the near future [2].

In the full-duplex scenario, the receive antenna collects the desired signal that comes from a different node with low power and receives its self-signal, which is sent by the transmitter of the same node with very high power. This signal interferes with the desired signal because their frequencies are the same. As a result, the self-interference signal, whose power can be 100 dB stronger than the desired signal, will

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prevent the system from detecting the desired signal. Consequently, a real full-duplex scheme cannot be accomplished without suppressing the self-interference signal down to the noise flower level (-115 dB), so the receiver will be able to detect the desired signal [4].

The full-duplex system firstly requires high isolation between the transmit antenna and receive antenna to reduce the self-interference signal to an acceptable level. This technique is called passive cancellation. However, this method alone cannot cancel the self-interference signal down to the noise floor level. Therefore, to entirely suppress this unwanted signal, an active cancellation technique must follow the passive technique stage for further reduction of the self-interference signal. Active cancellation can be divided into two types: Radio Frequency (RF) cancellation, and digital baseband cancellation [6].

In this paper, a novel antenna cancellation scheme for full-duplex systems is presented to cancel the self-interference signal. Computer simulation technology (CST) microwave studio software is utilized to model the proposed scheme, which consists of three patch antennas; one receiving antenna and two transmitting antennas. The two transmitters are fed by a developed coupler, which is constructed and integrated with the antennas on one substrate. Results show that this simple structure can provide a high cancellation over a wide band of frequencies.

2. REVIEW OF CANCELLATION METHODS

This section gives an overview of the methods that have been proposed for cancelling the self-interference signal in full-duplex systems. Basically, the self-interference cancellation techniques can be classified into three stages: Antenna cancellation, RF cancellation, and digital cancellation. The first technique is also called passive cancellation, while the other followed methods are known as active cancellation [2]. A number of techniques will be discussed with their advantages and disadvantages.

-The Full-duplex Model with More Than One Antenna: In this method, more than one antenna are exploited. These antennas are placed in such a way to produce high isolation between transmitters and receivers, and/or sending more than one transmit signal to create a null at the receiver, which can be achieved by using extra components, such as a phase shifter, transformer or directional coupler. This method can reduce part of the self-interference signal. Therefore, it must be followed by the next stages [8, 9].

In [8], three antennas are employed, two as transmitters, and a single receiver. The receiving antenna is fixed between the two transmitters, such that the transmitters are placed away from the receiver at distances of (d) and ($d+\lambda/2$), respectively, where λ represents the wavelength of the received signal. The two transmitters send two copies of the transmitted signal. Due to the distance difference of ($\lambda/2$), the two received signals will cancel each other at the receiver. This method can only provide significant cancellation at the operating frequency by placing the antennas in their right positions. There are two factors that cause deterioration on the performance of this technique: sending a signal with a frequency far from the operating frequency that is used to calculate the wavelength (λ), and the incorrect placing of the antennas [10].

-RF Self-interference Cancellation: This method exploits the adjacency between the transmit chain and the receive chain by utilizing the knowledge of the sending signal. This stage is achieved by taking a copy of the sending signal at the output of the Power Amplifier (PA) and using it before the Low Noise Amplifier (LNA) of the receive chain to cancel the self-interference signal [6]. However, this method cannot accomplish perfect cancellation without studying the behaviour of the channel between the transmitter and receiver in terms of attenuation and delay. Channel effects must be compensated by adding a tuning circuit at the path of the copied signal before adding or subtracting it from the received signal to cancel each other. Many taps of the tuning circuit can be implemented to enhance the cancellation performance [10].

The proposed methods in this stage provide a self-interference cancellation of 20 to 45 dB [6–8]. Nevertheless, the used tuning circuits are complex. In [11, 12], 4-tap circuits are used, where each tap consists of a variable attenuator and phase shifter. While 12-tap circuits are applied in [13], where each tap has a fixed delay line with a variable attenuator. In [8], the QHx220 chip was exploited as a tuning circuit to match between the copied signal and the received signal from the free space. The received signal is applied as input to the chip with the copied signal. The chip changes the amplitude and phase of the copied signal according to the received signal and then subtracts it from the received signal.

Results show that this chip can achieve around 20 dB cancellation. However, it affects negatively on the digital cancellation stage by adding non-linearities and distortion at the received signal [14].

-Digital Self-interference Cancellation: This stage is applied after the analogue to Digital Converter (ADC) at the receiver side. It aims to cancel any residual self-interference signal after applying the Antenna and RF cancellation stages. To implement the digital cancellation process, the generated symbols at the transmit side are subtracted from the output of the ADC at the receive side. However, it is necessary to estimate the self-interference channel and rebuild the generated symbols according to the result of that estimation, and then the obtained symbols are subtracted from the received symbols [14].

As illustrated in [8], a coherent detector is utilized to estimate the self-interference channel. The detector correlates the received signal with the transmitted signal, which is taken from the transmit chain. This process estimates the phase shift and delay between the two signals. The delay and phase shift can be known by detecting the peak of the correlation process. Then, the generated symbols are adjusted according to the delay and phase shift. Finally,the adjusted symbols is subtracted from the symbols that come out from the ADC of the receive chain.

