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# Characteristic Mode Analysis: Application to Electromagnetic Radiation, Scattering, and Coupling Problems

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**Abstract — Recent years, the theory of characteristic modes has emerged as a powerful analysis technique in antenna engineering, providing a means to reveal the natural resonant properties of objects and providing a variety of modal parameters. Based on these modal parameters, advanced techniques have been developed based on the theory of characteristic modes to address a wide range of electromagnetic radiation, scattering, and coupling problems. This review provides an overview of some of the latest characteristic mode-based techniques for wideband design, circular polarization, radiation pattern control, scattering control, and mutual coupling control. In addition, future perspectives are discussed, highlighting the potential of characteristic modes for addressing even more complex electromagnetics problems.**

**Key words — Characteristic modes, Antenna, Wideband, Scattering, Mutual coupling.**

## I. Introduction

In the past decade, characteristic modes (CMs) have become a popular topic in the microwave society, and tremendous progress has been made in both the theory and application aspects of the CMs. The original idea of the CMs, which was proposed by Garbacz [1], [2], is to represent the electromagnetic field in the exterior region by a set of incoming and outgoing types of characteristic fields. The characteristic fields have a close relation to the actual physical structure. Each characteristic field has an associated characteristic value and the value of characteristic values reflects the resonant property (e.g., resonant frequency) and the average stored energy relation of an object. These interesting properties of CMs make it a useful modal theory for resonant radiation and scattering problems. A MoM (method of moments) based method was proposed by Harrington [3], [4] for computing the CMs of perfect electric conductors. This pioneering numerical algorithm simplifies the computation of CMs with arbitrary shapes. The CMs provide additional information, including characteristic values, modal significance, characteristic angle, characteristic current, and characteristic field. These modal parameters give an in-depth physical interpretation of the resonant phenomenon of an arbitrary structure. Inspired by Harrington's work, the computation of CMs is extended to include dielectric bodies [5]–[11], impedance sheets [12], slots [13], etc. These works greatly enrich the usefulness of CMs in many complex electromagnetic (EM) problems.

The applications of CMs were revisited in [14]. After that, many CM-based techniques are developed and show their powerful capabilities in antenna engineering. Reference [15] showed the potential application of CMs to the MIMO multi-antenna system. The CM-based loading strategies [16], [17] were used to optimize the bandwidth and pattern of the antenna element. In [18], it showed that the bandwidth of antennas can be enhanced by combining multiple CMs. The CMs are independent of excitation which means the modal analysis can be performed without preset excitation. From the modal current distribution, the position and type of feeders can be determined with pure modal results [19] which greatly simplifies the design of feeders. The phase property revealed by the characteristic angle facilitates the circular polarization design [20]. In [21], [22], using the orthogonality of CMs, the isolation of two antennas with a shared radiator was guaranteed. These pioneering works established the basic CM-based techniques for antenna design and optimization. Many advanced

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CM-based techniques were proposed in recent years and the number of published articles was seeing rapid growth as can be seen in Fig.1. The aim of this article is to review the state-of-the-art CM-based techniques in antenna engineering. These CM-based techniques cover a wide aspect of applications including bandwidth enhancement, circular polarization design, multiport antennas, pattern optimization and synthesis, scattering control, and mutual coupling control. This review provides the latest developments in the application of CMs and guidelines on the application of CMs to a variety of EM problems.

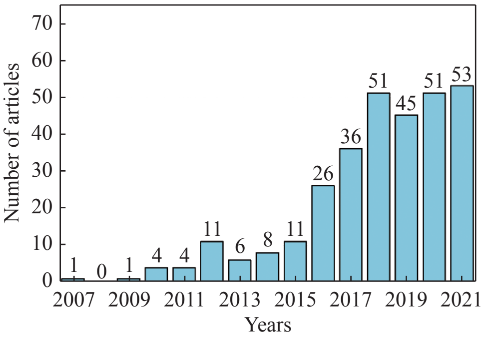


Fig. 1. The number of journal articles published in *IEEE TAP*, *IEEE AWPL*, and *IET MAP* with the keywords of characteristic modes (The data is extracted from the Engineering Village with unrelated articles filtered out).

## II. Theory of Characteristic Modes

The theory of characteristic modes is initially formulated by considering the problem of perfect electric conductors under incident electric field $\boldsymbol{E}^i$. The surface integral equation can be expressed as an operator equation with respect to surface current $\boldsymbol{J}$ and incident field $\boldsymbol{E}^i$ [3].

$$\left[L(\boldsymbol{J}) - \boldsymbol{E}^i\right]_{\tan} = 0 \tag{1}$$

The subscript "tan" denotes the tangential components on the conductor surface $S$. Defining a new operator as $Z(\boldsymbol{J}) = [L(\boldsymbol{J})]_{\tan}$ and separating its Hermitian parts [3], the characteristic equation for CMs is

$$X(\boldsymbol{J}_n) = \lambda_n R(\boldsymbol{J}_n) \tag{2}$$

where the operators $X(\cdot)$ and $R(\cdot)$ are

$$R = \frac{1}{2}(Z + Z^*) \tag{3}$$

$$X = \frac{1}{2j}(Z - Z^*) \tag{4}$$

$\boldsymbol{J}_n$ is the $n$th characteristic current and $\lambda_n$ is the associated characteristic value. The superscript "*" represents the conjugate operator. By solving the characteristic equation (2), the surface current $\boldsymbol{J}$ and the radiated/scattered field $\boldsymbol{E}/\boldsymbol{H}$ can be represented as summations,

$$\boldsymbol{J} = \sum_{n=1}^{N} a_n \boldsymbol{J}_n \tag{5}$$

$$\boldsymbol{E} = \sum_{n=1}^{N} a_n \boldsymbol{E}_n, \boldsymbol{H} = \sum_{n=1}^{N} a_n \boldsymbol{H}_n \tag{6}$$

where $a_n$ is the modal weighted coefficient of the $n$th CM. $\boldsymbol{E}_n$ and $\boldsymbol{H}_n$ are the modal far-field of the $n$th CM. The characteristic currents $\boldsymbol{J}_n$ are normalized so that it radiates unit power (i.e., $\langle \boldsymbol{J}_n^*, R\boldsymbol{J}_n \rangle = 1$). It can be proved that the characteristic current $\boldsymbol{J}_n$ satisfies the following orthogonality:

$$\langle \boldsymbol{J}_m^*, R\boldsymbol{J}_n \rangle = \delta_{mn} \tag{7}$$

$$\langle \boldsymbol{J}_m^*, X\boldsymbol{J}_n \rangle = \lambda_n \delta_{mn} \tag{8}$$

