

Offset Locking of a Fully Integrated Optical Phase-Locked Loop Using On-chip Modulators

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Abstract: We demonstrate an integrated heterodyne optical phase-locked loop for potential RF remoting. Offset-locking of the two on-chip lasers is achieved by applying a RF signal to an on-chip optical phase modulator and locking to an optical sideband.

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Over the years, microwave/millimeter wave photonic link technology, supporting the fiber optic remoting of RF signals based on remote heterodyne detection (RHD) [1], has attracted a great deal of attention for a wide range of applications including delay lines over phased-array antenna feeders and backbone networks for cellular phone systems [2]. Such a fiber-optic link at the transmitter or base station requires two widely-tunable lasers with slightly different wavelengths, the phases of which must be strictly correlated. The strict phase correlation between these two lasers can be achieved by using a heterodyne optical phase-locked loop (OPLL) [3] transmitter configuration.

There are two techniques that could be adopted for such heterodyne locking. As a first technique, the RF signal can be applied to an electronic mixer following optical detection in such a coherent photonic receiver and the RF difference frequency used for offset locking [4,5]. Another technique is to apply the RF to an on-chip optical modulator monolithically integrated on the photonic receiver following the tunable laser and to achieve the locking using an optical sideband [6]. Use of higher-order sidebands are also possible enabling higher offset frequencies than available from the RF source or the electronics.

In this work, we report the second technique using an InP-based photonic integrated circuit with an on-chip optical phase modulator following the LO laser for applying the offset. Outputs from the LO and signal lasers are combined into a pair of photodetectors that provide inputs to agile and highly-sensitive feedback electronics that control the phase section of the LO for locking. A net loop bandwidth of 500 MHz was obtained, and an offset locking frequency range ~ 16 GHz is achieved in the system, which can employ up to the third-order-harmonic optical sidebands for locking, yielding a locking range as high as 48 GHz.

Figure 1(a) shows a schematic of the coherent optical receiver PIC used for OPLL. It includes two widely-tunable sampled-grating distributed Bragg reflector (SG-DBR) lasers that are to be offset locked, MMI couplers, semiconductor optical amplifiers (SOAs), photodetectors, and several RF-modulators. The chip size is $7 \text{ mm} \times 0.5 \text{ mm}$.

As can be seen, light from each laser is first equally divided into two paths using 1×2 MMIs. One half from each laser is guided into a 2×2 MMI, which serves as a 180 degree hybrid to feed the two photodetectors for the feedback loop. Each input arm of the 2×2 MMI contains a phase modulator (M) that can be used for applying RF to generate optical sidebands. After adding the fields from these two lasers in the MMI coupler, light is detected in a pair of photodetectors (D) to provide a differential output.

The other half from each laser travels through semiconductor-optical-amplifiers (SOAs) to increase their amplitude and modulators for applying possible information. They are then combined in a 2×2 MMI at the right side of the OPLL-PIC. In the current experiment this is used for monitoring of the interference between the two SG-DBR lasers by coupling into an optical fiber.

An optical microscope photo of the fully-processed PIC on an InGaAsP/InP material platform is shown in Fig. 1(b). The process used to fabricate the devices is quantum-well intermixing (QWI) that creates self-aligned passive regions by intermixing the quantum-wells with their barriers and surrounding waveguide material by a patterned diffusion of implanted phosphorus ions after a first growth. Details of the processing steps for the well-established QWI-based material structure can be found elsewhere [7].

Two widely tunable on-chip SG-DBR lasers along with all of the other optical components were used to form the heterodyne OPLL. One of the lasers was used as a master (or signal) laser, while the other as a slave (or LO) laser to be offset phase-locked to the former. Prior to combining the outputs of these two lasers using a 2×2 optical coupler, the output of slave SG-DBR laser is phase-modulated for offset-locking using an integrated on-chip modulator and envelope detected using a pair of balanced on-chip photodetectors. The current output from the

photodetector was amplified and filtered through the feedback electronics and fed back into the slave laser. The functional schematic of such an OPLL system is illustrated in Fig. 2(a).

