From Antenna Design to Feeding Design: A Review of Characteristic Modes for Radiation Problems

(Invited Paper)

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***Abstract*-This paper briefly reviews the recent progress of characteristic modes (CMs) for radiation problems made in the Temasek Laboratories at National University of Singapore (TL @ NUS). Unique features of the CMs offer great flexibility for the design of high performance antennas. Based on our newly developed in-house software tools for modeling CMs for 3D EM structures and *N*-port networks, the applications we considered include reactively controlled antenna arrays, circularly polarized antennas, platform integrated antennas, and resonant frequency characterization of microstrip antennas. Effective use of CMs can be great help in many antenna designs through proper feeding designs for an existing radiating aperture. This proposed design concept will provide an alternative to change the conventional process of antenna designs, and is also what the CM theory can really benefit the antenna community.**

I. Introduction

Characteristic mode (CM) theory was initially developed by Garbacz [1] and then refined by Harrington and Mautz [2] in 1971. CMs define a set of orthogonal currents resulted from a generalized eigenvalue system. They can be used to accurately represent the total current induced by any external sources. Such attractive property made CMs helpful for many radiation problems [3]-[11]. Our studies on CMs mainly focus on three topics [11]. The first one is to develop in-house code for the CM computations of *N*-port networks, three-dimensional PEC structures, composite PEC-dielectric structures, and EM problems in multilayered dielectric materials. The second one is to develop techniques to compute the optimal excitations and loadings for certain radiation performances (*e. g*. radiation pattern, polarization, and resonant frequency) from a given radiating aperture. The third one is to design practical feeding structures to excite either mode currents or synthesized currents for the mentioned radiation performances.

This paper briefly reviews our recent progress, made in Temasek Laboratories at National University of Singapore (TL @ NUS), on how to apply the CM theory to diverse radiation problems, including reactively controlled antenna arrays, circularly polarized antennas, platform integrated antennas, and resonant frequency computations for microstrip antennas. Detailed discussion for techniques involved in the analysis and designs are reported in our previous publications [6]-[11]. Throughout these studies, we realized that many antennas can be effectively designed through the proper design of feeding structures for an existing radiating aperture with the help of CMs. The review of these studies also demonstrates CMs are very promising for many practical applications, and the concept of "From Antenna Design to Feeding Design" would change the way for many antenna designs.

II. Metric Quantities for Characteristic Modes

For the sake of brevity, the details of the CM theory [2] are omitted here and only two quantities, i.e., characteristic angle and modal significance as the function of eigenvalue λ are respectively defined in (1) and (2) as follows [4]:

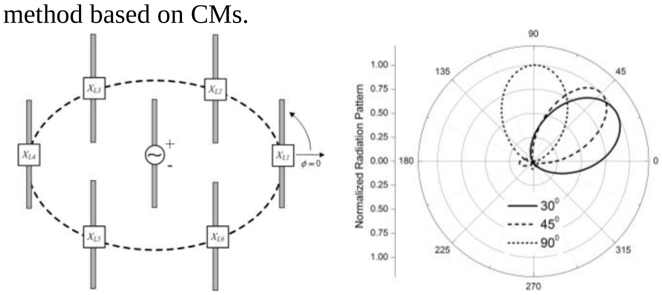
$$\alpha = 180^\circ - \tan^{-1}(\lambda) \quad (1)$$

$$MS = 1/|1 + j\lambda| \quad (2)$$

The characteristic angle physically characterizes the phase angle between a characteristic current and the associated characteristic field. Hence, a mode is at resonance when its characteristic angle is close to 180°. The modal significance represents the contribution of a particular mode to the total radiation when an external source is applied.

III. Reactively Controlled Antenna Arrays

Reactively controlled antenna arrays (RCAA) is an *N*-port radiating system consisting of one element connected to a RF port and a number of surrounding parasitic elements with reactive loads that can be realized by reversely biased varactor diodes. In [6], the RCAA is first analyzed as an *N*-port network using the *N*-port CM theory. Differential evolution (DE) algorithm is then applied to find the optimal reactance loadings using the CMs to avoid demanding a full-wave analysis of each possible candidate. Our study proves that the CMs are important decisions to the final design and demonstrates the effectiveness of the proposed synthesis method based on CMs.



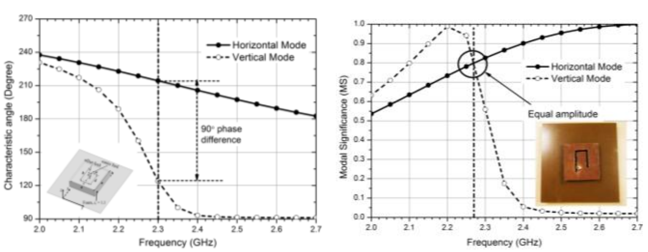
(a) (b)

Fig. 1 Reactively controlled steered radiation patterns of a 7-element RCAA.

