Ultra-wideband and Multiband Reflectarrays for Intelligent Multi-functional Platforms

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***Abstract*—This paper includes two parts. In the first part, a review of techniques for designing wideband or multiband reflectarrays is presented. In the second part, two case studies including the designs of one ultra-wideband (UWB) reflectarray and one multi-band reflectarray are presented. The UWB reflectarray is a novel tightly coupled dipole reflectarray (TCDR) whose unit cell is composed of a tightly coupled dipole and a delay line. The minimum distance between adjacent cells is about 1/10 wavelength at the lowest operating frequency. The TCDR operates from 3.4 to 10.6 GHz with stable radiation patterns and aperture efficiency. The multiband reflectarray is a novel dual-band, dual circularly polarized (CP) reflectarray. The dual-band operation of the reflectarray is obtained by using the interleaved circularly polarized triangular patches as the radiating elements. Within each frequency band, two simultaneous shaped beams with different circular polarization and independent control are realized. Both reflectarrays are fabricated and measurement results are presented.**

***Index Terms*—reflectarray, UWB, multiband, circularly polarized.**

I. INTRODUCTION

Reflectarrays have received a significant amount of research interest in recent years [1-2]. Reflectarrays combine the advantages of reflector antennas and phased arrays. A conventional microstrip reflectarray consists of a printed array (e.g. of patch antennas) illuminated by at least one feed antenna such as a circular horn. Each radiating element is designed to provide a pre-adjusted phase to form a focused beam to the desired direction. At its operation frequencies, a reflectarray antenna can substitute the traditional parabolic reflector with a lightweight planar structure. To reduce the profile of the conventional reflectarray, the folded configuration can be used to provide a low-profile solution [3-5]. Although reflectarray has many advantages, achieving wide bandwidth is always a challenging task. The bandwidth of the reflectarrays is limited by two factors: the inherent narrow BW of microstrip elements and the differential spatial phase delay caused by different path lengths from the feed to each element [6]. Thus, to meet the requirements of different applications, designing wideband or multiband reflectarrays has been widely investigated.

This paper starts with a brief review of the state-of-art techniques to realize the wideband and multiband reflectarrays. Then two recent research works from our group are presented as case studies.

II. REVIEW OF WIDEBAND AND MULTIBAND REFLECTARRAY DESIGN

A. Wideband Reflectarray

1) Unit Cell optimization: Most of the wideband designs reported so far are achieved by synthesizing and optimizing the unit cell of the reflectarray. Through designing unit cells with multi-resonant behavior, the phase shift range can be several times larger than 360^o with linear phase variation, which increases the bandwidth of the reflectarray. To realize the multi-resonant behavior, stacked patches [7-8], parallel dipole [9-10], fractal antenna [11], parasitic elements [12], sub-wavelength unit cells [13], and novel phasing element [14-15] were presented. In these reported designs, the achieved 1-dB gain bandwidths varied from 15% to 30%.

2) Phase Synthesis: Besides optimizing the unit cell designs, the bandwidth of the reflectarray can also be increased by performing phase synthesis. In [16], a wideband phase synthesis approach is presented. This method increases the bandwidth of the reflectarray antenna independent of the element frequency behavior. It was shown that with a single-layer design and a thin substrate, 16.7% 1.5 dB gain bandwidth can be obtained.

B. Ultra-Wideband Reflectarray

Regarding the ultra-wideband (UWB) designs, up to date, there are few reported works. In [17], reflective spatial time-delay units were developed to improve the bandwidth of the reflectarray. The spatial time-delay unit is a unit cell of a ground-plane-backed frequency selective surface (FSS) composed of stacked non-resonant patches. Gain variation of about 4 dB in the 8-12 GHz frequency range was achieved. The same approach was applied to the design of circularly polarized reflectarray and axial ratio lower than 1.5 over 40% bandwidth was reported [18]. Recently, Bessel filter method was introduced to design the UWB reflectarray [19]. The reported reflectarray was implemented as a scalar impedance surface composed of subwavelength elements, and the response of the unit cells was designed to realize Bessel filter responses. This reported design shows good beam characteristics from 5 to 10 GHz.

C. *Multiband reflectarray*

1) Multilayer Configuration: The first approach to realize a multiband reflectarray is to use a multilayer configuration where the reflectarray cells operated at different frequencies are placed in different layers. For example, in [20], two arrays of different sized rings were printed on different substrates separated by a foam layer. To suppress the mutual coupling between different layers, a frequency selective surface (FSS) layer was placed between the 20- and 30-GHz element layers [21].

