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Broadband Single-Layer Reflectarray Antenna Employing Circular Ring Elements Dented With Sectorial Slits

HUITING YU AND LU GUO, (Senior Member, IEEE)
Department of Communication Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

Corresponding author: Lu Guo (lu.guo@njust.edu.cn)

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ABSTRACT A broadband single-layer reflectarray antenna comprising circular ring elements dented with sectorial slits is presented. The sizes of circular rings are fixed and equal for all elements, while the variation of the reflected phase is obtained by varying the lengths of the sectorial slits dented within the circular rings. In this arrangement, the rapid geometric variations among the neighboring elements encountered in conventional reflectarray antennas can be prevented. The proposed element can yield a linear reflected phase together with a high reflected magnitude and important geometric parameters are examined to gain an insight into its broadband operation. Using the proposed unit cells, a 25° offset-fed reflectarray containing 529 elements with a grid periodicity of 0.3λ at 10 GHz, is designed, built, and tested. Experimental results indicate that the designed reflectarray antenna can realize a broad 30% 1-dB gain bandwidth with a 58.3% aperture efficiency. In addition, good sidelobe and cross-polarization levels in the ranges of 17.5 dB and 32 dB are also achieved at 10 GHz.

INDEX TERMS Circular ring element, single-layer, broadband, reflectarray antenna, subwavelength, sectorial slits.

I. INTRODUCTION

Reflectarray antennas present a great potential in various applications owing to their appealing features of low-cost, low-mass, and simple deployment despite the insufficient bandwidth is a key obstacle to be tackled [1]. For reflectarrays with a small or moderate size, the bandwidth is primarily dominated by the element behavior [2]. Therefore, considerable endeavors have been made for the element bandwidth enhancement, such as exploiting multi-resonant elements [3], polarization rotating elements [4], circular ring and complementary diagonal patch ring elements [5], and subwavelength elements [6], [7]. In addition, the bandwidth of reflectarrays can also be enhanced by attaching phase delay lines or arc stubs on the circular patch or rings / gapped rings, as demonstrated in [8]–[11]. By adjusting the lengths of phase delay lines or arc stubs, a wideband performance can be obtained.

However, it is seen that for all of the above-mentioned designs, abrupt geometry variations may take place for the adjacent cells, therefore dissatisfying the assumption of equal coupling when analyzing the unit cells [12], [13]. To tackle this issue, various designs have been proposed, such as using the dipole element loaded with an interdigital structure [14], the I-shaped patch surrounded by a circular ring [15], and the rectangular patch etched with slots [16]. By this means, the elements feature an identical dimension for all the cells while the variation of the phase is realized by adjusting the interior parameters inside the structures. Therefore, the rapid geometric variations for the neighboring cells in conventional reflectarray antennas are circumvented.

In this article, a novel unit cell consisting of a single-layer circular ring patch dented with sectorial slits is presented for broadband reflectarray antennas. Instead of attaching phase delay lines or arc stubs on the circular patch or rings / gapped rings as shown in [8]–[11], this work employs sectorial slits etched within the circular rings. The circular rings feature an equal size for all the cells and the variation of the phase is obtained by changing the lengths of the interior slits. The proposed unit cell combines the advantages of phase delay line or arc stub designs in [8]–[11] and equal element designs

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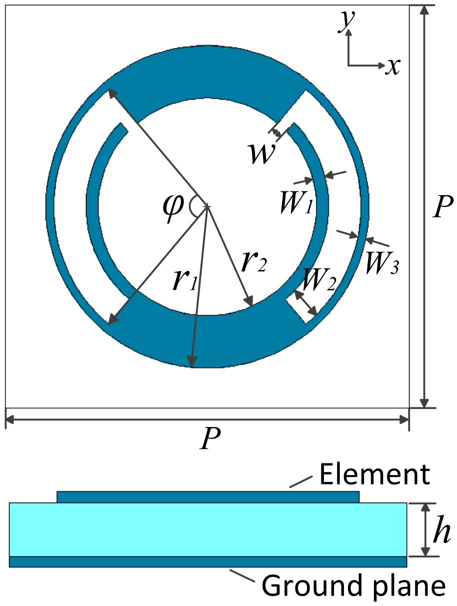


FIGURE 1. The proposed element layout.

