Silicon Evanescent Optical Frequency Comb Generator

B. R. Koch[a, b], A. W. Fang[a], R. Jones[b], O. Cohen[b], M. J. Paniccia[b], D. J. Blumenthal[a], and J. E. Bowers[a]

[a]University of California Santa Barbara, ECE Department, Santa Barbara, CA 93106, USA
[b]Intel Corporation, 2200 Mission College Blvd, SC-12-326, Santa Clara, CA 95054, USA
Email: brian.r.koch@intel.com

Abstract

A mode-locked silicon evanescent laser is used to generate over 100 wavelengths evenly spaced by 10 GHz. Optical injection locking reduces the linewidths of the remaining 30 modes to less than 100 kHz.

Introduction

Silicon based optical sources are an important area of research since they are required for fully integrated silicon optical communications [1-3]. Silicon evanescent lasers are one attractive optical source for silicon photonic integrated circuits. They are highly scalable and can have performance approaching that of conventional III-V lasers [1].

For some applications such as massive parallel computing, large amounts of data should be transmitted using separate channels. For example, 90 wavelength channels can allow each core in a 10-core computing system to communicate with each of the others. Similarly, for high bandwidth transmission, electrical multiplexing becomes difficult and optical multiplexing in the wavelength domain may be preferred to achieve high bandwidths. Recently a single wavelength silicon evanescent DFB laser was demonstrated [4]. An array of these lasers could provide the light needed for each channel.

When very large numbers of channels are required with narrow (<100 GHz) channel spacing it becomes more difficult to generate and control the wavelength of enough channels with separate lasers. Instead a single integrated mode-locked laser (MLL) can be designed to emit short pulses that have a corresponding wide optical spectrum of evenly-spaced phase-correlated modes, allowing it to be used as a multiple wavelength source [5-9] as shown in Figure 1. This arrangement might provide significant cost savings and design simplicity, and in some cases it can have considerably lower power consumption. Since the optical modes are phase-correlated other functions such as OCDMA transmission and arbitrary optical waveform generation are also possible using such a source [10].

Recently we made an initial demonstration of mode-locked lasers using a silicon evanescent laser approach [3] and here we show improved performance and potential application as multiple wavelength WDM sources. We present results from a hybrid silicon evanescent mode-locked laser (ML-SEL) that creates a comb of over 100 optical modes within 10 dB of the peak mode output power. We examine the linewidths and OSNRs of several longitudinal modes across the spectrum of this comb. We also investigate results from injecting CW laser seed light into the ML-SEL to stabilize the modes.

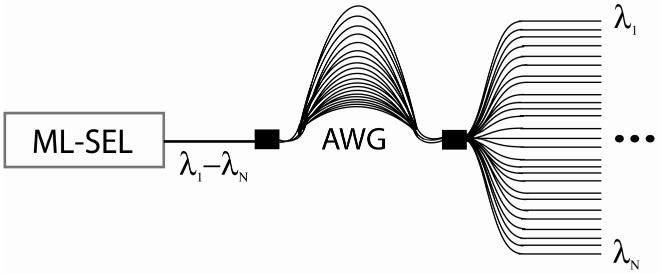


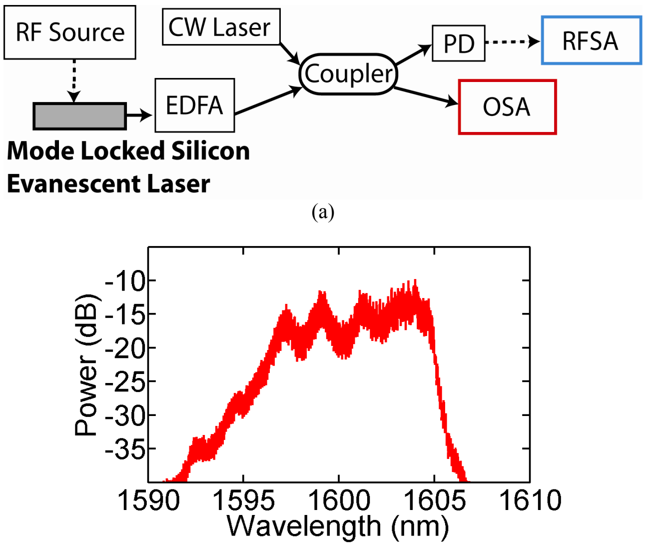
Figure 1: Envisioned implementation of a mode-locked silicon evanescent laser as a WDM source. The wavelengths could be: 1. modulated together at the output of the ML-SEL with the same data and then separated, 2. separated and modulated with different data, or 3. sent to separate destinations and then modulated.

