Semiconductor laser mode locking stabilization with optical feedback from a silicon PIC

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Abstract—Semiconductor mode-locked lasers can be used in a variety of applications ranging from multi-carrier sources for WDM communication systems to time base references for metrology systems. Their packaging in compact chip- or module-level systems remains however burdened by their strong sensitivity to back-reflections, quickly destroying the coherence of the mode-locking. Here, we investigate the stabilization of mode-locked lasers directly edge coupled to a silicon photonic integrated circuit, with the objective of moving isolators downstream to the output of the photonic circuit. A 2.77 kHz RF linewidth, substantially improved compared to the 15.01 kHz of the free running laser, is obtained. Even in presence of detrimental reflections from the photonic circuit, substantial linewidth reductions from 20 kHz to 8.82 kHz, as well as from ~300 kHz to 14.8 kHz, are realized.

Index Terms—Laser stabilization, Mode-locked lasers, Photonic integrated circuits, Semiconductor lasers.

I. INTRODUCTION

Bonchtop (Ti:sapphire) mode-locked lasers (MLLs) are able to produce pulse trains with extremely low phase noise [1], beating even the best radio-frequency (RF) oscillators including sapphire loaded microwave cavity oscillators. This has led, e.g., to the proposal of using them as reduced jitter clocks in optically enabled analog-to-digital converters (ADCs) [2]. While semiconductor MLLs do not currently feature such low phase noise pulse trains, relatively good operation has been achieved with help of long-delay external feedback by embedding a semiconductor optical amplifier (SOA) in a 6 meter long recirculating fiber loop [3]. Weak, fully passive optical feedback applied to a quantum (Q)-dash MLL has also proven conducive for improving both its optical and RF linewidths [4], i.e., reducing the phase noise of the underlying optical carrier as well as of the pulse train that would be obtained after applying dispersion compensation to the emitted comb [5]. While the improvement of the RF linewidth shown in [4], from 151 kHz down to 3 kHz, is not nearly sufficient for the aforementioned low jitter ADC applications, the demonstrated reduction of the optical linewidth from 10 MHz, typical for single section Fabry-Perot type MLLs [5], down to 100 kHz enables utilization of individual comb lines as optical carriers for coherent communications [6],[7]. Semiconductor MLLs have further been utilized to generate optical carriers for direct detection wavelength division multiplexed (WDM) transceivers. Here, mode-locking is merely used as a means to obtain sufficiently low relative intensity noise (RIN) via mode partition noise reduction [8]. Moreover, optical combs can be used for a variety of sensing applications such as dual comb spectroscopy [9] or optical ranging [10] in which a narrow RF linewidth is also advantageous.

Integration of MLLs into such transceivers by means of flip-chip bonding [11] is unfortunately difficult, as very weak levels...
II. DESCRIPTION OF PIC AND LASER

While broadband reflection of the entire comb spectrum has been proven to be conducive in free-space [4] and fiber [12],[13] based setups, the strong dispersion associated with integrated waveguides can be a problem, as ideally the phase of each back-reflected comb line should be dialed in to yield stabilizing feedback with a constructive interference condition. Rather than implementing broadband dispersion control, we opt for a scheme in which only two comb lines are fed back to the laser with narrowband reflectors, each adjustable with a tunable phase and intensity [17]. We build on a PIC architecture previously used for the stabilization of distributed feedback lasers [18], adding a second on-chip optical path to provide feedback for a second comb line (schematic in Fig. 1). While reflection of a single line only carries information on the phase of the underlying optical carrier, feeding back two lines also feeds back the RF phase (the phase of the pulse train) yielded by the beat note of the two lines. It is thus expected to contribute to RF linewidth reduction. The resonant frequencies of both rings as well as the phase delays interposed in each optical feedback path are independently tunable, so that in principle phase and amplitude can be independently set for both.

Figure 2 shows PIC reflection spectra recorded with different tuning currents applied to one of the rings. The frequency selective reflection induced by the ring takes the form of Fano resonances arising from interference with the broadband facet reflection, that is of commensurate amplitude. The facet reflection is evaluated as being on the order of -13 dB, while, based on the shape of the Fano resonances, the reflection from the tuned feedback path is evaluated to be on the order of -15.5 dB at resonance, i.e., 2.5 dB lower. The rings both feature quality (Q)-factors of ~20,000, an FSR of 8.7 nm, and one of the rings, ring 2, features pronounced Mie splitting [19] with 76.9 pm resonance splitting (see Suppl. Mat.). They can be thermally tuned at a rate of 70 pm/mA°. The cumulative waveguide length separating the chip facet from the Sagnac loops is ~880 μm for both paths, resulting in round trip group delays of ~26 ps in addition to the ~66 ps arising from the rings at resonance.

