An Orbital Angular Momentum-Based Array for In-Band Full-Duplex Communications

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Abstract—A uniform circular array (UCA) with dual orbital angular momentum (OAM) modes is proposed for in-band full-duplex applications. The proposed scheme includes two concentric ring subarrays for transmitting and receiving, respectively, where all elements are operated under the same linear polarization. To suppress the self-interference resulting from the mutual coupling, an OAM mode-selection method related to the proposed configuration is discussed. Results indicate that good isolation performance between the transmitter and receiver can be achieved by using the proposed scheme. To validate the performance, a demonstrator with OAM modes of −1 and +2 at Ku-band is developed, fabricated, and measured. Measurements show a relative bandwidth of 21.3% from 13.5 to 16.7 GHz, referring to a 40-dB suppression level, is achieved and the desired radiations are found.

Index Terms—Orbital angular momentum, full-duplex, mutual coupling, uniform circular array, self-interference suppression.

I. INTRODUCTION

Suffering from the limited available spectral source, improvement of the spectrum efficiency is of great significance for wireless communications. The in-band full-duplex scheme, utilizing a single channel to achieve the simultaneously transmitting and receiving, is found to be attractive since it can lead to a multiplication of spectrum utilization theoretically [1]–[4]. To realize a full-duplex system, a key challenge is the suppression of the self-interference mainly resulting from the strong mutual couplings at antenna level. A common method to provide good inter-port isolations is the use of polarization-based schemes [5], [6]. For instance, a dual-polarized antenna at 2.45 GHz was investigated in [5], where a three-port antenna element using the rat-race hybrid was employed. The inter-port isolation was improved significantly at the cost of a bulky system with a narrow band of 50 MHz and a low radiation efficiency of around 50%.

Recently, researches on orbital angular momentum (OAM) have drawn increasing interest for potentially enhancing the system capacity [7]–[10]. In [7], studies indicated that there existed optimal OAM modes for the Tx and Rx to maximize the system sum rate as well as isolation between the local transmitter (Tx) and receiver (Rx). But the influence of mutual couplings among antennas was out of the discussions in the study. In [9], a uniform circular array (UCA) with dual OAM modes and dual polarizations was designed to achieve a 20-dB level inter-port isolation. The studies imply that for the full-duplex applications, the self-interference suppression can benefit from the utilization of OAM-based schemes. However, the achieved suppressions are generally low, especially for the case that Tx and Rx are operated under the same polarizations. In [10], a circularly polarized UCA using sequentially rotated configuration was analyzed. With the derived OAM-mode-selection method, the mutual coupling within the UCA can be canceled. Nevertheless, the method focuses on the sequentially rotated schemes and therefore, it cannot be suitable for the non-sequential cases.

In this letter, a dual-OAM-mode UCA architecture using non-sequentially rotated configuration is studied and developed for line-of-sight full-duplex communication applications. To achieve good isolation performance between the Tx and Rx, a simple OAM mode-selection method for the proposed UCA is presented. Calculations, simulations and measurements demonstrate that the proposed UCA exhibits good isolation performance and the desired OAM-based radiations. Besides, the scheme can be easily extended for multi-links, thus presenting an important insight for improving the spectrum efficiency.

II. OAM-MODE SELECTION FOR SELF-INTERFERENCE SUPPRESSION

A typical method to generate OAM waves is the use of the uniform circular scheme. In this scheme, OAM-carrying beams can be realized by using a ring array composing of several identically linearly polarized elements with parallel directions.
and incremented excitation phases of \(2\pi f\) in a turn around a ring, where \(l\) denotes the OAM mode. Based on this scheme, a dual-OAM-mode UCA is proposed, as illustrated in Fig. 1, where the feeding network is also given. The feeding network consists of separated 2M- and 2N-way power dividers (PDs) with equal divisions as well as specified phase shifts. The proposed UCA has two concentric ring subarrays, including 2M and 2N elements for the outer and inner rings, respectively. As for both outer and inner rings, elements are positioned equidistantly and symmetrically with respect to x-axis. The excitation phases of the \(m\)th and \(n\)th elements of the outer and inner rings are respectively

