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Integrated optical phase locked loop

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Abstract: A silicon photonics based integrated optical phase locked loop is utilized to synchronize a 10.2 GHz voltage controlled oscillator with a 509 MHz mode locked laser, achieving 32 fs integrated jitter over 300 kHz bandwidth.

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1. Introduction

Mode locked lasers (MLL) provide optical pulse trains with extremely low jitter [1]. This property makes them an ideal candidate for distribution of precision timing information. On the other hand, since optical fibers are extremely low loss, the utilization of pulse trains emanating from a MLL enables the timing distribution over very long distances. In many instances, like X-ray free electron lasers, the purpose of this timing distribution is to synchronize a radio frequency oscillator at the remote location with the one in the base station [2]. As such, first and foremost, one should be able to accurately measure the phase difference between the RF signal and the optical pulse train. For this very same purpose, we recently proposed a balanced optical-microwave phase detector (BOMPD) [3]. The apparatus was used to accurately compare the arrival times of an optical pulse train with the zero crossing of a microwave signal, while being immune to excise phase noise imposed by direct photodetection at the same time. Here, we present a highly compact integrated version of a BOMPD, fabricated on a silicon photonics platform. The integrated silicon based BOMPD offers significant benefits: potential low cost and large volume production, convenient temperature stabilization, immunity to large acceleration, and potential integration with high speed SiGe CMOS electronics, to name a few. Although, the current results in terms of precision achieved are moderate, the full functionality of such a device is demonstrated and precision can be greatly improved in the future.

2. Experimental results

A Sagnac interferometer comprised of silicon nanowire waveguides was fabricated on a silicon photonics platform. Two high speed phase modulators were placed into the Sagnac loop at appropriate locations. Details of the location of modulators with respect to the coupler in the guided wave Sagnac loop can be found elsewhere[3]. The design and fabrication of the modulators are explained in [5]. The modulators were 1000 µm long each. The coupling to the outside world was performed through silicon nitride waveguide inverse tapers that when covered by an index matching liquid provided beam sizes comparable to the standard single mode fiber. Henceforth, coupling was done using cleaved SMF-28 fibers at both input and output ports.
The laser used in this study was a home built Er fiber soliton laser with linear cavity and fundamentally mode locked at 509 MHz with the aid of a saturable Bragg reflector (SBR). More information can be found in [4].
The experimental setup is shown in Figure 1. The output of the laser was divided into 3 parts. Half the power was directed to a home built Er doped fiber amplifier, boosting the average power to about 15 mW, to be launched into the Sagnac loop. The other half was equally split, one detected by a high speed photodetector to extract the 25th harmonic of the repetition rate at 12.8 GHz, which was then divided by two to obtain a 6.4 GHz tone, required to bias the interferometer to its quadrature point by driving the first modulator in the loop. The 10.2 GHz tone generated by the VCO drives the second modulator and acts as the signal.
When the VCO and the laser are not synchronized, the phase difference between the VCO and the 20th harmonic of the laser, which drives the second modulator, translates to time-varying phase modulation of the optical pulse train traveling through the loop. This time varying phase modulation results in amplitude modulation of the 6.4 GHz pulse train leaving the Sagnac interferometer. Extracting the amplitude of this modulation by mixing it with the corresponding frequency directly generated by the laser, a base-band tone is generated that acts as the error signal to feed the loop filter.
When the 300 kHz bandwidth feedback loop was closed, we performed two sets of measurements to analyze the optical-mirowave synchronization performance. The first one was in-loop, essentially the error signal that feeds the

