A Comparison of Widely Tunable, Narrow Linewidth Ring Cavity Lasers on Silicon Substrates

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Abstract: We review performance of widely-tunable narrow-linewidth ring based lasers on silicon substrates. We outline two mechanisms that significantly reduce the linewidth of such lasers. The key performance enablers are low loss waveguides and high-Q rings on the hybrid silicon platform.

1. Motivation

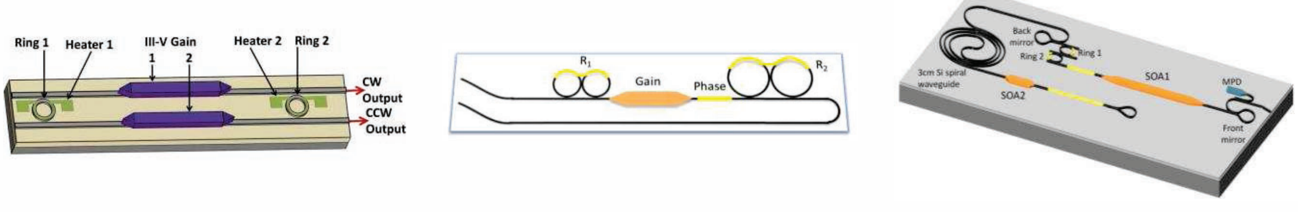
Photonic integration brings a promise of significant cost, power and space savings in today's optical data transmission networks as well as sensor applications. Monolithic integration using heterogeneous integration assembles many devices or optical functionalities on a single chip so that all the optical connections are on chip and require no external alignment and has the further advantage of improved performance, which we demonstrate here.

Narrow-linewidth is becoming increasingly important in modern communications and sensors. Modern 100G transceivers utilize dual-polarization quadrature-phase-shift-keying (DP-QPSK) in order to send 4 bits simultaneously and reduce the symbol speeds to 28 Gbauds. Moving to higher transmission-speeds at single wavelength such as 200G and 400G, while keeping same symbol speeds, necessitates using even more advanced modulation formats such as DP-16QAM or DP-256QAM where QAM stands for quadrature amplitude modulation. Such advanced modulations require lasers and local oscillators for demodulation with very low phase noise, or narrow-linewidth. For a 16-QAM constellation the linewidth should be <300 kHz and for 64-QAM linewidth should be around 1 kHz [1]. Furthermore for dense wavelength division multiplexing (DWDM) based systems, lasers have to be tunable to align to a dense grid. Tuning can also be exploited in switching scenarios and for improving network resilience to downtime. Sensors and related applications are other areas than can benefit from tunable, narrow-linewidth lasers..

Traditional III-V lasers had linewidths in the MHz range and only recently have been able to demonstrate sub-MHz and finally sub-100 kHz linewidths with careful optimization of resonator and gain sections. It should be noted that a direct comparison between quoted values is sometimes hard to make as methods to measure and quote linewidths differ. Hybrid-silicon lasers have shown sub-MHz linewidths for some time and recently results significantly surpassing the performance of pure III-V laser have been shown [2-6]. In both single-wavelength and widely-tunable lasers, key enablers for narrow linewidth are low-loss silicon waveguides and high-Q resonators.

2. Narrow-linewidth and ring resonators

Using rings inside the cavity [7,8] benefits the linewidth in two ways: (1) increasing the photon lifetime due to effective cavity length enhancement, and (2) providing negative optical feedback by slight detuning from the ring (resonator) resonance. Both mechanisms cannot be maximized at the same time, but there is an optimal point where combined influence is maximized [4]. A ring resonator mirror or a combination of ring resonators and cavity mirror (facet mirror, loop mirror, etc.) can be thought of as a frequency-dependent passive mirror with complex amplitude reflectivity $r_{\text{eff}}(\omega)$. The linewidth improvement due to feedback from this frequency dependant mirror is given by factor F^2 where $\Delta\nu$ and $\Delta\nu_0$ are the linewidths with and without the $r_{\text{eff}}(\omega)$ mirror as described in Eq. 1.



