

**SYSTEMS AND METHODS FOR MID-INFRARED LASER CHIPS****CROSS-REFERENCE TO RELATED PATENT APPLICATION**

**[0001]** This application claims the benefit and priority of U.S. Provisional Patent Application No. 63/626,475, filed on January 29, 2024, the entirety of which is incorporated by reference herein.

**GOVERNMENT LICENSE RIGHTS**

**[0002]** This invention was made with government support under 2221715 awarded by the National Science Foundation. The government has certain rights in this invention.

**TECHNICAL FIELD**

**[0003]** The present application relates generally to laser chips, and in particular to driven bright solitons on mid-infrared laser chips.

**BACKGROUND**

**[0004]** Short optical pulses can be used for imaging, spectroscopy, and/or communications.

**SUMMARY**

**[0005]** At least one aspect of the present disclosure is directed to a device. The device can include a laser. The device can include a waveguide coupled with the laser and configured to output a pulse having a plurality of wavelengths forming a frequency comb in a range between 3  $\mu\text{m}$  and 12  $\mu\text{m}$ . The device can include a resonator coupled with the waveguide. The resonator can include a closed loop. The device can include gain medium disposed in the resonator. A portion of the waveguide and a portion of the resonator can form a coupler.

**[0006]** Another aspect of the present disclosure is directed to a method. The method can include providing a laser. The method can include coupling a waveguide with the laser. The method can include outputting, by the waveguide, a pulse having a plurality of wavelengths forming a frequency comb in a range between 3  $\mu\text{m}$  and 12  $\mu\text{m}$ . The method can include coupling a resonator with the waveguide. The resonator can include a closed loop. The method can include disposing gain medium in the resonator. The method can include forming a coupler from a portion of the waveguide and a portion of the resonator.

[0007] Those skilled in the art will appreciate that the summary is illustrative only and is not intended to be in any way limiting. Other aspects, inventive features, and advantages of the devices and/or processes described herein, as defined solely by the claims, will become apparent in the detailed description set forth herein and taken in conjunction with the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

[0009] FIGS. 1A-1D illustrate pulse generation in optically bistable resonator systems.

[0010] FIGS. 2A-2I illustrate driven bright solitons in an active resonator, according to an embodiment.

[0011] FIGS. 3A-3E illustrate on-chip pump filtering, according to an embodiment.

[0012] FIGS. 4A-4E illustrate an integrated turnkey soliton generator, according to an embodiment.

[0013] FIGS. 5A-5B illustrate simulated detuning sweeps in passive and active resonators, according to an embodiment.

[0014] FIG. 6 illustrates the intensity of the stationary homogeneous solution of the forced complex Ginzburg-Landau equation as a function of the detuning  $\theta$ , according to an embodiment.

[0015] FIGS. 7A-7B illustrate a simulated soliton state in the presence of third order dispersion, according to an embodiment.

[0016] FIG. 8 illustrates a soliton generator across the laser bandwidth, according to an embodiment.

[0017] FIG. 9 illustrates real and imaginary parts of the laser medium susceptibility for  $\alpha_p = 0$  and  $\alpha_p = 0.5$ , according to an embodiment.

[0018] FIGS. 10A-10B illustrate a forward-backward wavelength scans, according to an embodiment.

- [0019] FIG. 11 illustrates a ring QCL power performance, according to an embodiment.
- [0020] FIGS. 12A-12D illustrate gain saturation in an active QC resonator below and above the transparency, according to an embodiment.
- [0021] FIGS. 13A-13D illustrate optical bistability in a driven RT QCL included by varying incident optical power, according to an embodiment.
- [0022] FIGS. 14A-14B illustrate the working principle of an active optical filter, according to an embodiment.
- [0023] FIGS. 15A-15B illustrate below threshold transmission of an active QC racetrack resonator, according to an embodiment.
- [0024] FIGS. 16A-16B illustrate the working principle of a Vernier notch filter, according to an embodiment.
- [0025] FIGS. 17A-17B illustrate filter tuning and operation, according to an embodiment.
- [0026] FIGS. 18A-18B illustrate below threshold transmission of the RT QCLs, according to an embodiment.
- [0027] FIG. 19 illustrates a turnkey algorithm for stable soliton generation, according to an embodiment.
- [0028] FIG. 20 illustrates shifted wave interference Fourier transform spectroscopy reconstruction of the integrated soliton generator, according to an embodiment.
- [0029] FIG. 21 illustrates an experimental forward-backward scan in the integrated laser chip, according to an embodiment.
- [0030] FIGS. 22A-22C illustrate on-chip mid-IR supercontinuum generation, according to an embodiment.
- [0031] FIG. 23 illustrates a method for soliton generation, according to an embodiment.
- [0032] Like reference numbers and designations in the various drawings indicate like elements.

#### DETAILED DESCRIPTION

**[0033]** Following below are more detailed descriptions of various concepts related to, and implementations of methods, systems, and apparatuses for mid-infrared laser chips. The various concepts introduced above and discussed in greater detail below may be implemented in any of a number of ways, as the described concepts are not limited to any particular manner of implementation. Examples of specific implementations and applications are provided primarily for illustrative purposes.

**[0034]** Ultrafast pulse emitters in the mid-infrared can be complex, bulky, and inefficient based on the down conversion of near-infrared or visible pulsed laser sources.

**[0035]** The systems and methods of the present disclosure are directed to a semiconductor laser chip (e.g., a purely DC-driven semiconductor laser chip) that generates one picosecond solitons at a center wavelength (e.g., of 8.3  $\mu\text{m}$ ) at GHz repetition rates. The soliton generation scheme can be similar to that of passive nonlinear Kerr resonators, but with differences. The scheme can rely on a fast bistability in active nonlinear laser resonators, unlike passive mode-locking which can rely on saturable absorbers or active mode-locking by gain modulation in semiconductor lasers. Monolithic integration of components (e.g., drive laser, active ring resonator, coupler, and pump filter) can enable turnkey generation of bright solitons that remain robust for hours of continuous operation without active stabilization. Such devices can be readily produced at industrial laser foundries using fabrication protocols. The systems and methods of the present disclosure can unify the physics of active and passive microresonator frequency combs, while simultaneously establishing a technology for nonlinear integrated photonics in the mid-infrared. Additionally, the systems and methods of the present disclosure can allow for compact sources of short bright pulses in the mid-infrared wavelength range (e.g., from 3  $\mu\text{m}$  to 12  $\mu\text{m}$ ).

**[0036]** Short optical pulses can have a range of applications, from high-resolution imaging and ultrafast spectroscopy to optical communications, laser-based medical procedures, and light ranging. They can play a pivotal role in nonlinear optics, enabling a variety of phenomena such as supercontinuum generation and optical frequency conversion that are at the heart of optical atomic clock technology. Pulsed optical sources can be miniaturized and transitioned from tabletop experimental setups to compact photonic integrated chips. Two technologies driving this effort can include semiconductor mode-locked lasers (SMLLs) and nonlinear microresonator frequency combs. These technologies may reduce the size and complexity of optical atomic clocks, pave the way to terabit-per-second telecommunication links, and provide new tools for linear and nonlinear absorption

spectroscopy. The near-infrared wavelength range (e.g.,  $0.8 - 2.5 \mu\text{m}$ ) can have an abundance of compact pulsed sources based both on SMLs and nonlinear resonators. In contrast, demonstrations of integrated photonic pulse generators in the mid-infrared wavelength range (e.g.,  $3 - 12 \mu\text{m}$ ) can be lacking. This wavelength range can be strategic to applications in gas sensing and spectroscopy. Devices in this range that are compatible with photonic integration and capable of directly generating coherent mid-infrared radiation can include interband cascade lasers (ICLs) and quantum cascade lasers (QCLs).

**[0037]** Limitations can exist that hinder deployment of ICLs and QCLs in applications. ICLs that operate at a wavelength range between  $3 - 6 \mu\text{m}$  can have modest milliwatt-level average optical power and the pulse durations can be limited to several picoseconds. QCLs, which can be most efficient in the  $4.5 - 12 \mu\text{m}$  range, can routinely reach Watt-level output power and can enter the femtosecond regime. However, achieving sub-picosecond pulse duration can require spectral broadening and external pulse shaping involving strong radiofrequency modulation of the laser bias, a tabletop delay line, and an optical isolator for preventing laser destabilization due to optical feedback. These aspects can pose a challenge for the miniaturization of the system.

**[0038]** This challenge can be addressed by the systems and methods of the present disclosure, which include a feedback-insensitive and isolator-free semiconductor laser architecture generating bright picosecond transform-limited mid-infrared pulses directly on a laser chip without any external compression. Pulse generation can be enabled by a driving scheme that does not rely on active or passive mode-locking as in SMLs. Instead, it can be inspired by the soliton excitation techniques developed for passive Kerr microresonators and can be enabled by an experimental unification of the physics of dissipative solitons in passive and active cavities based on a generalized Lugiato-Lefever equation. This equation can extend the LLE, which was originally formulated for resonators without population inversion, to ring lasers driven above threshold. Although the demonstration can be performed using a QCL emitting at  $8.3 \mu\text{m}$  in the atmospheric transparency window, this approach can apply to any device of such class across the mid-infrared. FIGS. 1A-1D illustrate pulse generation in optically bistable resonator systems. The chip-scale pulse generators described herein can extend the spectral gamut covered by the SMLs and Kerr microresonators to the entire mid-infrared range (FIG. 1A). FIG. 1A illustrates spectral coverage of three photonic integrated technology stacks for on-chip short pulse generation including semiconductor mode-locked lasers (SML), Kerr microresonators, and active quantum cascade (QC) resonators. The

systems and methods of the present disclose can include integrated pulse generators using active AC resonators.

**[0039]** Pulsed operation of a semiconductor laser can require both a mechanism for pulse formation and a mechanism for pulse stabilization. In SMMLs, the pulse can be formed and stabilized by an intracavity saturable absorber that opens a short temporal window of net gain only for the optical pulse, and attenuates the background, preventing its growth and pulse destabilization (FIG. 1B). SMLs can include a forward biased gain section and a reverse biased saturable absorber (SA) section. Reverse biasing the SA section and increasing the pumping of the forward-biased gain section can allow a transition from a CW waveform to a mode-locked pulsed operation. FIG. 1B shows the simulated waveforms and optical spectra of the intracavity field in a SMLL at different values of the gain section pumping. A competing destabilizing effect of the optical gain, that act to amplify the noise spikes on the low-intensity background, can be weak if the active medium is slow as the gain does not have the time to recover after being depleted by the pulse. In contrast, in lasers with a fast gain recovery a saturable absorber may not be able to stabilize the pulse. It can be for this reason that mid-infrared QCLs, where the gain recovery time can be typically less than a picosecond, until now, could not be passively mode-locked to emit pulses. In free-running standing-wave cavity Fabry-Perot QCLs, the locked frequency comb state can correspond to a frequency-modulated (FM) wave with a nearly flat intensity in the time domain. In traveling-wave ring QCLs, frequency comb operation can yield gray or dark (instead of bright) pulses, on a high intensity background.