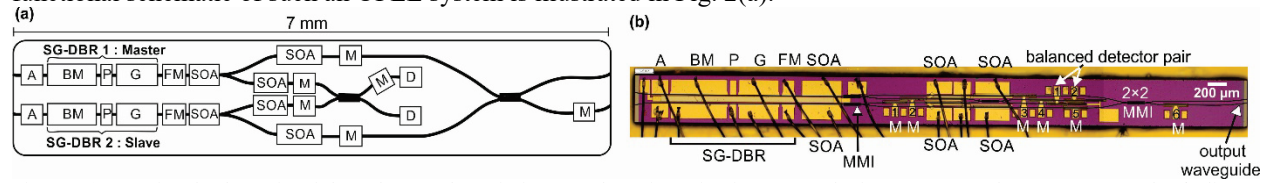


Fig. 1. (a) Functional schematic of the coherent photonic integrated receiver circuit composed of two SG-DBR lasers, MMI couplers/splitters, semiconductor optical amplifiers, phase modulators and a balanced photodetector pair, and (b) microscope image of the fully-processed PIC mounted on a separate aluminium-nitride (AlN) carrier and wirebonded. (BM: back mirror, FM: front mirror, G: gain, A: absorber, M: phase modulators, MMI: multimode interference, P: phase tuner, D: photodetector, and SOA: semiconductor optical amplifier).

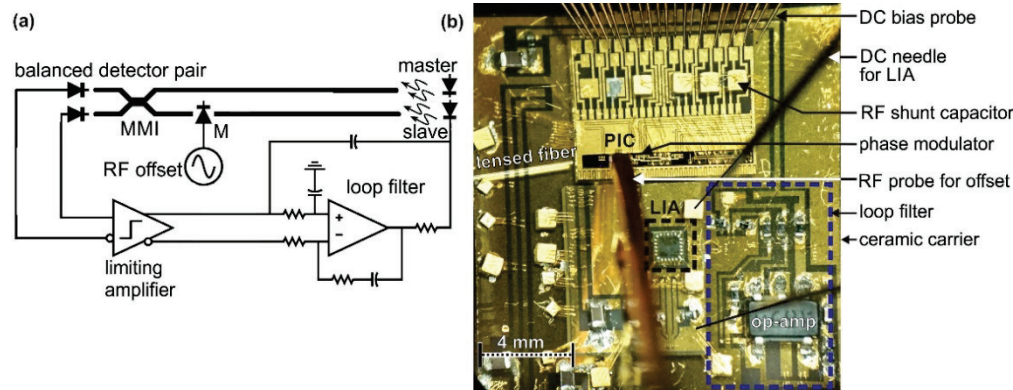


Fig. 2. (a) Functional architecture of the heterodyne OPLL system, and (b) optical microscope image of the system including PIC, limiting amplifier (LIA) and loop filter on a separate aluminium-nitride carrier.

Figure 2(b) shows an optical image of the assembled heterodyne OPLL system including PIC and the feedback electronic circuits. The electronic circuits were built by integrating a SiGe-based limiting amplifier (LIA) manufactured by ADSANTEC [8] and discrete loop filter components. These three parts were tightly integrated on a patterned AlN carrier by wirebonding. A DC coupled system was prepared since the PDs require reverse biasing by 2 V which was provided from the electronic circuits. In fact, due to current mode logic (CML)-type inputs of the LIA, together with the 50 Ω loads and off-chip level-shifting diodes, the LIA develops -2 V input voltage through self-biasing. The LIA directly interfaces to the PIC by reverse-biasing the photodiodes by 2 V. The random phase variation between the two lasers translates into intensity modulated error signals at the outputs of the 2×2 MMI in the PIC and finally into current error signals at the output of the photodetectors. The error signals generated by these reverse-biased photodetectors were amplified by the LIA and filtered by the loop filter. Finally, the filtered output is converted into current signals needed to control the injection of carriers into the forward-biased phase section of the slave (LO) SG-DBR laser.

To demonstrate offset-locking of the slave laser to the master one, the inner phase modulator after 1×2 MMI, connected with the slave laser was reverse biased using a bias tee. Based on the Franz-Keldysh effect through reverse bias modulation, this phase modulator generates optical sidebands after applying the RF signal into it. When the frequency separation between the two SG-DBR lasers equals the modulation frequency, the detected photocurrent will contain a phase-dependent DC component, and sideband locking of the slave laser to the master laser becomes possible. The combined beat signal of the slave and master lasers was coupled out from the output waveguide of the PIC using a lensed fiber for monitoring purposes, as shown in Fig. 3. An optical isolator was used at the combined output to reduce back reflections. To measure the OPLL tone, the combined optical output passes through an off-chip 2×2 coupler. One output was detected via an external high speed photodetector, and measured on the ESA. The other output of this coupler was connected to the optical spectrum analyzer (OSA) to measure the optical spectra of the lasers.