3. FULL DUPLEX MODEL

This paper presents a new and integrated full-duplex technique with the multiple antenna method to cancel the self-interference signal. The idea of this technique is based on creating two signals of equal magnitudes and 180° phase shift by designing a 180° coupler, which is developed from the quadrature coupler, and placing the two transmit antennas far from the receive antenna at equal distances. As a result, the two transmitted signals will cancel each other at the receiver across a wider range of frequencies as compared to the method of placing the two transmitters at two distances differing by ($\lambda/2$).

One of the significant features of this design is that the receiver can be used as a transmitter, while the two transmitters are exploited as receive antennas by switching only the feeding cables. Results show that the two scenarios achieve the same degree of cancellation. However, using one transmitter strategy is better in terms of the far-field radiation pattern, because it does not produce nulls at the far-field compared with the two transmitters strategy, which creates one null. The scenario of using two antennas as transmitters and one as a receiver will be used to explain the concept and the architecture of the proposed model.

The prototype consists of two parts: (i) a developed 180° directional coupler that provides two equal signals in amplitude with 180° phase shift between them, and (ii) three patch antennas, two as transmitters and the other as a receiver. The directional coupler is combined with the patch antennas. This integration is so crucial for enhancing the cancellation performance; because the degree of cancellation of the multiple antenna techniques can be deteriorated by any small mismatch between the amplitudes and phases of transmitted signals, and this mismatch usually happens due to connecting tools with antennas, such as connectors, cables. Additionally, the incompatibility between the components that feed the antennas by the signals also causes the mismatch, such as a directional coupler, phase shifter, circulator and attenuator.

The directional coupler and patch antennas are configured by using the CST software at a frequency of 2.45 GHz. The two parts are structured on the same substrate and simulated together to overcome the mismatch that leads to degrading the cancellation degree. The parameters of the directional coupler and antennas were adjusted to obtain higher cancellation, and this step could not be accomplished by the previously suggested works.

3.1. 180° Directional Coupler

The directional coupler is structured in such a way to provide two output signals that are equal in amplitude and have 180° phase difference. A small size branch line coupler or direct coupled operating at 2.45 GHz was designed. The hybrid coupler consists of four ports, one is the input port, port two and three are the through and the coupled ports respectively, and the fourth port is the isolation port, which is usually terminated by a 50 Ω load.

The coupler aims to split the input signal (the originally transmitted signal), at port one into two equal signals in power with 90° phase difference at port three and four respectively, while port four is terminated by 50 Ω load. The FR4 substrate having relative dielectric constant, $\varepsilon_r = 4.7$, substrate thickness $H = 1.6$ mm, and ground and metal thickness $T = 0.035$ mm was used. The width and length of microstrip line of the coupler can be calculated by exploiting the available online TX line tool calculators, or by the following equations:

To find the width of the hybrid main line (w):

$$B = \frac{377\pi}{2Z_o\sqrt{\varepsilon_r}} \tag{1}$$

$$\frac{w}{h} = \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right] \tag{2}$$

using Eqs. (1) and (2) it can be shown that $w = 2.95$ mm.

To find the length of the hybrid main line Eqs. (3) and (4) are used:

$$k_o = \frac{2\pi f}{c} \tag{3}$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\sqrt{\frac{1}{1 + \frac{12h}{w}}} \tag{4}$$

Using the above relations, it can be shown that $l = 16.3$ mm.

The same equations can be applied to find the width and length of the shunt arm transmission line with changing only the value of the impedance to $(Z_o/\sqrt{2})$. Figure 1 depicts the impedance values of each arm. After finding the length and width of the mainline, shunt arm and input line, the dimensions of the presented quadrature coupler are shown in Figure 2.

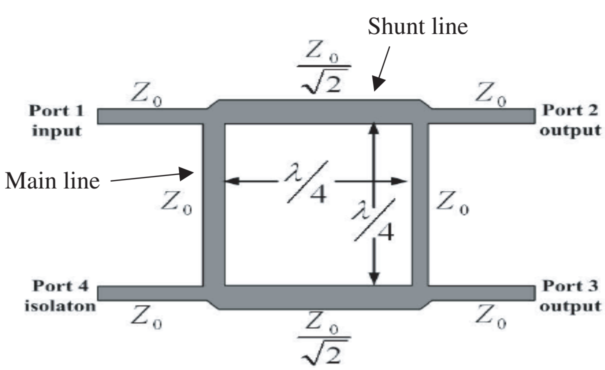

Figure 1. The 90° hybrid coupler.

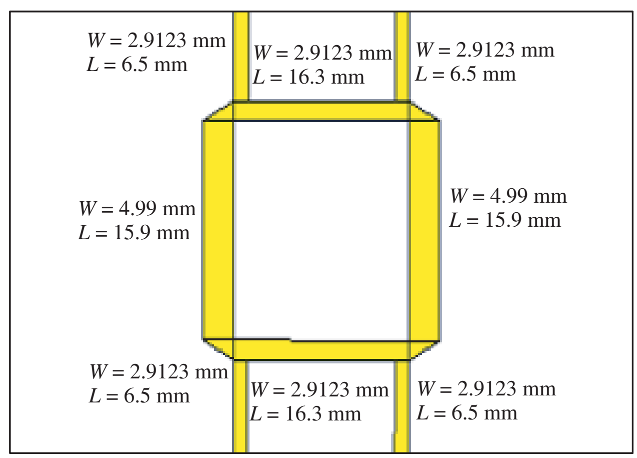

Figure 2. The model and dimensions of 2.45 GHz branch line coupler.