**[0040]** An alternative pulse stabilizing mechanism can include optical bistability that may occur in resonators where the optical susceptibility of the host material depends on the intracavity field intensity. In passive resonators, the susceptibility can be taken as purely real in the limit of large detuning of the frequency of optical field from the material absorption frequency. The intensity-dependent real part of susceptibility (e.g., the refractive index) can be at the origin of stable soliton formation in passive systems with no optical gain, such as fiber loop resonators and waveguide-based microresonators. In these systems, a coherent continuous wave (CW) laser field injected into the resonator may break up into one or multiple pulses that are formed by the competing action of the nonlinearity and the cavity dispersion. The typical soliton excitation scheme can involve scanning the wavelength of the external pump laser through resonance from the blue-detuned side to the red-detuned side (e.g., forward scan). During the scan, the CW pump can undergo an instability and can form

one or several cavity solitons (FIG. 1C). Once excited, these solitons can remain stable against noise when the driving field is effectively red-detuned from the cavity resonance. Solitons may not be able to be excited by scanning the laser wavelength from the red-detuned to the blue-detuned side of the resonance (e.g., backward scan), which can be a manifestation of the bistable behavior of this optical system (FIG. 1C). A soliton may comprise a wave, wave packet, quantum or quasiparticle, that may be propagated at a constant velocity, and may be strongly stable, self-reinforcing and/or non-dissipative in preserving its shape while propagating.

**[0041]** FIG. 1C shows a passive Kerr resonator optically pumped by an external laser. The passive Kerr resonator can experience a bistable behavior in the output intensity as a function of the detuning  $\theta$  of the laser wavelength from the Kerr cavity resonance. Here the middle panel shows the mean intracavity intensity as function of detuning. The intensity values are artificially flipped by multiplying with  $-1$  to facilitate the visual comparison with the experimental plots described herein, where the measured output intensity (as opposed to the intracavity intensity) is shown. On a forward scan (e.g., blue-detuned to red-detuned) the resonator transmission can show a series of steps signifying generation of one or several cavity solitons, which may not be able to be generated on a backward scan. The simulations can be based on the GLLE. Fabrication technology can allow monolithic integration of the pump laser with a passive resonator.

**[0042]** The systems and methods of the present disclosure can demonstrate hybrid nonlinear photonic devices by applying the framework of the soliton generation in passive Kerr microresonators to a semiconductor laser above its threshold. A traveling-wave ring cavity filled with the optical gain medium where the bistability stems from the resonant third-order nonlinearity can be considered. In a laser cavity the medium susceptibility can also be intensity-dependent, by virtue of gain saturation. Temporal changes in field intensity can lead to changes in the imaginary part of the susceptibility. The real part of the susceptibility, which can be inherently dependent on its imaginary part, can equally follow the changes in the intracavity field intensity (as shown in FIG. 9 below). This behavior can lead to the refractive nonlinearity that is similar to the Kerr nonlinearity of passive microresonators. In a semi-conductor with a fast gain, the refractive nonlinearity can be quantified by the laser linewidth enhancement factor (LEF). Remarkably, unlike the bulk crystal Kerr nonlinearity, the nonlinearity induced by the LEF can be strongly dispersive, and the nonlinear coefficient

may even attain both positive and negative values at different frequencies within the gain bandwidth.

**[0043]** There can be differences between the systems and methods of the present disclosure as compared to passive Kerr resonators. First, whereas the gain medium is fast, with the typical gain recovery time in mid-infrared QCLs of a few hundred femtoseconds, the nonlinearity itself that arises from the saturation of the fast gain can be slower than the almost instantaneous Kerr nonlinearity of passive resonators. The slow nonlinearity can limit the bandwidth over which it acts, on one hand, and can be stronger than a fast nonlinearity, on the other hand. Second, unlike in an optically pumped microresonator, the optical pump field can be generated directly inside the ring laser cavity above the threshold. In a free-running laser, the pump frequency can be tightly linked to the position of the laser cold cavity resonance, and its detuning from the resonance may not be freely controlled. The laser can operate at an optimal wavelength located between the peak of the cavity resonance and the peak of the saturated gain. As a result, the bistability cannot be reached without a control over the field detuning and the bright solitons may not be generated in a free-running laser.

**[0044]** Injecting an external control optical field derived from a wavelength-tunable laser can enable the bistability to overcome this limitation. In such an externally driven scheme, the intracavity field can injection lock to the drive field when the frequency detuning between the two is sufficiently small (FIG. 1D). The intracavity field frequency can follow the frequency of the drive field (as long as the drive field remains within the finite locking range of frequencies) thus effectively decoupling it from the cavity resonance. Such a scheme can allow the generation of optical solitons in a laser once the intracavity field is injection locked to the drive field and the intensity of the driving field is increased, and then decreased. Alternatively, akin to the soliton generation scheme of Kerr microresonators, in such a driven laser system, the solitons can be generated by performing a wavelength scan of the drive field through the lasing resonance (FIG. 1D). The intracavity field can injection lock to the drive and can generate one or several cavity solitons in analogy with passive Kerr microresonators.

**[0045]** FIG. 1D illustrate a device 100. The device 100 can include an active quantum cascade resonator with an on-chip integrated drive laser according to the systems and methods of the present disclosure. The device 100 can include a soliton laser chip. The device 100 can include a chip. The device 100 can include a single chip. The device 100 can include an integrated circuit (IC). The device 100 can include a semiconductor device. The soliton excitation scheme can be similar to that of passive Kerr resonators and can entail scanning

the frequency of the drive laser through the lasing resonance of the active racetrack resonator. The associated output intensity (e.g., forward scan, backward scan) can exhibit optical bistability and a characteristic step in transmission when generating one or several cavity solitons on a forward wavelength scan.

**[0046]** The device 100 can include one or more lasers 105. The laser 105 can include a drive laser. The laser 105 can be driven electrically. For example, the laser 105 can be electrically powered. The device 100 can include a single chip, integrated circuit, or semiconductor device, on which the laser 105 is fabricated. The laser 105 can include a quantum cascade laser. The laser 105 can include an interband cascade laser.

**[0047]** The device 100 can include one or more waveguides 110. The waveguide 110 can include a first waveguide. The waveguide 110 can be coupled with the laser 105. The waveguide 110 can output a pulse. The pulse can have a plurality of wavelengths. For example, the pulse can have a plurality of wavelengths forming a frequency comb. The frequency comb can be in a range between 3  $\mu\text{m}$  and 12  $\mu\text{m}$ . For example, the frequency comb can be in a range between 3  $\mu\text{m}$  and 6  $\mu\text{m}$ , 3  $\mu\text{m}$  and 9  $\mu\text{m}$ , 3  $\mu\text{m}$  and 12  $\mu\text{m}$ , 6  $\mu\text{m}$  and 9  $\mu\text{m}$ , 6  $\mu\text{m}$  and 12  $\mu\text{m}$ , or 9  $\mu\text{m}$  and 12  $\mu\text{m}$ . The pulse can include a soliton. The pulse can include a mid-infrared pulse (e.g., a pulse in a range of 3  $\mu\text{m}$  to 25  $\mu\text{m}$ ). The waveguide 110 can be driven electrically. For example, the waveguide 110 can be electrically powered. The device 100 can include a single chip, integrated circuit, or semiconductor device, on which the waveguide 110 is fabricated.

**[0048]** The device 100 can include one or more resonators 115. The resonator 115 can be coupled with the waveguide 110. The resonator 115 can include a closed loop. The resonator 115 can include a racetrack resonator. The resonator 115 can be in the form of a closed loop. The resonator 115 can form a closed loop. The resonator 115 can include a generator resonator. The generator resonator can include a racetrack resonator. The generator resonator can generate solitons. A portion of the waveguide 110 and a portion of the resonator 115 can form a coupler. The device 100 can include gain medium. The gain medium can be disposed in the resonator 115. The resonator 115 can be driven electrically. For example, the resonator 115 can be electrically powered. The device 100 can include a single chip, integrated circuit, or semiconductor device, on which the resonator 115 is fabricated. In some embodiments, the resonator described herein can be implemented as a close-looped resonator or a resonator where a signal follows a complete/closed physical/transmission path, and/or is fed back from an output point to an input point then

back to the output point. Some embodiments of the resonator may include gain medium, which can include/provide a source of optical gain. The optical gain may result from stimulated emission of photons through electronic or molecular transitions to a lower energy state from a higher energy state previously populated by a pump source for instance. The closed-loop structure of the resonator can be in the form/shape of a ring, oval, circular, racetrack, loop or other structure.

**[0049]** Solitons can be generated in active racetrack (RT) QC resonators, which can be operated above their lasing threshold. The RT can operate as a single-mode unidirectional laser when a drive signal injected through an on-chip directional coupler from an external cavity laser (ECL) is detuned far off the RT lasing resonance (FIG. 2A). By sweeping the current of the integrated heater (HT), the RT lasing resonance can be moved with respect to the drive to perform the wavelength scans. In the backward wavelength scan (e.g., RT lasing resonance scanning from the red-detuned side to the blue-detuned side of the ECL frequency), the RT can remain in single-mode operation, when being both in resonance and out of resonance (FIGS. 2B and 2C). On the forward wavelength scan (e.g., RT tuned from blue-detuned to red-detuned), the output intensity can feature a characteristic step-like drop, at which a soliton is generated (FIGS 2D and 2G). This step can be a defining feature of soliton generation in both passive Kerr resonators and fiber resonators. The RT can remain injection-locked to the ECL drive field throughout the backward scan, (FIG. 2E). The soliton spectrum can include a strong pump and drive field line and a family of equidistant modes on one side of the pump line (FIG. 2H). Performing identical backward scans multiple times can reveal the existence of several possible steps in the output intensity (FIG. 2F ) signifying the multistability of the soliton states. This feature can be inherent to solitons. Single- and multi-soliton states can be excited in a stochastic manner by performing the same scan multiple times (FIGS. 2H and 2I).

**[0050]** FIGS. 2A-2I illustrate driven bright solitons in an active resonator. This demonstration can use an off-chip external drive laser. FIG. 2A shows an experimental setup for external soliton driving. SWEEP can include a function generator used to apply triangular sawtooth modulation to the integrated heater ECL can include an external cavity laser. POL can include a polarizer. RT can include a racetrack resonator. WG can include a waveguide coupler. IFG can include interferogram signal. OUT can include an output intensity detector. DAQ can include a data acquisition board. The high-resolution optical spectrum can show RT and ECL in proximity to each other (e.g., ECL on the blue side of the RT) at the onset of the

detuning scan. FIG. 2B shows the output intensity and interferogram acquired upon a forward wavelength scan (e.g., blue-detuned to red-detuned). FIG. 2C shows the short-time FFT of the output intensity trace on the forward scan showing the heterodyne notes at the onset of injection locking of the RT lasing frequency to that of the ECL. FIG. 2D shows the output intensity and interferogram on a backward wavelength scan (e.g., red-detuned to blue-detuned). FIG. 2E shows the short-time FFT of the output intensity trace on the backward scan showing the characteristic step signifying soliton generation. FIG. 2F shows the overlaid output intensity curves over one thousand backward scans, showing multistability of the soliton states. The traces can be aligned so that the first steps in the output intensity coincide. FIG. 2G shows the reconstructed output temporal waveform of the driven soliton generator over two consecutive roundtrips. FIG. 2H shows the optical spectrum of the waveform in FIG. 2G. The inset shows the corresponding RF spectrum of the intermode beat note. FIG. 2I shows the optical spectra of multiple soliton states, obtained on the backward scan, corresponding to the different steps in the output intensity seen in FIG. 2F.

**[0051]** The salient spectral asymmetry can be a general feature of the active resonator solitons of the present disclosure. It can stand in a strong contrast with the highly symmetric spectra of passive resonator solitons. While the spectral asymmetry may not be captured by the GLLE model, three factors may be causing it. First, taking into account higher order dispersion in the GLLE can yield asymmetric states in simulations. Second, the highly dispersive nature of the nonlinearity induced by the LEF may be a contributing factor to the observed spectral shape. Third, the GLLE can assume laser operation with no detuning of the pump field from the gain peak. In reality it may hardly ever be the case. The intracavity field can be detuned from the gain peak by a finite value, which can be a contributing factor to the spectral asymmetry (as shown in FIG. 9 below).

