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A Dual-Polarized Linear Antenna Array with Improved Isolation Using A Slotline-Based 180° Hybrid for Full-Duplex Applications

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Abstract—This paper presents a simple and compact dual-polarized linear antenna array characterizing high inter-port isolation for in-band full-duplex communications. By using the symmetrically shared-interface configuration integrated with a 180° hybrid, the self-interference resulting from the impedance mismatching between the antenna and feeding network, and the coupling among the antenna elements can be well suppressed theoretically. Furthermore, to achieve the high isolation in practice among a wide frequency band, a slotline-based 180° hybrid is proposed and studied, which features a high isolation between the sum and differential ports. For further verification, a demonstrator of a 1×4 array centered at 5.0 GHz is developed and fabricated. The measurements denote that the shared -10 dB impedance bandwidth of the two ports is from 4.75 to 5.18 GHz, and the inter-port 50 dB-isolation bandwidth is from 4.55 to 5.66 GHz (over 21.7%).

Index Terms— In-band full duplex, self-interference, dual polarization, 180° hybrid, slotline.

I. INTRODUCTION

To realize a full-duplex system where the spectrum efficiency can be doubled compared to those using half-duplex operations, an essential work is the suppression of the self-interference caused by the leakage from the transmitter to the local receiver [1]-[9]. As mentioned in [7]-[9], the isolation achieved at the antenna level should be as high as possible to ease the burdens of the subsequent analog or digital cancellations and obtain a total level of over 100-dB isolation. Seeing that certain isolation can be observed between orthogonal polarizations naturally, using dual-polarized antennas with isolation-improved techniques is valuable for the in-band full-duplex communications [4]-[9].

By designing well-organized dual-polarized antennas, high inter-port isolation can be achieved for single-antenna scenarios [6]-[10]. For instance, in [8] and [9], differential-fed dual-polarized antennas were investigated at 2.4 GHz, where three- or four-port antenna elements using the rat-race hybrids were employed for realization. The inter-port isolations were higher than 70 dB within a narrow band around 50 MHz. The radiation efficiencies of the antennas were 45-55% within the band. However, for antenna-array systems, the complicated mutual coupling among the antenna elements makes it difficult to realize a high inter-port isolation level [11]-[13]. In [12], a 4×4 dual-polarized antenna array centered at 24.5 GHz was designed. Despite that aperture-coupled patch antennas featuring high isolation were utilized, the realized inter-port isolation of the array was around 35 dB from 22 to 26.5 GHz. Besides, using electromagnetic-bandgap structure or defected ground structure can suppress the mutual coupling within antenna arrays, at the cost of bulky systems [14]-[17].

In this work, a dual-polarized linear antenna array is studied for full-duplex communications. By integrating with the proposed slotline-based 180° hybrid, the leakage from the transmitter to the local receiver can be well canceled over a wide frequency band. The proposed architecture features simplicity, reciprocity, compact size, low profile as well as low insertion loss, making it valuable for antenna array-based full-duplex systems where high gain is required and strong mutual coupling should be suppressed, such as full-duplex base stations. The novelties of this work are as follows:

1) Different from the conventional schemes using differential-fed antennas reported in [8] and [9], the proposed scenario uses the typical two-port patch antennas and one 180° hybrid to simultaneously realize common-mode feeding and differential-mode feeding. This will effectively decrease the complexity of the patch array feeding work;

2) A compact slotline-based 180° hybrid is proposed, which features wideband impedance and high isolation responses. Besides, small magnitude and phase imbalances at the output ports are observed within a wide frequency band;

3) The isolation level and isolation bandwidth of the proposed array are significantly enlarged by using the proposed slotline-based 180° hybrid.

II. PROPOSED ARRAY CONFIGURATION

Fig. 1 shows the configuration of the proposed scheme. The array includes a dual-polarized linear antenna array consisting of 45°-rotated square patches and a 180° hybrid. The only requirement for the dual-polarized element is that the
configuration should be symmetrical. Without loss of
generality, the differential (Δ) and sum (Σ) ports of the hybrid
are defined as the transmitting and receiving ports of the array,
respectively. It is seen that when port 1 or port 2 is excited,
vertical or horizontal polarization would be generated
correspondingly. For this scheme, there are three kinds of
self-interference, the reflection between the antenna and the
hybrid, the coupling among antenna elements, and the leakage
through the hybrid. With this architecture, the first two kinds of
the mentioned self-interference can be well canceled as
discussed below.