\[
\varphi_m = \begin{cases} 
2\pi l_1 (m-1)/2M + \pi, & m \leq M \\
2\pi l_2 (m-1)/2M, & m \geq M + 1 
\end{cases}
\]

\[
\varphi_n = \begin{cases} 
2\pi l_1 (n-1)/2N + \pi, & n \leq N \\
2\pi l_2 (n-1)/2N, & n > N + 1 
\end{cases}
\]

(1a) and (1b)

where \(l_{2M}\) and \(l_{2N}\) are the excited OAM modes of the two rings, meeting with \([l_{2M}] < M\) and \([l_{2N}] < N\).

From Fig. 1(a), it is found that due to the parallel polarized directions of all elements, the strong mutual coupling between each pair of elements, where one of them belongs to the outer ring and the other belongs to the inner ring, would be generated, leading to strong self-interference. In view of the reciprocity of the two ports, the outer and inner ports are allocated as transmitting and receiving ports, respectively. When ignoring the influence of the feeding network, the transmission response from the Tx to Rx can be equivalent as

\[
S_{Rx, Tx} = \sum_{b=1}^{2N} \sum_{a=1}^{2M} C_{a,b} S_{2M} S_{2N} e^{-j\varphi_m + \varphi_n} 
\]

(2)

where \(C_{a,b}\) indicates the mutual coupling coefficient between the \(a\)th element of the inner ring and the \(b\)th element of the outer ring; \(S_{2M}\) and \(S_{2N}\) are the transmission coefficients of the 2M- and 2N-way PDs, respectively; \(\varphi_m\) and \(\varphi_n\) are the excitation phases of the elements as described in (1). Owing to the symmetry, for the coupling coefficient \(C_{a,b}\) described in (2), there would have another pair of elements, marked as the \(b\)th element of the inner ring and the \(a\)th element of the outer ring, that features an identical coupling coefficient \(C_{b,a}\), where

\[
\begin{align*}
e & = N + a, f = M + b, & a \leq N, b \leq M \\
e & = a + N, f = M + b, & a > N, b \leq M \\
e & = N + a, f = b - M, & a \leq N, b > M \\
e & = a + N, f = b - M, & a > N, b > M
\end{align*}
\]

(3)

It is seen that \(e = 1, 2, \ldots, 2N\) and \(f = 1, 2, \ldots, 2M\). In view of the one-to-one correspondence, it can be concluded that

\[
S_{Rx, Tx} = \sum_{b=1}^{2N} \sum_{a=1}^{2M} C_{a,b} S_{2M} S_{2N} e^{-j\varphi_m + \varphi_n} 
\]

(4)

where \(\varphi_m\) and \(\varphi_n\) are the excitation phases of the elements as described in (1). Based on (2) and (4), we have

\[
S_{Rx, Tx} + S_{Rx, Tx} = \sum_{b=1}^{2N} \sum_{a=1}^{2M} C_{a,b} S_{2M} S_{2N} e^{-j\varphi_m + \varphi_n} 
\]

(5)

Since \(C_{a,b} = C_{b,a}\) (5) becomes

\[
2S_{Rx, Tx} = \sum_{b=1}^{2N} \sum_{a=1}^{2M} C_{a,b} S_{2M} S_{2N} e^{-j\varphi_m + \varphi_n} + e^{-j\varphi_m + \varphi_n} 
\]

(6)

Substituting (3) into (6), the transmission coefficient can be simplified, expressed as

\[
S_{Rx, Tx} = \sum_{b=1}^{2N} \sum_{a=1}^{2M} C_{a,b} S_{2M} S_{2N} e^{-j\varphi_m + \varphi_n} 
\]

