Advances in Antenna Design Through Characteristic Modes: A Review of Simulation Techniques and Development

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Abstract

This paper presents a comprehensive review highlighting the progress made over the last few years, illuminating the state of the art in antenna designs based on characteristic modes theory and its application. The ultimate objective of this review is to provide an inclusive study of the recent advancements in characteristic mode analysis to design and optimize various antenna structures. The study will provide a broad coverage of characteristic modes theory, the underlying theoretical framework, and its significance in designing effective antenna structures. Additionally, the step-by-step methodology for antenna design using characteristic mode theory in commercial EM solvers has been extensively discussed. This article will be beneficial for beginners to explore the potential of characteristic modes and its applications enable them to embark on innovation working in this exciting field.

Keywords CMA, 5G, Millimeter Wave, MIMO antenna, Metasurface

1. Introduction

In recent years, adopting characteristic mode analysis (CMA) in antenna design has brought a new revolution among antenna designers. It has emerged as a powerful and innovative tool that enabling the development of highly efficient and optimized antennas. This approach has played a significant role and will likely open up new opportunities for maximizing the outcomes of various antennas and microwave circuit designs [1]-[2]. The initial research on CMA-based antenna design led to understanding the fundamental resonant modes of antennas and their relationship to radiation patterns and other performance characteristics. Newman proposed the first CMA-based structure for a small antenna [3]. The supporting structure was analyzed to find the optimal antenna location that improved efficiency. However, only a few investigations on CMA were published during this period. Subsequently a review of the theory of characteristic modes (CMs) was published in 2007 [4] emphasizing a systematic approach to designing and analyzing various antennas. In addition, it provided a clear insight into the radiation mechanism of the antenna. In the open literature, various antennas have been designed underlying the theory of characteristic mode (CMT). Besides several aspects of performance optimizations like antenna feed and radiation pattern optimizations [5]. Table 1 summarizes a few review articles discussing different aspects behind the design of antenna structures using CMA. In [6], a systematic approach to designing antenna and platform based on knowledge of the fundamental resonance properties using CMA was discussed. The state-of-the-art applications of CMA and optimization methods, including recent developments, were presented in [7]. Substantial advancements made in CMA and its different application domains, followed by prospects, were discussed in [8]. The studies in [9]-[10] have thoroughly assessed the development of several antenna structures, including multiport, circularly polarized, wideband, reconfigurable, and DRAs.

Although the studies presented in [6-10] have explored the theoretical foundation and mathematical principles behind CMA, its applications in recent developments towards antenna design and performance optimization. However, there seems to be a gap in the research as the detailed analysis of current works and their practical aspects have not been properly addressed. Simultaneously, a lack of comprehensive discussion exists on how CMA is specifically and practically applied in designing various antenna structures. This keeping in mind the present article intends to provide a critical review of advanced research achievements in CMA, covering a wide range of applications including wideband antennas, antenna radiation patterns optimization, metasurface inspired antenna designs, circularly polarized (CP) antennas, multiport/MIMO antennas, dielectric resonators (DRs) and reconfigurable antennas. Further, this study offers an in-depth understanding of the integration of CMA in commercial EM tools and the specific simulation strategies to design and optimize antenna structures. This will bridge the gap between the theoretical concepts of CMA and their real-world applications in antenna design. It is believed that such a comprehensive study would provide readers with a holistic understanding of the theoretical and practical aspects of antenna design using CMA. It would also be a valuable resource for individuals looking toward new research directions using the concept of CMA.

2. Theory of Characteristic Mode: The Basics

One of the key contributions to the advancement of CMA was the work of Garbacz and Turpin [11]-[12], where a general theory for the excitation of surface currents on perfectly conducting bodies has been illustrated. This laid the foundation for understanding how the

Table 1. Detailed comparison and summary of the review of the CMA-Based antenna designs

Ref.	Year	Research Focused on	Remarks/Summary
Martin et al. [6]	2015	Systematic approach to design antenna structures and the platform on which the antennas are mounted	This article is mainly focused on platform-based antenna design and has shown how CMA can be used to improve the antenna topology, optimizing the antenna shape
Bashar et al. [7]	2021	CMA-based recent development and its potential to design and analysis of antenna structures	Summarizes different studies related to CMA-based antenna designs and their results
Buon et al. [8]	2022	CMA-based different application domains and their prospects	A detailed overview has been presented on emerging topics within the field of CMA, indicating advancement in modelling techniques, and integration of CMA with other optimization methods
Jacob et al. [9]	2022	Recent applications of CMA to innovate various antenna designs	The work provides an overview of recent progress on CMA in designing several antenna structures.
D. Xuan et al. [10]	2023	Recent development of CMs-based techniques in antenna design	This review offers a comprehensive study of CMs in antenna design, encompassing wideband properties, circular polarization, radiation pattern manipulation, scattering modulation, and the regulation of mutual coupling
This Work	2024	CMA theoretical formulation, recent advancements toward antenna designs, and simulation enclosure	Presented a critical review of CMA's historical development, typical CMA based antenna design strategy in EM solver, and its recent developments towards designing and optimizing various antenna structures