A 7-element circular array with one quarter wavelength spacing is considered for the synthesis of steered radiation patterns with maximum front-to-back (F/B) ratio. Dipoles of length $\lambda/2$ and diameter $\lambda/200$ are taken as the antenna elements. Fig. 1(b) shows the steered radiation patterns obtained from the 7-element RCAA. As can be seen, when different loadings are applied, the beam was steered to the directions of $\phi_0 = 30^\circ$, 45°, and 90°, while the F/B ratio have successfully been minimized as low as possible.

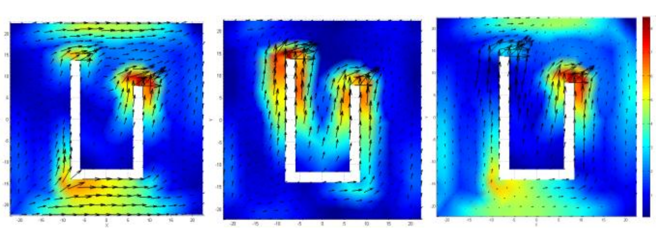
IV. Circularly Polarized Antennas

In [8], we focus on how to apply the CM theory as an efficient way to design circularly polarized (CP) antennas. An offset probe feeding for a U-slot CP antenna is determined from the CMs for better axial ratio performance. Fig. 2 shows the characteristic angle and modal significance of the first two modes. It is found that the two modes present exactly the same current amplitude and 90° phase difference at 2.3 GHz. Moreover, Fig. 3 shows that mode $\bar{J}_1$ is characterized as horizontal mode, with intense currents concentrate at the end of U-slot's short arm. It is also evident that mode $\bar{J}_2$ can be identified as the vertical mode, with its intense currents concentrate at the end of U-slot's long arm. To find the optimal probe positions, we subtract the vertical mode from the horizontal mode. Fig. 3(c) shows the current distribution after subtraction, we refer to it as the 'H-V' current $\bar{J}_1 - \bar{J}_2$ for convenience. It is interesting to note that the minimum current area locates at the inner edge of the U-slot's long arm, which indicates that the two modes present almost the same current amplitude in this area. Thus it is possible to get a CP antenna by placing feedings in this area to excite the two orthogonal modes simultaneously. Simulation and measurement results for the axial ratio and CP radiation patterns are presented in [8] to demonstrate the good performance of the U-slot CP antenna with offset feeding.



(a) (b)

Fig. 2 Horizontal and vertical modes of the U-slot antenna: (a) characteristic angle; (b) modal significance.



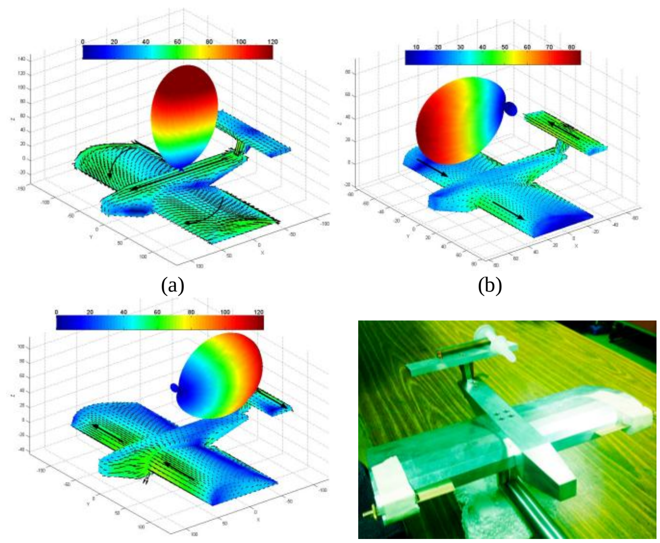
(a) (b) (c)

Fig. 3 Current distribution of the U-slot antenna at 2.3 GHz. (a) normalized horizontal mode $\bar{J}_1$; (b) normalized vertical mode $\bar{J}_2$; (c) 'H-V' current $\bar{J}_1 - \bar{J}_2$.

V. Platform Integrated Antennas

A novel concept of platform integrated antenna designs for electrically small unmanned aerial vehicle (UAV) using the CM theory is presented in [9], [10]. With the knowledge of the CMs of the UAV body, a multi-objective evolutionary algorithm is implemented to synthesize currents on the UAV body that will radiate desired power patterns. Compact and low-profile feeding structures are then designed to excite the synthesized currents, thus the UAV body serves as the radiating aperture. Reconfigurable radiation patterns are obtained through feeding the probes with proper magnitude and phase excitations. In this method, aperture of the UAV body is fully utilized, practical issues associated with large antennas at low frequency band are eliminated, and knowledge for probe placement on such platforms becomes more explicit.

