TOWARDS AN INTEGRATED OPTIC PHASE-LOCKED OSCILLATOR

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Abstract

A recent experiment, performed at the Massachusetts Institute of Technology, has demonstrated that by locking a microwave oscillator to an optical pulse train from a mode-locked laser, exceptional timing stability can be achieved. In the experiment, a 10.225-GHz microwave oscillator was locked to an optical phase detection apparatus consisting of a mode-locked laser, a Sagnac interferometer, and an optical phase modulator. A relative out-of-loop timing jitter of 6.8 fs rms was measured between the locked oscillator and the optical pulse train over a 1-MHz bandwidth and a 10-hour integration period, corresponding to a stability of 1.9×10^{-19}. Here, we consider the potential for an integrated version of this optical phase-locked oscillator. Detailed analysis of the components required for integration is used to estimate the timing performance of the integrated optic phase-locked oscillator. Initial estimates indicate potential for a single-sideband phase noise level of -153 dBc/Hz and corresponding jitter level of ~1 fs across a 10-MHz loop bandwidth. While this work is still in the design stages, if successful, the result will be a compact and low-power oscillator with exceptional phase noise and timing stability that can be applied across many applications including RADAR, global positioning, and communications systems.

INTRODUCTION

Mode-locked lasers have been considered as low phase noise sources of microwave signals. The short pulse width of the mode-locked laser source leads to a favorable scaling of timing jitter in comparison to microwave oscillators of the same cavity parameters. Fundamentally, mode-locked lasers do suffer from spontaneous emission noise [1], but the impact of this noise source on the pulse timing of femtosecond lasers is orders of magnitude below that experienced by a microwave oscillator due to thermal fluctuations. Moreover, the availability of atomic references in the near-infrared spectrum enables mode-locked lasers to offer excellent long-term as well as short-term stability [2]. Commonly, microwave

signals have been extracted from mode-locked lasers by direct detection and subsequent electrical filtering of the mode-locked laser pulse stream. Unfortunately, direct extraction of the microwave signal is plagued by timing instabilities in the photo-detector. Photo-detectors have temperature-dependent RC time constants and amplitude-dependent phase responses. The combination of these instabilities has limited the phase noise and timing performance of microwave signals extracted from mode-locked lasers [3,4]. The best frequency stability obtained using direct extraction is 2.7×10^{-17} [3].

Here, we present an indirect method for the extraction of microwave signals from mode-locked lasers. The approach, demonstrated in bench-top setups [5-8], uses a Sagnac interferometer to lock the phase of a microwave oscillator to a mode-locked laser and therein recover phase noise performance not limited by the photodetection process. In a recent demonstration [8], a timing stability of 6.8 fs over 10 hours was demonstrated, corresponding to a stability of 1.9×10^{-19}. Despite the success of the bench-top demonstration for wide deployment of this approach, in for example handheld radios, GPS receivers, RADAR, and navigation systems, a chip-scale implementation must be developed. Here, we propose and discuss our progress towards the integration of an integrated optic phase-locked oscillator (IO-PLO). While much work remains, a design for an integrated optic balanced optical-microwave phase detector (IO-BOMPD), a central component of an IO-PLO that is highly useful by itself, has been developed utilizing silicon photonic components.

BENCHTOP EXPERIMENTS

To demonstrate the approach, a bench-top experiment was put in place consisting of a mode-locked laser, a Sagnac interferometer, a lithium-niobate phase modulator, a photodiode, and a microwave mixer. A block diagram of the bench-top optical phase-locked oscillator is depicted in Figure 1. A mode-locked laser pulse train is sent into a Sagnac loop interferometer with a phase modulator driven by a pair of microwave signals, one at a repetition rate of Nf_R (10.225 GHz) and another at $f_R/2$ (in the experiment, $2.5f_R = 500$ MHz is used), where f_R (200 MHz) is the repetition rate of the mode-locked laser. The former is the frequency of the microwave voltage-controlled oscillator (VCO) to be locked and the latter is the bias signal required to set the interferometer to a more sensitive region of the interference function. When the VCO is synchronous with the timing of the mode-locked laser pulse train, the clockwise and counter-clockwise pulses receive identical phase shifts and no modulation of the output is observed (Fig. 1a). However, when a timing error between the VCO and the mode-locked laser exists, a non-zero output signal at the frequency $f_R/2$ is produced, which is multiplied down to baseband to produce an error signal that then drives the VCO back into synchronization with the mode-locked laser (Fig. 1b).

