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Ph.D. DISSERTATION DEFENSE

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Title:	Mathematical Modeling and Structure-Aware Design of Complex Physical Systems
Chairperson:	Dr. Michael Zabarankin, Department of Mathematical Sciences, School of Engineering & Sciences Dr. Yuping Huang, Department of Physics, School of Engineering & Sciences
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ABSTRACT

This dissertation develops mathematical modeling and structure-aware design frameworks for two complex physical systems whose behavior is controlled by geometry and field response.

The first part studies electrohydrodynamic deformation of toroidal drops in electric fields. For a prescribed toroidal interface with elliptic cross section, an inverse-optimization framework is used to determine the permittivity ratio and electric capillary number that minimize the residual normal velocity. Boundary-integral representations from previous work provide the electric and hydrodynamic field descriptions, while the arbitrary-viscosity construction combines these representations with least-squares projection to treat drop-to-ambient viscosity ratios beyond the equal-viscosity case. Numerical results identify admissible parameter regimes and use reconstructed streamlines as visual checks of approximate stationarity.

The second part develops an automatic mode-aware design framework for nonlinear lithium-niobate photonic crystal cavities for intrinsic second harmonic generation. Starting from regular photonic crystal band selection, the framework constructs an L4/3 cavity benchmark, identifies cavity-like first-harmonic and second-harmonic modes, forms nonlinear-overlap-aware mode pairs, tracks modal branches during geometry updates, and verifies optimized structures through higher-fidelity recalculations. The intrinsic SHG objective depends jointly on radiative quality factors, frequency matching, nonlinear overlap, and modal identity. The optimized designs demonstrate systematic enhancement of the intrinsic SHG figure of merit across the benchmark region and reveal a physical mechanism in which branch-managed geometry evolution increases radiative confinement while preserving nonlinear mode-pair compatibility.

Collectively, these studies show how mathematical formulation, field representations, and structure-aware design principles can be used to analyze and engineer physical systems whose behavior is controlled by geometry and modal response.