Narrow-Linewidth Lasers Using On-Chip High-*Q* Resonators

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Abstract: *We present heterogeneously integrated widely-tunable semiconductor lasers with narrow-linewidth. 50 kHz integrated linewidth was demonstrated using controlled feedback to the laser, and sub-kHz Lorentzian linewidths are predicted using high-Q ring resonators made in Si. Low-frequency noise was suppressed by more than 30 dB using an ultra-high Q* Si_3N_4 *resonator.*

Keywords: *Semiconductor lasers, Optical resonators, Laser stabilization*

1. INTRODUCTION

Integrated widely-tunable lasers are very attractive due to their small size, weight and low cost. Historically, linewidths of III-V semiconductor lasers have typically been in the few MHz range, and recently sub-MHz instantaneous linewidths have been demonstrated [1]. The main restriction in further improvement of the linewidth with III-V designs comes from the limitation in obtainable *Q* factor of the resonator, as photon generation and storage are made in the same material. Heterogeneous silicon photonics removes this limitation by combining efficient III-V electrically-pumped sources and low-loss silicon waveguides. Here we show recent improvements in the laser linewidth utilizing low loss Si and ultra-low loss Si_3N_4 waveguide platforms available with heterogeneous integration. Narrow linewidth or low phase noise is important for modern coherent communications as well as for a number of sensing applications.

2. HETEROGENEOUS III-V SILICON WIDELY-TUNABLE LASERS

Wide-tunability in semiconductor lasers is commonly achieved by utilizing the Vernier effect. The effect has been utilized both with sampled Bragg grating reflectors and ring resonators. Ring resonators, with sufficiently low propagation loss have an advantage because the effective cavity length at ring resonance is enhanced by factors of five or more, directly reducing linewidth [2]. The majority of widely-tunable lasers that utilize Si waveguides as a part of their cavity (either heterogeneous or hybrid) utilize rings. Due to lower propagation loss, the linewidth of such lasers is repeatedly below MHz, often in 100-200 kHz range [3]. Linewidth can further be improved by operating the lasers slightly off resonance and utilizing the negative optical feedback effect [4]. To utilize the negative optical feedback, the laser longitudinal mode has to be tuned to shorter wavelength than the ring resonance frequency by using phase tuner inside the cavity. In that case, when the wavelength of laser changes due to noise, there is an optical feedback loop that stabilizes the lasers. A decrease in wavelength will increase the reflectivity, which in turn increases the photon density in the main cavity, and hence decreases carrier density. This causes the wavelength to increase due to the carrier plasma effect. The opposite happens when laser wavelength increases, once again stabilizing the laser. The negative feedback effect occurs only on the long wavelength side of the resonance and is optimum at the wavelength of highest slope in the transmission spectrum. On the short wavelength side of the ring resonance, the effect is reversed and operates in positive feedback, broadening the linewidth.

To further improve the linewidth, we have introduced a delayed reflector providing feedback to the laser [5]. Controlled feedback from a ~4 cm long on-chip cavity made in low-loss silicon waveguide platform (<0.7 dB/cm)

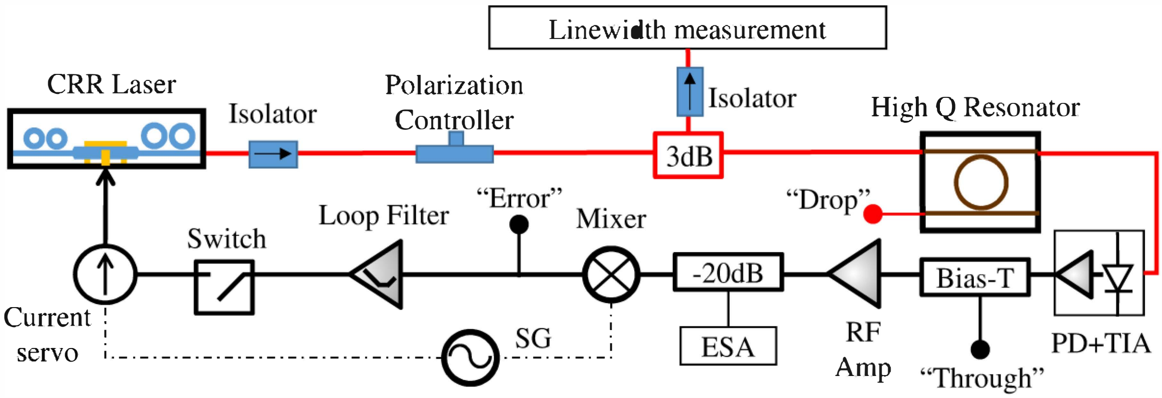

Fig. 1 Schematic of the PDH setup used to lock a coupled ring resonator (CRR) based laser to high-*Q* resonator made in Si_3N_4. Optical fibers are shown in red, with electronic signals shown in black. Results of locking are shown in Fig. 2c.