Fig. 4 shows the synthesized currents and radiation patterns using the CMs of the UAV body. Simulated and measured results are presented in [10] to verify the feeding design approach for such electrically small platform antenna designs.



(a) (b) (c) (d)

Fig. 4 Synthesized currents and radiation patterns for the UAV antenna systems using CMs. (a) broadside radiation; (b) forward radiation; (c) backward radiation; (d) prototype of the UAV integrated antenna system.

VI. Resonant Frequency Computations for MSAs

To cater to irregular shaped microstrip antenna (MSA) designs using the feeding design concept, we have also addressed the accurate resonant frequency computations for irregular shaped MSAs using the CMs in spectral domain. When the resonant frequency and current distributions of both fundamental and high order radiating modes are accurately described, the rest work for MSA design is simply to design proper feeding structures for certain resonant frequency and radiation patterns.

Fig. 5 shows the modal significances of an equilateral triangular patch with edge length of 10 cm. It is printed on a dielectric substrate with relative permittivity ε_r = 2.32 and thickness h = 1.6 mm. The resonant frequencies marked in Fig. 5 agree well with those obtained from measurement [12], cavity modal [13], and the said plane-wave incident method [14]. Fig. 6 gives the dominant characteristic modes at the resonant frequencies. The mode pairs that resonant at the same frequency have different current distributions. On the other hand, mode currents computed from the plane-wave incident method [14] are dependent on the incident field, and will sometime leads to misunderstanding and confusing mode currents.

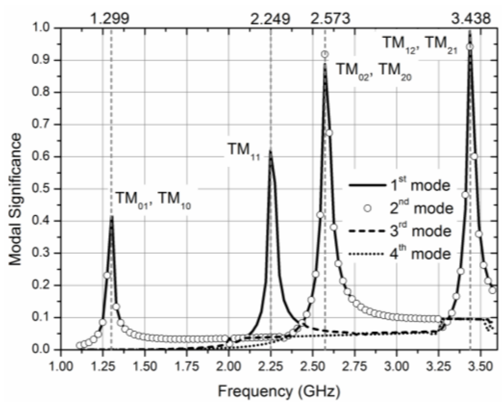
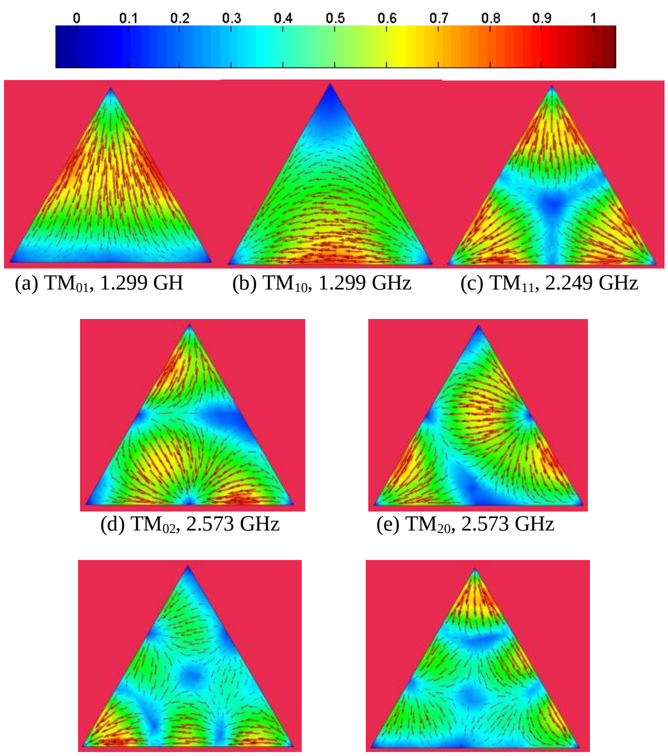


Fig. 5 Modal significance for the equilateral triangular patch antenna.



(a) TM_{01}, 1.299 GH (b) TM_{10}, 1.299 GHz (c) TM_{11}, 2.249 GHz

(d) TM_{02}, 2.573 GHz (e) TM_{20}, 2.573 GHz

(f) TM_{21}, 3.438 GHz (g) TM_{12}, 3.438 GHz

Fig. 6. Dominant characteristic modes at the resonant frequencies.

VII. Conclusions

Recent achievements on the theoretical study, numerical implementation, and practical applications of CMs in various radiation problems are reported. With the help of many unique and attractive features of CMs, physical understandings to the radiating problems can be much clearer, computation burdens in antenna optimization procedure can be greatly alleviated, and designs with favorite features such as compact and low-profile can often be obtained. Throughout this study, we have proposed the CM based feeding design concept that can be great help in simplifying many radiation problems into feeding structure designs for an existing radiating aperture. The proposed concept will provide an alternative to change the conventional process of antenna designs. It is also hoped that the CM theory will benefit the antenna community in more radiation problems in the future.

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