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All-Optical Clock Recovery with Retiming and Reshaping Using a Silicon Evanescent Mode Locked Ring Laser

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Abstract: A novel silicon evanescent mode locked ring laser is used to perform all-optical clock recovery from 30.4 Gb/s data. The recovered clock has dramatically improved jitter, ER, and pulse reshaping compared to the input data.

OCIS codes: (250.5300) Photonic integrated circuits, (200.6015) Signal regeneration

1. Introduction

Regenerators for optical data signals are essential components for long distance communication systems and may have applications in other systems as well. Thorough signal regeneration requires retiming, reshaping, and reamplification (3R) of the input data [1-3]. To reduce the cost of such regenerators it is desirable to perform these tasks without electronics, especially at high data rates of 40 Gb/s and above [1, 2]. Chip-scale integration techniques that combine multiple components of a regenerator offer cost and size improvements, and silicon based approaches might be the best overall solution if the performances of the devices are adequate.

In this paper we present a hybrid silicon evanescent ring mode-locked laser and evaluate its performance as an all-optical clock recovery element. The device, shown in Fig. 1, is capable of generating a reshaped and retimed clock signal from 30.4 Gb/s data, even when the input data is severely degraded. For input data with 3.8 dB extinction ratio (ER) and 14 ps of jitter, the recovered clock has an ER over 10 dB and 1.7 ps of jitter. Experiments show that the laser suppresses any noise that is outside the locking range (3 MHz). This implies that by carefully designing similar devices with predetermined locking ranges, it should be possible to reliably manufacture mode locked lasers that can reduce jitter in compliance with ITU specifications, suppressing jitter outside only specific frequency offsets from the carrier frequency. Also, since the laser's ring cavity is defined using photolithography it is possible to match the repetition rate of the laser to a specific data rate in future designs, which is essential for practical applications. The ring configuration also allows for integration with optical amplifiers and demonstrates potential for more complex photonic integrated circuits utilizing this mode locked laser.

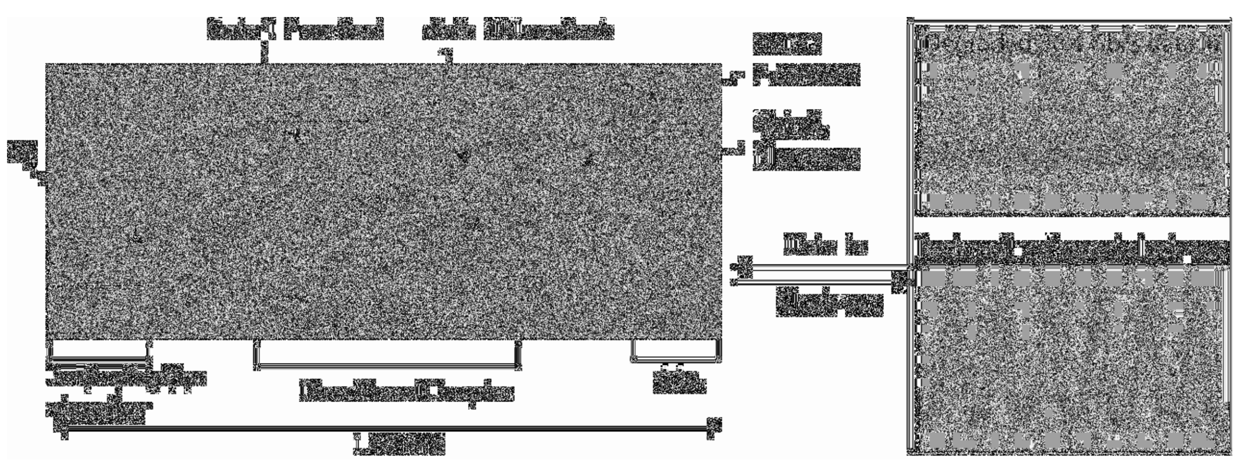


Fig. 1. Scanning electron micrograph of the silicon evanescent mode locked ring laser with oscilloscope traces of the input data and output clock. SA=saturable absorber, SOA=semiconductor optical amplifier

2. Device design

The silicon evanescent mode locked ring laser is shown in Fig. 1. The material structure consists of AlGaInAs quantum well-based active layers wafer bonded to silicon waveguides [4]. The silicon waveguide dimensions result in a quantum well confinement factor of 5.2% and a silicon confinement factor of 59.2%. The laser has a racetrack design [4], with two gain sections and a 50-µm long saturable absorber section that locks the multiple longitudinal modes in phase. Outside the cavity there are also active sections, which can act as photodetectors or amplifiers. All sections are electrically isolated from each other by proton implantation. The directional coupler of length 400 µm, allows approximately 55% of the light out of the laser, based on measurements. When the laser is properly biased it becomes passively mode locked with counter propagating pulses that collide in the absorber section. Pulses are emitted from both ends of the coupler at a repetition rate given approximately by $f_{rep} \approx c/(n_g L)$,where c is the speed of light, n_g is the group index of refraction (~3.7), and L is the length of the laser cavity (2657 µm), so the expected mode locking frequency is 30.5 GHz. The theoretically predicted Q factor is 31,700.

