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Review

Multimode Resonator Technique in Antennas: A Review

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Abstract — During the past several decades, the multimode resonator (MMR) technique has been extensively investigated and widely used, with successful exploration of a variety of high-performance patch antennas, slot antennas, dielectric resonant antennas, dipole antennas, and so on. In this review paper, we summarize the research milestones for these MMR antennas worldwide as one of the most contributive research teams in this field. First, the basic working principles of the MMR technique are clearly illustrated and studied, including mode excitation, mode suppression, impedance performance improvement, and radiation performance improvement. Next, the research topics regarding impedance performance enhancement, i.e., wide-bandwidth operation, multibandwidth operation, and mutual coupling reduction, based on the MMR method are intensively described. After that, the relevant works on radiation performance enhancement, i.e., high-gain, wide-beamwidth, multibeam, multipolarization, low-cross-polarization, filtering-response, and leaky-wave antennas, based on the MMR method are extensively illustrated. By using this technique, several ideas about operating frequency reallocation, electric-field null control, radiation pattern reshaping, and efficiency null generation of the antennas are proposed and demonstrated by our team for the first time. In addition, the application of the MMR technique for wireless communication systems is introduced and presented, such as implant communication, wireless power transfer, and multiple-input multiple-output communication. With these arrangements, exploration and reporting of more interesting and useful MMR design methods can be anticipated in the future.

Keywords — Antennas, Multimode resonator, Impedance performance, Radiation performance.

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I. Introduction

With the rapid development of modern wireless communication systems, antennas with multifunction, multiscenario, and multiuser performance are in high demand [1]–[3]. To meet these critical requirements, the multimode resonator (MMR) technique has been reported and developed as one of the most effective approaches for antennas since the MMR technique has several unique advantages, such as fewer units, fewer layers, low cost, high efficiency, controllable performance, and simple working principle.

The roots of the MMR technique lie in dielectric resonant antennas [4], horn antennas [5], monopulse antennas [6], biconical antennas [7], and reflector antennas [8]. Meanwhile, based on the well-known cavity model theory [9], the microstrip patch antenna (MPA) has been demonstrated to maintain the multiple-resonant-mode property, with the advantages of a low profile and easy fabrication compared to the above antennas [4]–[8], thus being extensively studied and widely used in wireless communication systems [10]–[12]. Therefore, this paper takes the single-layer MPA as a representative antenna to introduce the MMR technique used worldwide.

First, the history of the development of MPAs is briefly introduced. In 1953, the microstrip line was introduced to an antenna by Deschamps [13], and then, the first MPA was proposed by E. V. Byron in 1970 [14]. Subsequently, Munson and Howell successfully fabricated the first practical MPAs in 1972 and 1974 [15], [16]. To efficiently design high-performance MPAs, Derneryd built the transmission line model in 1976 to implement a few rectangular MPAs [17]. After that, Lo proposed the well-known cavity model theory in 1979, which demonstrated that a set of resonant modes could be excited for different types of MPAs [9]. In the same year, an international symposium focused on MPAs was held by New Mexico State University. Since then, MPAs have attained an important position in the antenna field. Unfortunately, traditional MPAs often suffer from many drawbacks, i.e., narrow bandwidth, high loss, large discrete distribution of resonant modes, and distorted radiation beams of higher-order modes. To circumvent these problematic issues, a large number of researchers have extensively investigated the MMR technique in designing the desired MPAs.

Researchers have focused on the MMR technique not only for MPAs but also for other types of antennas, such as dielectric resonant antennas [4], horn antennas [5], monopulse antennas [6], biconical antennas [7], and reflector antennas [8]. In this background, the MMR technique has become increasingly popular worldwide. Figure 1 plots the research results obtained from the Web of Science published from 1998 to 2021 based on the keyword "antenna mode" [18]. The results depict that the relevant works about antenna modes have dramatically increased each year. Recently, characteristic mode analysis (CMA) has been used to analyze different types of MMR antennas.

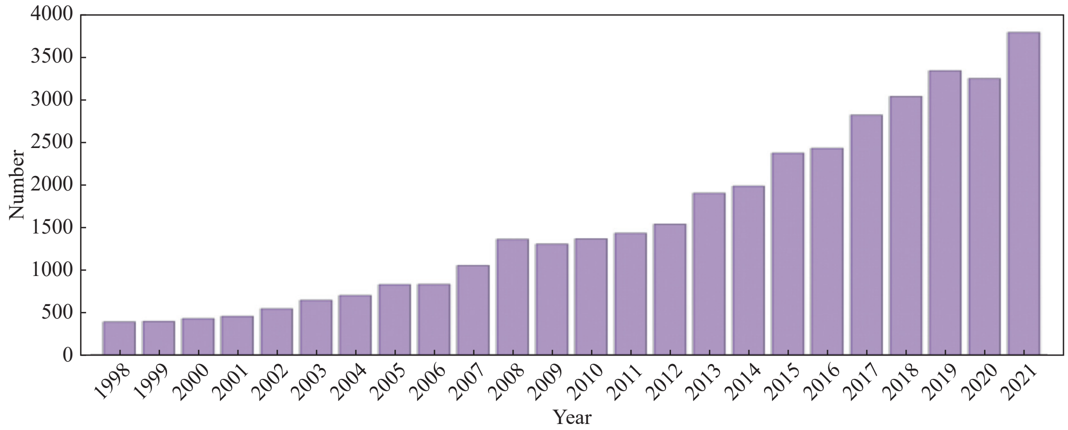

Figure 1 Remarkable increasing trend: the number of research papers in recent years on the topic of antenna modes.

This review paper is organized as follows. Section II explains the basic principles of the MMR technique based on patch antennas, which include mode excitation, mode suppression, frequency reallocation, and radiation pattern control. Section III discusses the impedance performance improvement of antennas obtained by using the MMR technique, which contains wide-bandwidth operation, multi-bandwidth operation, and mutual coupling reduction. Section IV introduces the radiation performance enhancement of antennas obtained by using the MMR technique, which illustrates wide-beamwidth, high-gain, multibeam, multipolarization, low-cross-polarization, and filtering-response characteristics. Section V briefly exhibits some advantages and practical applications of antennas realized via the MMR technique. Finally, Section VI concludes this paper.

II. Basic Principles of the MMR

In general, the fundamental mode of the traditional antenna has the inherent advantages of compact size, stable radiation beam, and high efficiency. As a result, the fundamental mode is typically investigated and widely used in modern communication systems. However, cavity model theory has demonstrated that both fundamental and higher-order modes are simultaneously maintained for these different antennas, i.e., slot antennas, patch antennas, dipole antennas, waveguide antennas, and so on. If these higher-order modes could be properly adjusted and used in designing antennas, then a large number of benefits could be obtained, including low cost, fewer layers, a compact size, and attractive impedance or radiation performance. In the following, we introduce the basic working principles of the MMR technique, thus implementing high-performance antennas more efficiently.

1. Mode excitation and suppression

As is well known, a set of resonant modes can be excited for a single MPA [9]. However, there are several distinct differences in the resonant frequency, radiation beam, or polarization between these modes. To realize the desired performance, some of these modes should be defined as the desired modes to effectively excite them in the working band. In contrast, the rest of these modes should be defined as the undesired modes to be fully suppressed or removed in the working band. In the following, we illustrate the working principles of mode excitation and suppression in more detail.

As is well known, an equivalent electric wall is formed at the patch center under the even-order modes. In contrast, an equivalent magnetic wall is formed at the patch center under the odd-order modes. 1) With respect to even-order mode suppression and odd-order mode excitation, the main principle is to build an equivalent electric wall around the center of the patch. As a result, differential feed [11], aperture-coupled feed [19], and shorted walls [20] could be adopted for the antennas in Figures 2(a), (b), and (c), respectively. 2) With respect to odd-order mode suppression and even-order mode excitation, the main principle is to build an equivalent magnetic wall around the center of the patch. As such, equal feed and center feed could be adopted for the antennas in Figures 3(a) and (b), respectively.

In summary, the radiative modes of an antenna could be successfully excited or suppressed by controlling or reallocating the internal electric field distribution.

2. Frequency reallocation of different modes

Although some of the undesired modes are successfully

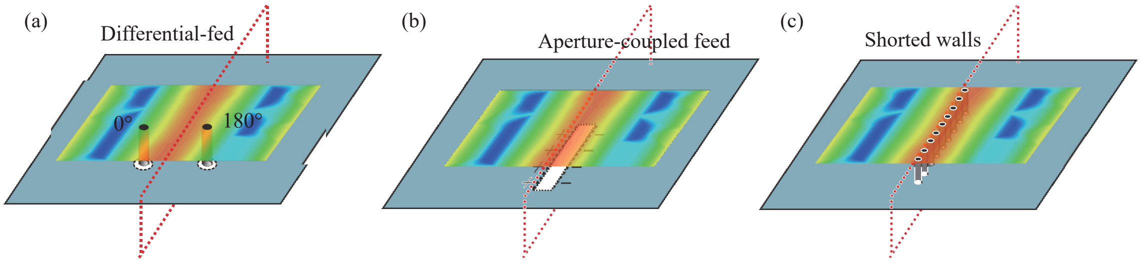

Figure 2 Even-order mode suppression of an MPA. (a) Differential feed; (b) Aperture-coupled feed; (c) Shorted walls.