CMs are excited in the presence of electromagnetic fields and how they contribute to the overall behavior of the antennas. Later, it was demonstrated by Harrington and Mautz in the frequency domain based on the integral equations [13]. Although the analysis was not limited to conducting bodies, it was extended to dielectric and magnetic bodies, where the modes were represented by a weighted eigenvalue equation using both generalized and scattering matrices [14]-[15]. Therefore, in the context of the design and analysis of antenna structure generally, two important conditions need to be known: the structure of the antenna and its excitation. Once these two conditions are known, various techniques such as the Method of Moments (MoM), Finite Element Method (FEM), and other numerical methods can be employed to design and analyze the antenna behavior. Characteristic mode analysis is fundamentally used to generate orthogonal modes that excite electric currents $(\vec{J})$ on the conducting bodies [16]-[17]. Below, several equations are derived, highlighting the characterization of currents on the conducting element as a summation of Eigen-currents $(\vec{J}_n)$ each associated with a weighted coefficient α_n [18].

$$\vec{J} = \sum_n \alpha_n . \vec{J}_n \quad (1)$$

$$X(\vec{J}_n) = \lambda_n R(\vec{J}_n) \quad (2)$$

where, $(\vec{J}_n)$ is the Eigen current, λ_n is the Eigen value, $[X, R]$ are the real and imaginary ports of the impedance operator $(Z(J_n))$, and α_n is the modal weighting coefficient.

$$\alpha_n = \frac{V_n^i}{1+J\lambda_n} \quad (3)$$

where, V_n^i represents the modal excitation coefficient, which can be expressed as

$$V_n^i = (\vec{J}_n . \vec{E}_i) \quad (4)$$

where, $\vec{E}_i$ is the impressed source, substituting (3) in (1)

$$\vec{J} = \sum_n \frac{V_n^i . \vec{J}_n}{1+J\lambda_n} \quad (5)$$

The modal significance (MS) is characterized as

$$MS_n = \left| \frac{1}{1+J\lambda_n} \right| \quad (6)$$

For the design of a practical antenna structure, the characteristic angle (β_n) is also considered to be one of the critical parameters, which is represented by

$$\beta_n = 180^\circ - \tan^{-1}(\lambda_n) \quad (7)$$

Eqn. (7) indicates that when the mode is excited, i.e $\lambda_n = 0$, and β_n becomes 180°, the mode is significant and strongly radiates. The modes excitations depend on the modal weighting coefficients α_n, which further depend on Eigenvalues and modal excitation coefficients V_n^i. When the value of β_n becomes less or greater than 180°, the mode is considered non-significant and provides weak radiation. Therefore, in the perspective of antenna geometry, a high modal excitation coefficient can be retained by placing the excitation where the concentration of Eigen current is dense [19]-[20].

3. CMA-based Antenna Design: Stepwise Methodology

Commercial electromagnetic simulation software has recently become the most significant tool in antenna design worldwide. Compared to analytical methods of designing antenna systems, commercial software has achieved much popularity among the antenna designer's community due to its user-friendly interface, and it can easily predict the performances without being fabricated by being able to the actual physical prototype with all of its detail. However, the time required to design an antenna system will significantly increase. Simultaneously, to retain desired results, optimizing the design parameters based on a trial-error method is also time-consuming. Noteworthy, the computational time depends on the structure's complexity, numerical techniques, and the created mesh [21]. Consequently, by understanding the structure's physical principles, the electromagnetics solver-based antenna design and optimization process can be more straightforward with minimal time consumption. This will also avoid the arbitrary tuning of design parameters. Therefore, a systematic and effective CMT design process is highly desirable and has become a nominal design methodology. Various computational electromagnetic solvers have adopted CMs to determine the electromagnetic properties of any radiating structure without excitation sources, offering a more deterministic antenna design approach by understanding the antenna's physical behavior compared to the arbitrary or trial-error design approach, the CMA technique provide a clear insight into antenna resonance, radiation patterns, and specific modes, etc. The importance of CMA and its stepwise antenna design methodology utilizing commercial EM solvers is shown in Fig. 1. The following steps must be followed to design an efficient antenna structure using CMA.

