A Dual-Beam Eight-Element Antenna Array With Compact CPWG Crossover Structure

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***Abstract*—In this letter, a dual-beam eight-element antenna array is proposed with compact coplanar waveguide with ground (CPWG) crossover structure. The feeding network is composed of a microstrip-line feeding network with four 90° hybrids and a CPWG feeding network with compact crossover structures. Compared to the conventional Butler matrix feeding network, the proposed network has fewer 90° hybrids and circuit is less complex. By exciting different port of the feeding network, the eight-element antenna can be excited by phase step of 22.5° or –22.5° and achieve two beams pointing at two different directions. The measured gain is 10.2 dBi, and beam directions of the two peaks are ±7° at 5.8 GHz.**

***Index Terms*—Antenna array, coplanar waveguide with ground crossover, dual-beam, feeding network.**

I. INTRODUCTION

IN THE 5G era, massive multiple-input–multiple-output (MIMO) is expect to play an important role to solve the severe spectrum shortage and provide much more capacity. However, when antenna arrays are composed of a very large number of elements, traditional MIMO systems are limited by the high cost of hardware and energy consumption due to the large number of radio frequency (RF) chains. In order to reduce the cost, several methods are investigated to reduce the RF chains by using multibeam antenna arrays [1], [2]. A widely adopted method to form multibeam antenna array is Butler matrix [3]–[5]. However, the conventional Butler matrix feeding network is not suitable for cost reduction of massive MIMO because it has many 90° hybrids and crossover structures. Most of the crossover structures are of narrow bandwidth or have broad bandwidth at the expense of a multilayer and complicated structure [6]. Recently, a compact broadband crossover structure based on coplanar waveguide with ground (CPWG) is proposed and utilized to design antenna arrays [6], [7]. In modern communication systems, the conventional Butler matrix is also limited by the redundant beams. Newer studies have indicated that in a massive MIMO system, two or three beams in the elevation plane are enough to achieve nearly optimal performance. An eight-element antenna array based on a conventional Butler matrix can provide eight beams, however, most of those beams are redundant and unnecessary. Some previous studies have proposed dual-beam antenna arrays that generate two beams simultaneously [8]–[10]. Microstrip leaky-wave antenna arrays [8], [9] are utilized to achieve dual beams, but the beams are steered when sweeping the operating frequency. These antenna arrays are not suitable for the purpose of reducing RF chains. Lens antenna array [1], [2] is a novel spatial multiplexing scheme for massive MIMO techniques. This scheme can achieve multiple beams and reduce RF chains without crossover structures, but the spatial multiplexing scheme limits its compactness.

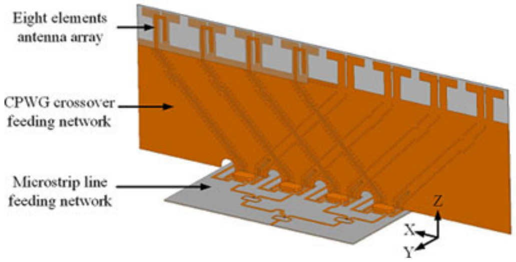

Fig. 1. Topology of the proposed 1 × 8 antenna array with microstrip-line feeding network and CPWG crossover feeding network. The substrate is shown as transparent for ease of viewing.

In this letter, a dual-beam eight-element antenna array is proposed. Exciting different input ports of the proposed antenna array makes the antenna elements with phase step of 22.5° or –22.5° and achieves two beams pointing at ±7°, respectively. Compared to a conventional 8 × 8 Butler matrix that uses 12 90° hybrids, the proposed antenna array has only four 90° hybrids and compact crossover structures. This property is important when it comes to massive MIMO systems. A conventional $N \times N$ Butler matrix needs $(N/2)\log_2 N$ 90° hybrids, while using the proposed feeding network, an N-element dual-beam antenna array only needs $(N/2)$ 90° hybrids.

II. ANTENNA DESIGN

The topology of the proposed antenna array is illustrated in Fig. 1. The antenna array is composed of three parts. The first part is the horizontal substrate with a microstrip-line feeding network and four 90° hybrids. The second part is the CPWG feeding network in both sides of the vertical substrate. The last part is the 1 × 8 printed dipole antenna array at the top of the CPWG substrate. When different input ports are excited, the antenna array can achieve two independent beams pointing at ±7° respectively.

