Hybrid Silicon Colliding-Pulse Mode-Locked Lasers With On-Chip Stabilization

Sudharsanan Srinivasan, Erik Norberg, Tin Komljenovic, Michael Davenport, Gregory Fish, and John E. Bowers, *Fellow, IEEE*

***Abstract*—We investigate the design of hybrid silicon colliding-pulse mode-locked laser diodes and the dependence on quantum well design. We show the reduction in microwave linewidth using two techniques. First, reducing the number of quantum wells reduces the confinement factor thereby lowering the spontaneous emission contribution to the linewidth. Second, a ∼4-cm long on-chip feedback cavity is used to provide optical feedback to stabilize the laser and further reduce the linewidth. The linewidth achieved at 17.36 GHz using the above two techniques is 29 kHz.**

***Index Terms*—Semiconductor lasers, mode-locked lasers, colliding pulse mode-locking, photonic integrated circuits.**

I. Introduction

MODE-LOCKED laser diodes (MLLD) are compact, low cost solutions to generating high frequency microwave signals. The root mean squared timing jitter of the generated optical pulses/microwave frequency can be <1ps [1], surpassing the state of the art jitter performance provided by microwave oscillators using CMOS/SiGe technology [2]. Hence, they can be used in a variety of applications such as high speed optical time-division multiplexing, all optical signal processing, microwave/millimeter wave transmission and clock distribution. However, the adoption of these sources is currently limited by the cost and complexity that surround the MLLD. Most MLLD demonstrations use cleaved facet mirrors, which are not ideally suited for on-chip photonic integration and typically have external cavities. The cost, size and environmental sensitivity can all be improved with monolithic integration.

Some of the better results for MLLD use quantum dot (QD) active regions and the low optical confinement factor in the QD material is often cited as the primary reason for reduced timing jitter, because of reduced amplified spontaneous emission (ASE) [3]. The hybrid silicon technology [4] inherently allows the manipulation of the confinement factor in the quantum well (QW) active region by means of changing the silicon waveguide width underneath. One can also incorporate fewer QWs in the active region to reduce confinement. In this text we discuss the integration of a 1.3 μm QW based colliding pulse mode-locked laser with two different QW numbers, three and five. The three QW device has a confinement factor that is 60% (three-fifths) of that in the five QW device. In order to get further reduction in optical/ microwave linewidth, we adopt the technique shown in Refs. [5]–[7], where a portion of the pulse emitted from the laser is fed back into the cavity to reduce ASE noise. We achieve the feedback on chip, without the need for any coupling optics by adding a ∼4 cm long waveguide delay at the output of the laser back mirror and terminating with a semiconductor optical amplifier (SOA) followed by a 100% reflecting loop mirror. The purpose of the SOA was to overcome the losses of the waveguide delay and also serve as a control switch to adjust the level of on-chip feedback. This technique of stabilization using intentional feedback is also known to stabilize the laser from other unknown spurious reflections, which can come from the rest of the photonic circuit.

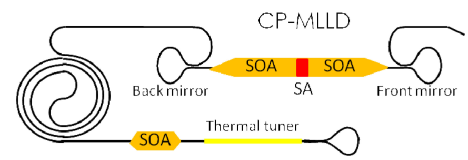

Fig. 1. Schematic showing the laser circuit. Black lines indicate the silicon waveguide, SOA-semiconductor optical amplifier, SA-saturable absorber.

The paper is divided into the following sections. We provide the device details of the lasers in Section II. We present the measurement results from each laser in Section III along with the influence of on-chip feedback on the microwave linewidth. In Section IV we interpret the results and provide design suggestions to improve the laser, and finally conclude in Section V.

II. Device Design

The schematic of the photonic circuit is shown in Fig. 1. All the lasers reported here have the same circuit configuration and the only variation is in the number of QWs in the active region. The basic CP-MLLD consists of 1.2 mm long SOA with a centered 40μm absorber and two 15 μm isolation sections, one on either side of the absorber. The hybrid section tapers down to the silicon waveguide and the laser cavity is formed using directional coupler based loop mirrors. The reflectivity of the front facet is 10% and that of the back mirror is 55%. The total cavity length is 3.934 mm which corresponds to a fundamental cavity frequency of 8.7 GHz. The output of the front facet loop mirror is terminated at the chip facet at an angle to avoid reflections. The output from the back mirror goes through a spiral silicon delay line followed by an SOA and

Manuscript received January 26, 2015; revised March 30, 2015 and April 27, 2015; accepted May 4, 2015. Date of publication May 21, 2015; date of current version June 29, 2015.