**[0052]** One impeding characteristic of the driven cavity solitons can be the presence of a strong background driving field that manifests itself in a mode 20 – 30 dB greater than the rest of the soliton spectrum. This feature can necessitate the use of detectors with high dynamic range and may cause gain depletion of optical amplifiers by the unnecessarily strong laser line. In passive Kerr resonators the pump can typically be filtered out by an external fiber Bragg grating or by outcoupling the intracavity field through an add-drop waveguide. The first approach may not be compatible with photonic integration as the mid-infrared optics can be based on free-space components. The second approach may not work with the active resonators presented herein, since the pump field that drives soliton formation, despite being

controlled by an externally injected field, can arise directly inside the cavity and could be equally outcoupled through the drop port.

**[0053]** Pump suppression can be achieved with a photonic integrated notch filter. An active ring resonator driven below the lasing threshold can act as such a filter, where the coupling condition, the quality factor, and the resonance frequency can be tuned independently via electrical pumping. Such a notch filter targeting only one laser line can be naturally integrated on the same chip with the soliton generator. In this implementation, both the soliton generator and the notch filter can be identical racetrack resonators connected via a bus waveguide. However, the soliton generator and the notch filter can be different resonators connected via the bus waveguide. The resonators can have nominally equal free spectral ranges (FSRs), which can be finely tuned by adjusting the pump current in both resonators and the integrated heaters (FIG. 3A). The soliton can be generated by an off-chip ECL in the first RT QCL driven above threshold, as in FIGS. 2A-2I, and the pump line can be subsequently filtered by the second RT QCL, operated below threshold (FIG. 3A). FIG. 3B shows the spectrogram of the output of this chip while tuning the bias of the notch filter. The filter can be close to the critical coupling, and its FSR can be slightly detuned from the intermode spacing of the soliton frequency comb, so that, relying on a Vernier effect, it can filter out one comb line at each current setting. The filter can suppress the pump line by 45 dB when tuned in resonance with the driving field (FIG. 3C). FIG. 3D shows the spectra of the output state when the filter is turned off and on, signifying the highly selective suppression of the driving field, while mildly affecting the rest of the comb spectrum. A soliton on a high-intensity background can turn into a background-free bright pulse when the filter is switched on (FIG. 3E).

**[0054]** FIGS. 3A-3E illustrate on-chip pump filtering. FIG. 3A shows an optical microscope image of the active resonator photonic integrated chip (e.g., device 100). The device 100 can include a soliton generator and a filter 305 (e.g., notch filter). The filter 305 can be coupled with the waveguide 110. The filter 305 can suppress a primary mode of the pulse. The filter 305 can include a filter resonator. The filter resonator can include a racetrack resonator. The filter resonator can suppress/filter the pump frequency. The filter resonator can be coupled with the waveguide 110. The chip can include two identical racetrack resonators connected via a bus waveguide. One resonator can be for soliton generation and one resonator can be for pump filtering. Integrated heaters can be implemented as concentric racetracks on the inner side of the soliton generator and of the filter.

[0055] FIG. 3B shows a spectrogram of the soliton state from the left racetrack resonator in FIG. 3A, as the filter response is tuned with the pump current. The critically coupled ring resonator (e.g., sometimes referred to as a “filter”) can progressively filter out comb teeth one by one, shown by the dashed line. FIG. 3C shows the filter response at the pump mode wavelength ( $1227\text{ cm}^{-1}$ ), showing the extinction ratio (ER) of 42 dB. FIG. 3D shows the optical spectra of the soliton generator when the filter (e.g., filter resonator) is switched off and switched on. The suppression of the pump frequency by 45 dB is achieved by fine-tuning the current of the filter and of the integrated heater. FIG. 3E shows reconstructed temporal waveforms of the soliton generator over two consecutive cavity roundtrips with filter off and filter on.

[0056] The requirement of an additional external laser to drive the formation of solitons and the reliance on the precise optical alignment of the system can hinder the practical deployment of devices in real applications. To address this issue, a mid-infrared photonic chip where the pump laser is monolithically integrated with the racetrack resonator can be implemented. FIG. 4A shows such a chip (e.g., device 100) in which the drive signal is derived from a Fabry-Perot (FP) cavity laser that is butt-coupled to the waveguide directional coupler. The device 100 can include the laser 105, the waveguide 110, and the resonator 115. The device 100 can include one or more heaters 405. The heater 405 can be disposed proximate to the resonator 115. The heater can modify a frequency of the resonator 115. All components can be active and can be DC biased individually in absence of any electrical crosstalk. Bringing both the FP and RT above their lasing thresholds, both in single-mode operation, and tuning the current of the heater (HT) integrated next to RT, the wavelength sweep of the FP through the RT resonance can be performed in the same way as was done with an external drive laser. On a red-detuned to blue-detuned backward scan over a finite range of detuning the output intensity can exhibit low-frequency fluctuations (FIG. 4B), which can be reminiscent of the modulation instability comb regime in passive Kerr resonators. As in Kerr resonators, the associated RF spectrum of the intermode beat note can feature multiple frequency tones. On the forward scan (e.g., blue-detuned to red-detuned), soliton formation can be associated with the disappearance of the intensity fluctuations in the laser output, while the driver laser is still in resonance, and the emergence of a stable microwave tone at the roundtrip frequency, which can signify the high degree of the phase coherence of the multimode state (FIG. 4B). The spectrum of the soliton state can feature tens

of lines, all mutually locked, giving rise to a stable bright pulse emission on top of the CW background (FIG. 4C).

**[0057]** Another superior attribute of the integrated soliton generator, besides its compactness, can include the long-term stability of the soliton state and its ability to recover upon power cycling. Turnkey soliton generation and perfect state recovery can be demonstrated in a sequence of power cycles by switching on and off the drive currents of the integrated components in a prescribed manner (FIG. 4D). The soliton state initiated in this way can remain stable for hours of continuous operation (FIG. 4E). These features of the fully integrated system can be prevalent in Si<sub>3</sub>N<sub>4</sub> Kerr resonators heterogeneously integrated with III-V semiconductor pump lasers.

**[0058]** FIGS. 4A-4E illustrate an integrated turnkey soliton generator. FIG. 4A shows an optical microscope image of the QC photonic integrated chip. The chip can include two identical devices that each include four components: a Fabry-Perot drive laser (FP), a waveguide coupler (WG), a resistive heater (HT) and a racetrack resonator (RT). The insets show blown up micrographs of the coupling regions between the FP and the WG (butt coupler) and between the WG and the RT (directional coupler). The top of FIG. 4B shows the output intensity, interferogram, and the optical spectra of the RT resonator on a backward and on a forward scan of the FP through the RT lasing resonance. The bottom of FIG. 4B shows a spectrogram of the radio frequency beat note on the backward and on the forward scan as function of the detuning. FIG. 4C shows the power spectral density (PSD) and the reconstructed temporal waveform of the soliton state obtained on the forward wavelength scan. FIG. 4D shows the interferogram and output intensity when the soliton generator is turned on and off. The same state can be recovered at each power cycle following the on-off algorithm that involves adjusting the biases of RT, FP, and HT. FIG. 4E shows the PSD in the soliton state, acquired at equally distributed time intervals, showing an uninterrupted and intact soliton state over a span of four hours.

**[0059]** The demonstrated devices can be prototypical components for more elaborate mid-infrared photonic integrated architectures for short pulse generation. The systems and methods of the present disclosure can include the first DC-driven, chip-scale pulse generator in this wavelength range (e.g., mid-infrared). The peak pulse intensity can be raised to the level suitable for supercontinuum generation and second harmonic generation in nonlinear crystals, chalcogenide glass fibers, and passive III-V/Si/Ge waveguides. Power gains can be achieved by improved chip thermal management (e.g., buried heterostructure regrowth, epi-

down mounting) and by combining the designs shown in FIGS. 3A and 4A with an additional integration of a semiconductor optical amplifier at the end of the waveguide coupler (as shown in FIG. 22A below). Although the demonstration can be performed at  $8.3\ \mu\text{m}$ , this approach can be applicable throughout the mid-infrared (e.g.,  $4 - 12\ \mu\text{m}$ ) utilizing the band structure engineering paradigm and to shorter wavelengths using other semiconductor laser gain media (e.g., interband cascade, quantum well, quantum dot, and quantum dash). Soliton mode-locking reliant on a bistability may be a compelling alternative to passive mode-locking with a saturable absorber in these laser systems as the absorber induces additional cavity loss that limits the average optical power and the pulse energy.

**[0060]** The maturity of both semiconductor lasers, active resonators, and nonlinear Kerr cavities, passive resonators, can invite consideration towards hybrid passive-active nonlinear integrated systems. On one hand, passive  $\text{Si}_3\text{N}_4$  nonlinear resonators can be endowed with active functions (e.g., amplification and lasing) by ion implantation or by heterogeneous and monolithic integration. On the other hand, as described herein, concepts initially coined in the context of passive cavities can be extended to resonators with gain, allowing observation of new phenomena, such as direct on-chip bright pulse generation, up to now regarded as improbable in QCLs due to the absence of a suitable mode-locking mechanism.

**[0061]** All components, including the routing waveguides, can be made of active media, which can include electrical biasing to reduce optical loss. Further monolithic integration of III-V passive semiconductor waveguides with QC active media can enable larger-scale integrated architectures for linear and nonlinear absorption spectroscopy, absolute time and frequency metrology in the  $4 - 12\ \mu\text{m}$  window, and free-space optical communications. This can include on-chip dual-comb QCL spectrometers. It can be possible to have multiple active components on a chip (including lasers above threshold) biased independently and working simultaneously, each fulfilling their own function. The intrinsic immunity of the ring resonator based QCL frequency combs to delayed optical feedback can justify the on-chip integration of such components to create functional spectroscopic and metrological systems, which can eliminate the need for an optical isolator.

#### **Generalized model**

**[0062]** Numerical simulations can be carried out by integrating the GLLE model on a regular CPU. The simulations of both passive and active devices based on the GLLE can be

performed using two different integration schemes, which can verify the robustness of the theoretical predictions. One code can be based on the Exponential Time Stepping scheme with large spatial grids (500-10000 points) and time steps optimized for stability, convergence and numerical efficiency. The second scheme can be based on the modal decomposition of the electric field  $E$  in terms of the longitudinal modes of the cold cavity. The field can be expanded into  $2N + 1$  modes (e.g., the central one and  $N$  modes for each side of the spectrum). Typically,  $N = 100$ . An application for a custom GUI-enhanced GLLE solver used for rapid prototyping of the longer parameter sweeps can be provided.

### Device fabrication and operation

**[0063]** The lasers can emit at around  $8.3 \mu\text{m}$  and have a structure that includes GaInAs/AlInAs layers on an InP substrate. The active region band structure design can be based on a single-phonon continuum depopulation scheme. The waveguides can be dry etched ( $6 \mu\text{m}$  depth) using the ridge process with optical lithography. The dry etch can result in nearly  $90^\circ$  vertical waveguide sidewalls. Waveguide width can be  $10 \mu\text{m}$ . The curved section of the racetrack can be a semicircle with a radius of  $500 \mu\text{m}$ . The length of the straight section can be  $785 \mu\text{m}$  for the devices in FIGS. 2A and 3A (FSR  $18.6 \text{ GHz}$ ) and  $1.5 \text{ mm}$  for the device in FIG. 4A (FSR  $13.8 \text{ GHz}$ ). The air gap in the directional coupler section can be  $1 \mu\text{m}$  wide. The facets of the Fabry-Perot pump lasers and of the waveguide couplers can be left as cleaved or can be dry etched in places where the optical coupling occurs on the chip. Laser dies can include indium soldered epi-side up on copper carriers and individual contact sections can be wire-bonded to PCBs. All chips can be placed on temperature-stabilized heat sinks at  $16^\circ\text{C}$ . All components (e.g., laser resonators, waveguide couplers, heaters) can be individually biased with low-noise current sources (e.g., Wave-length Electronics QCL1500 or QCL2000).