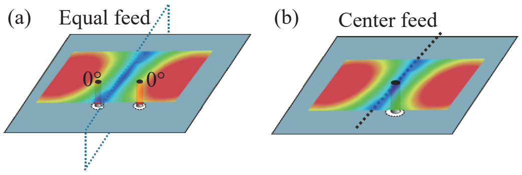

Figure 3 Odd-order mode suppression of an MPA. (a) Equal feed; (b) Center feed.

suppressed by using the above techniques, the desired modes suffer from a large frequency spacing and connection. To realize wideband or multiband operation, the resonant frequencies of these modes must be independently reallocated. In the following, we illustrate the working principles of frequency increase and reduction in more detail.

With respect to frequency increase, the main principle is to transform the maximum internal electric field into the counterpart minimum value, thus decreasing the wavelength of this mode. In contrast, with respect to frequency reduction, the main principle is to change the minimum internal electric field into the counterpart maximum value, thus enlarging the wavelength of this mode. Based on this principle, the transmission line model for an MPA loaded with shorting pins was built, as shown in Figure 4(a) [10]. Subsequently, the transmission line model of the differential-fed MPA loaded with open-ended stubs was constructed, as shown in Figure 4(b) [11], for theoretical investigation. The detailed calculation results with relevant discussions cannot be presented herein due to the page limit.

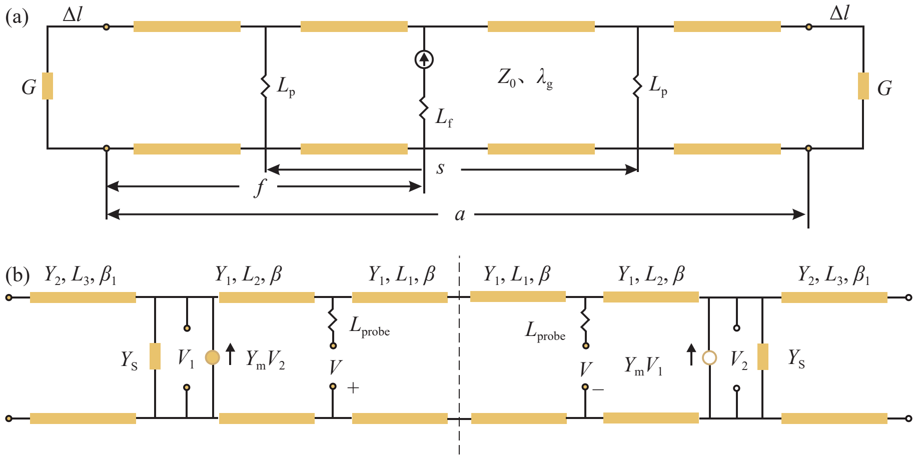

Figure 4 Transmission line model of an MPA. (a) Pin-loaded transmission line model in [10]; (b) Stub-loaded transmission line model in [11].

To illustrate this principle more clearly, the frequency increase and reduction in [21] are selected as an example in Figure 5. For the traditional MPA in Figure 5(a), the even-order mode between the TM_{10} and TM_{30} modes could be successfully suppressed based on the basic principle. Next, by loading shorting pins around the maximum and minimum electric fields of the MPA under the TM_{10} and TM_{30} modes, respectively, the resonant frequency of the TM_{10} mode could be significantly increased, as illustrated in the Figure 5(b) while keeping that of the TM_{30} mode almost constant. In contrast, if slot1 is etched around the maximum and minimum electric fields of the MPA under the TM_{10} and TM_{30} modes, respectively, then the resonant frequency of the TM_{30} mode could be significantly decreased, as shown in Figure 5(c) while keeping that of the TM_{10} mode almost constant. Additionally, slot2 is cut in the center of the radiator to improve the impedance matching, as shown in Figure 5(d). In summary, the impedance performance of an antenna under different modes could be independently reallocated by independently changing the electric field distributions.

3. Radiation improvement of different modes

Apart from the input impedance, the radiation performance is another key parameter in designing the desired antennas. Unfortunately, a large number of serious issues have arisen for the traditional antenna, as shown in Figure 6, i.e., high sidelobe level, large cross-polarization, distorted radiation beam, and so on. All of them have significantly increased the challenges in realizing high performance of these anten-

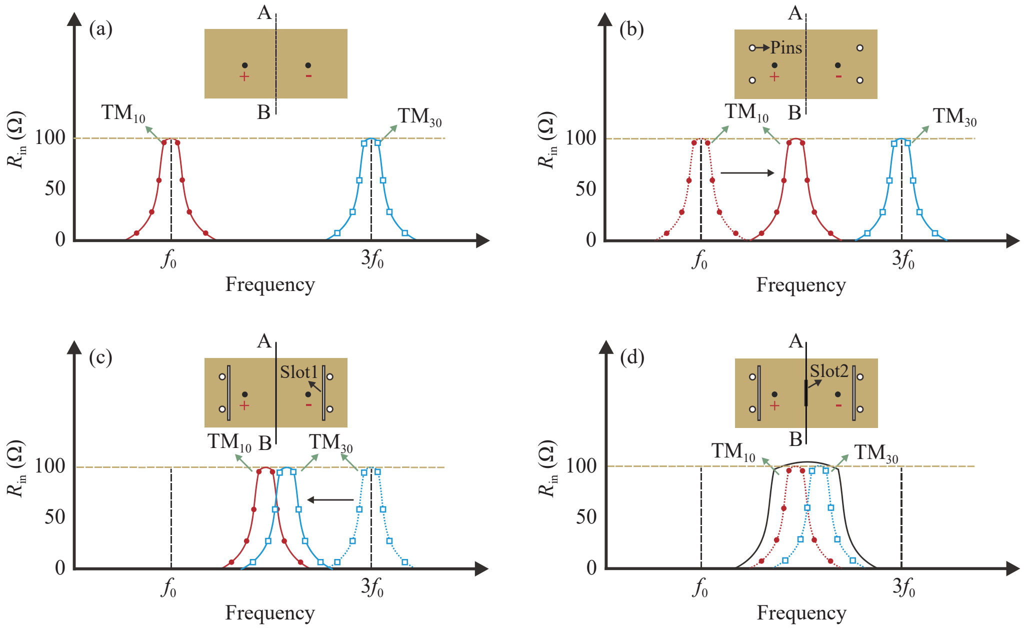

Figure 5 Input resistance improvement of an MPA under the TM$_{10}$ and TM$_{30}$ modes by using metallic shorting pins and etched-out slots [21]. (a) Conventional differential-fed MPA; (b) MPA with shorting pins; (c) MPA with shorting pins and slot1; (d) MPA with shorting pins, slot1, and slot2.

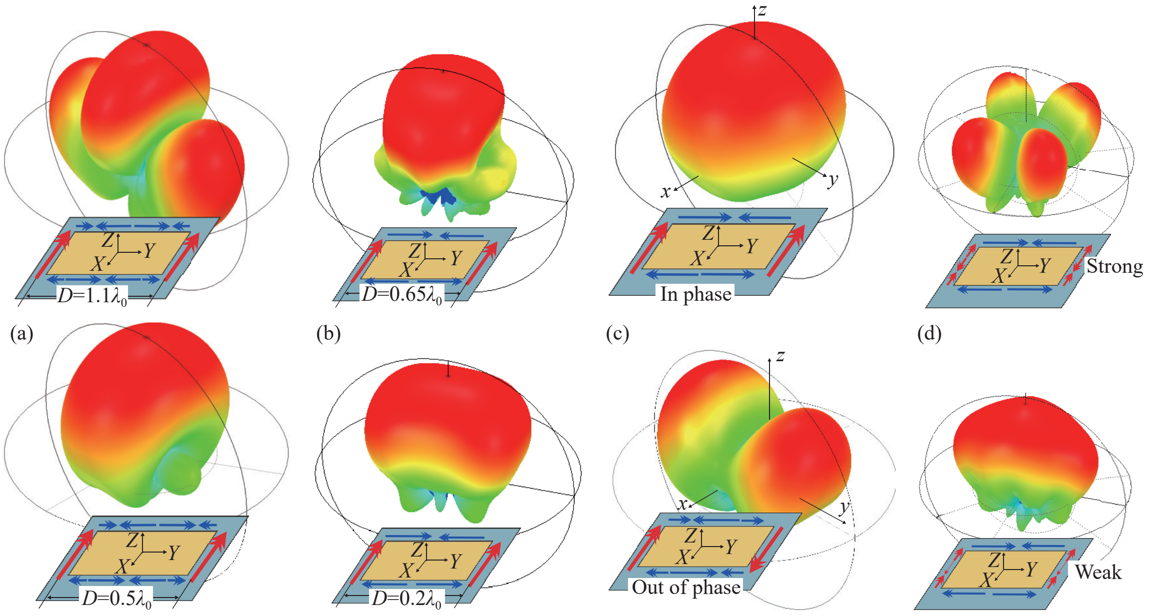

Figure 6 Evolution of the MPA for radiation performance improvement under different modes. (a) Sidelobe reduction. (b) HPBW enhancement. (c) Multibeam generation. (d) Non-broadside to broadside transformation.

nas based on the MMR concept. In the following, we illustrate the working principle of radiation pattern improvement in more detail.