(7)

where

\[
S_{MN} = \begin{cases} 
1 + e^{-j\varphi_m + \varphi_n}, & a \leq N, b \leq M \\
1 - e^{-j\varphi_m + \varphi_n}, & a > N, b \leq M \\
1 - e^{-j\varphi_m + \varphi_n}, & a \leq N, b > M \\
1 + e^{-j\varphi_m + \varphi_n}, & a > N, b > M
\end{cases}
\]

(8)

From (7) and (8), it can be observed that the transmission coefficient \(S_{Rx, Tx}\) would be zero when \(S_{MN} = 0\), thus enabling the self-interference resulting from the mutual coupling to be suppressed. At this point, we have

\[
l_{2M} + l_{2N} = 2k + 1, k = 0, \pm 1, \pm 2, \ldots
\]

(9)

The above discussions show that using the derived OAM mode-selection Eq. (9), the proposed dual-OAM-mode UCA can provide ideal isolation between the Tx and the local Rx, since the leakage through the mutual coupling is well canceled. This is simply different from the OAM-mode-selection method for the arrays using sequentially rotated configurations as discussed in [10], where the excitation mode \((l_c, l_d)\) of the two OAM modes for the self-interference suppression should meet with \(l_c + l_d \neq 0\). Moreover, it is reasonable to conclude that the self-interference suppression level of the proposed scheme shown in Fig. 1 would be still high when elements with asymmetrical radiation patterns are used as a result of the symmetrical layout. To verify the performance of the proposed architecture, a prototype is further developed and examined.
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III. DESIGN DESCRIPTIONS OF THE DEMONSTRATOR

![Diagram](image)

Fig. 4. (a) Layout of the feeding networks for the proposed UCA. (b) 3D view of the proposed UCA.

(a) 8-way PD and (b) 16-way PD.

For demonstration purposes, a typically wideband microstrip antenna using a coupling aperture [11] is employed as the basic element for the proposed UCA. The geometry of the element is illustrated in Fig. 2, where the multi-layer scheme is adopted for bandwidth improvement. The configuration of the proposed UCA using the aperture-coupled antenna without feeding network is shown in Fig. 3(a). The outer and inner rings contain 16 (marked from 1st to 16th) and 8 (marked from 17th to 24th) elements, respectively. The radius of the two rings are \( R_0 = 1.35 \lambda_0 \) and \( R = 0.85 \lambda_0 \), where \( \lambda_0 \) is the wavelength in free space at 15.0 GHz. To show the strong mutual couplings between the elements, a full-wave simulation is performed. Some results based on the 24th element are presented in Fig. 3(b), where the maximum coupling is approximately \(-17 \) dB at 15.0 GHz. As discussed above, all mutual couplings can be canceled by using the proposed architecture.

The layout and 3D view of the proposed UCA with OAM modes \( I_{EM} = -2 \) and \( I_{2N} = -1 \) are presented in Fig. 4. The T-junction-based feeding network for the outer ring is placed on the back side of substrate 1, whereas the one for the inner ring is separated into two parts and respectively placed on the back side of substrate 1 and the front side of substrate 2. Interconnections are utilized between the two parts. On the other hand, to improve the phase imbalance of the feeding networks, phase compensation technique is utilized for the 90° and 180° phase shifters [12].

Figs. 5(a) and 5(b) provide the simulated impedance-matching performance of the inputs and the transmission responses of the 8-way and 16-way feeding networks respectively, where the subscript numbers correspond to the port numbers illustrated in Fig. 3. Notice that due to the symmetric/quasi-symmetric responses, some representative simulated results are provided for brevity. It can be observed from Fig. 5 that within the studied frequency range, the phase imbalances are \( \pm 4^\circ \) and \( \pm 9^\circ \) for 90° and 180° phase delays, respectively. The full-wave simulations of the proposed UCA are provided below along with the measurements.