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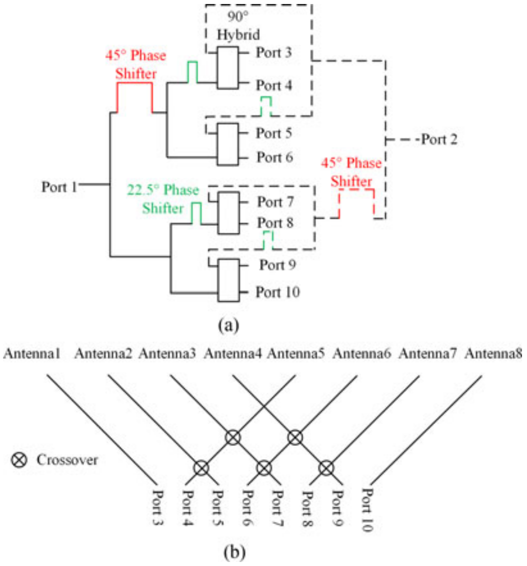
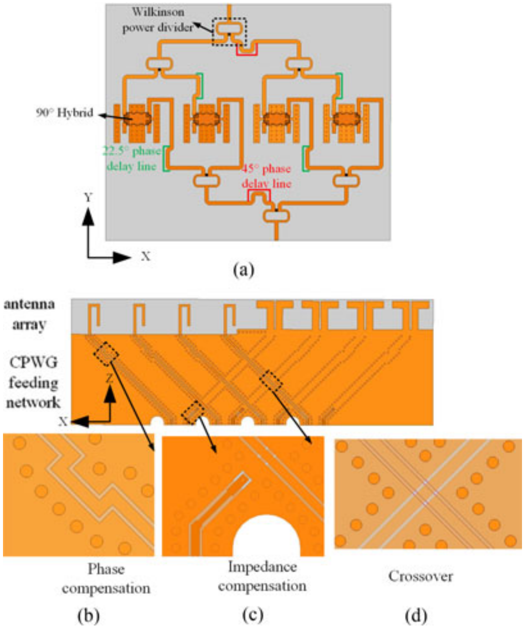


Fig. 2. Schematic diagrams of the proposed antenna array. (a) Microstrip-line feeding network. (b) CPWG crossover feeding network.



Phase compensation (b)

Impedance compensation (c)

Crossover (d)

Fig. 3. Geometry of the proposed antenna: (a) microstrip-line feeding network, (b) phase compensation structure, (c) impedance compensation structure, and (d) crossover structure on CPWG feeding network.

Fig. 2 depicts a schematic diagram of the proposed antenna array. Fig. 2(a) shows the scheme of a microstrip-line feeding network. It consists of six Wilkinson power dividers, two 45° phase shifters, four 22.5° phase shifters, and four 90° hybrids. Fig. 2(b) shows the scheme of CPWG feeding network with a crossover structure. The combination of phase shifters, 90° hybrids, and crossover structures makes the signals output to the antenna elements with the same amplitude and required phase step. When port 1 is excited, the output signals to antenna elements have a phase step of 22.5° from antennas 1 to 8. When port 2 is excited, the phase step is –22.5° from antennas 1 to 8.

Fig. 3 depicts the geometry of the proposed antenna array. The antenna array is fabricated on the Teflon substrates with dielectric constant of 2.65 and thickness of 0.5 mm. The orange part represents the metal, and gray part represents the Teflon substrate. Fig. 3(a) shows the geometry of the microstrip-line feeding network. The width of the microstrip line is 1.34 mm, and its characteristic impedance is 50 Ω. Two 45° phase delay lines, four 22.5° phase delay lines, four Anaren 90° hybrids (model 1M803S), and six Wilkinson power dividers are used to complete the microstrip-line feeding network. Fig. 3(b)–(d) illustrates the details of the CPWG feeding network. The orange cylinders represent the metal vias, and the characteristic impedance of the CPWG is 50 Ω. Fig. 3(d) shows the crossover structure on the CPWG feeding network. Phase and impedance compensation structures are utilized to compensate the discontinuity that is introduced by the crossover structures. Fig. 3(b) shows the phase compensation structure that uses phase delay line to increase length of CPWG and compensate phase. Fig. 3(c) shows the impedance compensation structure that uses an impedance transformer to compensate the impedance mismatch. For the convenience of soldering, four CPWG lines are flipped from the bottom side to the top side, as shown in Fig. 3(c). Simulated results show these transitions have little effect on the CPWG feeding network, which is not presented here for simplicity. The antenna elements resonate at 5.8 GHz. The distance between two adjacent antenna elements is 26 mm, which is approximate to half-wavelength in the free space at 5.8 GHz.