The semiconductor MLL is a Q-dash buried ridge stripe (BRS) laser operated as a single section laser [5]. It has a stripe width of 1.5 μm, 6 layers of InAs Q-dashes in an InGaAsP barrier grown on an InP wafer and a length of 1140 μm resulting in an FSR of 36.7 GHz. The current setpoint of the laser, 240 mA, was chosen to yield a stable and narrow RF linewidth at 30°C, resulting in a 15.01 kHz RF linewidth when free running without optical feedback.

Figure 3 shows the ~13 nm wide laser spectrum centered on 1543 nm, as well as the electrical spectrum featuring a single RF beat note at 36.7 GHz. Figure 4 shows the RF spectra of the MLL as a function of injection current as a color plot. At 220 mA, a jump in the laser’s FSR is apparent as it transitions to another collective supermode [20], however a relatively wide range of stable operation is given around the chosen bias point. It should be noted that while the optical feedback is applied to two lines only, RF linewidths reported below are measured from the entire spectrum. Since the PIC applies a weak feedback to an already closed laser cavity, a full spectrum spanning >10 nm is generated as for the stand-alone laser diode.
III. CHARACTERIZATION RESULTS

Operation of the laser was investigated under optical feedback, i.e., after placing the laser at a few micrometer distance of the PIC’s edge coupler and aligning its position with a piezoelectric actuator to maximize the coupling efficiency. Tuning currents in the range 4 mA to 6 mA were independently applied to both rings, shifting their resonances by > 4 laser FSRs around the center of the laser spectrum. Adjacent ring resonances on the edges of the laser spectrum only interact with very weak comb lines, more than 10 dB below the power of the central lines, thus with weak effect on lasing dynamics.

Figure 5 shows a summary of the characterization results with panels (a), (b) and (c) respectively showing the optical power transported to the main output port of the PIC (marked by arrows in Figs. 1(a) and 1(c)), as well as the FSR and RF linewidth of the MLL. Small drops in the transmitted power mark the spectral alignment of a ring with an MLL comb line, which is then dropped and filtered out before reaching the output port. These ring bias points are marked by white lines in the figure, wherein these occur in pairs for ring 2 as a consequence of the split resonance. Five regions of operation, marked as R1 to R5, are visible in the RF linewidth. They respectively correspond to RF linewidths on the order of ~5 kHz, 80 kHz, 20 kHz, several hundred kHz and 3 kHz. While the RF linewidths are better than those of the free running laser in regions R1 and R5, and comparable in region R3, in regions R2 and R4 the RF linewidths are much worse. These regions are independent of the spectral alignment of the rings, since they are much wider than the regions in which the ring 2 resonance overlays with a comb line. Rather, they are a consequence of the broadband reflections from the PIC to the MLL (including reflections from the PIC facet as well as on-chip devices such as grating couplers), that, depending on their phase, either help or hinder mode-locking. Indeed, in the automated measurement, the ring 1 current sweep is embedded inside the ring 2 sweep, i.e., while ring 1 is rapidly and repeatedly swept between 4 mA and 6 mA, ring 2 is only swept once at a much slower pace. Thus, the ring 2 bias can also be taken as the time axis (21 hours total). Transitions from R1 to R5 are the consequences of slow drifts in the test setup changing the phase of the broadband reflections, for example due to overall heating of the chip and its submount over time. It is apparent in Fig. 5(b) that in regions R2 and R4, in which the RF linewidth is considerably broadened, the MLL FSR is also lowered by a few MHz.

It is apparent that frequency selective feedback can modify the RF linewidth when a ring resonance overlays with an MLL comb line. Here too, the linewidth is reduced or enhanced depending on the feedback phase, but since the latter is also changed by the exact ring bias point, it can be fine-tuned with the ring provided the feedback phase at resonance is close enough to target (in the most general case, the phase shifters would ensure that such a constructive interference condition can be reached). E.g., in region R3 a crisscross pattern of deeper blue regions is seen corresponding to ring resonances overlaying with MLL comb lines, in which the RF linewidth is improved, from ~20 kHz down to 8.82 kHz at the point marked by PA in Fig. 5(a). The RF linewidth minima can be seen to occur slightly to the left of the ring 2 resonances, with the lower bias currents corresponding to a detuning of about one half of the resonance’s full width at half maximum (FWHM). At points PD, PB and PA on the other hand, the RF linewidth is increased from the surrounding ~5 kHz to respectively 133 kHz, 14.5 kHz and 26.9 kHz as a consequence of the destructive interference condition.