The coupler is modelled and simulated by using CST microwave studio. Then, extra transmission lines similar to the main line and having proper lengths were added to facilitate connection to the three microstrip patch antennas. Additionally, an extra transmission line similar to the main line is connected to port three and extended at the right side as shown in Figure 3. This extra line will delay the signal at port three by another 90°. Consequently, the signal at port three will be 180° out of phase with the signal at port two. The optimization process has been applied many times to obtain equal signals in amplitude with 180° phase difference between port two and three at the chosen frequency band.

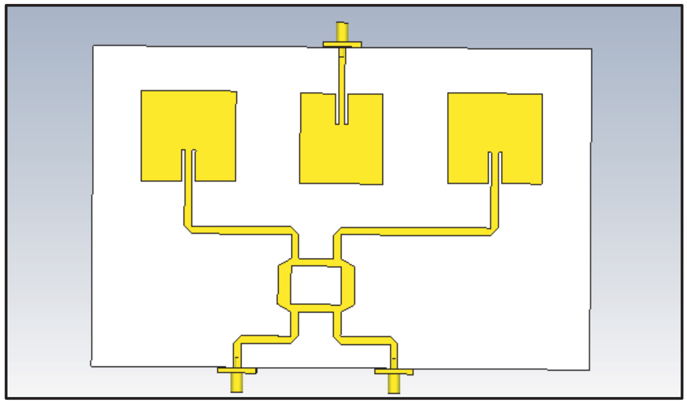

Figure 3. The complete structure of the full duplex model.

3.2. Antennas Configuration

Three patch antennas are utilized in this prototype, two as transmitters, while the other as a receiver. The same substrate material and thickness of the coupler is used for the antennas. Antennas are constructed to work at a band frequency centered at 2.45 GHz, and the inset feed method is used to match the patch antenna. Following the design procedure in [15], the parameters of the square patch antenna were found to be; the length of the patch (L) equals its width $W = 36.26$ mm, and the feed inset distance $Fi = 4.8$ mm.

The two transmitters are separated by a distance D:

$$D = 6 \times \text{length of the main coupler line} - \text{length of the patch}$$

This distance equals the space between ports two and three of the coupler. Then, the receive antenna is placed at the middle of this distance. The three antennas are simulated by using CST microwave studio. Then, the receive antenna is rotated by 180° from the two transmitters. This rotation will not affect the received signal, and will allow measuring the received signal easily.

The three antennas structure was simulated by using CST microwave studio after rotating the receiver, and the same results have been obtained before rotating the receiver. The optimization process has been implemented many times to obtain a similar reflection coefficient of the two transmitters and to equalize and increase the isolation between the receiver and both transmitters. These two considerations lead to transmitting two equal power signals with 180° phase shift, when feeding the two transmitters by equal power signals with 180° phase shift, and they will cancel each other at the receiver because they will cross the same distance, and suffer from same channel attenuation.

After obtaining the best results, the substrate of the patch antennas was merged with the substrate of the coupler, where both are made from the same material (FR4), and the same thickness. The feed lines of the two transmitters are connected directly with port two and port three after merging the two substrates of the two structures. In the design of the patch feed line, the feed line width (Wf) is chosen to be similar to the width of the main line coupler (W). The time domain solver in CST microwave studio is used to simulate the prototype, and the simulation process has been applied many times with the help of CST optimization feature to obtain high cancellation. After merging the coupler and antennas, the prototype occupies 16 cm in length, and the width is 7.8 cm, as shown in Figure 4. The cancellation performance can be enhanced by increasing the space between the patch antennas. However, the structure size will be larger.

In this method, three reasons lead to achieving high cancellation over a wide bandwidth. Firstly, the method does not exploit the spacing idea to create the phase difference between the two transmitted signals, because the cancellation performance will be restricted by the frequency that is used to find the wavelength. So the three antennas are separated by similar distances. Secondly, the coupler is constructed to produce two equal power signals with 180° phase shift at a wide frequency band. Lastly, the previously suggested techniques employ components such as phase shifter, external directional coupler, and attenuator to create the two sending signals. Connecting these components with antennas

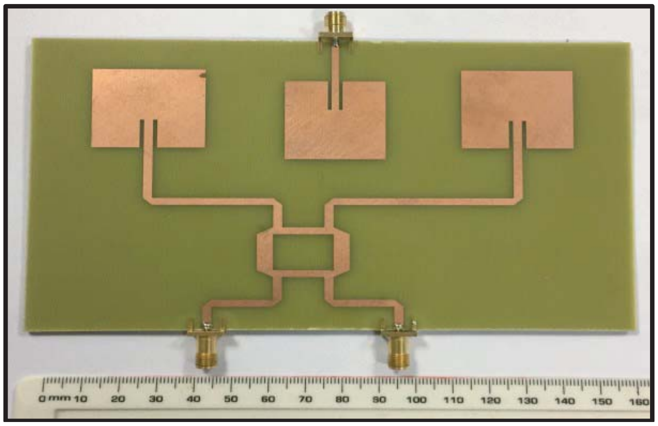

Figure 4. The complete fabricated prototype of the proposed full duplex model.

need cables and connectors, and these tools add losses and delay to the signals. Therefore, they cause a mismatch between the two sending signals and eventually lead to degrading the cancellation performance. In contrast, the presented method in this paper solved this problem, by constructing a coupler and integrating it with the antennas so that there is no need for cables and connectors.

