A Heterodyne Optical Phase-locked Loop for Multiple Applications

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Abstract: A novel heterodyne optical phase-locked loop (OPLL) has been achieved and testing results are demonstrated with a 0.03 rad^2 phase error variance. Based on the superior performance of this OPLL, a system prototype is shown for multiple applications, including free-space LIDAR systems, widely-and-fast-tunable ultra-narrow-linewidth lasers, and ultra-accurate optical spectrum analyzers.

OCIS codes: (250.5300) Photonic integrated circuits; (060.2840) Heterodyne; Optical phase-locked loop; (010.3640) LIDAR.

1. Introduction to the highly-integrated heterodyne OPLL

Since the first optical phase-locked loop (OPLL) was demonstrated in 1965, considerable effort has been devoted to the research of OPLLs. However, the biggest roadblock is the short loop delay requirements for stable operation. By using traditional free space optics, most OPLLs show a loop delay of more than tens of nanoseconds, which makes the loop bandwidth smaller than 10 MHz, according to the fundamental control theory of feedback systems. Narrow loop bandwidth not only gives rise to a high requirement on the laser linewidth and stability, but also makes the system more sensitive to environmental fluctuations. Micro-optics can possibly improve this number to close to 200 MHz, but it still suffers the same stability issue. Limited bandwidth is one of the major reasons why the OPLL is not as widely used today as that of its counterpart, the PLL in electronic communication systems [1,2].

In order to decrease the loop delay and therefore increase the loop bandwidth, photonics integration becomes necessary. Recent research shows that an integrated OPLL can have a closed-loop bandwidth of several hundreds of MHz [3-5], or even more than 1 GHz [6]. Based on advanced photonic and electronic integration technology, a heterodyne OPLL is made and a part of the testing results can be found in [5]. This OPLL is integrated with an I/Q receiver, a phase/frequency detector (PFD) and a single-sideband mixer for the first time [5,6]. The whole OPLL system has been realized within a size of 10 × 10 mm^2. The architecture is shown in Fig. 1. The system includes a photonic integrated circuit (PIC), an electronic integrated circuit (EIC) and a hybrid loop filter built on an AlN carrier. An on-PIC sampled-grating DBR (SG-DBR) laser is used as a widely-tunable slave laser, and it covers a 40 nm bandwidth. By integrating the I/Q receiver and the PFD in the system, frequency pull-in has been achieved, which means that even if the free running slave laser is several GHz away from the targeted locking frequency, it will be pulled-in and become phase-locked automatically. The SSBM enables the system to achieve offset locking, and the offset frequency between two lasers can be either positive or negative [7]. The sign is set by the control pad on the EIC and there is no frequency ambiguity. Based on the frequency pull-in function and the SSBM, a phase-locked frequency sweep has been achieved from -9 GHz to -1.5 GHz, and from +1.5 GHz to +7.5GHz. The electrical beating spectra are shown in Fig. 2. Injection locking is observed below 1.5 GHz frequency offset because of internal reflections on the PIC.

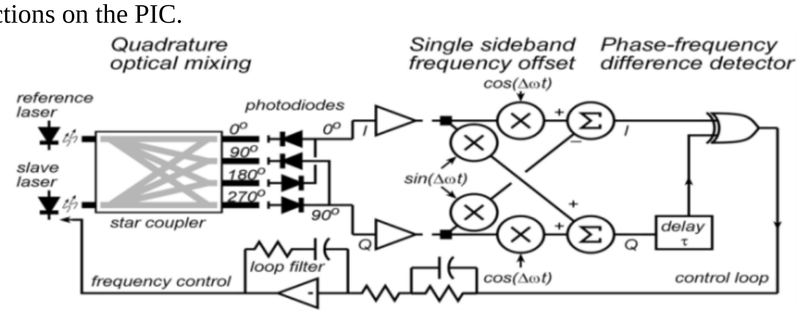

Fig. 1. The architecture of the OPLL.

