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Dual-Polarized High-Isolation Antenna Design and Beam Steering Array Enabling Full-Duplex Communications for Operation Over a Wide Frequency Range

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ABSTRACT A new dual-polarized antenna and array are presented for In-Band Full-Duplex (IBFD) applications, offering high inter-port isolation. The single-element antenna system consists of four H-shape slots, stacked patches for wide bandwidth, and two external hybrid couplers. The multilayer antenna is well matched from about 2.1 to 2.4 GHz and provides high isolation in this frequency range in excess of 60 dB. Two different prototypes are simulated and measured to highlight the design process. In addition, a new and compact hybrid coupler with excellent phase and magnitude stability is also presented for improved antenna radiation and IBFD performances. When compared to other similar types of hybrid coupler and antenna systems, the proposed configurations are simple to manufacture, provide a higher isolation bandwidth (10%), and higher gain of 7.3 dBi with cross-polarization levels of 30 dB or lower. The single-element design was also extended to a 2×2 array and studied for different beam steering and feeding scenarios. The operating bandwidths and isolation values offered by these S-band antenna and array systems can support new data link possibilities for beam steering and future low-cost IBFD wireless networks by simple antenna fabrication.

INDEX TERMS Dual-polarization, double-differential antenna, full duplex, isolation, simultaneous transmit and receive (STAR).

I. INTRODUCTION

With the advancements of wireless communications, full-duplex (FD) antenna systems are once again a topic of interest [1]. These systems are attractive not only because of their ability to simultaneously transmit and receive thus requiring less antenna hardware, but also, due to the possibility of increased channel capacity and spectrum density [2]–[4]. However, due to this simultaneous transmit and receive capability, these systems can experience high self-interference (SI) where the transmitted signal is so strong that it suppresses the received signal making FD data transmission challenging.

One of the first implementations of FD systems was in radar. Due to technological limitations, the only way to reduce interference was to control the transmitting power which causes the operating range of the radar to be limited. With more recent advances, there are now a number of technologies that can be employed to suppress this interference. One way to cancel out the SI is to implement an analogue cancellation mechanism, for example, using coupler phase compensation systems to cancel out the received signal or expensive and bulky circulators which might have only 20 or 40 dB of isolation [5], [6]. Another method of SI suppression is digital cancellation. Examples of digital cancellation
techniques are the use of specific transmission protocols [7] or digital-domain cancellation [8]. Finally, one of the most efficient and low-cost means of SI suppression is to adopt antenna-related approaches for signal isolation. This could be the utilization of different frequencies for up-link and down-link data transmission (dual-band) [9], or if a single frequency (in-band) is required, a dual-polarized antenna with high port-to-port isolation might be preferred [10]. Both approaches can support FD communications.

Depending on the application, these techniques can be combined or employed to suppress the SI to the required level. Typical examples of isolation values that have been reported in the literature are in the order of 70 to 80 dB [11] over a bandwidth of 3%. To achieve good FD operation [12], with a bit-error-rate (BER) suitable for robust two-way communications, the total SI cancellation must be approximately 100 dB [12] or higher (reaching the noise floor of the system). For example, in [11] and [13], isolation values in excess of 100 dB were reported when using FPGA digital cancellation, circulator-based antennas, and analogue circuit cancellation.

One of the earliest designs of an inter-port antenna with high isolation was a circular patch design in [14]. In that paper, two antenna designs were investigated. Both consisted of two H-shaped slots and circular shaped patches elevated above the ground plane. As a result, the antennas offered bandwidths of 8% with isolation values of only 31.3 dB. In that same work [14] the authors extended the system to four H-shaped slots and a feeding circuit consisting of two Wilkinson power dividers. Using this approach, the authors were able to improve the antenna bandwidth to 17% and the port-to-port isolation to 34 dB. The antenna gains reached 6.8 dBi with cross-polarization levels of 14 dB at the center frequency.