![Fig. 4. RF spectra of the MLL as a function of injection current recorded at 30 C. A sudden jump is apparent in the laser’s FSR as the injection current drops below 220 mA. The arrow marks the operating current used in the system characterization. The inset shows the extracted RF linewidths as a function of bias point.](image47x104 to 569x258)

![Fig. 5. Characterization of the MLL under feedback from two independently tuned rings. (a) Optical power recorded at the main output port of the PIC (marked by an arrow in Fig. 1(a)). Color coding shows the power in dBm relative to the average output power. Changes are slight, as at most two lines out of ~40 are filtered out. (b) FSR change and (c) RF linewidth of the MLL. White lines indicate bias points at which a ring resonance is aligned with a comb line. Regions R1 to R5 correspond to a slow drift of the broadband reflection phases. In the measurement sequence, scanning of ring 1 bias is embedded into a single ring 2 scan, so that the ring 2 bias can also be taken as the time axis (21 hours total) during which the laser-to-PIC distance slowly drifted. Data in (c) was recorded with a 16 kHz RBW.](image67x594 to 300x749)

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RF linewidths were measured with a resolution bandwidth (RBW) of 16 kHz, to avoid prohibitively long measurement times. Measured spectra have been fitted to a Voigt profile resulting from the convolution of a Lorentzian with the known Gaussian frequency response of the spectrum analyzer, with good fitting accuracy and stability (Suppl. Mat.). Numbers reported here correspond to the FWHM of the underlying Lorentzian linewidth. Figure 6 shows exemplary spectra in a small range around the RF beat note together with the Voigt profile fits. Clear improvements relative to the free running spectrum can be seen at both the tuning point \( P_A \) and in the exemplary spectrum from feedback range \( R_5 \). Figure 7 shows the spectra for tuning point \( P_A \) (both rings tuned into separate MLL comb lines) as well as for another exemplary tuning point within range \( R_3 \) in which both rings are detuned. It is apparent that both spectra feature a unique RF beat note and that their maximum power is of comparable magnitude, with a slight decrease in the case of \( P_A \) (0.5 dB) attributed to the signal reduction associated to two comb lines being filtered out.

Figure 8 shows the extracted RF linewidths as the tuning current of ring 1 is swept but the tuning current of ring 2 is maintained either around 4.68 mA, blue curve, or 4.88 mA, red curve (for better statistical significance each curve corresponds to an average of ~0.02 mA, 0 mA and +0.02 mA from the nominal ring 2 bias current). In the blue curve, ring 2 is maintained detuned relative to the MLL comb lines, while in the red curve ring 2 remains tuned to an MLL comb line throughout. In both, ring 1 moves in and out of alignment with the MLL lines. The red tuning curve connects points \( P_A \), \( P_B \) and \( P_C \), while the blue runs to its left in Fig. 5. It is apparent that the latter features a reduced RF linewidth at three tuning points, whenever ring 1 overlaps with an MLL comb line. The baseline of the red curve is at that same level, as a consequence of the collective action of both feedbacks. When both rings are aligned to separate comb lines (points \( P_A \) and \( P_C \), as labeled), further enhancement is visible as a consequence of the collective action of both feedbacks. When both rings are aligned to the same comb line, no significant further improvement is observed (\( P_B \)). Since very little of that comb line reaches the downstream ring, no additional feedback is created by the latter. The improved feedback under the collective effect of both rings might be explained by the feedback qualitatively containing more information, as the beat tone between the two comb lines also provides feedback in respect to the RF phase, as opposed to only the optical phase as in the case of a single line. It is however also possible that it is simply a consequence of the feedback being quantitatively stronger, as the power from two lines is being sent back. In particular, the applied tunable feedback is weak compared to the broadband parasitic feedback from the chip facet, as a consequence of the former only being applied to two lines and the latter to 40+ lines. This is however partially compensated by the group delay of the tunable feedback being considerably larger, which leads to a stronger effect [18].