2) Interleaved Aperture: Another approach is to use the interleaved concept where different radiating elements are interleaved in the same layer. In [22], dual-band operation was achieved by interleaving the concentric split-rings and modified Malta Cross in the same aperture. By interleaving three different types of elements, including split circular ring, split square loops, and cross-dipole, a single layer tri-band circularly polarized (CP) reflectarray was presented in [23].

3) Multiband Unit Cell: The other method to realize a multiband reflectarray is to design the unit cells that can operate at multiple frequency bands, similar to design a multiband array antenna. A dual reflectarray unit cell was presented in [24]. This dual-band unit cell combines the shorted annular patch and inverted-shorted annular patch. Novel element geometries, such as Phoenix Elements [25], were also applied to the design of multiband reflectarray and showed promising radiation performance in terms of gain bandwidth and aperture efficiency.

III. CASE STUDY 1: UWB TIGHTLY COUPLED DIPOLE REFLECTARRAY

In this case study, a UWB reflectarray designed by using the concept of the tightly coupled antenna is presented. This approach combines the advantages of tightly coupled arrays and those of conventional reflectarrays. The developed tightly coupled dipole reflectarray (TCDR) antenna has a wide bandwidth and stable radiation patterns from 3.4 to 10.6 GHz.

A. *Design*

Fig. 1 shows the configuration of the TCDR unit cell. It consists of a printed dipole, phase delay lines, and two metal surfaces. The phase delay line consists of a pair of parallel microstrips. The distance between the top of the element and the first metal surface is h_1. This parameter determines the impedance matching of the dipole. Thus, the value of h_1 is fixed. The phase shift of the unit cell is realized by introducing an additional phase delay line between the first and second metal surface. In order to accommodate the phase delay lines, a hole is introduced on the first metal surface and the delay lines pass through this hole. The distance between the first metal surface and the second metal surface is h_2, which is chosen to be large enough so the length of the phase delay lines can be varied to provide at least 360° phase shift range for the lowest operation frequency. In this design, h_2 is chosen to be 20 mm.

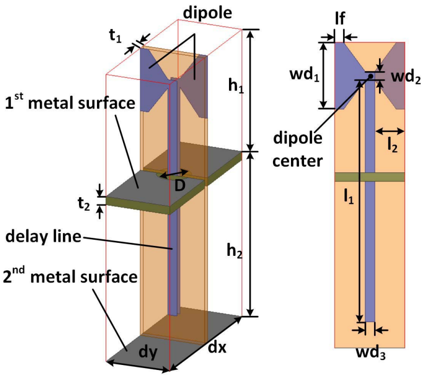


Fig. 1. Side and front views of the TCDR unit cell [26].

Fig. 2 shows the phase shift of the unit cell with different length of the phase delays lines at different frequencies. As shown, when the length of the delay line increases to 25mm, the unit cell provides phase delays up to 400° at the lowest operation frequency.

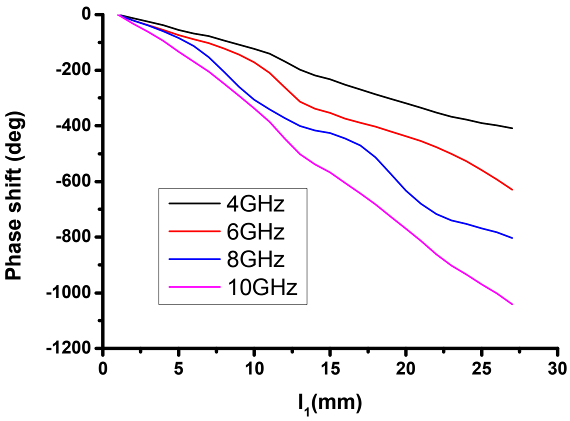


Fig. 2. The phase shift of the TCDR unit cell at different frequencies.

Fig. 3 shows the photo of the developed TCDR. A wideband log-periodic dipole array (LPDA) consisting of dipoles and a pair of parallel microstrips is chosen as the feed antenna. The planar array is composed of 26 × 11 elements. The dimension of reflecting surface is $210 \times 210 \times 34.8 mm^3$. The distance between the top of reflecting surface and feed antenna Rh_1 is 97.6 mm. The distance between the phase center of the LPDA and reflecting surface Rh_2 is 119 mm.