Device and experimental setup

The ML-SEL has a similar structure to the 10 GHz device that was described previously in reference [3] and was fabricated using the same techniques. The device has a 4,160 µm-long gain region and an 80-µm saturable absorber (SA) region separated by a 10-µm electrical isolation region. The gain section was biased at 1.03 A. A 15 dBm RF signal at 10.26 GHz is sent to the SA section along with a -2.5 V DC bias using a bias T. The device is temperature

978-1-4244-1768-1/08/$25.00©2008 IEEE

stabilized at 13°C and the output light was taken from the front facet opposite the SA, using a lensed fiber.



(a)

(b)

Figure 2: (a) Experimental setup. (b) Optical spectrum of the 10-GHz ML-SEL with 0.06 nm resolution, which can not resolve the individual modes well.

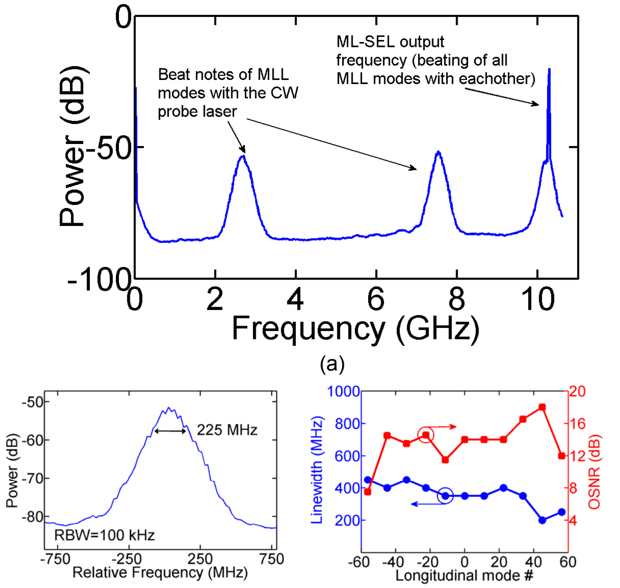
The experimental setup is shown in Figure 2 (a). The output of the ML-SEL is sent into an EDFA and to a coupler. At the coupler the signal is combined with a stable (<0.1 pm resolution), narrow linewidth (<100 kHz) CW probe signal used to measure the individual modes of the ML-SEL. The output is sent to a 0.06 nm resolution optical spectrum analyzer (OSA) and a 40 GHz photodetector (PD) connected to a DC-41 GHz RF spectrum analyzer (RFSA).

Experimental Results

The optical spectrum is shown in Figure 2 (b). The 10-dB spectral width is 9 nm, with over 100 modes spaced by 0.089 nm. The pulsewidth was measured using an autocorrelator to be 5.8 ps and the average output power was -2.8 dBm in fiber (after 6 dB coupling loss). When the probe laser is combined with the ML-SEL output, beat notes are created between the probe wavelength and the individual longitudinal modes of the ML-SEL. By looking at the RF spectrum of these combined signals as shown in Figure 3 (a), we can determine the linewidth [6, 9] and OSNR [9] of the ML-SEL modes from the beat notes.