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Digital Object Identifier 10.1109/JSTQE.2015.2432018

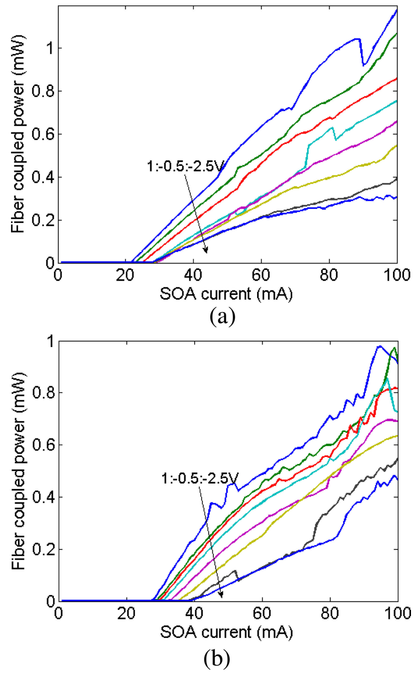

Fig. 2. Light current curves for different absorber bias voltages for three (a) and five (b) QW device.

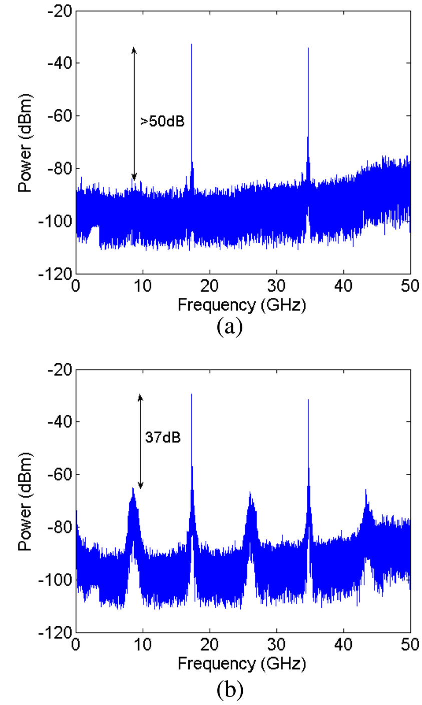

Fig. 3. RF spectrum (resolution bandwidth-RBW 3 MHz) for the three (a) and five (b) QW device. Bias points (a) 75 mA-SOA current, –0.4V-SA voltage and (b) 67 mA-SOA current, –0.8V-SA voltage.

a 100% loop mirror reflector using a 1 × 2 MMI. The total feedback cavity length is 39.343 mm i.e. a free spectral range (FSR) of 870 MHz, which is designed to be exactly ten times the base laser cavity length. There is a thermal tuner in the feedback cavity to control the phase of the fed back pulses. The feedback cavity SOA is 560 μm long to partially compensate the waveguide loss. The total device area is 2.5 × 1 mm^2.

III. Experimental Results

This section is divided into two parts. First, we consider the various laser cavities without feedback. This corresponds to applying a –3V bias on the feedback cavity SOA. The feedback was negligible as the thermal tuner had little effect on the microwave signal. Second, we consider the same laser cavities with feedback and show the region of optimum bias conditions to achieve narrow linewidth. All the experiments were carried out on a temperature controlled stage kept at 20 °C. The RF port of the bias-T connected to the absorber was terminated at 50 Ω. The light output is collected using a 2 μm spot-size lensed fiber, which is spliced to a 37 dB return loss isolator.

A. Without On-Chip Feedback

The light-current curves for the device with five and three QWs are shown in Fig. 2. The threshold current is slightly higher for the five QW laser as expected, and the fiber coupled output power level is comparable. The cause for the kinks in the light-current curves is likely from the mode transition to a second group of modes that co-exist in the laser and compete for gain. The upward kink near 70 mA and –0.5 V (cyan curve) in the 3 QW device is the saturable absorption effect seen in most MLLDs.

