Active Ring Resonators Using Mid-Infrared QCLs

ABSTRACT

Researchers in Massachusetts, Austria, and Portugal have designed an active mid-infrared ring resonator incorporating a quantum cascade active region in the waveguide core with directional couplers. The resonance frequency, quality factor, and coupling regime and coefficients can all be tuned electrically to better fit multiple applications. By changing these parameters, the active ring resonator can act as a tunable filter, a nonlinear frequency converter, or a frequency comb generator. This design allows active ring resonator integration into the mid-infrared spectral region (3-12 μm) for a variety of applications in photonic integrated circuits with significant power output of 10 mW for spectroscopy, communication, and microwave generation.

RING RESONATORS

Ring resonators are one of the most versatile building blocks of photonic integrated circuits (PICs).[1] They have contributed to scaling down optical laboratory experiments and making commercial technologies more portable. The PIC world is growing in applicability and physically shrinking in size, and it can enable reduction of global electricity consumption, improved classical and quantum optical signal processors, and lightweight and cost-effective devices for spectroscopy.[1] But how do ring resonators work?

High quality optical ring resonators use a set of waveguides to confine light in a small volume and store it for millions of round-trips. One of the waveguides is a closed loop coupled to the input and output light (**Figure 1**). Light injected through the input waveguide is partially coupled into the closed loop and ring resonator, and the other portion is transmitted into the output facet. Depending on the material and characteristics of the ring resonator, the field experiences gain or attenuation for particular wavelengths and is controlled by the round-trip loss coefficient (α).

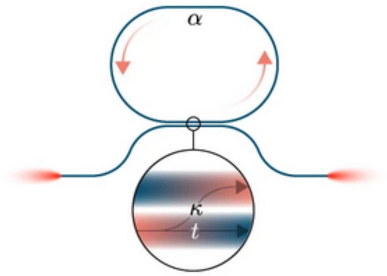


Figure 1. Schematic of a ring resonator with a directional coupler. The field experiences gain or attenuation depending on the value of α.[1]

There are two types of resonators using waveguides: passive and active. Passive resonators can adjust the resonance frequency of a transparent dielectric waveguide at kilohertz rates using thermal tuning of the refractive index or at gigahertz rates using the electro-optic effect. Active resonators use an amplifying medium in the waveguide core instead of a transparent medium. This allows not only the resonance frequency and coupling strength but also the intrinsic quality factor of the resonator, to be tuned via electrical or optical pumping to turn absorption into gain.[1]

Due to the selective wavelength nature of the ring resonance within the closed loop, ring resonators can be utilized as optical wavelength filters, modulators, and frequency converters. The distance between the waveguide and the ring resonator, the coupling length, and the refractive indexes of both materials can be tuned for different applications.

PROBLEMS AND GOALS

Ring resonators are nothing new to the PIC world in near-infrared (near-IR) and visible ranges, but the mid-IR range lacks development of PIC tools and solutions. The mid-IR range is largely dominated by spectroscopy, chemical and biological sensing, and free space communications applications, yet compact and powerful laser sources in this range have been missing. Ultimately, this resulted in less manufacturing and design of waveguides, resonators, and integrated photonic chips for these applications. Simply extending the wavelength range for well established techniques in the near-IR and visible ranges is not an option with large losses and the requirement of unconventional materials.[1] A new, state-of-the-art, mid-IR technique for photonic integration is crucial for ring resonators.

Quantum cascade lasers (QCLs) and inter-band cascade lasers (ICLs) have advanced in the last couple of decades to provide a promising laser source for the 3-12 μm range under direct current at room temperature. With these laser sources, numerous developments have been made in the mid-IR with integrated waveguides and high quality passive ring resonators.[1] What is needed now is a design for an active ring resonator to add versatility in function and application.

METHOD

Researchers from Harvard University, Massachusetts Institute of Technology, Institute of Solid State Electronics in Austria, and Institutes in Portugal have developed and integrated a mid-infrared ring resonator and directional couplers, using a quantum cascade active region in the wave core. Because of this unique design, many of the parameters of the ring resonator can be varied to give electronic control over the resonance frequency and the coupling strength between the waveguide and the resonator. This ring resonator and waveguide design is seen in **Figure 2**.The lasers emit at around 8.2 μm within the mid-IR range. The active coupler waveguide (WG) allows for separate control over the injected electrical currents into the WG and the racetrack (RT). Asymmetric electrical driving can result in a mismatch of mode indices inside the ring resonators and waveguide.[1]

Parameters such as the width of the gap, the index of material in the gap, the length of the coupling region, the resonator length and its intrinsic loss can be carefully altered to define the amount of light coupled into the resonator at a specific wavelength.[1] To affect the resonance of the ring resonator, the amplitude and the phase response can be tuned. Thus, the resonance frequency, the coupling strength, and the intrinsic quality factor of the resonator can be modified for different effects and applications in the mid-IR range. **Figure 2**b shows the theoretical transmission intensities of different coupling modes based on the tunable refractive index (*n*') and round-trip loss coefficient (*α*) in three regimes. **Figure 2**c shows an optical microscope image of the racetrack quantum cascade resonator with an integrated active directional coupler.

