Gain-Enhanced Wideband Circularly Polarized Antenna with a Non-Uniform Metamaterial Reflector

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Abstract **–** In this paper, a gain-enhanced wideband circularly polarized (CP) antenna with a non-uniform metamaterial (NUM) reflector is presented, which is composed of a modified wide S-shaped slot antenna and a NUM reflector. To achieve a wideband CP operation, a modified S-shaped slot is fed by an L-shaped microstrip feedline that ends with a triangular patch to improve axial ratio (AR) bandwidth and impedance bandwidth. A NUM reflector composed of rectangular metal units with different sizes is employed and its units are unevenly distributed. The proposed CP antenna is designed, fabricated, and measured. The measured results show that the impedance bandwidth covers 3.0-6.0 GHz (66.7%) and a 3-dB AR bandwidth covers 3.1-5.6 GHz (57.4%). A peak gain of 6.0 dBi is obtained at 3.8 GHz by using the reflector. The advantages of the proposed antenna are the simple structure, high gain, and broad CP bandwidth.

Index Terms **–** Circular polarization, gain enhancement, broadband antenna, non-uniform metamaterial reflector

I. INTRODUCTION

With the rapid development of wireless communication, circularly polarized (CP) antennas play important roles in creating high-performance communication systems due to the superiorities of overcoming polarization mismatch, immunity to the Faraday rotation, and suppressing multipath [1–11]. To enhance the capacity of wireless communication systems, wideband CP antennas are good candidate for transmitting and receiving signal, which becomes an attractive option. However, wide axial ratio (AR) bandwidth and high gain are quite challenging directions for CP antenna designs.

To realize wideband CP operation, a variety of structures and methods have been proposed in the past few years. In [12-14], wide slots fed by L-shaped microstrip and co-planar waveguide (CPW) are utilized to realize wide AR bandwidth. The complementary split ring resonator (CSRR) structure is loaded on the L-shaped feeding structure to further expand the AR bandwidth [15]. Furthermore, modified trapezoid and inverted L-shaped strip structures are introduced to the antenna [16, 17] to achieve 92% and 56.4% AR bandwidths, respectively. L-shaped structure expands AR bandwidth at the expense of the radiation pattern stability, which leads to the radiation pattern tilted with frequency increment. Antennas [18, 19] expend the AR bandwidth by using defective square rings, which provide an additional CP operation band. However, the antennas mentioned above suffer from low gain caused by bidirectional radiation patterns, limiting their application such as long-distance communication. Additionally, feeding network with power divider and phase shifter to provide constant phase difference is also employed in antennas [20–23] to achieve wideband CP operation. The feeding network significantly increases the size of the antenna compared to a single-fed antenna. Moreover, cross-dipole antennas fed by a quarter of microstrip ring are proposed in [24] and [25], and parasitic elements are introduced to expand AR bandwidth. Recently, metamaterial technique is also a good choice to improve CP bandwidth. For antennas [26–29], electromagnetic bandgap (EBG), high-impedance surface (HIS) [27], and artificial magnetic conductor (AMC) [28, 29] are utilized to enhance gain over the operating band. Besides, the metal cavity is placed under the aperture antenna [30, 31] to alleviate the undesirable back radiation, which also improves the gain of the antenna. However, all of these antennas have the disadvantage of being difficult to install and complex in geometry.

In this paper, a wideband CP antenna with a non-uniform metamaterial (NUM) reflector is proposed. To achieve wide AR bandwidth, a modified S-shaped slot is etched on the ground and an L-shaped microstrip line is used to feed the developed CP antenna. Diagonally distributed cutting corners are also employed in the

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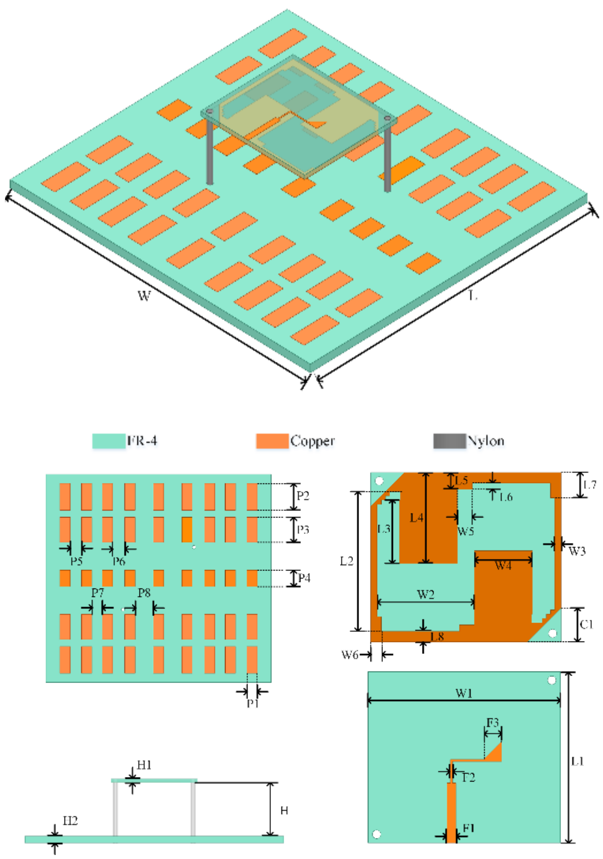