To further study the effect of crossover structures and impedance compensation structures, Fig. 4 illustrates the six types of CPWG transmission line and their simulated S-parameter results. As shown in Fig. 4(a), type 1 is CPWG transmission line, type 2 is CPWG transmission line with one crossover structure, type 3 is CPWG transmission line with two crossover structures, type 4 is the structure of type 3 with impedance structure, type 5 is CPWG transmission line with three crossover structures, and type 6 is the structure of type 5 with impedance compensation structure. The orange part represents the metal, the gray part represents the Teflon substrate, and the cylinders represent the metal vias. Moreover, all the transmission line models are simulated with the same length. Fig. 4(b) and (c) depicts S_{11} impedance curves and S_{21} phase curves of the six types shown in Fig. 4(a). Fig. 4(b) indicates one crossover structure, such as type 2, does not affect the impedance match. However, when there are two or three crossover structures, such as type 3 and type 5, the results of impedance match deteriorate since the distance between every crossover structure is 18.4 mm, which is about a half-wavelength at operating frequency, and the reflected signals are in phase at the input port. When an impedance compensation structure is introduced as type 4 and type 6, the mismatch issue can be solved successfully as shown in Fig. 4(b). Fig. 4(c) indicates every crossover structure introduces phase delay of about 5.1°, every impedance compensation structure introduces phase delay of about 4.2°, and the S_{21} phase delay of type 2, type 4, and type 6 to 1 is about 5.8°, 14.7°, and 20.9°, respectively. To solve the phase delay issue, phase compensation structures are utilized as shown in Fig. 3(b). The parameters of the proposed antenna array are optimized by ANSYS High Frequency Structure Simulator (HFSS) version 14. The optimized values are listed in Table I.

III. MEASUREMENT RESULTS

To validate the design strategy, a prototype of the proposed dual-beam antenna array is fabricated and measured. Fig. 5 shows the photograph of the antenna array. The array