IV. MEASUREMENTS ON THE DEVELOPED DEMONSTRATOR

![Photo](image)

Fig. 6. Photographs of the developed demonstrator.

![Graph](image)

Fig. 7. Measured VSWRs and transmission response between the Tx and Rx of the developed demonstrator.

Shown in Fig. 6 is the photographs of the fabricated demonstrator, where some plastic screws are utilized for assembling. The overall size of the demonstrator is 92 mm \( \times \) 92 mm, and the radius of the inner and outer rings are 17 mm and 27 mm, respectively. Depicted in Fig. 7 is the measured VSWRs and the transmission responses between the two ports of the demonstrator. The impedance bandwidths with VSWR \( \leq 2 \) are over 4.55 GHz (from 13.35 to beyond 18.00 GHz) and over 5.52 GHz (from 13.35 to beyond 18.00 GHz) for ports 1 and 2 from measurements respectively, indicating wideband impedance matchings. The isolation also exhibits high self-interference suppressions. Plotted in Fig. 8 is the far-field radiation patterns at 13.5 GHz, 15.0 GHz, and 16.7 GHz, where the large side lobes generated can be primarily attributed to the relatively large spacing between the adjacent elements. Employing compact designs to decrease the element spacing is an efficient way to suppress...
these lobes. On the other hand, the divergence angles for mode \(-1\) and mode \(-2\) are 22° and 25°, 19° and 20°, 18° and 16° corresponding to 13.5 GHz, 15 GHz and 16.7 GHz respectively. In Fig. 8, it is also found that the central magnitude nulls (phase singularities) are generated except the case for \(I = −2\) at 13.5 GHz. A reasonable explanation for this case is that although the phase compensation technique is utilized, the frequency at 13.5 GHz is 10% offset from the central frequency of 15.0 GHz, leading to some phase and magnitude imbalances from the feeding network as shown in Fig. 5. Despite the non-ideal radiation patterns at 13.5 GHz, the generated waves are still OAM waves with mode \(I = −2\), as confirmed below.

Described in Fig. 9(a) is the simulated spatial phase distributions of electric fields, which is observed at \(\phi = 0°\) plane when port 1 or 2 is excited. This indicates that OAM waves with mode \(I = −2\) are generated. Similar performance can be found for mode \(I = −1\), which is two periods within 360°. These results denote that the developed dual-OAM-mode UCA characterizes high self-interference suppressions, good OAM mode distributions and the desired radiation patterns within a wide bandwidth. The results also confirm the case for \(I = −2\) shown in Fig. 8(a) exhibits the desired OAM mode.

Finally, the azimuth spectrum \(\phi_{\text{azi}}\) representing the weight of the OAM \(m\)-mode in the OAM-carrying beam with the desired OAM mode, is analyzed to show the mode purity of the OAM waves generated by the proposed antenna array, as presented in Table I. The method utilized in [10] and [13] is employed to evaluate the measured azimuth spectrum at the divergence angles. It is found that the desired azimuth spectrums for \(I = −1\) and \(I = −2\) are both close to the studies in [10] and [13], thus featuring a good OAM mode purity performance.

V. CONCLUSION

For full-duplex applications, an OAM-based architecture is proposed and studied. The self-interference caused by mutual couplings among antenna elements can be well suppressed. Compared with the polarization-based isolation methods, the advantage of this method is the simple antenna elements, which can avoid some specified performance such as high inter-port isolations between orthogonal polarizations. Besides, an effective OAM mode-selection method is presented for the self-interference cancellations. The two links of the proposed architecture are operated under the same linear polarizations. This facilitates the implementations of multi-links with the help of the proposed mode-selection method, where the high isolation between each pair of links can be achieved by further extending the proposed scheme to more ring subarrays. A demonstrator prototype at Ku-band is developed and measured with good agreement between measurements and simulations.
REFERENCES