When data is injected, most of the laser characteristics such as output power, wavelength, pulsewidth, ER, and spectral width are unchanged from passive mode locking conditions. The input data pulses modulate the carriers in the absorber and laser cavity and if the data rate matches the repetition rate of the laser, the laser pulses become synchronized to the data, generating a clock signal. With data injected, the laser jitter is reduced due to synchronization to the long term (low frequency) stability of the input data. However, if the data rate is outside of the laser locking range, then synchronization will not occur. In other words the laser does not track short term changes in the input. For this very reason, the injected data's jitter is also reduced because any noise that is outside the locking range of the laser is suppressed. The interaction between the input data (S_{in}) and light in the passively mode locked cavity (S_{laser}) results in an output power spectral density (S_{out}) that is determined by the equations [3]:

$$S_{out}(f) = \left|H_J(f)\right|^2 \cdot \left(\frac{f}{\Delta f_{lock}}\right)^2 \cdot S_{laser}(f) + \left|H_J(f)\right|^2 \cdot S_{in}(f), \qquad H_J(f) = \frac{1}{1 + i\dfrac{f}{\Delta f_{lock}}}$$

where H_j is the jitter transfer function and Δf_{lock} is the locking range of the laser, determined by the Q factor of the laser and the power of the input signal relative to the power in the cavity. For a known input power, it should be possible to predetermine the locking range and jitter transfer function of the laser based on its Q.

3. Experimental setup

The experimental setup is shown in Fig. 2. Data is generated using separate clock and data modulators. The clock used to drive the clock modulator is mixed in a double balanced mixer with another frequency, Δf, to induce jitter on the data stream. To degrade the extinction ratio of the input signal, the data can be attenuated before entering the EDFA. 2^{31}-1 PRBS data is sent into the device through a circulator. The device is temperature stabilized at 10˚C and biased with the SOA at 47 mA, each gain section at 220 mA, and the absorber at -0.77 V. The left output section is unbiased, thus absorbing any incident light. By sending data into the laser and collecting the clock from the same waveguide, we require only one fiber coupling and do not need to filter the input data signal at the output. The output from the laser exits the circulator to an EDFA and 2 splitters leading to an optical spectrum analyzer, a 40 GHz photodetector (PD) connected to an RF spectrum analyzer, and an oscilloscope.

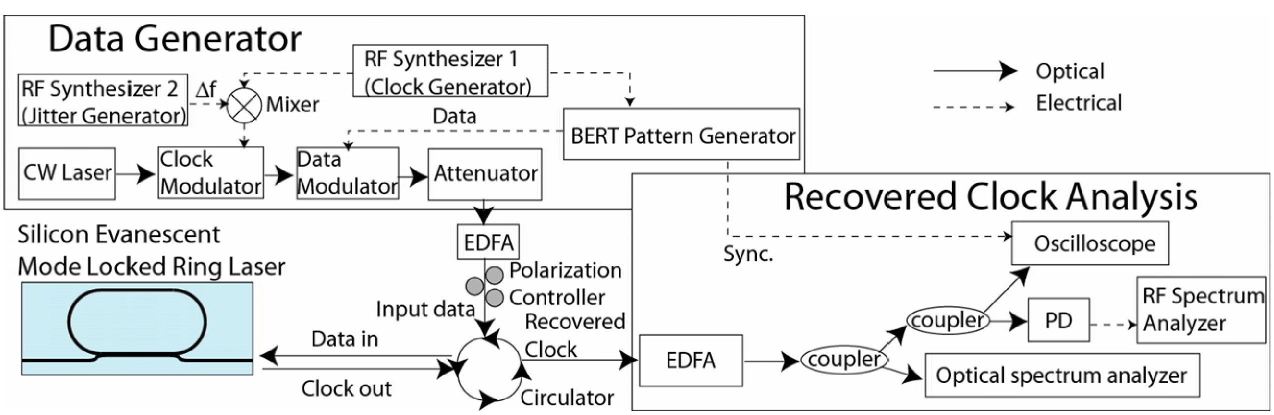
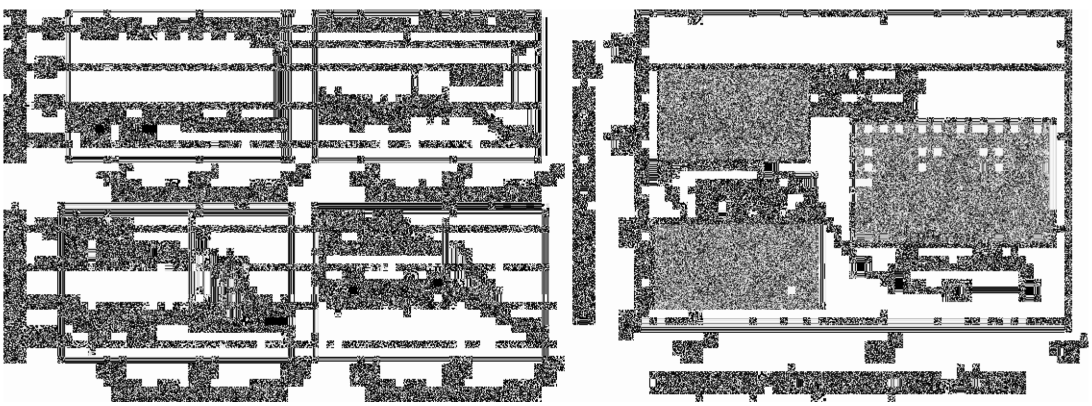


