Mode-locked silicon evanescent lasers

Brian R. Koch1, Alexander W. Fang1, Oded Cohen2, and John E. Bowers1

1. Electrical and Computer Engineering Department, University of California, Santa Barbara, California, 93106
2. Intel Corporation, S.B.I Park Har Hotzvim, Jerusalem, 91031, Israel

koch@ece.ucsb.edu

Abstract: We demonstrate electrically pumped lasers on silicon that produce pulses at repetition rates up to 40 GHz. The mode locked lasers generate 4 ps pulses with low jitter and extinction ratios above 18 dB, making them suitable for data and telecommunication transmitters and for clock generation and distribution. Results of both passive and hybrid mode locking are discussed. This type of device could enable new silicon based integrated technologies, such as optical time division multiplexing (OTDM), wavelength division multiplexing (WDM), and optical code division multiple access (OCDMA).

©2007 Optical Society of America

OCIS codes: (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers; (060.4510) Optical communications

References and Links

1. Introduction

Silicon photonics aims to use the established CMOS electronics infrastructure to fabricate inexpensive optical links for a wide variety of applications, from on-chip and chip-chip interconnects to conventional optical networking applications. Moving towards this aim, much research has been focused on optimizing the individual devices needed to fabricate an optical link with a 20 GHz silicon modulator (and more recently 40 GHz) and 39 GHz SiGe detector recently being demonstrated [1-6]. However, lasing in silicon is difficult to achieve due to its indirect bandgap and until recently has been limited to optically pumped configurations using Raman amplification [7-9]. Recently Fang et al. demonstrated a novel wafer bonding approach to fabricate electrically pumped continuous wave hybrid silicon evanescent lasers. Here we expand on this work and demonstrate both passive and hybrid mode locking of a silicon evanescent laser to produce pulsed laser sources at repetition rates up to 40 GHz.

Mode locked lasers (MLLs) are capable of generating stable short pulses which have a corresponding wide optical spectrum of phase correlated modes. MLLs can have high extinction ratios, low jitter, and low chirp, making them excellent transmitters when combined with a data-encoding modulator. Their characteristics also make them useful for diverse applications such as optical clock signal generation, OTDM, WDM, OCDMA, light detection and ranging (LIDAR), clock recovery, and coherent communications systems [16-20]. Monolithic MLLs have been demonstrated on III-V semiconductor materials at repetition rates between 5 and 500 GHz [18-27]. Integrating MLLs on silicon enables new silicon based photonic communications devices and could provide fundamental novelities that would improve the performance of MLLs and photonic integrated circuits incorporating them. For example, by combining gain sections with long spiral waveguide cavities, monolithic MLLs with low repetition rates can be made. Additionally, material properties such as the low dispersion and absence of free carriers in silicon may aid in generating ultra-short pulses.

In passive mode locking, current is injected into the gain sections and the absorber is DC biased so that it absorbs light. No RF signal is applied. Due to the randomness of spontaneous emission in the gain section, larger than average bursts of energy occur from time to time. When a burst reaches the saturable absorber, it gets absorbed less than the surrounding energy, because the absorber attenuates high powers less than it attenuates low powers. When
this burst reenters the gain section, it gets amplified preferentially. When it returns to the absorber, it again passes through with more energy than the surrounding lower level energy. In this manner, a pulse builds up in the cavity and pulses are emitted through the mirrors at a repetition rate determined by the cavity length:

\[ f_{\text{rep}} = \frac{c}{2nL} , \]

where \( c \) is the speed of light, \( n \) is the group index of refraction, and \( L \) is the cavity length. The absorber recovery time affects the minimum pulsewidth, but very high repetition rate pulses can be generated even using absorbers with relatively long recovery times [28]. This is possible because the absorber must only partially recover between pulses for stable mode locking to occur. In hybrid mode locking, an RF signal is applied to the saturable absorber section of a passively mode locked laser. This determines when the pulses pass through the absorber, synchronizing the laser’s output to the RF signal.

Fig. 1. (a) Schematic of the mode locked silicon evanescent laser. (b) Scanning electron micrograph of the saturable absorber end of an MLL with the adjacent gain section.
The devices presented here (Fig. 1) were made by transferring thin films of III-V material on to silicon waveguides using low temperature wafer bonding [10,11] with self alignment of the optical mode between the silicon and III-V materials [12]. Most of the optical mode is contained in the silicon (67.4% confinement factor in silicon), so coupling to purely silicon waveguides is straightforward, as has been demonstrated previously [13]. Gain is provided by evanescent coupling of the mode to the quantum wells with 4.3% confinement factor. The platform used to make these devices has previously been used to make linear Fabry-Perot and ring cavity lasers [12,14], optical amplifiers [15], and photodetectors [13].