The key to mid-IR operation is the core formed by a QCL active region. The InGaAs waveguides with a low doped InP cladding contain this core with intersubband transitions. By changing the optical gain electrically, different parameters of the waveguide and coupling regime can be tuned. Researchers demonstrated the ability to tune parameters and set its operating regime by measuring the transmission and output of the designed mid-IR ring resonator.

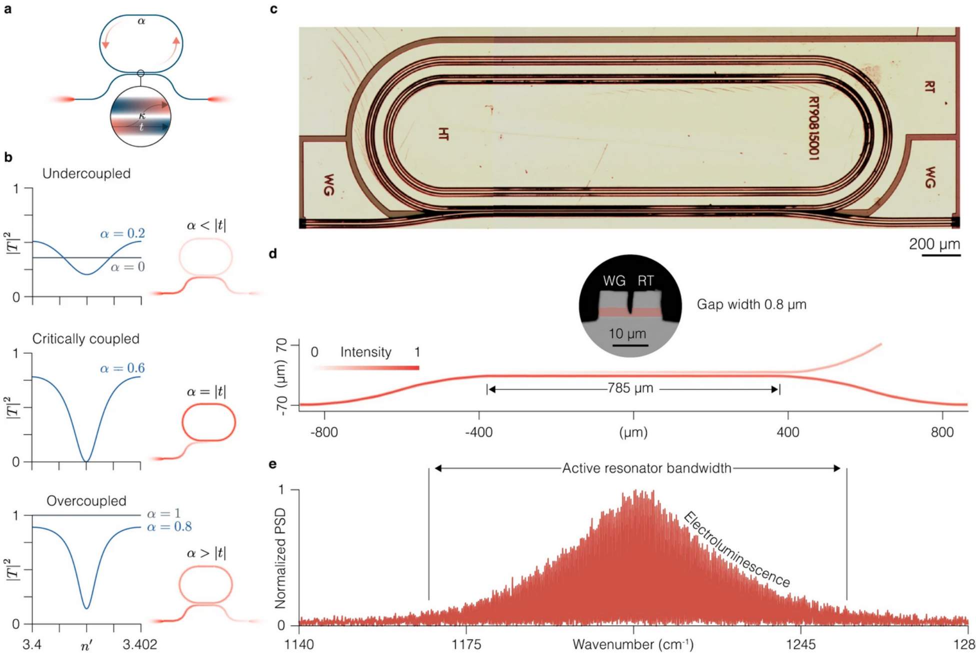
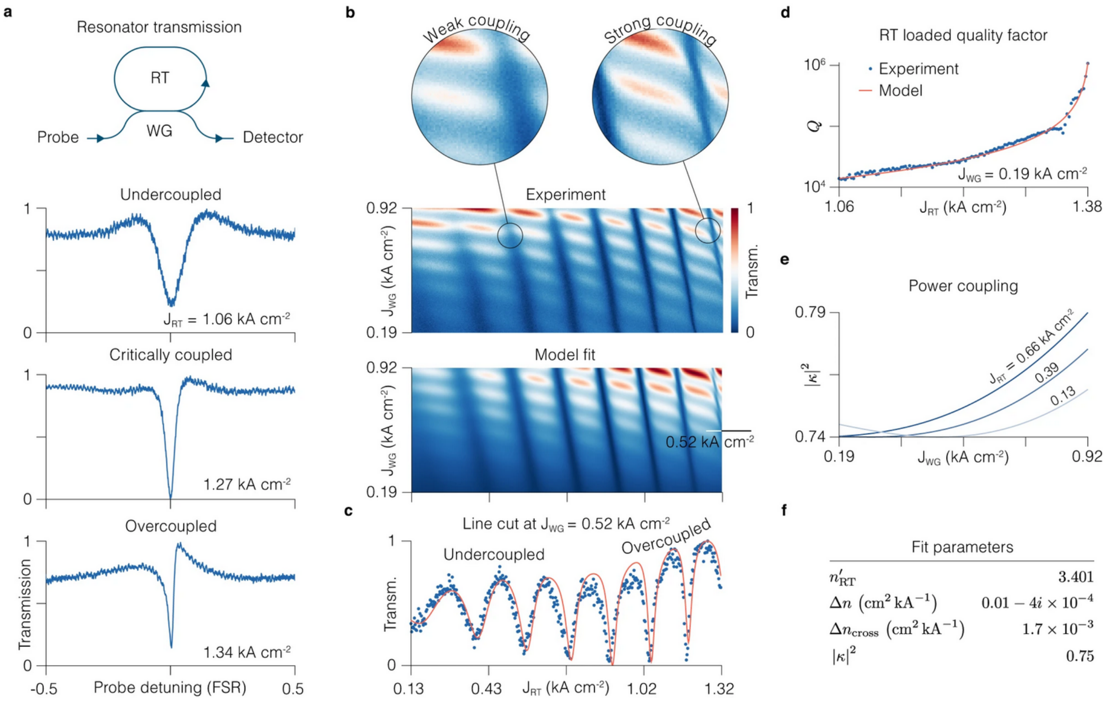


