Predicting and Controlling Quantum and Classical Noise Response in Multimode Nonlinear Photonics

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Multimode nonlinear photonic systems are often noise-generating: quantum and classical fluctuations of light can be strongly amplified, limiting a wide range of laser applications. Although the governing equations for multimode nonlinear systems have been known for decades, in many systems physical insight and predictability remain elusive. In this talk, I will present new computational tools and experimental methods for understanding, predicting, and controlling noise in multimode nonlinear systems.

First, I will introduce a computational framework that we call quantum sensitivity analysis (QSA). QSA predicts quantum and technical noise responses of arbitrary observables without stochastic simulation, using the Jacobian of a classically computed observable obtained efficiently through automatic differentiation or adjoint methods. Using this framework, we predict and observe a regime in which the intensity fluctuations of a femtosecond pulse undergoing nonlinear propagation decouple from amplified spontaneous emission, the dominant noise channel. This enables directly detectable intensity squeezing even when large input fluctuations would normally mask it. QSA identifies the interplay of Raman scattering and soliton dynamics as central to this effect, pointing to a manner in which complex multimode interactions can provide useful noise-protection mechanisms.

In a second example, we demonstrate active co-control of the mean field and fluctuations in a spatiotemporally multimode photonic system. By programmable spatial phase modulation at the input of a nonlinear waveguide, we show that a beam can be partially focused while its intensity fluctuations are reduced by over an order of magnitude. QSA explains this in terms of an optimal input wavefront that orthogonalizes the field against the relevant gradient.

Looking forward, the ability to predict, explain, and control multimode nonlinearities should enable new approaches to robust and precise laser systems, as well as inspire unique approaches to generating quantum states of light, even beyond the Gaussian regime.