The loop described in Figure 1 was implemented and has been demonstrated [8]. The phase noise of the locked VCO was measured relative to the mode-locked laser pulse train using a second optical-microwave phase detector apparatus. The noise spectrum is plotted in Figure 2a. Further, a long-term phase noise stability measurement was made and is plotted in Figure 2b. The results of the measurements demonstrate a relative phase noise level below -130 dBc/Hz across the 1-MHz loop bandwidth. A stability of 6.8 fs over 10 hrs corresponding to a relative stability of 1.9×10^{-19} was achieved.
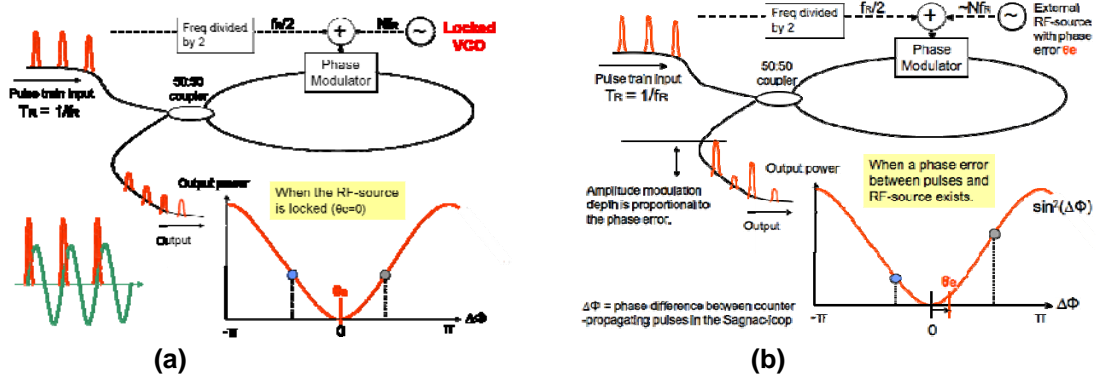
(a) **(b)**

Figure 1. Loop diagram for an optical phase-locked oscillator for locking a Voltage-Controlled Oscillator (VCO) to a mode-locked laser pulse stream. A pulse stream from a mode-locked laser is fed into a Sagnac loop mirror with a phase-shifter offset within the loop. A microwave VCO drives the phase modulator. When the VCO is synchronous (a) with the timing of the mode-locked laser pulse train, the clockwise and counter-clockwise pulses receive the identical phase shift and no modulation of the output is observed. However, when a timing error between the VCO and the mode-locked laser exists (b), a non-zero output signal at the frequency $f_R/2$ is produced, which is multiplied down to baseband to produce an error signal that then drives the VCO back into synchronization with the mode-locked laser.
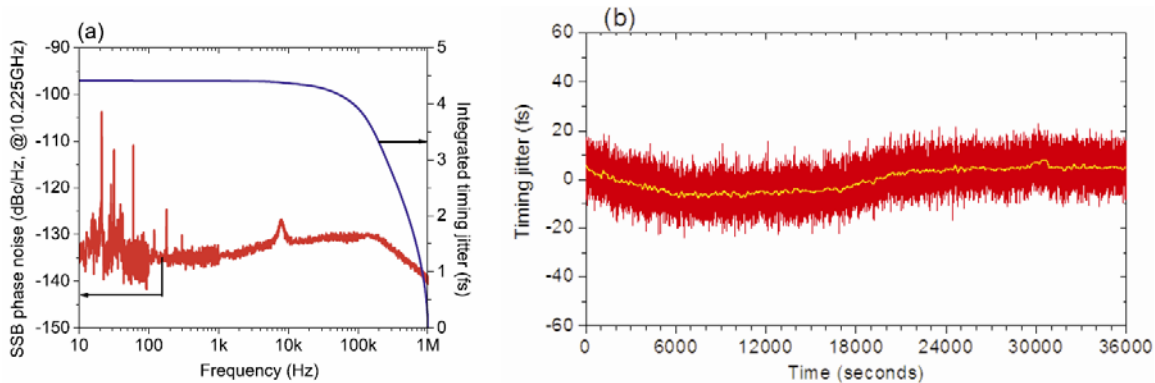