### Optical injection setup

**[0064]** The coherent optical drive signal can be derived from a custom-built external cavity tunable QCL (ECL) by DRS Daylight Solutions. The beam from the ECL can be focused onto the WG facet with an aspheric antireflection coated lens ( $\text{NA} = 0.56$ ) and the output radiation can be collected at the opposite WG facet with an identical lens. Part of the output can be focused directly onto an MCT photodetector (VIGO photonics,  $300 \text{ MHz}$  cutoff) for the output power/transmission measurement. Another part can be sent through a Michelson interferometer onto an MCT photodetector (VIGO photonics,  $1 \text{ GHz}$  cutoff) for

acquisition of an interferogram and of an optical spectrum. The detector outputs can be sampled at 1.8 GSa/s (output intensity) and 7 MSa/s (interferogram) using data acquisition (DAQ) and oscilloscope (OSC) modules of the Zurich Instruments MF and UHF lock-in amplifiers. The resonance detuning can be controlled and the resonance sweep scans can be performed by fixing the wavelength of the ECL and applying a triangular wave modulation with a function generator (SWEEP box) to the electrical drive current of heater integrated next to the racetrack resonator. An RF spectrum of the intermode beatnote can be acquired by bringing an RF probe in contact with a laser die. The temporal waveforms can be reconstructed using shifted wave interference Fourier transform spectroscopy (SWIFTS).

### Generalized theory of solitons in active and passive resonators

[0065] The numerical model used for the simulations of the soliton states in active ring resonators can be based on the generalized Lugiato-Lefever equation (GLLE) for the spatiotemporal evolution of an electric field envelope  $E$  in an optical cavity:

$$\tau_p \frac{\partial E}{\partial t} = \overset{\text{driving}}{E_I} + \overset{\text{damping-detuning}}{(-1 - i\theta_0)E} + \overset{\text{diffusion-dispersion}}{(d_R + id_I) \frac{\partial^2 E}{\partial z^2}} + \overset{\text{gain/loss, nonlinearity}}{\mu(1 - i\Delta)(1 - |E|^2)E} \quad \text{Eq. 1}$$

[0066] In Eq. 1,  $t$  and  $z$  are the temporal and spatial coordinates along the cavity axis, in a reference frame moving at the light velocity in the cavity,  $\tau_p$  is the damping time of the cavity field,  $E_I$  is the amplitude of the driving field,  $\theta_0$  is the detuning of the driving field with respect to the cavity resonance, and  $\mu$  is the unsaturated gain ( $\mu > 0$ ) or absorption ( $\mu < 0$ ) parameter. In the diffusion-dispersion term, the differential operator applied to cavity modes  $\propto e^{ik_n z} E_n$  provides an algebraic term  $-id_k k_n^2 E_n - d_R i k_n^2 E_n$ , whose imaginary part is associated with frequency dispersion while the real part (for  $d_R > 0$ ) is a diffusion term that acts as a cutoff on the frequency spectrum. The Lugiato-Lefever equation (LLE) describing the case of a *passive* Kerr resonator under external optical pumping can be derived from Eq. 1 by assuming a weakly absorbing medium ( $\mu < 0$  and  $|\mu| \ll 1$ ) in the limit of strong negative atomic detuning ( $\Delta < 0$  and  $|\Delta| \gg 1$ ) and large resonance curve bandwidth ( $d_I \gg d_R$ ). The LLE is shown according to Eq. 2:

$$\text{Passive resonator (LLE): } \frac{\partial F}{\partial \tau} = F_I - [1 + i(\theta - |F|^2)]F + i \frac{\partial^2 F}{\partial \eta^2} \quad \text{Eq. 2}$$

with  $\theta = \theta_0 + \mu\Delta$ ,  $F = \sqrt{\mu\Delta}E$ ,  $F_I = \sqrt{\mu\Delta}E_I$ ,  $\tau = t/\tau_p$ . To show the formation of intracavity solitons as the detuning of the drive laser is scanned, Eq. 2 can be integrated numerically. On a forward detuning scan (e.g., increasing the value of  $\theta$  from negative to positive values) the

soliton can be formed accompanied by a sharp step in mean intracavity intensity (FIG. 5A). This can be a signature feature of soliton formation which can be seen in the experiments.

**[0067]** The model describing an *active* resonator can be derived from Eq. 1 for  $\mu > 1$  ( $\mu = 1+r$ ,  $|r| \ll 1$ , ring resonator above threshold for  $r > 0$  and below threshold for  $r < 0$ ), yielding a forced complex Ginzburg-Landau equation (FCGLE):

$$\text{Active resonator (FCGLE): } \frac{\partial F}{\partial \tau} = F_I + \gamma(1 - i\theta)F - (1 - i\Delta)|F|^2F + (1 + iG) \frac{\partial^2 F}{\partial \eta^2} \quad \text{Eq. 3}$$

with  $\gamma = r/|r|$ ,  $\theta = \theta_0 + \mu\Delta/r$ ,  $G = d_I/d_R$ ,  $F = E/\sqrt{|r|}$ ,  $F_I = E_I/|r|^{3/2}$ ,  $\tau = |r|t/\tau_p$ ,  $\eta = z\sqrt{|r|}/d_R$ . The detuning of the drive laser frequency  $\omega_0$  from the frequency of the ring laser  $\omega_L$  is given by  $(\omega_L - \omega_0)\tau_p = r(\theta - \Delta)$ . Performing sweeps of the detuning parameter  $\theta$  and integrating Eq. 3 can yield the generation of a bright cavity soliton on a forward scan. One of the differences between the active resonators driven above the threshold and the passive resonators can be the presence of the low-frequency modulation of the intracavity intensity outside of the injection locking range due to the beating between the drive laser field and the intracavity field of the ring laser. This characteristic can set active resonators above threshold apart from fiber-based active nonlinear resonators. They can be dubbed “active” due to the incorporation of an amplifier inside the fiber loop cavity. However, the amplifier setting is such that the fiber resonator remains *below the lasing threshold*, and the optical nonlinearity responsible for soliton formation is the Kerr nonlinearity of the passive fiber, rather than the nonlinearity due to gain saturation, as is in the case of semiconductor laser resonators described herein. The purpose of the amplifier in the case of active fiber resonators can be that of increasing the cavity quality factor. In the active semiconductor resonators described herein, the gain both provides the nonlinearity necessary for comb formation and brings the system *above the lasing threshold*.

**[0068]** Eq. 3 can be derived from the full laser model based on the effective semiconductor Maxwell-Bloch equations (ESMBEs) in the presence of an external coherent optical drive. The assumptions that enable model reduction can include: (1) a fast gain medium, such that the field evolves on the timescale of the photon lifetime  $\tau_p$ —much longer than the polarization dynamics and the carrier dynamics, and (2) the ring laser operates just slightly above its threshold,  $|r| \ll 1$ .

[0069] Even though these assumptions may seem restrictive, and the model is simplified, they can be justified by the fact that by simulating the full ESMBE model, one can obtain stable bright solitons induced by the coherent drive. In the experiments, the ring laser can be driven substantially (e.g., 1.4 – 1.6 times) above the threshold, which can enable high optical power levels for applications.

[0070] FIGS. 5A-5B illustrate simulated detuning sweeps in passive and active resonators. FIG. 5A shows the spatiotemporal evolution of the intracavity waveform obtained by sweeping the detuning parameter  $\theta$  of the LLE (Eq. 2) in the forward and in the backward directions. The line plot on top shows a mean intracavity intensity at each value of the detuning. The panel on the right shows a single cavity soliton obtained at  $\theta = 3.5$ , other parameters are  $F_I = 1.8$ ,  $\Delta = -100$ ,  $G = 100$ ,  $\gamma = -1$ ,  $r = 0.01$ . FIG. 5B shows the spatiotemporal evolution of the intracavity waveform obtained by sweeping the detuning parameter  $\theta$  for the case of an active resonator by integrating the FCGLE (Eq. 3). The panel on the right shows a single cavity soliton obtained at  $\theta = 10.3$ , other parameters are  $F_I = 50$ ,  $\Delta = G = 2.5$ ,  $\gamma = 1$ .

[0071] The behavior shown in FIG. 5B can be understood by a study of the homogeneous stationary solution of the FCGLE and its stability. FIG. 6 shows the stationary intensity  $X$  as a function of the detuning  $\theta$ . The negative slope branch between the saddle nodes  $SN_1$  and  $SN_2$  can be unstable as usual. The stability analysis can show that the laser gets locked to the driving field when the stationary intensity  $X = 0.5$ . The locking points can be denoted by  $IL_1$  and  $IL_2$ . To the left of  $IL_1$  and to the right of  $IL_2$  the output can be oscillatory, as shown in FIG. 5B. Finally, the point MI can mark the onset of a modulational instability. The Rolls points can indicate the maximum and minimum intensity of the roll patterns that emerge from MI. As  $\theta$  increases, these patterns can destabilize and transform into one or more cavity solitons (CSs). The CS points can indicate the peak intensity of the CS. In correspondence with the appearance of the CSs, the average intensity, which is the quantity shown by the white line in FIG. 5B, can drop, and the so-called soliton step can be observed. Increasing further  $\theta$  the homogeneous solution can be reached, which can be stable first and then unstable. In a backward scan, the CS branch cannot be reached, and the laser jumps directly from the stable homogeneous solution to the roll pattern.

[0072] FIG. 6 illustrates the intensity of the stationary homogeneous solution of the forced complex Ginzburg-Landau equation as a function of the detuning  $\theta$ . The parameters are in FIG. 5B. The dashed parts of the curve represent unstable solutions. SN represents

saddle node, IL represents injection locking, and MI represents modulational instability. The Rolls dots represent the maximum and minimum intensities of the roll patterns that emerge from MI, and the CS dots are the maximum intensities of the cavity solitons (CS).

[0073] Finally, removing the external coherent drive ( $F_I = 0$ ,  $\theta = 0$ ) can lead to the complex Ginzburg-Landau equation (CGLE):

$$\text{Active resonator (CGLE): } \frac{\partial F}{\partial \tau} = \gamma F - (1 - i\Delta)|F|^2 F + (1 + iG)\frac{\partial^2 F}{\partial \eta^2} \quad \text{Eq. 4}$$

[0074] CGLE can have the same form as the equation formulated in for the ring laser. Eq. 4 can be used to predict the onset of modulation instability and the formation of stable structured waveforms in free-running ring QCLs, also detected in the experiments (e.g., homoclons and Nozaki-Bekki solitons). Eq. 4 can be derived from the complete master equation laser model.

### The single-sided spectrum

[0075] One of the discrepancies between the experiment and the model can be that the perfect symmetry in the simulated soliton spectra is in strong contrast with highly asymmetric single-sideband experimental spectra. As shown, the spectral asymmetry is a systematic feature, rather than an anomaly, and deserves a separate analysis. One of the effects that could be behind this experimental asymmetry can be described below.