Another method to achieve high isolation between the transmitting and receiving ports is to design a Dual-Band (Out-of-Band) system. Antennas in such systems are less affected by SI due to having different transmitting and receiving frequencies. One such antenna was proposed in [9]. In that design the data was transmitted at a center frequency of 4.7 GHz and a received frequency of 6 GHz. The antenna consisted of coupled-resonators with a patch placed on top. The reported antenna −10 dB impedance bandwidth was about 5.5% with isolation values around 35 dB and a maximum gain of 6.7 dBi. The antenna was further expanded into a 2 × 2 array system which slightly reduced the isolation to 30 dB and increased the gain to a maximum of 12 dBi. In a similar fashion, the dual-polarized antenna reported in [15] utilized a four-port system to achieve dual-band operation at 1.8 GHz and 2.0 GHz for transmitting and receiving, respectively. The proposed antenna consisted of resonator-based filtering channels, slot lines, and a radiating patch. The reported gain was 7.2 dBi and the isolation was greater than 23 dB.

Following these recent developments, in-band full-duplex (IBFD) antennas are generally of greater interest than their dual-band counterparts, for reasons of their single frequency re-use and doubled spectral efficiency [16]. The main focus of recent research studies was to achieve wider bandwidths, high as possible inter-port isolation, and to operate using dual-polarization. Previous FD antennas, which operate over a wide frequency range, as proposed in the literature are generally complex, might require careful feed and design considerations, and possibly can be expensive to manufacture. One such antenna was proposed in [17]. The involved design consisted of four T-shape parasitic elements mounted on a metallic ground plane. However, the antenna provided an impressive bandwidth of 98% and operated at frequencies between 0.6 to 1.75 GHz with isolation values below 40 dB. Maximum realized gain for the receive and transmitting mode was approximately 7 dBi and 6 dBi, respectively, and with an omnidirectional-like radiation pattern. Similarly, a metallic-based, four-port antenna was reported in [18]. It provided an wider bandwidth of 108% and operated from 0.8 GHz to 2.7 GHz. The antenna design consisted of resonating metallic ring elements with dipole-like arms, producing a monopole-like radiation pattern. The reported maximum realized gain was 7 dBi with inter-port isolation values of 37 dB over the entire operating range.

These antennas are suitable for use in base station applications due to their wide operational bandwidth and their physical size. However, simpler and lower-cost solutions using printed circuit board (PCB) manufacturing techniques, for example, can be more attractive for use in more basic or low-power radio transmission links for day-to-day communication systems such as Wi-Fi.

Recently, different structures have been reported which consist of hybrid couplers and a single resonating patch antenna [19], [20]. These designs are based on a single- and double-differential signal shift, where a phase shift of 180° is achieved between two coupler ports while a third port is terminated by a 50-Ω load. With this feeding, SI is reduced and a high isolation of 40 to 50 dB can be achieved whilst the antenna system is matched. Moreover, due to the signal cancellation effect at the coupler, i.e., the 180° phase shift, the antenna cross-polarization in the far-field is also improved. However, previous designs [19], [20] which have implemented this technique have offered narrow isolation bandwidths. On the other hand, the antenna presented in [21], which operated at 5 GHz, achieved isolation levels of over 50 dB with a bandwidth of about 9%. That antenna system [21] was implemented using only one slot-line type hybrid coupler supported by a network of power dividers making it a single-differential feeding approach. In that work, port one of the coupler provided an equal signal phase shift, while port two provided a differential shift. This possibly limited the antenna performance and increased the cross-polarization levels. Moreover, the −10 dB impedance bandwidth over frequency for ports 1 and 2 were not the same.

Another IBFD dual-CP antenna based on a sequential rotation array (SRA) and an additional phase compensation control circuit was proposed in [22]. The system consisted of four circularly polarized patches, two 180° hybrid couplers,
FIGURE 1. Antenna design exploded view: four-port antenna system with H-shaped slots and two parasitic square patch elements on top to increase bandwidth. Two external couplers are required (as in Fig. 2) to enhance the isolation.

