# Frequency noise reduction of heterogeneous Si/III-V lasers locked to ultra-high Q $Si_3N_4$ resonators

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**Abstract:** A heterogeneous Si/III-V laser is frequency locked to a waveguide coupled ultra-high Q $Si_3N_4$ resonator in the Pound-Drever-Hall configuration. The FM noise is reduced 33 dB to $10^3$ $Hz^2/Hz$, promising for stable integrated reference lasers.

**OCIS codes:** (140.3425) Laser stabilization; (130.0130) Integrated optics; (140.4780) Optical resonators

## 1. Introduction

A stable reference laser, that is low cost and compact, is critical in many optical metrology, communication, and sensor systems. The existence of spontaneous emission noise at high offset frequencies, and even higher noise spectral density at low offset frequencies create low signal-to-noise ratios (S/N) in these applications. In this work, we utilize a heterogeneous Si/III-V laser which has monolithically integrated coupled ring resonator (CRR) mirrors in Si waveguides to suppress the high frequency Lorentzian FM noise to 160 kHz linewidth levels ($\sim 60\times10^3$ $Hz^2/Hz$) [1]. On its own, this laser behaves like many other semiconductor lasers and exhibits orders of magnitude higher frequency noise above millisecond time scales and are a huge burden for the receive side signal processing to track the laser frequency, thereby reducing the overall efficiency. To overcome this, we utilize an ultra-high Q $Si_3N_4$ resonator [2] and the Pound-Drever-Hall (PDH) locking system [3], to reduce FM noise levels below the laser's fundamental spontaneous emission noise level, and >1000× improvement in the frequency noise power spectral density at a few kHz offset frequency. This result can be extended to realize a fully integrated stable narrow linewidth laser source on a single chip and can provide large improvements in consumed power and cost.

## 2. The Pound-Drever-Hall system

The PDH system requires a frequency tunable laser that can be phase modulated at a frequency much larger than the full width half maximum (FWHM) of the reference high Q resonator. The resonator performs the FM to AM conversion, most efficiently in the through port (notch filter) configuration, and is detected on a high speed photodetector (PD). This RF signal is demodulated on a mixer with the same signal generator driving the laser modulation. The baseband error signal contains information on the difference between the laser frequency and resonance frequency from baseband to the modulation frequency. This error signal is then filtered with op-amps and drives the DC portion of the laser modulation pad in negative feedback. The system schematic is shown in Fig. 1 and the components will be discussed next.

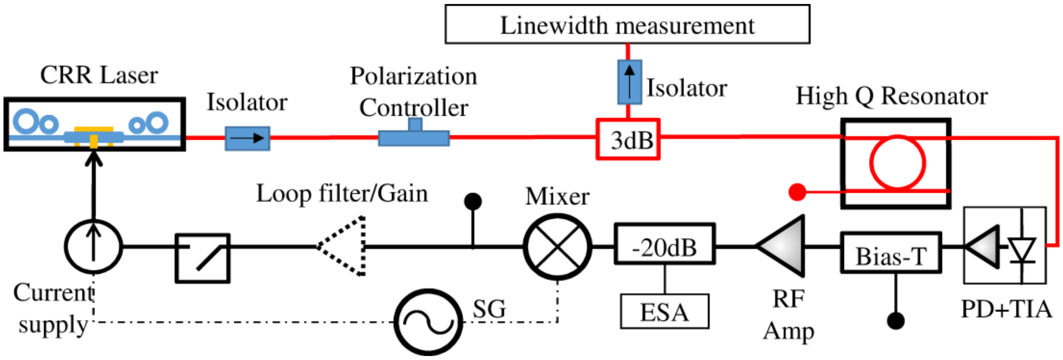

**Fig. 1. System schematic of the PDH setup. The integrated CRR laser is isolated from the waveguide coupled Si3N4 resonator and measured separately. Commercial components are used for the RF mixing and baseband filtering, and multiple monitor points are shown with bubbles.**