Figure 2. (a) Phase noise spectrum at 10.225 GHz. The integrated jitter is 4.4 fs between the regenerated microwave signal and the pulse train. (b) The long-term out-of-loop jitter measurement shows that the integrated jitter is 6.8 fs over 10 hours. The yellow line indicates the slow drift calculated from the jitter measurement with a time constant of 100 s. The maximum drift is 15 fs. The relative stability reaches 1.9×10^{-19} in 10 h. Data figures are from **[8]**.

INTEGRATION

Our vision for an integrated optic phase-locked oscillator (IO-PLO), depicted in Figure 3a, consists of a modulator, a Sagnac loop, a 3 dB splitter, a photodetector, and an integrated mode-locked laser. Optionally, the electronics required to lock a microwave oscillator can be directly integrated in a CMOS-compatible silicon photonics platform, enabling an inexpensive and widely deployable high-precision

timing reference for use in radio, RADAR, GPS, and navigation systems. An IO-PLO requires an integrated mode-locked laser, a device of active research [9]. A more readily implemented device is an integrated optic balanced optical-microwave phase detector (IO-BOMPD), which is highly useful for distributed timing applications and forms a central component of an IO-PLO. The IO-BOMPD represents our initial focus.
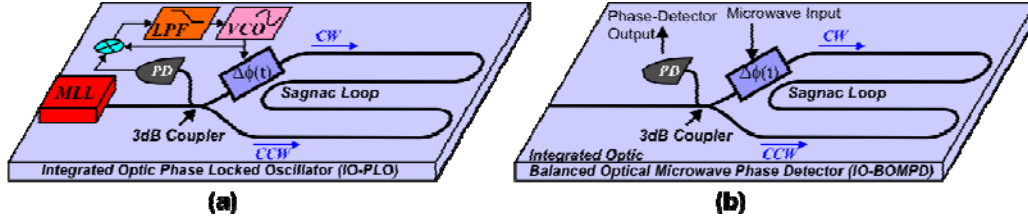

Figure 3. (a) Our vision for an integrated optic phase locked oscillator (IO-PLO). The basic circuit consists of a mode-locked laser source, a 3dB coupler, a Sagnac loop, a phase modulator, a photodiode, and, optionally, the electronics. (b) Without the integrated source, the chip is an integrated optic balanced optical microwave phase detector (IO-BOMPD), which is highly useful for distributed timing applications and a first step towards an IO-PLO.

The performance of an IO-PLO (or, alternatively, an IO-BOMPD in an optical phase-locked oscillator loop) is ultimately dictated by shot noise considerations. The shot noise single-sideband phase noise limit is described by equation (1) below [10]

$$S_{\phi,shot} = \frac{q}{2RP_{Avg}\phi_0^2} \qquad (1)$$

where q is the charge of the electron, R is the responsivity of the detector, P_{avg} is the average optical power incident on the photodiode in the bright port of the interferometer when no phase modulation is applied, and ϕ_0 is the modulation depth of the phase modulator. Based on equation (1), to minimize phase noise and, therefore, timing jitter[1], it is important to maximize the amount of optical power on the detector along with the modulation depth of the VCO/phase-modulator combination. Our goal is to achieve a ~1 fs jitter level across a 10-MHz bandwidth. To do so, we need to maximize the power at the detector and the modulation depth of the VCO/phase-modulator combination while taking material power handling limitations into consideration.

Optical power at the detector is maximized by minimizing the waveguide, fiber-to-chip coupling, and modulator losses. Low-loss silicon waveguides and fiber-to-chip couplers have been demonstrated at Sandia and elsewhere and are not expected to present a major concern. If we assume 1 dB of propagation loss, 5 dB loss within the modulator, and 4 dB loss for the fiber-to-chip coupling, we achieve a loss budget of 10 dB. In silicon, optical power densities above 1 GW/cm^2, have been shown to lead to significant nonlinearities [11]. For a waveguide cross-section of 0.25 μm × 1 μm, a maximum on-chip peak power level of 250 mW can be applied. If we assume a 10% duty cycle for a stretched pulse train emanating from the mode-locked laser, and take into account the 10 dB loss budget, we achieve an average power level of 2.5 mW on the photodetector.