Fig. 1. Configuration of the proposed antenna.

developed antenna. A NUM reflector is placed under the slot antenna to enhance the gain in the boresight direction while maintaining wide AR bandwidth. The proposed broadband CP antenna is simulated, optimized, fabricated, and measured, and the results show that the NUM reflector-backed S-shaped slot antenna achieves an impedance bandwidth of 66.7% (3.0-6.0 GHz), a wide CP bandwidth of 57.4% (3.1-5.6 GHz), and more than 3 dBi gain enhancement is obtained over the operating band.

II. ANTENNA DESIGN

A. Wideband CP S-shaped slot antenna design

As shown in Figure 1, the proposed CP antenna is designed on FR-4 substrate (ε_r = 4.4; tanδ = 0.02) with substrate thicknesses of H1. The modified S-shaped slot and inverse L-shaped feeding stub are utilized in the upper of the antenna to generate CP characteristics. Stepped structures on the edge of the wide slot extend the path of the current, improving impedance matching and achieving CP operation at lower frequencies. By cutting two corners symmetrically on the diagonal, the antenna radiates CP waves at a higher frequency. The S-shaped slot structure is symmetrical about the center

Table 1: Parameters of the proposed antenna (unit: mm)

Param.	Size	Param.	Size	Param.	Size
W	130	L	120	H	23.8
H1	1.6	P1	6	P2	15.5
P3	14.5	P4	9.5	P5	6.5
P6	7	P7	6	P8	10.5
F1	2.1	F2	0.5	F3	4
W1	45	W2	23	W3	1.5
W4	13.7	W5	3.5	W6	2.5
L1	40	L2	32.9	L3	14.9
L4	21.5	L5	4	L6	1.5
L7	6	L8	2.5	C1	8

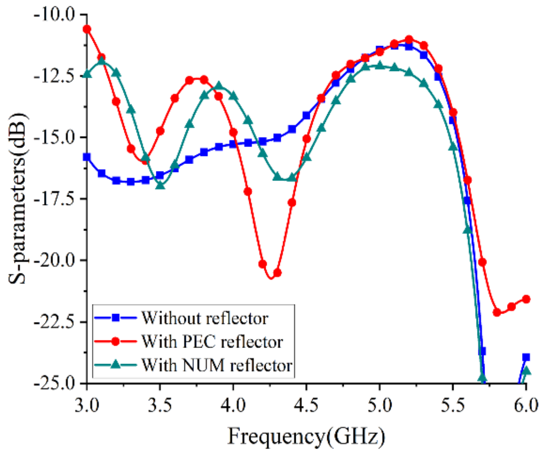
of the antenna, effectively overcoming the drawbacks of the beam tilted with frequency increments. Moreover, an inverted L-shaped strip is employed to connect with the end of the 50-Ω feedline and the modified triangle patch to obtain broadband property. The triangular patch is designed to excite two mutually orthogonal modes with equal magnitude.

B. Non-uniform metamaterial reflector

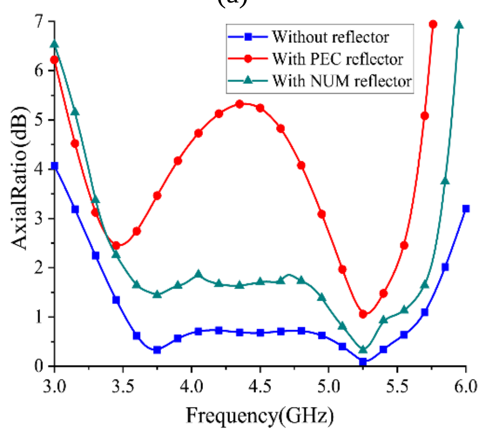
Although the S-shaped slot antenna has obtained good CP performance, the gain of right-hand circular polarization (RHCP) in broadside direction is low due to bidirectional radiation pattern, which limits its application. To increase the gain of the antenna, a NUM reflector is placed underneath the slot antenna with a distance of H. The upper and lower substrates are supported by nylon cylinder. The reflector is also designed on FR-4 with substrate thicknesses of H2. The reflector consists of 9 $\times$ 5 metal cells of different sizes, and the spacing of the metal cells and their dimensions are shown in Figure 1 and Table 1. With unevenly distributed metal cells, the NUM reflector acts as a perfect magnetic conductor and reflects the backward wave effectively. The reflected and forward waves interfere with each other, achieving high gain in the operating band.