FIGURE 2. Bottom view of the feed system and coupler layout. a) Bottom view: 50-Ω microstrip lines are printed on the bottom to feed the H-shaped slots which are isolated using vias. b) Rat-Race coupler: Coupler Port 1 is the input port to the antenna and feeding network and system, Coupler Ports 2 and 4 are connected using external cables to Antenna Ports 1 and 2 to provide a 180° phase shift; i.e., differential feeding while Coupler Port 3 is terminated with a 50-Ω load. A second coupler and analogous connections are required for Antenna Ports 3 and 4.

TABLE 1. Prototype comparisons considering the cables and couplers.

<table>
<thead>
<tr>
<th>Developed Prototype</th>
<th>Measured / Simulated</th>
<th>Frequency Range</th>
<th>Percentage Bandwidth</th>
<th>Corresponding Isolation Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam Spacers</td>
<td>Simulated</td>
<td>2.15 to 2.34 GHz</td>
<td>10%</td>
<td>45 to 49 dB</td>
</tr>
<tr>
<td>Foam Spacers</td>
<td>Measured</td>
<td>2.15 to 2.35 GHz</td>
<td>9%</td>
<td>48 to 49 dB</td>
</tr>
<tr>
<td>Nylon Screws</td>
<td>Simulated</td>
<td>2.25 to 2.45 GHz</td>
<td>10%</td>
<td>60 to 70 dB</td>
</tr>
<tr>
<td>Nylon Screws</td>
<td>Measured</td>
<td>2.14 to 2.42 GHz</td>
<td>11%</td>
<td>48 to 60 dB</td>
</tr>
</tbody>
</table>

and an additional circuit on the receiver port with an attenuator and phase shifter. The reported radiation bandwidth was 10% with a maximum realized gain of 10 dBi. In addition, the developed cancellation circuit on the receiver side, integrated on a separate board, compensated the phase instabilities of the cables and the hybrid coupler. This improved the isolation beyond 50 dB.

Following these developments we propose a new and low-cost antenna and array offering high inter-port isolation which can be useful for future wireless networks and RF-IBFD systems. Our design process is reported in Sections II and III. By the inclusion of simple antenna excitation approaches for improved bandwidths, double-differential feeding, and by adopting different isolation techniques not explored previously in the literature for FD antennas, the problem of SI can be further alleviated whilst offering an advancement from previous studies. For example, isolation values in excess of 60 dB are observed for a corresponding 10% impedance bandwidth for the developed antenna (see Figs. 1 and 2). A second coupler and analogous connections are required for Antenna Ports 3 and 4.

To reduce leakage effects and improve the isolation, the H-shaped slots in both designs were surrounded by a network of metalized vias (see Fig. 9) with a diameter and periodicity of 2 mm and 3.3 mm, respectively. The antenna PCB design material was FR-4 (see Fig. 1, for stacked patch # 1 and # 2) with a relative permittivity of 4.6 and thickness of 1.6 mm. The H-shaped slots serve as an excitation mechanism for the top radiating patches [23] with square dimensions of 48.3 mm for the bottom patch and 42.5 mm for the top patch. This multilayer configuration can increase the bandwidth of the antenna system. The overall dimensions of the system are 150 mm by 150 mm (which corresponds to 1.13 λ₀ and 2.25 GHz, where λ₀ is the free-space wavelength). The choice of the relatively large ground plane size increases the antenna gain whilst reducing the sidelobe levels (SLLs) caused by any parasitic radiation from the H-shaped slots.
As a first step in the feeding system design a basic microstrip-based hybrid coupler was employed (see Fig. 2). This enables double-differential external feeding making the feeding network for the single-element consist of two simple Rat-Race couplers. These couplers were designed and manufactured using a Taconic TLY-5A substrate which has a relative permittivity of approximately 2.2 and a thickness of 1.6 mm. With this external feeding approach, the two driven Antenna Ports (1 and 2, or 3 and 4, see Figs. 1 and 2) will have a 180° phase shift. This antenna and feed configuration can provide two orthogonal linear polarizations with a main beam radiating at broadside. For example, by driving Antenna Ports 1 and 2, the generated far-fields in the x-z plane will be linearly polarized. Similarly, by exciting antenna ports 3 and 4, the dominant fields in the y-z plane will also be linearly polarized. Moreover, when the two couplers have perfect phase balance and the same amplitude; i.e., minimal magnitude imbalance, the inter-port leakage of the transmitted and the received signal can be minimized.

