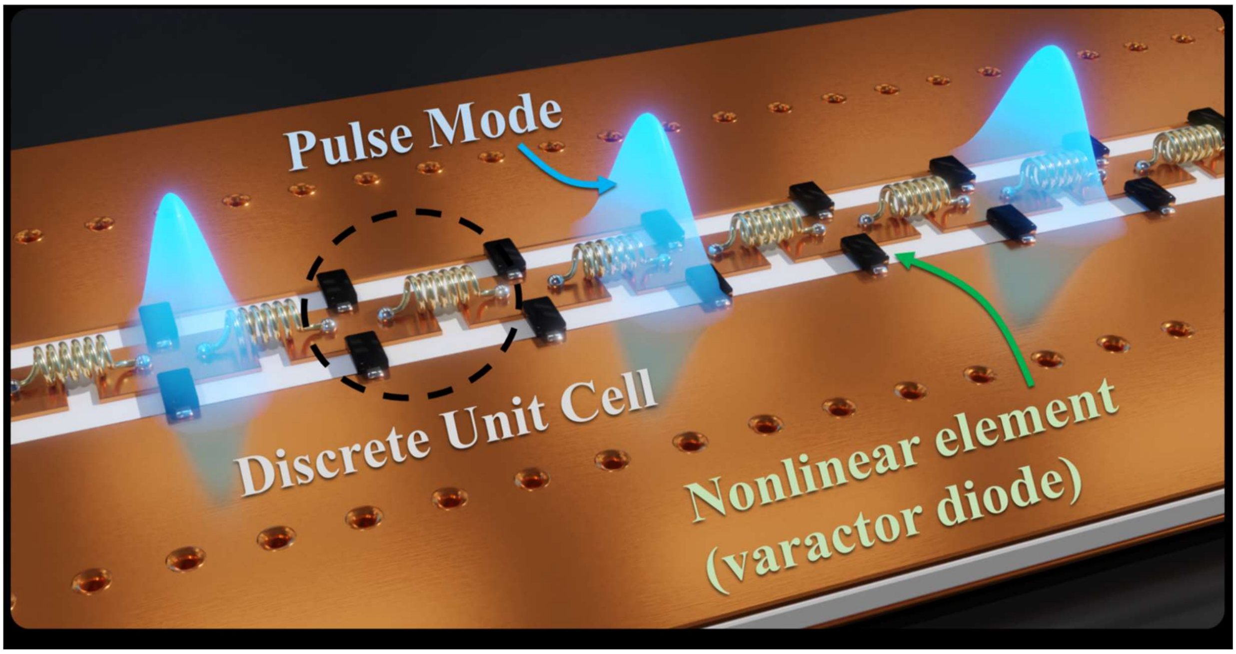
The 18th European Conference on Antennas and Propagation (EuCAP)
17 - 22 March 2024

Modeling and Design of Space-Time Modulated Electromagnetic Structures

Abstract:

Space-time modulation (STM) has recently emerged as an avenue to achieve practical electromagnetic functions such as isolation, circulation, frequency-mixing, and amplification. In this short course, participants will learn modelling techniques and design considerations for STM devices including modulated metasurfaces, nonlinear transmission lines, and space-time periodic electrical networks. The course will provide a background on the fundamental capabilities and behaviour of STM. Modern research advances will also be presented including recent demonstrations, theoretical developments, and novel applications. Guidelines on the analysis of STM structures will be presented in terms of more familiar time-invariant techniques, e.g., modified periodic boundary conditions, integration with full-wave commercial simulators, frequency-dependent array factor calculations, and linearized descriptions of nonlinear devices. Participants will learn to apply these techniques to representative examples of STM structures designed for non-reciprocal propagation, amplification, and pulse/frequency-comb generation.

Graphical abstract:



Recommended prerequisites for attendees:

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.
- Recognize the principal capabilities of time and space-time modulated electromagnetic structures
- Identify modulation techniques for electromagnetic structures, such as semiconductor devices, phase-change materials, and electromechanical modulation.
- Obtain linearized models for nonlinear electrical components which are compatible with standard analysis techniques.
- Relate the analysis and behaviour of periodic space-time modulated structures to familiar spatially-periodic structures such as antenna arrays.
- Identify emerging applications of time and space-time modulated electromagnetic structures.
- Understand the appropriate boundary conditions for modelling STM devices, e.g., the interpath relation for staggered modulation of electromagnetic structures
- Set up simulations of space-time modulated electromagnetic structures, such as circuit networks, metasurfaces and antennas, using commercial solvers.
- Synthesise electromagnetic structures which achieve frequency-conversion, non-reciprocal propagation, andamplification, and pulse generation.

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:

- Nonlinearities in electromagnetics. How is space-time modulation realised and where is it applied?

- A brief history of time and space-time modulated structures in the antennas and propagation and microwave communities.
- Fundamental properties and models of space-time modulated structure: The Floquet theorem in space-time, time and space-time harmonics, analogies to time-invariant spatially-periodic structures.
- Analysis techniques for space-time modulation: Spectral-domain methods, spatial-domain methods, coupled mode theory, time-domain techniques.
- The Interpath Relation: the periodic boundary condition for spatially discretized travelling wave modulated structures
- Synthesis methods for STM devices. Tailored modulation for amplification, frequency-mixing, non-reciprocal propagation, and pulse generation.
- Dispersion Analysis: deriving dispersion equations, the definition of modes, plotting dispersion diagrams
- Examples: metasurfaces and nonlinear modulated electrical 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.

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.

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. J. Johnson and C. Scarborough, “An Iterative Technique for Computing Soliton Solutions to Periodic Nonlinear Electrical Networks,” Optical Materials Express, submitted Nov. 15, 2023.
2. S. Young, Z. Fritts, and A. Grbic, “Increasing the Efficiency-Bandwidth Product of Electrically-Small Antennas by Time-Dependent Parametric Coupling of Characteristic Modes,” IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Portland, OR, USA, Jul. 2023.
3. Z. Fritts, S. M. Young, C. Scarborough and A. Grbic, "Increasing the Efficiency-Bandwidth of Small Antennas by Coupling Radiative and Non-Radiative Modes Using Time-Variation," 2023 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), pp. 77-78, Boulder, CO, USA, 2023.
4. Z. Fritts and A. Grbic, “Circuit models for electrically-small time-varying spherical scatterers,” in 2022 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), pp. 57–58, Jan. 2022.
5. C. Scarborough and A. Grbic, “Efficient Computation of Spatially-Discrete Traveling-Wave Modulated Structures,” IEEE Transactions on Microwave Theory and Techniques, .
6. 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.
7. 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.
8. 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.
9. 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. Alu, and H. Krishnaswamy, “Nonreciprocal components 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–time-modulated metamaterials,” Proceedings of the National Academy of Sciences, vol. 116, no. 50, pp. 24 943–24 948, Dec. 2019.