

Physics-Informed Machine Learning for Causal Sensitivity and Bifurcation Discovery in Bragg-Grating Modulation Instability

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Abstract

We develop a physics-informed machine-learning framework to study causal sensitivity and bifurcation behavior in a vector Bragg-grating model. The modulation instability problem is analyzed using an eigenvalue-based spectral formulation, allowing us to compute gain curves, dominant instability wavenumbers, and bandwidths across a wide parameter range. These predictions are validated through direct pseudo-spectral simulations of the corresponding coupled Bragg-grating system. Based on the generated parameter-response data, we perform causal sensitivity analysis to identify the parameters that most strongly influence instability onset, amplification, and asymmetry. Machine-learning models are then trained for stability classification and for predicting key bifurcation observables, including maximum gain and critical thresholds. We also explore operator-learning approaches for predicting full gain curves from model parameters. These results suggest that machine learning serves not as a replacement for bifurcation theory, but as an interpretable accelerator for identifying instability boundaries, dominant causal drivers, and rare asymmetric regimes in coupled Bragg-grating dynamics.

Keywords: modulation instability, Bragg-grating systems, bifurcation discovery, causal sensitivity, machine learning