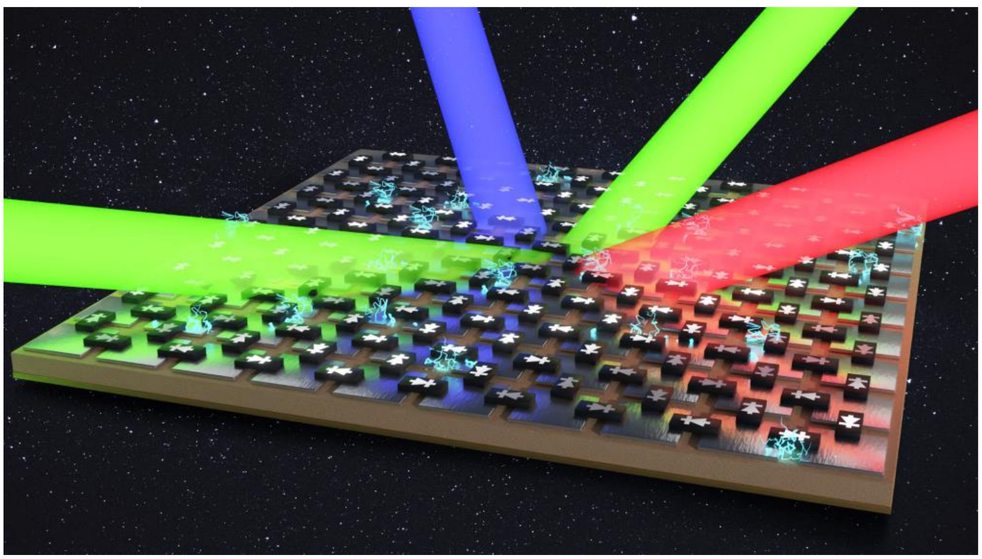
Time and Space-Time Varying Electromagnetic Structures and Circuits

Abstract

The short course will introduce participants to the emerging topic of time modulated and space-time modulated electromagnetic structures. It will provide a brief history of time and space-time modulation in the antennas and propagation community, and identify traditional as well as emerging application areas of this research topic. The tutorial-style course will cover concepts fundamental to understanding these systems. Periodic boundary conditions that govern structures that are periodic in both space and time will be reviewed and applied to the analysis of various structures including metasurfaces, antennas and circuit networks. Analogies will be drawn with systems that are spatially modulated, but invariant in time, in order to gain understanding. Guidelines on how to analyse practical travelling-wave modulated structures in the frequency-domain using commercial simulators will be provided. Representative examples of space-time modulated electromagnetic structures will be examined to demonstrate their capabilities beyond time-invariant systems (including amplification, space-time beam shaping, and nonreciprocity).

Graphical abstract



Recommended prerequisites

The course requires a basic knowledge of:

- Transmission-line analysis
- Plane-wave analysis
- Microwave network theory (S-parameters, Z parameters)
- Antenna theory

Learning objectives

After the course, the participant will be able to:

• Identify early works on space-time modulation in the antennas and microwave community.
• Understand concepts fundamental to the study of electromagnetic structures that are periodically modulated in time, and those that are modulated in both space and time.
• Relate the analysis and behaviour of periodic space-time modulated structures to familiar spatially-periodic structures such as antenna arrays.
• Identify application areas of time modulated and space-time modulated electromagnetic structures.
• Synthesise electromagnetic structures which achieve frequency-conversion, non-reciprocal propagation, and amplification.
• Recognize the simplifications that result when analysing a special class of space-time modulated structures known as travelling-wave modulated structures.
• Understand the space-time periodic condition for travelling-wave modulated structures that are discretized in space, known as the interpath relation.
• Apply the interpath relation to perform dispersion analyses of travelling-wave modulated structures.
• Set up simulations of travelling wave modulated electromagnetic structures, such as circuit networks, metasurfaces and antennas, using commercial solvers.

Course outline

The short course will be of the tutorial type. It will be taught jointly by Prof. Anthony Grbic (U. Michigan, USA) and Prof. Cody Scarborough (CU Boulder, USA). The short course will consist of a number of subsections that will be taught alternately by Prof. Grbic and Prof. Scarborough. Each subsection will be following by a question and answer period. The subsections of the course are listed below:

● Going Beyond the linear time invariant assumption. What is time and space-time modulation?
● A brief history of time and space-time modulated structures in the antennas and propagation and microwave communities.
● Methods of modulation, and application areas of time and space time modulated structures.
● Basic concepts fundamental to the understanding time and space time electromagnetic structures: the linear periodically time varying (LPTV) assumption, the Floquet theorem, time and space-time harmonics, analogies to time-invariant spatially-periodic structures,
● Travelling-wave modulated structures: continuous vs. spatially discretized structures

● The Interpath Relation: the periodic boundary condition for spatially discretized travelling wave modulated structures
● Dispersion Analysis: deriving dispersion equations, the definition of modes, plotting dispersion diagrams
● Examples: metasurfaces and circuit networks.
● Simulating travelling-wave modulated electromagnetic structures using commercial solvers: combining full-wave simulation and harmonic balance simulation.
● Open forum: a discussion with the attendees on future prospects, emerging applications.