$$\langle \boldsymbol{J}_m^*, Z\boldsymbol{J}_n \rangle = (1 + j\lambda_n)\, \delta_{mn} \tag{9}$$

where $\delta_{mn}$ is the Kronecker delta (0 if $m \neq n$, and 1 if $m = n$) and $\langle \cdot, \cdot \rangle$ denotes the symmetric inner product of two vectors. The complex power balance for $\boldsymbol{J}$ on $S$ is given by

$$\begin{aligned} P &= \langle \boldsymbol{J}^*, Z\boldsymbol{J} \rangle \\ &= \langle \boldsymbol{J}^*, R\boldsymbol{J} \rangle + j\langle \boldsymbol{J}^*, X\boldsymbol{J} \rangle \\ &= \oint_{S^\infty} \boldsymbol{E} \times \boldsymbol{H}^* \cdot \mathrm{d}S \\ &\quad + j\omega \iiint_V (\mu \boldsymbol{H} \cdot \boldsymbol{H}^* - \epsilon \boldsymbol{E} \cdot \boldsymbol{E}^*)\, \mathrm{d}V \end{aligned} \tag{10}$$

where $S^\infty$ is a closed surface at infinity and $V$ is the region enclosed by $S^\infty$. Adding (10) to its conjugate with $m$ and $n$ interchanged, the orthogonality for far-field is

$$\frac{1}{\eta} \oint_{S^\infty} \boldsymbol{E}_m \cdot \boldsymbol{E}_n^*\, dS = \delta_{mn} \tag{11}$$

$$\eta \oint_{S^\infty} \boldsymbol{H}_m \cdot \boldsymbol{H}_n^*\, dS = \delta_{mn} \tag{12}$$

Equations (7)–(9), (11), and (12) show the important properties of CMs that the CMs are orthogonal to each other. Substituting (7)–(9) into (10) with $m = n$, the characteristic value becomes

$$\lambda_n = \omega \iiint_V (\mu \boldsymbol{H}_n \cdot \boldsymbol{H}_n^* - \epsilon \boldsymbol{E}_n \cdot \boldsymbol{E}_n^*)\, \mathrm{d}V \tag{13}$$

Equation (13) gives the physical interpretation of the characteristic value $\lambda_n$. $\lambda_n$ is $2\omega$ times the total average stored magnetic energy minus the total average stored electric energy. If $\lambda_n = 0$, the reactive power of the $n$-th mode is equal to 0 and this mode is called resonant mode. In the case of $\lambda_n > 0$, the stored magnetic field energy dominates over the stored electric field energy, and this mode is known as the inductive mode. In the case of $\lambda_n < 0$, the stored electric field energy dominates over the stored magnetic field energy, and this mode is known as the capacitive mode.

Using the orthogonality of equations (7)–(9), the modal weighted coefficient $a_n$ is calculated with

$$a_n = \frac{\langle \boldsymbol{E}^i, \boldsymbol{J}_n \rangle}{1 + j\lambda_n} \tag{14}$$

From (14), three important modal parameters can be defined [23] as follows.

1) Modal excitation coefficient $V_n$:

$$V_n = \langle \boldsymbol{E}^i, \boldsymbol{J}_n \rangle \tag{15}$$

The parameter $V_n$ quantifies the interaction between the incident field $\boldsymbol{E}^i$ and CMs, providing an indication of mode excitation.

2) Modal significance $\mathrm{MS}_n$:

$$\mathrm{MS}_n = \left| \frac{1}{1 + j\lambda_n} \right| \tag{16}$$

$\mathrm{MS}_n$ provides insight into the resonant characteristics of the CMs. When $\mathrm{MS}_n = 1$, the $n$th CM is considered to be in resonance, and the associated frequency is referred to as the resonant frequency.

3) Characteristic angle $\alpha_n$:

$$\alpha_n = 180^\circ - \tan^{-1}(\lambda_n) \tag{17}$$

where $\alpha_n$ represents the fixed phase lag between $\boldsymbol{J}_n$ and the tangential component of $\boldsymbol{E}_n$ on surface $S$. It also signifies the resonant characteristics of CMs. When $\alpha_n = 180^\circ$, the $n$th CM is considered to be in resonance. Furthermore, the cases where $90^\circ < \alpha_n < 180^\circ$ and $180^\circ < \alpha_n < 270^\circ$ correspond to the inductive and capacitive modes, respectively.

Based on the aforementioned formulations, it is evident that the CMs obtained from equation (2) are independent of external excitation $\boldsymbol{E}_i$. Consequently, the CMs only depend on the geometry, size, and material of the structure. The theory of characteristic modes for other structures, including the dielectric bodies, impedance sheets, etc., are studied in literature [5]–[13], which is omitted here for conciseness. Fig.2 presents the computed CM results for a rectangular metal patch, illustrating its modal parameters. The resonant characteristics of arbitrary conductor bodies can be effectively characterized by three parameters, namely $\lambda_n$, $\mathrm{MS}_n$, and $\alpha_n$. Each parameter possesses a distinct physical in-

