Hertz-level-linewidth semiconductor laser via injection locking to an ultra-high Q silicon nitride microresonator

Warren Jin^{1,†}, Qi-Fan Yang^{2,†}, Lin Chang^{1,†}, Boqiang Shen^{2,†}, Heming Wang^{2,†}, Mark A. Leal¹, Lue Wu², Maodong Gao², Avi Feshali³, Mario Paniccia³, Kerry J. Vahala^{2,*}, and John E. Bowers^{1,*}

[†]These authors contributed equally to this work

¹ECE Department, University of California Santa Barbara, Santa Barbara, CA 93106, USA

²T. J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA

³Anello Photonics, Santa Clara, CA

*vahala@caltech.edu, bowers@ece.ucsb.edu

Abstract: A conventional semiconductor DFB laser is self-injection-locked to a CMOS-foundry-fabricated ultra-high Q silicon nitride microresonator, suppressing high-offset frequency noise to $0.2 \text{ Hz}^2 \text{ Hz}^{-1}$ and yielding instantaneous linewidth of 1.2 Hz. © 2021 The Author(s)

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The integration of semiconductor lasers with high spectral purity and stability will be critical for future scalable coherent optical systems, including light detection and ranging (LIDAR) [1,2], laser gyroscopes [3,4], spectroscopy [5], optical frequency synthesis [6], optical atomic clocks [7], coherent communication networks [8], and microwave photonics [9-12]. A key ingredient for many of these systems is a mass-produced, low-noise laser. However, typical communication laser linewidths range from 100 kHz to a few MHz [8], which is orders of magnitude too large for these applications. Applying optical feedback through an external reflector is a powerful method of quieting a laser [13-16]. Since the degree of noise suppression scales inversely with the optical linewidth of the reflector [15], ultra-high- Q microresonators are excellent candidates to achieve substantial linewidth narrowing and have been demonstrated across a wide range of materials as standalone [17] or integrated [18-20] components. Here, we harness CMOS-foundry fabrication to achieve an ultra-high intrinsic Q of over 200M in a silicon nitride integrated photonic platform. We self-injection-lock an ultra-high Q resonator chip to a conventional semiconductor distributed-feedback (DFB) laser, thereby reducing laser noise to a frequency noise of $0.2 \text{ Hz}^2 \text{ Hz}^{-1}$ with corresponding instantaneous linewidth of 1.2 Hz-- a previously unattainable level for integrated lasers.

Fig. 1: (a) Intrinsic and loaded Q factors of a ring resonator featuring a drop port, measured at various wavelengths. (b) Optical micrograph of the fabricated ring resonator with 10.8 GHz FSR. (c) Frequency noise of the DFB laser operating at 1556 nm when self-injection-locked to the resonator, measured from the through port and drop port.

The waveguide geometry of the ultra-high Q resonator consists of a 100 nm thick silicon nitride core embedded within 14.5 μm silicon dioxide lower cladding, and 2.2 μm of silicon dioxide upper cladding. A waveguide width of 2.8 μm allows single mode propagation, however within the resonator itself the waveguide width is 25 μm to minimize sidewall scattering losses. The coupler is designed to access the fundamental TE mode of the resonator, which takes the form of a whispering-gallery mode. Additionally, the resonator is fabricated with two sets of couplers, allowing the optical output to be taken from either the through port or the drop port. The device is fabricated on a 200 mm diameter silicon wafer within a high-volume CMOS foundry. The intrinsic and loaded Q factors of the device are shown in Fig. 1(a), demonstrating that an intrinsic Q factor over 200 M and loaded Q factor over 100 M is achieved for wavelengths longer than 1550 nm. An optical micrograph of the fabricated device is shown in Fig. 1(b). A commercial DFB laser is butt-coupled to the bus waveguide of the silicon nitride chip. The laser is able to deliver power up to 120 mW at 1556 nm. The optical feedback is provided by backward Rayleigh scattering in the microresonator, which reaches its maximum once the laser is on-resonance. Such feedback spontaneously aligns the laser frequency to the closest mode, where the phase accumulated in the feedback is critical to determining the stability of injection-locking. In our experiment, the feedback phase is precisely controlled by adjusting the air gap between the laser chip and the bus waveguide. In the case of a rigidly co-packaged laser and resonator, feedback phase control could instead be achieved by the addition of a resistive heater to the waveguide linking the laser and resonator. The laser output is taken from either the through port or drop port of the resonator as indicated within Fig. 1(b).

The measured frequency noise of the self-injection-locked laser system is shown in Fig. 1(c). For laser output taken at the through port, the frequency noise is observed to reach a minimum at 4 MHz offset frequency, beyond which the frequency noise begins to rise at a rate proportional to the square of offset frequency. This is because the maximum noise suppression bandwidth in an injection locking system is limited to the bandwidth of the resonator [15]. To achieve an ultra-low white frequency noise floor at high offset frequency, the laser output is instead taken from the drop port of the resonator. The drop port provides low-pass filtering action and yields a white-noise floor of 0.2 $\text{Hz}^2 \text{Hz}^{-1}$ with corresponding instantaneous linewidth of 1.2 Hz.

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