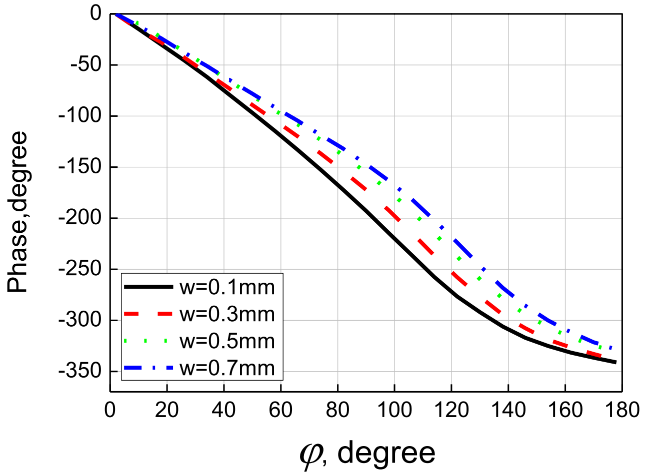


FIGURE 2. Reflection phases versus interior slits' lengths φ at 10 GHz for different w of the unit cell.

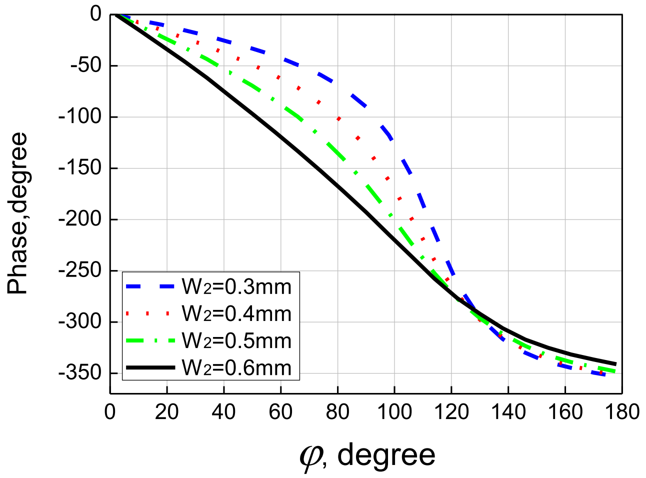


FIGURE 3. Reflection phases versus the interior slits' lengths φ at 10 GHz for different W_2 of the unit cell.

in [14]–[16], consequently leading to a greatly improved performance. Numerical investigations are performed for the unit cell optimization to realize a linear phase and a broadband behavior. Using the novel unit cells, a 25° offset-fed reflectarray formed by 529 elements with a grid periodicity of 0.3λ at 10 GHz, is designed and constructed. Experiment results exhibit that a broad 30% 1-dB gain bandwidth with a 58.3% aperture efficiency is achieved. Furthermore, the sidelobe and cross polarization levels are 17.5 dB and 32 dB at 10 GHz, respectively. Compared with various recently published designs, such as [8], [9] and [16], this work presents a noticeably wider bandwidth.

II. UNIT CELL DESIGN AND CHARACTERISTICS

The geometry of the proposed unit cell is illustrated in Fig. 1. A circular ring patch dented with sectorial slits is etched on the upper side of a F4BM substrate whose height and dielectric constant are 3.175 mm and 2.2, respectively, while a ground plane is etched underneath the substrate. The proposed element is a single-layer structure without an additional air layer as required in many other designs, and the element periodicity is 9 mm in both x- and y-directions, respectively. The variation of the phase is obtained by changing the lengths of interior slits etched within the circular ring. By adopting this method, almost identical mutual coupling among the neighboring elements can be obtained. The element design is conducted at 10 GHz and characterized by using CST Microwave Studio, where Floquet ports and periodical boundaries are employed.

As clearly shown in the simulations, the dimension w of the inner gap of the slits, and the width of the sectorial slits W_2, have a notable impact on the reflection phase. As depicted in Fig. 2, by decreasing w, the reflected phase curve becomes linear and the phase span also becomes wider. The optimal w is chosen as 0.1 mm featuring a linear behavior.

Fig. 3 displays the influence of W_2 on the reflection phase curves. By increasing W_2, the phase curve shows more and more linear characteristic in spite of the phase span is slightly decreased. The optimal dimension of W_2 is chosen to be 0.6 mm.

The phase shifting responses of the element for both normal and oblique wave incidences are evaluated. It can be seen in Fig. 4 that for incident angles up to 40°, the variation between reflection phase curves is insignificant.

