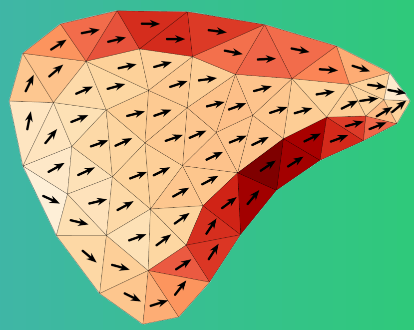

$$\mathbf{XJ}_n = \lambda_n \mathbf{RJ}_n$$

# Characteristic Modes Special Interest Group

**Newsletter, Volume 3, Number 1, March 1st, 2023**

## In This Issue:



## Scholar Spotlight:

**Miloslav Capek** (Czech Technical University in Prague), **Mats Gustafsson** (Lund University), **Lukas Jelinek** (Czech Technical University in Prague), and **Kurt Schab** (Santa Clara University) have collaborated on projects related to electromagnetic theory and antenna design since 2016. Their previous collaborative research focused on bounds and optimal design in various areas of electromagnetics, from antenna design to photonics to cloaking. During the last several years, however, their work together has expanded to cover many aspects of scattering-based characteristic mode analysis.

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## Featured Article

### Scattering-based Characteristic Modes
### *Beyond Method of Moments*

*by Miloslav Capek, Mats Gustafsson, Lukas Jelinek and Kurt Schab*

Characteristic Mode Analysis (CMA) is commonly associated with the method of moments (MoM) and, until recently, nearly all published work on CMA utilized in-house or commercial MoM-based solvers. In a recent series of papers [1–4] we, nevertheless, demonstrate that the use of MoM is not necessarily required for CMA once it is approached from a "scattering" perspective. In fact, any computational tool capable of solving bistatic electromagnetic scattering problems (ranging from finite element method (FEM) to finite difference time domain (FDTD) solvers) can be used to perform CMA. In this two-part newsletter feature, we summarize the main concepts behind the scattering-based formulation of CMA and give a step-by-step tutorial on its implementation in arbitrary full-wave solvers. The tutorial is accompanied by GitHub repositories with MATLAB codes for CMA performed using several commercial solvers like CST, FEKO, HFSS, Comsol, and AToM, showing direct and iterative solutions as well as modal tracking.

**Scattering versus impedance-based approaches**

The impedance-based decomposition of Harrington and Mautz varies slightly between specific MoM implementations, but the most recognizable form is a generalized eigenvalue problem involving the real and imaginary parts of the EFIE impedance matrix with the eigenvectors $\mathbf{I}_n$ representing modal currents and the eigenvalues $\lambda_n$ being associated with characteristic mode eigenvalues. In the scattering approach, an eigenvalue problem is formed not using an impedance operator, but rather a scattering operator which maps incident fields to scattered fields. The exact representation of the scattering operator can take several different forms, each with its own practical advantages but all leading to equivalent characteristic modes.

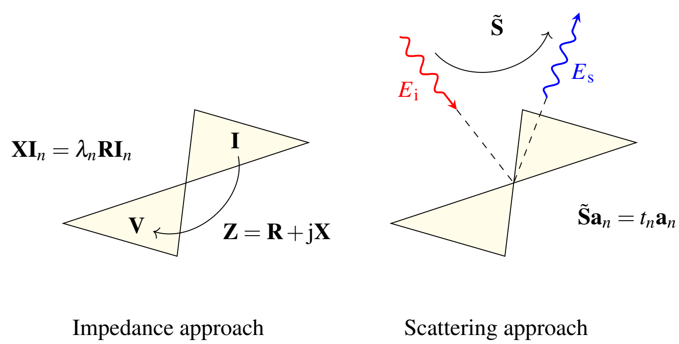



**Figure 1:** In the impedance-based approach, a method of moments operator is used to form an eigenvalue problem leading to characteristic modes. In the scattering-based approach, the matrix forming the characteristic mode eigenvalue problem is one of several choices of scattering operators mapping incident to scattered fields. If needed, it is straightforward to reconstruct modal currents from data produced by the scattering-based approach.

As shown in [1-3], all of the information associated with MoM-based CMA can be easily computed without an impedance matrix, so long as scattering responses from the object under study can be computed. The computation of either of these matrices is detailed in a subsequent tutorial in this newsletter, but it should be emphasized here that their calculation requires only the solution of the scattered fields produced by the object under test when excited by known incident fields. Hence any electromagnetic solver capable of solving a scattering problem can be used to acquire the information necessary to carry out CMA. Further, a numerical method can be selected which easily accommo-