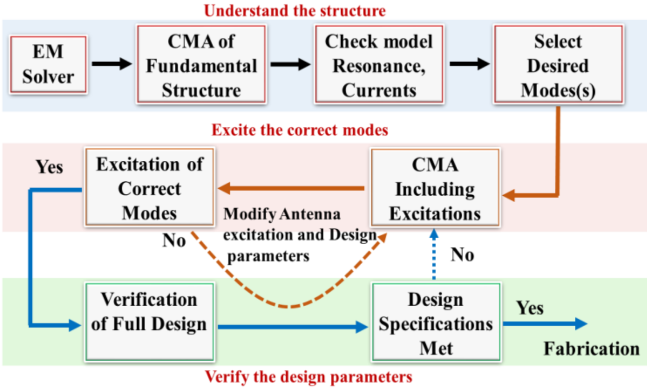

Fig. 1. Steps of designing an efficient antenna structure using CMA

i. Utilizing an EM solver, the first step involves conducting an initial investigation to understand the behavior of a structure. In order to streamline the analysis, it is imperative to employ a representative structure that may not incorporate every intricate detail but must encapsulate the fundamental characteristics necessary for the study. During this stage, certain factor, such as the excitation and the feed are deliberately omitted to circumvent complexities in execution. Instead, the focus is on conducting CMA to identify modes naturally in or near resonance within the desired frequency range. CMA also assesses whether a single mode or a combination of modes is optimal for specific applications. Subsequently, the appropriate mode is selected based on these analyses.

ii. Once the desired mode or combination of modes has been identified and selected through CMA, the next step is to design an excitation that effectively couples to these modes. A detailed CMA analysis of the antenna structure needs to be performed at this stage, which will aid in determining proper antenna geometry, feeding type, and location, as well as controlling the amplitude and phase of the excitation in the case of multiport antennas. Here, in this analysis, the modal weighting coefficient will be evaluated to assess the extent to which the designed antenna satisfies the desired modal behavior. If the observed modal characteristics deviate from the intended performance criteria, iterative modifications to the antenna geometry, design parameters, or excitation scheme will be necessary to achieve optimal mode excitation and desired operational performance.

iii. In the final stage, a rigorous verification process is undertaken to ensure that the design parameters align with the desired outcomes. If the verification confirms adherence to the specified requirements, the next step involves proceeding with prototype fabrication. If discrepancies are identified, it becomes necessary to revisit certain design parameters or excitation configurations for modification. This iterative process continues until the design meets the prescribed criteria, ensuring optimal performance and functionality of the antenna system.

4. Design and Performance Optimization using CMA

Fig. 2 illustrates the classification of antenna design using CMA, which depends on the specific application and the optimization objectives. This can be used to tailor antenna designs to meet various performance criteria, leading to improved antenna bandwidth, efficiency, and other relevant characteristics. This section discusses how CMA is utilized to simplify the design planning and optimization of various antenna designs, including wideband antennas [22]-[28], optimization of antenna radiation patterns [30]-[33], metasurface-inspired antenna designs [34]-[40], circularly polarized (CP) antennas [42]-[47], multiport/MIMO antennas [48]-[55], Dielectric resonators (DRs) [60-63], and reconfigurable antennas [64]-[72]. More information on the theoretical and practical advancements of CM-based techniques for various antenna designs and optimization has been presented in each section.

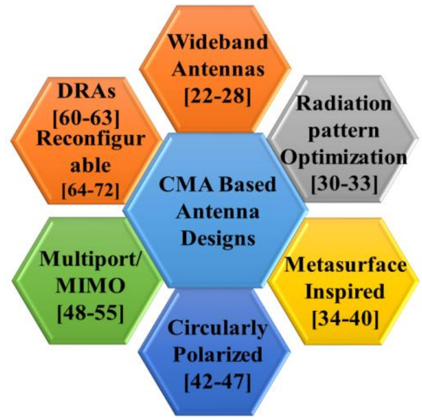

Fig 2: Classification of different CMA-based antennas

4.1 Wideband Antennas

Wideband antennas are integral to modern communication systems, as they facilitate seamless operation across an extensive frequency spectrum. Their ability to support a broad bandwidth is particularly critical in applications such as WLAN and fifth-generation (5G) wireless networks, where high spectral efficiency, low latency, and enhanced data transfer rates are required. By accommodating multiple frequency bands simultaneously, wideband band behaviour can be achieved. Over the years, characteristic mode theory has been widely employed in the design of wideband antennas across various applications. To design a wideband antenna system using CMT, two common approaches based on modal analysis must be considered. The first approach involves exciting wideband modal resonance, which simplifies the design by concentrating on the activation of a single wideband mode or a small set of wideband modes. This method enables broad frequency coverage while maintaining relatively simple antenna structures. Further, this wideband modal resonance can be acquired by properly adjusting the feeding mechanism [9]. An example of bandwidth enhancement of up to 46% was achieved by optimizing the feeding structure [22]. Consequently, higher-order modes were retained by adjusting the dimension of slots in rectangular microstrip antenna [23]. Initially, a slot-loaded circular patch antenna with a shorting pin was designed. Later, four groups of shorting pins and slots were introduced for wideband behavior based on the study of modal currents and electric field distributions [24]. The second approach combines several closely spaced narrowband modal resonances shown in Fig. 3, where CMA determines the modal characteristic of narrowband antennas. Multiple CMs are brought into proximity through modal tuning. Further, to obtain the necessary bandwidth, appropriate excitation locations are chosen based on the information on modal current distributions. This approach is suggested by several contemporary antenna designs reported in [25]-[28]. Combining several narrowband CMs excited from a large metallic platform improves the bandwidth of platform-mounted high-frequency antennas [25]-[26]. Similarly, combining six significant resonant modes retained a wide operational bandwidth [27]. In [28], a narrow slot antenna for bandwidth augmentation using CMT was proposed and depicted in Fig. 4(a). The antenna excites CM1, CM2, and CM3 modes at 2.39, 4.78, and 7.17 GHz. Thus, the antenna offers wide bandwidth by combining modes CM1 and CM2. Both approaches have their advantages and trade-offs. The