Figure 3 (b) shows a zoom of one of the beat notes. The resolution of this linewidth measurement is determined by the linewidth of the probe laser, which is less than 100 kHz. We define the OSNR as one half of the ratio of the peak level to the bottom level of the comb as measured on the RFSA, which corresponds to the visibility of the longitudinal mode in the optical domain [7]. This measurement provides a lower limit of the OSNR because the RF spectrum between the modes also contains noise from beating between other harmonics of the CW probe laser with other ML-SEL modes. Figure 3 (c) shows linewidth and OSNR measurements for several modes across the ML-SEL 10-dB spectral width.

These OSNRs are large enough to provide error-free operation assuming significant signal degradation is not accumulated during transmission ($BER<10^{-12}$, assuming OSNR limits performance). The average power of each mode is low (~-17 dB on chip) but it is still ~6 dB above a typical PIN PD sensitivity at 2.5 Gb/s (~17 dB above a typical APD sensitivity), allowing for some loss from to modulation and transmission.



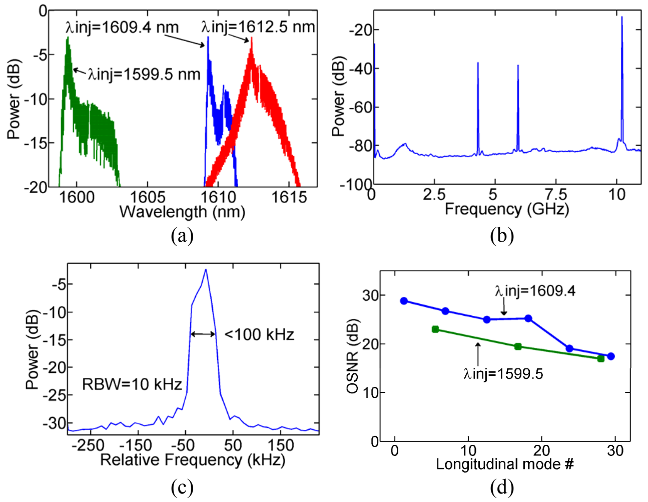
(a)

(b)

(c)

Figure 3: (a) RF spectrum of the ML-SEL output combined with the CW probe laser. (b) Zoom of the RF spectrum of the CW signal beat together with the ML-SEL output with 100 kHz resolution. (c) OSNR and 3-dB linewidth versus ML-SEL mode number. Mode 0 corresponds to 1600 nm.

To improve the results a stable 0 dBm (in fiber) CW seed signal was injected into the back of the ML-SEL. This reduced the 10-dB spectral width to ~2.5 nm but drastically improved the other characteristics. The optical spectrum of the ML-SEL for 3 different injected wavelengths is shown in Figure 4 (a). For injected laser wavelengths in the approximate range of 1599 to 1610 nm the linewidth was reduced to that of the CW input signal (~100 kHz) across 30 modes. As seen in Figure 4 (b) and (c), it is clear that the ML-SEL mode linewidths are considerably reduced and that the RF width of the ML-SEL is also reduced, indicating the jitter has been reduced due to the injection locking. The absolute jitter from 1 kHz-100 MHz offset was reduced to just 338 fs, compared to 3.1 ps without injection locking. Figure 4 (d) shows that the OSNR was improved by approximately 10 dB due to the injection locking. Again, this number is likely limited by the measurement capabilities. Injection locking offers the additional capability of determining the absolute wavelength of the modes. Since all of the modes in the ML-SEL are locked to each other, by injection locking a single ML-SEL mode to an input we can determine the wavelength position of all of the modes. This is significantly simpler than using separate wavelength lockers for each laser.



(a) (b)

(c) (d)

Figure 4: (a) Optical spectrum of the ML-SEL output under optical injection locking to an external CW laser, for 3 different wavelengths of the injected laser. (b) RF spectrum of the injection locked ML-SEL output with a CW probe laser. (c) Zoom of the RF spectrum showing the linewidth under CW injection to the ML-SEL at 1609.4 nm, with 100 kHz resolution. (d) OSNR versus mode number for 2 different injected wavelengths. Mode 0 corresponds to the injected CW wavelength.