[0076] Eq. 3 can be modified by including a third-order dispersion (TOD) term. Indeed, may not be a good reason to assume that TOD is negligible in QCLs, given a highly dispersive line shape of the susceptibility of the active medium. TOD can have a profound effect on the dynamics of the frequency comb states in free-running Fabry-Perot QCLs, resulting in lobed spectra and discontinuous frequency chirps in the output waveform. These effects can be properly accounted for in the modeling of the ring QCLs. The modified FCGLE incorporating the TOD term reads:

$$\frac{\partial F}{\partial \tau} = F_I + \gamma(1 - i\theta)F - (1 - i\Delta)|F|^2 F + (1 + iG)\frac{\partial^2 F}{\partial \eta^2} + G_1 \frac{\partial^3 F}{\partial \eta^3} \quad \text{Eq. 5}$$

where the third order dispersion parameter is:

$$G_1 = \tilde{c}^4 \tau_p \frac{k^m}{6} \frac{\sqrt{r}}{d_R \sqrt{d_R}} \quad \text{Eq. 6}$$

[0077] Running the simulation using  $G_1 = 1.25$ ,  $Y = 7$  can yield an asymmetric spectrum for a single soliton state (FIGS. 7A and 7B). The simulated asymmetry in the spectrum can appear less drastic than in the experiment. The origins of the asymmetry can point towards the aspects of device engineering to make the spectrum symmetric, thus increasing comb bandwidth and decreasing pulse duration.

[0078] FIGS. 7A-7B illustrate a simulated soliton state in the presence of third order dispersion. FIG. 7A shows an asymmetric soliton spectrum. FIG. 7B shows its time domain profile that emerge from the simulation of the FCGLE when adding a third-order dispersion term.

[0079] To emphasize the universal nature of the single-sided spectrum, FIG. 8 shows a series of experimental soliton spectra where each spectrum was taken while driving the ring QCL at a different wavelength setting of the ECQCL widely across the ring QCL gain bandwidth. It is apparent that when injecting at longer wavelengths the spectral lobe appears on the blue side of the drive laser frequency, whereas injecting at the shorter wavelengths, the spectral lobe moves to the red side of the drive laser frequency. It is almost as if there was a “tipping point” (e.g., an unstable equilibrium, the wavelength at which the lobe switches from the blue side to the red side).

[0080] To find this “tipping point” and to generate a symmetric spectrum, the region can be narrowed down to below 2 GHz where the switching of the spectral lobe occurs. Still, even over such a small tuning range there occurs a drastic switch of the lobe from the blue to the red side of the pump, as the spectra in the bottom panel of FIG. 8 show.

[0081] FIG. 8 illustrates a soliton generator across the laser bandwidth. The top panels show a series of optical spectra when tuning the wavenumber of the ECQCL, indicated in  $\text{cm}^{-1}$ , through different resonances within the ring laser gain bandwidth. The gain profile can be extracted from a subthreshold electroluminescence measurement of a Fabry-Perot QCL fabricated on the same wafer with the ring QCL. The bottom panel shows two spectra, overlaid, when tuning the injected resonance over 1.92 GHz, around  $1220 \text{ cm}^{-1}$ .

#### **The role of the linewidth enhancement factor**

[0082] In the FCGLE and the CGLE, the coefficient in front of the nonlinear term can be a compound one containing two contributions:  $\Delta = \alpha_p + \beta$ , where  $\beta$  is the Kerr coefficient of the bulk crystal, whereas  $\alpha_p$  is the linewidth enhancement factor (LEF), per original

definition of Charles Henry. Similarly, the coefficient of the GVD term can include two contributions  $G = \alpha_p + \zeta$ , where  $\zeta$  is proportional to the dispersion coefficient  $k''$ .

**[0083]** The LEF can be introduced into the expression for the complex susceptibility of the lasing transition following the treatment developed in. Here,  $\alpha_p$  is the LEF value at the gain peak (e.g., where the laser is assumed to operate). Despite being a scalar quantity, it can modify the line shape of the entire frequency-dependent susceptibility  $\chi(\omega)$ , both its real part  $\chi'(\omega)$  associated with the refractive index  $n \approx n_r[1 + \chi'(\omega)/2]$  and its imaginary part  $\chi''(\omega)$  associated with gain  $g = \omega n_r \chi''(\omega)/2c$ , where  $n_r$  is the refractive index of the bulk crystal:

$$X(\omega) = -\frac{\mu^2 T_2 \Delta N}{\epsilon_0 h} \frac{i(1 - i\alpha_p)}{1 - i\alpha_p - i\omega T_2} \quad \text{Eq. 7}$$

**[0084]** Here  $\omega$  is the frequency measured with respect to the frequency of the gain peak,  $\Delta N$  is the excess of carriers with respect to transparency,  $\mu$  is the dipole moment associated with the optical transition, and  $T_2$  the dephasing time. The spectrally-resolved LEF at an arbitrary detuning from the gain peak can then be found as:

$$\alpha(\omega) = \frac{\partial \chi' / \partial \Delta N}{\partial \chi'' / \partial \Delta N} = \frac{\chi'(\omega)}{\chi''(\omega)} = \frac{\alpha_p(1 + \alpha_p^2) - \omega(1 - \alpha_p^2)}{1 + \alpha_p^2 + 2\omega\alpha_p} \quad \text{Eq. 8}$$

**[0085]** The second equality holds because  $\chi(\omega)$  can be proportional to  $\Delta N$ , the last expression shows that  $\alpha(0) = \alpha_p$ . From Eq. 8, it can follow that the optical nonlinearity is dispersive (e.g., it attains frequency-dependent values). This property of active nonlinear resonators can be in contrast with the crystalline Kerr nonlinearity of passive microresonators, which can operate in a limit of strong atomic resonance detuning with the Kerr nonlinearity being constant across the entire bandwidth of the attainable comb states. Nonlinearity dispersion that naturally arises from the gain curvature may have non-negligible effects on the dynamics of the soliton states in active resonators. For instance, it can be one of the origins of the strong asymmetry of the comb spectrum.

**[0086]** To visualize the effects of non-zero  $\alpha_p$  on the complex susceptibility in the presence of population pulsations (time-dependent  $\Delta N = \Delta N(t)$ ), its real and imaginary parts can be plotted for  $\alpha_p = 0$  and  $\alpha_p = 0.5$  and for different values of  $\Delta N$  (FIG. 9). For zero LEF the gain can be symmetric and  $\chi'(0) = 0$ . Modulation of  $\Delta N$  can affect only the imaginary part of the susceptibility at the position of the gain peak, while the real part can be pinned to zero regardless the value of  $\Delta N$ . Non-zero LEF ( $\alpha_p = 0.5$ ) can induce the asymmetry in both real and imaginary parts of the susceptibility. As a result  $\chi'(0) = 0$  at the gain peak and modulation

of  $\Delta N$  leads to the modulation of both real and imaginary parts of the complex susceptibility. The optical field inside the laser will see both gain and index modulation leading to the modulation of its amplitude and phase. Furthermore, it is evident from the plots in FIG. 9 and from Eq. 8 that the nonlinear coefficient due to the LEF changes its sign at  $\omega = \alpha_p(1 + \alpha_p^2)/(1 - \alpha_p^2)$ . FIG. 9 illustrates real and imaginary parts of the laser medium susceptibility for  $\alpha_p = 0$  and  $\alpha_p = 0.5$ .

**[0087]** Taking into account Eq. 7, the constitutive relation  $P_0(\omega) = \epsilon_0 \chi(\omega) E_0(\omega)$  can be written as Eq. 9.

$$(1 - i\alpha_p - i\omega T_2)P(\omega) = (1 - i\alpha_p)^2 DE(\omega) \quad \text{Eq. 9}$$

where  $P(\omega) = iP_0(\omega)/(\mu\Delta N_0)$ , where  $\Delta N_0$  is the unsaturated carrier density,  $E(\omega) = T_2\mu E_0(\omega)/\hbar$ , and  $D = \Delta N/\Delta N_0$ .  $P$ ,  $E$ , and  $D$  are dimensionless. By Fourier transforming Eq. 9 and assuming  $D$  constant, a dynamical equation for the polarization  $P(t)$  can be obtained:

$$T_2 \frac{\partial P}{\partial t} = (1 - i\alpha_p)[(1 - i\alpha_p)DE - P] \quad \text{Eq. 10}$$

**[0088]** The FCGLE can be obtained by an adiabatic elimination of the material variables. Keeping terms up to the second time derivative, the following can be obtained from Eq. 10:

$$P = (1 - i\alpha_p) \left[ 1 - \tilde{T}_2 \frac{\partial}{\partial t} + \tilde{T}_2^2 \frac{\partial^2}{\partial t^2} \right] (DE) \quad \text{Eq. 11}$$

with  $\tilde{T}_2 = T_2/(1 - i\alpha)$ . Since  $D$  is a slow variable, it can be taken out from the time derivative and approximated with its stationary value  $D = 1/(1 + |E|^2)$ . For a laser close to threshold, the saturation can be small and  $D \simeq 1 - |E|^2$  and even  $D \simeq 1$  in the terms containing the time derivative, which are small by themselves. Therefore, the following can be written:

$$P \simeq (1 - i\alpha_p) \left[ E - |E|^2 E - \tilde{T}_2 \frac{\partial E}{\partial t} + \tilde{T}_2^2 \frac{\partial^2 E}{\partial t^2} \right] \quad \text{Eq. 12}$$

**[0089]** By inserting this expression for  $P$  in the Maxwell equation for the electric field, Eq. 13 can be obtained:

$$\tilde{c} \frac{\partial E}{\partial z} + \frac{\partial E}{\partial t} = \frac{1}{\tau_p} \left[ -(1 + i\theta_c)E + E_l + P + i\beta|E|^2 E - i\tilde{c} \frac{k''}{2} \frac{\partial^2 E}{\partial t^2} \right] \quad \text{Eq. 13}$$

[0090] The ubiquitous role of the LEF, which appears in the linear term and combines with the Kerr coefficient  $\beta$  in the nonlinear term and with  $k''$  in the GVD term, can be seen.

#### **System setup and device characterization - Forward-backward scans**

[0091] Forward-backward wavelength scans can be performed either by finely tuning the wavelength of the drive laser through the resonance of the RT QCL, or, fixing the wavelength of the drive laser, tuning the resonance of the RT QCL past the frequency of the drive laser. Resonance tuning can be achieved by modulating the current of an integrated heater (HT), placed adjacent to the RT QCL. Triangular sawtooth modulation can be applied to the filter bias (FIG. 10A) and the output intensity from WG facet can be monitored alongside with the field autocorrelation (interferogram) at the output of the Michelson interferometer on a linear intensity detector. On a forward scan the heater current can be decreased which can result in the decrease of resonator refractive index, which can shift the drive laser frequency from the blue to the red side of the ring resonance. On a backward scan, the heater current and refractive index can increase, and the drive laser can scan from the red to the blue of the ring laser resonance. Both scan directions can be associated with the sharp asymmetric resonances visible in the output intensity signal. There can be a bistable behavior (e.g., the resonance on the backward scan can appear broader than the one on the forward scan). Moreover, on the backward scan, the interferogram can signify a transition to multimode operation, associated with a sharp step (or a series of sharp steps) seen in transmission. On these steps, the ring laser can generate one or several cavity solitons.

[0092] The resonance asymmetry and their depths can be a function of the incident optical power from the drive laser. Reducing the power to 20 mW can result in a much reduced resonance contrast and no soliton generated on a backward scan (FIG. 10A). Increasing the power to 55 mW can recover the soliton steps (FIG. 10B). Overall, the soliton generation can occur past a certain threshold of incident power, like in passive Kerr microresonators.