The antenna and hybrid couplers were designed and simulated in the commercial full-wave simulator CST microwaves studio. Since the antenna ports will be driven simultaneously, the proposed structure was initially optimized and analyzed using active F-parameters (i.e., active S-parameters), with the applied 0° and 180° shifts and without the external hybrid coupler system. Simulations suggest that the antenna is well matched between about 2.2 GHz to 2.46 GHz where the reflection coefficient is below \(-10\) dB. Also, the corresponding port isolation is below 60 dB in this frequency range (see Fig. 4). This defines an operating bandwidth of about 10%. The simulated maximum realized gain can be observed at 2.3 GHz in Fig. 4 with a value of 7.8 dBi. Also, the antennas and couplers were simulated independently which allowed us to use the S-parameter combination tool in CST. Isolation values of more than 70 dB over the operating frequency.
FIGURE 6. Simulated (dashed lines) and measured (solid lines) normalized beam patterns at the operating frequencies for the antenna as in Fig. 3. Results are in agreement and cross-polarization levels are 20 dB (or more) below the main beam at boresight.

FIGURE 7. Simulated (black line) and measured (red/green dots) realized gains for the antenna system considering foam spacers (see Fig. 3). It should be noted that the single-element was measured in both transmit and receive mode.

range of the antenna and coupler system can be observed (see Fig. 5).

III. SINGLE-ELEMENT FABRICATION AND SYSTEM MEASUREMENTS

The proposed prototype IBFD antenna and couplers were manufactured and measured. A photograph of the antenna prototype with foam spacers and nylon screws can be seen in Figs. 3 and 9, respectively. The S-parameter measurements were done using Keysight PNA's N5225A and 5234A. The antenna was loaded with the elevated patches. Ideally the H-shaped slots and the patches would by spaced apart by air layers. For implementation of the first prototype, Laird Eccostock PP-4 type foam with a relative permittivity of 1.06 was used as a spacer between the patches and the H-shaped slots.

To verify the beam pattern performance in the far-field, the antenna measurement system DAMS 7100 Diamond Engineering was used in the anechoic chamber at Heriot-Watt University. As a reference antenna, a Flann Horn (type 08240) was employed. The simulated and measured beam patterns can be observed in Fig. 6 while the antenna gain (measured in both receive and transmit modes) is reported in Fig. 7. It should be mentioned that the maximum measured realized gain was 7.3 dBi at 2.3 GHz, which is slightly less than what was simulated by about 0.5 dBi. Measured realized gain from ports one and two, and three and four, are similar since the antenna is fully symmetrical. However, in receive mode the measured gain was slightly lower. These minor discrepancies could be related to measurement tolerances or interactions with the antenna positioner. Regardless, the normalized beam patterns for the operating frequencies can be seen in Fig. 6 which match the simulations. Measured cross-polarization levels are more than 20 dB from the main beam maximum at broadside.

Subsequent simulations which took into account the foam materials, some possible misalignments, and other fabrication tolerances showed that the frequency was shifted by about 50 MHz which better matched the S-parameter measurements (see Fig. 8). Due to these practicalities the inter-port isolation was reduced by about 5 to 10 dB over...
the frequency range of interest. To circumvent this practical design challenge and improve the isolation, the second antenna prototype was optimized and manufactured using nylon screws with extended substrate layers for the top patches. This helped to improve the alignment and positioning of the various layers (see Fig. 9). The antenna F-parameters were simulated to validate the coupling of these approaches as reported in Fig. 10. It can be observed that the antenna with the nylon screws and vias provided the best isolation suggesting structure fabrication and further testing.