We begin with identifying the bias conditions for mode-locking in colliding pulse operation. The light output is collected with a high speed detector with a bandwidth and responsivity of 50 GHz and 0.23 A/W respectively. Fig. 3 shows the RF spectrum for the two devices in colliding pulse operation at the optimum bias point. We observe a greater suppression of the fundamental in the three QW device by more than 13 dB. We also notice a noise pedestal at the foot of the 17.4 GHz signal for the five QW device.

We then obtained the optical time and frequency domain data of the laser output at these bias points. Fig. 4 shows the optical spectrum from the two lasers. The lasing wavelength is red shifted in the five QW device, most likely due to the increased absorption in any of the un-pumped areas of the hybrid section, which include the isolation region and a portion of the tapers. Another interesting observation is the difference in the peak to valley extinction ratio for the comb lines (distance between the top and bottom envelope). The ASE noise power is significantly higher in the five QW device.

The laser output was amplified using a praseodymium-doped fluoride fiber amplifier (PDFA) to measure the autocorrelation signal. Fig. 5 compares the optical pulses obtained from the two devices. Since the lasing wavelength was not the same, the gain from the PDFA was different in the two cases and the strength of the autocorrelation signals were different despite the comparable optical power from the devices. The pulsewidths for the three and five QW devices are 7.7 and 4 ps respectively. The corresponding time-bandwidth products are 0.335 and 0.348 respectively. The five QW device shows a pedestal, indicative of a slow decay or a trailing pulse. The trailing pulse could come

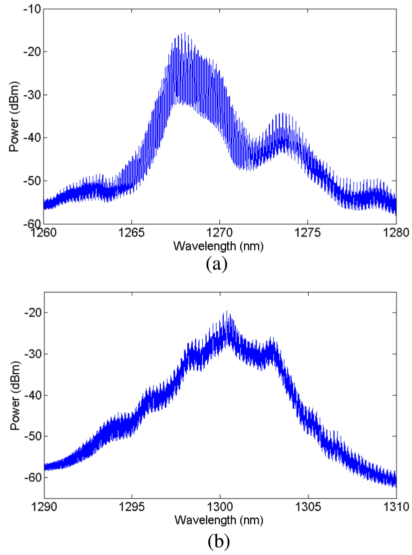

Fig. 4. Optical spectrum (RBW–0.02 nm) for the three (a) and five (b) QW device. Bias points are the same as in Fig. 3.

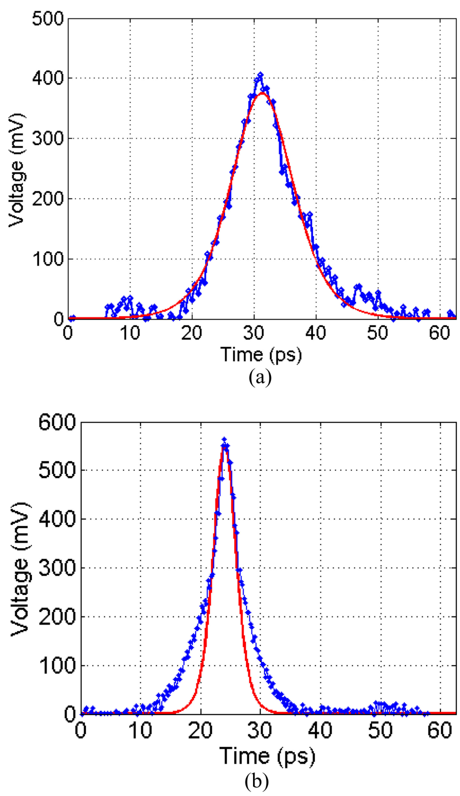

Fig. 5. Autocorrelation traces (blue) for the three (a) and five (b) QW device. Bias points are the same as in Fig. 3. The red lines are the $sech^2$ fit to data.

from one of two reasons. First, the insufficient suppression of the group of modes locked at the fundamental appears as a daughter pulse once every two cycles. Second, the daughter pulse has the same repetition rate as the main pulse and is from a second group of higher order lateral modes in the cavity. We will discuss more on this topic in the next section.

Fig. 6 shows the improvement in phase noise of the microwave signal by reduced spontaneous emission in the three QW device.