[0093] FIGS. 10A-10B illustrate a forward-backward wavelength scans. FIG. 10A shows the interferogram and the output intensity, acquired at a lower sampling rate and the corresponding voltage signal applied to the heater of the RT QCL, in order to perform the wavelength scan. Sweeping the bias of the heater can change the refractive index of the RT QCL, which effectively scans its lasing resonance through the fixed frequency of the drive laser. The SWEEP box in the schematics of the experimental setup can be a function generator that outputs the sawtooth waveform shown. The incident power of the drive laser

can be 150 mW. The pronounced slow modulation on the interferogram can be a beating between the drive laser and the ring laser, that have almost equal intensities. FIG. 10B shows the interferogram and intensity on the forward-backward wavelength scans for different levels of the drive laser power (20 mW and 55 mW). Decreasing the power of the drive laser can result in the reduction of the beating modulation in the interferograms, as compared to the one in FIG. 10A.

#### **Stochastic switching of the soliton states**

**[0094]** The optical spectrum of the coherently driven ring QCL can switch every few seconds even under constant driving conditions. This phenomenon, called multistability, can be typical of such coherently driven systems that support soliton generation. On each such switch the number of the cavity solitons and their relative positions may change, resulting in different modes of operation, each stable for several seconds. The mechanical and thermal fluctuations of the system can lead to these switches when the optical components are discrete. The chip with an integrated drive laser may not exhibit such multistable behavior.

#### **LIV of the racetrack QCL**

**[0095]** The racetrack (RT) QCLs with integrated waveguide (WG) couplers can be operated above their lasing thresholds in a unidirectional regime. A prototypical device (e.g., characterized in FIG. 11) can exceed 80 mW of continuous-wave power when cooled to 16°C and soldered epitaxial-side up on a copper heat sink. The lasing threshold for a RT QCL with a 6.14 mm circumference can be 531 mA, which can correspond to a threshold current density of  $J_{th} = 0.865 \text{ kA/cm}^2$ . The integrated WG can be separated from the straight section of the RT by an air gap of 1  $\mu\text{m}$ , permitting efficient extraction of light generated in the RT. In addition, separate electrical contacts for the RT and WG can allow their independent driving without electrical crosstalk. The WG can be biased below its lasing threshold to a value of 500 mA. The lasing directionality can spontaneously switch while tuning the bias of either the RT or the WG. Here, laser emission can switch from predominately clockwise (CW) emission to counter-clockwise (CCW) at  $I_{RT} = 730 \text{ mA}$ , noted by drop in the output power measured from the CW facet of the WG, then can switch back to CW at  $I_{RT} = 1000 \text{ mA}$  when the CW facet power rapidly increases. Peaks and valleys in the light output can correspond to the WG resonances. The WG facets can be left uncoated with a reflectivity of 0.28.

**[0096]** FIG. 11 illustrates a ring QCL power performance. FIG. 11 shows the light-current-voltage (LIV) of a racetrack (RT) QCL from the laser chip with an integrated drive

laser showing the output power above 80 mW at room temperature. The RT emission can switch directions as its bias is increased.

#### **Gain saturation in a ring QCL**

**[0097]** Being able to injection lock the ring laser frequency to the drive laser, perform the wavelength scans over wide detuning range, and generate solitons, can require reaching a certain input power level. To make sure the power of the drive laser is sufficient, given the power budget of the free-space link between the output facet of the drive laser and the input facet of the waveguide coupler, it can be verified that the gain of the ring laser can be saturated. Even moderate input power levels (20 mW) can be sufficient to saturate the gain of the ring laser, as shown in FIGS. 12A-12D.

**[0098]** FIGS. 12A-12D illustrate gain saturation in an active QC resonator below and above the transparency. FIG. 12A shows that driving the ring QCL below its transparency current results in a resonance dip in transmission. The shape of the resonance dip and on-resonance attenuation does not change when increasing the incident power of the probe laser. Scanning through the resonance in this case can be achieved by sweeping the current of the ring laser over a narrow range around the operating point. FIG. 12B shows the transmission of the ring QCL above transparency at increasing incident power of the probe laser. Peak in transmission at low incident power levels turns into a dip at higher power due to gain saturation. FIG. 12C shows on-resonance output intensity as function of the input power and calculated gain as function of incident power for below transparency driving. FIG. 12D shows on-resonance output intensity as a function of input power and calculated gain as a function of incident power for the above transparency driving.

#### **Optical bistability on power scans**

**[0099]** The bistability can equally be observed while fixing the detuning of the drive laser from the ring laser frequency and sweeping the power of the drive laser. The input power of the drive laser can be such that the RT is in the regime of strong gain saturation. Due to the non-zero linewidth enhancement factor, saturation of the gain, which can be proportional to the imaginary part of the optical susceptibility  $\Im\{\chi\}$  of the active medium, can lead to a change of its real part  $\Re\{\chi\}$ . Provided the picosecond gain recovery time of the QC active region, this saturation-induced change of  $\Re\{\chi\}$  can result in an effective ultrafast Kerr nonlinearity, as in passive nonlinear resonators, which can lead to an optical bistability in the input-output power relation of the driven RT resonator when the coherent drive laser is red-detuned from the RT's lasing resonance (FIG. 13A), but not when it is blue-detuned (FIG.

13B). Depending on the bias of the RT, the upper branch of the bistability curve can be stable or unstable (FIGS. 13C and 13D).

**[0100]** FIGS. 13A-13D illustrate optical bistability in a driven RT QCL included by varying incident optical power. FIG. 13A shows output power of the driven RT resonator above the threshold as function of the drive laser input power, when it is 150 MHz red detuned from the RT frequency. Bistable behavior can emerge when first increasing the drive power, and then decreasing it. The top panels show the spectra of the heterodyne beat note between the RT and the drive laser. FIG. 13B shows output power in the case of 200 MHz blue detuning. FIG. 13C shows output power in the case of 200 MHz red detuning. FIG. 13D shows output power in case of 200 MHz red detuning for a higher bias setpoint of the RT.

#### **Suppressing drive laser field with an integrated active filter - Theory of active filter operation**

**[0101]** Aspects that enable tunable on-chip pump filtering with high extinction ratios > 40 dB can be reviewed. A prototypical device for filter implementation can include a ring resonator with a directional coupler (FIGS. 14A and 14B). Its complex amplitude transmission T is given by Eq. 14:

$$T = \frac{-\alpha + te^{-i\theta}}{-\alpha t^* + e^{-i\theta}} \quad \text{Eq. 14}$$

where  $\alpha$  is a loss parameter that quantifies the residual fraction of the electric field amplitude after one roundtrip along the ring resonator,  $t$  is an amplitude transmission coefficient of the coupler that quantifies the fraction of the field amplitude that is not coupled to the ring resonator, and  $\theta$  is the phase accumulation across resonator roundtrip, which quantifies the input detuning from the cavity resonance. For  $0 < \alpha < 1$  the ring resonator can be lossy, for  $\alpha > 1$  the ring resonator can be amplifying. The detuning parameter  $\theta$  can span from  $\pi$  to  $\pi$  (with  $\theta = 0$  being the resonance condition) and can be related to the resonator length  $L$  and the light wavelength  $\lambda$  via  $\theta = 2\pi L/\lambda$ . The transmission coefficient  $t$  can quantify the coupling strength  $\kappa$  between the waveguide and the ring resonator via  $|\kappa| = \sqrt{1 - |t|^2}$  assuming no scattering loss in the coupling region. The value of  $\alpha$  relative to  $t$  defines the on-resonance attenuation of the incident field. For  $\alpha < t$  the resonator is said to be over-coupled; for  $\alpha = t$  the resonator is critically coupled. The critical coupling condition can be used to attenuate the pump field in the experimental demonstration described above. When  $\alpha > t$ , the resonator can be under-coupled. When  $\alpha = 1$ , the resonator can be transparent and can be used as a phase

shifter with a unity intensity transfer function. For  $\alpha > 1$  the resonator can be amplifying until the lasing threshold is reached at  $\alpha = 1/t$  (FIGS. 14A and 14B).

**[0102]** FIGS. 14A-14B illustrate the working principle of an active optical filter. FIGS. 14A and 14B show an active ring resonator with a directional coupler, which can showcase varying complex transmission (amplitude and phase) across the resonance depending on the value of the gain/loss parameter  $\alpha$ . Here,  $\alpha$  quantifies the residual fraction of the electric field amplitude after one roundtrip along the ring resonator.

**[0103]** Setting  $\theta = 0$ , all coupling regimes can be conveniently traced by plotting  $T(\alpha)$  according to Eq. 15:

$$|T(\alpha)|^2 = \frac{(\alpha - t)^2}{(1 - \alpha t)^2} \quad \text{Eq. 15}$$

**[0104]** The plot of on-resonance transmission  $|T(\alpha)|^2$  is shown in FIG. 14B. In a ring filter based on an electrically pumped semiconductor gain medium, the coupling regime can be selected post-fabrication simply by setting the value of  $\alpha$  via the change of the laser bias below threshold. This feature can be illustrated by performing an experimental characterization of a ring QCL below the lasing threshold. Changing the bias point of the RT resonator and sweeping the wavelength of a probe laser can result in a set of resonance transmission curves with a varying coupling condition from over-coupled to amplifying (FIG. 15A). FIGS. 15A-15B illustrate below threshold transmission of an active QC racetrack resonator.

### **Integrated filter transmission**

**[0105]** Monolithic integration of such active filters with the soliton generators can amount to placing two ring resonators along one bus waveguide. Biasing one resonator above threshold and generating the soliton using the external driving scheme, the drive laser mode can be filtered out by the second resonator biased below the threshold with the current set to satisfy the critical coupling condition. Additional heaters implemented as concentric racetrack resonator on the inside of the soliton generator and the filter can allow for two extra independent control knobs to tune the resonance frequency, and thus the FSRs of the resonators. In the presence of thermal crosstalk between the integrated components, the soliton generation procedure with subsequent drive laser filtering can involve a sequence of steps.

**[0106]** The first step can include (1) presetting the filter bias to bring it close to the critical coupling condition. This can be done after the initial calibration transmission measurement, such as the one shown in FIGS. 15A-15B. The second step can include (2) bringing the soliton generator ring to the bias current above threshold, where it remains in single mode, in absence of the external coherent drive. The third step can include (3) by tuning the current through the ring filter and through its heater, progressively fine tuning the resonance frequency and the attenuation by minimizing the output power from the integrated chip. The procedure can include increasing the filter bias red-shifts its resonance and increases its quality factor. The procedure can include increasing the heater bias red-shifts the resonance of the filter and decreases its quality factor. Combining these two knobs it is possible to optimize for maximum attenuation and to align the resonance frequency with the frequency of the ring laser (FIG. 17A). The fourth step can include (4) once the filter condition is optimized, forward scanning the frequency of the drive laser through the ring resonance to generate soliton, according to the technique introduced above. Alternatively, the drive laser frequency could remain fixed and the wavelength scan through the resonance can be performed by sweeping the current of the ring laser heater. In this case the filter settings can be readjusted to anticipate the shift in the ring laser frequency in the soliton regime.

**[0107]** The steps above present an iterative procedure that can be performed manually, but those could be fully automated with control electronics. The compact form factor of the system can be maintained by including an on-chip detector for transmission monitoring, relying, for example on a bifunctional QCL active medium. In addition to the filtered single soliton state, FIG. 17B shows a spectrum with a filtered primary mode of a 3 FSR-spaced comb state in a free-running ring laser (with no coherent drive).

