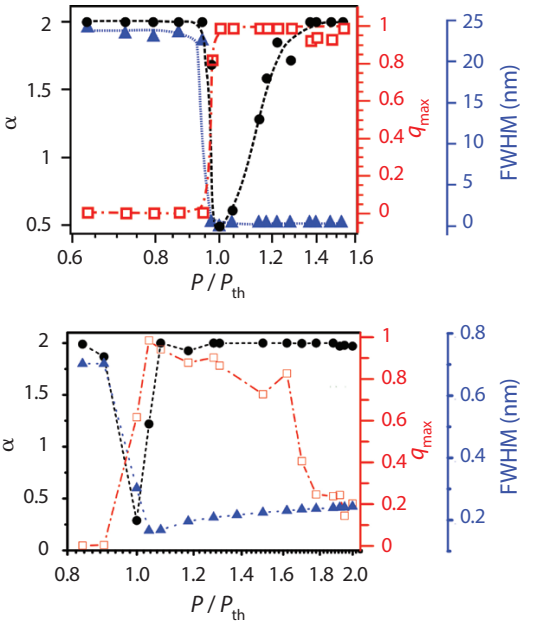
LASERS

Universal Phase Transitions in Random Lasers

The recent exploitation of random lasers (RLs) as a photonic platform for studying complex systems, such as spin glasses, has opened new cross-disciplinary avenues for understanding RL behavior. RLs are cavityless systems, with a disordered gain medium and with feedback for laser action provided by strong light scattering. These lasers have two remarkable properties. First, strong RL intensity fluctuations present heavy-tailed Lévy distributions, which contrast with the Gaussian statistics apparent before lasing. Second, the tendency of the disorder to hamper synchronous mode oscillation produces a photonic spin-glass phase, with nontrivial correlations among modes, that is very distinct from the uncorrelated, paramagnetic-like regime below the lasing threshold.[1]

Recent theoretical approaches based on Langevin equations for the dynamics of the mode amplitudes have now unified the descriptions of these two phase transitions at the RL threshold.[1,2] For the Gaussian-to-Lévy transition, the Lévy index, α, identifies the intensity distribution as Gaussian ($\alpha = 2$) or Lévy ($0 < \alpha < 2$). For the paramagnetic-to-spin-glass transition, q_{max}, a parameter that measures the overlap among mode amplitudes, phases or intensity fluctuations, can be used to characterize the photonic paramagnetic ($q_{max} = 0$) or spin-glass ($q_{max} \neq 0$) phase. The presence of nontrivial correlations among RL intensity spectra emitted under identical experimental conditions (system replicas) leads to replica symmetry breaking (RSB) in the glassy phase.



Transition from Gaussian ($\alpha = 2$) to Lévy ($0 < \alpha < 2$) intensity-fluctuation statistics (black curves) and from photonic paramagnetic ($q_{max} = 0$) to RSB spin-glass ($q_{max} \neq 0$) phase (red curves), as a function of the normalized pump energy, occur simultaneously with the transition from pre-lasing to random-lasing behavior (FWHM, blue curves), in (top) a 1-D Er-doped random fiber laser with random fiber grating, pumped by a CW source, and (bottom) 3-D crystalline powders of Nd^{3+}-doped YBO_3 pumped by a pulsed Nd:YAG laser.

In addition to providing this unified theoretical description, we have demonstrated the universality of such phase transitions in a wide variety of RL systems, including diverse pump sources, spatial structures and physical arrangements. Gaussian-to-Lévy and paramagnetic-to-spin-glass transitions simultaneously occur at the RL threshold, both for a 1-D fiber laser system[3] and a 3-D solid-state system[2] (see figure). The glassy transition concurrent with the RL threshold has also been characterized in a TiO_2 particle-based dye-colloidal (3-D liquid) RL,[4] and in a functionalized T_5OC_x oligomer in a 2-D amorphous solid-state RL.[5] OPN

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