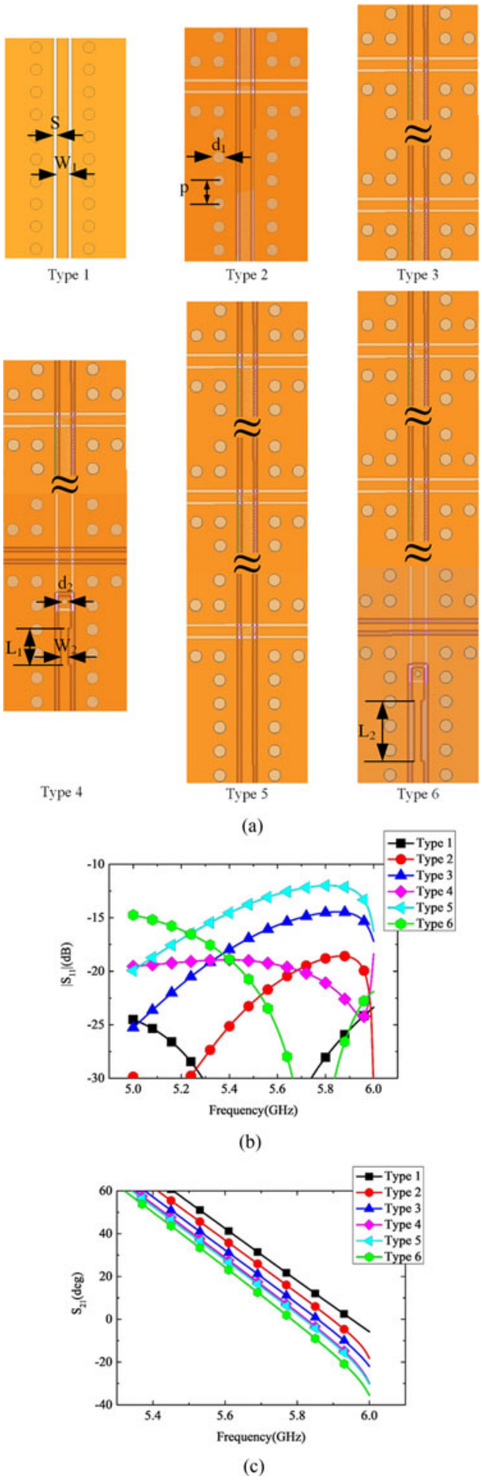


Fig. 4. Six structures in the CPWG feeding network. (a) Geometry of the six types. (b) Simulated curves of $|S_{11}|$ with different types. (c) Simulated phase curves of S_{21} with different types.

TABLE I
OPTIMIZED DIMENSIONS (UNIT: mm)

S	W_1	d_1	p	d_2	L_1	W_2	L_2
0.3	1	1	2	0.5	3	0.6	5

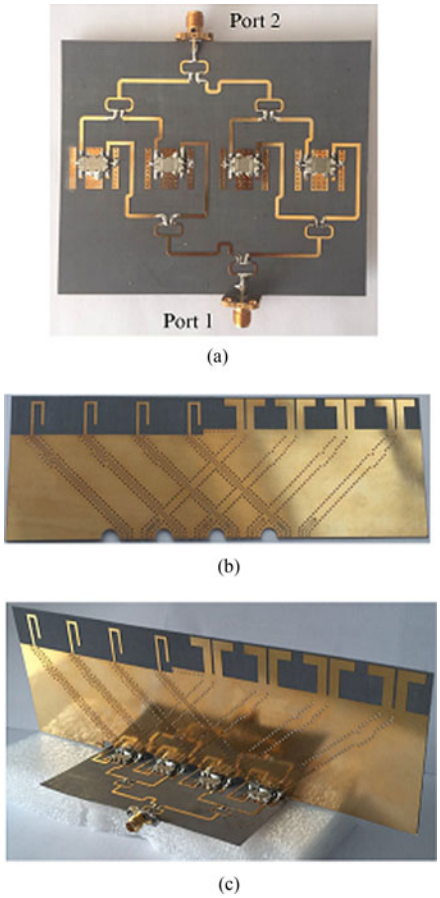


Fig. 5. Photograph of the proposed antenna array. (a) Microstrip-line feeding network. (b) CPWG feeding network and antenna elements. (c) Prototype of the antenna array.

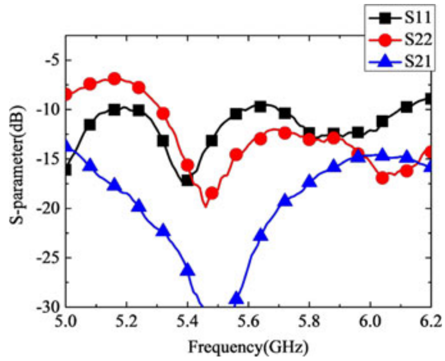
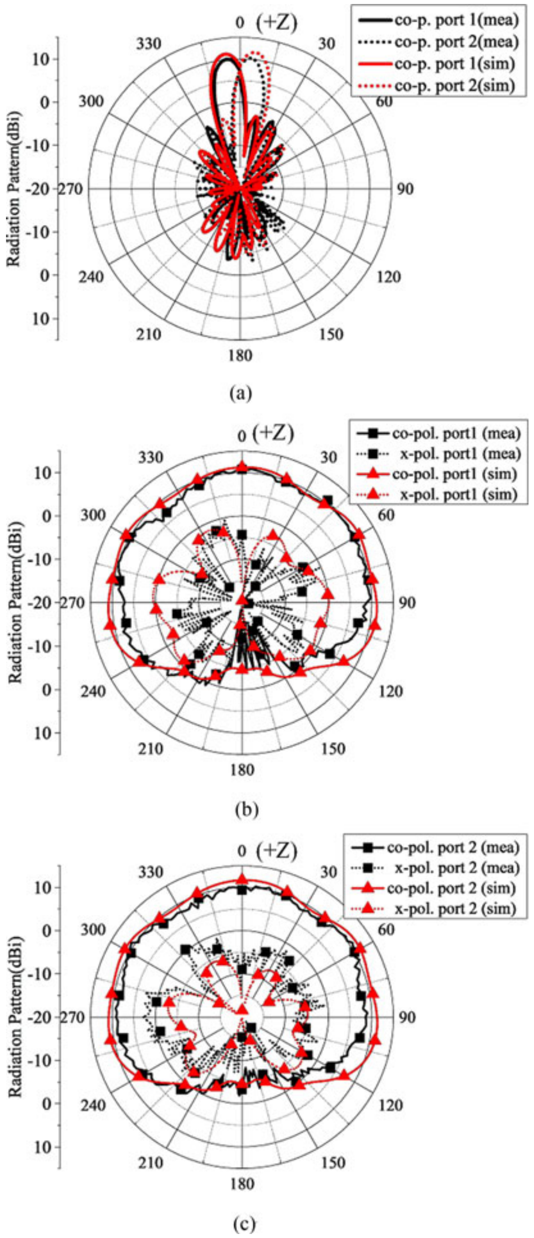