The high sidelobe level of the TM$_{03}$ mode in Figure 6(a) is mainly caused by the large spacing $D = 1.1\lambda_0$ between the two parallel red equivalent magnetic currents (EMCs) [22]. Thus, we could cut slots on the radiating patch [23] or enlarge the dielectric constant [24] to reduce D to approximately $0.5\lambda_0$ and obtain a low E-plane sidelobe. A similar principle is exhibited in Figure 6(b) for beamwidth enhancement. As reported in Figure 6(c), a broadside beam could be reshaped as a dual beam by changing the phase difference between two red EMCs. As shown in Figure 6(d), the non-broadside beam of the TM$_{21}$ mode [25] or the slot antenna under the second mode [26] could be transformed into a broadside beam by controlling the magnitude of these EMCs for the first time. In addition, large H-plane cross-polarization of the TM$_{1/2,2}$ mode is mainly caused by the strong amplitude of parallel blue EMCs [27]. Hence, by reducing the amplitude via open-ended stubs, the cross-polarization of the H-plane radiation patterns could be successfully reduced. Overall, the radiation performance of the antenna under different modes could be properly reshaped by controlling their EMCs around the radiator edges. Detailed calculation results with relevant discussions cannot be presented herein due to the page limit.

To illustrate this principle more clearly, the half-power beamwidth (HPBW) of the MPA is selected as an example [24]. Based on the cavity model, the far-zone radiated fields of the MPA in Figure 6(b) at the E-plane can be calculated by using two red EMCs. When the thickness is much smaller than $\lambda 0$, the radiated fields of the single red EMC under the TM_{01} mode can be expressed as

$$\begin{cases} E_\theta = -j\dfrac{k_0 HDE_0 e^{-jk_0 r}}{\pi r} \\ E_\varphi = 0 \end{cases} \tag{1}$$

Meanwhile, the H-plane radiated fields of the MPA under the TM_{01} mode can be expressed as

$$\begin{cases} E_\theta = 0 \\ E_\varphi = j\dfrac{k_0 HDE_0 e^{-jk_0 r}}{\pi r}\left\{\cos(\theta)\dfrac{\sin(0.5k_0 D\sin(\theta))}{0.5k_0 D\sin(\theta)}\right\} \end{cases} \tag{2}$$

Additionally, the array factor of dual red EMCs is given by

$$f_{AF}(\theta,\varphi) = 2\cos(0.5k_0 D\sin\theta\sin\varphi) \tag{3}$$

Finally, the far-zone normalized E-plane radiation pattern of the MPA ($\varphi = 90$) can be simplified as

$$E_\theta(\theta) = \cos(0.5k_0 D\sin\theta) \tag{4}$$

$$E_\varphi(\theta) = 0 \tag{5}$$

Equation (4) proves that the E-plane radiation pattern of the antenna in Figure 6(b) is mainly dependent on the spacing D between two red EMCs. Hence, the calculated HPBW of the MPA on an infinite ground under the TM_{01} mode, shown in Figure 7, is discussed. First, a narrow HPBW of approximately 50° is generated at $D = 0.6\lambda_0$, thus restricting the application of the antenna in wide-scanning systems. By decreasing D from $0.6\lambda_0$ to $0.2\lambda_0$, the HPBW of the E-plane beam is progressively enlarged. When D is reduced to below $0.2\lambda_0$, the antenna can successfully acquire a wide HPBW of approximately 180°. Therefore, the above theoretical results demonstrate that the value of D for the antenna in Figure 6 should be effectively decreased to less than $0.2\lambda_0$ to achieve a wide E-plane HPBW.

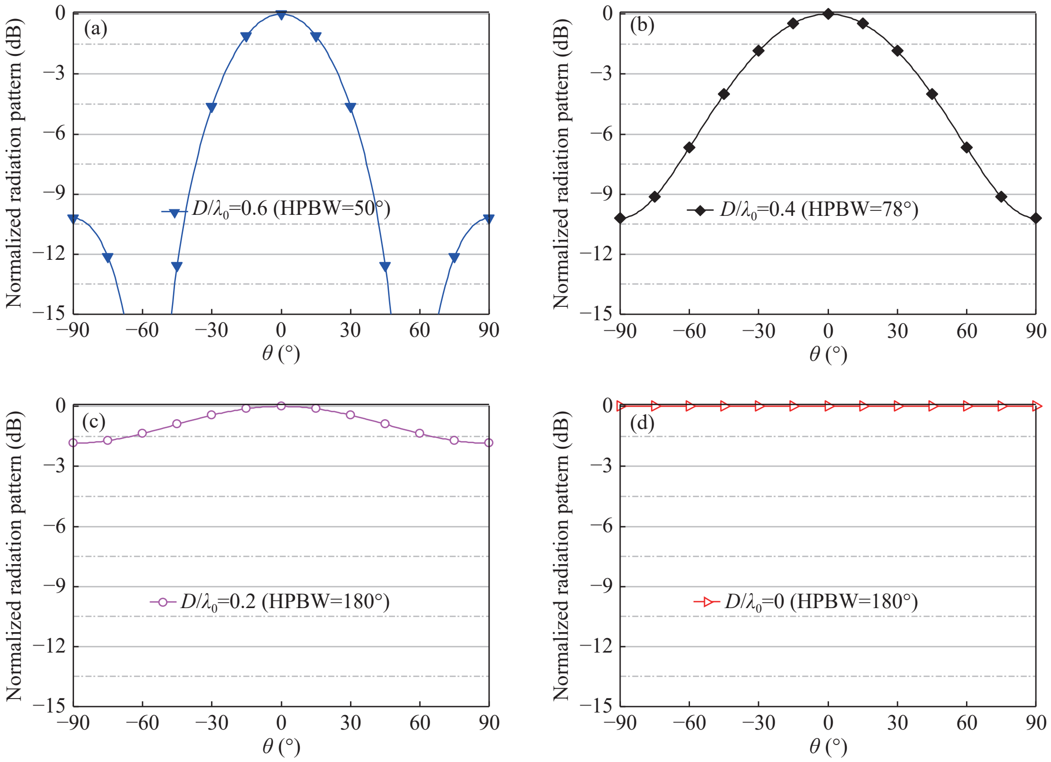

Figure 7 HPBW and sidelobe of the MPA in Figure 6(b) under the TM_{01} mode for different D/λ_0. (a) D/λ_0=0.6; (b) D/λ_0=0.4; (c) D/λ_0=0.2; (d) D/λ_0=0.0.

III. Impedance Improvements of the MMR

In principle, traditional antennas working under fundamental modes always suffer from a narrow bandwidth, a single bandwidth, and other defects, which seriously restricts their application and development in communication systems. During the past three decades, research on impedance improvement based on the MMR technique has become a hot research topic worldwide. In the following, the concept of using the MMR technique to design antennas with wide-bandwidth operation, multibandwidth operation, and mutual coupling minimization is further extensively discussed.

1. Wideband MMR

Antennas with attractive wideband performance are widely used in communication systems, thus attracting great research efforts on this topic. Based on the above principle in Section II.2, the resonant frequencies of different modes could be reallocated by varying their internal electric fields. Unfortunately, the frequency spacing between these modes keeps them far from each other, thus increasing the challenge of realizing wide-bandwidth operation.

To address this issue, several effective approaches have been proposed during the past three decades. Liu and Xue [28] loaded shorted vias to increase the resonant frequency of the TM_{10} mode close to that of the TM_{12} mode for bandwidth enhancement (12.48%) at the cost of an unexpected monopole-like beam, as shown in Figure 8. To achieve a wideband broadside beam with high efficiency, Liu and Zhu used a stepped-impedance resonator (SIR) [11] or shorting pins [19] on patch antennas, thus merging their TM_{10} and TM_{30} modes for impedance bandwidth improvement to above 10%, as shown in Figure 9. Nevertheless, these antennas suffer from a large electrical size for the radiating patch. After that, the shorted patch antenna (SPA) instead of the traditional MPA was alternatively used and designed, and a slot was cut at the minimum electric field of its higher-order modes for simultaneous bandwidth improvement (33.3%) and size reduction [29]. Recently, the MMR design concept was developed for wideband MPAs by further improving the feeding scheme [30]–[32].