3.3. Practical Prototype

After obtaining the best cancellation result, the model was fabricated at Bradford University Laboratory. Then, a network analyser was used to measure the scattering parameters and the cancellation performance as shown in Figure 4.

4. NUMERICAL RESULTS AND DISCUSSION

This section presents the simulation and practical results of the coupler and antennas after combining them together.

4.1. Simulation Results of the Coupler

Figure 5 shows the scattering parameters (S-parameters) of the four ports of the constructed coupler. Figure 6 displays the reflection coefficients of the four ports (S_{11}), (S_{22}), (S_{33}) and (S_{44}). It can be noted that the values of the four mentioned parameters are less than -20 dB over a wide bandwidth

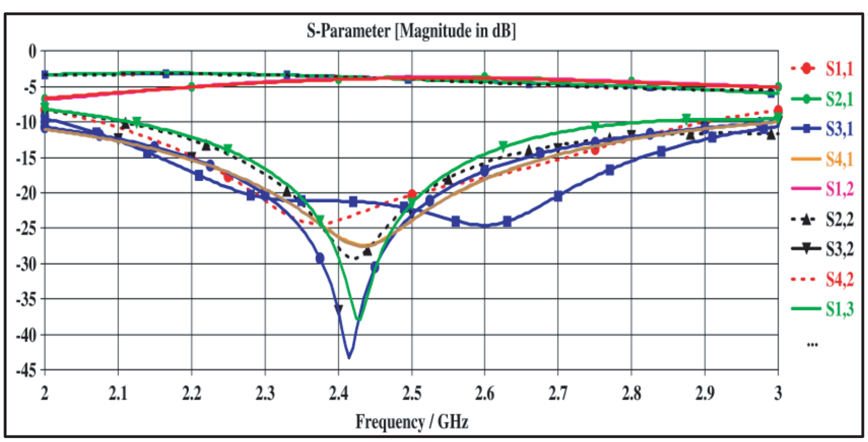

Figure 5. The four ports S-parameters for the 180° directional coupler.

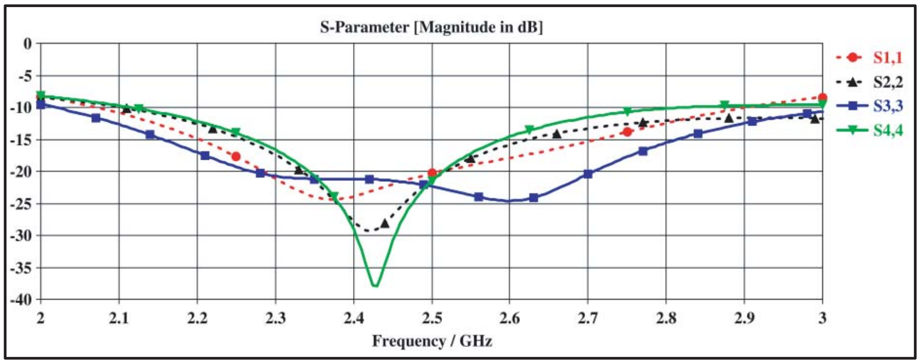

Figure 6. The reflection coefficients (S_{11}, S_{22}, S_{33}, and S_{44}) at the ports of the constructed 180° directional coupler.

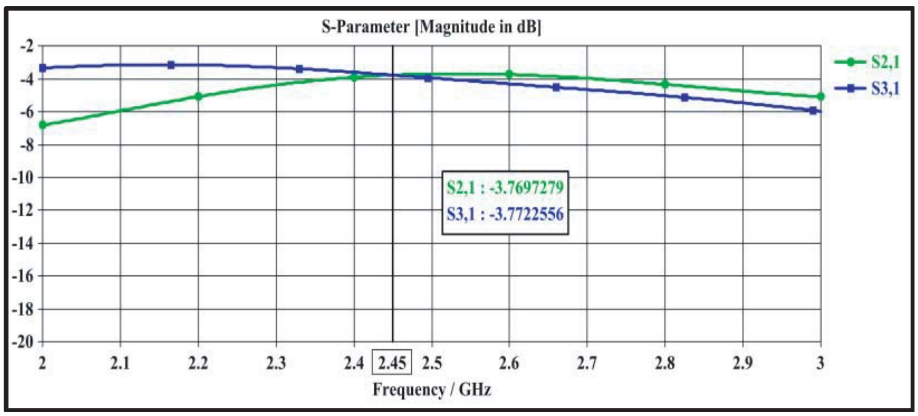

Figure 7. Power outputs of the through and coupled output (the two sending signals).