C. Comparison of different reflector surface

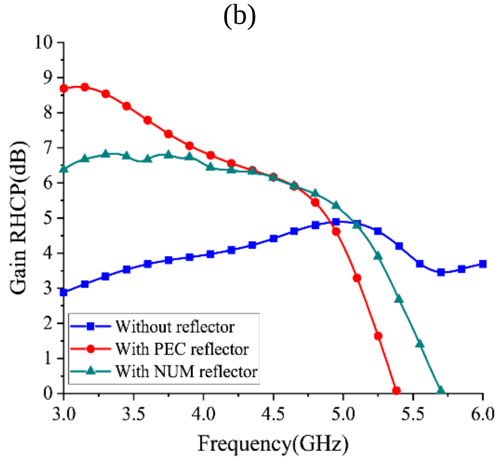
To further demonstrate the function of the NUM reflector in improving antenna performance, three different antennas are simulated and compared, including the S-shaped slot antenna without reflector, with perfect electric conductor (PEC) surface, and with NUM reflector. As shown in Figure 2 (a), there is a slight deterioration of S11 from 3 to 4.25 GHz due to the introduction of the reflector. Simulated AR bandwidths of three antennas are illustrated in Figure 2 (b), and the S-shaped slot antenna obtains the widest 3-dB AR bandwidth of 60.1% (3.2-5.95 GHz). AR bandwidth of the slot antenna with NUM reflector is slightly reduced, which is 54.9% (3.3-5.8 GHz). Due to the mirror image current generated on the PEC radiated waves of opposite polarization,



(a)



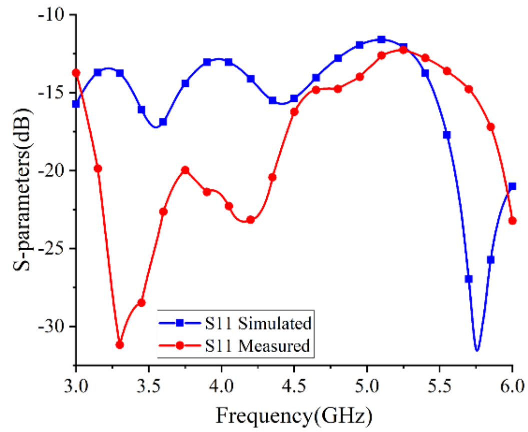
(b)



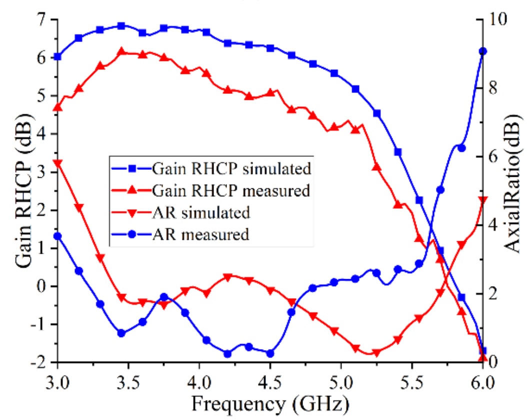
(c)

Fig. 2. Comparisons of different antennas' performances. (a) S11 of the antenna. (b) AR of the antenna. (c) Gain of the antenna.

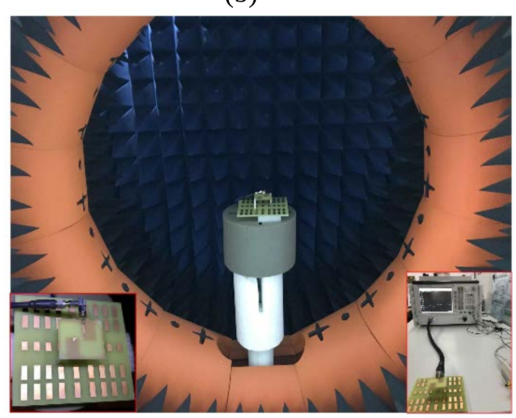
the PEC reflector severely deteriorates the AR performance of the antenna. For Figure 2 (c), it can be concluded that the gain of the S-slot antenna can be improved by the reflector, where the NUM reflector provides a lower gain improvement than the PEC reflector since the incident wave is only partially reflected. From the comparison of the three antennas, the antenna with NUM reflector achieves a gain improvement of more than 3 dBi over the CP operating band, whereas the S-shaped slot antenna maintains its wideband CP properties.