During the measurements of these antenna systems, it was also observed that the phase matched cables and port connectors (which where made consistent for all antennas), introduced additional phase imbalances, which likely resulted in reduced isolation levels between the antenna ports. The full system S-parameter simulations and measurements including the cables, the couplers, and the antenna for the foam prototype are presented in Fig. 8 with results for both structures in Table 1. In these measurements two short low-loss (phase-matched) cables were used. It is important to note that due to the long 50-Ω microstrip feeding lines, coaxial cables were required to feed the signals to the coupler ports. These additional cable lengths and the required connector ports, which is not possible to avoid with the external couplers, introduced some practical phase and magnitude imbalances and reduced port-to-port isolation.

It is also important to note that at low frequencies the environmental noise could also be problematic (even in a fully enclosed anechoic chamber) when trying to achieve low isolation responses which are inline with the simulations (all results not reported for brevity). Regardless, from the simulations and measurements, the antenna with nylon screws provided a similar response, but with improved isolation as outlined in Table 1. For example, the measured isolation range, when the antennas are matched (i.e., the external port reflection coefficients are $-10$ dB or less), is higher than 49 dB and 60 dB for the antenna prototype with foam spacers and nylon screws, respectively.
To improve these results, a slot-based coupler was designed using transmission line meandering for compactness (see Fig. 11). From the simulations of the designed slot-line coupler, the phase imbalance is less than 0.5° while the magnitude imbalance is less than 0.2 dB (see Fig. 12). In the case of Rat-Race couplers, and thus for the antenna design reported in the previous section, it can be observed that the coupler is narrow-band and can only deliver stable operation at the center frequency (see Fig. 12). Moreover, it can be seen that the magnitude imbalances can reach as high as 1 dB while the phase imbalances reach values which are higher than 5°. As described in the following sections, the proposed slot-line based couplers can also be used to improve the phase and magnitude responses as applied to the antenna in transmit and receive mode.

### A. SLOT-LINE COUPLER DESIGN APPROACH USING MEANDERING

One of the earliest slot-line based coupler designs can be found in [28] where magic-T slot-line based stubs were used to control the even and odd modes of operation. Additionally, the structure consisted of coplanar waveguide (CPW) connections and a hybrid-like ring. Using this approach the authors were able to achieve wideband operation from 2.4 to 6 GHz with maximum phase imbalances of 2.5° and a magnitude imbalance of 0.4 dB. Another similar example of such a coupler, but based on microstrip technology can be seen in [29] where a similar magic-T like structure was presented. The placement of the slots above the feeding line provided a stable power split. The authors claimed that by carefully balancing the impedances of the system, by using open stubs and stepped circular rings, the currents can be exploited to enable good operation of the hybrid coupler. The designed structure was able to achieve an almost 80% bandwidth (center frequency of 10 GHz) with maximum magnitude imbalances of 0.25 dB and phase imbalances of 1°. It should also be mentioned that generally slot-line based couplers operate and have better performance at higher frequencies [27].

Advancing on these works we designed a new slot-line/ microstrip-based coupler to operate with a 2.3 GHz center frequency. Meandering of the transmission lines was applied for compactness (see Fig. 11). Also, the initial size of the non-meandered coupler was \( a = 0.38 \lambda_0 \) by \( b = 0.5 \lambda_0 \) (considering lambda at the center frequency of 2.3 GHz). This was reduced to \( c = 0.17 \lambda_0 \) by \( d = 0.26 \lambda_0 \) (see Fig. 13) for the meandered structure which was fabricated and measured as reported in Figs. 14 to 16.

### B. COUPLER PERFORMANCE AND ANTENNA RESULTS

The meandered coupler was designed using CST microwave studio. The reflections for all ports are minimal at port 1 which is matched from 1.9 to 2.6 GHz, and at port 4 which is matched from 2.1 GHz to 3 GHz (see Figs. 15 and 16). The highest magnitude and phase imbalances are around 0.1 dB and 1°, respectively. The isolation between ports 1 and 4 is well below 40 dB. The hybrid coupler was compared to existing devices in the literature (see Table 4) and it can be observed that the developed coupler offers improved compactness, port isolation, and operating bandwidths. These features are important for low-cost, FD antenna systems.