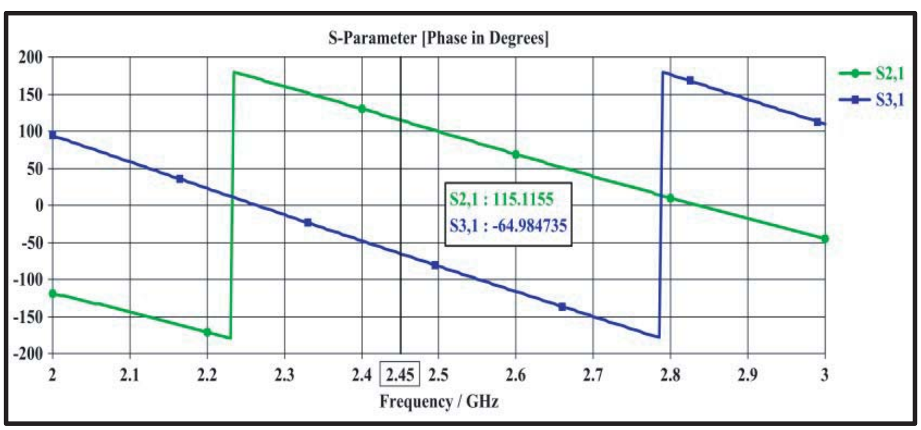

Figure 8. The phase of the through and coupled outputs.

($\sim$ 100 MHz), and less than -10 dB over 350 MHz bandwidth. Therefore, the coupler can be utilized for systems that deal with a range of frequencies.

Figures 7 and 8 illustrate the magnitude and phase of the forward transmission gains of the through and coupled port (S_{21} and S_{31}). It can be seen that the magnitude of the parameters are equal at the operating frequency (2.45 GHz) with value -3.7 dB, and there is a small difference between the two values ($\sim$ 0.2 dB) across the desired bandwidth (2.4 GHz–2.5 GHz = 100 MHz), which is considered as a very small difference. However, it has a negative effect on the cancellation performance due to the sensitivity of the cancellation process to the amplitude and frequency of the two sending signals. As shown in Figure 8, there is exactly 180° phase difference between the two values at the frequency 2.45 GHz. Results also show that this coupler can provide (178°–182°) phase difference between the two output signals across 100 MHz bandwidth. These accurate results in amplitude and phase difference lead to achieving high cancellation at a wide bandwidth.

Phase difference ($\Delta\theta$) = (the phase of $S_{21}(\theta 1)$ − the phase of S_{31}) = (115.116 − (−64.985) = 180.1°.

4.2. Simulation Results of the Antenna Structure

Figure 9 illustrates the S-parameters of the three antennas. It can be noted that because of the antenna structures are identical, some parameters are equal ($S_{12} = S_{21}$) and ($S_{13} = S_{31} = S_{23} = S_{32}$). The similarity between the reflection coefficients of the two transmit antenna leads to radiating two equal signals. Additionally, due to the equal distance separation between the two transmitters and receiver, the two signals suffer from equal channel attenuation. As a result, it is not required to study channel effects by using this method, and the two sending signals reach the receiver with equal power and 180° phase difference.

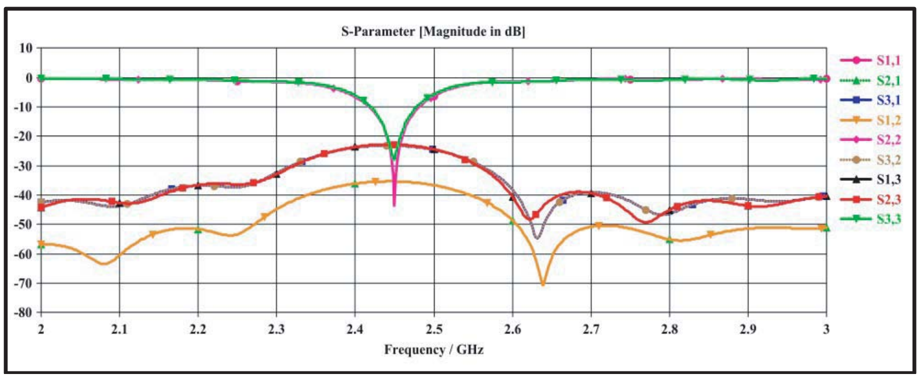

Figure 9. The S-parameters of the three patch antennas.