As the 20 kHz linewidth in region \( R_3 \) has been reduced to 8.82 kHz, the best linewidth at \( P_A \), it is apparent that a linewidth narrowing with a factor better than 2 has been obtained. While this is a substantial improvement, it is still not as good as when the broadband reflection itself contributes to linewidth reduction, as in regions \( R_1 \) and \( R_3 \) in which significantly smaller
linewidths have been obtained, respectively on the order of 5 kHz and 3 kHz. As an example, Fig. 6 also shows a typical spectrum obtained in R5, with an extracted linewidth of 2.77 kHz corresponding to an improvement better than a factor 5 relative to the free running laser.

An open question remains how much the RF linewidth of an MLL broadened substantially beyond the free running condition due to detrimental broadband feedback, for example due to an ill-controlled laser to chip-facet distance in a flip-chip attachment process [11], can be improved by artificially feeding back a finite number of lines. This could only be partially verified with the dataset reported above, as regions R2 and R4, that correspond to a significant degradation of the RF linewidth, did not overlay with ring resonator 2 being tuned to one of the MLL lines (detrimental broadband reflection was randomly obtained due to long term drift of the laser-to-chip distance). However, the effect of feedback from a single ring could be investigated.

As seen in Fig.9(a), feedback from ring 1 allows a substantial reduction of the RF linewidth in region R4, in which it is otherwise significantly deteriorated by the broadband reflections. As further seen in Fig. 9(b), the obtained linewidth under feedback (blue curve) is about a factor 20 better than the linewidth without ring 1 feedback (continuous and dashed red curves). The ring 2 tuning current shown on the x-axis is a proxy for measurement time, as previously explained, during which the detrimental broadband feedback becomes progressively worse. The dashed and continuous red curves show the RF linewidths changing their phases as the setup drifts. At the point $I_2=5.06$ mA, the linewidth is for example improved from 280-430 kHz to 14.8 kHz as the ring 1 feedback is applied. Corresponding RF spectra are shown in Fig. 9(c).

A study revealing more systematically the limits and capabilities of this stabilization scheme for different mode locking conditions proved difficult to implement due to drifts of the setup and would require improved long term mechanical stability, e.g. with a flip-chipped MLL.

One may remark that while the obtained RF linewidth improvements are adequate for the main application pursued here – the utilization of single section semiconductor MLLs as multi-carrier sources for direct detection communication systems with an isolator moved to the output of the PIC – others, in particular in the field of metrology, would require much more regular pulse trains. In order to achieve substantially lower RF phase noise operation, longer low delay lines (resonant or linear) would be desirable. Such could e.g. be provided by PIC platforms with low loss, silicon nitride (SiN) waveguides. Platforms with high confinement (and thus densely routable) waveguides have been shown with Q-factors as high as a couple of millions [21]. Even higher Q-factors of 80 million have been obtained in low confinement platforms [22]. Corresponding waveguide losses of respectively $\sim 1$ dB/m and 0.1 dB/m are respectively 2 and 3 orders of magnitude better than silicon waveguides. Delays equivalent to a few meters of fiber [3] can be obtained in such platforms, giving a prospect of much more substantial RF linewidth improvements. Finally, adding an anti-reflective coating to the input facet of the PIC would also be conducive for further improvements.

IV. CONCLUSIONS

In conclusion, we have shown improvement of the RF linewidth of a single section semiconductor MLL by feedback from a SiP PIC beyond the level obtained from the free running laser even in the presence of adverse broadband reflections from the PIC. RF linewidths as low as 2.77 kHz, adequate for the targeted SiP direct detection transceiver application, have been obtained. Further improvements may require longer, low loss delay lines that could be implemented in a low loss SiN waveguide platform and tighter control of the feedback conditions, e.g. by a flip-chip mounted MLL on a rigid PIC, to avoid microphony and drift.

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Supplementary Materials

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I. EXTRACTION OF RF LINEWIDTHS

RF linewidths were measured with the resolution bandwidth (RBW) of the electrical spectrum analyzer set to 16 kHz with Gaussian filtering. As a consequence, the recorded spectra are convoluted with the frequency response of the spectrum analyzer. Assuming the spectra to be initially Lorentzian shaped, the end result would be a Voigt profile with a known Gaussian content. The goal of this section is to verify the adequacy of the Voigt profile fitting for extraction of the underlying RF linewidths.