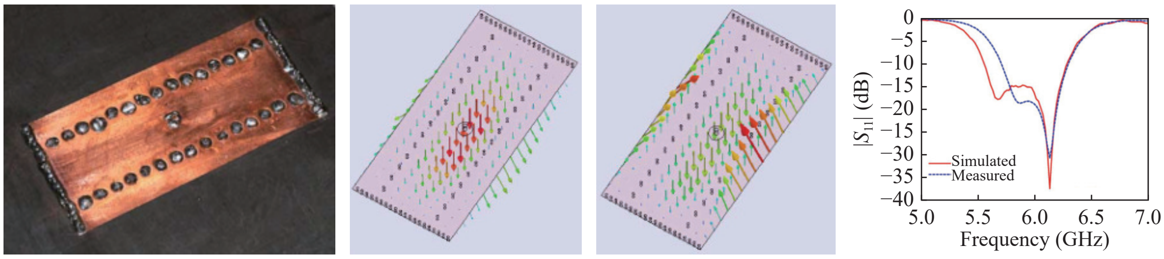

Figure 8 Bandwidth enhancement of the MPA with a monopole-like pattern based on the TM_{10} and TM_{12} modes in [28].

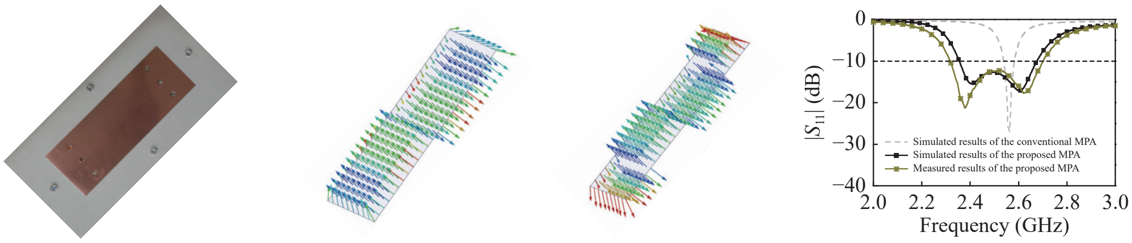

Figure 9 Bandwidth enhancement of the MPA with a broadside pattern based on the TM_{10} and TM_{30} modes in [19].

Apart from patch antennas, the MMR technique could be alternatively used for other types of wideband antennas. In [33], Lu and Zhu introduced several stubs on a slot antenna for bandwidth enhancement (31.5%) by using its first and second odd-order modes. Xia and Leung [34] merged the $TM_{01\delta}$, $TM_{02\delta}$, and $TM_{03\delta}$ modes of a dielectric resonator antenna (DRA) to provide a 60.2% 10-dB impedance bandwidth. The work in [35] generated dual orbital angular momentum modes for broadband performance (25%).

2. Multiband MMR

In parallel, antennas with multiband operation have been rapidly developed to offer multifunctional services and perform well in more complex electromagnetic environments. For example, Liu and Zhu presented a single MPA with 2.4/5.2/5.8 GHz operation and similar broadside radiation beams by sharing its TM_{10}, TM_{12}, and TM_{30} modes [22], as shown in Figure 10. Similarly, the stacked MMR technique was used for the MPA in [36] to shift its TM_{01}, TM_{02}, and TM_{03} modes for monopole-like radiation performance from 2.28–2.55 GHz and 5.15–5.9 GHz simultaneously.

To provide distinct radiation characteristics, two different types of radiation beams were generated for antennas based on the MMR [37]–[40], such as monopole-like patterns in the lower band and broadside patterns in the upper band [37], [38] or broadside patterns in the lower band and monopole-like patterns in the upper band [39], [40]. Consequently, a polarization difference was introduced based on the MMR [41]–[45] to meet different coverage requirements, as shown in Figure 11. Herein, selecting the radiative modes for the desired polarization in the fixed bands is challenging. Additionally, multiband operation is often highly demanded in smartphone systems to satisfy the extremely compact size. In this context, the multimode design concept for the inverted-L antenna was commonly used and developed [46], [47], as shown in Figure 12. Note that its radiation efficiency and size are much more important than its radiation pattern.

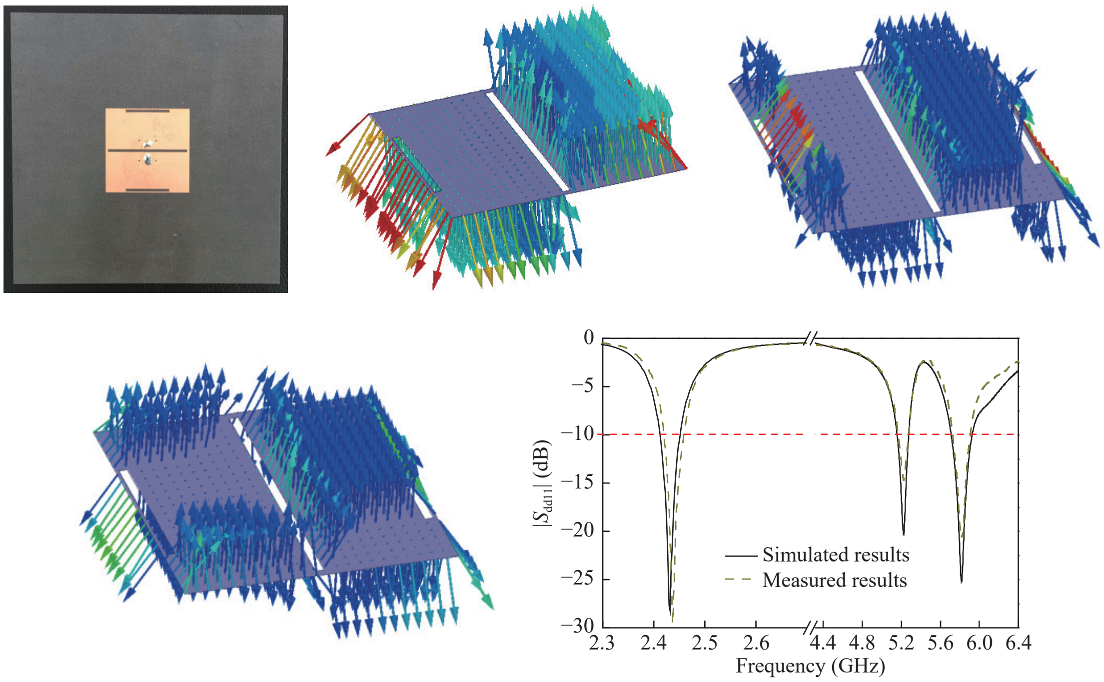

Figure 10 Triple-band generation of the MPA with similar broadside patterns based on the TM_{10}, TM_{12}, and TM_{30} modes in [22].

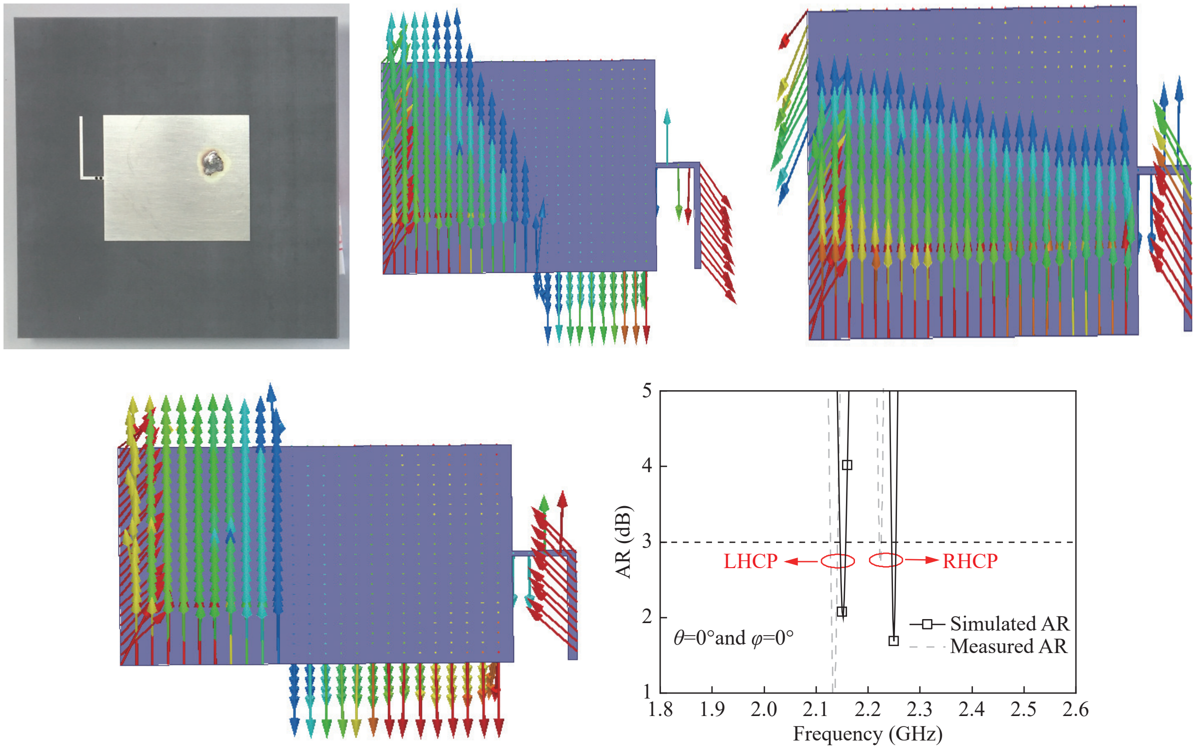

Figure 11 Dual-band dual-polarized CP antenna with an extremely small spacing based on the TM_{10}, TM_{01}, and TM_{20} modes in [41].