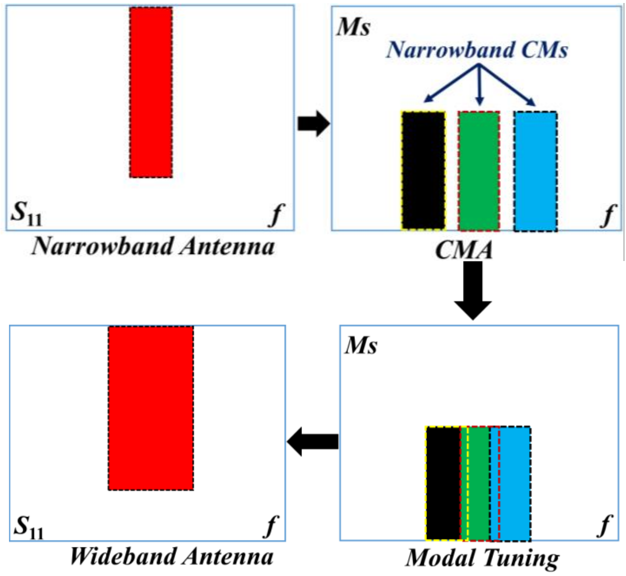

Fig. 3: Typical wideband antenna design using CMA

first approach provides a simpler design and broad bandwidth coverage but may not achieve optimal performance at specific frequencies. Consequently, the second approach offers more flexibility and controls antenna response but may require more complex designs and tuning procedure. The choice between these approaches depends on the specific requirements of the applications.

4.2 Optimization of Antenna Radiation Patterns

Pattern synthesis techniques are fundamental in designing antennas for various applications, including cellular communication, radar systems, and MIMO technology. These techniques enable antenna engineers to tailor the radiation pattern of the antennas to meet specific requirements, optimize system performance, and improve overall wireless communication capabilities. It is being extensively used in phase array antennas because it gives users more freedom to manipulate the patterns by changing the phase and amplitude of each antenna element. However, this is not viable in the case of a single antenna element due to its inherent limitations. Therefore, to design an antenna structure with precisely controlled radiation characteristics, CMT provides a powerful analytical framework for synthesizing radiation patterns through the selective excitation of multiple characteristic modes. By leveraging CMT, designers can systematically analyze and manipulate the inherent modal behaviors of a radiating structure, enabling the optimization of current distributions to achieve the desired radiation performance. This approach allows for a deeper understanding of the electromagnetic scattering and radiation mechanisms of the structure [29].

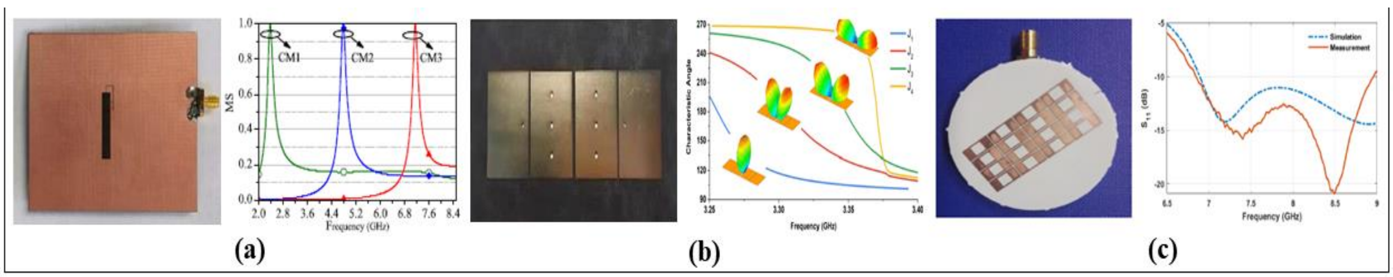

Fig. 4. CMA-based antenna geometry for different applications (a) Wideband [28], (b) radiation pattern optimization [31], (c) Metasurface inspired [40]

This section focuses on demonstrating the implementation of the CMA technique for various antenna structures to enhance the radiation characteristics. As an illustration, a broad omnidirectional radiation pattern with low cross-polarization was accomplished by combining quasi-TM_{01} and TM_{02} modes [30]. Two different planar patch antenna array configurations were presented in [31] and [32]. The antenna structures were analyzed based on CMT, which offered useful guidelines for selecting modes to reduce side lobe level while increasing gain (See Fig. 4(b)). Relying on CMT, a shorting pin microstrip patch antenna is designed by exciting three modes. Thus, by merging TM01 and TM02 modes, the antenna bandwidth was improved with conical radiation patterns. Meanwhile, the TM_{11} mode generated broadside radiation patterns [33].