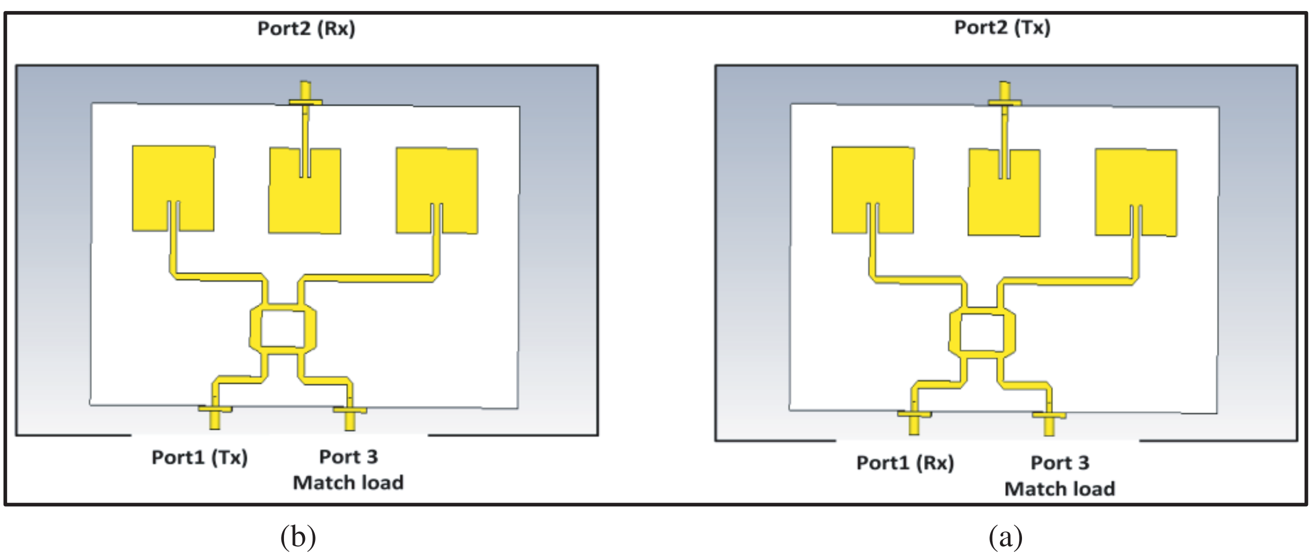

Figure 10. The two scenarios for transmitting the signal. (a) One transmit antenna and two receivers, (b) two transmit antennas and one receive.

4.3. Simulation Results after Combining the Antenna and Coupler Structures

The proposed model can be used to transmit the signal in two scenarios. The first one uses two transmit antennas and one receiver, while the second scenario uses one transmitter antenna and two receiving antennas. The two scenarios are illustrated in Figure 10. The same model can also be used on the other side of the communication link.

4.3.1. The Results When Using Two Antennas as Transmitters and One Receiver Antenna (Scenario One)

Figure 11 demonstrates the forward transmission gain parameter (S_{21}), which refers to the cancellation performance of the system for the scenario shown in Figure 10(b). It is obvious that this prototype has achieved high cancellation of 67.7 dB at 2.45 GHz, while a 50 dB cancellation can be obtained across a 17 MHz bandwidth: (2.4494 GHz–2.432 GHz = 17 MHz). However, the cancellation performance decays to 40 dB across a larger bandwidth of 60 MHz band, and 36 dB cancellation across a 100 MHz bandwidth. According to these results, this simple system can offer about 40 dB reduction to the self-interference signal over a wide bandwidth (100 MHz). Thus if this design is followed by other cancelation stages, such as RF and digital cancellation, the design will aid to cancel the self-interference signal to the noise floor, and furnish the implementation of the full-duplex system in real.

Figure 12 displays the far-field radiation pattern of the model for the scenario shown in Figure 10(b). It is obvious that there is one null at the far-field, and the maximum gain is 6.11 dB. This null attributes to using two transmitting antennas sending two signals with 180° phase shift, which leads to destructive

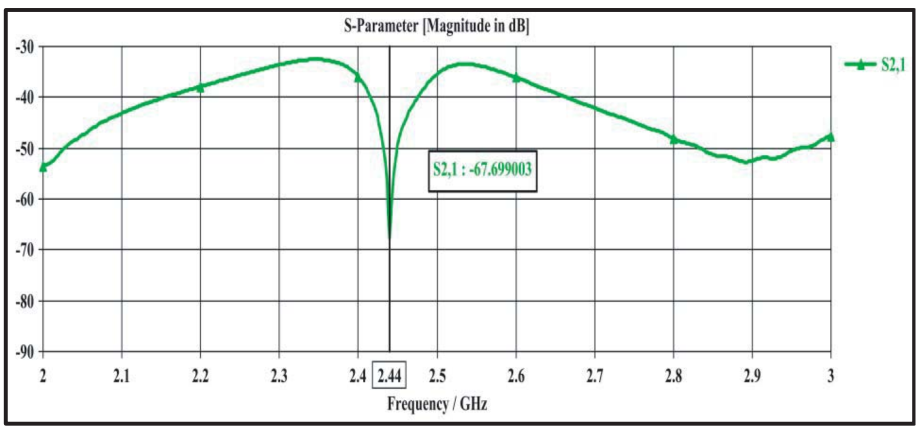

Figure 11. The cancellation performance of the model (S_{21}) for the scenario shown in Figure 10(b).

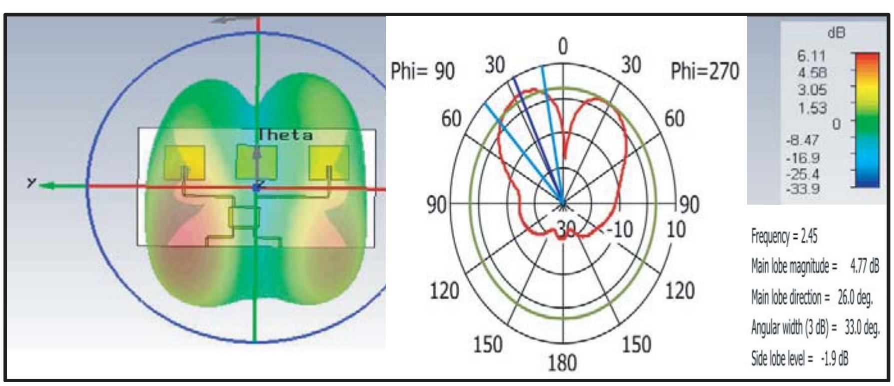

Figure 12. The far-field radiation pattern when using the two-transmitters scenario shown in Figure 10(b).

interference in the direction normal to the plane of the antenna. Consequently, the receiving end will not receive a signal when it is placed along the normal to the transmitting antenna. The antenna at the transmitting side can be oriented so that one of the two main beams is directed towards the receiving side.