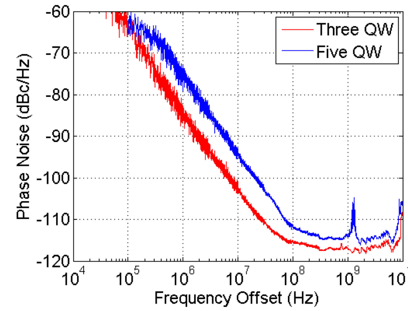

Fig. 6. Phase noise comparison of the 17.4-GHz signal for the three and five QW devices. Bias conditions are the same as in Fig. 3.

The improvement is as large as 8 dB in the $1/f^2$ region. On the same note, the 3 dB linewidth of the three QW device was 44 kHz while that of the five QW device was 200 kHz. The spur at ∼1 GHz in the phase noise of the five QW device is an indication of reflections of the SOA taper in the feedback cavity. The timing jitter obtained from integrating the phase noise from 100 kHz to 100 MHz, was 2.7 and 9.5 ps for the three and five QW device respectively. We now discuss measurements with on-chip feedback.

B. *With On-Chip Feedback*

While the lasers are in colliding pulse operation as shown in the previous section, we start applying a forward bias to the SOA to increase the power being fed back into the lasing cavity, and mapping the microwave linewidth for various feedback cavity SOA current and thermal tuner current. Changing the feedback SOA current corresponds to changing the reflectivity and changing the thermal tuner current alters the phase delay. We measure the RF spectrum by averaging ten traces with a sweep time for each trace set to 125 ms. The linewidth is extracted by fitting a Lorentzian to the data. The linewidth measurements were taken when the laser SOA was pumped using a battery powered supply to reduce the amount of Gaussian noise added.

Figs. 7 and 8 show the influence of on-chip feedback cavity for the three and five QW devices, respectively. The desired region of operation for narrow linewidth is the blue shaded regions in plots (a) and (b). The five QW device shows a more clear pattern for regions of linewidth narrowing than the three QW device. The islands of instability are periodic and grow in size with increasing SOA current. The phase and amplitude of the pulse being feedback is important and shows that the phase noise reduction happens only at certain bias conditions (blue shaded regions) for the feedback cavity SOA and the tuner. Figs. 7(a) and (b) shows some randomness because the measured linewidths are very narrow and significant Gaussian noise from stage temperature drift or fluctuations affects the linewidth estimate from measurement to measurement. In both cases, the linewidth starts to re-broaden for large SOA currents and eventually fails to mode-lock. The re-broadening is due to the increased ASE noise being injected back unfiltered into the cavity and eventually the round trip gain of the feedback cavity longitudinal modes is sufficient to start multi-mode operation and we observe periodic spur tones around the comb

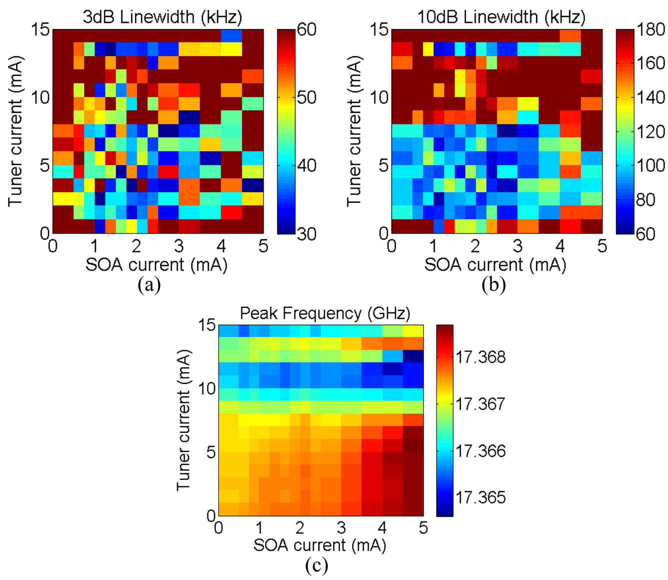

Fig. 7. (a) 3 dB, (b) 10 dB linewidth, and (c) oscillation frequency of the microwave signal as a function of feedback SOA current and thermal tuner current. The optimum bias condition is at 2.5 mA SOA current and 7 mA tuner current. Data measured from three QW device.