4.3. CMA Based Metasurface Inspired Antennas

The integration of metasurface structures (MTS) with antennas leverages the resonant modes of finite MTS to enhance overall antenna performance, including bandwidth, gain, and radiation characteristics. Unlike traditional analysis methods, CMT is widely regarded as the most effective approach for exploiting the intrinsic resonant behavior of MTS, as it provides a rigorous mathematical framework to analyze and control surface current distributions. By utilizing CMA, designers can systematically identify and excite dominant modes while suppressing non-dominant or undesired modes, leading to optimized radiation efficiency and improved impedance matching. Numerous metasurface-based antennas have been developed using this methodology, where CMA has been successfully employed to guide the design process, predict modal behaviors, and tailor the electromagnetic response of MTS for specific applications. This section presents a significant amount of literature that employs CMA to forecast the modal behaviors of MTS structures. The results are then utilized to analyze and improve these structure's operating band and radiation performances. The detailed explanations are as follows. Huang et al. [34] presented a metasurface-based high-gain antenna with high side lobes levels. Further, by analyzing the corresponding current distribution using CMA, the suggested MTS structure is modified by incorporating meandering slots in order to cancel the higher order modes and side lobe level. In a similar vein, CMA has been magnificently utilized for the synthesis of MTS in substrate integrated wave guide fed antenna arrays. This results in achieving wideband characteristics with side lobe-level suppression [35]. Two metasurface-based antennas are designed for 5G applications [36]-[37]. The CMT approach is utilized here to predict the modal behaviors of the Metasurface. The relationship between the surface impedance and the characteristic mode of the metasurface antenna is studied to design a high-gain antenna for ISM band applications [38]. Similarly, a metasurface relies on a low-profile MIMO antenna system designed for a 5G smartphone to meet high gain and directivity requirements. The performance of the MTS is investigated at 28 GHz using CMT [39]. Fig. 4(c) shows a 4×4 MTS was employed in the antenna structure and analyzed through CMA for realizing circularly polarized radiation patterns [40]. Table 2 summarizes the performance achievements of CMA-based wideband and metasurface antennas.

Table 2. Performance overview of CMA-based wideband and metasurface-inspired antennas

	Ref.	Antenna Geometry Description	Achievements
Wideband Antennas	[24]	Compact Slotted circular patch antenna with a shorting pin	BW Improvement
	[25]	Platform-mounted loop antenna	BW Improvement
	[26]	Electrically Small platform mounted antenna	BW improvement
	[27]	Modified Tri-modal Patch antenna	BW Enhancement
Metasurface Inspired Antennas	[34]	Dual-band circularly polarized antenna	High gain
	[35]	SIW with non-uniform excitation	BW improvement
	[36]	Single layer dual band antenna	BW improvement
	[38]	A linearly polarized antenna operating at 5.8 GHz	High gain

BW: Bandwidth

4.4 CMA Based Circularly Polarized Antennas

Exploiting orthogonal CMs current and radiated fields in any antenna structure can generate circularly polarized (CP) waves. Two conditions should be satisfied to achieve the desired circular polarization; first, a phase difference 90^0 between two orthogonal linearly polarized modes should exist. Secondly, both modes' excited modal significance (MS) values should be similar at the resonant frequency, meaning the fields of the orthogonal modes are equal in magnitude. Figure 5(a) depicts the condition on the characteristic angle (CA), where two CMs deviate by 90 degrees at the resonant frequency, and Figure 5(b) depicts the required MS behavior. If these two requirements are strictly met, the corresponding axial ratio (AR) will equal 0 dB at the resonant frequency, but AR increases if the MS and CA depart from the required values. In order to increase the CP frequency bandwidth, it is also possible to use the stated recommendations to construct more than two CMs with the correct amplitude-phase condition [41]. Several CP antennas based on CMA modal currents and eigenvalues were designed and presented in [42]-[47]. A U-slot CP antenna was reported in [42]. After analyzing the suggested using CMA, five