Instructor 1 – biography

Cody Scarborough received a B.A.Sc. degree in electrical engineering from the University of Texas at Austin in 2017, and a Ph.D. degree from the University of Michigan in 2022. He is a professor of Electrical, Computer and Energy Engineering at the University of Colorado, Boulder, Colorado, USA. His research interests include electromagnetic metamaterials, non-linear microwave and optical systems, radio-frequency circuits, and antenna theory. His research accomplishments include the introduction of a novel space-time periodic boundary condition that dramatically reduces the computational resources needed to analyse/optimise space-time periodic structures, as well as early demonstrations of space-time modulated antennas and metastructures. These contributions have been recognized with a variety of honours and awards at conferences such as EuCAP, Metamaterials, the Waves in Time-Varying Media Workshop Series, and the International Symposium on Antennas and Propagation. In 2021, he received best student paper awards at both the EuCAP and Metamaterials conferences.

Instructor 2 – biography

Anthony Grbic received the B.A.Sc., M.A.Sc., and Ph.D. degrees in electrical engineering from the University of Toronto, Canada, in 1998, 2000, and 2005, respectively. He is a professor with the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor, Michigan, USA. His research interests include electromagnetic theory, engineered electromagnetic structures, antennas, and microwave circuits. Anthony Grbic is a Fellow of IEEE. He has made fundamental contributions to the theory and development of electromagnetic metamaterials and metasurfaces: finely textured, engineered electromagnetic structures/surfaces that offer unprecedented wavefront control. Dr. Grbic is a Fellow of the IEEE. He is currently an IEEE Microwave Theory and Techniques Society Distinguished Microwave Lecturer (2022-2025). He is serving on the IEEE Antennas and Propagation Society (AP-S) Field Awards Committee and IEEE Fellow Selection Committee. He is a member of the Scientific Advisory Board of the International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials.

Key bibliography

Papers by the Instructors:

1. C. Scarborough and A. Grbic, "Efficient Computation of Spatially-Discrete Traveling-Wave Modulated Structures," IEEE Transactions on Microwave Theory and Techniques, accepted for publication Sept. 2022.
2. C. Scarborough, Z. Wu, and A. Grbic, "Efficient Computation of Spatially-Discrete Traveling-Wave Modulated Structures," IEEE Transactions on Antennas and Propagation, vol. 69, no. 12, pp. 8512-8525, Dec. 2021.
3. Z. Wu, C. Scarborough, and A. Grbic, "Space-Time-Modulated Metasurfaces with Spatial Discretization: Free-Space N-Path Systems," Physical Review Applied, vol. 14, no. 6, pp. 64060-64079, Dec. 2020.
4. C. Scarborough and A. Grbic, "Accelerated N-Path Network Analysis Using the Floquet Scattering Matrix Method," IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 4, pp. 1248-1259, Apr.2020.
5. Z. Wu and A. Grbic, "Serrodyne Frequency Translation using Time-Modulated Metasurfaces," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp.1599-1606. Oct. 2019.

Early Papers:

1. A. Cullen, "A travelling-wave parametric amplifier," Nature, vol. 181, no. 4605, pp. 332– 332, Feb. 1958.
2. H. Zucker, "Traveling-wave parametric amplifier analysis using difference equations," Proceedings ofthe IRE, vol. 49, no. 3, pp. 591–598, Mar. 1961.
3. P. Tien and H. Suhl, "A traveling-wave ferromagnetic amplifier," Proceedings of the IRE, vol. 46, no. 4, pp.700–706, Apr. 1958.
4. E. S. Cassedy and A. A. Oliner, "Dispersion relations in time-space periodic media: Part I stable interactions," Proceedings ofthe IEEE, vol. 51, no. 10, pp. 1342–1359, Oct. 1963.
5. E.S. Cassedy, "Waves guided by a boundary with time—space periodic modulation." In Proceedings of the IEE, vol. 112, no. 2, pp. 269-279, Feb. 1965.
6. J.-C. Simon, "Action of a progressive disturbance on a guided electromagnetic wave," IRE Transactions on Microwave Theory and Techniques, vol. 8, no. 1, pp. 18–29, Jan. 1960.
7. W. Mumford, "Some notes on the history of parametric transducers," Proceedings of the IRE, vol. 48, no. 5,pp. 848–853, May 1960.
8. J. Armstrong, N. Bloembergen, J. Ducuing, and P. S. Pershan, "Interactions between light waves in a nonlinear dielectric," Physical review, vol. 127, no. 6, p. 1918, Sep. 1962.

Recent Papers:

1. N. Reiskarimian and H. Krishnaswamy, "Magnetic-free non-reciprocity based on staggered commutation,"Nature Communications, vol. 7, no. 11217, Apr. 2016.
2. A. Nagulu, T. Dinc, Z. Xiao, M. Tymchenko, D. Sounas, A. Al´u, and H. Krishnaswamy, "Nonreciprocalcomponents based on switched transmission lines," IEEE Transactions on Microwave Theory and Techniques, no. 11, pp. 4706–4725, Aug. 2018.
3. S. Taravati and C. Caloz, "Mixer-duplexer-antenna leaky-wave system based on periodic space-time modulation," IEEE Transactions on Antennas and Propagation, vol. 65, no. 2, pp. 442–452, Nov. 2016.

4. S. Taravati and G. V. Eleftheriades, “Generalized space-time-periodic diffraction gratings: Theory and applications,” Physical Review Applied, vol. 12, p. 024026, Aug. 2019.
5. C. Caloz and Z.-L. Deck-L´eger, “Spacetime metamaterials—part I: general concepts,” IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 1569–1582, Oct. 2019.
6. P. A. Huidobro, E. Galiffi, S. Guenneau, R. V. Craster, and J. Pendry, “Fresnel drag in space–timemodulated metamaterials,” Proceedings of the National Academy of Sciences, vol. 116, no. 50, pp. 24 943–24 948, Dec. 2019.