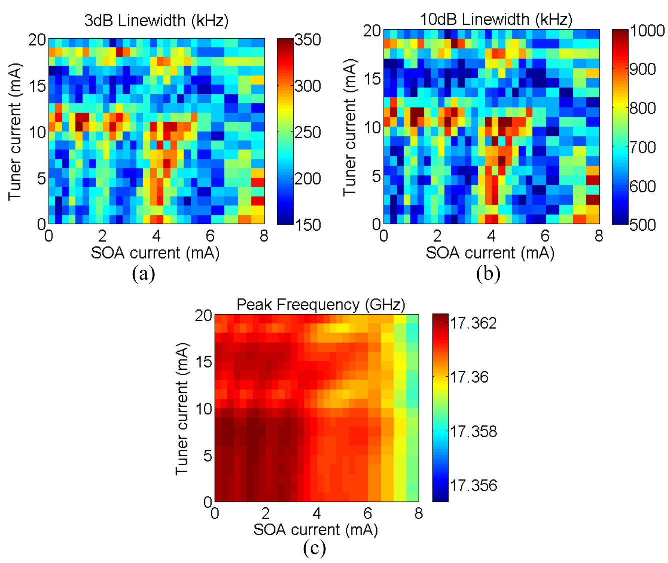

Fig. 8. (a) 3 dB, (b) 10 dB linewidth, and (c) oscillation frequency of the microwave signal as a function of feedback SOA current and thermal tuner current. The optimum bias condition is at 0.25 mA SOA current and 2 mA tuner current. Data measured from five QW device.

frequencies. The optimum bias conditions for the three QW device was found at 2.5 mA SOA current and 7 mA tuner current. The 3dB linewidth is reduced from 44 kHz to 29 kHz. For the five QW device the optimum bias was at 0.25 mA SOA current and 2 mA tuner current. The 3 dB linewidth was reduced from 200 to 136 kHz. The linewidth is reduced by ∼1.5 times in both cases. The peak frequency shifts in Figs. 7(c) and Figs. 8(c) is from the frequency pulling effect of the mode-locking frequency to the changing FSR of the external cavity from decreasing group index of the SOA with increasing injection current. However, with increasing tuner current the group index increases decreasing the FSR.

TABLE I
SUMMARY OF LINEWIDTH IMPROVEMENT WITH ON-CHIP FEEDBACK

RF linewidth (kHz) measured @	Without feedback	With feedback
	Three QW device	
3 dB	44	29
10 dB	103	60
20 dB	292	159
	Five QW device	
3 dB	200	136
10 dB	607	409
20 dB	2010	1356

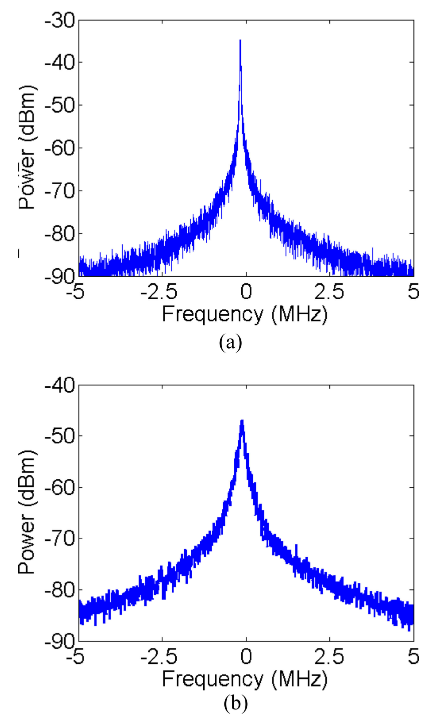

Fig. 9. RF spectrum showing the best linewidth achieved with feedback for the three (a) and five (b) QW device centered at 17.362 and 17.367 GHz respectively. RBW-10 kHz.

Table I shows the summary of linewidths with and without feedback for the two devices. For a perfect Lorentzian lineshape, the 10 dB linewidth should be $3(=\sqrt{9})$ times the 3 dB linewidth and the 20 dB linewidth is $\sim 10(=\sqrt{99})$ times the 3 dB linewidth. The five QW device shows an ideal Lorentzian behavior as the linewidth is quite broad, however, the three QW device shows broadening from excess Gaussian noise, despite using battery powered supplies. This could be from temperature fluctuations. If we disregard the Gaussian noise contribution and fit a pure Lorentizan to match the 20 dB linewidth, the 3 dB linewidth is at best $\sim 16\,\text{kHz}(=159/\sqrt{99})$, which is a record for QW based MLLDs. The RF spectrums for the optimal bias conditions of feedback for both three and five QW device are shown in Fig. 9.