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[1] Timing jitter can be calculated by integrating the double-sided phase noise spectrum.

Even more important than achieving a high power level at the photodiode is maximizing the modulation depth of the phase modulator. Since the VCO output is largely fixed, maximizing the modulation depth requires maximizing the modulator transfer function (i.e. minimizing V_π, the voltage required to achieve π phase shift). Phase modulation in a silicon platform can be achieved through the free-carrier dispersion effect **[12]**. By injecting or depleting carriers into the waveguide, the real and imaginary components of the refractive index are altered and, consequently, both the amplitude and phase of the optical signal traveling through the waveguide are affected. High-speed silicon amplitude modulators have been demonstrated using reverse-biased vertical *p-n* junctions with low voltages and switching energies **[13]**. To maximize the effect, here, we consider an *n-p-n* modulator which enables the *p*-region to be depleted from both sides, effectively doubling the index change for a given voltage. The basic structure, depicted in Figure 4a, according to rigorous finite-element electronic and finite-difference optical simulations, achieves a phase shift of $\pi/2$ with 2.5 V applied in a 1-mm-long device, with a maximum loss of only 4.9 dB (Figures 4b and 4c). As a further requirement, high-speed operation (3 dB bandwidth ~10 GHz) is necessary. Despite the intrinsic 16 GHz 3 dB bandwidth of the modulator structure, at device lengths approaching 1 mm, the low device impedance is modified upwards by the 50 Ω coaxial line required to drive the modulator. As a result, the modulator bandwidth is greatly reduced. To maximize the speed of the modulator, and minimize the loss, a short, 0.5 mm modulator length was chosen. This short modulator length reduces the available modulation depth at 2.5 V to $\pi/4$ or $\pm\pi/8$ and still a 3 dB bandwidth at 10 GHz is not recovered. To extend the 3 dB bandwidth, the modulator is broken up into (Figure 5a) single-, (Figure 5b) double-, and (Figure 5c) quad-stage designs hooked up in series in order to reduce capacitance and flatten the frequency response. Simulation results for a 0.5 mm modulator as a function of frequency and number of stages are presented in Figure 5d. With a double-stage modulator design, a $\sim\pi/4$ phase shift is achieved with 2.5 V applied.