Figure 2. a) Schematic of a ring resonator with a directional coupler. b) Theoretical intensity transmission of the ring resonator with a tunable refractive index and the round-trip loss coefficient *α* in the three coupling regimes. The depictions to the right of the transmission curves schematize the light intensity distribution in the waveguide and the ring. c) Optical microscope image of the racetrack quantum cascade (QC) resonator with an integrated active directional coupler. Integrated components are denoted with RT, for the racetrack, WG, for the waveguide coupler and HT, for the integrated heater. d) Simulated light intensity distribution ($\lambda = 7.9\,\mu m$, $n_{RT} = 3.323$) in the coupling region. The inset shows an optical microscope image of the cross-section of the coupling region. e) Experimental spectrum of the sub-threshold emission of a Fabry-Perot QC laser fabricated from the same epitaxial material as the ring resonator shown in c.[1]



Fit parameters	
n'_{RT}	3.401
Δn $(\mathrm{cm}^2\,\mathrm{kA}^{-1})$	$0.01 - 4i \times 10^{-4}$
$\Delta n_{\mathrm{cross}}$ $(\mathrm{cm}^2\,\mathrm{kA}^{-1})$	1.7×10^{-3}
$\lvert\kappa\rvert^2$	0.75

Figure 3. a) Experimental transmission of the RT coupled to the WG as the wavelength of the probe laser is swept across the RT resonance. b) Transmitted intensity of the probe signal at 1222 cm^{-1} as function of current density of the racetrack (RT) and the directional waveguide coupler (WG) and the corresponding least squares model fit. c) Experimental transmission (dots) and model fit (solid line) as function of the RT current density for the fixed WG current density of 0.52 kA cm^{-2}. d) Extracted (dots) and modeled (solid line) RT loaded quality factor (Q) as function of the RT current. e) Power coupling coefficient, calculated based off the extracted experimental values for the complex indices of the WG and RT, as function of the WG current for three different values of the RT current. f) Values extracted from the fit shown in b and c. nRT, background mode index (when the electrical pumping is off) of the RT. Δ*n*, complex index change per unit of current density. Δn_{cross}, index change due to thermal crosstalk between WG and RT. $|\kappa|^2$, power coupling coefficient.[1]

With the RT kept below the lasing threshold, regime control and tunability of the active quantum cascade resonators are possible. When the RT is brought to above lasing threshold, the ring resonator can function as a nonlinear optical frequency conversion element. When the external probe laser is removed, the right QCLs can be characterized as standalone lasers and self-starting frequency comb generators. In this special experiment, the differences between RT QCLs with active or directional couplers and ring QCLs without coupling ports is discovered.

RESULTS

Figure 3 shows the transmission characteristics of the racetrack-waveguide (RT-WG) system while keeping the RT below its lasing threshold. By sweeping the wavelength of the probe laser, a dip in transmission (Figure 3a) is seen as a function of probe detuning, and this correlates to an RT quality factor Q that can be continuously tuned over two orders of magnitude as population inversion increases (Figure 3d). By sweeping the drive currents of both the WG and the RT (Figure 3b), the thermal and carrier-induced change of the refractive index effectively sweeps the RT cavity mode resonances. Increasing pumping leads to narrowing of the resonances, and the mode index mismatch between the coupled waveguides leads to the change of the power coupling coefficient $|\kappa|^2$ between the WG and the RT.[1] By making both simple and complex changes, the parameters of the active RT resonators and the coupling regimes can be tuned and controlled.