For ease of analysis, the proposed array is considered as a
combination of two subarrays marked as subarray A (from
ports \( A_1 \) to \( A_N \)) and subarray B (from ports \( B_1 \) to \( B_N \)). As
depicted in Fig. 2(a), defining the input voltage at port 1 as \( V_0 \),
the output voltage \( V_{\text{total}} \) at port 2 through paths A and B can be
estimated as

\[
\text{Path A: } V_A = S_H e^{j\pi/2} S_A - S_B e^{-j\pi/2} V_0 \quad (1a)
\]

\[
\text{Path B: } V_B = S_B e^{-j\pi/2} S_A - S_H e^{j\pi/2} V_0 \quad (1b)
\]

Total voltage at port 2: \( V_{\text{total,1}} = V_A + V_B = 0 \). \hspace{1cm} (1c)

where \( S_H \) is the transmission coefficient of the 180° hybrid, \( S_A \)
and \( S_B \) are the reflection coefficients at the input interfaces of
the two subarrays, respectively. Owing to the symmetrical
configuration, it is found that \( S_A = S_B \). Consequently, the
voltage \( V_{\text{total,1}} \) is zero as shown in (1c). Using similar analysis,
the total output voltage \( V_{\text{total,2}} \) at port 2 through paths C and D
depicted in Fig. 2(b) can be estimated, expressed as

\[
\text{Path C: } V_C = S_H e^{j\pi/2} C_{BA} - S_B e^{-j\pi/2} V_0 \quad (2a)
\]

\[
\text{Path D: } V_D = S_B e^{-j\pi/2} C_{BA} - S_H e^{j\pi/2} V_0 \quad (2b)
\]

Total voltage at port 2: \( V_{\text{total,2}} = V_C + V_D = 0 \). \hspace{1cm} (2c)

where \( C_{BA} \) is the coupling coefficient between the subarray A
and subarray B. Note that the self-coupling within the subarray
A or subarray B is also canceled since it can be considered as a
part of the reflection signal and has been analyzed based on Fig.
2(a), and thus are not detailed here for brevity. Furthermore,
assuming that a high isolation level between the sum and
differential ports of the 180° hybrid can be obtained, a good
self-interference suppression would be achieved according to
the above discussions, leading to a high inter-port isolation.

As mentioned that the residue of the self-interference is the
leakage through the 180° hybrid. In this work, a slotline-based
180° hybrid characterizing a wideband response with a high
isolation level is presented. Please note that slotline-based
microwave components have been studied widely, such as
differential filters [18] and multi-layer transitions [19].
However, it is the first time to propose such a 180° hybrid
where slotline is used to expand the bandwidth, reduce the
magnitude/phase imbalance, and improve the isolation. As
depicted in Fig. 3(a), the proposed hybrid includes a ring and a
50-Ω transmission line, which are connected by a
half-wavelength slotline. All the electrical lengths refer to the
center frequency \( f_0 \), which are \( \theta_1 = 90° \), \( \theta_2 = 180° \), \( \theta_3 = 45° \), \( \theta_4 = 90° \), \( \theta_5 = 60° \), \( \theta_6 = 30° \). The part with the electric length of \( \theta_3 \) is
realized by a T-shape structure for practice to increase the
distance between the slotline and port 1, and reduce the
coupling between the differential and sum ports. The
characteristic impedance of the transmission lines will be
determined based on the following discussions. According to
the operational characteristics of the slotline, the phase
difference between the two outputs would be 180° among a
wide frequency band when port 2 is excited, while it should be
always zero when port 1 is excited. For impedance matching,
simplified equivalent circuits are constructed, as shown in Figs.
3(b) and 3(c). Subsequently, the input impedance \( Z_{\text{in,1}} \) at port 1
seen looking into the output interfaces versus frequency \( f \) can be
given by

\[
Z_{\text{in,1}} = Z_{11}/2 \quad (3a)
\]

\[
Z_{11} = Z_i Z_{22} + j Z_i \tan(\theta_1 f / f_0) \quad Z_{22} = \frac{Z_i Z_{11}}{Z_i + j Z_0 \tan(\theta_1 f / f_0)} \quad (3b)
\]