(a)



(b)



(c)

Fig. 3. Simulated and measured results of the proposed antenna.

III. EXPERIMENTAL VERIFICATION

As shown in Figure 3 (c), an assembled prototype for the designed CP antenna is fabricated and measured to verify simulated results. According to the simulated and measured reflection coefficients illustrated in Figure 3 (a), the impedance matching is enhanced at lower frequencies with a -10 dB bandwidth of 66.7% (3.0-6.0 GHz) and completely covers the AR bandwidth of 57.4% (3.1-5.6 GHz). Figure 3 (b) shows that the 6.0 dBi measured gain of RHCP is obtained at 3.8 GHz in boresight. The major performance metrics of the proposed antennas are compared with other reported CP antenna of similar structures, as shown in Table 2. In comparison, the proposed antenna has demonstrated the advantages of wider AR bandwidth. Furthermore, stable radiation patterns are achieved over the CP operation band, as illustrated in Figure 4. The difference between measurement and simulation is caused by alignment problems and the experimental environment in the Lab.

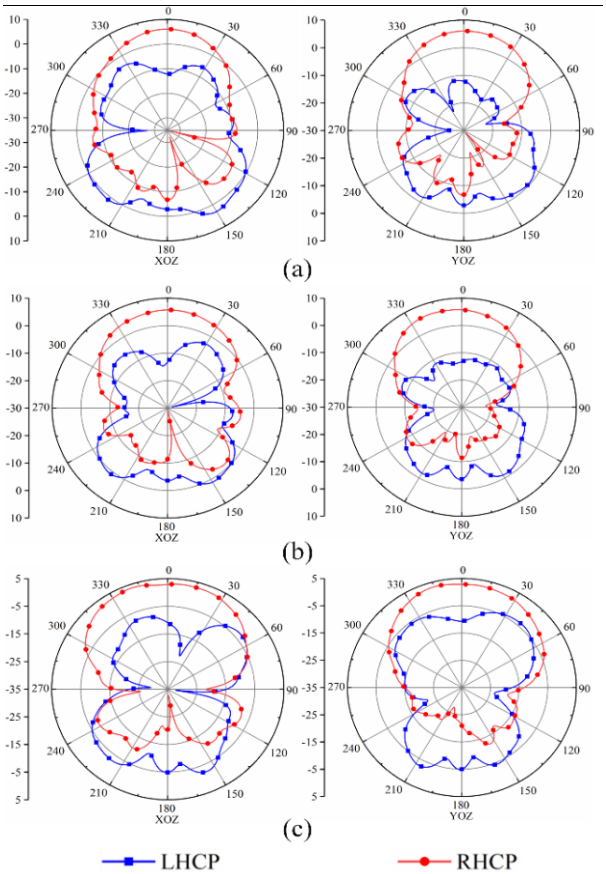


Fig. 4. Measured radiation patterns in XOZ and YOZ planes. (a) 3.5 GHz. (b) 4.0 GHz. (c) 4.5 GHz.

Table 2: Performance comparison between the proposed antenna and previous CP antenna with similar structure

Ref.	Antenna structure	Dimension (λo/GHz)	Peak gain (dBic)	IMBW (%)	ARBW (%)
Proposed	Single-layer NUM	1.88 × 1.74 × 0.35/4.35	6.0	66.7	57.4
[21]	Single-layer AMC	1.14 × 1.14 × 0.22/4.50	4.9	86.2	44.1
[22]	Single-layer AMC	0.83 × 0.69 × 0.35/8.27	5.6	137.1	56.6
[23]	Single-layer FSS	1.35 × 1.40 × 0.33/6.25	10	84.8	56.0
[24]	Single-layer AMC	0.81 × 0.53 × 0.20/6.25	7.5	38.3	31.6
[25]	Three-layer AMC	0.72 × 0.60 × 0.19/6.0	7.0	33.2	36.2

IV. CONCLUSION

A wideband circular polarized antenna with a NUM reflector for achieving wide CP operation bandwidth and high gain is presented. The optimized antenna is fabricated and measured. The antenna achieves 57.4% (3.1-5.6 GHz) AR bandwidth in practice and 54.9% (3.3-5.8 GHz) in simulation. Moreover, 66.7% (3.0-6.0 GHz) of the relative impedance bandwidth is obtained in both simulation and measurement. With the NUM reflector, the gain of the S-shaped slot antenna is enhanced by up to 3 dBi during the CP operating bandwidth, and steady radiation patterns are achieved. The proposed wide CP antenna with high gain property is suitable for high-capacity long-distance communications in 5G applications.

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