4.3.2. Results When Using Two Antennas as Receivers and One Antenna as a Transmitter (Scenario Two)

Figure 13 shows the forward transmission gain parameter (S_{12}), which refers to the cancellation performance of the system for the scenario shown in Figure 10(a). It can be noted that the accomplished cancellation performance is similar to the former scenario, i.e., when using one antenna as a receiver and two antennas as transmitters. Additionally, the results of Figure 13 show that there is no null when using one antenna as a transmitter, and the far-field pattern is similar to that of a patch antenna, as shown in Figure 14. The radiation pattern is wider in this case and the maximum gain is 2.23 dB (lower than the 6.11 dB of the other scenario) since here one patch antenna is transmitting. This feature is considered as an advantage of using this scenario as compared to implementing two antennas as transmitters. However, there will be a null at the receiving side in the direction of the transmitter due to using two antennas as receivers. This problem arises when the antenna at both sides of the communication link are placed in the planes normal to the line of sight. This issue can be solved by directing the antenna at the transmitter side towards one of the two main lobes of the two receive antennas. Alternatively, the antennas at the two ends can be configured as shown in Figure 15. The figure shows the signal flow for the two scenarios of using one transmitter and that of using two transmitters.

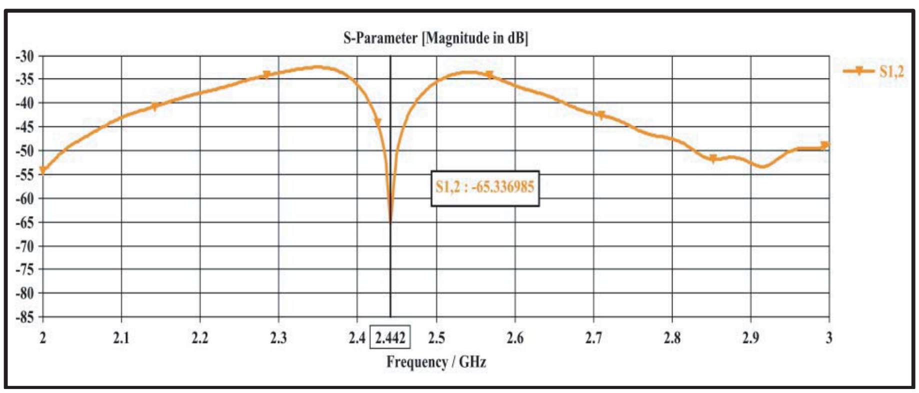

Figure 13. The cancellation performance of the model (S_{12}) for the scenario shown in Figure 10(a).

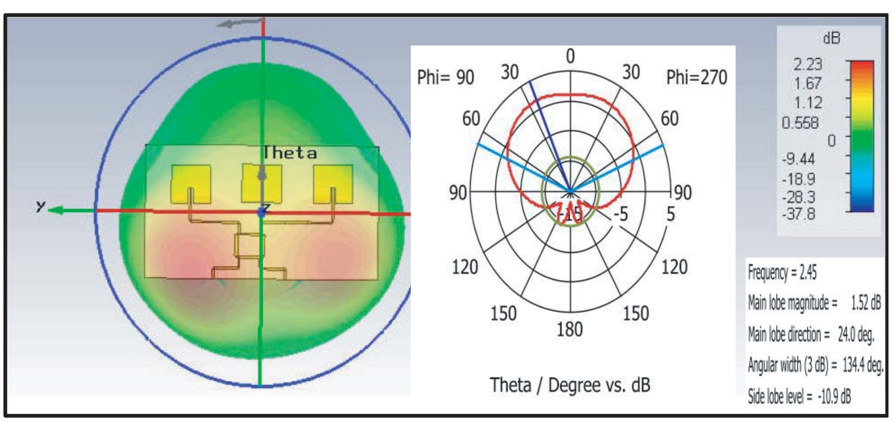

Figure 14. The far-field radiation pattern when using one transmitter scenario.