3. Mutual coupling reduction MMR

In multiple-input multiple-output (MIMO) communication systems, antennas with multiple ports greatly help in increasing the channel capacity, improving the spectrum utilization, and alleviating the multipath fading problem [2], [3]. As a result, research on reduction of the mutual coupling between multiple ports of antennas has become a hot topic during the past two decades.

First, one of the most straightforward approaches is to use orthogonal modes, i.e., TM_{10} and TM_{01} modes of the MPA, for mutual coupling reduction. In [48], Sun and Zhang presented the orthogonal dipole mode and monopole

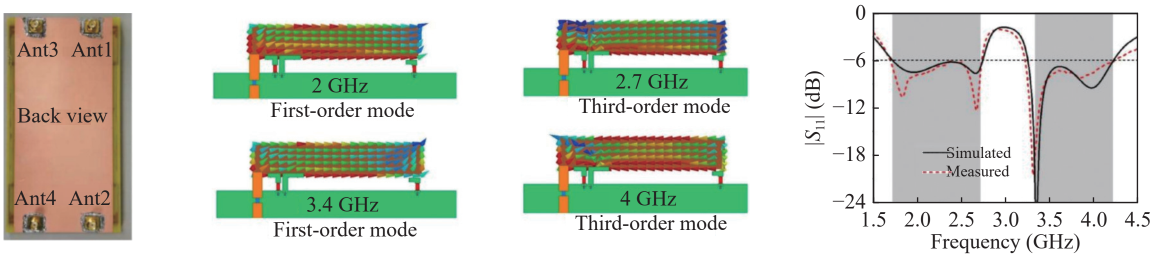

Figure 12 Multiband monopole antenna for a smartphone based on four resonant modes in [46].

mode shown in Figure 13 to mitigate the mutual coupling to below −17 dB in 5G MIMO mobile phone antennas. Second, pattern diversity could be utilized for mutual coupling improvement. Deng and Zhu pushed the resonant frequencies for TM_{10} and TM_{20} modes close together, thus gaining pattern diversity and isolation improvement [49].

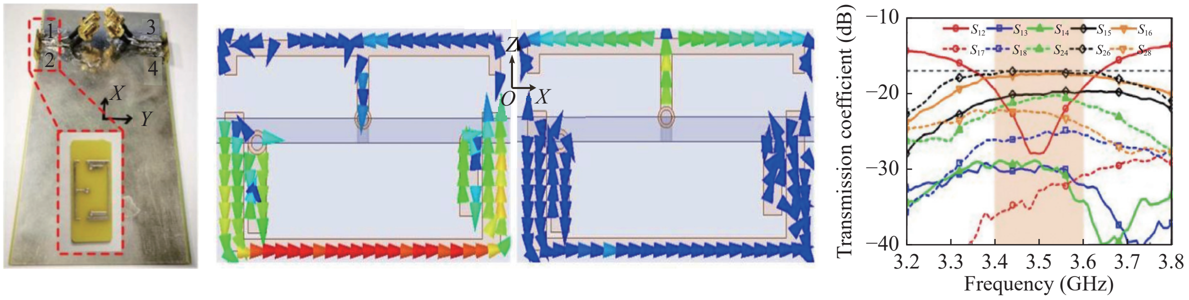

Figure 13 Mutual coupling reduction of a mobile-phone antenna based on dipole and monopole modes in [48].

Recently, the mutual coupling of multiport antennas with the same polarization and radiation pattern has been deeply investigated. Initially, the coupled-resonator theory based on multimode antennas was proposed and developed in [50], [51] to improve their isolation to above 20 dB. Next, two out-of-phase TM_{10} modes modified the excited electric field distribution inside the resonant cavity, thus achieving a small mutual coupling of less than −15 dB [52]. Recently, a work combined two modes of a single low-profile MPA [53]. Through analysis, the researchers found for the first time that the electric-field null could be theoretically bent to the unexcited port by controlling the magnitude ratio between different modes, as illustrated in Figure 14, to enhance the isolation to above 17 dB.

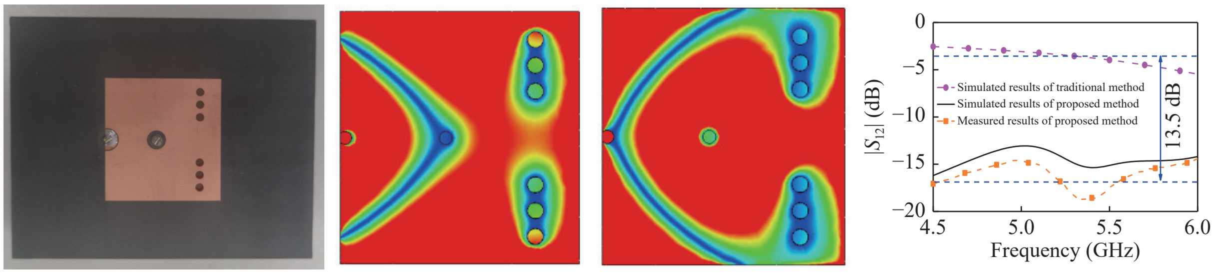

Figure 14 Mutual coupling reduction of the MPA based on the TM_{01} and TM_{20} modes in [53].

IV. Radiation Improvements of the MMR

In addition to impedance performance improvement, the radiation performance of the antennyas also needs to be controlled as desired. Unfortunately, based on the cavity model, antennas under multimode radiation suffer from low gain, distorted radiation patterns, or high sidelobe levels, which seriously restricts their application and development in modern wireless communication systems. During the past three decades, research on radiation improvement with the MMR technique has become a hot research topic worldwide. In the following, the design concept of the MMR technique employed for high-gain, wide-beamwidth, multibeam, multipolarization, filtering-response, and leaky-wave antennas is discussed.

1. High-gain/Wide-HPBW MMR

To satisfy point-to-point communication systems, antennas need to have high gain. Therefore, a set of researchers have conducted several works based on the multimode technique, as discussed in the following. As reported in [25], [54], and [55], Liu, Zhu, Zhang, *et al.* successfully reduced the

HPBW of an MPA at fundamental and higher-order modes, as shown in Figures 15 and 16, thus realizing a high gain of approximately 11 dB for linear polarization (LP) or circular polarization (CP). In [56] and [57], Juyal and Shafai theoretically investigated the dielectric constant of higher-order modes, aiming to simultaneously obtain a high directivity of above 10 dB and a sidelobe level of below −10 dB. Luo *et al.* [58] alternatively used higher-order modes of a dipole antenna to realize both wide-bandwidth (11.2%) and high-gain (4 dBi) performance, as shown in Figure 17.

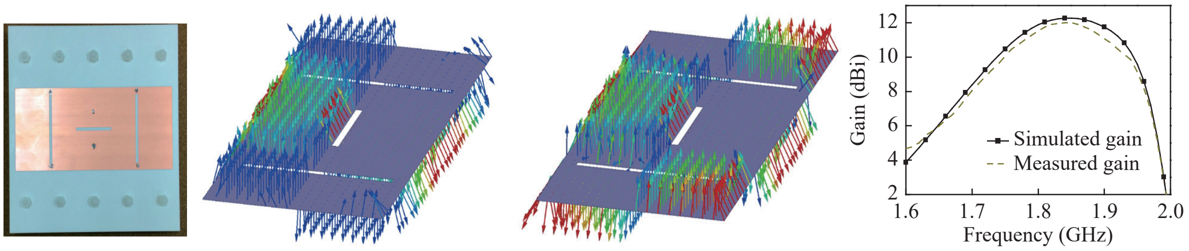

Figure 15 Gain enhancement of the LP MPA based on the TM_{10} and TM_{12} modes in [25].

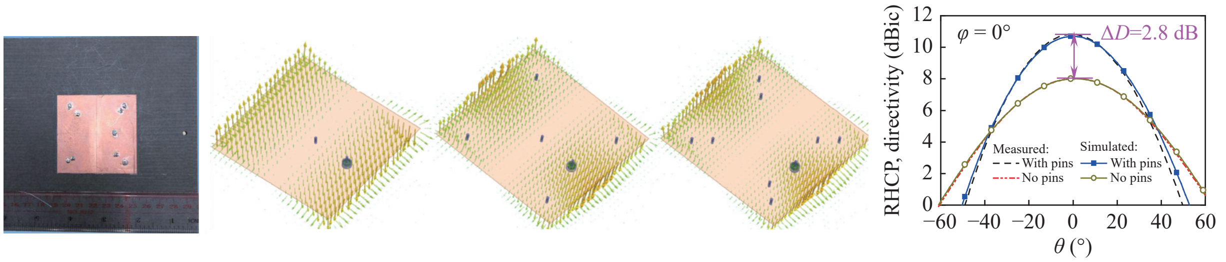

Figure 16 Gain enhancement of the CP MPA based on the TM_{10} and TM_{01} modes in [54].