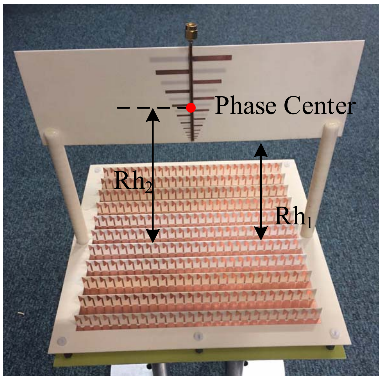
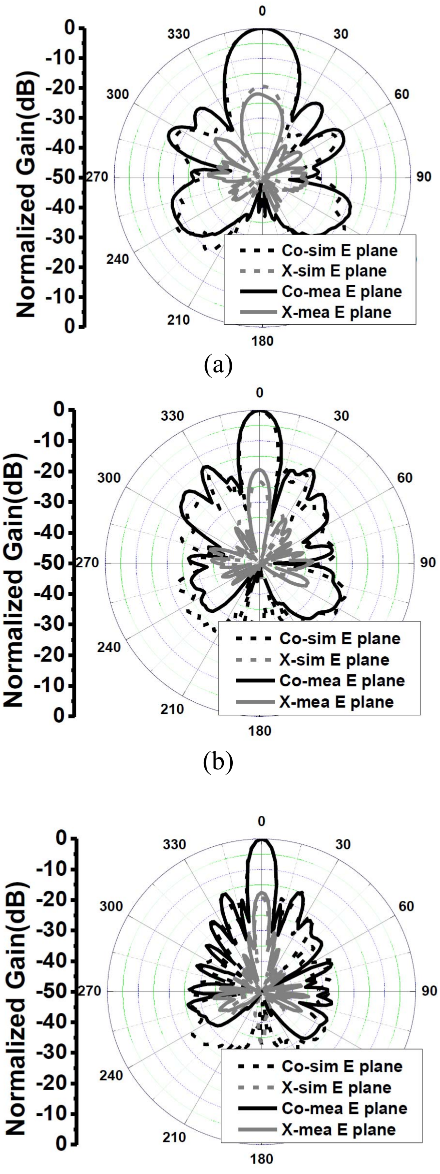


Fig. 3. The configuration of the TCDR antenna.



(a)

(b)

(c)

Fig. 4. Measured and simulated radiation patterns of the TCDR antenna in E-plane at (a) 4GHz. (b) 7GHz. (c) 10GHz.

B. *Simulation and Measurement Results*

Fig. 4 shows the simulated and measured radiation pattern of the TCDR. Due to the page limits of the paper, radiation patterns of only three frequencies in E-plane are shown in this paper. There is good agreement between the simulated and measured results. It can be seen that the radiation pattern performance keeps stable and the shape of the main beam is not distorted. Fig. 5 shows the simulated and measured gains of the antenna. The simulated gain varies from 12.7 to 21.9 dB while the measured gain varies from 13.8 to 22.6 dB from 3.4 to 10.6 GHz. The simulated and measured aperture efficiency (AE) of the antenna is also shown in this figure. The simulated AE of the TCDR is more than 20% from 3.4 to 10 GHz, and it is more than 17.8% from 10 to 10.6 GHz. The measured AE of the TCDR is higher than 20% from 3.4 to 10.6 GHz.

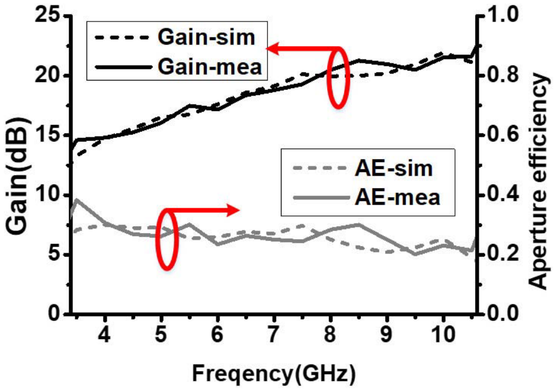


Fig. 5. Simulated and measured gains and aperture [26].

IV. CASE STUDY 2: DUAL BAND DUAL-CIRCULARLY POLARIZED REFLECTARRAY

In this case study, a dual-band dual-CP reflectarray is presented. This reflectarray is realized by interleaving circularly polarized triangular patches of different sizes in the same aperture. At each frequency band, there are two simultaneous shaped beams with different circular polarization and independent control.