Conclusions

We have tested a 10-GHz mode-locked silicon evanescent laser as a potential multi-wavelength source for WDM applications. The output contains over 100 modes within 10-dB output power, each having a linewidth below 500 MHz and OSNR better than 11 dB. For applications such as on-chip, chip-chip, or short reach WDM, the output directly from this laser has adequate OSNR and optical power for 2.5 Gb/s transmission. For applications with more stringent requirements, injection locking can improve the longitudinal mode quality. In this case 30 laser modes have an OSNR better than 18 dB, and linewidth equal to that of the CW input.

Designs utilizing ring cavities [11] or integrated mirrors can precisely determine the cavity length and channel spacing. These designs also allow for integration with other components such as AWGs, modulators [12, 13], or DFB lasers [4] for injection locking, enabling a fully integrated multi-wavelength WDM source on silicon.

References

[1] A. W. Fang, *et al.*, “Integrated AlGaInAs-silicon evanescent race track laser and photodetector,” Opt. Express , vol. 15, no. 5, pp. 2315-2322, Mar. 2007.

[2] P. R. Romeo *et al.*, “Heterogeneous integration of electrically driven microdisk based laser sources for optical interconnects and photonic ICs”, Opt. Express, 14(9), p.3864-3871 (2006)

[3] B. R. Koch, A. W. Fang, O. Cohen, and J. E. Bowers, “Mode-locked silicon evanescent lasers,” Opt. Express, vol. 15, no. 18, pp. 11225-11233, Sep. 2007.

[4] A. W. Fang, *et al.*, "A distributed feedback silicon evanescent laser," Opt. Express, vol. 16, no. 7, pp. 4413-4419, 2008

[5] P. J. Delfyett *et al.*, “Optical frequency combs from semiconductor lasers and applications in ultrawideband signal processing and communications,” J. Lightwave Technol., vol. 24, no. 7, pp. 2701-2719, Jul. 2006.

[6] M. Teshima, K. Sato, and M. Koga, “Experimental Investigation of Injection Locking of Fundamental and Subharmonic Frequency-Modulated Active Mode-Locked Laser Diodes,” IEEE J. Quantum Electron., vol. 34, no. 9, pp. 1588-1596, Sep. 1998.

[7] K. Mori and K. Sato, “Supercontinuum Lightwave Generation Employing a Mode-Locked Laser Diode with Injection Locking for a Highly Coherent Optical Multicarrier Source,” IEEE Photon. Technol. Lett., vol 17, no. 2, pp. 480-482, Feb. 2005.

[8] K. Haneda, *et al.*, “Measurements of Longitudinal Linewidths and Relative Intensity Noise in Ultrahigh-Speed Mode-Locked Semiconductor Lasers,” Electron. and Commun. in Japan, vol. 89, no. 2, pp. 28-36, 2006.

[9] F. Quinlan, S. Gee, S. Ozharar, and P. J. Delfyett, “Stabilized optical frequency comb source for coherent communication and signal processing,” Opt. Fiber Commun. Conf. (OFC 2007), paper OMS7.

[10] R. G. Broeke, *et al.*, “Optical-CDMA in InP,” J. Sel. Top. In Quantum Electron., vol. 13, no.5, pp. 1497-1507, Sept/Oct 2007.

[11] A. W. Fang, *et al.*, "A racetrack mode-locked silicon evanescent laser," Opt. Express, vol. 16, no. 2, pp. 1393-1398, 2008

[12] A. Liu, *et al.*, “High-speed silicon modulator for future VLSI interconnect,” Indium Phosphide and Rel. Mat. Conf. (IPNRA 2007).

[13] Q. Xu, *et al.*, "12.5 Gbit/s carrier-injection-based silicon micro-ring silicon modulators," Opt. Express vol. 15, no. 2, pp. 430-436, Jan. 2007.

Acknowledgements

We thank J. Shah, M. Haney, H. Park, and K.-G. Gan for useful discussions. We also thank H.-H. Chang, Y.-H. Kuo, and O. Raday for assisting with device fabrication. This research was supported by DARPA/MTO and ARL and by Intel.