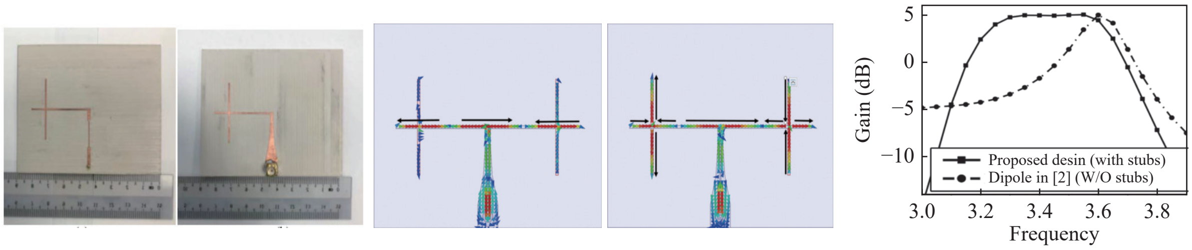

Figure 17 Gain enhancement of the slot antenna based on third-order and fifth-order modes in [58].

Apart from high-gain performance, antennas with a wide HPBW are also in high demand to provide a wide radiation range. As such, the primary TM_{10} and TM_{12} modes of an MPA were properly reshaped to realize a wide HPBW of approximately 135° over dual operating bands [59], as shown in Figure 18. Additionally, to achieve versatility, a high gain and a wide HPBW of an MMR antenna [60] of approximately 9.4 dBi and 144° were obtained in the lower and upper bands, respectively.

2. Multibeam/Multipolarization MMR

The radiation beam and polarization of an antenna could be reshaped into scanned-beam, tilted-beam, null-steering, null-to-broadside, beam-forming, multipolarization, and other configurations. Tian and Itoh adopted the coupled modes of an MPA to realize beam scanning from 14° to 34° [61], as shown in Figure 19. As discussed in [62], Shi *et al.*

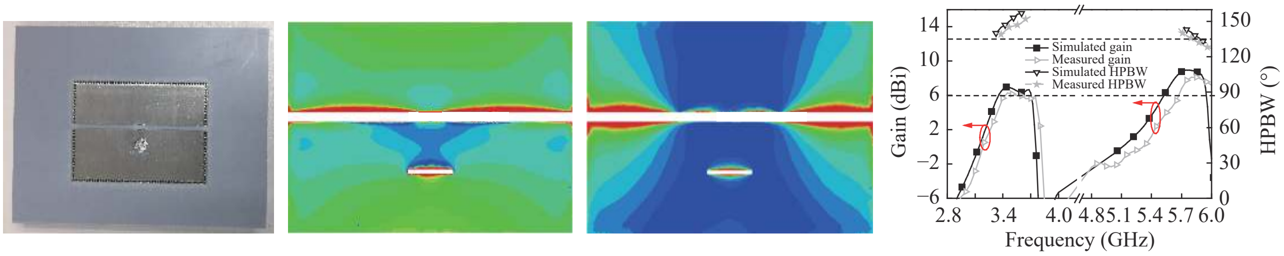

Figure 18 HPBW enhancement of the MPA based on reshaped TM_{10} and TM_{12} modes in [59].

proposed a switched beam of a microstrip Yagi antenna by using its resonant TM_{10} and TM_{20} modes. Tran and Sharma controlled the amplitude and phase of combined modes for beam scanning from 0° to ±30° in [63].

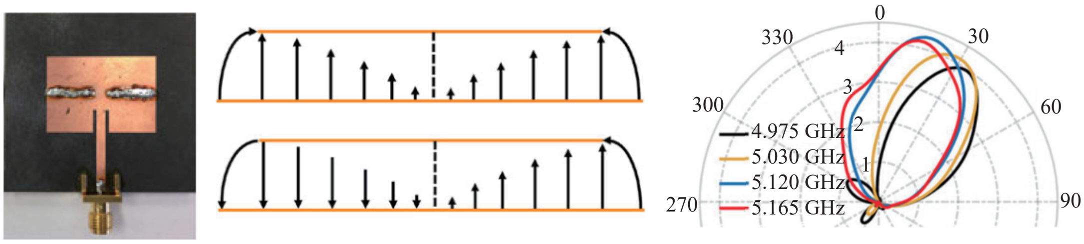

Figure 19 Beam scanning of the MPA based on coupled modes in [61].

Similarly, null steering performance is also required for some special systems. In [64], by using phase-shifted characteristic modes of an MPA, the null scanning angle could be changed from 0° to ±32°. Additionally, Liu and Zhu successfully reshaped the non-broadside radiation beam into a broadside beam by controlling the equivalent magnetic currents of a slot antenna [26], as shown in Figure 20, or an MPA [65] under higher-order modes. To further extend the MMR concept, a steerable multiport antenna was explored in [66]. And the results showed that the multimode radiator could act as a beamforming strategy herein.

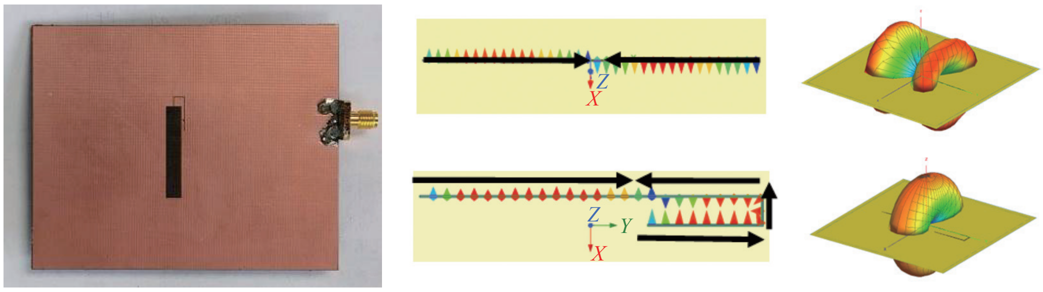

Figure 20 Non-broadside beam-to-broadside beam reshaping of the slot antenna based on the second mode in [26].

Apart from multibeam performance, multipolarization is a key performance characteristic of antennas. In [67] and [68], wideband dual-polarized or triple-polarized performance was implemented by using the MMR technique. As reported in [69] and [70], a set of polarizations about the radiation pattern was generated via dual modes, as shown in Figures 21 and 22.

3. Cross-polarization reduction MMR

In addition to the main radiation beam, research on the cross-polarization levels of antennas has attracted great attention in recent years. As is well known, the traditional MPA suffers from a high cross-polarization level due to the unbalanced feeding port. To address this critical issue, Zhang adopted the differentially driven scheme for the MPA to construct the electric-field null at the center of the radiator, thus suppressing its high H-plane cross-polarization to below −20 dB, as depicted in Figure 23 [71]. Similarly, aperture-coupled feeding [72] and shorting pins [73] could be used to decrease the H-plane cross-polarization to below −19 dB. Recently, Liu and Zhu used shorted metals or open-ended stubs, as shown in Figure 24, to decrease the H-plane cross-polarization to below −12.3 dB [74], [75], [27]. Herein, reallocating the electric-field nulls of the $TM_{1,1/2}$ mode around the primary maximum electric field positions

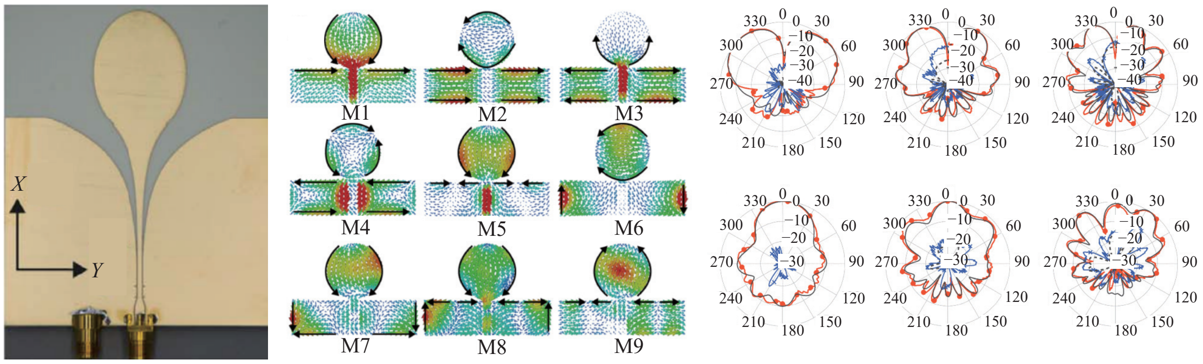

Figure 21 Pattern diversity of the ultrawideband (UWB) antenna based on multimode resonance in [69].