**[0108]** FIGS. 16A-16B illustrate the working principle of a Vernier notch filter. FIG. 16A shows two racetrack resonators with identical length. The resonators can be tuned to exhibit slightly different free spectral ranges (FSRs) due to different injected electrical power levels and a resulting refractive index thermal shift. As a result, only one line in the laser spectrum is in resonance with one of the longitudinal modes of the filter. This condition can be periodic (e.g., every  $n$ -th line where integer  $n = \text{FSR}_L / (\text{FSR}_L - \text{FSR}_F)$  can coincide with the filter resonance). FIG. 16B shows an experimental transfer function of the integrated filter, calculated by normalizing the output spectrum in the filter “on” state by the spectrum in the filter “off” state. The spectrum prior to filtering (filter “off” state) is shown in the background.

[0109] FIGS. 17A-17B illustrate filter tuning and operation. FIG. 17A shows integrated filter transmission as function of the current through the ring filter (FT) and through the embedded heater (HT). The plot shows the influence of both current settings on the resulting filter transmission. FIG. 17B shows optical spectra of a free-running ring laser generating a 3 FSR spaced comb state when the integrated filter is switched off and switched on. The suppression of the primary mode by 38 dB can be achieved by fine-tuning the current of the filter and of the integrated heater.

#### **Integrated soliton generator - Below threshold transmission**

[0110] To demonstrate the coupling of the light from the integrated FP drive laser into the ring QC resonator, the FP laser can be operated in a single-mode regime above the threshold, and the drive current of the RT resonator can be swept, keeping it below the threshold. The light intensity collected from the output facet of the WG can show a series of resonances as function of the RT drive current, as in an externally driven system (FIGS. 18A and 18B). With increasing current, the resonances can narrow due to the decrease of the optical loss in the RT resonator.

[0111] FIGS. 18A-18B illustrate below threshold transmission of the RT QCLs. FIG. 18A shows experimental transmission of an RT QCL probed by an off-chip ECL at  $1218\text{ cm}^{-1}$  as function of the RT drive current. The WG current is at 9 mA. The RT free spectral range is 18.6 GHz. FIG. 18B shows experimental transmission of RT QCL with an on-chip FP drive laser. The FP laser can be used to probe the below threshold resonances of the RT QCL. The FP can be driven at 804 mA, the WG is at 50 mA, and the HT can be off. Sweeping the current of RT can result in a change of its mode index, which can effectively sweep its resonance past the fixed wavelength of the FP laser. Narrowing of the resonances can be due to the reduction of the optical loss with increased pumping. The lasing threshold of RT QCL can be at 550 mA and the FSR can be 13.8 GHz.

#### **Algorithm for turnkey soliton generation**

[0112] Soliton generation in the integrated device (e.g., a drive laser and a resonator on-chip) can be fully automated using a simple algorithm, which is shown in FIG. 19. There can be four independent bias points on the device: the FP drive laser, the RT, the HT, and the WG, each of which can be automatically swept to the optimal bias point for soliton generation. The bias of the WG and HT can remain fixed, while the FP and RT can both be automatically brought above their lasing thresholds. The RT in particular can be brought below its lasing threshold again as to follow the “correct” bias path to generate a unidirectional, single-mode field (which is subsequently injection locked by the drive FP

laser). Afterwards, the RT can make several small (1 mA) steps to sweep its frequency with respect to the frequency of the FP laser. Once the soliton is generated, the algorithm can halt for approximately 25 seconds to allow for thermal stabilization. One last bias step can be made to the RT to lock the laser chip at the most optimal point for stable soliton emission. The emitted soliton can be stable over the course of several hours after the turnkey algorithm is completed.

**[0113]** FIG. 19 illustrates a turnkey algorithm for stable soliton generation. The bias points for each device section (e.g., FP, RT, HT, WG) are plotted as a function of time to repeatably generate stable solitons from the integrated device described above.

#### **Waveform reconstruction**

**[0114]** SWIFTS reconstruction technique can be performed on the integrated soliton generator. The top row of FIG. 20 shows the optical spectrum overlapped with the SWIFTS spectrum. The overall shapes of both spectra can strongly resemble those of externally generated solitons of the previous section. The phases can closely match those of the off-chip-driven device. Finally, the reconstructed waveform can show isolated, bright picosecond pulses of light on top of a CW background. The pump line can be filtered out using a similar procedure described above with a fully integrated device.

**[0115]** FIG. 20 illustrates SWIFTS reconstruction of the integrated soliton generator. The top row shows the both the optical spectrum and SWIFTS spectrum for the soliton generated in the integrated system. The second row shows the intermodal phases associated with the SWIFTS spectrum, while the reconstructed waveform is shown in the bottom row. The bright pulse of lights lies atop a CW background, which can be filtered out using an on-chip filter described in the previous section.

#### **Detailed forward-backward wavelength scan**

**[0116]** An example sweep through a resonance can generate a bright soliton in the integrated laser chip. FIG. 21 shows the real-time interferogram and RT output as the FP laser is swept first from the red to blue side (e.g., backward scan) of the RT resonance, then from the blue to the red side (e.g., left to right) of the RT resonance (e.g., forward scan). In practice, the sweep can be performed using the integrated heaters on the RT, but the detuning can be plotted as an arbitrary quantity to aid in qualitative understanding of the measurement. First, the pump can be swept from red to blue. The FP can lock to the resonance of the RT when the total RT output exhibits a sharp discontinuity. This can be accompanied by modulations in the IFG, indicating the formation of a structured spatiotemporal pattern inside the RT. The emission can return to single mode when the RT unlocks from the FP. Next, the

FP can be swept back through the resonance, but from the blue side to the red. Again, the RT can lock to the FP at approximately the same detuning point as in the backward scan. However, the RT resonance now extends further (e.g., caused by a bistability due to the large Kerr nonlinearity induced by the LEF). Continuous detuning of the pump laser can lead to deeper penetration into the red-detuned region. At one point of the bistable region, the RT output can become oscillatory (e.g., reminiscent of passive Kerr soliton generators). These oscillations can manifest themselves in multiple RF tones around the laser roundtrip frequency, seen in Fig. 4. After the oscillations subside, a sharp step in the RT output can indicate the formation of the soliton. The bottom row shows measured optical spectra at different points during forward scan (points 1 to 4). The RT output can slowly morph from a narrowband frequency comb with several lines at point 1 to a broadband soliton in the bistable region of the resonance at point 4.

**[0117]** FIG. 21 illustrates an experimental forward-backward scan in the integrated laser chip. The output intensity from the chip (combined FP intensity and RT intensity) of the drive FP with respect to the RT resonance is shown as a function of detuning along with the interferograms (IFGs) of the laser state (gray for backward scan, red for forward scan). On a backward scan (red-detuned to blue-detuned), the soliton does not form. On a forward scan (blue-detuned to red-detuned), the soliton forms in the bistable region of the resonance. Spectra plots show the PSD of the laser state at different points along the forward scan

#### **On-chip mid-IR supercontinuum generation**

**[0118]** Photonic integration of the discreet components on one semiconductor laser chip can produce chip-scale ultrabroadband coherent mid-IR sources. The device 100 is shown in FIG. 22A. The device 100 can include the laser 105, the waveguide 110, the resonator 115, and the filter 305. The device 100 can include an amplifier 2205 (e.g., semiconductor optical amplifier, SOA). The amplifier 2205 can be coupled with the waveguide 110. The amplifier 2205 can amplify the pulse. The device 100 can include a second waveguide. The second waveguide can include a non-linear waveguide. The non-linear waveguide can be coupled with the semiconductor optical amplifier. The non-linear waveguide can broaden a spectrum of the pulse.

**[0119]** Combining the designs in FIG. 3A and FIG. 4A, the first two stages can represent soliton generation by coherent driving of an active QC resonator above threshold and drive laser filtering by an integrated active filter (QC resonator driven below threshold). Subsequently, the waveform can be amplified by an inverse-tapered semiconductor optical amplifier, implemented from the same gain region as the rest of the structure. The amplifier

can output sub-picosecond sub-kW peak power pulses that are fed into a tapered passive nonlinear waveguide where the short pulse undergoes spectral broadening. In the interest of increasing the wall-plug efficiency of the device, the waveguides can be passive, implemented by regrowing a passive InGaAs layer after etching the QCL active region. With InGaAs waveguides exhibiting propagation loss of 0.5 - 1.5 dB/cm, even more complex multicomponent architectures can be produced, such as on-chip dual-comb spectrometers or self-referenced mid-IR frequency combs.

**[0120]** The large nonlinear coefficient of InGaAs ( $n_2 = 5 \times 10^{-17} \text{ m}^2/\text{W}$ ), its wide transparency window in the mid-IR, and the fact that it can be monolithically integrated with active III-V layers by epitaxial regrowth make this material one of the suitable candidates for the architecture shown in FIG. 22A. The requirements for on-chip supercontinuum generation (SCG) in InGaAs passive waveguides can be evaluated by carrying out numerical simulation of nonlinear spectral broadening based on the generalized nonlinear Schrödinger equation with an open-source solver pychi. Assuming an integrated laser chip with 0.8 W average output power after amplification, 1 ps pulse duration at 10 GHz repetition rate, a considerable broadening to more than an optical octave can be observed after propagation through a 7-mm-long passive waveguide when pumped at 8  $\mu\text{m}$  — close to the center wavelength of the devices shown above (FIG. 22B). This approach can be readily extended to QCLs across the mid-IR, therefore, on-chip SCG can be achieved at any wavelength, as the simulation in FIG. 22C shows an example of a pump wavelength of 4  $\mu\text{m}$ .

**[0121]** FIGS. 22A-22C illustrate on-chip mid-IR supercontinuum generation. FIG. 22A shows integrated components which can be assembled together with few modifications to create an on-chip supercontinuum generator. InGaAs on InP passive waveguides for light routing can be implemented using selective epitaxial regrowth on top of the active QC layer. Inverse-tapered semiconductor optical amplifier (SOA) based on a QC active medium can be used to amplify the soliton after filtering out the drive laser signal. SOA output can be fed into a tapered passive nonlinear waveguide (InGaAs) for nonlinear broadening. FIG. 22B shows simulated nonlinear broadening in a 7 mm long waveguide (InGaAs on InP). TM mode group velocity dispersion (GVD) is simulated for the waveguide width of 8  $\mu\text{m}$ , and the height of 4  $\mu\text{m}$ . The input pulse has a  $\text{sech}^2$  envelope, 1 ps duration, 80 pJ pulse energy. The center wavelength is 8  $\mu\text{m}$ . The nonlinear index of InGaAs is taken as  $n_2 = 5 \times 10^{-17} \text{ m}^2/\text{W}$ . FIG. 22C shows the same simulation as in FIG. 22B, but for an input pulse center wavelength of 4.5  $\mu\text{m}$ . Nonlinear simulations are performed using the pychi package.

[0122] Even though the average power of 0.8 W chosen in the SCG simulations exceeds the average power of the devices shown (FIG. 11), up to multi-Watt emission at room temperature can be routinely achieved with the state-of-the-art active region designs and better chip heat management. The structures can be further optimized for power performance. The systems and methods of the present disclosure can be used for photonic integrated mid-IR frequency comb sources, spanning an optical octave or more, fully stabilized using the f-2f self-referencing scheme with applications in ultrabroadband dual-comb spectroscopy.

[0123] FIG. 23 illustrates a method 2300 for soliton generation. In brief summary, the method 2300 can include providing a laser (BLOCK 2305). The method 2300 can include coupling a waveguide with the laser (BLOCK 2310). The method 2300 can include outputting a pulse (BLOCK 2315). The method 2300 can include coupling a resonator with the waveguide (BLOCK 2320). The method 2300 can include disposing gain medium in the resonator (BLOCK 2325). The method 2300 can include forming a coupler (BLOCK 2330).