Moreover, this heterodyne OPLL also shows > 15 GHz hold-in range. The phase locking is very stable. Within a submount temperature change of 2.3 °C, the OPLL can keep phase-lock. The phase noise measurement also shows that the beating tone of the master laser and the slaver laser has a phase noise <-100 dBc/Hz above 5 kHz, and the phase error variance is 0.03 rad^2, integrating from 100 Hz to 10 GHz.

The details about this heterodyne OPLL can be found in [5]. The preliminary testing result of this OPLL is summarized in Table 1. Compared to all the OPLLs that have been proposed in the past, this heterodyne OPLL has superior performance in almost all the specifications listed in Table 1. The hold-in range, stability, pull-in range have improved by orders of magnitude.

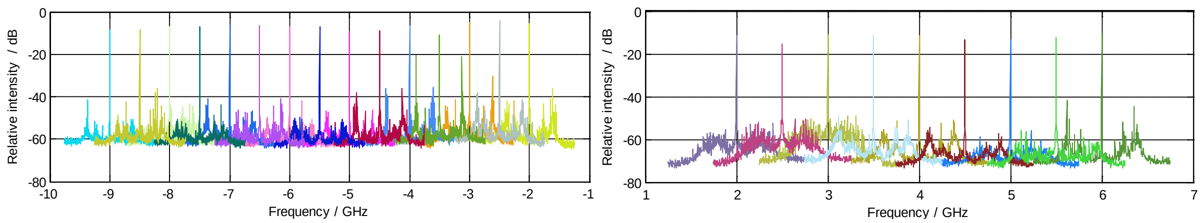

Fig. 2. Shows the beating tones of the two lasers when they are phase locked at various frequency offsets.

Loop delay	~ 200 ps	Hold-in range	> 15 GHz
Closed-loop bandwidth	~ 400 MHz	Temperature range	2.3 °C
Pull-in range	Close to 10 GHz	System size	10 × 10 mm^2
Offset frequency range	-9- + 7.5 GHz	Phase error variance	0.03 rad^2

Table 1. Performance summary of the heterodyne OPLL system.

By replacing the PIC with a new PIC with wider photodetector bandwidth, which has already been demonstrated in [8], the continuous frequency sweeping range can be as wide as the laser cavity mode spacing (~40 GHz for the SG-DBR laser). Furthermore, no injection locking has been observed on this new PIC, because of a fundamental design change of the waveguide structure. Therefore, continuous sweeping across the zero frequency offset is achievable.

2. System prototypes

Using the heterodyne OPLL discussed in Section 1 as a key building block, many communication or sensing systems can be created with superior performance. Full engineering control over the optical phase of the laser becomes feasible. The system stability ensures that it is possible to build some commercial systems based on this heterodyne OPLL.

i) Frequency-Modulated Continuous-Wave (FMCW) Light Detection and Ranging (LIDAR) systems

FMCW radar has been using in the field for decades and a lot of research based on this principle has been carried out [9]. Compared to FMCW radar, FMCW LIDAR has much higher resolution. The resolution of the LIDAR is inversely proportional to the frequency sweeping range, which is mainly limited by the laser tuning range. By applying this heterodyne OPLL to a LIDAR system, 40 nm quasi-continuous tuning is achievable, which potentially leads to a 30 μm resolution.

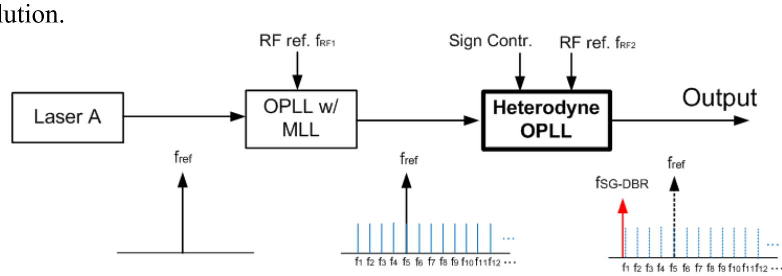

Fig. 3. A system built on the heterodyne OPLL.