A. *Design*

Fig. 6 shows the configuration of the unit cell of the reflectarray. Two equilateral triangular patches of different sizes, one resonates at the higher frequency and the other resonates at the lower frequency, are positioned in a parallelogram with one of the patches rotated by 180°. Using this configuration, the unit cell can be scaled to a dual-band interleaved array antenna with the hexagonal lattice. Because the feed lines are electromagnetically coupled, there is no need for using any vias, thus the fabrication complexity and cost for the reflectarray antenna design is significantly reduced. To verify the design concept, it was decided to design an X-band reflectarray prototype. Two frequencies within X-band were selected, 8.6 GHz and 10.1 GHz, representing a frequency ratio of 1.17. It should be noted that small frequency ratio is chosen in this study but this is not the limitation of the design method. Since the size of the patch can be independently adjusted to operate at different frequencies, the realized frequency ratio can be flexible.

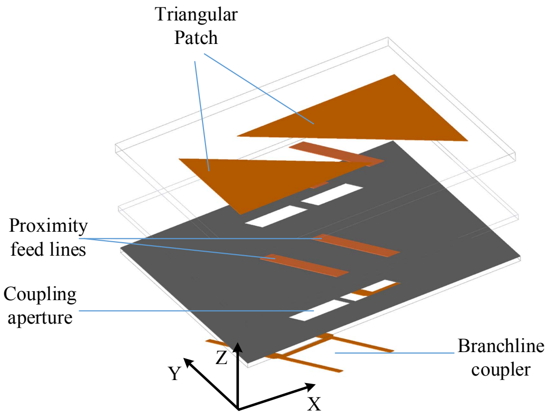


Fig. 6. The configuration of the reflectarray unit cell.

Fig. 7 shows the configuration of the designed reflectarray antenna. As shown, two planar array antennas are interleaved in the same aperture which has a diameter of 234 mm. Each of the array antennas has 75 radiating elements positioned in a hexagonal lattice with a separation distance of 22.5mm ($0.64\lambda_{8.6\mathrm{GHz}}$ and $0.75\lambda_{10.1\mathrm{GHz}}$). An X-band dual-CP septum horn antenna that operates from 8 to 12 GHz is designed to be used as the feed of the reflectarray. Considering the CP beamwidth of the feed, to ensure that most of the radiating elements are illuminated by the CP waves radiated from the feed, the position of the horn antenna is chosen to be 135mm above the center of the planar array.

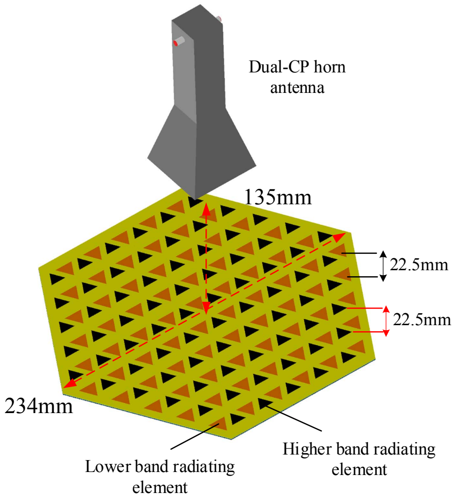
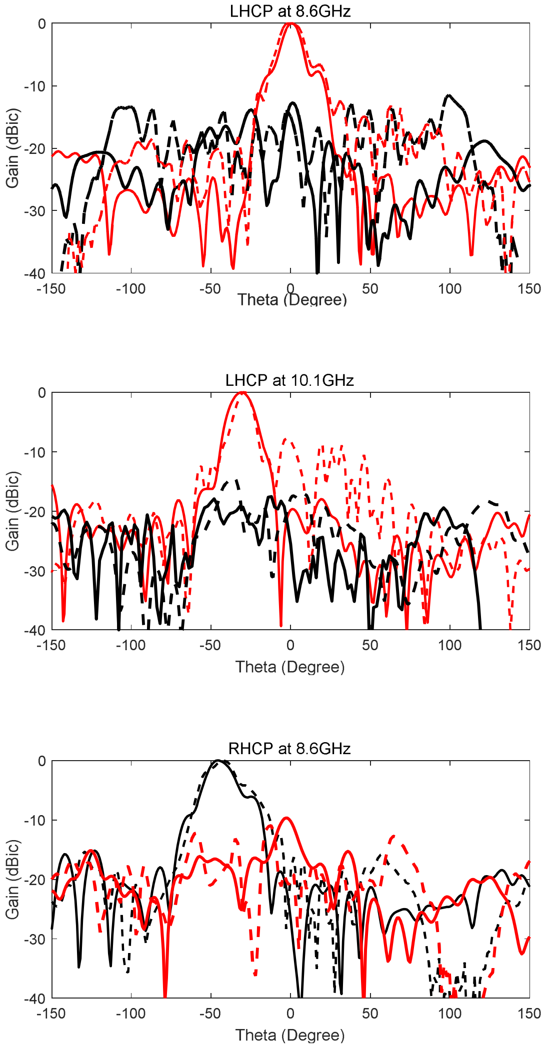


Fig. 7. The configuration of the reflectarray.