[0124] The method 2300 can include providing a laser (BLOCK 2305). The laser can include a drive laser. The laser can be driven electrically. For example, the laser can be electrically powered. The device 100 can include a single chip, integrated circuit, or semiconductor device, on which the laser is fabricated. The laser can include a quantum cascade laser. The laser can include an interband cascade laser.

[0125] The method 2300 can include coupling a waveguide with the laser (BLOCK 2310). The waveguide can include a first waveguide. The waveguide can include a linear waveguide. The waveguide can be coupled with the laser. The waveguide can be driven electrically. For example, the waveguide can be electrically powered. The waveguide can include a second waveguide. The waveguide can include a non-linear waveguide.

[0126] The method 2300 can include outputting a pulse (BLOCK 2315). The pulse can have a plurality of wavelengths. For example, the pulse can have a plurality of wavelengths forming a frequency comb. The frequency comb can be in a range between 3  $\mu\text{m}$  and 12  $\mu\text{m}$ . For example, the frequency comb can be in a range between 3  $\mu\text{m}$  and 6  $\mu\text{m}$ , 3  $\mu\text{m}$  and 9  $\mu\text{m}$ , 3  $\mu\text{m}$  and 12  $\mu\text{m}$ , 6  $\mu\text{m}$  and 9  $\mu\text{m}$ , 6  $\mu\text{m}$  and 12  $\mu\text{m}$ , or 9  $\mu\text{m}$  and 12  $\mu\text{m}$ .

[0127] The method 2300 can include coupling a resonator with the waveguide (BLOCK 2320). The resonator can be coupled with the waveguide. The resonator can include a closed loop. The resonator 115 can include a generator resonator. The resonator can be

driven electrically. For example, the resonator can be electrically powered. In some embodiments, the resonator described herein can be implemented as a close-looped resonator or a resonator where a signal follows a complete/closed physical/transmission path, and/or is fed back from an output point to an input point then back to the output point. Some embodiments of the resonator may include gain medium, which can include/provide a source of optical gain. The optical gain may result from stimulated emission of photons through electronic or molecular transitions to a lower energy state from a higher energy state previously populated by a pump source for instance. The closed-loop structure of the resonator can be in the form/shape of a ring, oval, circular, racetrack, loop or other structure.

**[0128]** The method 2300 can include disposing gain medium in the resonator (BLOCK 2325). The gain medium can be disposed in the resonator.

**[0129]** The method 2300 can include forming a coupler (BLOCK 2330). For example, the method 2300 can include forming the coupler from a portion of the waveguide and a portion of the resonator.

**[0130]** In some embodiments, the method 2300 can include coupling a filter with the waveguide. The method 2300 can include suppressing, by the filter, a primary mode of the pulse. In some embodiments, the resonator can include a generator resonator. The filter can include a filter resonator. The filter resonator can be coupled with the waveguide.

**[0131]** In some embodiments, the method 2300 can include coupling a semiconductor optical amplifier with the waveguide. The method 2300 can include amplifying, by the semiconductor optical amplifier, the pulse.

**[0132]** In some embodiments, the waveguide is a first waveguide. The method 2300 can include coupling a nonlinear waveguide with the semiconductor optical amplifier. The method 2300 can include broadening, by the nonlinear waveguide, a spectrum of the pulse.

**[0133]** In some embodiments, the method 2300 can include disposing a heater proximate to the resonator. The method 2300 can include modifying, by the heater, a frequency of the resonator. In some embodiments, the method 2300 can include electrically driving the laser, the waveguide, and the resonator.

**[0134]** Any references to implementations or elements or acts of the systems and methods herein referred to in the singular can include implementations including a plurality of these elements, and any references in plural to any implementation or element or act herein can include implementations including only a single element. References in the singular or

plural form are not intended to limit the presently disclosed systems or methods, their components, acts, or elements to single or plural configurations. References to any act or element being based on any information, act or element may include implementations where the act or element is based at least in part on any information, act, or element.

**[0135]** Any implementation disclosed herein may be combined with any other implementation, and references to “an implementation,” “some implementations,” “an alternate implementation,” “various implementations,” “one implementation” or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described in connection with the implementation may be included in at least one implementation. Such terms as used herein are not necessarily all referring to the same implementation. Any implementation may be combined with any other implementation, inclusively or exclusively, in any manner consistent with the aspects and implementations disclosed herein.

**[0136]** References to “or” may be construed as inclusive so that any terms described using “or” may indicate any of a single, more than one, and all of the described terms. References to at least one of a conjunctive list of terms may be construed as an inclusive OR to indicate any of a single, more than one, and all of the described terms. For example, a reference to “at least one of ‘A’ and ‘B’” can include only ‘A’, only ‘B’, as well as both ‘A’ and ‘B’. Elements other than ‘A’ and ‘B’ can also be included.

**[0137]** As used herein, the singular terms “a,” “an,” and “the” may include plural referents unless the context clearly dictates otherwise. Spatial descriptions, such as “above,” “below,” “up,” “left,” “right,” “down,” “top,” “bottom,” “vertical,” “horizontal,” “side,” “higher,” “lower,” “upper,” “over,” “under,” and so forth, are indicated with respect to the orientation shown in the figures unless otherwise specified. It should be understood that the spatial descriptions used herein are for purposes of illustration only, and that practical implementations of the structures described herein can be spatially arranged in any orientation or manner, provided that the merits of embodiments of this disclosure are not deviated by such arrangement.

**[0138]** As used herein, the terms “approximately,” “substantially,” “substantial” and “about” are used to describe and account for small variations. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close

approximation. For example, when used in conjunction with a numerical value, the terms can refer to a range of variation less than or equal to  $\pm 10\%$  of that numerical value, such as less than or equal to  $\pm 5\%$ , less than or equal to  $\pm 4\%$ , less than or equal to  $\pm 3\%$ , less than or equal to  $\pm 2\%$ , less than or equal to  $\pm 1\%$ , less than or equal to  $\pm 0.5\%$ , less than or equal to  $\pm 0.1\%$ , or less than or equal to  $\pm 0.05\%$ . For example, two numerical values can be deemed to be “substantially” the same if a difference between the values is less than or equal to  $\pm 10\%$  of an average of the values, such as less than or equal to  $\pm 5\%$ , less than or equal to  $\pm 4\%$ , less than or equal to  $\pm 3\%$ , less than or equal to  $\pm 2\%$ , less than or equal to  $\pm 1\%$ , less than or equal to  $\pm 0.5\%$ , less than or equal to  $\pm 0.1\%$ , or less than or equal to  $\pm 0.05\%$ .

**[0139]** Additionally, amounts, ratios, and other numerical values are sometimes presented herein in a range format. It is to be understood that such range format is used for convenience and brevity and should be understood flexibly to include numerical values explicitly specified as limits of a range, but also to include all individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly specified.

**[0140]** The systems and methods described herein may be embodied in other specific forms without departing from the characteristics thereof. The foregoing implementations are illustrative rather than limiting of the described systems and methods.

**[0141]** Where technical features in the drawings, detailed description or any claim are followed by reference signs, the reference signs have been included to increase the intelligibility of the drawings, detailed description, and claims. Accordingly, neither the reference signs nor their absence have any limiting effect on the scope of any claim elements.

**[0142]** The systems and methods described herein may be embodied in other specific forms without departing from the characteristics thereof. The foregoing implementations are illustrative rather than limiting of the described systems and methods. Scope of the systems and methods described herein is thus indicated by the appended claims, rather than the foregoing description, and changes that come within the meaning and range of equivalency of the claims are embraced therein.

**[0143]** While the present disclosure has been described and illustrated with reference to specific embodiments thereof, these descriptions and illustrations do not limit the present disclosure. It should be understood by those skilled in the art that various changes may be

made and equivalents may be substituted without departing from the true spirit and scope of the present disclosure as defined by the appended claims. The illustrations may not be necessarily drawn to scale. There may be distinctions between the artistic renditions in the present disclosure and the actual apparatus due to manufacturing processes and tolerances. There may be other embodiments of the present disclosure which are not specifically illustrated. The specification and drawings are to be regarded as illustrative rather than restrictive. Modifications may be made to adapt a particular situation, material, composition of matter, method, or process to the objective, spirit and scope of the present disclosure. All such modifications are intended to be within the scope of the claims appended hereto. While the methods disclosed herein have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of the present disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations are not limitations of the present disclosure.

## WHAT IS CLAIMED IS:

1. A device, comprising:
  - a laser;
  - a waveguide coupled with the laser and configured to output a pulse having a plurality of wavelengths forming a frequency comb in a range between 3  $\mu\text{m}$  and 12  $\mu\text{m}$ ;
  - a resonator coupled with the waveguide and comprising a closed loop; and
  - gain medium disposed in the resonator;wherein a portion of the waveguide and a portion of the resonator form a coupler.
2. The device of claim 1, further comprising:
  - a filter coupled with the waveguide and configured to suppress a primary mode of the pulse.
3. The device of claim 2, wherein:
  - the resonator is a generator resonator; and
  - the filter comprises a filter resonator coupled with the waveguide.
4. The device of claim 1, further comprising a semiconductor optical amplifier coupled with the waveguide and configured to amplify the pulse.
5. The device of claim 4, wherein the waveguide is a first waveguide, the device further comprising:
  - a nonlinear waveguide coupled with the semiconductor optical amplifier and configured to broaden a spectrum of the pulse.
6. The device of claim 1, further comprising:
  - a heater disposed proximate to the resonator and configured to modify a frequency of the resonator.
7. The device of claim 1, wherein the laser, the waveguide, and the resonator are configured to be driven electrically.

8. The device of claim 1, wherein the device comprises a single chip, integrated circuit, or semiconductor device, on which the laser, the waveguide and the resonator are fabricated.
9. The device of claim 1, wherein the closed loop is at least one of a ring, an oval, or a racetrack.
10. The device of claim 1, wherein the laser is at least one of a quantum cascade laser or an interband cascade laser.
11. The device of claim 1, wherein the pulse is a soliton.
12. The device of claim 1, wherein the pulse is a mid-infrared pulse.
13. The device of claim 1, wherein the waveguide is configured to generate the frequency comb.
14. A method, comprising:
  - providing a laser;
  - coupling a waveguide with the laser;
  - outputting, by the waveguide, a pulse having a plurality of wavelengths forming a frequency comb in a range between 3  $\mu\text{m}$  and 12  $\mu\text{m}$ ;
  - coupling a resonator with the waveguide, the resonator comprising a closed loop;
  - disposing gain medium in the resonator; and
  - forming a coupler from a portion of the waveguide and a portion of the resonator.
15. The method of claim 14, further comprising:
  - coupling a filter with the waveguide; and
  - suppressing, by the filter, a primary mode of the pulse.
16. The method of claim 15, wherein:
  - the resonator is a generator resonator; and
  - the filter comprises a filter resonator coupled with the waveguide.
17. The method of claim 14, further comprising:

coupling a semiconductor optical amplifier with the waveguide; and  
amplifying, by the semiconductor optical amplifier, the pulse.

18. The method of claim 17, wherein the waveguide is a first waveguide, the method further comprising:

coupling a nonlinear waveguide with the semiconductor optical amplifier; and  
broadening, by the nonlinear waveguide, a spectrum of the pulse.

19. The method of claim 14, further comprising:

disposing a heater proximate to the resonator; and  
modifying, by the heater, a frequency of the resonator.

20. The method of claim 14, further comprising:

electrically driving the laser, the waveguide, and the resonator.