The final geometric parameters of the unit cell are listed in Table 1. The reflection magnitude and phase of the proposed unit cell against φ with final geometric dimensions at 10 GHz, are displayed in Fig. 5. A linear reflection phase response covering nearly 360° and a high reflection magnitude close to 0 dB are obtained.

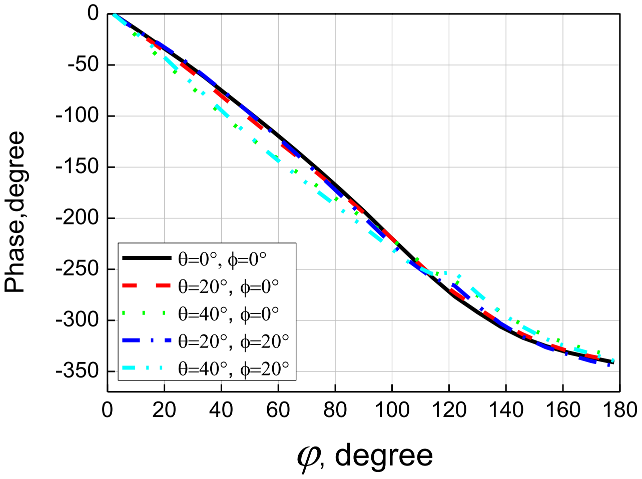


FIGURE 4. Reflection phases of the unit cell for different wave incidence angles.

TABLE 1. Unit cell design parameters.

Parameters	Value
P	9 mm
r_1	3.3 mm
r_2	2.4 mm
w	0.1 mm
W_1	0.2 mm
W_2	0.6 mm
W_3	0.1 mm

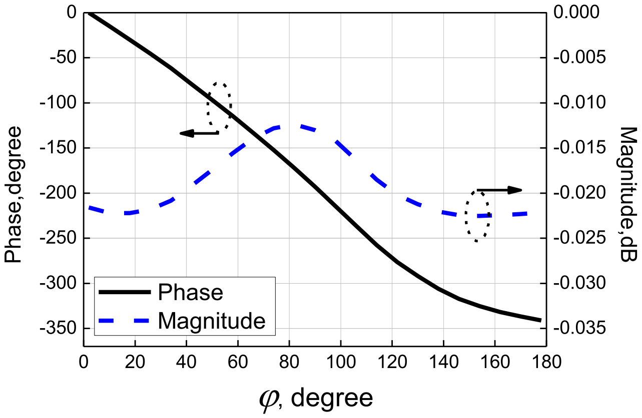


FIGURE 5. Reflected magnitude and phase of the unit cell with final dimensions at 10 GHz.

Fig. 6 plots the reflected phases of the proposed element versus sectorial slits' lengths φ for different frequencies. As can be seen, the reflection phases feature a good linearity and insensitivity with the variation of frequency, therefore indicating a wideband behavior.

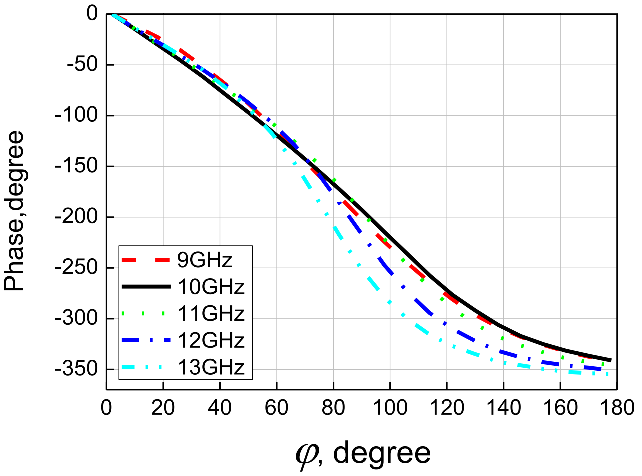
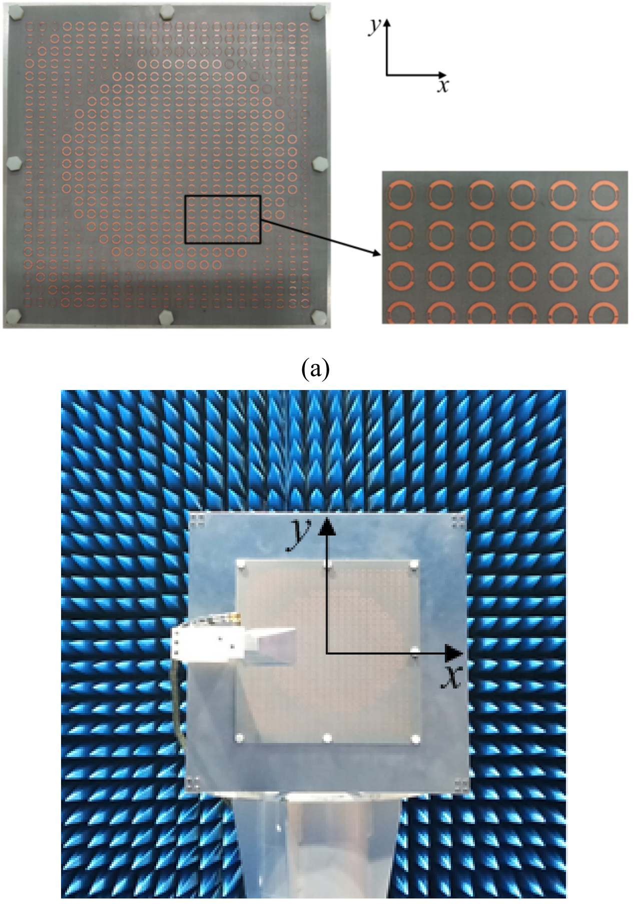