With 250 mW peak input power, a 10% duty cycle, and 10 dB loss, an average power of 2.5 mW can be achieved at the photodetector. If we further achieve a phase modulation depth of $\pi/4$ with 2.5 V applied at 10 GHz, a single-sideband phase noise level of -153 dBc/Hz can be achieved enabling a shot noise jitter limit of 1 fs across a 10-MHz loop bandwidth.
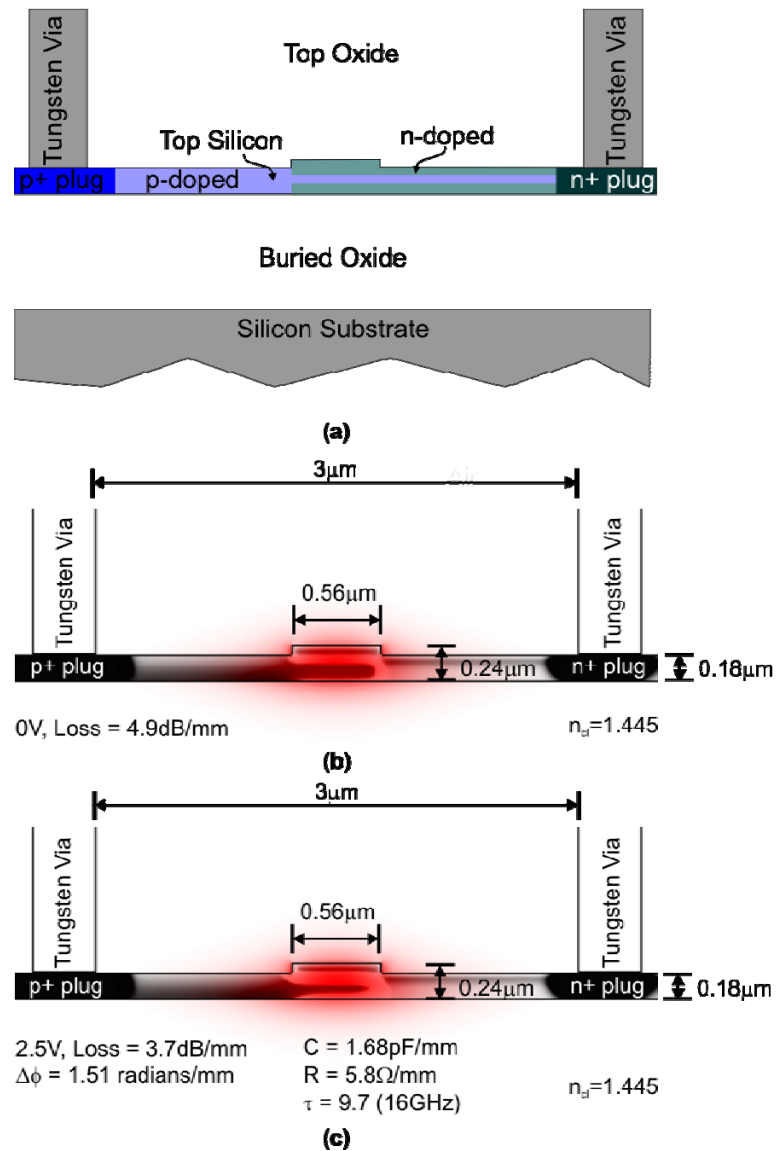
Figure 4. Cross-sectional diagrams our silicon phase modulator design, highlighting (a) the structure of the phase modulator, and using finite-element and finite-difference simulations the overlap of the mode (shown in red) with the free-carriers (shown in gray) for (b) 0 volts and (c) 2.5 volts applied. The simulations indicate that a phase shift of $\pi/2$ can be achieved for 2.5 V applied in a 1-mm-long device.
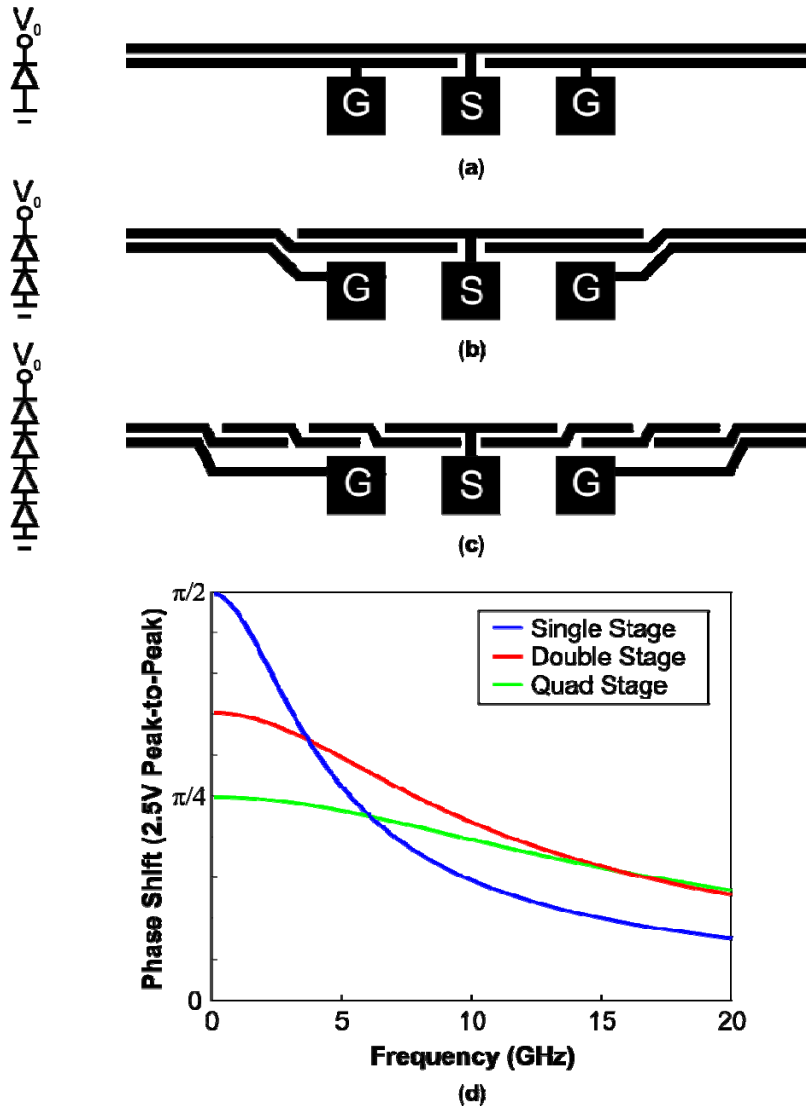
Figure 5. The modulator is broken up into (a) single-, (b) double-, and (c) quad-stage designs hooked up in series in order to flatten its frequency response. Simulation results for a 0.5-mm-long modulator as a function of frequency and number of stages. The more stages, the flatter the response.