B. Simulation and Measurement Results

Fig. 8 show the measured and simulated radiation patterns of the developed dual-band dual-CP reflectarray at the two resonance of the triangular patch. The angles of the beams are designed to point in different directions. The measurement results show higher side lobes and wider beamwidth, which are mainly caused by the phase errors from fabrication inaccuracy, the reflections from the RF connectors, the mounting structure of the feed horn as well as the coaxial cables. Moreover, during the measurement, one port of the dual-CP horn is terminated by a broadband load, which also caused some unavoidable reflections.



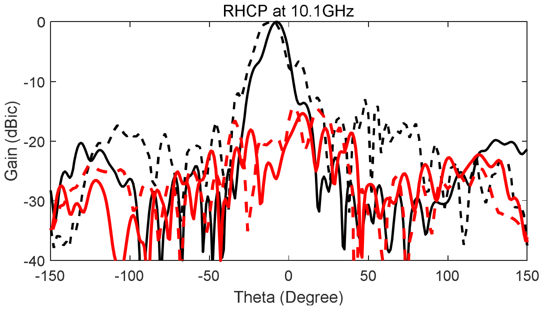


Fig. 8. The simulated and measured dual-CP radiation patterns of the reflectarray at 8.6 GHz and 10.1 GHz. (Black solid line: simulated RHCP, Black dash line: measured RHCP, Red solid line: simulated LHCP, Red dashed measured LHCP)

V. CONCLUSION

In this paper, a review of the techniques to design wideband and multiband reflectarrays are presented in the first part. Then, two recent research works on the UWB reflectarray and multiband reflectarray are presented. The UWB reflectarray is a novel tightly coupled reflectarray, which shows stable radiation patterns and aperture efficiencies from 3.4 to 10.6 GHz. The multiband design is a single aperture dual-band dual-CP reflectarray. This design realizes four simultaneous CP beams with independent beam control. Each of the beams corresponds to different frequencies or different polarizations.

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REFERENCES

[1] P. Nayeri, F. Yang, A. Z. Elsherbeni, Reflectarray Antennas: Theory Designs and Applications., New York, NY, USA: IEEE-Wiley, 2018

[2] J. Huang, J. A. Encinar, Reflectarray Antennas, New Jersey, USA: IEEE-Wiley, 2008

[3] W. Menzel, J. Li and S. Dieter, "Folded reflectarray antenna based on a single layer reflector with increased phase angle range," 2009 3rd European Conference on Antennas and Propagation, Berlin, 2009, pp. 2757-2760.

[4] Q. Luo, S. Gao, C. Zhang, D. Zhou, T. Chaloun, W. Menzel, V. Ziegler, M. Sobhy, "Design and Analysis of a Reflectarray Using Slot Antenna Elements for Ka-band SatCom," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 4, pp. 1365-1374, April 2015.

[5] C. Zhang, Y. Wang, F. Zhu, G. Wei, J. Li, C. Wu, S. Gao, and H. Liu, "A Planar Integrated Folded Reflectarray Antenna With Circular Polarization," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 1, pp. 385-390, Jan. 2017.

[6] D. M. Pozar, "Bandwidth of reflectarrays", Electron. Lett., vol. 39, no. 21, pp. 1490-1491, Oct. 2003.

[7] J. A. Encinar, "Design of two-layer printed reflectarrays using patches of variable size," in IEEE Transactions on Antennas and Propagation, vol. 49, no. 10, pp. 1403-1410, Oct. 2001.

[8] P. Robustillo, J. Zapata, J. A. Encinar and M. Arrebola, "Design of a Contoured-Beam Reflectarray for a EuTELSAT European Coverage Using a Stacked-Patch Element Characterized by an Artificial Neural Network," in IEEE Antennas and Wireless Propagation Letters, vol. 11, pp. 977-980, 2012.