Fig. 6. Measured S-parameters of the proposed antenna array.

is composed of two feeding networks and a 1 × 8 antenna array. The dimension of the microstrip-line feeding network is $106 \times 88 \times 0.5\,\text{mm}^3$, and the dimension of CPWG feeding network is $208 \times 72 \times 0.5\,\text{mm}^3$. The proposed array utilizes four 90° hybrids and CPWG crossover structures, which makes it more compact and have less cost than the conventional Butler matrix feeding network. Fig. 6 shows the measured S-parameters of the proposed antenna array. When one port is excited, another port is terminated with matched load. In the band of 5.4–6.0 GHz, the two ports' $|S_{11}|$ responses are almost lower than –10 dB and $|S_{21}|$ is lower than –15 dB. Because the software cannot simulate 90° hybrids [11], the simulated results are not presented here.



(a)

(b)

(c)

Fig. 7. Radiation patterns of the proposed antenna array at 5.8 GHz. (a) E-plane patterns of two ports. (b) H-plane patterns of port 1. (c) H-plane patterns of port 2.

Fig. 7 shows the radiation patterns of the proposed antenna array at 5.8 GHz. The E-plane patterns are shown in Fig. 7(a). Good agreement between measured and simulated results is observed. The two main beams point at ±7° depending on different input ports. Simulated and measured cross-polarization levels are lower than –24 and –15 dB for both ports, respectively. For simplicity, the cross-polarization curves are not shown in Fig. 7(a). Fig. 7(b) and (c) illustrate the H-plane radiation patterns of two input ports. Good agreement between measured and simulated results is observed.

Fig. 8 shows the simulated and measured peak gain in band of 5.3–6.1 GHz. The simulated peak gains vary from 10.8 to 11.9 dBi, and the measured peak gains vary from 10.2 to 10.5 dBi. The difference between simulated and measured results contributes to fabrication and measurement errors.

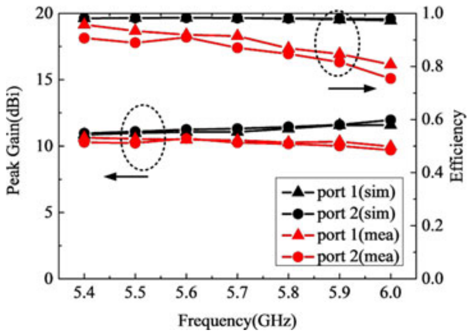


Fig. 8. Peak gain of the proposed antenna array.

The radiation efficiency is also illustrated in Fig. 8. The simulated efficiency is about 0.98 in the band of 5.4–6.0 GHz. The measured efficiency is almost above 0.8 in the desired band because the HFSS cannot simulate the 90° hybrids, so the simulated results are obtained by simulating CPWG feeding network and antenna array without microstrip feeding network and 90° hybrids. The difference between simulated and measured results contributes to limitations of software and fabrication errors.

IV. CONCLUSION

In this letter, we have designed a dual-beam eight-element antenna array by introducing compact CPWG crossover structures. The feeding network is less complex and uses fewer 90° hybrids than conventional Butler matrix. With different input ports, the array achieves two beam directions at ±7° with peak gain of 10.2 dBi at 5.8 GHz, which can be utilized to reduce the cost of RF chains in massive MIMO systems.

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