Solitons in quantum cascade laser based Kerr combs

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Optical frequency combs (OFCs) stand as the cornerstone of modern optics, with applications ranging from fundamental science to sensing and spectroscopy. Generation of short optical soliton pulses in passive media such as optical fibers and microresonators has been an established technique for stable OFC formation with a broad optical spectrum – however these platforms are driven by an external optical signal and often rely on additional bulky elements that increase the complexity of the system. Here, we aim to overcome these difficulties by extending the soliton concept to active media that are electrically-driven and demonstrate a new type of solitons in a free-running semiconductor laser integrated on a chip.

We utilize a quantum cascade laser (QCL), embedded in a ring resonator (Fig. 1a). The ring cavity is coupled with a separately-biased waveguide, which allows for the intracavity light to efficiently outcouple and reach output intensities that are comparable with a Fabry-Perot laser processed from the same material [1].

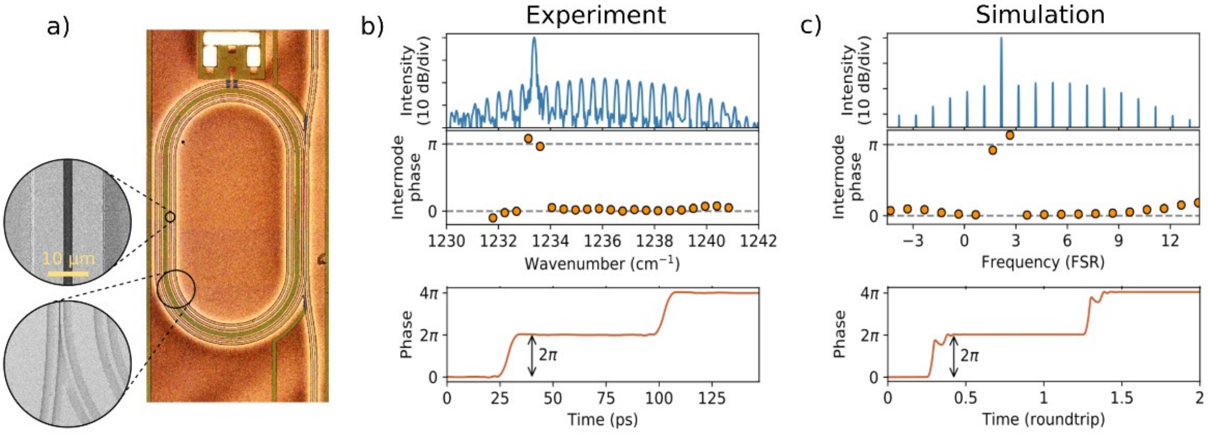

Figure 1 a) Ring laser device with the active coupler waveguide. b) Experimental and simulated c) free-running soliton. The soliton spectrum is displayed in the top, showing a strong mode surrounded by a smooth spectral envelope comprised of weaker sidemodes. The corresponding intermodal phases, given below, indicate a π jump between the sidemodes and the strong mode. The temporal phase profile is plotted in the bottom.

In order to explain the multimode laser operation in a ring cavity, which is a prerequisite for OFC emission, we rely on the complex Ginzburg-Landau equation (CGLE) [2]. The main mechanism that allows for the sidemodes to overcome the lasing threshold is the modulational instability (MI), which arises due to the interplay of dispersion and a giant Kerr nonlinearity. In QCLs, the later originates from the optical gain itself and is several orders of magnitude

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larger than the bulk crystalline nonlinearity, making QCLs the ideal test bed for nonlinear phenomena [3]. Within the CGLE framework, we furthermore predict how appropriate values of the dispersion and the nonlinearity can even lead to soliton generation from the initial MI by forming self-starting localized pulses in the intracavity intensity.

We rely on both the experimental measurements (Fig. 1b) and simulations based on the Maxwell-Bloch formalism (Fig. 1c) to corroborate our predictions. The soliton spectrum consists of a strong mode surrounded by weaker equidistant sidemodes with a smooth spectral envelope. Their intermodal phases reveal that all of the weaker modes are synchronized in phase, thus forming a narrow pulse in the time domain, while the strong mode is shifted and forms the continuous wave background around the pulse. The solitonic nature of the comb is furthermore visible from the temporal phase profile, which shows that the narrow localized soliton region, where the phase changes over 2π, is surrounded indeed by a constant background containing a single frequency equal to the one of the strong mode in the spectrum. We additionally demonstrate soliton molecules with multiple pulses forming within one roundtrip. These results pave the way for electrically-driven soliton generation on monolithically-integrated platforms.

References

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