FIGURE 6. Reflection phases versus φ of the unit cell for various frequencies.



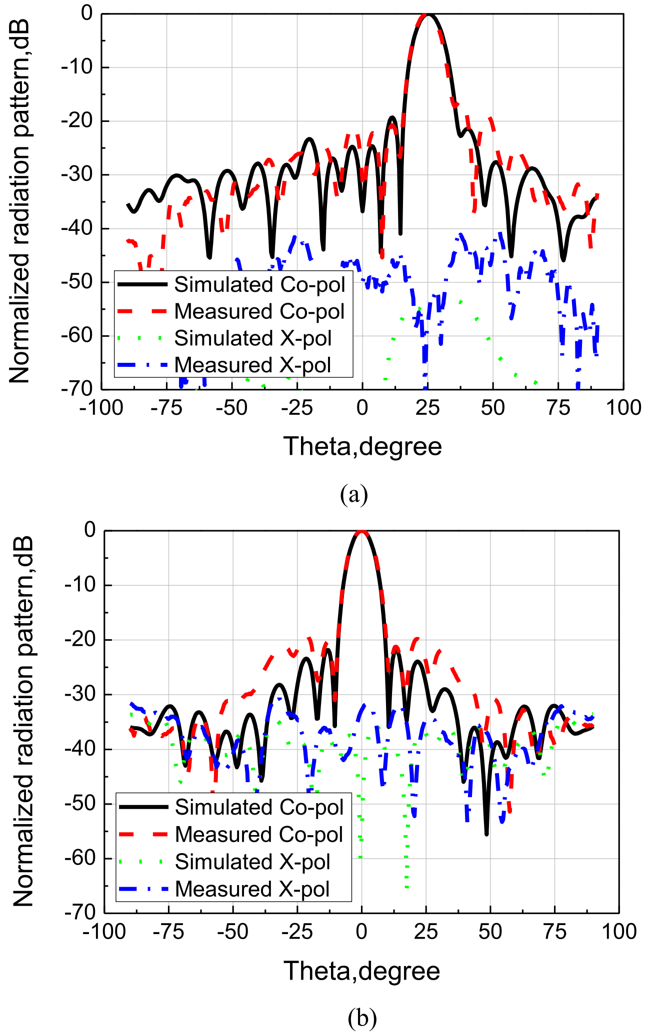
(a)

(b)

FIGURE 7. (a) Proposed reflectarray prototype and (b) measurement setup.