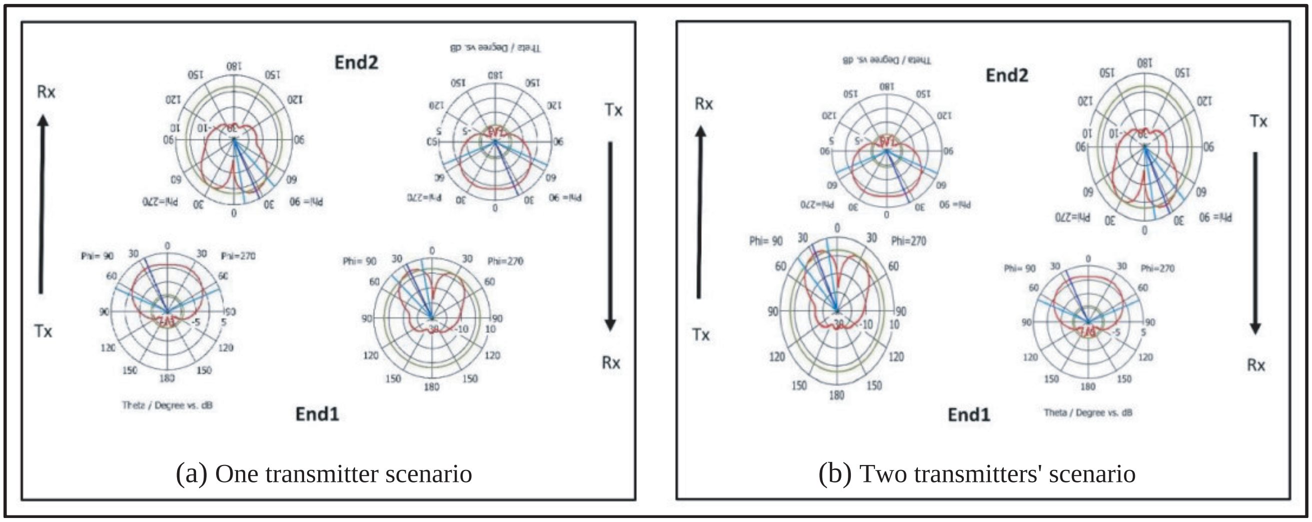

Figure 15. The alignment of the two ends of the communication link to avoid the nulls.

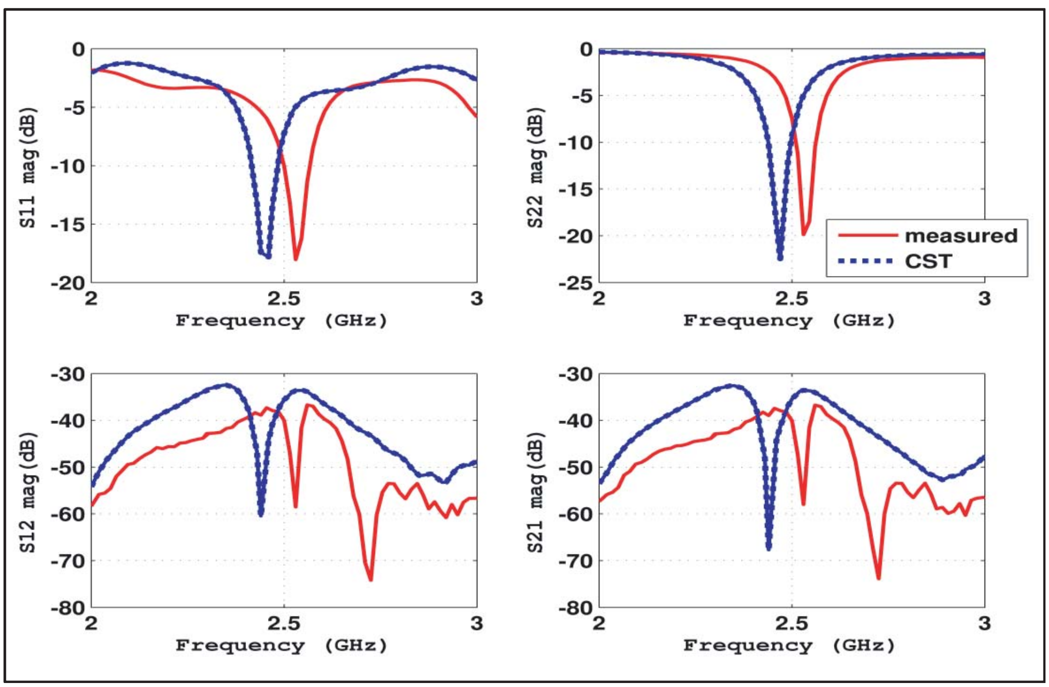

Figure 16. The measured and simulated S-parameters of the proposed design.

4.4. Practical Results

This section displays the results of the fabricated prototype which were obtained using a network analyser. Figure 16 compares the simulated and measured S-parameters. It is clear that the values of the reflection coefficients of the input (S_{11}) and output (S_{22}) ports have a minimum of less than -18 dB at the frequency 2.53 GHz. This means the best matched frequency has been shifted from 2.45 GHz of the simulation to 2.53 GHz for the measured results. This small shift of 3.3% can be attributed to the accuracy of the fabrication process. The figure also shows the cancellation performance (S_{12} and S_{21}), where it can be seen that more than 55 dB cancellation can be obtained by using either of the two scenarios (two transmitters and one receiver scenario, or one transmitter and two receiver scenario).

5. CONCLUSIONS

A full-duplex system with a new antenna cancellation method has been presented. Three patch antennas are utilized to model this technique, two as transmitters, and one as a receiver. The receive antenna is placed at the centre between the two transmitters to ensure equal distances to both antennas. The transmitters are fed by two signals with equal magnitudes and 180° phase difference. These two signals are generated by a coupler, which is integrated with the three antennas on a single substrate. The design was modelled by the CST microwave studio and investigated at operating frequency 2.45 GHz. The model can be changed to form two receivers and one transmitter scenario, and this can be simply implemented by switching the feed points. This prototype does not require any further components to perform the cancellation as it is a complete and compact system.

Simulation results showed that the model could reduce the self-interference signal by 67.7 dB at a single tone frequency of 2.45 GHz. However, the cancellation performance was degraded gradually to reach 35 dB cancellation over 100 MHz bandwidth. This degrading attributes to the mismatches and departure of the 180° phase shift as the frequency departs from the centre value. It is clear that this method accomplishes high cancellation across a wide range of frequencies.

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