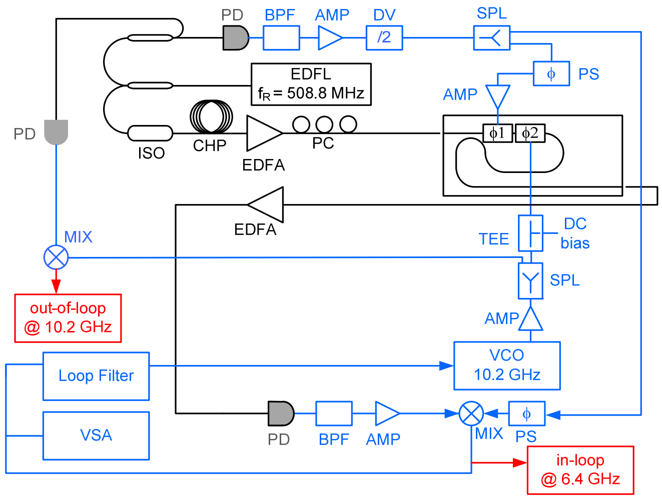

Figure 1 Experimental setup for locking the VCO to EDFL. PD: photo detector, BPF: band pass filter, AMP: amplifier, DV: frequency divider, SPL: power splitter, PS: phase shifter, EDFA: Er doped fiber amplifier, PC: polarization controller, TEE: bias TEE, VCO: voltage controlled oscillator, VSA: vector signal analyzer, CHP: pulse stretching element, ISO: isolator, EDFL: Er doped fiber laser, MIX: mixer.

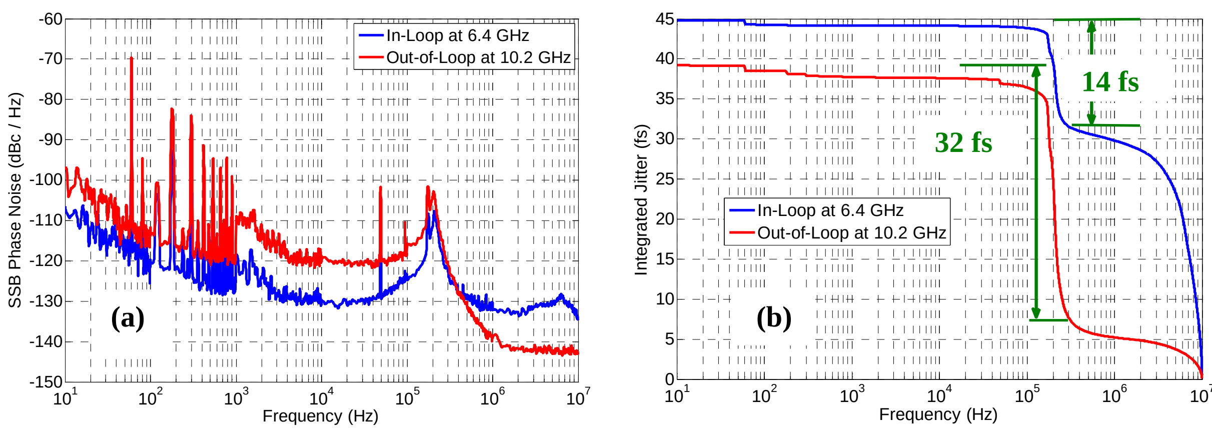

Figure 2 (a) Single side band phase noise measured for both in-loop at 6.4 GHz and out-of-loop at 10.2 GHz. (b) Integrated jitter of in-loop and out-of-loop measurements.

loop filter. The measured signal was generated by mixing the 6.4 GHz signal directly extracted from the laser by the one regenerated at the output of the BOMPD. The out-of-loop measurement is performed by mixing the 10.2 GHz output of the VCO with the corresponding harmonic of the laser, generated by direct photodetection. The single side band phase noise spectral densities of the two sets of measurements are shown in Figure 2(a). The integrated jitter for the two traces are shown in Figure 2(b). The performance metric in this case is the quality of the lock over the feedback loop bandwidth of 300 kHz. As it can be seen from the figure, over the range of 10 Hz to 300 kHz, the in-loop and the out-of-loop measurements have a respective aggregate jitter of 14 and 32 fs.

3. Conclusions

Using a silicon photonic integrated optical PLL, a microwave oscillator at 10.2 GHz is locked to the 20^{th} harmonic of a 509 MHz Er soliton fiber laser with a loop bandwidth of 300 kHz. The in-loop and out-of-loop integrated jitters are measured to be 14 and 32 fs, respectively.

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