

Deep Learning Techniques for Lossless and Passive Metasurface Design—A Review

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Metasurfaces are powerful tools for manipulating electromagnetic (EM) waves. Their design typically involves macroscopic and microscopic stages, which can be achieved using different techniques including gradient based optimization, lookup tables, or deep learning (DL) approaches. An important advantage of DL techniques is their rapid prediction performance, which is important for dynamic beam shaping scenarios. Herein, we review our recent progress in developing DL techniques for the design of lossless and passive transmissive metasurfaces. For the macroscopic design stage, our DL technique determines an appropriate aperture field that (i) fulfills the desired far-field (FF) specifications such as FF lower and upper masks, and (ii) meets the local power conservation (LPC) constraint with respect to a known incident field (Epstein and Eleftheriades, IEEE Trans. Antennas Propag., vol. 64, 2016). Since building a labeled dataset is challenging when considering these two requirements, unsupervised learning is a natural choice. This requires integrating a forward solver into the DL framework, which computes the aperture field and FF. This then allows us to assess the satisfaction of LPC and FF requirements. (The aperture field can support auxiliary surface waves to redistribute power, thereby satisfying the LPC constraint.) Since the forward solver is part of the DL framework, it needs to be differentiable, allowing its derivatives to be computed either manually or using frameworks such as PyTorch as is the case in our implementation. (If differentiability is not achievable, alternative DL methods like reinforcement learning can be used.) Another aspect of the macroscopic design stage is to ensure that the aperture field remains Maxwellian and that the field variation between adjacent unit cells is sufficiently smooth to be consistent with the local periodicity assumption typically used in the microscopic design stage. To this end, our approach trains the neural network to generate the so-called synthetic source arrays, which serves as an auxiliary step to compute the required aperture field before being discarded. This method offers two key advantages: (1) the aperture field is inherently Maxwellian and (2) its smoothness can be controlled to some extent. We have noticed that our neural network may get stuck in LPC local minima, thus, degrading FF performance. To resolve this, we have implemented a dynamic weighting strategy, which starts with a low LPC weight and gradually increases it to a baseline value.

Once the DL macroscopic design stage is completed, we have access to an appropriate aperture field that meets the FF requirements (e.g., lower and upper masks) and the LPC constraint. This aperture field and the known incident field are then converted to required scattering parameters per unit cell, which are subsequently passed to the microscopic design stage for the metallic trace design. We implemented our DL microscopic design stage using a diffusion-based neural network inspired by conditional image generation. As a supervised generative approach, creating a large and diverse dataset is crucial but computationally expensive due to its reliance on a full-wave solver. To address this issue, we trained another neural network to generate synthetic data, which we then mixed with the dataset generated using a full-wave solver.

Using this combined macroscopic and microscopic approach, we designed, fabricated, and experimentally verified a transmissive metasurface for FF masks under the two-dimensional (2D) propagation assumption where the metasurface has spatial modulation along either its rows or columns. We have recently extended our framework to 3D beam shaping where the metasurface requires spatial modulation along both its rows and columns. However, the increased computational load with full-wave solvers for 3D beam shaping presents challenges. To address this issue, we have simulated our design using a recently developed zero-thickness integral equation (IE) solver that incorporates the generalized sheet transition conditions (GSTCs), known as the IE-GSTC solver, which shows promising preliminary results. Our presentation at the conference will first review our previous work on an end-to-end DL based design framework for 2D beam shaping and will then focus on our recent progress toward extending our framework to 3D.