Fig. 2. Experimental setup of the all-optical clock recovery experiments.

4. Experimental results

Under passive mode locking conditions the laser emits 12.5 ps pulses at a repetition rate of 30.37 GHz. The center wavelength is 1589 nm and the spectral width is 0.5 nm. The time bandwidth product is 0.74. The Q factor, measured as the repetition rate divided by the 3-dB RF linewidth, was 27,000. The power emitted from the laser is estimated to be 5 dBm based on on-chip photocurrent measurements (reverse biased output SOA operated as a PD). However, the output power in fiber is -15 dBm due to severe scattering losses at the imperfectly polished output facet. The input data power is 13 dBm, although only 0 dBm reaches the laser coupler due to the coupling losses. The input wavelength was 1550 nm and results did not vary with small changes (~1nm) in the wavelength. Upon injection of the data, the mode locked laser synchronizes to the input signal at 30.356 GHz, with a locking range of 3 MHz on either side of the peak. For normal input data, the recovered clock has an ER of at least 10.4 dB and 1.2 ps of absolute RMS timing jitter, calculated by integrating two times the single sideband (SSB) noise from 1 kHz to 100 MHz offset from the carrier frequency. Absolute jitter measurements provide an upper estimate of the timing jitter, since the SSB noise also contains amplitude noise. Next we induced timing jitter at specific offset frequencies, Δf, from the carrier. In this case we know that the added noise is all due to timing jitter, so most of the noise reduction is in fact timing jitter reduction. As shown in Fig. 3(a) upper plots, we find that for Δf=62.5 MHz, the noise spike is suppressed by 30 dB in the output clock. This corresponds to jitter reduction from 14 ps to 1.7 ps. This measurement was repeated for different Δf values. The timing jitters of the output clock for different frequencies of timing jitter in the input signal are shown in Fig. 3(b). We find that when jitter is added inside the locking range of 3 MHz as in Fig. 3(a) lower plots, the laser does not synchronize as well to the input, indicated by the higher SSB noise level at low offset frequencies. In this case, the injected jitter is only minimally reduced, with reduction only occurring at the higher harmonics of Δf. For all measurements above, the input ER was degraded to 3.8 dB and the input data bit full width at half maximum was 15 ps. The output had 12.5 ps pulsewidth and >10 dB ER.



(a) (b)

Fig. 3. (a) SSB noise plots of the input data and output clock for injected jitter at different frequencies, Δf. (b) Plot of jitter (1 kHz-100 MHz) in the recovered clock as a function of Δf. Insets show the OSO traces of the input data and output clock for Δf=617.5 kHz and Δ f=62.5 MHz.

5. Conclusion

We have demonstrated all-optical clock recovery using a silicon evanescent mode locked ring laser. The recovered clock has over 10 dB ER and 1.7 ps of jitter for an input signal with 3.8 dB ER and 14 ps of jitter. To our knowledge this is the largest amount of jitter reduction in a mode locked laser, and is due to the laser's ability to suppress any noise outside its relatively narrow 3-MHz locking range. The ring design can enable integration with other optoelectronic or passive devices and precise determination of the laser's repetition rate, allowing for matching to a desired bit rate. By tailoring the Q factor of future lasers, we believe it is possible to manufacture similar mode locked lasers to perform jitter reduction in compliance with ITU recommendations, while also providing significant reshaping capabilities. We acknowledge the funding support of DARPA and ARL through LASOR grant W911NF-04-9-0001, 3R grant W911NF-06-1-0019, and grant W911NF-05-1-0175, and Intel.

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