### *2.1 System components*

The CRR laser [1] is based off the standard heterogeneous Si/III-V laser platform which has a 7 quantum well InGaAlAs epitaxial material that is wafer bonded to Si waveguides. The CRR mirrors are designed to yield a high Q laser cavity whose center frequency can be tuned using micro-heaters and set to obtain the lasing wavelength of 1577 nm in this work. The current bias, RF frequency drive, and feedback signal are combined in a Vescent D2-105 supply and probed to the CRR chip on a TEC stage. The laser's output is coupled with 2 µm spot size lensed fiber, and immediately spliced to an inline fiber isolator and polarization controller to control the polarization launched into the ring resonator. After the 3 dB tap, the fiber runs through the through port of a cleaved fiber packaged $Si_3N_4$ resonator, which has a 40 nm thick low confinement core and wafer bonded top cladding that has been high temperature annealed to yield ~35 million unloaded quality factor [2]. The electrical detection and amplification is done with a commercial PD and transimpedance amplifier (TIA), bias T, broadband amplifier, and mixer. The signal generator is a dual output Agilent 33520B function generator, which has the proper phase between outputs to bias the mixer at quadrature. The error signal is filtered and appropriately shaped with 2 stages of op-amps soldered on surface mount evaluation boards, before being fed back to the current supply for the laser.

## 3. Laser FM measurement

To properly characterize the system performance, we perform an exact measurement on the laser's FM power spectral density (PSD) by taking a 3 dB optical tap after the laser output to an isolator, 13 m unbalanced fiber based Mach-Zehnder interferometer, and PD+TIA. The interferometer contains a fiber stretcher in one arm, and the PD has a monitor tap, which we use to apply a low frequency (<100 Hz) quadrature locking circuit. Once the laser is at quadrature, the PD+TIA output goes through a DC block (2 Hz – 40 MHz) and the RMS noise PSD is measured across different spans of a Rhode and Schwarz FSU spectrum analyzer.

## 4. Results

In Fig. 2 we show the CRR laser FM noise PSD with and without locking to the ultra-high Q resonator. At high offset frequencies, both cases exhibit ~10× lower spontaneous emission noise than standard DFB style commercial lasers. But the unlocked laser suffers from low frequency noise with $1/\sqrt{f}$ dependence, and increases 20 dB in our measurement range of interest. By using the PDH system with the ultra-high Q ring, we achieve a high S/N ratio discrimination of the laser FM noise, and are able to apply enough feedback gain to reduce the noise level to $10^3$ $Hz^2/Hz$, a 33 dB improvement over the unlocked CRR laser. Compared to the unlocked laser, this system represents a stable master oscillator for various optical metrology experiments, which can be readily integrated together on the same monolithic platform or system in package solution.

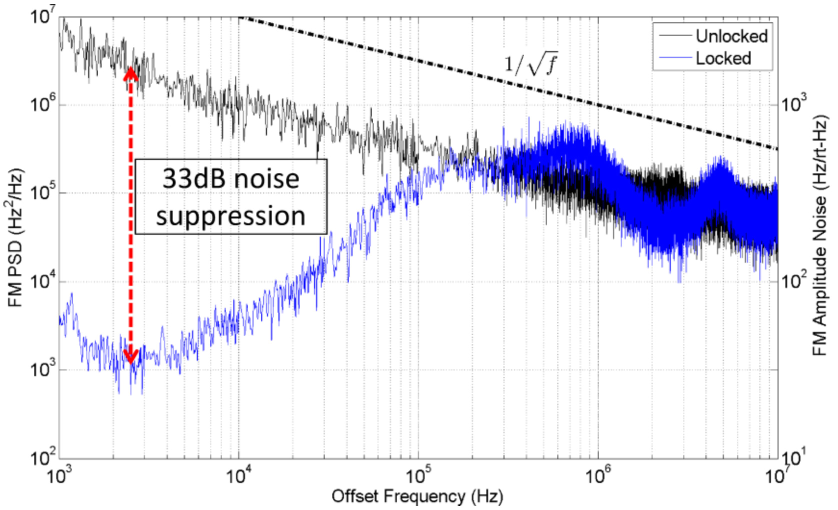

**Fig. 2 FM PSD of the CRR laser unlocked (black) and locked (blue) to the $Si_3N_4$ resonator.**

## 5. References

[1] S. Srinivasan et al., "Coupled-Ring-Resonator-Mirror-Based Heterogeneous III–V Silicon Tunable Laser," IEEE Photonics J. **7**, 1–8 (2015).
[2] D. T. Spencer et al., "Integrated waveguide coupled $Si_3N_4$ resonators in the ultrahigh-Q regime," Optica **1**, 153–157 (2014).
[3] E. D. Black, "An introduction to Pound–Drever–Hall laser frequency stabilization," Am. J. Phys. **69**, 79–87 (2001).