The antenna with the foam spacers was simulated considering the phase shifts due to the slot-line and Rat-Race couplers. Results show that the beam tilt and cross-polarization values are improved due to the slot-line coupler (see Table 5).
For example, unwanted beam squints can be observed with the Rat-Race coupler, while improved cross-polarization levels are observed with the slot-line coupler for all cases. Also, when two of these compact, slot-line couplers were used to feed the antenna with nylon screws, measured isolation values were about 50 dB (or better) as shown in Fig. 17. These results demonstrate a clear advantage when using the slot-line couplers in terms of enabling no beam squint over frequency and generally providing lower cross-polarization levels as well as sustained isolation for the practical antenna.

V. FULL-DUPEX ARRAY FOR BEAM STEERING APPLICATIONS

The described single-element using nylon screws and the meandered slot-line couplers were employed to design an antenna array system. For 2-D beam steering scenarios, the array configuration was designed to be a 2×2 configuration (see Fig. 18).

The distance between the radiating elements (patches) was 72 mm (0.57 λ₀ at 2.4 GHz) and the extended ground plane has a total size of 232 mm². Additionally, to reduce cable length, the feed system was redesigned to provide the shortest transmission line path possible. Unfortunately due to such a feeding approach and array configuration, the integration of vias to improve isolation was not possible due to the proximity of the feeding system to the H-shaped slots. Regardless of these practical challenges the simulated beam patterns show a half-power beamwidth of less than about 35° over the operating bandwidth of the array (see Fig. 19, considering a uniform excitation of the transmitting elements) with cross-polarization levels in excess of 40 dB from the main beam maximum. Also, as reported in Fig. 20 the array is well matched from about 2.15 GHz to 2.4 GHz while the realized gain approaches 12 dBi. In addition, isolation values are about 70 dB at the coupler ports (see Table 7).

The array also offers FD beam steering capabilities. The normalized beam patterns can be see in Fig. 21 at 2.3 GHz. Other characteristics for the FD array are outlined in Table 6. For beam steering in the −y direction, the phases of the ports for antenna port 1 (AP1), and AP2, AP5, as well as AP6 (see Fig. 18) must remain as 0° and 180° for each element, while for AP9, AP10, AP13 and AP14 the phase applied is outlined in Table 6. It should be noted that for about a 65°
TABLE 6. Full-duplex antenna array characteristics considering different steered beam positions in the y-z plane.

<table>
<thead>
<tr>
<th>Applied Phase</th>
<th>2.2 GHz</th>
<th>2.3 GHz</th>
<th>2.4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Position</td>
<td>Max. Gain (dB)</td>
<td>SLL (dB)</td>
<td>Cross-pol. (dB)</td>
</tr>
<tr>
<td>0°</td>
<td>11</td>
<td>&lt;30</td>
<td>-94</td>
</tr>
<tr>
<td>20°</td>
<td>10.9</td>
<td>&lt;30</td>
<td>-92</td>
</tr>
<tr>
<td>45°</td>
<td>9.2</td>
<td>&lt;30</td>
<td>-90</td>
</tr>
<tr>
<td>65°</td>
<td>10.7</td>
<td>&lt;14</td>
<td>-53</td>
</tr>
<tr>
<td>90°</td>
<td>10</td>
<td>&lt;8</td>
<td>-52</td>
</tr>
</tbody>
</table>

FIGURE 15. Simulated (dashed lines) and measured (solid lines) coupler response considering Port 1 as the input which provides a differential phase output.

FIGURE 16. Simulated (dashed lines) and measured (solid lines) coupler response considering Port 4 as the input which provides an equal phase output.

FIGURE 17. Simulated (dashed lines) and measured (solid lines) S-parameters of the antenna (nylon screws prototype, Fig. 9) with the newly proposed slot-line coupler (Fig. 14). Simulations are inline with the measurements which used the same experimental setup as outlined for Fig. 8.

phase shift at the ports, the sidelobe level (SLL) performance needs to be taken into account. In addition, for an increased shift of 90°, the SLL reaches −7 dB at 2.4 GHz. It should be mentioned that cross-polarization levels are well below 40 dB (from the main beam maximum) over all simulated beam steering responses.