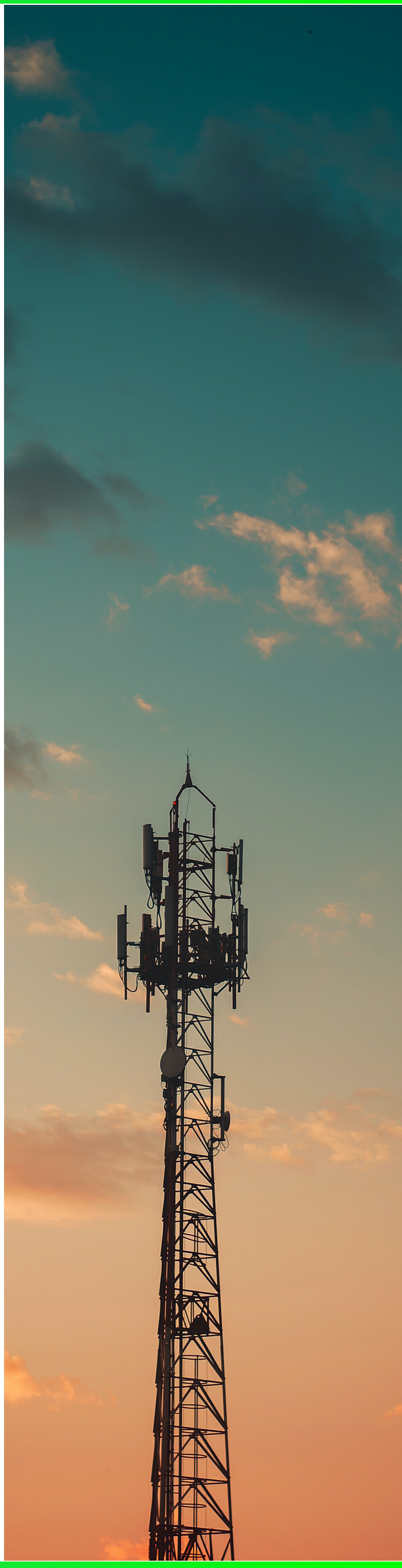
-dates highly inhomogeneous media (e.g., dielectric structures in FEM) or which naturally produces broadband scattering data (e.g., pulse excitation in FDTD) to apply CMA to an enormous range of devices that were exceptionally difficult to analyze using MoM-based tools. A decomposition of the scattering operator leads to a simple eigenvalue problem and allows for fast and precise tracking.

A tutorial outlining the steps to perform scattering-based CMA in commercial tools is planned for an upcoming edition of this newsletter. In the meantime, please refer to the following recent articles on several theoretical and practical aspects of scattering-based CMA. Each paper includes supplemental online materials with implementation examples.

1. M. Gustafsson, L. Jelinek, K. Schab, and M. Capek, "Unified Theory of Characteristic Modes - Part I: Fundamentals," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 12, pp. 11801-11813, Dec. 2022.
   General theoretical treatment of scattering-based characteristic modes using the transition matrix (spherical wave representation).
2. M. Gustafsson, L. Jelinek, K. Schab, and M. Capek, "Unified Theory of Characteristic Modes - Part II: Tracking, Losses, and FEM Evaluation," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 12, pp. 11814-11824, Dec. 2022.
   Discussion of specific technical aspects of non-MoM implementations of scattering-based CMA, including unique opportunities for simplified modal interpolation and tracking.
3. M. Capek, J. Lundgren, M. Gustafsson, K. Schab, and L. Jelinek,"Characteristic Mode Decomposition Using the Scattering Dyadic in Arbitrary Full-Wave Solvers," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 1, pp. 830-839, Jan. 2023.
   General treatment of CMA based on the scattering dyadic (plane wave representation).
4. J. Lundgren, K. Schab, M. Capek, M. Gustafsson, and L. Jelinek, "Iterative Calculation of Characteristic Modes Using Arbitrary Full-Wave Solvers," *IEEE Antennas and Wireless Propagation Letters*, (in press), 2023.
   An iterative method for accelerating scattering-based CMA in matrix-free methods, such as FEM, FDTD, and FMLMA.

# News and Events

1. The 2023 European Conference on Antennas and Propagation (EuCAP 2023) in Florence (26-31 March 2023) is coming soon! As usual, we expect that many of our members will attend the conference. Apart from CM papers in regular sessions, we have also organized the convened session "CS13 Characteristic Mode Analysis for Next Generation Systems and Technologies", with Dave Bekers (TNO, The Netherlands) and Mahrukh Khan (The College of New Jersey (TCNJ), USA) being the conveners. A big thanks to Dave and Mahrukh for their efforts. We will hold our annual meeting there on Wed 29 March 2023, at 13.45-14.45 in Polveriera, located in a separate building next to the Spadolini Pavillion where all sessions occur.
2. Three articles on CMA are among the top 10 most accessed articles in TAP (link here)
   - J. Zeng, X. Liang, L. He, F. Guan, F. H. Lin and J. Zi, "Single-Fed Triple-Mode Wideband Circularly Polarized Microstrip Antennas Using Characteristic Mode Analysis," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 2, pp. 846-855, Feb. 2022.
   - J. Chen, M. Berg, K. Rasilainen, Z. Siddiqui, M. E. Leinonen and A. Pärssinen, "Broadband Cross-Slotted Patch Antenna for 5G Millimeter-Wave Applications Based on Characteristic Mode Analysis," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 12, pp. 11277-11292, Dec. 2022.
   - J. Zeng, Z. Zhang, F. H. Lin and F. Guan, "Penta-Mode Ultrawideband Circularly Polarized Stacked Patch Antennas Using Characteristic Mode Analysis," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 10, pp. 9051-9060, Oct. 2022.
3. Prof. Chao-Fu Wang's short course proposal at IEEE AP-S 2023 has been accepted. Do not miss the opportunity to register for SC8: Theory of Characteristic Modes and Its Applications to the Analysis and Design of Antennas. Click here for details.



