Controlling Multimode Gaussian States of Light in Nonlinear Micro-Resonators

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Controlling multimode states of light is a long-standing challenge in optics. Recent advances in fabricating nonlinear micro-resonators with dispersion engineering now allow for the dramatic enhancement of all-optical interactions, necessitating new approaches to generating, controlling, and measuring multimode light. Specifically, multimode Gaussian states represent a rich domain for exploring complex phase-sensitive optical phenomena.

In this talk, I will discuss our recent results in observing, controlling, and programming multimode quadrature-dependent Hamiltonians to enable new on-chip functionalities. First, I will present the experimental realization of an optical dimer exhibiting quadrature nonreciprocity [1]. By leveraging Kerr nonlinearity in a microring resonator, we create an isolated pair of modes with optically controlled two-mode squeezing and Bragg scattering. This system successfully demonstrates programmable unidirectional quadrature transport, where simultaneous squeezing and Bragg interactions result in an asymmetric distribution of vacuum noise outside the cavity.

Expanding beyond the dimer, I will also detail the observation of complex quadrature-dependent lattice dynamics emerging in dissipative Kerr micro-combs [2]. By mapping the comb's discrete frequency modes onto a synthetic lattice, we demonstrate how phase-sensitive parametric interactions govern the nonlinear dynamics and inter-mode coupling across multimode amplified vacuum states. This provides a novel mechanism to program and control broadband, multimode continuous-variable states.

Ultimately, these demonstrations of phase-sensitive control scaling from isolated optical dimers to broadband micro-combs pave the way toward new regimes of light-matter interactions on scalable photonic microchips, offering transformative implications for fundamental physics, advanced quantum sensing, and continuous-variable quantum information processing.

References

[1] J Sloan, E Lustig, L Schul, *et al.*, "Optical quadrature nonreciprocity", in CLEO 2026, Technical Digest Series (Optica Publishing Group, 2026)

[2] E Lustig, M Guidry, D Lukin, S Fan and J Vuckovic, Nat. Photon. **19**, 1247 (2025)