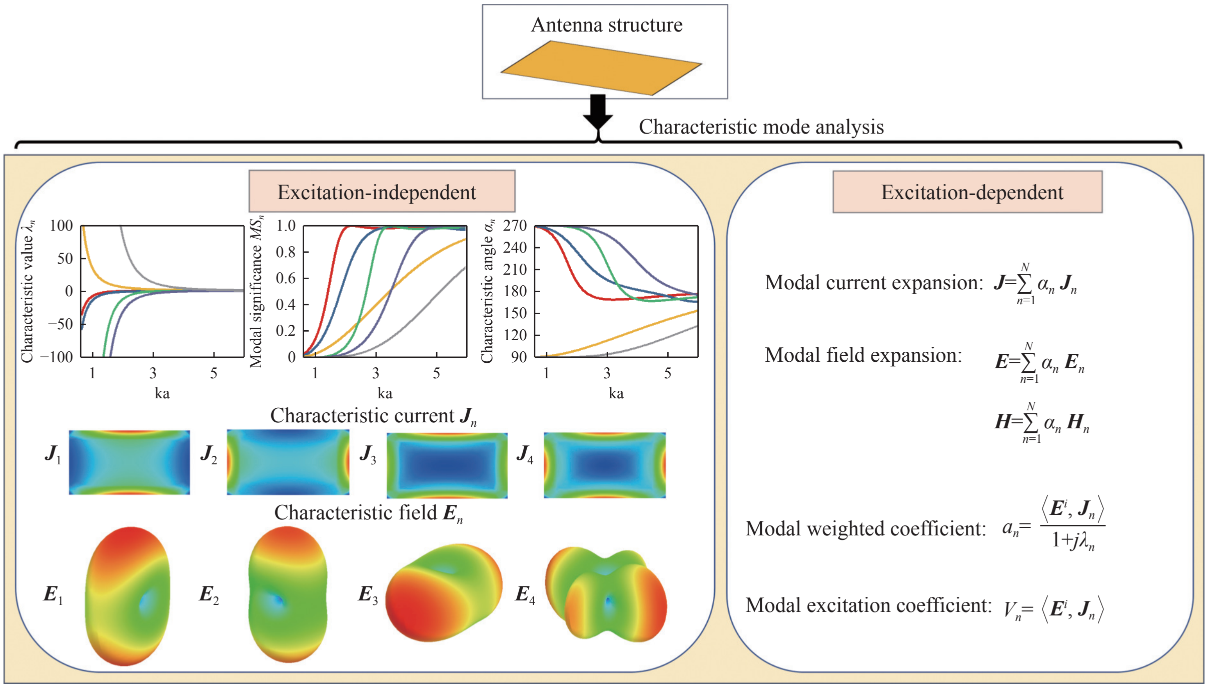


Fig. 2. Example of characteristic mode analysis for a rectangular metal patch. The modal analysis can derive the excitation-independent parameters including characteristic value, modal significance, characteristic angle, characteristic current, and characteristic field. Once the external excitation field is specified, the surface current distribution and radiation field can be expressed as modal current expansion and modal field expansion, respectively. These expansions include excitation-dependent parameters, modal weighted coefficient, and modal excitation coefficient, which can be calculated by equations (14) and (15).

terpretation and finds numerous practical applications. The excitation-related parameter $V_n$ is also an important criterion for the feeder placement in the antenna design. Applications regarding the CMs are discussed in the following sections.

## III. Application to Radiation Problems

The main function of antennas is to radiate electrical signals into free space. Thus, the radiation performance of antennas is the most concern in most applications. The radiation performance of antennas includes impedance bandwidth, polarization, radiation pattern, gain, etc. In the case of array antennas, isolation plays a crucial role, reflecting the mutual coupling between individual antenna elements. According to specific radiation performance objectives, the CM-based antenna designs mainly include four categories: impedance bandwidth enhancement, circular polarization designs, multiport antennas, and pattern optimization and synthesis.

### 1. Impedance bandwidth enhancement

Modern communication systems demand a broad physical bandwidth to enhance channel capacity, forcing antenna systems to operate across a wide frequency range. The impedance bandwidth has long been a research topic in antenna engineering [24], [25]. In the classical modal theory, the antennas are typically operated in their fundamental mode, which inherently restricts the working bandwidth. Moreover, the classical modal theory is derived for canonical antennas with simple geometric shapes, making its extension to complex antenna structures a challenging job. The theory of characteristic modes offers a numerical method to perform the modal analysis for complex antennas and the CM-based impedance bandwidth enhancement techniques have been studied in recent years.

The basic idea of CM-based impedance bandwidth enhancement techniques is illustrated in Fig.3. For narrowband antennas, characteristic mode analysis is conducted to extract the modal properties of the antennas. Through modal tuning, multiple CMs are brought into proximity, forming a potential wide frequency band. Subsequently, based on the knowledge of modal current distribution, appropriate excitation locations are determined to achieve the desired bandwidth. Modal tuning and excitation placement are two important factors in CM-based impedance bandwidth enhancement. Both modal tuning and excitation placement play vital roles in CM-based impedance bandwidth enhancement.

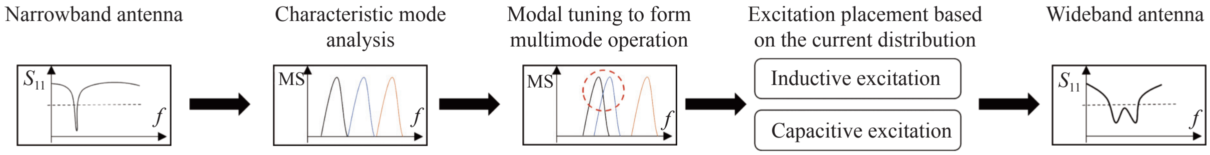


Fig. 3. The basic flow of CM-based impedance bandwidth enhancement techniques.

Since most of narrowband antennas are operated in their fundamental mode, using the higher-order modes of the antenna structure is a straightforward way for impedance bandwidth enhancement which expects to fully utilize the CMs of one structure. Using the higher-order modes requires a comprehensive understanding of the operating mechanics of different CMs and fine-tuning of several CMs. Reshaping the antenna geometry [26], [27] serves as a fundamental approach for CM tuning. As shown in Fig.4 Wang *et al.* proposed a wideband dual-polarized slot antenna which combines two CMs of an H-shaped slot. The H-shaped slot was reshaped to alter the electric length of the current path and the two desired CMs were moved to the desired frequency band. With four differential fed capacitive coupling elements, the proposed dual-polarized antenna achieved a relative bandwidth of 48%, in contrast to the initial H-shaped slot antenna, which provides only 13.6% relative bandwidth.

An alternative method to enhance the impedance bandwidth involves the artificial introduction of new modes [28]–[30]. The introduction of new modes is typically achieved by adding parasitic elements. By modifying the shape of the parasitic element and the spacing between the parasite element and the original antenna, the parasitic element can operate at a frequency near the resonant frequency of the original structure. The impedance bandwidth can be enhanced by the multi-mode operation. In [29], a dipole and a parasitic loop were combined to produce an omnidirectional pattern. The dipole operated at 2 GHz and the parasitic loop was set to operate at 2.75 GHz which realized a wide impedance bandwidth of 1.85–2.9 GHz (44.2%, $S_{11} < -10$ dB). The coupling between the parasitic element and the original structure can be controlled through the adjustment of spacing, thereby enhancing the impedance bandwidth. Additionally, references [28] and [30] showed that impedance bandwidth can be enhanced by properly adjusting the inductive or capacitive coupling between the parasitic element and the driv-

