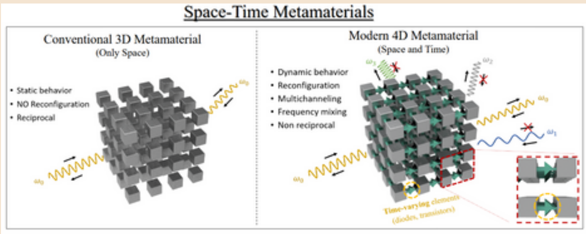
SC03- Electrodynamics of Space-Time Systems: Modern Analysis Techniques and Applications



Abstract

This short course introduces key techniques for solving problems in spacetime-varying systems, focusing on metamaterials with frequency-dispersive/non-dispersive properties. Such systems are increasingly studied for their unique electromagnetic behaviors. The course begins by reviewing concepts as metamaterials and FSSs, and how they evolve under time modulation. The significant lack of time-modulation analysis tools in commercial software leads the community to develop their own solvers based on existing numerical techniques. This course covers commonly-used methods and offers guidelines to select the most efficient one . The participants will conduct their own simulations using these techniques to gain practical experience with the topic.

Recommended prerequisites

During the Short Course, we will explore state-of-the-art techniques for the analysis of spatiotemporal systems and metamaterials. Thus, a basic knowledge of electrostatics, magnetostatics and electrodynamics (Maxwell equations, boundary conditions, wave equation, plane waves, diffraction) is recommended. A basic knowledge of calculus and vector algebra is also needed. Moreover, we will propose short programming exercises in Matlab to fully understand the nature of the covered topics. The programming tasks will be simple and guided by the instructors. However, a basic knowledge of Matlab/Python or similar programming languages is recommended, although it is not critical.

Learning objectives

1. to identify the keys of spacetime-modulated systems and their main differences with respect their space-modulated counterparts.
2. to identify the advantages associated with time modulation in metamaterials and metasurfaces in general.
3. to have have a general conception of the potential of time-modulation beyond metamaterials and metasurface domains, such as all kind of FSSs, leaky wave antennas, time-varying circuits, dispersive and non-dispersive materials, etc.
4. to address an electromagnetic problem from the basis, due to the necessity of revisit Maxwell equations when periodic and not periodic time variations are considered.
5. to be familiarized with the current challenges in time-varying systems from the simulation point of view: lack of commercial softwares, difficulty to apply the existing analysis techniques to some electromagnetic problems.
6. to be familiarized and be users of most of the current techniques (FDTD, equivalent circuits or dispersive analysis among others) and the scenarios where they can be applied efficiently.
7. to identify advantages and disadvantages of the different techniques: time consuming, physical insight, etc.
8. to know the state-of the-art of the topic, enhancing the simulation point of view, but also the challanges encountered in the design, fabrication and experimental parts.

Course outline

1. Introduction
   - Metamaterials, periodic structures, spatial modulations, space-time systems, applications (beamforming, frequency mixing, nonreciprocity, amplification, etc.), in-house methods, commercial software, experiments
2. Electrodynamics and Temporal Modulations
   - Maxwell equations and space-time boundary conditions
   - Nondispersive and dispersive materials
   - Periodic systems
   - Dispersion curves

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Course outline

3. Finite-Difference Time-Domain (FDTD) Methods Applied to Space-Time Media
- Introduction to the General FDTD Method
- Examples of application
- Programming exercise in Matlab

4. Analytical Circuit Approach
- Introduction to the method. Examples of application on spatially-modulated 1D metasurfaces
- Extension to temporally-modulated 1D metasurfaces
- Space-time-modulated (1+1)-D metasurfaces
- Programming exercise in Matlab

5. General Analytical Methods
- Introduction to common methodologies.
- Methods applied to nondispersive materials
  - Frequency pumping due to temporal transitions. Electromagnetic fields
  - Dispersion diagrams
  - Programming exercise in Matlab
- Methods applied to dispersive materials
  - Frequency pumping. Electromagnetic fields
  - Use of Laplace's transform
  - Examples and applications

Carlos Molero (Member, IEEE) was born in Seville, Spain, in April 1987. He received the Licenciado and Ph.D. Degrees in Physics from the Universidad de Sevilla, Seville, in 2011 and 2017, respectively. From March 2017 to July 2020, he held a post-doctoral position at INSA Rennes, Rennes, France. He currently holds a researcher position at the Universidad de Granada, Granada, Spain.

Dr. Molero is author and co-author of more than 90 papers including both journals and national/international conferences. He was a recipient of some prizes, including the Best Engineer Prize in the European Microwave Conference of 2015 in Paris. He has taught courses on Electromagnetics, Electronics and Advanced Signal Processing. He has supervised 2 PhD, 4 MSc, and 6 BSc students.

His research interests focus on the study of periodic structures, both in planar and 3-D architectures, for the design of polarizing devices single and multi-band. He is also expert in circuit-model development, applied for 1D, 2D 3D FSSs and metasurfaces, even modulated in time. He also worked in the design and fabrication of full-metal and fully-dielectric devices from the perspective of additive manufacturing techniques. Recently, he studies and develops time-modulated systems, from the circuit engineering point of view and also applied to spatially-modulated metasurfaces.

