Optical Thermodynamics of Nonlinear Highly Multimoded Systems

Demetrios Christodoulides[1]

[1]USC, Los Angeles, United States

For years, it has been speculated that statistical mechanics could offer a route for deciphering the dynamics of multimode nonlinear optical systems. However, it is only recently that a self-consistent theoretical framework has been put forward, offering a new perspective on an array of complex nonlinear phenomena, including beam self-cleaning and beam cooling schemes. Grounded in entropic principles, this theory establishes a universal equation of state by means of which the ensued Rayleigh–Jeans (RJ) equilibria can be uniquely determined from the invariant quantities of the system, and consequently for arbitrary excitation conditions. On this front, recent experimental studies have provided direct evidence of single-frequency RJ thermalization as well as other archetypical thermodynamic processes in multimode fibers and time-synthetic photonic mesh lattices. Moreover, further theoretical and experimental advancements have extended this framework to encompass more complex scenarios, including configurations with orbital angular momentum (OAM) and non-Hermitian settings. This progress now paves the way for the exploration of similar phenomena across multiple degrees of freedom, aiming to provide an altogether new understanding of frequency conversion processes in highly multimode photonic arrangements. A longstanding question in this context is whether heavily multimode settings can achieve complete conversion to a target frequency, akin to single mode optical systems, thus facilitating frequency generation at significantly higher power levels.

In this talk, we will show that frequency generation in spatially multimode structures is inherently an all-optical thermodynamic process. In this context, all interacting frequency components can be viewed as photonic “chemical reactants”, capable of undergoing thermodynamic reactions driven by optical nonlinearities. In accord with the second law of thermodynamics, the maximization of optical entropy across all frequencies, leads to RJ equilibria that can be predicted from any possible excitation condition. We address this problem in the most general sense by introducing a stoichiometric model that encompasses all possible frequency conversion processes such as difference-frequency generation (DFG), sum-frequency generation (SFG) and four-wave mixing (FWM). Ultimately, we develop a comprehensive strategy to optimize conversion efficiencies in highly multimode environments, offering a promising pathway to enable platforms like parametric oscillators and comb sources at power levels otherwise inaccessible in single-mode configurations. In this context, we identify a regime of RJ thermalization, where a reaction at near-zero temperatures not only maximizes frequency conversion but also promotes the entropically irreversible funneling of power to the fundamental mode at the target frequency. These optimization capabilities are underpinned by a key result in our study: an expression that formally relates the stoichiometric coefficients to the optical chemical potentials, in full analogy to what is expected in molecular/atomic chemical reactions, where the Gibbs free energy is extremized.