Similarly, for the circuit illustrated in Fig. 3(c), we have

\[
Z_{\text{in,2}} = \frac{Z_i}{j \tan(\theta_2 f / f_0)} + \frac{j Z_i Z_{11} \tan(\theta_2 f / f_0)}{Z_{11} + j Z_0 \tan(\theta_2 f / f_0)} \quad (4a)
\]
\[ Z_{y3} = Z_3 + j Z_3 \tan(\theta f / f_o), \quad Z_{y3} = \frac{j Z_3 Z_{y3} \tan(\theta f / f_o)}{Z_{y3} + j Z_3 \tan(\theta f / f_o)} \] (4b)
\[ Z_{y3} = Z_3 + j Z_3 \tan(\theta f / f_o), \quad Z_{y3} = \frac{j Z_3 Z_{y3} \tan(\theta f / f_o)}{Z_{y3} + j Z_3 \tan(\theta f / f_o)} \] (4c)

where \( Z_{in,2} \) is the input impedance at the interface of port 2. \( Z_{s1}, Z_{s2}, Z_{s3}, Z_{s4}, \) and \( Z_{s5} \) are the input impedances as marked in Fig. 3. For impedance matching purpose, we have

\[ Z_{in,1} = Z_{in,2} = Z_n. \] (5)

Based on (3)-(5), all the characteristic impedance can be calculated and determined.

Fig. 4. Simulated transmission responses of the proposed slotline-based 180° hybrid. (a) S-parameters. (b) Magnitude and phase imbalances

Fig. 5. (a) Simulated S-parameters of a typical rat-race hybrid centered at 5.0 GHz. (b) Magnitude and phase imbalances.

Consequently, a slotline-based 180° hybrid centered at 5.0 GHz is developed. The optimized physical sizes are (unit: mm): \( L_1 = 7.0, L_2 = 17.4, L_3 = 3.8, L_{4a} = 2.0, L_{4b} = 8.0, L_5 = 7.0, L_6 = 4.3, W_1 = 1.0, W_2 = 0.8, W_3 = 2.3, W_{4a} = 0.6, W_{4b} = 0.8, W_5 = 0.3, W_6 = 0.6. \) The full-wave simulated results (using CST STUDIO SUITE software) of the proposed hybrid are plotted in Fig. 4. It is found that a broadband isolation between the sum and differential ports from 4.0 to over 7.0 GHz is achieved referring to 50 dB. Within the studied frequency band, the errors in magnitude and phase imbalances are ±0.3 dB and ±1°, respectively. Fig. 5 illustrates the simulated results of the rat-race hybrid, a most common 180° hybrid, centered at 5.0 GHz for performance comparison, where the substrate Rogers RO3003 is used. It is found that the isolation of over 30 dB corresponds to a rather narrow bandwidth from 4.76 to 5.25 GHz, and degrades quickly as the frequency departs from the center frequency. As for the proposed hybrid, both the isolation level and the isolation bandwidth are significantly enhanced compared with those of the rat-race hybrid. Moreover, the errors in magnitude and phase imbalances of the proposed hybrid are much smaller over a wide frequency band.

B. 1x4 microstrip antenna array

For demonstration purpose, a 1x4 linear antenna array, centered at 5.0 GHz (around 4.9-6.0 GHz band) which is allocated for 5G systems, is designed as shown in Fig. 6(a). The array includes three stacked substrates. The radiation patches are printed on the top of substrate 1, and the feeding network is positioned on the bottom of substrate 3. A shared ground plane is inserted between substrates 2 and 3. The center distance \( d \) between adjacent elements is 0.5 \( \lambda_0 \), where \( \lambda_0 \) is the free space wavelength at 5.0 GHz. Fig. 6(b) illustrates the feeding networks of the 1x4 array using the conventional rat-race hybrid and without using any hybrids, marked as cases B and C respectively. For comparison purposes, full-wave simulations of cases A, B, and C are performed, where case A represents the proposed scheme. It is observed from Fig. 7 that within the impedance band, the isolation of case B has been only improved by 5 dB compared to that of case C, while the improvement for case A is 27 dB. This indicates that by using the proposed slotline-based 180° hybrid, the isolation level of the proposed array can be significantly enhanced as expected. Other simulated results of the antenna array integrated with the proposed 180° hybrid will be provided in the next section along with the measured results.

Fig. 6. Configurations of (a) the proposed 1x4 antenna array, and (b) the feeding networks of the 1x4 antenna array using the typical rat-race hybrid (case B) and the one without using any isolation improvements (case C).

Fig. 7. Full-wave simulated transmission responses of the three cases, where case A is the proposed layout shown in Fig. 6(a).