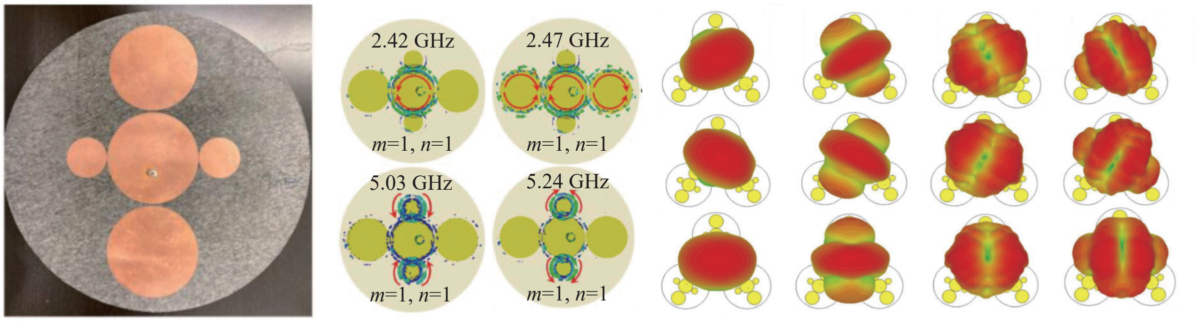

Figure 22 MIMO communication with the MPA based on dual modes in [70].

for the first time is novel for us. Recently, Shao and Zhang also used the coupled $TM_{0,1/2}$ mode for H-plane 25 dB cross-polarization reduction while simultaneously maintaining an enhanced gain and a compact size [76].

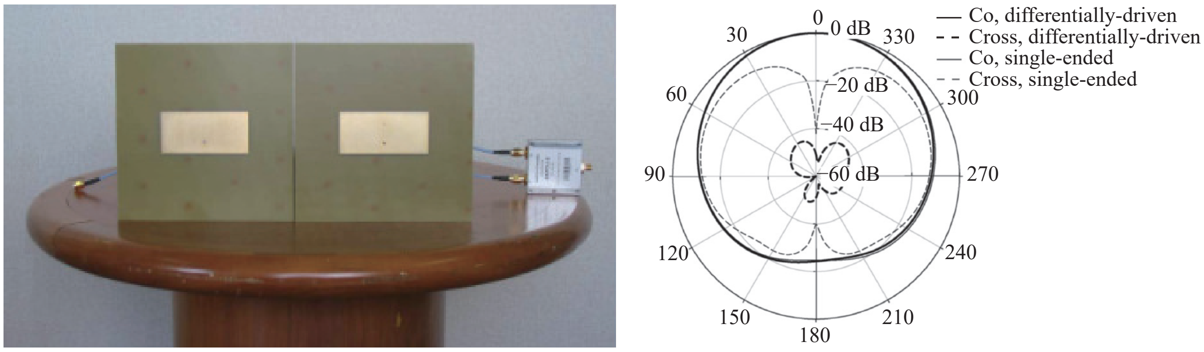

Figure 23 Cross-polarization reduction of the MPA based on the differentially driven scheme in [71].

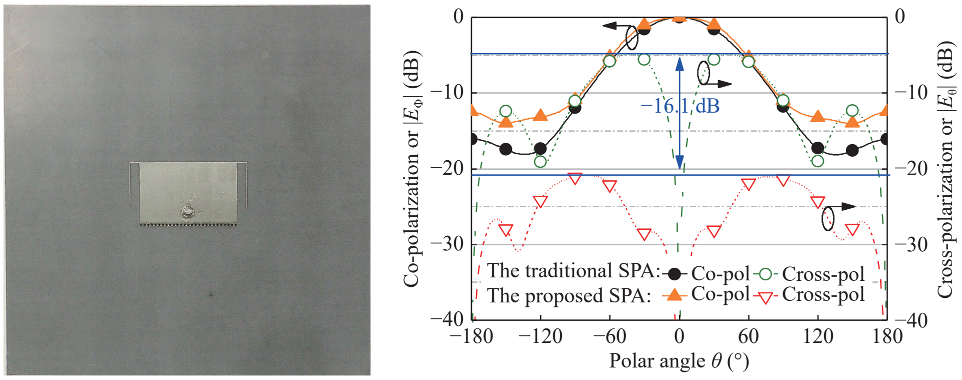

Figure 24 Cross-polarization reduction of the MPA based on the $TM_{1,1/2}$ mode in [27].

4. Filtering-response MMR

During the past decades, the radiation properties of antennas with a frequency-selective nature, such as microwave filters, which are called filtering antennas, have been highly demanded and developed by using the MMR technique. In [77] and [78], the coupled modes of a cavity-based planar antenna were utilized to obtain an out-of-band gain suppression level of beyond 15 dB. In addition, the resonant mode derived from the feeding network was utilized for the generation of a gain-filtering response in [79]–[82].

To remove the insertion loss from feeding networks, a novel design concept based on the MMR antenna itself was introduced to obtain a filtering response without an extra circuit. Zhang, Duan, and Pan [83] achieved an out-of-band suppression level of more than 21 dB by adding parasitic elements and a U slot to excite multiple modes, as shown in Figure 25. Liu and Zhu [84] added shorting pins for frequency reallocation and efficiency null generation of a DRA, thus generating the wideband omnidirectional radiation pattern and 14 dB out-of-band suppression level shown in Figure 26. Most importantly, the antenna still maintained a compact size via these shorting pins.

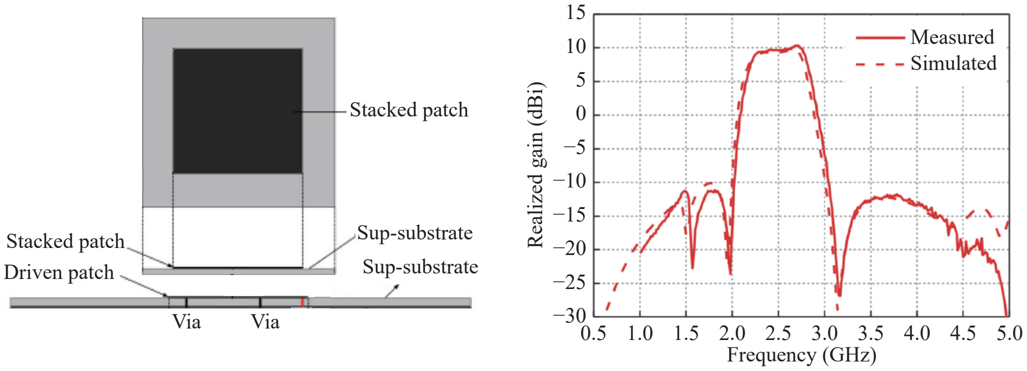

Figure 25 Filtering-response of the MPA based on the stacked mode in [83].

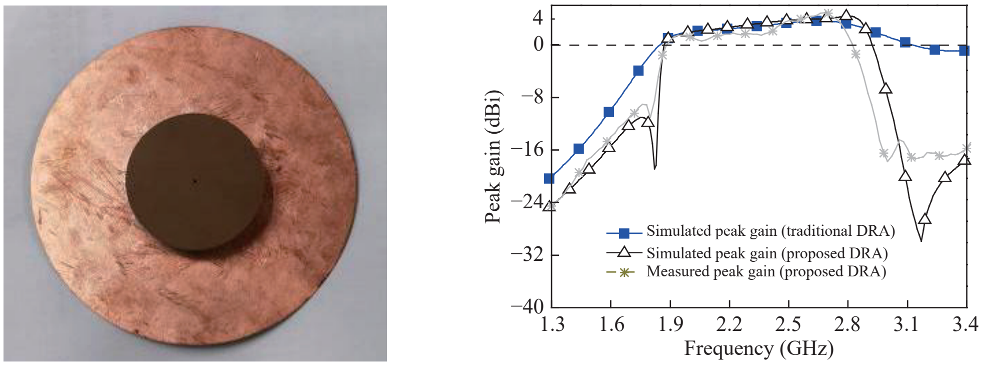

Figure 26 Filtering response of the DRA based on the multimode resonance in [84].

5. Leaky-wave MMR

The leaky-wave antennas (LWAs) have maintained several radiative propagating modes, such as EH_0, EH_1, and EH_2. To improve the radiation performance of LWAs, a large number of studies have been conducted based on the MR technique over the past two decades. With respect to the EH_0 mode, periodical loading of shorting pins was introduced on a microstrip LWA, thus achieving a dual-beam pattern ranging from 4.54–5.8 GHz [85]. To reshape the radiation beam, asymmetric pins [86] and the coupled pin-loaded structure [87] in Figure 27 were independently used to transform the dual-beam pattern into a broadside beam in the working band. With respect to the higher-order modes, the EH_1 mode of the LWA was adopted by Liu, Li, and Long in [88]. Meanwhile, the EH_2 mode was excited for single main-beam radiation by Zhang, Zhu, and Sun, as shown in Figure 28 [89]. A similar mode was also used and investigated by Chen, Lin, and Sheen in [90].