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*This research was supported by the DARPA EPHI and DODOS programs. This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

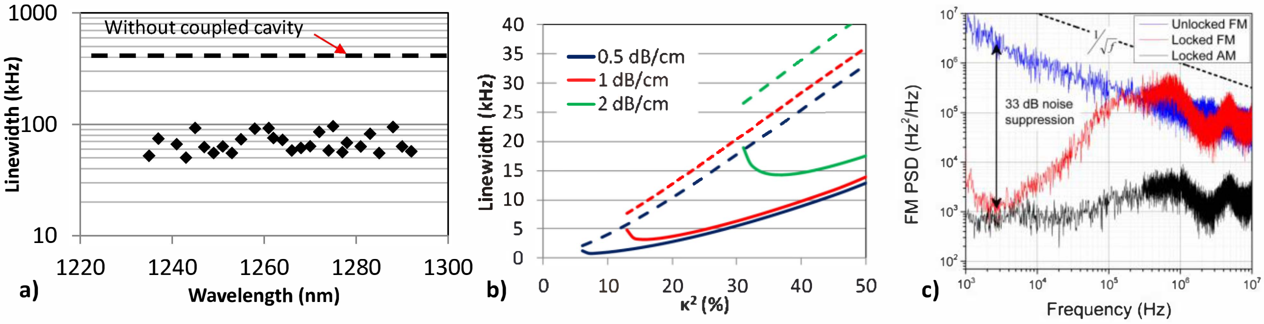

Fig 2. (a) Integrated linewidth of the semiconductor laser with and without controlled feedback from on-chip external cavity [5] (b) Lorentzian linewidth estimate when using a high-*Q* ring inside the laser cavity for various propagation loss values [4]. Dashed line is for operation at ring resonance and full line is for operation at slight detuning and utilizing negative-optical feedback. (c) Power spectral density of free running coupled-cavity laser [3] and same laser locked to high-*Q* SiN ring resonator [7].

allowed for a reduction of integrated linewidth down to 50 kHz (~6x improvement, Fig 2.a). The approach, as outlined in [5], had some design limitations. The use of a very long external cavity limited feedback levels for single mode operation (the tuning rings inside the cavity couldn't filter out a single longitudinal mode of long external cavity), and also limited the bandwidth of the feedback loop. Furthermore the use of a semiconductor optical amplifier (SOA) in the external cavity to control the feedback level combined with a need for low feedback levels, due to potential multi-moding, increased the noise in feedback as the amplifier was driven below transparency.

In order to break these limitations we have studied the use of ring resonators for providing feedback and improving the laser linewidth. The high-*Q* resonators were, typically, used external from laser cavity to lock the laser to the resonator or to provide optical feedback [6]. Heterogeneous integration allows us to place a high-*Q* resonator directly on chip. With demonstrated losses in Si waveguides below 1 dB/cm in both O- and C-bands, it is possible to have ring resonators with internal *Q* exceeding 1 million. Furthermore, it is also possible to have such resonators as an integral part of the laser cavity. We study the use of high-*Q* cavities for obtaining narrow-linewidth with widely-tunable designs [4]. A ring resonator in an all-pass configuration provides for the highest *Q*, so we predict that such configuration can provide narrowest linewidth, but is more sensitive to laser frequency drift due to e.g. temperature and other factors. The use of a high-*Q* ring inside the laser cavity should provide sub-10 kHz linewidths (Fig 2.b). Devices are currently being fabricated and we expect to show preliminary results at the conference.

3. ULTRA-LOW-LOSS Si$_3$N$_4$ WAVEGUIDE PLATFORM

Further improvement in low-frequency noise performance is possible by locking a laser to a ring resonator made in the ultra-low-loss Si$_3$N$_4$ waveguide platform. In Fig. 2c we show 33 dB of noise suppression by locking a laser to a resonator with 30 million *Q* factor using a Pound-Drever-Hall (PDH) loop. A schematic of the measurement setup is shown in Fig. 1. In this experiment we used a fiber to couple light between the laser chip and the resonator chip. This resulted with ~15 dB of coupling loss. We have demonstrated more efficient coupling between SiN and Si waveguides with ~ 1 dB loss on a same chip [7], so full integration would reduce the noise floor and allow for an increase in the feedback loop bandwidth due to reduced optical delay. The use of ultra-low loss propagation waveguides inside the laser cavity will be presented.

4. CONCLUSION

We show that ring resonator based widely-tunable lasers can offer superior linewidth performance. The Lorentzian linewidth is improved due to the effective cavity length enhancement of the ring and the negative optical feedback. Low-frequency noise performance of such laser can further be improved by locking the laser to a high-*Q* Si$_3$N$_4$ cavity. Heterogeneous integration platform allows integration of all said components on a single chip.

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