III. REFLECTARRAY RESULTS AND DISCUSSIONS

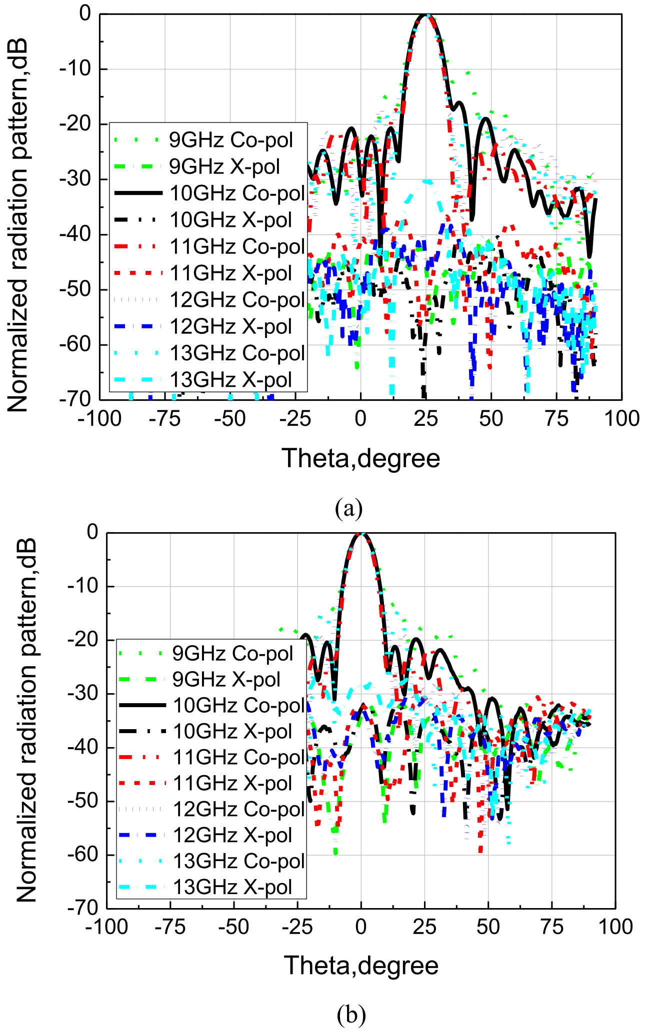
A reflectarray illuminated by a 25° off-set pyramidal horn is designed at 10 GHz and simulated by CST Microwave Studio. The horn is located 148 mm above the reflectarray to ensure a satisfactory aperture efficiency. The reflectarray is formed by 529 elements in a 207 mm × 207 mm aperture.



(a)

(b)

FIGURE 8. **Normalized patterns at 10 GHz. (a) *E*-plane. (b) *H*-plane.**



(a)

(b)

FIGURE 9. **Measured (a) *E*-plane and (b) *H*-plane patterns of the antenna at various frequencies.**

To reduce the cross polarization, the elements are mirror symmetrically arranged against the x-direction.

Fig. 7 (a) shows the proposed reflectarray prototype and the antenna radiating behavior was tested in a chamber, as shown in Fig. 7 (b).

Both simulated and measured normalized patterns of the antenna at 10 GHz are presented in Fig. 8. It is evident that the experimental results and simulated results agree well. The minor discrepancy is most likely due to the manufacture tolerances and imperfect measurement environment. Fig. 8 (a) shows that the main lobe takes place at 25° as designed. The measured E-plane and H-plane side lobe levels are 17.5 dB and 19 dB down from the peak of the main lobe, respectively. It can be also seen that the cross-polarization levels are 40 dB and 32 dB near the main beam region in the E- and H- planes, respectively.

Fig. 9 depicts the experimental patterns of the reflectarray at various frequencies in the E- and H- planes, respectively. It is noticed that except at 9 GHz which is out of band and not of interest, the radiation patterns generally remain consistent across the band in both the E- and H- planes. For the E-plane, the main beams occur at 25°, and the side lobe and cross polarization levels become slightly degraded with the increase of frequency. The similar trend is also observed in the H-plane. At the higher frequency of 13 GHz, the sidelobe and cross polarization levels rise to 16 dB and 28 dB, respectively. On the whole, a good radiation behavior in terms of main lobe direction, sidelobe level, and cross polarization level, is achieved.

The gain and aperture efficiency of the antenna in both simulation and measurement are depicted in Fig. 10. It is observed that the experimental and simulated results again agree reasonably well. The measured gain at 10 GHz is 25 dBi, equivalent to a 58.3% aperture efficiency. The 1-dB gain bandwidth of the proposed reflectarray is 30%, which ranges from 10.4 GHz to 13.8 GHz, demonstrating a wideband performance. Note that the deviation of the center frequency of the 1-dB gain bandwidth from designed 10 GHz

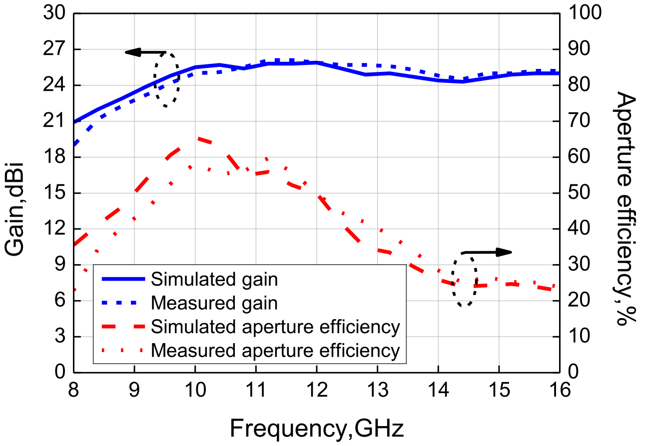


FIGURE 10. Simulated and measured gain and aperture efficiency of the antenna.