Fits are made by minimizing the residual sum of squares (RSS) obtained by comparing the data and the model on a dBm scale with data points spaced between -400 kHz and +400 kHz from the center of the spectrum on a 3 kHz grid. Lorentzian linewidth, the spectrum’s center frequency and the maximum power are left as free parameters, wherein only tiny adjustments are made to the latter two since they are straightforwardly determined from the data beforehand. The RBW of the spectrum analyzer is fixed during RSS minimization. For the two spectra taken under optical feedback shown in Fig. 6 of the main text, with extracted RF linewidths of respectively 8.82 kHz and 2.77 kHz, Fig. SM1 shows the RSS and the extracted underlying linewidths as a function of the assumed Gaussian filter bandwidth. It is apparent that the RSS is minimized between 14 kHz and 15 kHz for both spectra, very close to the 16 kHz expected from the spectrum analyzer settings. Figure SM1(b) shows the sensitivity of the extracted Lorentzian linewidth on the assumed Gaussian RBW. In both cases, minimizing the RSS while leaving the Gaussian RBW freely adjustable would have resulted in even smaller extracted Lorentzian linewidths, 2.56 kHz instead of 2.77 kHz and 8.79 kHz instead of 8.82 kHz. Moreover, these differences in fitting results are quite small. From Fig. 6 (main text) it is apparent that the fits follow the data closely in both the center region dominated by the Gaussian filter shape and on the sides dominated by the skirts of the Lorentzian transfer function.

![Fig. SM1. (a) RSS and (b) extracted Lorentzian linewidth for the two spectra under optical feedback shown in Fig. 6 of the main text plotted as a function of the assumed RBW. The same color coding is used as in Fig. 6, i.e., the red and orange curves respectively correspond to the spectra from R5 and P1.](image)

As a further benchmark of the measurement methodology, we compared a direct measurement of the free running RF linewidth of an MLL nominally identical to the one used for the measurements reported in the main text, as obtained with a relatively small RBW of 1 kHz, to the linewidth extracted from a spectrum recorded with a RBW of 24 kHz with the methodology described above. Unfortunately the laser used for the experiments described in the main text was no longer available due to an ESD event, however this serves to ascertain the soundness of the methodology. Moreover, since the dataset shown in the main text corresponds to 10201 spectra, taking the data directly with a low RBW would have taken a prohibitive amount of time (as is, it already took 21 hours).
Fig. SM2. Comparison of RF linewidth measurements (free running MLL) taken with (a) a 1 kHz RBW and (b) a 24 kHz RBW. The 24 kHz RBW spectrum is fitted to a Voigt profile with a fixed Gaussian part and the underlying Lorentzian linewidth extracted (11.67 kHz). The Lorentzian is overlaid over the 1 kHz RBW spectrum shown in (a). The measured PSD are shown both as raw data as well as smoothed with a running average (r.a.). The Lorentzian FWHM extracted from the 24 kHz RBW data appears to fit the 1 kHz RBW data quite well.

II. Mie Splitting of Ring 2

Via the monitor ports shown in Fig. 1 of the main text, we were able to measure the spectra of the light dropped through the rings to their drop ports as a function of the tuning current (Fig. SM3). The expected parabolic dependence of the resonance wavelength on the current sent through the thermal tuner is clearly visible (the dissipated power is proportional to the square of the current). Both ring 1 and ring 2 feature periodic dips in the transmitted power, exemplarily marked by dashed circles, that are attributed to Fabry-Perot resonances occurring due to spurious reflections inside the PIC. Importantly, it can be seen that the rate at which the center wavelength of these dips varies is different from the rate at which the ring resonance moves (the change of the former being attributed to the variable phase offset resulting from the ring as it is being tuned). In addition, ring 2 features a marked split resonance, exemplarily marked by a continuous circle, wherein both resonances are tuned with the exact same rate. Figure SM4 shows an exemplary transmission spectrum to a monitor port through ring 2. It features the characteristic shape of a split resonance, with a 76.9 pm splitting.

Fig. SM3. Power transmitted from the main PIC input port (usually connected to the MLL, replaced here by a lensed fiber connected to a tunable laser) through either ring 1 (a) or ring 2 (b) to a corresponding monitor port tapped from the drop waveguide, plotted as a function of wavelength and tuning current. Both ring 1 and ring 2 feature periodic drops in the transfer function (dashed circles) attributed to Fabry-Perot resonances. In addition, ring 2 features pronounced resonance splitting.

Fig. SM4. Exemplary transmission spectrum to the drop waveguide of ring 2 as monitored through a monitor tap. The characteristic spectrum of split resonances can be seen, with a resonance splitting of 76.9 nm.