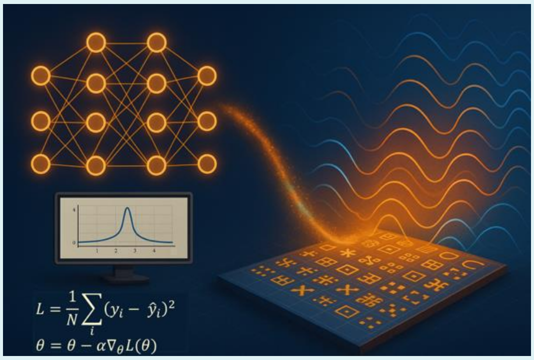
SC05 - Machine Learning-Augmented Metasurface Design: From Theory to Practical Implementation

Abstract:



This advanced short course introduces cutting-edge machine learning techniques for metasurface design, bridging traditional electromagnetic theory with modern AI-driven methodologies. Participants will gain hands-on experience implementing generative adversarial networks (GANs), inverse design optimization, and multi-objective design workflows. Through live demonstrations and practical tools, attendees will learn to accelerate complex metasurface designs for applications in satellite communications, 5G/6G systems, and advanced radar. The course combines theoretical foundations with immediately applicable implementation strategies, enabling participants to deploy ML-augmented workflows in their own research and development projects.

Recommended pre-requisites:

Attendees should have a solid foundation in electromagnetics, including understanding of metasurface basics, electromagnetic wave interactions, and fundamental antenna/reflectarray principles. Familiarity with optimization concepts and basic programming experience (Python) is beneficial but not mandatory. Prior exposure to machine learning fundamentals (supervised/unsupervised learning concepts) is helpful; however, the course includes foundational ML concepts tailored to electromagnetic applications for those new to the field.

Learning Objectives:

1. Understand the theoretical foundations of machine learning applied to electromagnetic design and recognize when ML approaches offer advantages over traditional optimization methods
2. Implement and adapt generative adversarial networks (GANs) for automated metasurface synthesis across multiple frequency bands and polarizations
3. Design and execute combined ML/optimization workflows for inverse design of complex structures, including bianisotropic and nonuniform metasurfaces
4. Apply multi-objective optimization techniques using machine learning to handle competing design specifications in real-world applications
5. Select appropriate ML architectures, perform hyperparameter optimization, and validate ML-generated designs through electromagnetic simulation
6. Utilize practical software tools and frameworks for end-to-end ML-augmented design workflows
7. Generate and preprocess training datasets from electromagnetic simulations for model development
8. Deploy ML-augmented design techniques to real-world problems in satellite communications, beam steering surfaces, and frequency selective applications
9. Transition from theoretical concepts to immediate implementation using provided code, templates, and pre-trained models

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Course Outline:

SESSION 1: FOUNDATIONS & MOTIVATION (45 minutes)

• Traditional metasurface design challenges: computational burden, design space complexity, limited exploration

• Introduction to machine learning paradigms for electromagnetic applications: supervised, unsupervised, and generative approaches

• Why GANs and generative models transform metasurface design: enabling novel geometries difficult to discover conventionally

• Real-world case studies from satellite communication applications demonstrating practical impact

• Overview of the course architecture and hands-on elements

SESSION 2: ML-AUGMENTED DESIGN METHODOLOGIES (75 minutes)

• Variational autoencoders (VAE) and Generative Adversarial Networks (GANs) for automated metasurface synthesis: architecture, training strategies, and convergence techniques

• Data generation pipelines: electromagnetic simulation-to-ML workflow for creating training datasets

• Combined ML/optimization approaches: hybrid strategies for inverse design that leverage ML predictions with rigorous optimization

• Multi-objective optimization using machine learning: Pareto frontier exploration and trade-off analysis

• Handling complex geometries: bianisotropic structures, nonuniform surfaces, and practical fabrication constraints

• Model validation and uncertainty quantification

SESSION 3: PRACTICAL IMPLEMENTATION & TOOLS (50 minutes)

• Software frameworks and open-source tools for ML-augmented design (TensorFlow/PyTorch, CST/HFSS integration)

• End-to-end workflow: from problem definition through data generation, model training, and design validation

• Hyperparameter optimization and model selection strategies

• Hands-on exercise: participants implement a simplified GAN-based design workflow

• Validation methodologies: comparing ML-generated designs against full-wave simulations

• Deployment considerations for production environments

SESSION 4: LIVE DEMONSTRATION & ADVANCED APPLICATIONS (30 minutes)

• Real-time metasurface design synthesis using ML techniques with live code execution

• Multi-band polarizing converter design: from specification through ML generation to electromagnetic validation

• Q&A and discussion of participant-specific applications

• Access to online tools and pre-trained models; next steps for participants

Participants should bring a laptop with internet access. Participants interested in running local simulations should have Python 3.8+ installed. Course materials, code examples, design templates, and pre-trained models will be provided to all attendees for post-course work. Live demonstrations will be projected for full visibility; direct hands-on coding is optional but encouraged for those with laptops present.

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Instructor:

Dr. Parinaz Naseri is an Assistant Professor, Teaching Stream, in the Department of Electrical & Computer Engineering at the University of Toronto. She received her Ph.D. from the University of Toronto's Reconfigurable Antenna Laboratory and her M.Sc. from the Universityof Alberta. She previously held a research fellowship at Instituto de Telecomunicações, Portugal,working on European Space Agency-funded projects on metasurface-based satellite communication.
Her research and professional expertise span metasurfaces, reflectarrays, radar, ultra-wideband antennas, and the application of machine learning in electromagnetic design. She has authored more than 30 peer-reviewed publications. She was recognized with the 2023 Governor General's Gold Medal nomination from ECE, University of Toronto, and is a recipient of the 2022 IEEE AP-S Mojgan Daneshmand Award and 2020 IEEE AP-S Doctoral Research Grant, among other honors.

Dr. Naseri has developed approaches combining machine learning with electromagnetic design, including generative models for multi-band polarizing metasurfaces and optimization workflows for inverse design of bianisotropic structures. Her unique profile—bridging theoretical EM, industry practice, and education—positions her to deliver a forward-looking short course that equips the AP-S community with both conceptual foundations and practical tools for machine learning-augmented metasurface design.

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Key Bibliography

1. Naseri, P., et al. "A Generative Machine Learning-Based Approach for Inverse Design of Multilayer Metasurfaces." IEEE Transactions on Antennas and Propagation, 2023.

2. Naseri, P., et al. "A Combined Machine-Learning/Optimization-Based Approach for Inverse Design of Nonuniform Bianisotropic Metasurfaces." IEEE Journal on Multiscale and Multiphysics Computational Techniques, 2023.

3. Naseri, P., et al. "Synthesis of Multi-Band Reflective Polarizing Metasurfaces Using a Generative Adversarial Network." IEEE Transactions on Antennas and Propagation, 2022.

4. Naseri, P. et al. "Dual-Band Dual-Linear-to-Circular Polarization Converter in Transmission Mode Application to-Band Satellite Communications" IEEE Transactions on Antennas and Propagation, 2018.

Note: Full publication list available at: https://scholar.google.pt/citations?user=OXJuiUgAAAAJ&hl=en