The proposed system architecture is shown in Fig. 3. The continuous-wave laser A is a single-fixed-wavelength narrow-linewidth laser, which is used as a reference laser in this system. By using an OPLL with an integrated mode-locked laser (MLL), one of the comb lines of the MLL can be phase-locked to laser A, and at the same time, the MLL is actively mode-locked. By both phase locking and active mode locking, timing jitter is eliminated and the linewidth of each line is the same as the CW laser A. The RF source frequency f_{RF1} is the same as the mode-locking frequency. Hence, stable and narrow-linewidth comb lines can be generated.

The comb lines are then used as the reference for the heterodyne OPLL. RF frequency f_{RF2} is applied on the EIC of the OPLL to introduce a frequency offset, which is $f_{RF2}/2$ [7]. By tuning the SG-DBR mirror currents, phase section current and f_{RF2}, SG-DBR laser can phase-lock to the frequency of $f_i \pm f_{RF2}/2$, where i=1,2,3,4… As long as the heterodyne OPLL offset frequency range is larger than half of the comb line spacing, quasi-continuous frequency sweeping can be achieved. Moreover, the SG-DBR linewidth can be the same as CW laser A, because of the linewidth 'cloning' of OPLL. Since the linewidth is directly related to the detection range, by using a better reference, the system range can be greatly increased. In addition, the sweeping speed can be quite fast. It will not be limited by the interaction between red-shifting thermal effects and blue-shifting carrier density effects.

Our preliminary results have already shown that an InGaAsP/InP integrated MLL can achieve 2.06 THz spectrum width with 29 GHz line spacing under active mode-locking [10]. A MLL has also been used as a reference laser, and the heterodyne OPLL has successfully phase locked to one of the comb lines [11].

Furthermore, since both the MLL and the PIC in the heterodyne OPLL system are integrated on InGaAsP/InP platform and the fabrication processes are very similar, integrating them on the same PIC monolithically is feasible. If the LIDAR system doesn't have strict requirement on linewidth, it is possible to get rid of the CW laser A, and the system size will decrease down to the tens of millimeter scale, which means that a 30 μm-resolution handheld FMCW LIDAR can be achieved, and it becomes possible to integrate in a watch or a cell phone.

ii) Widely-and-fast-tunable ultra-narrow-linewidth lasers

Commercial state-of-the-art fixed-wavelength lasers can achieve <1 kHz linewidth, whereas the linewidth of most widely-tunable lasers is still at the 100's of kHz range. 1/f noise on the tuning sections is a fundamental noise source that limits the linewidth of rapidly tunable lasers to be higher than fixed-linewidth laser.

By utilizing the topology in Fig. 3, and using a narrow-linewidth fixed-wavelength laser as CW laser A, the narrow linewidth can be 'cloned' to comb lines and therefore to the SG-DBR laser in the heterodyne OPLL system. The low phase error of the system ensures the linewidth does not get broadened when it gets 'cloned'.

iii) Ultra-accurate optical spectrum analyzers

Optical spectrum analyzers (OSAs) normally have limited resolution bandwidth at the GHz range. By using the frequency sweeping system in Fig. 3 as a local oscillator (LO), and beating the measuring signal with the LO on a photodetector, the resolution of the OSA is only limited by the linewidth of the LO, which can be as small as 1 kHz across the whole C band. The resolution of this new prototype of OSA can be so high that it is possible to measure the linewidth of a DFB laser accurately without any extra test setup.

3. Conclusions

In this work, preliminary results of a heterodyne OPLL have been demonstrated. Based on this novel OPLL, a new system prototype has been shown for the first time, and several potential applications have been illustrated. The applications of this OPLL include, but are not limited to: FMCW LIDAR, narrow-linewidth widely-tunable lasers, and ultra-accurate optical spectrum analyzers. The applications can also extend to the area of fiber optic sensing and coherent communications. More system testing results will be shown at the conference.

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