To further enhance the performance, Li and Wang [91] utilized the quasi-TEM mode and TE_{10}-like mode in designing a dual-band LWA for microwave and millimeter-wave applications. In addition, Zheng and Wu used the MMR concept to design the stable radiation performance [92]

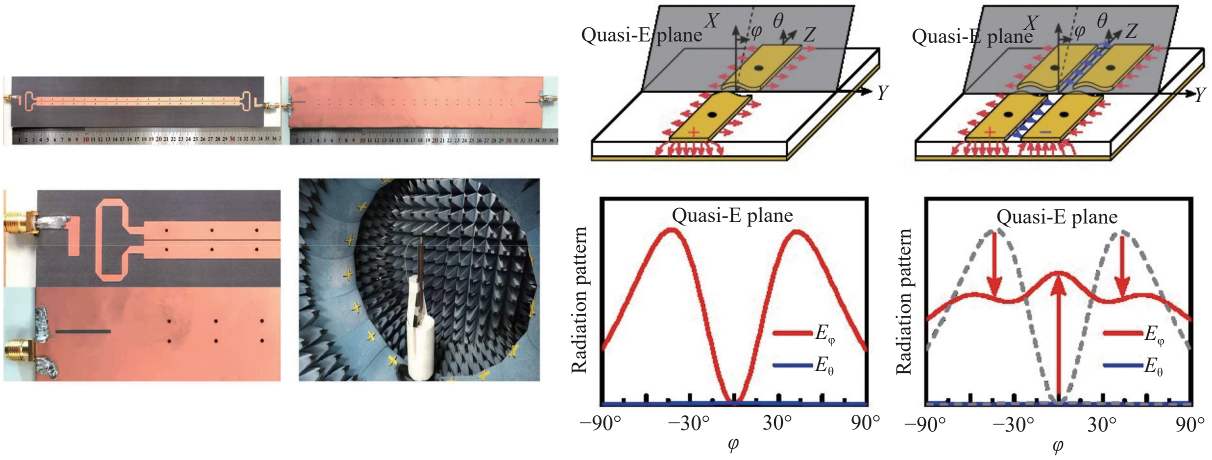

Figure 27 Leaky-wave performance of the antenna based on the EH_0 mode in [87].

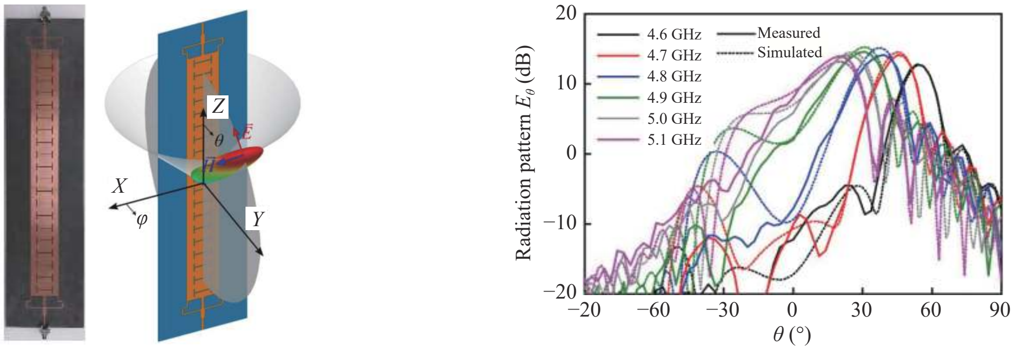

Figure 28 Leaky-wave performance of the antenna based on the EH_2 mode in [89].

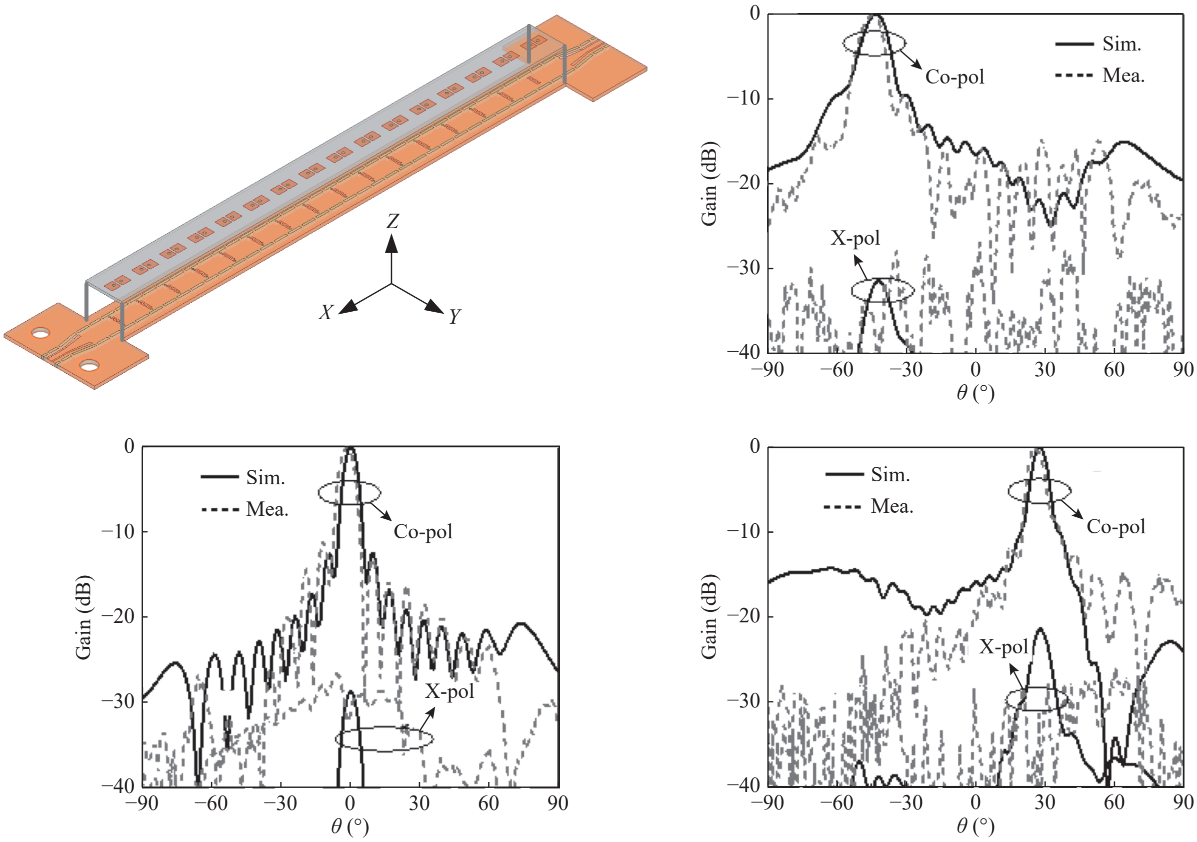

Figure 29 Multifunctional leaky-wave performance of the antenna based on multiple resonant modes in [92].

shown in Figure 29 or tailored radiation [93].

V. Advantages and Application of the MMR

The MMR has several advantages compared to these classical methods, i.e., stacked elements and an improved feeding scheme. First, MMR antennas have fewer layers and elements, thus maintaining a low cost and a simple fabrication process. Second, MMR antennas have a controlled radiation beam in a single radiator, i.e., a wide HPBW, a high gain, a similar radiation pattern, and pattern diversity. Third, MMR antennas have unexpected performance characteristics, such as an extremely small frequency ratio and a filtering response without a feeding network. Fourth, MMR antennas have a simple working principle.

With respect to the applications of the MMR method, first, the MMR method could be used to reduce the layer and thickness of antennas while maintaining the desired wideband/multiband performance. Hence, the MMR approach could be well applied in implant communications [94], on-body and off-body communications [95], and wireless power transfer [96]. Second, antennas based on the MMR method can exhibit multiport, multiband, and multipolarization properties. Therefore, they could be well employed in MIMO communications [97], [98] and solar cell systems [99]. Third, MMR antennas have been popularly adopted in the direction-of-arrival (DOA) and direction-of-departure (DOD) estimations [100]–[102], the spatially encoded data transmission [103], and global navigation satellite-reflectometry (GNSS-R) [104]. Considering this background, we believe that the MMR technique could be increasingly widely used in the future.

VI. Conclusions

In this paper, the basic characteristics of MMR antennas have been discussed, along with their impedance improvement, pattern improvement, and applications. These research topics, however, are not the only ones that should be further studied. In addition, there is a set of other attractive topics that numerous researchers and engineers have been working on, i.e., reconfigurable MMRs, frequency selective surface MMRs, and phase-shifted MMRs, to name a few.

Finally, note that the antennas based on the MMR technique are attractive not only for wireless communications but also for sensor design, medical sciences, IOT communications, and so on. With the rapid increase in research on and development of MMR antennas, exploration and development of more interesting and useful MMR design methods can be anticipated in the future.

Acknowledgments

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