(a) (b) (c)

Fig. 1 (a) Vernier ring laser [3], (b) Coupled ring resonator laser [4], (c) Monolithically-integrated external-cavity lasers [5]

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$$\Delta\nu = \frac{\Delta\nu_0}{F^2},\quad F = 1 + A + B,\quad A = \frac{1}{\tau_{in}}\mathrm{Re}\left\{i\frac{d}{d\omega}\ln r_{eff}(\omega)\right\},\quad B = \frac{\alpha_H}{\tau_{in}}\mathrm{Im}\left\{i\frac{d}{d\omega}\ln r_{eff}(\omega)\right\} \qquad (1)$$

where α_H is the linewidth enhancement factor. $\tau_{in} = 2n_{eff}L_a/c$ where n_{eff} is the effective index of the gain section, L_a is the length of active region and c is the speed of light. The A term, corresponding to the linewidth reduction from reduced longitudinal mode confinement, is often denoted as the ratio of the external (passive section) cavity path length to the gain section path length. As the effective length of the ring resonator is maximized at resonance, the A factor is maximized when the ring is placed exactly at resonance. For weakly coupled rings ($\kappa \ll 1$), the effective length will be largely extended and can even dominate the total cavity length. The B term corresponds to the reduction from the negative feedback effect where a decrease in wavelength increases reflectivity (increasing photon density in the cavity) and hence decreases carrier density, which in turn causes the wavelength to increase due to the carrier plasma effect. The phase condition in the cavity can be used for a slight detuning of the laser oscillation with respect to the minimum cavity loss condition (resonator resonance). This 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. At the ring resonance, i.e. the optimal condition for A term, it is equal to zero. On the short wavelength side of the resonance the effect is reversed and operates in positive feedback, broadening the linewidth. We believe that these two mechanisms, the effective cavity length enhancement and the negative optical feedback are responsible for exceptional linewidth results shown by ring-coupled lasers. As the loss in the rings ultimately limits the performance (obtainable Q), low-loss silicon waveguides are a key enabler of exceptional performance shown by recent devices.

The Vernier ring lasers [3] featured a linewidth of 330 kHz, coupled ring resonator lasers [4] have shown linewidth of 160 kHz and monolithically-integrated external-cavity lasers [5] have brought the linewidth below 100 kHz across full tuning range with record single-mode linewidth of 50 kHz (Fig. 2). We have seen even better results at higher feedbacks from the external cavity, but our ring filter structure could not filter out a single longitudinal mode of the external cavity at higher feedback levels. An assembled hybrid design using butt coupling between InP and Si chips with ring resonators have shown even better performance with linewidths lower than 15 kHz along the entire C-band and with record values at 5 kHz [2].

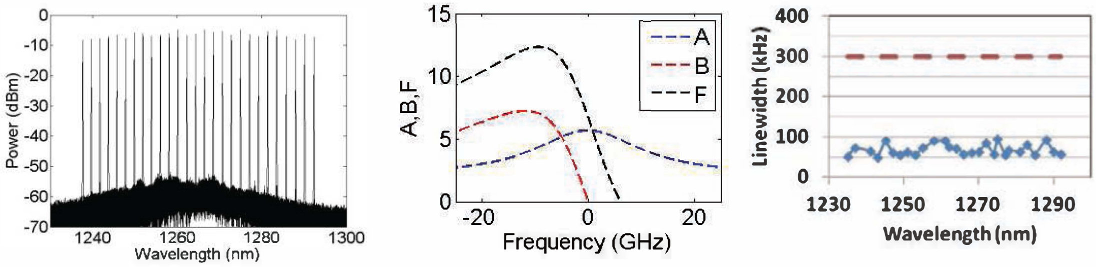

Fig. 2. (left) Monolithically-integrated external-cavity lasers [5] are tunable over 54+ nm range with SMSR > 45 dB. (middle) The linewidth improvement factor F as a function of detuning from ring resonance, see Eq 1. The combined effect of A and B is at maximum when the laser is slightly detuned on the long wavelength side (lower frequency). (right) Linewidth of monolithically-integrated external-cavity lasers as a function of wavelength. The red curve shows linewidth when there is no feedback from external cavity.

3. Acknowledgment

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