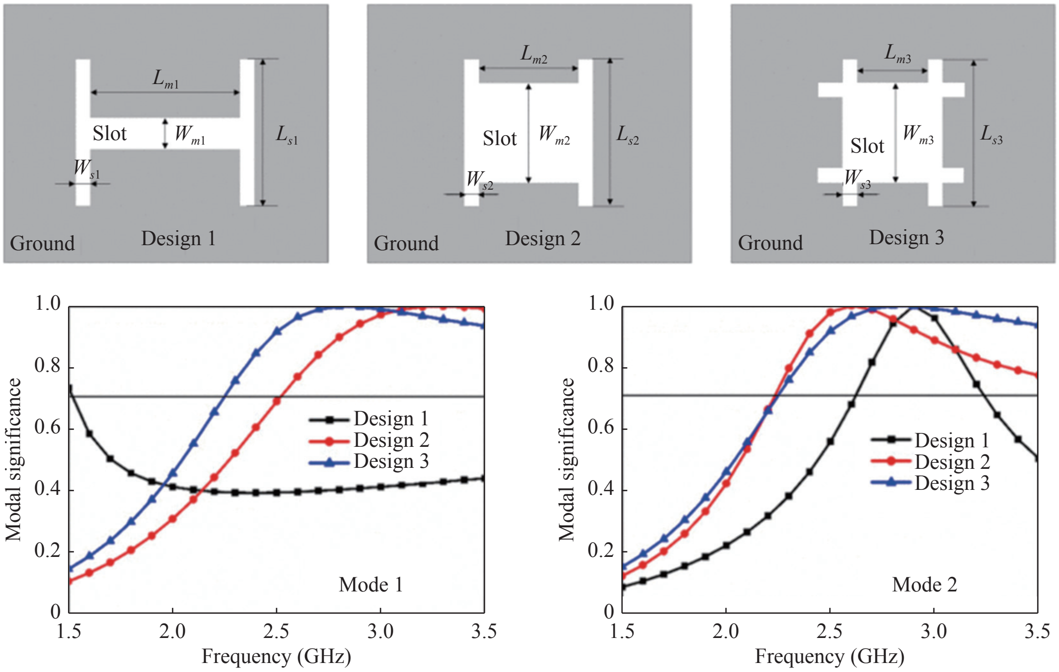


Fig. 4. Evolution of the H-shaped slot antenna, mode 1 and mode 2 are moved to the desired frequency band by properly reshaping the H-shaped slot.

en element.

Loading is another commonly employed method for tuning the CMs. The procedure of this method is similar to the reshaping method while the modal tuning is achieved through loading. In [31], the original ring slot was loaded with two shorted slot lines. A combined mode was moved to near the original mode of the ring slot, resulting in an increased fractional bandwidth of 18.2%.

Metasurface (MTS) antennas are also a novel type of antenna with low-profile and wideband properties. The MTS antennas contain periodic arranged subwavelength units. Modal analysis for a truncated MTS reveals that it typically resonates at quasi TM30 mode and has a high gain-bandwidth product [32]. Using the multimode resonance of CMs, the MTS antennas can reach a wide impedance bandwidth of 45% in [33] and 79% in [34].

### 2. Circular polarization designs

The circularly polarized wave can be decomposed into two orthogonal linearly polarized waves with equal amplitude and a 90° phase difference. The basic procedure of CM-based circular polarization design is depicted in Fig.5. Characteristic mode analysis can directly reveal the potential orthogonal linearly polarized modes that can be chosen to generate a circularly polarized wave. Another interesting property is that the phase difference of characteristic angle $\alpha_n$ has a direct link to the phase difference between the characteristic fields and the characteristic currents [23]. This property greatly facilitates the design of circularly polarized antennas. The circular polarization condition is now expressed as the equal magnitude of modal significance and a 90° phase difference of the characteristic angle. Carefully modal tuning is required to ensure that the selected CMs satisfy the new circular polarization condition. Finally, the feeders are appropriately positioned based on the characteristic current distribution.

A typical application of this property is illustrated in Fig.6. By adjusting the slots on U-slot and E-shaped patches [20], the two orthogonal modes can meet the required magnitude and phase criterion for circular polarization design. This application demonstrates that the 90° phase difference in characteristic angles is reflected in

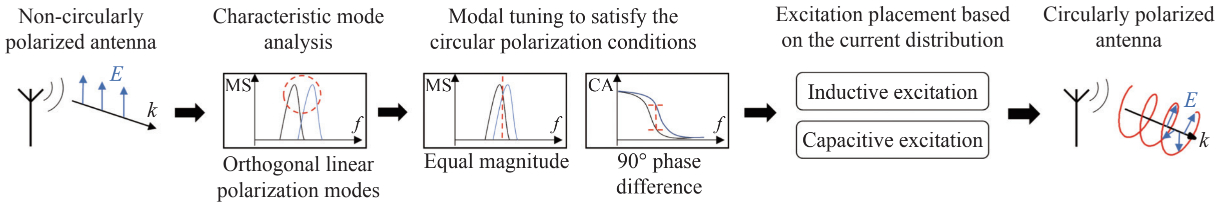
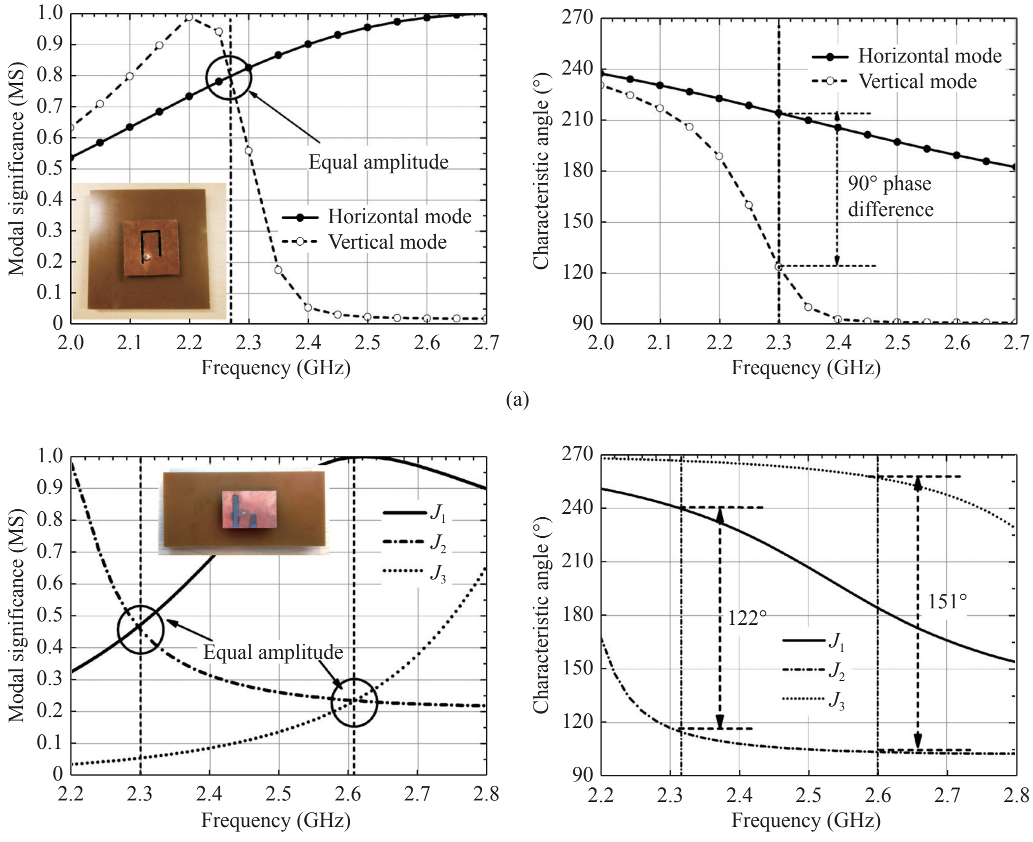


Fig. 5. The basic flow of CM-based circular polarization design method.