IV. MEASUREMENTS

The developed 1x4 antenna array shown in Fig. 6(a) is fabricated and assembled, as photographed in Fig. 8. The metal screw positions have been carefully checked in simulations before the fabrication, which will not affect the performance of the antenna array. The transmission response of the array is measured in the lab environment by using the Agilent 85309B network analyzer, and the radiation performance is tested with the in-house SATIMO SG24L spherical near-field scanner.
When measuring one port, the other one was terminated with a 50-Ω load. As shown in Fig. 9, the measured impedance bandwidths of ports 1 and 2 are from 4.75 to 5.44 GHz, and from 4.69 to 5.18 GHz respectively, referring to $|S_{11}| \leq -10$ dB. A high isolation level of over 50 dB is obtained from 4.55 to 5.66 GHz with the percentage bandwidth of 21.7%. Good accordance between the measurements and the simulations is observed, except for some fluctuations mainly due to the practical errors and small environment reflections. The measured radiation patterns at 5.0 GHz are illustrated in Fig. 10. Excellent correlation is observed between the measured and simulated results. Besides, low cross-polarization levels are found, which are less than −30 dB and −24 dB corresponding to port 1 and port 2, respectively. The realized gains at the boresight direction are measured as illustrated in Fig. 11, which are higher than 11 dBi among the impedance bandwidths. The measured total efficiency is over 80% as also plotted in Fig. 11, exhibiting the low insertion-loss performance. The difference of the radiation between ports 1 and 2 is probably due to the differential feeding of the antenna when port 1 is excited.

Fig. 8. Photographs of the developed 1×4 dual-polarized antenna array.

Fig. 9. S-parameters of the proposed 1×4 array.

Fig. 10. Radiation patterns of the array at 5.0 GHz. (a) Port 1 and (b) Port 2 with the co-polarization of γ- and s-directions, respectively.

Table I summarizes some recently published dual-polarized antennas for comparison purpose. For these studies, in spite of some additionally isolation-improvement methods, the inter-port isolation did not achieve a high level (≥ 50 dB) within a wide band. As for the proposed array, both simulated and measured results denote that a high isolation level of over 50 dB is observed among a wide frequency band, exhibiting the well-designed self-interference cancellation response. Please note that all the inter-port isolation in the comparison is from the measured results. This is because some practical issues of implementing different techniques may severely distort the isolation, which should be considered. Moreover, the proposed configuration is simple and compact, which can be readily extended to large-scale linear antenna arrays with low insertion loss and high efficiency.

![Graph showing measured and simulated radiation patterns at 5.0 GHz.](image)

**Table I**

<table>
<thead>
<tr>
<th>Ref./Year</th>
<th>2014</th>
<th>2008</th>
<th>2018</th>
<th>This work</th>
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<tr>
<td>Antenna configuration</td>
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<td>2x2</td>
<td>1x4</td>
</tr>
<tr>
<td>Antenna type</td>
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<td>Patch</td>
<td>Patch</td>
<td>Patch</td>
</tr>
<tr>
<td>Center distance among adjacent antennas</td>
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<td>$0.65d_0$</td>
<td>$0.5d_0$</td>
<td>$0.5d_0$</td>
</tr>
<tr>
<td>Impedance bandwidth (GHz)</td>
<td>11.5–15.3</td>
<td>5.45–5.56</td>
<td>11.9–15.4</td>
<td>4.75–5.18 $^a$</td>
</tr>
<tr>
<td>Improvement method of the isolation</td>
<td>SIRMHs $^a$</td>
<td>Measured feeding line</td>
<td>Q-SIW $^c$</td>
<td>Hybrid-based feeding</td>
</tr>
<tr>
<td>Improvement level of the isolation</td>
<td>17 dB</td>
<td>14 dB</td>
<td>14 dB</td>
<td>27 dB</td>
</tr>
<tr>
<td>Inter-port isolation bandwidth (GHz) $^{(≥ 40,\text{dB})}$</td>
<td>11.0–16.0</td>
<td>5.45–5.56</td>
<td>11.9–14.8</td>
<td>4.55–5.66</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>$≥ 80%^{(d)}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ denotes the shared band that $|S_{11}| \leq -10$ dB and $|S_{22}| \leq -10$ dB.

$b$ denotes the substrate-integrated rows of metalized via holes.

c denotes the quasi-substrate integrated waveguide.

d denotes the measured total efficiency among the shared impedance band.

### V. CONCLUSION

In this letter, a dual-polarized linear antenna array using shared-interface configuration is presented and studied for in-band full-duplex communications. By integrating with the proposed slotline-based 180° hybrid featuring a high isolation level between the sum and differential ports, the self-interference within the array can be well canceled. The simulated and measured results indicate that the presented array characterizes a high inter-port isolation level, leading it valuable and attractive for full-duplex applications.
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