[9] J. H. Yoon, Y. J. Yoon, W. S. Lee, and J. H. So, “Broadband microstrip reflectarray with five parallel dipole elements,” IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 1109–1112, 2015.

[10] E. Carrasco et al., "Design, Manufacture and Test of a Low-Cost Shaped-Beam Reflectarray Using a Single Layer of Varying-Sized Printed Dipoles," in IEEE Transactions on Antennas and Propagation, vol. 61, no. 6, pp. 3077-3085, June 2013.

[11] F. Xue, H. J.Wang, M. Yi, and G. Liu, ``A broadband KU-band microstrip reflectarray antenna using single-layer fractal elements," Microw. Opt. Technol. Lett., vol. 58, no. 3, pp. 658-662, Mar. 2016.

[12] L. Li et al., ``Novel broadband planar reflectarray with parasitic dipoles for wireless communication applications," IEEE Antennas Wireless Propag. Lett., vol. 8, pp. 881-885, 2009.

[13] P.-Y. Qin, Y. J. Guo, and A. R. Weily, “Broadband reflectarray antenna using subwavelength elements based on double square meander-line rings,” IEEE Trans. Antennas Propag., vol. 64, no. 1, pp. 378–383, Jan. 2016

[14] L. Zhang, S. Gao, Q. Luo, W. Li, Y. He and Q. Li, "Single-Layer Wideband Circularly Polarized High-Efficiency Reflectarray for Satellite Communications," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 9, pp. 4529-4538, Sept. 2017.

[15] R. Deng, S. Xu, F. Yang and M. Li, "A Single-Layer High-Efficiency Wideband Reflectarray Using Hybrid Design Approach," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 884-887, 2017.

[16] Y. Mao, S. Xu, F. Yang and A. Z. Elsherbeni, "A Novel Phase Synthesis Approach for Wideband Reflectarray Design," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 9, pp. 4189-4193, Sept. 2015.

[17] S. Abadi, K. Ghaemi and N. Behdad, "Ultra-Wideband, True-Time-Delay Reflectarray Antennas Using Ground-Plane-Backed, Miniaturized-Element Frequency Selective Surfaces," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 2, pp. 534-542, Feb. 2015.

[18] S. Abadi and N. Behdad, "True-time-delay UWB reflectarray with linear to circular polarization transformation," 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), Fajardo, 2016, pp. 1205-1206.

[19] L. Liang and S. Victor Hum, "Design of a UWB Reflectarray as an Impedance Surface Using Bessel Filters," in IEEE Transactions on Antennas and Propagation, vol. 64, no. 10, pp. 4242-4255, Oct. 2016.

[20] C. Han, C. Rodenbeck, J. Huang, and K. Chang, “A C/Ka dual frequency dual layer circularly polarized reflectarray antenna with microstrip ring elements,” IEEE Transactions on Antennas and Propagation, vol. 52, no. 11, pp. 2871–2876, Nov 2004.

[21] R. Deng, F. Yang, S. Xu and M. Li, "An FSS-Backed 20/30-GHz Dual-Band Circularly Polarized Reflectarray With Suppressed Mutual Coupling and Enhanced Performance," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 2, pp. 926-931, Feb. 2017.

[22] R. Deng, Y. Mao, S. Xu, and F. Yang, “A single-layer dual-band circularly polarized reflectarray with high aperture efficiency,” IEEE Transactions on Antennas and Propagation, vol. 63, no. 7, pp. 3317-3320, July 2015.

[23] F. Yang, A. Yu, A. Elsherbeni, and John Huang, "Single-Layer Multi-band Circularly Polarized Reflectarray Antenna: Concept, Design, and Measurement," in URSI General Assembly, 2008

[24] Boccia, L., G. Amendola, and G. Angiulli, "Single layer dual band reflectarray cell," IEICE Electronics Express, Vol. 10, No. 12, 1-8, 2013.

[25] R. Deng, S. Xu, F. Yang and M. Li, "Single-Layer Dual-Band Reflectarray Antennas With Wide Frequency Ratios and High Aperture Efficiencies Using Phoenix Elements," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 2, pp. 612-622, Feb. 2017.

[26] W. Li, S. Gao, L. Zhang, Q. Luo and Y. Cai, "An Ultra-Wide-Band Tightly Coupled Dipole Reflectarray Antenna," in IEEE Transactions on Antennas and Propagation, vol. 66, no. 2, pp. 533-540, Feb. 2018.