(a)

(b)

Fig. 6. Modal analysis for unsymmetrical circularly polarized (a) U-slot patch antenna and (b) E-shaped patch antenna.

the phase difference in the far-field.

Loading is a commonly used method for tuning the magnitude and phase of CMs. In [35], two clock-shaped strips were loaded onto the metal annular ring. By adjusting the angle between the two hands and employing a multimode design, the designed antenna achieved a wide 3 dB axial ratio (AR) bandwidth of 2.4–3.73 GHz. Similarly, in [36], stubs were selectively loaded on one pair of edges of the square patch to perturb the TM12 mode while it had little influence on the orthogonal TM21 mode. Furthermore, in [37], a cross-slot coupling structure was loaded to uniform metasurface antenna which introduce new modes and broaden the 3 dB AR bandwidth to 31.3%.

Cutting is another method for modal tuning by artificially cutting out part of the antenna geometry. In [38], a long slot was cut on the quarter patch antenna and the circularly polarized pattern was realized in a compact size of $0.33\lambda \times 0.33\lambda$. In [39], C-shaped slotted monopole antenna was studied. By combining five CMs and carefully design of the cutting shape, broadband circular polarization of 91% 3 dB AR bandwidth was realized with a compact size of $0.29\lambda_L \times 0.29\lambda_L$.

For MTS antennas, the unsymmetrical design of the MTS can also be utilized to tune the CMs. In [40], an H-shaped MTS was adopted to tune the phase difference of two orthogonal CMs, and 14.3% 3 dB AR bandwidth was realized. In [41], nonuniform MTS was employed to adjust the phase difference of CMs, achieving a 3 dB AR bandwidth of 17.43%.

All the aforementioned designs are based on the modal analysis of the original structure. The derived modal parameters, including $\mathrm{MS}_n$ and $\alpha_n$, reveal the potential resonant modes and the phase relationship. And the characteristic current distribution provides guidelines for mode-tuning and excitation positioning. This insightful method forms a systematic design procedure that greatly facilitates the design burden.

## 3. Multiport antennas

The emergence of the theory of characteristic modes has stimulated some CM-based new antenna designs. Multiport antennas greatly benefit from CMs. Multiport antennas are antennas with more than one port and the ports share the same radiator. Multiport antennas become popular since the growing demand for multiple-input multiple-output (MIMO) systems. The MIMO systems require multiple inputs, multiple outputs, low correlation, and diversity to improve the overall system performance [42]. The number of antennas becomes a critical factor for improving the MIMO performance. Increasing the number of antennas in a finite-dimensional array leads to poor isolation between antennas which will degrade the MIMO performance. The decoupling of antennas with small spacing is a challenging job. An alternate way is to use multiport antennas which only occupy one physical element and increase the overall number of elements in a limited space. The CMs can play an important role in the design of multiport antennas, as depicted in Fig.7.

Due to the presence of multiple CMs within one antenna structure, it becomes possible to independently excite each CM to form a multiport antenna where each port excites one distinct CM. The orthogonality of CMs guarantees the isolation between each port. Consequently, this property makes CMs an ideal tool for low-correlation multiport antenna design. Many CM-based MIMO base station antennas and MIMO terminal antennas have been proposed in the past years.

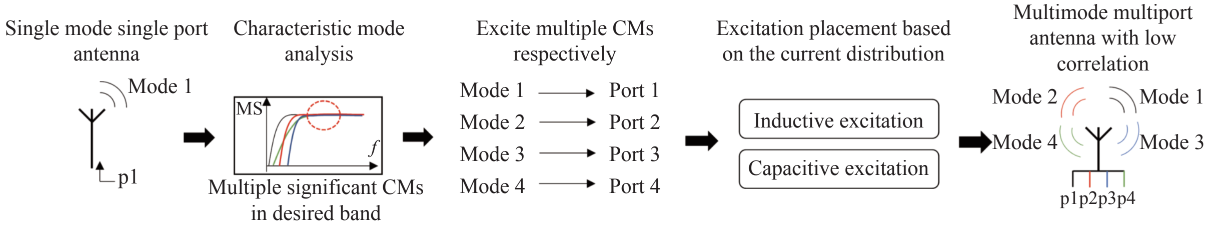


Fig. 7. The basic flow of CM-based multiple modes multiport antenna designs.

The multimode multiport antenna (M$^3$PA) described in [43] and [44] have made full use of the potential radiation modes to achieve a maximum number of uncorrelated ports. The modal analysis was performed to find the significant modes of a metal patch and these significant CMs were selected as the radiation modes. Guided by the modal current distribution, the slot feeder was placed in suitable positions to excite each CM. A four ports case in [43] and a six ports case in [44] were studied, showing a low correlation ($\rho < 0.05$) among all ports. The low correlation, pattern and polarization diversity of the CM-based M$^3$PA are ideal for MIMO applications. Another application of CM-based multiport antennas is the in-band full-duplex antennas [45]. The orthogonality of CMs permits the two isolated ports to work simultaneously.

The CMs has become an important tool in terminal multiport antennas design, including mobile handsets and wearable devices. These devices typically have limited space for antenna placement. For mobile handsets, the chassis is used as the main radiator. The overall dimension of the chassis is approximately 0.5–1.5 wavelength of the mobile communication bands. Thus, the available modes are restricted especially in the lower band. To increase the number of available modes, two T-shaped strips were loaded to move the interested CMs to the desired frequency band [46]–[48]. The offset short-circuited pins of strips can further move the CMs to the lower band. Bezel [49], [50] is another commonly used method to generate new modes. In higher frequency bands, the design of multiport antennas becomes more challenging due to the increased number of required ports. In [51], an effective method was proposed to address this challenge by appropriately combining over 10 available CMs from the bezel and chassis. Four loop exciters were placed at four corners of the chassis and the other four slot exciters were placed at the current null to minimize the correlation. By implementing this technique, eight-ports antennas were realized with correlations lower than 0.16.

