Physics-aware neural surrogates for high-fidelity ultra-fast simulation of nanophotonic sensors

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Date:

Abstract

Nanophotonic sensors rely on spatially localized electromagnetic fields for signal transduction, but full-wave simulation of these fields is computationally expensive for large-scale design exploration. Existing machine-learning methods for metasurfaces mainly predict scalar optical responses, leaving spatial field prediction for fabrication-aware nanophotonic sensors largely unexplored. Here we introduce MetaField, a physics-aware neural surrogate that directly learns geometry-to-field mappings from periodic MetaSPR structures. The framework combines a fabrication-aware simulation database, physics-aware tensor representations and a boundary-consistent neural architecture to predict dominant full-wave field distributions under TM-like illumination across variable sizes and dispersive materials. Over the visible spectrum, MetaField reproduces full-wave fields with high spatial consistency while achieving orders-of-magnitude faster inference than conventional FDTD on diverse hardware. Integrated with a surrogate-assisted genetic algorithm, MetaField enables inverse design evaluating >106 candidates in hours instead of years of brute-force optimization. Experimental validation with nanopillar MetaSPR structures shows that MetaField-predicted near-field enhancement trends match measured SERS responses. Thus, MetaField provides a field-resolved neural surrogate for ultra-fast nanophotonic sensor simulation, inverse design and field-guided analysis.

Note: Figure translations are in progress. See original paper for figures.