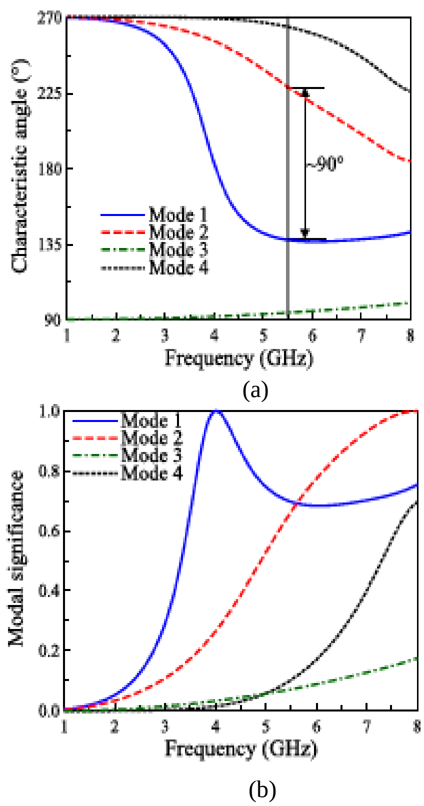

Fig. 5. Circularly polarized antenna specifications (a) Two characteristic angles at a difference of 90 degrees, (b) Identical MS value at the resonant frequency

different linear polarized modes were achieved, where each pair of adjacent LP modes made up of orthogonal polarization with equal amplitude and quadrature phase difference to improve the CP bandwidth. A similar framework demonstrates the design of two different single-fed CP microstrip antennas. The antenna consists of a U-slot and an E-shaped patch designed using CMT. Instead of using LP modes with quadrature phase, orthogonal LP modes are employed to increase CP bandwidth [43]. The CMT is applied to design a hexagon-shaped wideband CP antenna [44]. Different modes and modal currents have been studied, and according to that, the antenna patch and ground plane were modified to achieve the desired CP radiation of the antenna. A high directivity CP patch antenna was designed in [45]. The theory of CMs was used to determine the proper feeding position by observing the modal currents. Further, two orthogonal slots were used, which improved the radiation properties in the broadside direction. A broadband metasurface-inspired patch antenna using CMA was presented by Gao et al. [46]. On analyzing the suggested structure, two orthogonal characteristic modes had a 90° phase difference, leading to circular polarization radiation behavior as seen in Fig. 6(a). The article [47] provides a systematic approach to designing a novel logarithmic spiral patch antenna, where CMA is used to achieve CP with enhanced performance.

4.5 Multiport/MIMO Antenna Design using CMA

Characteristic mode analysis has been extensively applied in the design and optimization of multiport and multi-input multi-output (MIMO) antenna systems. A key advantage of CMA in MIMO antenna design is its ability to leverage the orthogonality of characteristic modes, which inherently exhibit distinct radiation patterns with minimal spatial correlation. This property serves as a strong foundation for developing novel MIMO antenna architectures with enhanced diversity gain and improved channel capacity. By strategically exciting characteristic modes, MIMO antenna designs can achieve minimal mutual coupling, which is essential for ensuring high isolation between antenna elements. Furthermore, in MIMO antenna systems, the excitation of multiple modes is highly desirable, as it directly contributes to improved spatial diversity and multiplexing efficiency. If the required modes are not inherently present in the antenna structure, the geometry must be reshaped or modified to support multimode behavior. In general, microstrip or loop antennas have been regarded as the initial choice and layout for a radiating component. Due to their simple structural geometry, CMA can be easily applied and modified the geometry according to the requirements. The in-depth explanation of this method and the corresponding literature are discussed in this section. UWB MIMO antenna based on CMT was designed in [48]. The antennas are located on the opposing sides of the ground layer and have a different current distributions that excite two orthogonal fundamental CMs, producing diverse radiation patterns. The least square (LS) approach and CMT were employed for multiport chassis antenna to develop the most effective beam steering algorithm. The suggested algorithm effectively guides the antenna's radiation pattern in the preferred direction [49]. In recent days, the potential of CMT has also bee used to reduce SAR in mobile phone antennas [50], [51], and implantable antennas [52]. A general design methodology for a four-port MIMO antenna for 5G mobile phones was proposed in 50] (See Fig. 6(b)). Further, based on CMT, the PEC, and lossy dielectric substrate is analyzed to obtain a low value of SAR. Similarly, by exciting symmetric and reverse modal current distributions, a low SAR 5G mobile phone MIMO antenna was designed [51]. An implanted MIMO antenna was developed at 2.45 GHz (ISM band) for biomedical applications in [52]. The decoupling and feeding position of the antenna is guided according to the electromagnetic properties of the implantable device and CMT. In MIMO antenna design, mutual coupling is an important parameter induced by the close placement of antenna elements. Hence, placing and properly feeding antenna elements in MIMO antenna design is essential to achieve low coupling effects. Generally, an independent single CM is enough to excite isolation over the entire antenna by a distributed feed network. However, it is practically impossible to excite a single mode, as the MIMO antenna excites orthogonal CMs. When the antennas are fed by local excitations, there is a high chance of getting coupled to other modes with low Eigen values, and mutual coupling will consequently occur at the antenna ports. Further, antenna feeds can be placed properly to reduce the coupling effects by ensuring all modes other than the desired one have low modal excitation coefficients. The CMT has been utilized to reduce coupling effects in multiport antenna systems [53-55]. A two-port MIMO antenna system with high isolation for smartwatch applications operating over 2.4-2.9 GHz was designed using CMT [53]. Here, port-to-port isolation is achieved by employing a pair of degenerated modes.

