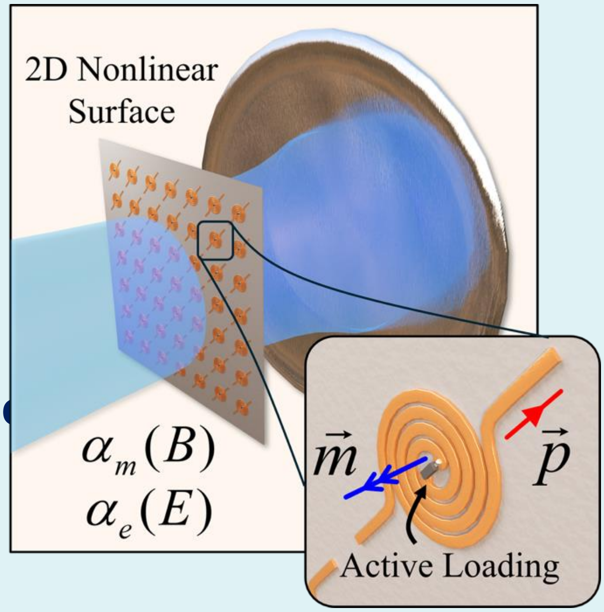
SC12 - Nonlinear Periodic Circuits and Surfaces



Abstract:

Advances in electromagnetic analysis and the performance of active elements has led to a surge of interest in electromagnetic surfaces with integrated nonlinearities. These surfaces can achieve practical functions such as filtering, power generation, power measurements, frequency mixing, frequency multiplication, amplification, and non-reciprocal behavior. This tutorial will review analysis methods for nonlinear surfaces dating back to the 1960s. These methods will be studied in the context of practical surfaces demonstrated by the presenters and others within the antennas community for beamforming, phase-shifting, solid-state microwave power generation, and mixing. Trade-offs associated with the choice of active device technology will also be addressed.

Recommended pre-requisites:

Microwave network theory, Antenna theory, Transmission line analysis
Antenna array theory

Learning Objectives:

Participants in the course will learn essential analysis, simulation, and experimental techniques to design, predict, and evaluate the performance of nonlinear circuits and electromagnetic surfaces.

Analysis: Participants will learn the fundamentals of active devices typically incorporated within EM surfaces. These include varactor diodes and transistors such as MESFETs, HEMTs, and HBTs operating as varactors, switches or amplifying elements. Participants will formulate classical microwave conditions (e.g. for stability, efficiency, and noise figure) in the context of electromagnetic surfaces. Techniques for treating nonlinear surfaces as effective sheets and surface polarizabilities will also be reviewed. These methods will provide participants with the insight needed to formulate an initial design.

Simulation: Participants will learn to incorporate fully-modeled nonlinear elements into full-wave simulations in a manner which is efficient and readily optimized. This will include a review of frequency-dependent boundary conditions for modulated electromagnetic surfaces as well as co-simulation techniques using well-established commercial solvers like Microwave Office, Ansys HFSS, Keysight ADS, COMSOL, and Feko.

Measurement: A guide will be provided for the techniques needed to characterize nonlinear surfaces and their constitutive components from on-chip characterization to waveguide measurements to free-space testing. Participants will learn which laboratory equipment is needed to perform such a comprehensive study.

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Course Outline:

The short course will include three parts. The third section is designed to be interactive with discussion questions and technical prompts used to reinforce participant comprehension.

Section I: Historical Overview and Capabilities - The literature overview will walk participants through useful references from key historical contributors in the design of nonlinear surfaces. The presenters will draw from a diverse range of scientists within optics, circuits, microwave engineering, and metamaterials to provide a complete picture. These references can be found in the Key Bibliography section below and include authors like Robert Boyd, Author Oliner, David Rutledge, and John Pierce.

Section II: Analysis, Simulation, and Measurement - The technical overview will address conditions which are often overlooked within the antennas community but nonetheless play a critical role in the design of nonlinear electromagnetic devices. These include the Kurokawa condition for stable oscillation, phase noise metrics and analysis, the EMF method, etc. Homogenization techniques well known within the antennas community will be extended to nonlinear structures to capture the interaction between these surfaces and EM waves. Finally, efficient simulation techniques will also be given which fully capture nonlinear behavior. These methods will be presented in the context of recent works which have advanced the state-of-the-art.

Section III: Case Studies - The final interactive section of the course will consist of detailed case studies authored by Prof. Scarborough and Prof. Popovic, respectively. These examples include the design of a metasurface for simultaneous frequency-mixing and beamforming and a nonlinear surface known as a grid oscillator for distributed power generation. The conclusion of the course will be a panel-style discussion on the future directions of research and prospectives within the field of spatially-distributed nonlinear surfaces.

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Instructors:

Cody Scarborough received his B.S. in electrical engineering from the University of Texas at Austin, Austin, TX, USA in 2017. He received his Ph.D. degree from the University of Michigan, Ann Arbor, MI, USA in 2022. His dissertation is entitled “Spatially-Discrete Traveling-Wave Modulated Electromagnetic Structures.” In August 2022, he joined the Department of Electrical, Computer and Energy Engineering, University of Colorado Boulder, Boulder, CO, USA, where he is currently an Assistant Professor. Professor Scarborough has made key research contributions in the analysis of space-time modulated electromagnetic structures. In 2021, Professor Scarborough’s work on space-time modulated structures has been recognized with best student paper awards at both the 15th International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials) and the 15th European Conference on Antennas and Propagation (EuCAP 2021). As of 2025, Prof. Scarborough is a named recipient of the FY25 AFOSR Young Investigator Program. His current research interests include non-linear electromagnetics, periodic structures, reconfigurable intelligent surfaces, and conformal metamaterials.

Zoya Popovic is a Distinguished Professor and the Lockheed Martin Endowed Chair in Electrical Engineering at the University of Colorado, Boulder. She obtained her Dipl. Ing. degree at the University of Belgrade, Serbia, and her Ph.D. at Caltech. She was a Visiting Professor at the Technical University of Munich, ISAE in Toulouse, France and a Chair of Excellence at Carlos III University in Madrid. She has graduated over 70 PhDs and currently advises 18 doctoral students. Her research interests are in microwave and millimeter-wave high-performance circuits for communications and radar, medical applications of microwaves, quantum sensing and metrology, and wireless powering. She is a Fellow of the IEEE, IEEE MTT Distinguished Educator and the recipient of two IEEE MTT Microwave Prizes for best journal papers. She was named the White House NSF Presidential Faculty Fellow and was the first woman to receive the URSI Issac Koga Gold Medal. She is a Fellow of the National Academy of Inventors and a Member of the National Academy of Engineering.

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Key Bibliography

Historical Background and Overview

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From the Authors

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