A block diagram of our first design for an IO-BOMPD is depicted in Figure 6a. To simplify the first fabrication, an off-chip detector will be used instead of a germanium on-chip detector. Further, we decided to separate out the bias and drive signals using a pair of phase modulators. The lengths L_1 and L_2 determine the relative timing between the signals. In order to achieve the correct phase relationship between the reference signal (6.5 GHz) and the VCO (10.225 GHz), delays of 49 ps ($L_1 = 4$ mm) and 78 ps ($L_2 = 6.5$ mm) are necessary. The full chip has been laid out and is currently being fabricated. To show just how compact the IO-BOMPD chip design is, the mask design is presented in Figure 6b. The device is only 125 μm × 6.5 mm offering ample room for CMOS circuitry to be implemented alongside the microphotonic circuit.
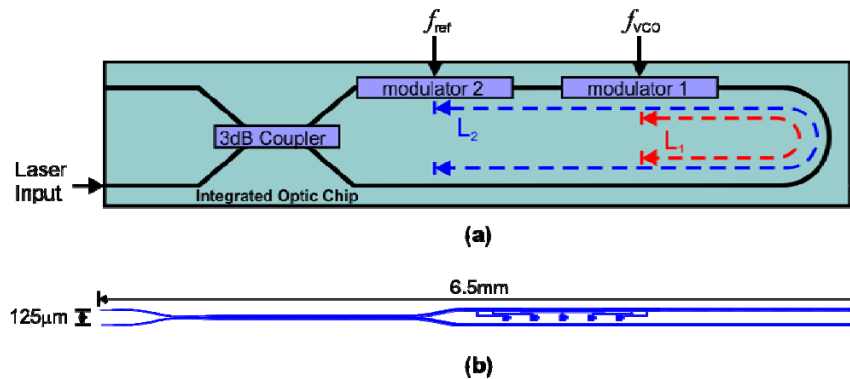
Figure 6. (a) Diagram and (b) mask layout of our initial IO-BOMPD design. The IO-BOMPD is a compact microphotonic circuit that can be used for distributed timing applications.

CONCLUSIONS

Low-phase-noise extraction of microwave signals from mode-locked lasers leading to a relative timing stability of 1.9×10^{-19} has been demonstrated, a result that is orders of magnitude better than that achieved by direct extraction methods. This read-out technique for microwave signals can be used to realize optical phase-locked oscillators. Development of integrated optic balanced optical microwave phase detectors (IO-BOMPDs) and ultimately integrated optical phase-locked oscillators (IO-PLOs) will enable compact and distributed high-precision timing references that can be applied to radio, RADAR, GPS, navigation, and other high-precision timing applications. Here, we have presented our first design for an integrated optic balanced optical microwave phase detector (IO-BOMPD) and the initial design study suggests that a compact IO-BOMPD can be utilized in an optical phase-locked oscillator platform to achieve ~1 fs timing across a 10-MHz loop bandwidth with a single-sideband phase noise level of -153 dBc/Hz. Power handling and silicon phase modulator development represent the principal challenges to successful implementation.

ACKNOWLEDGMENTS

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