### 4. Pattern optimization and synthesis

The radiation pattern is an important property of antennas which control the radiation energy distribution in free space. Based on the fundamental concept of CMs, the surface current on the considered structure can be decomposed into a series of orthogonal characteristic currents. Similarly, the radiation field can be decomposed into a series of orthogonal characteristic radiation fields. Consequently, the modal expansion of the radiation field offers a novel approach to control the radiation field through the adjustment and combination of different CMs.

Radiation field can be related to two kinds of characteristic parameters, namely, characteristic current distribution and the modal weighted coefficients. Therefore, the CM-based pattern optimization and synthesis technology can be categorized into three ways: 1) Directly changing the modal current distribution; 2) Appropriately setting the excitation structure and designing the feeding network to obtain desired modal weighted coefficients; 3) Simultaneously performing the aforementioned two operations. The way 1) mainly involves modification and loading techniques, which is essentially the same as the CM-based antenna design. Therefore, this subsection focuses on the second way where the expected radiation pattern is obtained only by weighting the inherent CMs of the radiator without changing the original structure. This basic framework of CM-based radiation optimization and synthesis techniques is illustrated in Fig.8.

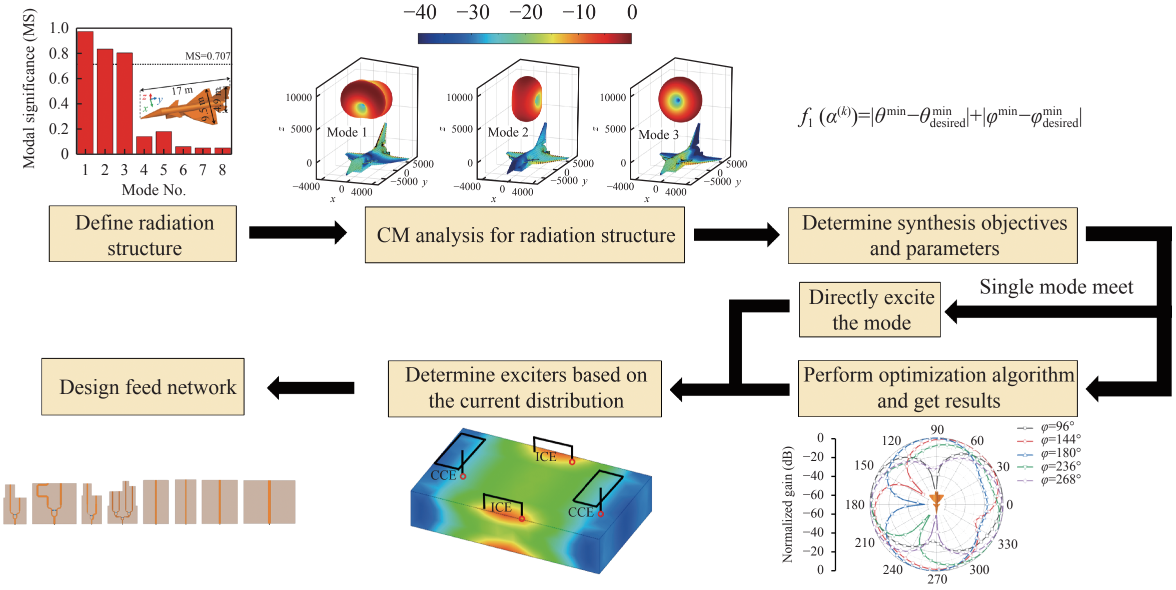


Fig. 8. The basic framework of the CM-based pattern optimization and synthesis techniques.

There are several design approaches for realizing the way 2). In the first approach, multiple ports are utilized to independently excite different CMs at predetermined feeding locations, and the modal weighted coefficients corresponding to each mode are subsequently determined for each port. Then, the feeding amplitudes and phases of each port can be obtained using the traditional array active pattern synthesis method. This approach has been successfully used for 2D and 3D null steering and antenna design with tilt angle [52]–[54]. More specifically, through properly design of the feeding network, each feeding port can excite only one characteristic mode. In this case, the complexity of traditional synthesis methods can be reduced by making full use of the orthogonality of the characteristic fields. For instance, in [55], the orthogonality of the characteristic fields was used to avoid the time-consuming matrix inversion in the least squares pattern synthesis method. Another approach is to directly synthesize a specific number of CMs of the radiators without considering the feeding position, and the feeding position is subsequently determined according to the synthesized modal current distribution [56]–[61]. The selection of the CMs for pattern synthesis can be determined by the modal significance [56], pattern correlation coefficients [61], and other algorithm related technical indicators. Considering the diversity of modes, there may be many current distribution solutions that satisfy the requirements of the radiation pattern, especially if there are many significant modes. Therefore, in the design of the optimization objectives, not only the radiation pattern can be constrained, but also the current distribution can be further constrained to avoid the optimized feeding position appearing in undesirable regions. In [57], the current constraint was set to avoid the feeding position appearing in the fire control zone when the broadside radiation pattern is excited on the ship. The existence of multiple solutions is advantageous for the design of multi-antenna systems. In [59], multiple solutions of current distributions without intersection were selected to achieve the design of aircraft highly isolated multi-antenna systems. Conversely, if the current distribution solutions with intersection are selected, a set of excitation structures can be used to reconstruct the radiation pattern [56]. However, it is worth noting that this method can only solve the loading position of the excitation structure qualitatively at present, and the feeding vector of the practical feeding port needs to be further optimized by the algorithm [56]. To address this issue, references [60], [61] proposed a technique based on norm minimization to sparsify the distribution of feeding vectors. This technique aims to utilize fewer feeding points to achieve the desired modal weighing coefficients, so as to provide accurate formation of feeding location, amplitude, and phase. The challenge in this technique lies in designing a suitable feeding network that ensures the consistency between the excitation vector of the feeding points and the optimized feeding vector or modal weighting coefficients.

Another application of CMs in pattern synthesis is the design of reactively controlled directive arrays and reactively loaded antennas [62], [63]. In these applications, the network characteristic modes were used as the basis function to synthesize the radiation pattern and calculate the required lumped loads, which can effectively avoid blind parameter adjustment and time-consuming full-wave simulation.

## IV. Application to Scattering Problems

The theory of characteristic modes was originally proposed for scattering problems. Although most of the applications of the CMs are focused on radiation problems, the theory of characteristic modes is still useful in scattering analysis and control.

