Nonlinear Dynamics in Semiconductor Ring Lasers: From Phase Turbulence to Solitons

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The recent study of ring quantum cascade lasers [1,2] (QCLs, Fig. 1a) revealed a new laser instability. It is triggered by phase turbulence akin to the wave instabilities that occur in other nonlinear systems such as fluids, superconductors and Bose-Einstein condensates. The choice of the ring geometry took inspiration from Kerr combs [3], that are commonly generated in passive ring microresonators and have attracted great attention within the photonics community in the last years thanks to their rich physics.

In this contribution we show that similar physics can occur in ring QCLs, that are active media and do not require an external optical pump. These new laser frequency combs are characterized by bell-shaped optical spectra exhibiting a sech^2 envelope—a characteristic commonly seen in microresonator Kerr combs. The behavior of the laser is explained by rewriting its governing equations in the form of the complex Ginzburg-Landau equation—one of the most famous nonlinear equations in physics [1].

To prove further the connection with Kerr combs, we propose a generalization of the well-known Lugiato-Lefever equation (LLE) [4], unifying the description of the spatiotemporal dynamics in nonlinear passive and active cavities with cubic nonlinearity (Fig. 1b-d). This model makes it possible to connect for the first time from a formal viewpoint Kerr microresonators and QCLs in terms of spontaneous optical frequency combs generation. Our comprehensive description also captures the physics of a hybrid device, a unidirectional ring QCL driven by an external coherent field [5]. The new system shows a wealth of spatiotemporal dynamics ranging from phase and amplitude turbulence to the self-generation of highly correlated dissipative patterns, such as Turing rolls and localized cavity solitons.

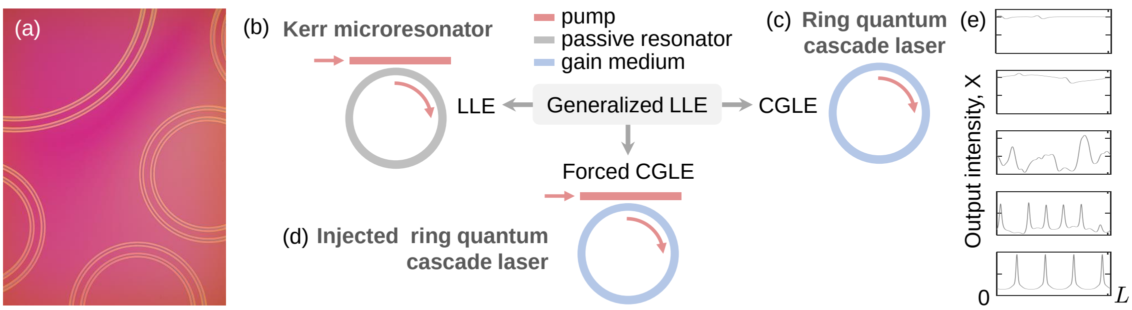

Fig. 1 (a) Microscope image of fabricated ring quantum cascade lasers. (b)–(d) The generalized Lugiato-Lefever equation unifies three distinct active/passive optical systems with cubic nonlinearity. (e) Localized structures emerging from phase instability, phase turbulence, amplitude turbulence, filamentation, and cavity solitons, when the ring laser transitions from free-running to externally driven.

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