Each coupling regime can be utilized for appropriate applications. When the ring resonator is critically coupled, the extinction ratio on the resonance is useful for sharp notch filters and intensity modulators. Over-coupled ring resonators can be used as phase modulators due to the sharp pi phase change across the resonance and a reduced resonance contrast.[1] These regimes can be chosen on demand by tuning α.

The next step of testing and proving this mid-IR active ring resonator is pumping the RT above the lasing threshold to compensate the loss through the coupler with the stronger internal gain, creating a nonlinear optical frequency conversion element. When the ring resonator is operating in

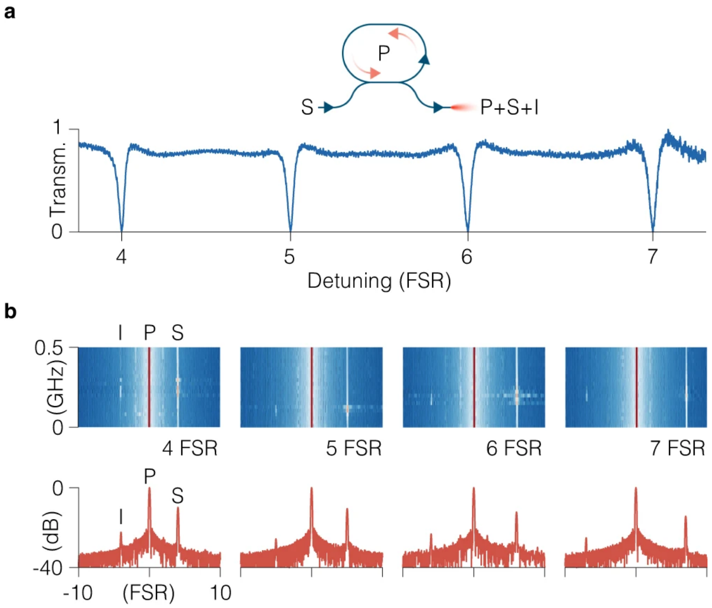


Figure 4. a) Experimental transmission, below the lasing threshold, of the ring resonator, showing four consecutive resonances on the blue side of the pump wave (P) generated by the ring QCL, into which we inject signal light (S) to generate idler sidebands (I) by four-wave mixing. b) Top graphs are the experimental spectrograms of the ring QCL above the threshold under external optical injection as the detuning of the signal is swept across the ring resonance, shown for four subsequent resonances, 4, 5, 6 and 7 FSRs to the blue of the ring lasing frequency. Bottom graphs depict optical spectra for the detuning of the signal wave when the idler wave is the strongest.[1]

the lasing regime, it creates a strong single-frequency unidirectional intracavity field. **Figure 4** shows the transmission of the ring resonator when sweeping the wavelength of the injected signal through four adjacent resonances of the RT resonator. When tuning, an idler sideband appears symmetrically on the red side of the pump, showing parametric amplification via four-wave mixing from coherent interaction of the pump and the signal waves. As shown in the graphs, a signal and an idler photon with frequencies of the four interacting waves are generated from two pump photons.[1]

The last step was to generate frequency combs with the ring QCLs as standalone lasers. Once the external probe laser was removed, the ring QCLs can be characterized. Previous techniques for mid-IR and THZ frequency comb generators have revolved around Fabry-Perot (FP) QCLs due to their compact nature and high power levels in the 10-100 mW range. However, with ring QCLs gaining momentum, better stability, higher power efficiency, and larger spectral coverage can be realized.[1] Ring QCLs, compared to FP QCLs, have had very limited output power in the submilliwatt levels due to the low outcoupling efficiency of the generated radiation. However, researchers have solved this problem with RT QCLs with directional couplers to enable the extraction of optical power above 10 mW at room temperature. This puts RT QCLs on the same level as FP QCLs as seen in **Figure 5**. The ring resonator was also injected with regimes of bidirectional and unidirectional lasing. Ultimately, the clockwise direction leads to lasing at higher pumping levels. Once the parametric gain is high enough, a frequency comb is generated (**Figure 5**c), proving the versatility of this mid-IR ring resonator.