The modal decomposition (5) and (6) quantify the contribution of each CM to the overall current distribution or radiation field. This scattering decomposition serves as an important tool for identifying the CMs with the most significant impact. In [64], scattering decomposition was employed to analyze and control the scattering behavior of an aircraft through the use of lossy dielectric coating. The microwave absorbers are another type of device used in scattering control. By combining multiple CMs, a wideband absorber was proposed in [65] with a 126.66% fractional bandwidth of 90% absorption. The absorptivity was over 90% at normal incidence and remains above 85% for oblique incident angles within ±45°. In [66], complementary patch and hole units were stacked to produce an ultra-wideband response. A 147.6% fractional bandwidth with 90% absorption was achieved for oblique incidents within ±25°. These applications for absorbers are similar to the impedance bandwidth enhancement in radiation problems, which the multimode operation is utilized to enhance the absorption bandwidth. Scattering problem for antennas presents unique properties compared to normal scattering objects. Theoretically, the scattering of antennas can be decomposed into structural mode and antenna mode scattering [67]. Antenna mode scattering is the reradiated field due to the impedance mismatch and the residual part is called the structural mode scattering. The basic idea of the CM-based scattering analysis and control is depicted in Fig.9. Recalling the modal decomposition (5) and (6), this decomposition can be used to analyze the contribution of each CMs to radiated or scattering field. Thus, the CM decomposition can be used to distinguish the "Radiation mode" and "Scattering mode" [68], [69]. This idea finds application in the antenna scattering control [70], [71], [72]. In [70], a T-shaped slot antenna was analyzed with the theory of characteristic modes. The scattering mode was identified and suppressed by loading lumped inductors and slots. At least 5 dB radar cross-section (RCS) reduction was achieved across the operating frequency band (2–3.7 GHz). In [71], a U-slot patch antenna was studied with the theory of characteristic modes. By adding a virtual port, a higher order can be excited and used to cancel the scattering from other sources. Lumped elements with the values calculated at a certain frequency were loaded at the virtual port. A 26 dB RCS reduction was obtained at the desired frequency and the frequency can be adjusted with different values of lumped elements. In [72], modal current and MWC were used to step-by-step reduce the RCS of a ring patch antenna. The modal current hotspots were loaded with slots to suppress its scattering. An average 6 dB reduction was

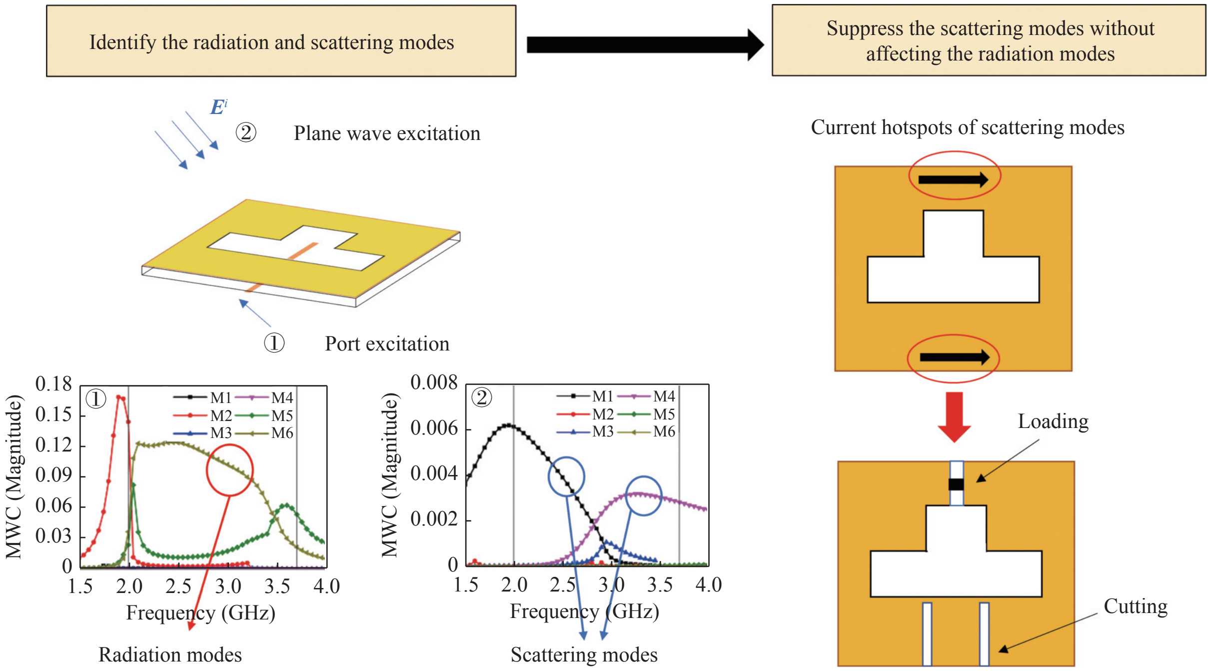


Fig. 9. CM-based scattering control for a T-shaped slot antenna [70]. The modal analysis is performed for identifying the radiation modes and the scattering modes. Guided by the modal current distribution, the scattering modes are suppressed without affecting the radiation modes which balances the radiation and scattering performance.

realized over a wide frequency band of 0.5–5 GHz.

## V. Application to Electromagnetic Coupling Problems

The theory of characteristic modes can provide clear insight into the physical problems of coupling, and its main application to coupling problems can be divided into two categories. One is for the application scenarios that the performance of an isolated antenna needs to be considered in the presence of other structures (parasite elements). The coupling relationship between isolated antennas and other structures can be considered by the characteristic mode analysis, which provides guidelines for structural design and parameter optimization. Another category involves scenarios that require the design of highly isolated antenna arrays. The theory of characteristic modes can provide a guideline for designing isolated antenna arrays from the perspective of resonant characteristics of antenna arrays. Various applications of CMs to coupling problems are summarized in Fig.10.