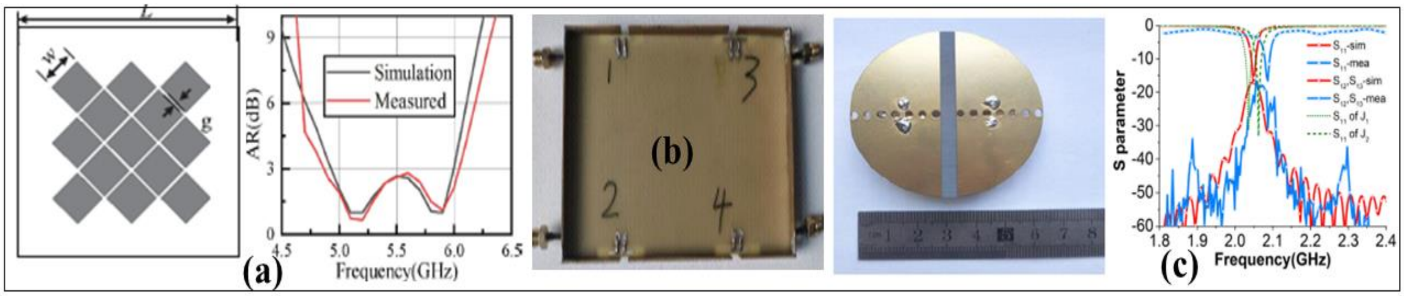

Fig. 6. Antenna geometries for various applications based on CMA (a) Circularly polarized [46], (b) multiport/MIMO [50], and reconfigurable [71]

Table 3. CMA-based circularly polarized antennas and multiport/MIMO antenna: Performance summary

	Ref.	Antenna Geometry Description	Achievements
Circularly Polarized Antennas	[42]	Penta-mode ultra-wideband stacked patch antenna	CP-BW improvement
	[43]	Single-fed triple-mode microstrip patch antenna	CP-BW improvement
	[45]	Low-profile differential-fed patch antenna	RP improvement
	[46]	Low-profile broadband metasurface antenna	CP-BW improvement
Multiport/ MIMO Antennas	[48]	Mobile platform-based Planar UWB MIMO antenna	High port isolation
	[51]	Four-antenna MIMO antenna for 5G mobile phones	Low SAR
	[52]	Conformal MIMO antenna for implantable devices	Low SAR
	[53]	Dual-port MIMO antenna design for smartwatch	High port isolation
	[54]	Twelve-port MIMO antenna system for 5G smartphone	High port isolation

CP: Circular Polarization, BW: Bandwidth, SAR: Specific absorption rate

For the applications of 5G smartphones a twelve port MIMO antenna system was designed and analyzed using CMT. The systematic utilization of CMA helped in selecting optimal port locations that provided high isolation [54]. By exploring the current paths through CMs, a self-decoupling method was developed for antenna arrays [55]. This was originated by analyzing the radiating mode (RM) and decoupling mode (DM), which led to suppressing the flow of currents through the feed ports, resulting in increased isolation. Table 3 illustrates the performance summary of circularly polarized antennas and multiport/MIMO antennas that rely on CMA.