IV. Discussion

In this section we will analyze the measurement results and provide suggestions to improve the laser performance in the future. The absorber region was probably too short. We shall start the discussion with the expression for RF linewidth ($\Delta\nu_{\mathrm{RF}}$) in a mode-locked laser [8], as

$$\Delta\nu_{\mathrm{RF}} = C_1\,(\Delta\nu_{\mathrm{ST}}) + C_2\,(\mathrm{RIN}) \tag{1}$$

where the expressions for C_1 and C_2 can be found in [8]. $\Delta\nu_{\mathrm{ST}}$ is the Schawlow-Townes optical linewidth. The first term is the direct contribution of optical phase noise to microwave phase noise and the second term is the noise due to AM-PM conversion, also known as the coupling between energy and timing fluctuations of the pulses in the cavity. The second term is usually quite small for semiconductor lasers because the relative intensity noise is significantly lower. The approach taken in this article is to try and reduce the microwave phase noise by reducing the optical phase noise originating from spontaneous emission. This can be done by reducing the confinement factor (Γ) of the optical mode. The cavity being three dimensional, the confinement factor can be separated into the individual confinement factors in the lateral (Γ_x), transverse (Γ_y) and longitudinal (Γ_z) direction, i.e. $\Gamma = \Gamma_x\Gamma_y\Gamma_z$. We reduced the transverse confinement by reducing the number of QW and the longitudinal confinement by using the external cavity. Both techniques help to reduce the microwave linewidth. However, as observed in Ref. [5] the reduction from the feedback cavity was not as appreciable as the mode-locking optical bandwidth was quite low (<100 GHz). On closer inspection of the optical spectrum, we find that the reason for low bandwidth is because of the existence of a higher order lateral mode with a different group index, which modulates the gain spectrum due to the Vernier effect. Mode-locking happens only when both groups of modes are locked.

On reviewing the results, we propose the following suggestions to improve the laser performance. First, the back mirror reflectivity was designed to be quite high in the interest of keeping the output power from the front mirror high. Since the optical linewidth reduction increases with decreasing back mirror reflectivity, the reflectivity can be reduced to allow greater coupling to the external cavity. Second, since the power out of the back mirror is sufficiently high and the waveguide loss was quite low (<1 dB/cm) the feedback cavity SOA can be removed and replaced with a variable optical attenuator such as a Mach-Zehnder interferometer (MZI) switch in the external cavity or an MZI based loop mirror to directly tune the coupling between the two cavities. This reduces the ASE noise introduced in the feedback cavity. If the SOA is necessary, then a filtered feedback configuration using ring resonators is necessary to filter out the excess noise. Third, longer delay lines can be fabricated for lower waveguide loss systems. A general rule being the length of the feedback cavity $\mathrm{L_p}$ should be less than $1/(2\alpha)$, where α is the waveguide propagation loss in cm^{-1} [9]. Last, we could reduce the number of QWs further, but should also increase the absorber length accordingly.

V. Conclusion

In conclusion, we presented results from two hybrid silicon CP-MLLD with different number of QW in the active section. By means of reducing the transverse confinement factor by reducing the number of QW and reducing the longitudinal confinement factor by using an on-chip feedback cavity, we were able to achieve a microwave linewidth of 29 kHz at 17.36 GHz. The integrated jitter is reduced from 2.7 to 1.2 ps with on-chip optical feedback, which is similar jitter performance to the laser demonstrated earlier with the delay line inside the laser cavity and harmonically locked at 20 GHz using an intra-cavity filter [10]. The advantage of this laser, however, is higher optical output power and lower threshold current as the loss from the delay line is removed. The integrated jitter compared to the laser shown by Koch *et al*. [11] is a factor two better. The pulses from our lasers are less chirped and suffer less from excess self phase modulation and excess dispersion because the cavity does not have gain region everywhere [11], [12]. However, having gain region everywhere avoids taper transitions and enables an unmodulated optical comb. We believe that taper transitions are necessary to enable on-chip integration with other optical elements and hence the design of a low reflection taper is a very important first step. We also recommend certain design considerations to improve the performance of the coupled cavity mode-locked laser. The results shown here of a fully integrated chip scale mode-locked laser will be useful for applications that require generation of simultaneous high frequency and low jitter microwave signals in a small form factor.

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