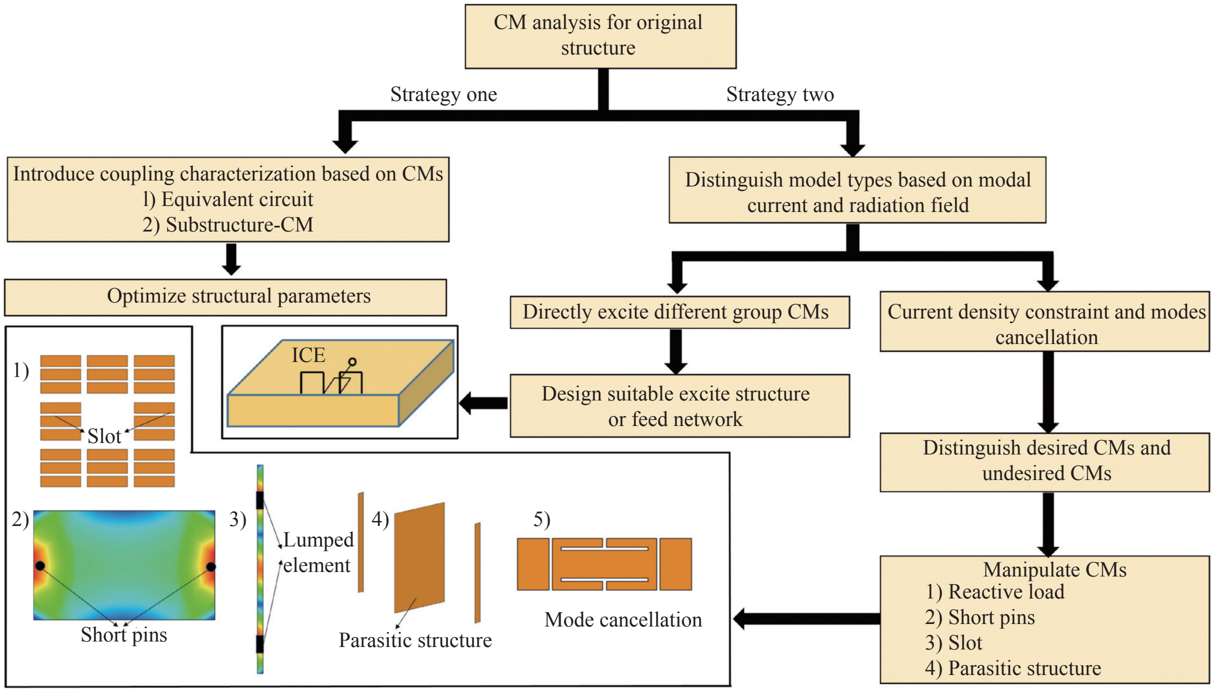


Fig. 10. Coupling analysis and control based on the CMs concept.

For the first type of application, one approach is to introduce CM-related equivalent circuit schematics to characterize the coupling effect. In [30], the modal impedance derived from the characteristic mode analysis was combined with J/K inverters to establish an equivalent circuit, which guided the design of patch antenna with parasitic structures. Another approach is to employ the theory of substructure characteristic modes [73], which is a further improvement on the classical characteristic mode theory. In this theoretical framework, the structures that do not belong to the target body are regarded as background structures, and the coupling effect of the background structure on the concerned body is considered by reconstructing the impedance matrix according to the original block matrix. This idea has been successfully applied to study the effect of ground plate coupling on the resonant characteristics of the radiator [74].

For the second application, the core of improving isolation is to generate a weaker current distribution at the desired ports when other ports are excited. The characteristic mode analysis provides the following approaches for the realization of this core objective.

The most straightforward approach is to excite different CMs for each port. Benefit from the orthogonality of CMs, the ports designed in this way naturally have good isolation. Reference [21] introduced a more special case of mobile phone antenna design, that is, the fundamental mode of chassis was excited by monopole while this mode was not excited by other ports, therefore realizing a high isolation dual antennas design. However, independently exciting a single mode is a challenging task when there are multiple significant modes, because attempting to excite desired CMs inevitably excites high-order CMs. In order to improve the purity of CMs excited by ports, a novel balanced inductive coupling element was proposed in [75]. This article pointed out that the balance feed structure has higher mode excitation purity than the traditional nonbalanced structure. Although the coupling problem is not reported in detail in this paper, its consideration of the purity of mode excitation is consistent with the approach described in this subsection. Therefore, reasonable excitation structure design has the potential to improve port isolation. Another implementation approach is to design a decoupling network at the back of predetermined feeding ports [76]. In [76], the back-end feeding network was carefully designed according to the CMs information excited by the feeding points, realizing the function of single port excites a single mode. In [77], the modal energy occupied coefficient derived from the theory of characteristic modes was proposed to guide the MIMO antenna design. This reference parameter provided a guideline for exciting different groups of characteristic modes. It is worth noting that exciting different modes to achieve high isolation is not always effective. Reference [78] made this point clear from the correlation coefficient of current. In [79], the authors further analyzed the upper bounds and design guidelines for realizing uncorrelated ports based on characteristic mode analysis. Several approaches for direct suppression of undesired modes have been proposed in [80]–[86]. In [80], a slotting technique was proposed to change the modal current path and move the resonant point of the undesired mode out of the working frequency band, thus inhibiting the undesired characteristic current. In references [80]–[82], the short-circuit pins were loaded at the position where the undesired modes have strong electric field distribution and the desired modes have weak electric field distribution so as to suppress undesired modes without affecting the desired modes [80]. Techniques for loading lumped components are also often used to suppress unwanted modes. In [83]–[85], the parameter characteristic modal mutual admittance was used to represent the coupling between each port. By analyzing the current distribution of functional modes and non-functional modes, the loading position of lumped elements was determined, so that the non-expected modes were removed from the working frequency band, realizing a high cross-band isolation antenna array design. In addition, the technique was also used to reduce the distortion of the radiation pattern [86].

Another possible approach is to deliberately design the structure of radiators such that when one port is excited, multiple characteristic currents cancel each other at the positions of other ports. Based on this strategy, a highly isolated MIMO dipole pair for base-station application was designed [87]. In this design architecture, multiple ports shared the same radiator, and special slot structures were introduced between ports to adjust different characteristic modes with different current directions to the same resonant frequency, so as to realize mode cancellation and achieve high isolation. The approach of cancellation has also been introduced into the design of parasitic decoupling structures [74]. In addition, the paper introduced a concept of coupled characteristic mode [88] to assist the parameter optimization of the parasitic structure.

## VI. Conclusions and Future Perspectives

This article reviews the recent development of CM-based techniques in antenna design. It highlights the capacity of CMs in a wide range of problems including bandwidth, polarization, pattern, scattering, and coupling. These problems cover most of the design requirements for antennas which demonstrates the versatility of CMs. Despite the well-developed applications in the context, there are still some challenges in the theory of characteristic modes involving periodic structure, electrically large objects, complex materials (lossy, anisotropy, etc.). These concepts relate to some potential applications, including frequency selective surfaces (FSS), metamaterials, platform-integrated multiantenna systems, user-effect, scattering control, etc. Predictably, by overcoming these problems, the theory of characteristic mode would be a more powerful and efficient tool in antenna engineering.

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