## New Member Introduction

**Bio: Sani Mubarak Ellis** received his B.S degree in Telecommunication Engineering at the Kwame Nkrumah University of Science and Technology (KNUST), Ghana, and his M.S degree in Microwave and Photonics Engineering at the Chalmers University of Technology, Gothenburg, Sweden in 2011. He pursued his Ph.D. degree at the University of Electronic Science and Technology, Chengdu, China in 2015. He is currently working in the Department of Telecommunication Engineering at KNUST, Ghana where he leads the Antenna Group. His research includes printed unidirectional antennas, circularly polarized antennas, wearable antennas, reconfigurable antennas, reflectarray antennas, and more.

**View on CMA:** The behavior of antennas at their core is dependent on the current behavior of the conductors. This can be studied using some current distribution diagrams. However, tatis not always sufficient. In circular polarization, for instance, it is common knowledge that some techniques rely on trial and error with little physical and analytical insight. The Characteristic Mode Theory (CMT) has introduced an analytical and physical insight into the performance of antennas by studying characteristic modes and their relation to the antenna's electrical performance. The Antenna Group in KNUST has done active work using CMT to design circularly polarized antennas and also for bandwidth enhancement purposes. Currently, we are working on using CMA to analyze reflectarray antennas and Quasi-radiator (Ellis *et al.*), a technique that converts a conventional printed monopole antenna with an omnidirectional radiation pattern to a unidirectional radiation pattern without cavity-backed structures or reflectors.

**Summary of CMA Research:** We have used CMA to design 4 circularly polarized (CP) antennas: both printed monopoles and printed slots. Unlike most work in this area, we didn't use CMA as a tool to detect whether a radiator has circular polarization ability, but we used CMA to validate the AR bandwidth instead. We have published 3 papers in this area and a few more are under review. We have also worked on CMA for bandwidth enhancement and enhanced gain. Our current work is focused on using CMA for reflectarray antennas and to further increase the peak gain on the novel Quasi-radiator antenna by Ellis *et al*.

## Recent Articles on CM Theory


- M. Kuosmanen, P. Ylä-Oijala, J. Holopainen and V. Viikari, "Orthogonality Properties of Characteristic Modes for Lossy Structures," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 7, pp. 5597-5605, July 2022.
- K. D. Paschaloudis, C. L. Zekios, S. V. Georgakopoulos and G. A. Kyriacou, "A Finite Element-Based Characteristic Mode Analysis," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 287-303, Feb. 2022.
- Q. Wu, "Characteristic Mode Formulations of Composite PEC and Lossy Dielectric Objects," *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 8, pp. 1557-1561, Aug. 2022.
- Z. Sun, W. Li and Q. H. Liu, "Characteristic Mode Analysis Based on Rayleigh Quotient Iteration," *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 4, pp. 2060-2066, April 2022.
- K. Schab, "Sparsity of Radiating Characteristic Modes on Infinite Periodic Structures," *IEEE Antennas and Wireless Propagation Letters,*, vol. 21, no. 2, pp. 312-316, Feb. 2022.


## Resources

**Open Source Tools for CMA:**

- FEKO-student edition
- CM MATLAB Software
- AToM Antenna Toolbox

**Webinars:**

- Our webinars on YouTube
- Our webinars on Bilibili
- Webinars from FEKO

**Benchmarking Activity:**

- Benchmarking in 2018

**Available Courses:**

- Courses offered by ESoA

**Past Special Issues on CMA:**

- July 2016 issue of IEEE Trans. Antennas Propag.
- April 2022 issue of IEEE Antennas Propag. Mag.

**Past Issues of CM-SIG Newsletter:**

- CM-SIG Newsletter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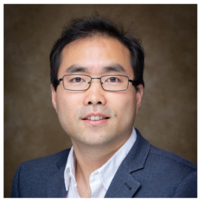

**About CM-SIG:** Characteristic Modes-Special Interest Group was initiated at the Special Session on CMs during the 2014, IEEE International Symposium on Antennas and Propagation in Memphis, TN, on 10 July 2014. CM-SIG was formed as a platform to promote technical activities in the field of CMs. For more information, please visit our website: http://www.characteristicmodes.org/.