2. Device design and fabrication

As shown in Fig. 1, each mode locked laser consists of a long gain section and a short absorbing section, which are separated by electrical isolation regions. Figure 1(b) shows a scanning electronic micrograph of one end of a device. The absorber pad was designed to match a coplanar stripline probe to enable efficient injection of RF signals for hybrid mode locking. P metal pads connect to p metal above the optical waveguide, and n metal pads connect to n metal on both sides of the mesa via a metal bridge. The absorber p contact appears to overlap the gain section’s n contact, but it is isolated by a layer of SiO2 between the two metals. The fabrication is done in four major parts. First, the silicon waveguides are formed on the SOI wafer. Then the III-V epitaxial layer structure is transferred to the SOI wafer through oxide plasma assisted wafer bonding [10,11]. The III-V layers are then processed to control the flow of current to the optical mode and to isolate separate electrical contact regions. Using a hydrogen implantation step, current flowing from the p contact to the n contacts is confined to the center region above the silicon waveguide, improving the efficiency drastically. Electrical isolation regions between adjacent sections are created by a second hydrogen implantation. Over 500 kΩ of isolation allows the two sections to be independently biased. Finally the devices are diced and polished to create high quality mirror facets and to define the cavity length. The mirror facets were left uncoated in these experiments, yielding power reflectivities of ~0.32. The III-V epitaxial layer structure and detailed fabrication procedure can be found in reference [14]. The silicon waveguide has a width of 2.5 microns, height of 0.69 microns, and rib etch depth of 0.39 microns, resulting in silicon confinement factor of 67.4% and quantum well confinement factor of 4.3%.

3. Experimental setup

The experimental setup is shown in Fig. 2. It allows for simultaneous monitoring of the pulsewidth, optical spectrum, and RF spectrum. The devices were temperature stabilized at 13°C and the output was coupled into a lensed fiber at the saturable absorber end, with a coupling loss of approximately 5 dB. Since both facets were uncoated and pulse evolution was negligible for a single pass through the cavity, the pulse characteristics were the same for both facets of the laser. DC probes were used to bias the gain sections while a coplanar stripline probe was used to probe the absorber. A bias T was connected to the absorber’s coplanar stripline probe to simultaneously reverse bias the absorber and apply an RF input when desired.
4. 10 GHz mode locked silicon evanescent laser results

First we tested a 10 GHz mode locked laser under passive mode locking operation. The cavity length is 4,160 microns and the absorber is about 80 microns long. The designed length was 100 microns, but uncertainty in the polishing process made it slightly shorter. We estimated this to be near the minimum absorber length required to absorb enough light to enable good pulse characteristics. Due to the low confinement factor of the material, the absorber is longer than is commonly used in MLLs. However, we did not observe any problems such as walk-off between the RF signal and optical group velocity. The optimal absorber bias was -2.3 V. This provided an appropriate amount of absorption and allowed for faster recovery times in the absorber material compared to lower reverse biases. Shorter absorber lengths with higher reverse biases applied may prove superior in future designs. Four separate, equal length gain sections allow for independent control of the current in each section. This gives the device more versatility by avoiding or enhancing certain effects such as self-phase modulation (SPM). For optimal mode locking, it is desirable for the saturation energy of the absorber to be much lower than that of the gain medium [28]. Thus high reverse bias is desirable in the absorber and high gain currents are desirable in the gain region. However, SPM tends to occur in gain regions for pulses with high peak powers, caused by too much gain in the laser cavity. This can lead to spectral broadening and chirp, which is not desirable for pulse transmission. Alternatively, this may be beneficial for applications such as WDM and OCDMA in which more longitudinal modes with similar power levels are desired. By using high gain currents in some sections and low gain currents in other sections, SPM effects can be minimized while effective mode locking still occurs. Except where noted, the bias conditions were as follows: Gain 1 and Gain 2 (adjacent to the saturable absorber) were biased together at 531 mA, Gain 3 was biased at 140 mA, Gain 4 at 149 mA, and the saturable absorber was biased with -2.3 V.