The experiment demonstrates phase locking between the two on-chip lasers. Figure 4(a) shows the optical spectrum when the lasers are offset locked at ~ 2.5 GHz, as determined by the RF frequency synthesizer. The OSA spectral separation between the lasers is ~ 0.02 nm which corresponds to ~ 2.5 GHz. The beating tone of the locked lasers is shown in Fig. 4(b) both before and after the locking circuit is activated. The beat note has a linewidth in the order of a MHz before the phase locking. The differential linewidth is less than could be measured with our microwave spectrum analyzer (100 Hz) after phase locking as expected. Figure 4(c) shows a series of electrical

spectra for the different offset locking conditions up to the fundamental frequency of 16.3 GHz. Such a highly-sensitive OPLL system can employ up to the third-order-harmonic optical sidebands for locking, yielding the locking range as high as 48 GHz. The corresponding results will be reported at the conference.

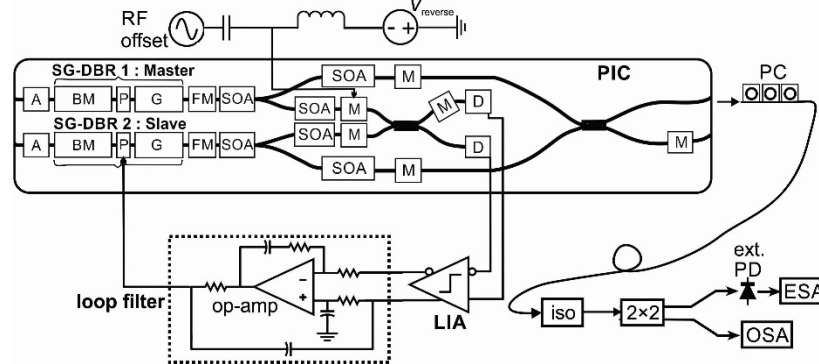


Fig. 3. The test setup of the OPLL system. (ECL: external cavity laser, ESA: electrical spectrum analyzer, OSA: optical spectrum analyzer, PT: phase tuner, FM: front mirror, PD: photodiode, PC: polarization controller)

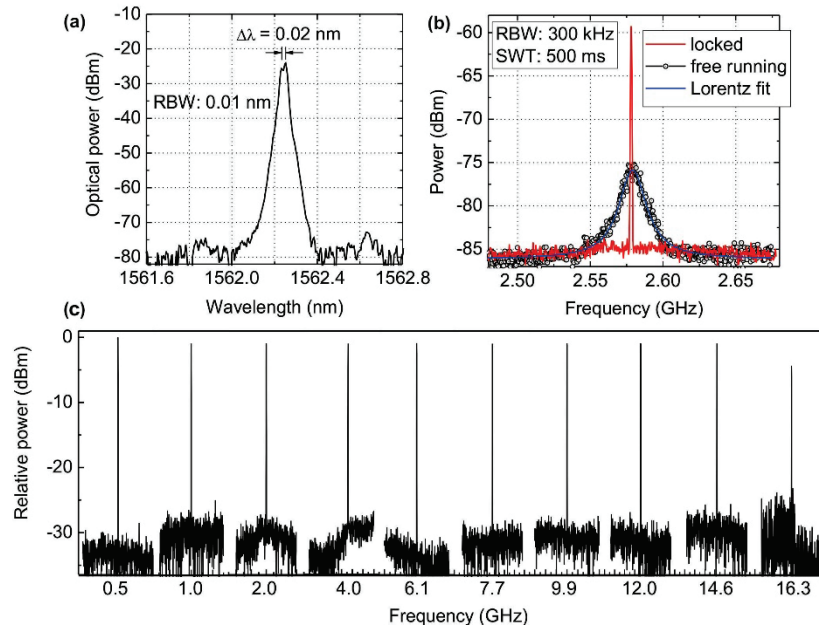


Fig. 4. (a) The optical spectrum when two on-chip lasers are offset locked at ~ 2.5 GHz with a wavelength separation of 0.02 nm; (b) corresponding RF spectra measured at a 300 kHz resolution bandwidth (RBW), showing the locked beat note together with the unlocked case at ~ 2.5 GHz, and (c) offset locking at multiple frequencies at a RBW of 300 kHz.

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