To further investigate the 2×2 array element coupling, the antenna system was simulated with a set of 8 hybrid couplers (see Fig. 22). The combined S-parameters showed that the cross-coupling between the elements are highest for AP1+AP2 and AP9+AP10 (which relate to antenna elements #1 and #3 indicative of the same polarization) which was at most −20 dB (see S31 in Fig. 23). However, for the orthogonal polarization, which is important when considering FD operation, coupling between AP1+AP2 and AP7+AP8 (which relate to antenna elements #1 and #2) approaches −30 dB (see S71 in Fig. 23). Similar responses were observed for the other antenna elements due to symmetry of the array. These results suggest that the antenna is capable of FD beam steering but that additional coupling...
FIGURE 20. Combined simulation of the slot-line hybrid couplers and the FD antenna array (see inset of the models) for broadside radiation; i.e., no beam steering and no phase shifters as in Fig. 19. The two port setup consists of two slot-line couplers and 12 Wilkinson power dividers connected to the antenna ports (AP) as outlined in Fig. 18 where S-parameter results are defined at port 1 for the two couplers. It should be mentioned that simulations do not include the response of the connecting cables.

FIGURE 21. Simulated beam steering capabilities in the $y$-$z$ plane for the $2 \times 2$ array at 2.3 GHz using the considered phase shift definitions as in Table 6.

FIGURE 22. Architecture to model the coupling for the elements within the array. It should be noted that to feed such a system, 8 couplers will be required (see Table 7, option 2).

reduction approaches might be required depending on the isolation levels needed. The remaining S-parameter results for all elements are presented in Fig. 23.

From these findings and the architecture of the array it should be identified that such a beam steering antenna system can be fed in two different ways: 1) as a two-port system when only two couplers and a set of power dividers employed with the response presented in Fig. 20, and, 2) as an 8-port system using 8 couplers to feed each element as depicted in Fig. 22 with responses in Fig. 23. These proposed feeding options and some results are presented in Table 7. Other feeding systems are possible as well.

VI. CONCLUSION

In this paper a new IBFD dual-polarized antenna element and $2 \times 2$ array were presented for S-band applications. Two different single-element prototypes based on foam spacers and nylon screws were discussed and the presented designs offer improvements in terms of isolation and bandwidth when compared to similar structures previously reported (see Table 3). Two simple external hybrid-couplers were manufactured and used with the combined antenna system. The measured single element isolation was around 45 dB for the foam spacer and approached 70 dB for the nylon screw system complimenting the design approach. Most notably, a meandered slot-line based coupler to reduce the magnitude and phase imbalances feeding the antenna was also
demonstrated, and this coupler offers better performances when compared to other structures in the literature in terms of bandwidth, isolation, and reduced coupler imbalances (see Table 4). A 2×2 array was also proposed for FD beam steering applications and two different options for feeding the array were investigated. The array offers similar matching to the single-element antenna, showing almost 12 dB of realized gain and cross-polarization levels below 50 dB.

The antenna isolation might be improved by considering a larger ground plane, mainly to increase gain and reduce any leakage currents and unwanted coupling to the feeding system and network analyzer. Basically, an increase in ground plane size might improve practical isolation levels, however, our aim was to achieve a compact structure which is competitive in size when compared to other FD antenna systems as found in the literature. Improved operating bandwidths for the antenna might also be possible with a third patch layer, however, misalignment could be a practical issue for the multi-layer design. Additionally, the developed differential feed circuits could be integrated within the proposed antenna system to avoid the need of external cables. This attractive solution for future work would hopefully minimize any phase imbalances introduced by the many required mechanical cable connections. Ideally this effort for complete feed circuit integration when considering the developed differential couplers required for FD operation, would also improve the practical inter-port isolation levels.

REFERENCES


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