As shown in Fig. 3(a), the autocorrelation full width at half maximum (FWHM) pulsewidth is 6 ps, and the data trace closely matches a sech^2 pulse shape. Dividing by 1.54 yields the deconvolved intensity FWHM pulsewidth of 3.9 ps. The extinction ratio between the pulse peak and null is over 18 dB, approaching the limit of the autocorrelator’s measurement capabilities. A high extinction ratio is desirable for MLLs that are intended to be used as part of a transmitter, particularly in fiber optic networks and in OTDM applications.
The optical spectrum for this pulse is shown in Fig. 3(b). It has 3.8 nm spectral FWHM, with 45 modes evenly spaced at 0.088 nm within 3 dB of the peak. The time bandwidth product is 1.7, indicating that these pulses are chirped. Chirp could be further reduced in future designs by incorporating passive silicon waveguide sections in the laser cavity and using a shorter gain section [13,27]. By increasing the gain current in the third and fourth sections to 250 mA each, the spectral FWHM for this device can be increased to as much as 7 nm, with a 10 dB spectral width of 11 nm. More results will be discussed in another paper.

Figure 3(c) shows the RF spectrum of the laser’s output under passive mode locking. A typical mode locked laser spectrum is present with sharp peaks at 10.16 GHz and its harmonics. Figure 3(d) shows a 100 MHz span around the mode locking frequency of 10.16 GHz. When an RF signal is injected into the saturable absorber, the laser’s RF spectral peak aligns to the input signal and the RF spectrum narrows significantly. The relaxation resonance is also damped compared to the passive case. Aside from reduced jitter, pulse characteristics such as pulsewidth and power are negligibly changed when RF signals below 20 dBm are applied. The sideband noise, and thus jitter, are reduced as the RF power increases up to 15 dBm, at which point the absolute jitter is 2 ps, and the residual jitter is 199 fs. Absolute jitter is the total RMS jitter out of the source, and residual jitter is the jitter of the optical source relative to the microwave drive signal [29]. Jitter was calculated using the formula

$$\Delta t = \frac{1}{2\pi f_r} \sqrt{2 \int |L(f)|^2 df},$$

Fig. 3. 10 GHz MLL (a) SHG autocorrelation trace, (b) optical spectrum, (c) 0 to 40 GHz RFSA trace, and (d) RFSA trace for a 100 MHz span about the fundamental frequency, for passive mode locking and hybrid mode locking at various RF input powers.
where \( f_r \) is the repetition frequency of the laser. In the case of absolute jitter measurements, \( L(f) \) is the noise, normalized to the carrier power, from 1 kHz to 100 MHz offsets from the carrier frequency. In the case of the 10 GHz laser, this jitter measurement was verified by evaluating the noise at offsets from the higher order harmonics as well [29]. For residual jitter measurements, \( L(f) \) is the noise measured from 1 kHz to 100 MHz offset from DC, after mixing the RF driving signal with the laser’s output signal in a double balanced mixer with 90° relative phase shift [29]. A plot of the jitter is shown in Fig. 4(a) for different operating conditions. Note that the absolute jitter is below the ITU specified standard of 0.1 IU (10 ps) even for passive mode locking. However, lower jitter is required for many applications such as multiplexing pulses to achieve higher data rate signals via OTDM. Increasing the Q of the cavity via high reflectivity facet coatings or other methods would reduce the jitter in passive mode locking operation. As shown, the laser is capable of hybrid mode locking and synchronization to an RF input signal below -10 dBm, but the jitter is lowest for higher input powers. A 2.5 GHz input signal was used to perform subharmonic hybrid mode locking with the 10 GHz laser. This required more power to achieve the same jitter.

Figure 4(b) shows the FWHM pulsewidth and fiber coupled peak power as function of reverse bias applied to the saturable absorber for fixed gain current. The pulsewidth can be tuned between 4 and 9 ps, while the fiber coupled average output power remains between -2 and 1 dBm. Considering the sech\(^2\) pulse shape, the corresponding peak powers for these pulses are 10-12 dBm for all cases. The fiber coupling loss is between 4 and 6 dB [12-15].

