Temporal Solitons in Coherently-Driven Ring Lasers

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Pulsed lasers have been the workhorse of ultrafast optics since their advent and rapid development throughout the 20th century, revolutionizing a wide variety of fields from spectroscopy to tattoo removal. Over the past twenty years, pulsed laser sources have shrunk from tabletop laboratory setups down to micron-sized chips, making them ideal components for integrated photonic devices. Despite this miniaturization, chip-scale pulsed laser sources have eluded the mid infrared (IR) spectral region. Active mode-locking of mid IR semiconductor lasers—such as quantum cascade lasers (QCLs)—has produced pulse widths on the order of 6 picoseconds [1]. Pulse compression techniques can be utilized to shrink these pulses to hundreds of femtoseconds [2], but rely on large optical setups that cannot be scaled down. Here, we present a fundamentally new way to produce bright pulses of mid IR light by optically pumping ring QCLs. This technique unifies the physics of passive, Kerr microresonator combs and ring QCLs [3]. Using a modified racetrack QCL with an integrated directional coupler, we injection-lock the unidirectional laser field circulating in the racetrack to a commercial external cavity QCL. Much like in Kerr microresonator combs, when the injection-locked field is detuned from its natural cavity resonance, the resonance becomes bistable, with its unstable branch supporting bright solitons with pulse widths of ~1 picosecond at a center wavelength of 8 µm. This method of pulse formation is well-suited for lasers with fast gain dynamics, which encompasses the entire family of QCLs, spanning from 3 µm to 300 µm. Furthermore, the optical drive can, in principle, be integrated with the racetrack, providing a route for on-chip, ultrashort pulse formation throughout the entire mid-IR.

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Supplementary Pages

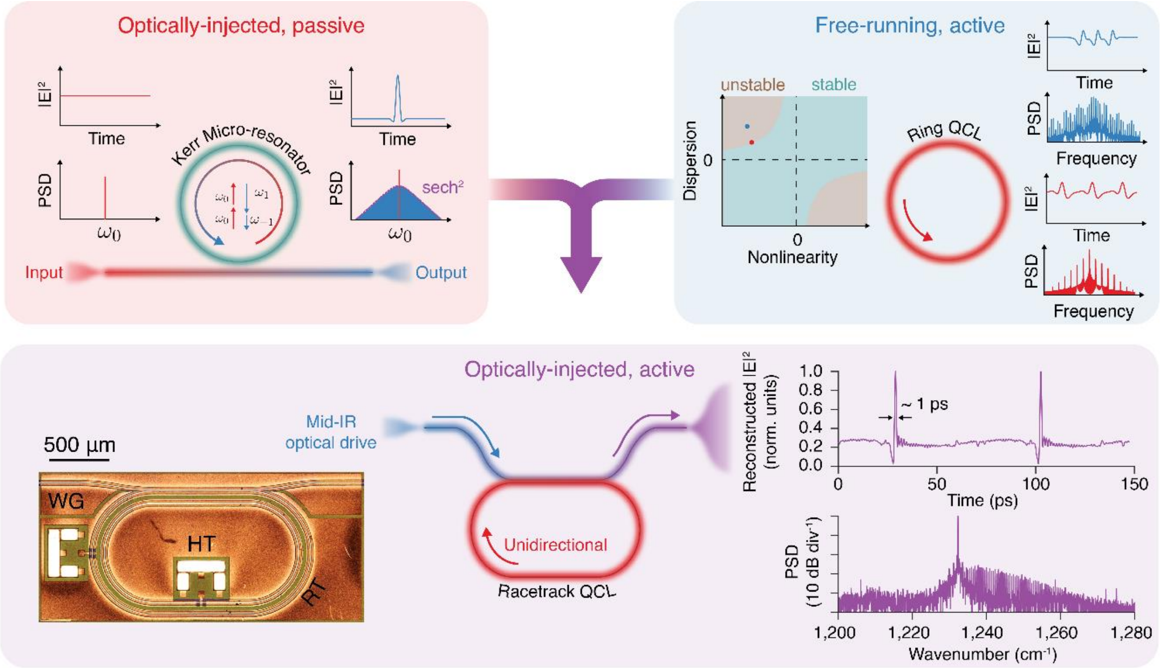

Figure 1: Unifying Kerr Microresonators and Ring Quantum Cascade Lasers (QCLs). Kerr microcombs form by coupling continuous-wave (CW) optical fields to passive microresonators. The resonator's strong non-linearity promotes the production of parametric sidebands which phase-lock via four-wave mixing. Ring QCLs can either operate as stable, single-mode lasers, or as multimode frequency combs depending on their dispersion and non-linearity. In free-running ring QCLs, pulse formation is prevented by fast gain recovery times. This limitation can be bypassed if the ring QCL is coherently-driven with an external laser source. To couple the external optical drive to the ring QCL, we utilize a racetrack (RT) geometry, where light is coupled to the RT using a waveguide directional coupler (WG). We use an integrated heater (HT) to finely tune the cavity resonance of the RT. When the field circulating in the RT is locked to the external laser, the resonance becomes bistable, with its unstable branch supporting bright solitons with pulse widths of ~1 picosecond at a center wavelength of 8 µm.

Dissipative cavity solitons are stable, single-peaked waveforms that maintain their shape while propagating through a nonlinear and dispersive medium at constant velocity. In the frequency domain, optical solitons constitute frequency combs, where the spacing between frequency components is locked down to one part in 10^{12}. Dissipative solitons form through the delicate balance of both dispersion and nonlinearity, as well as gain and loss. One way to form bright solitons is to pump a high-quality (Q) factor, passive microresonator possessing anomalous dispersion with a strong, continuous-wave (CW) optical field. Upon sweeping the field frequency through the cavity resonance, the input field undergoes a modulational instability and may form a bright soliton once it is effectively red detuned from the cold cavity resonance. These so-called 'Kerr soliton microcombs' can span across the visible to the near-infrared, often covering a full spectral octave. Their combination of compact size with high output power has propelled them to the forefront of scientific innovation, finding use in spectroscopy, LIDAR, metrology, microwave photonics, and astrophysics.

With the exception of some recent designs [1], the lack of high-Q microresonators past 4 µm has so far limited the impact of Kerr microcombs in the mid-IR. Quantum cascade lasers (QCLs), on the other hand, are a dominant source of mid-IR light. As such, they make the perfect platform to design low-loss, integrated photonics devices for the mid-IR. Furthermore, when biased sufficiently above laser threshold, their multimode emission can spontaneously lock together, forming frequency combs. Due to the ultrashort carrier lifetimes, QCL frequency combs do not emit pulses under normal operation. In the case of ring QCLs, their output waveform is affected by two key parameters: their dispersion and their nonlinearity.

In order to stimulate pulse formation in the mid-IR, we combine the broadband spectral coverage of QCLs with the soliton physics of Kerr microresonators by introducing a new class of device. This hybrid device consists of a racetrack (RT) QCL with a directional coupler (WG), which both evanescently couples out the RT field and couples in an external optical drive. The RT resonances can be finely tuned using an integrated heater (HT). We use a commercial external cavity QCL from DRS Daylight Solutions to injection lock a unidirectional field circulating in the RT. Once locked, the external laser can detune the RT field from its natural cavity resonance, making it bistable. By sweeping the frequency of the external drive laser along the unstable branch of this bistable resonance, in the effectively red detuned regime, we produce a broadband frequency comb. Using a waveform reconstruction technique known as Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS) [2], we recover the intermodal beat note amplitudes and phases, confirming that this comb state corresponds to a bright temporal soliton with a pulse width of ~ 1 picosecond.

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