TABLE 2. Performance comparison of proposed antenna with various published works.

Ref.	[8]	[9]	[10]	[16]	**Proposed**
Center Frequency (GHz)	8.5	10	10	10	**10**
Gain Bandwidth (%)	16.5 (1-dB)	20 (1-dB)	31.5 (1-dB)	23 (1-dB)	**30 (1-dB)**
Additional Air Layer	Yes	Yes	Yes	No	**No**
Cross-Pol Level (dB)	<-25	<-26	<-26	< -26	**< -32**
Sidelobe Level (dB)	<-20	<-17.5	<-20	<-19	**<-17.5**
Aperture Efficiency (%)	59.2	51.3	50	67	**58.3**

to about 11.2 GHz is mostly due to the electrical size of the antenna aperture increases when the frequency goes up. Moreover, the phase center errors of the feed horn, phase errors for large incidence angles, fabrication tolerances, and imperfect testing environment may also contribute to the deviation.

Table 2 shows a performance comparison between the proposed antenna and some recently published works that employ phase delay lines [8]–[10] and the equal element [16]. It is observed that the proposed antenna combines the advantages of both bandwidth enhancement approaches, and it presents a better or comparable behavior in terms of aperture efficiency, sidelobe / cross polarization levels, and gain bandwidth among all the designs.

IV. CONCLUSION

A broadband single-layer reflectarray containing circular ring elements dented with sectorial slits is presented. The circular rings feature an equal size for all the cells and the phase swing is obtained by changing the interior slits' lengths. The unit cell can yield a linear phase and a high reflected magnitude. Based on the novel unit cells, a 25° offset fed reflectarray is designed and constructed at 10 GHz. The experimental data indicate that a broad 30% 1-dB gain bandwidth with a 58.3% aperture efficiency is achieved. Furthermore, the sidelobe and cross polarization levels are 17.5 dB and 32 dB at 10 GHz, respectively.

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HUITING YU was born in Nantong, Jiangsu, China, in 1995. She received the B.Eng. degree in communication engineering from the Nanjing University of Science and Technology, Nanjing, China, in 2017, where she is currently pursuing the M.Sc. degree.

LU GUO (S'06–M'10–SM'16) was born in Beijing, China, in 1981. He received the B.Eng. degree from the University of Electronic Science and Technology of China (UESTC), in 2003, and the M.Sc. (Hons.) and Ph.D. degrees from the Queen Mary University of London, U.K., in 2004 and 2010, respectively.

From 2007 to 2008, he was a Research Assistant with the Queen Mary University of London. From 2008 to 2009, he was a Knowledge Transfer Partnership (KTP) Engineer with Jaybeam Wireless, U.K. He was also a Postdoctoral Researcher with the Queen Mary University of London, from 2009 to 2011. He was a Research Scientist with Temasek Laboratories, National University of Singapore (NUS), from 2011 to 2017. He is currently a Professor with the Nanjing University of Science and Technology, Nanjing, China. His current research interests include ultra-wideband (UWB) antennas, compact antennas, low-profile antennas, metamaterial-based antennas, and reflectarray and transmitarray antennas.

Dr. Guo is a Senior Member of the Chinese Institute of Electronics (CIE) and the China Institute of Communications (CIC). He was a recipient of the International Workshop on Antenna Technology 2010 (iWAT2010) Wiley Student Paper Prize Award and the Outstanding Reviewer Award for the IEEE Antennas and Wireless Propagation Letters, in 2019. He is currently an Associate Editor of the IEEE Access and the *IET Electronics Letters*, and an Editorial Board Member of the *International Journal of RF and Microwave Computer-Aided Engineering* (RFMiCAE). He also serves as a Reviewer for over 15 scientific journals, including the IEEE Transactions on Antennas and Propagation, the IEEE Transactions on Vehicular Technology, and the IEEE Antennas and Wireless Propagation Letters.

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