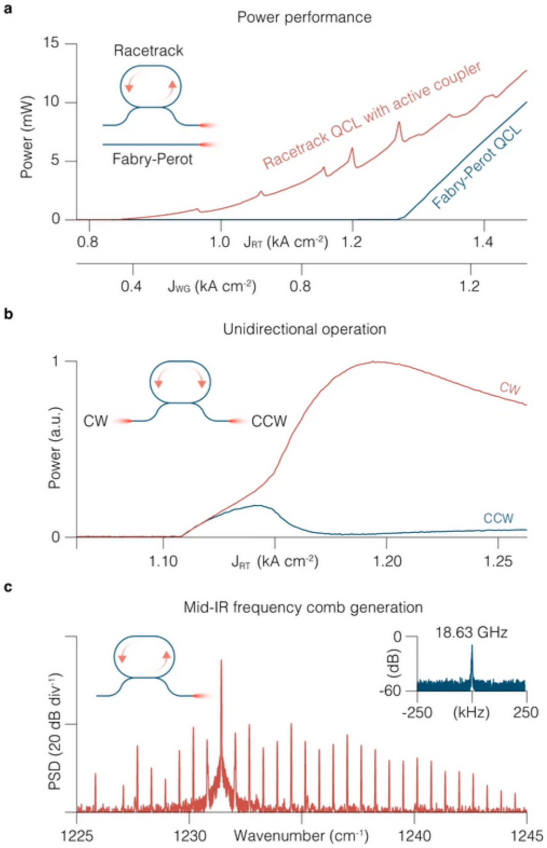


Figure 5. a) Output power from the front waveguide facet of the ring QCL above the threshold as both RT and WG currents are swept simultaneously. Both WG and RT are operated under continuous wave electrical current injection. b) Experimental intensities as function of the injected current collected simultaneously from both WG ports on two external detectors, showing the regimes of bidirectional and unidirectional lasing. c) Experimental spectrum of the self-starting frequency comb in a ring QCL, when it operates in a unidirectional regime. PSD, power spectral density. Inset shows a corresponding RF spectrum of the intermode beat note. RBW is 750 Hz, sweep time is 1 s.[1]

The developed mid-IR active ring resonator can act as a filter, wavelength converter, or a frequency comb generator. Due to the control coupling, resonance detuning, and the quality factors, the end function of this multifaceted device can be user-defined post-fabrication.[1] These researchers[1] realize, "Active ring QCL resonators thus have the potential of serving as reconfigurable building blocks of larger-scale agile hybrid mid-IR PICs." This design can also extend to the entire mid-IR range for many ICL and QCL applications.

WAVELENGTH'S ROLE

All laser devices, including a Fabry-Perot QCL, were driven with Wavelength Electronics' low-noise current drivers QCL1500 LAB or QCL2000 LAB and their temperature was stabilized at 16ºC using Wavelength Electronics' low thermal drift temperature controller TC5 LAB. It was critical to have precise control of the drive current as the probe wavelength was tuned by ramping the injection current. The RT QCL operation state is highly dependent on the injection current especially when dealing with frequency comb generation.

Wavelength Electronics' QCL1500 LAB and QCL2000 LAB QCL drivers can provide up to 1.5 A and 2.0 A of current to the QCLs, respectively, with noise current as low as 0.4 μA (RMS). The average noise density of 4 nA/√Hz is necessary for the functionality of room temperature frequency combs, frequency converters, and tunability of the RT QCL design.

Researchers also utilized the precision temperature control of the TC5 LAB instrument with output current of up to 5 A and compliance voltage of 15 V. This controller provides temperature stability of better than 0.0009ºC and provides the necessary safety for the user and the laser with integrated and adjustable limit features.

All three instruments make use of an intuitive touchscreen user interface, automatic settings and data collection, and complete command sets for remote control. The high-performance and precision of Wavelength Electronics provided the necessary stability of the laser sources in the active mid-IR ring resonators.

PRODUCTS USED
QCL1500 LAB, QCL2000 LAB, TC5 LAB

KEYWORDS
Ring resonator, microresonator, mid-infrared photonics, integrated optics, PICs, quantum cascade laser, tunable filter, frequency converter, frequency comb generator, spectroscopy, temperature controller, QCL1500 LAB, QCL2000 LAB, TC5 LAB

REFERENCES

1. Kazakov, D., Letsou, T.P., Beiser, M. et al, Active mid-infrared ring resonators. *Nat Commun*. 2024, 607, **15**. https://doi.org/10.1038/s41467-023-44628-7

USEFUL LINKS

- QCL1500 LAB Product Page
- QCL2000 LAB Product Page
- TC LAB Series Product Page

PERMISSIONS

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The captions for Figures 1 - 5 were modified. Figure 1 was cropped from Figure 2. No changes were made to the other figures. They are presented in their original form.

REVISION HISTORY

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REVISION	DATE	NOTES
A	March 2024	Initial Release