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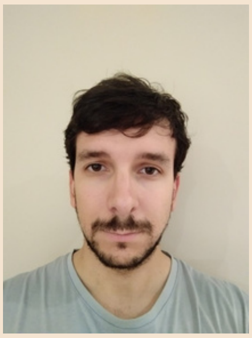
Antonio Alex-Amor received BSc Degree in Telecommunication Engineering from Universidad de Granada (Granada, Spain) in 2016, and the MSc and PhD Degrees in Telecommunication Engineering (Extraordinary PhD Award) from Universidad Politécnica de Madrid (Madrid, Spain), in 2018 and 2021, respectively. From 2021 to 2023, he was an Assistant Professor at Universidad CEU San Pablo (Madrid, Spain). In 2024, he has been a Researcher at University of Pennsylvania (Philadelphia, USA) under the supervision of Prof. Nader Engheta. Currently, he is an Assistant Professor at Universidad Autónoma de Madrid.



Dr. Alex-Amor has coauthored more than 65 papers in journals and international/national conferences. He holds a patent on reconfigurable 3D metadevices. He was recipient of some awards, including the Best Electromagnetics Paper Award at EuCAP 2020. He has taught courses on Electromagnetics, Fields & Waves, Advanced Signal Theory and Electronics. He has supervised 1 PhD, 4 MSc, and 6 BSc students. Early in his career, he started working on broadband antenna design and EMC system characterization. During his PhD, he developed numerical and analytical techniques (mode matching, FDTD, integral equations, circuit models) for the study of glide-symmetric metastructures and reconfigurable materials such as liquid crystal or graphene. Almost three years ago, he became interested in the physics and applications of space-time-modulated metastructures. He has made contributions in this innovative area, such as the development of analytical techniques and analysis of metallic space-time metasurfaces with application as beamformers and frequency converters.

Bibliography

1. *F. R. Morgenthaler, "Velocity modulation of electromagnetic waves," IRE Transactions on Microwave Theory and Techniques, vol. 6, no. 2, pp. 167–172, 1958.*
2. *L. Felsen and G. Whitman, "Wave propagation in time-varying media," IEEE Transactions on Antennas and Propagation, vol. 18, no. 2, pp. 242–253, 1970.*
3. *R. Fante, "Transmission of electromagnetic waves into time-varying media," IEEE Transactions on Antennas and Propagation, vol. 19, no. 3, pp. 417–424, 1971.*
4. *C. Caloz and Z.-L. Deck-Leger, "Spacetime metamaterials—part I: general concepts," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 1569–1582, 2019.*
5. *C. Caloz and Z.-L. Deck-Leger, "Spacetime metamaterials—part II: Theory and Applications" IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 1569–1582, 2019.*
6. *E. Galiffi et al. "Photonics of time-varying media," Advanced Photonics, vol. 4, no. 1, pp. 014002–014002, 2022.*
7. *Victor Pacheco-Peña, Diego M. Solís, and Nader Engheta, "Time-varying electromagnetic media: opinion," Opt. Mater. Express 12, 3829-3836 (2022).*
8. *S. Taravati and G. V. Eleftheriades, "Generalized spacetime-periodic diffraction gratings: Theory and applications," Physical Review Applied, vol. 12, no. 2, p. 024026, 2019.*
9. *P. A. Huidobro, M. G. Silveirinha, E. Galiffi, and J. Pendry, "Homogenization theory of space-time metamaterials," Physical Review Applied, vol. 16, no. 1, p. 014044, 2021.*
10. *D. M. Solıs, R. Kastner, and N. Engheta, "Time-varying materials in the presence of dispersion: plane-wave propagation in a Lorentzian medium with temporal discontinuity," Photon. Res., vol. 9, pp. 1842–1853, Sep 2021.*
11. *M. S. Mirmoosa, T. T. Koutserimpas, G. A. Ptitcyn, S. A. Tretyakov, and R. Fleury, "Dipole polarizability of time-varying particles," New Journal of Physics, vol. 24, no. 6, p. 063004, 2022.*
12. *Z. Wu, C. Scarborough, and A. Grbic, Space-Time Modulated Metasurfaces with Spatial Discretization: FreeSpace N-Path Systems, Phys. Rev. Appl. 14, 064060, 2020.*
13. *S. Moreno-Rodrıguez, A. Alex-Amor, P. Padilla, J. F. Valenzuela-Vald´es, and C. Molero, "Space-time metallic metasurfaces for frequency conversion and beamforming," Phys. Rev. Appl., vol. 21, p. 064018, 2024.*
14. *J. R. Zurita-Sanchez, P. Halevi, and J. C. Cervantes-Gonzalez, "Reflection and transmission of a wave incident on a slab with a time-periodic dielectric function ε(t)," Phys. Rev. A, vol. 79, no. 5, p. 053821, 2009.*
15. *J. S. Martínez-Romero, O. M. Becerra-Fuentes, and P. Halevi, "Remporal photonic crystals with modulations of both permittivity and permeability," Phys. Rev. A, vol. 93, 063813, 2016.*

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