![Figure 4](image_url)

The lasing threshold for the 10 GHz MLL occurred when the gain sections had approximately 200 mA of current each at the absorber bias of -2.3 V. This threshold is in agreement with theory, although it is relatively high compared to many III-V MLLs. This is largely due to the low confinement factor and low mirror reflectivity used in this laser, making direct comparison to III-V lasers difficult. In comparison, an InGaAsP 15 GHz bulk ring laser with 35% output coupling and a 0.28 confinement factor had 340 mA threshold current, and approximately 8 dBm single sided fiber coupled average output power [26]. In another case, a 10 GHz colliding pulse MLL with uncoated facets and a short gain section combined with longer passive sections had a threshold around 150 mA and an average output power of about 0 dBm [27]. The threshold would be significantly reduced by high reflectivity (HR) coatings on one or both facets, and by increasing the confinement factor. This has been done recently in CW lasers based on this platform, which had thresholds as low as 25 mA. Additionally, shorter gain sections integrated with passive waveguide sections would also reduce the threshold of these MLLs, and might have additional advantages as discussed earlier. Finally, by optimizing the depth and width of the current-confining proton implantation step, the injection efficiency can be further improved to reduce the threshold current and improve...
power efficiency. By using these techniques, MLL thresholds below 20 mA should be possible.

5. 40 GHz mode locked silicon evanescent laser results

Next, a 40 GHz MLL was tested. This laser had a total cavity length of 1060 microns and an absorber length of 50 microns, although about 20 microns of unpumped active material extends beyond the absorber due to impreciseness of the polishing process. The absorber length was chosen to be shorter for this laser because the gain is much lower due to the short cavity length. For bias conditions of Gain=206 mA and absorber=0.4 V, passive mode locking was achieved and the average fiber coupled output power was -3 dBm. The threshold gain current was 196 mA for this absorber bias. Although the absorber was forward biased, it still absorbed light and generated a photocurrent of 1.15 mA. The fact that the absorber had to be forward biased in this laser indicates that this absorber length is near the upper limit of what is acceptable for mode locking to occur. An autocorrelation trace and optical spectrum are shown in Fig. 5(a) and (b). The pulse has a sech² shape, with 4.2 ps intensity pulsewidth. Again, the extinction ratio is over 18 dB. The optical spectrum is 0.9 nm, with modes spaced evenly by 0.33 nm. The time bandwidth product is 0.4, close to the transform limited value of 0.32 for sech² pulses. This means that the chirp is low for this laser, as expected because of its shorter gain section.

The RF spectra are shown in Fig. 5(c) and (d). To achieve (subharmonic) hybrid mode locking, we used a 20 GHz RF source, which again reduces the sideband noise and jitter significantly. With 17 dBm of RF input power, the absolute jitter of this laser is 1 ps (1 kHz-100 MHz). Again, the output characteristics such as power were unchanged in the hybrid mode locking case compared to the passive mode locking case. Using a 40 GHz RF source, hybrid mode locking and synchronization to the source is possible with just 3 dBm of RF power. Residual jitter measurements were not performed for the 40 GHz lasers due to lack of a 40 GHz bandwidth double balanced mixer, and subharmonic injection was used for the 40 GHz lasers due to lack of a high spectral purity 40 GHz synthesizer.
6. Conclusion

In conclusion, we have demonstrated mode locked lasers on silicon at 10 and 40 GHz repetition frequencies. The lasers have high quality output characteristics such as low jitter and large extinction ratios, rivaling those of high performance III-V semiconductor MLLs. This makes them potential candidates for optical data transmitters when combined with an optical modulator to encode data onto the pulses. Their ability to be synchronized to low power RF signals enables applications such as OTDM and clock recovery [20-22]. Future designs incorporating ring structures [14,26], distributed Bragg reflector (DBR) mirrors [21], or deeply etched mirrors will allow for on-chip integration with other optoelectronic components, integration with CMOS electronics, and precise determination of the repetition frequency [21]. These photonic integrated circuits should be useful for on-chip, chip-ship, and chip-network communications. The ability to transition from gain regions to low loss passive regions will allow new possibilities for MLLs such as lower repetition rate integrated MLLs and single chip OTDM, WDM, and OCDMA sources on silicon.

Acknowledgments

This work is supported by DARPA through contracts W911NF-05-1-0175 and W911NF-04-9-0001, and Intel. We thank Dan Blumenthal, Jag Shah, Michael Haney, Kian-Gap Gan, Richard Jones, Hyundai Park, and Mario Paniccia for useful discussions. We also thank Hsu-Hao Chang, Ying-Hao Kuo, and Omri Raday for help with device fabrication.