4.6 CMA Based Dielectric Resonator Antennas (DRAs)

During the last few decades' dielectric bodies have been investigated for radiation and scattering purposes. However, limited research related to dielectric resonator antennas (DRAs) has undergone. It is widely acknowledged that dielectric materials are among the most appealing for wireless applications because of their numerous advantages, such as low ohmic loss, low surface wave loss, lightweight, high radiation efficiency, and providing different resonant modes [56]. For proper design and analysis of DRAs, one of the crucial steps is to determine their resonant modes. This will help the antenna engineers recognize the desired operating modes and the feeding position of DRAs. Different techniques have been used to conduct the modal analysis of various DRAs. For example, the resonant modes of both circular and rectangular DRAs can be determined using an approximate boundary model. Correspondingly, the resonant modes of spherical DRAs can be calculated through spherical wave functions [57]. However, analysis using the traditional modal theory is not applicable when dealing with arbitrary DRA structures. The analysis of resonant modes in arbitrary shaped DRAs can only be possible using numerical methods, such as determinant root seeking and characteristic mode method [58]. Nevertheless, the determinant root-seeking method suffers a significant computational load. The CMT has emerged as a fundamental approach for identifying intrinsic electromagnetic properties and systematically analyzing the modal behavior of DRAs with arbitrary geometries. By decomposing the total electromagnetic response into a set of characteristic modes, CMT provides deep physical insight into the resonance behavior, radiation characteristics, and current distributions of DRAs, enabling optimized antenna design. Initially, CMs were formulated based on the scattering matrix representation, which characterizes the interaction between incident and scattered electromagnetic fields. However, to achieve a more rigorous and computationally efficient framework, CMs were later reformulated using Volume Integral Equation (VIE) and Surface Integral Equation (SIE) methods [59]. Both VIE and SIE approaches have some definite benefits, such as similar current distributions in the VIE method aid in finding the suitable position for the placement of feed points; without the producing any spurious mode. In [60], the volume surface integral approach is used to evaluate the CMs of DRAs. Observing different modes' excitation, the feeding structure was modified properly, generating dual and triple band operations. Conversely, the mentioned VIE approach requires more computational time. Therefore, an interpolation algorithm was proposed to reduce the computational time in volume integral equation-based CMA [61]. Whereas the surface integral equation (SIE) approach provides an accurate analysis of the DRAs resonant modes of DRAs with a finite ground plane, with reduced computational time. An efficient design methodology based on the surface integral equation (SIE) based substructure CMs was proposed for precisely identifying resonant modes in DRAs [62]. In [63], the resonant modes of DRAs with the finite ground plane were successfully investigated using the same surface integral equation-based substructure CMs. Further, the modal behavior of the proposed DRAs was compared with traditional full-structure CM formulations.

4.7 Reconfigurable Antennas Based on CMA

Despite the aforementioned topics discussed in the preceding section, another interesting approach of CMA is directed toward designing reconfigurable antennas. This will help fulfill the antenna's requirements to switch its state of operation from one frequency to another and can reconfigure its radiation pattern shape and polarization behavior. The traditional approach of reconfigurability in antenna circuits uses PIN diodes, RF switches, and varactor diodes [64]. However, the underlying principle has not been properly discussed in published articles. Later, it is verified that using the CMT can acquire reconfigurable features by suitably controlling the resonant modes through reactive loads. Based on CMA, the first approach to analyze reactive load was presented in [65], which illustrates that the sum of the impedance matrix of the unloaded structure is used to determine the modal resonance. Using graphical representation, the impact of reactive stress on an antenna structure was demonstrated in [9], where an unloaded antenna with a Z_1 matrix is initially considered, offering three resonant modes corresponding to three frequencies. When the antenna is loaded with lumped elements, the resonant modes shift and provide a new impedance matrix Z_2 (sum of unloaded impedance matrix and loaded impedance matrix). For instance, a reconfigurable antenna is designed based on reactive load [66]. The utility of CMs aids in the systematic computation of reactive load, offering six different reconfigurable states within the frequency band of 50-350 MHz. The use of CMA has also been extended to achieve pattern [67] and polarization [68] reconfigurability. Two different patterns of reconfigurable antennas with slots and shorting pins were proposed. Based on CMA, the positions of slots and shorting pins were analyzed, enabling the antenna to switch between two orthogonal bidirectional beams [69]-[70]. Similarly, in [71], a radiation pattern reconfigurable antenna of the circular patch with a vertical slot and shorting post was proposed and analyzed using CMT (See Fig. 6(c)). Zhang et al. [72] proposed a reconfigurable quad-polarization antenna with suppressed cross-polarization. Different polarization modes were achieved due to the implementation of two-pin diodes. More significantly, a novel CMA approach was used to achieve low cross-polarization. The performance summary of CMA-based reconfigurable antennas is tabulated in Table 4.

Table 4. Performance summary of CMA-based reconfigurable antennas

	Ref.	Antenna Geometry Description	Achievements
Reconfigurable Antennas	[66]	Reactive load based center fed dipole antenna	Frequency Reconfigurable
	[69]	Modified circular loop patch antenna	Pattern Reconfigurable
	[70]	Stacked circular patch with four shorting pins	Pattern Reconfigurable
	[71]	Shorting post-loaded slotted circular patch antenna	Pattern Reconfigurable
	[72]	Square conductive slab with four groups of balanced inductive exciters	Polarization Reconfigurable

5 Conclusion

A detailed study on designing and optimizing different antennas using the theory of characteristic modes (CMT) has been discussed thoroughly. CMA's historical development, formulation of underlying theory, and the importance of antenna elements and design methods have also been discussed. The article has highlighted and comprehensively addressed studies related to designing and optimizing various CMA-based antenna systems e.g; wideband antennas, metasurface antennas, circularly polarized antennas, multiport/MIMO antennas, dielectric resonator (DR), and reconfigurable antennas. The process of CMA in antenna design steps using a commercial EM solver is explained thoroughly.

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