

# An Integrated Heterodyne Optical Phase-locked Loop with Record Offset Locking Frequency

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**Abstract:** A highly-integrated optical phase-locked loop (OPLL) is realized by photonic and electronic integration. The experiment shows the full functionality of this heterodyne OPLL and 25 GHz offset locking frequency is achieved.

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

Ever since the first optical phase-locked loop (OPLL) was demonstrated in 1965, a lot of effort has been devoted to the development of OPLLs. Much of the motivation has been to achieve what has been achieved in the electrical domain, where almost every electronic system that we are using today relies on phase locked loops (PLLs) to realize their basic functions, such as frequency/phase synthesis, clock recovery, RF down/up-conversion. The realization of PLL in the optical domain, i.e. OPLL, may bring a fundamental change to the way how optical systems are designed and may also lead to many applications in the area of optical coherent communication and optical sensing [1].

The early work on OPLLs was mainly based on free-space optics and fiber pigtailed devices [2][3], and the resulting system size was large and the stability was generally poor, mainly because of a large loop delay. The loop delay directly relates to the loop bandwidth, and consequently the loop stability and phase noise suppression range. Control theory indicates that for a second-order type-II loop, the loop delay and bandwidth must satisfy,  $\tau \cdot B_n < 0.12 \text{ ns} \cdot \text{GHz}$ , for absolute loop stability [4]. For example, in order to achieve a loop bandwidth of 1 GHz, the maximum allowable loop delay is 120 ps, which corresponds to 36 mm of optical propagation in free space. Because of difficulties due to limited loop delay, OPLLs are historically regarded as one of the most unstable optical systems. Any perturbation such as mechanical vibration, might lead to a malfunction of such OPLLs. However recently, the situation has changed [5][6][7][8]. Several prototypes of highly integrated OPLLs have been demonstrated by the authors with high stability and other desirable characteristics [7][8]. Integration has provided orders of magnitude reductions in the loop bandwidth, and in addition, novel single-sideband mixer (SSBM) and phase/frequency detector (PFD) designs have increased the offset frequency range and OPLL stability as well [7].

In this paper, we demonstrate an integrated OPLL with a record laser offset frequency of 25 GHz. The system architecture is shown in Fig. 1. It is composed of three parts: a photonic IC (PIC), an electronic IC (EIC) and a loop filter (LP).

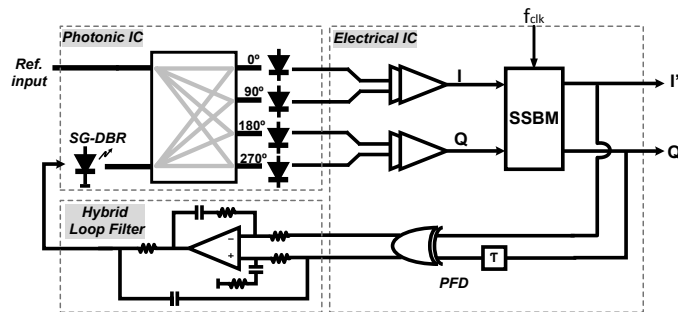


Fig. 1. Architecture of the heterodyne OPLL.

On the PIC, we integrate a widely-tunable sampled-grating DBR (SG-DBR) laser, a star-coupler-based optical 90 degree hybrid [7], four single-ended uni-travelling-carrier (UTC) photodetectors, and microstrip transmission lines. The SG-DBR laser acts as the widely-tunable slave laser. By injecting current into the back and front mirrors, the laser can be tuned over a 40 nm range. Meanwhile, the current injection into the phase section can tune the laser wavelength finely within one cavity mode, which is around 40 GHz, and this is used to phase lock the SGDBR laser so that its frequency is determined to Hz-level offset accuracy from the reference. On the EIC, trans-impedance limiting amplifiers, a delay line, an XOR gate and an SSB mixer are integrated [9]. The delay line and the XOR gate

together act as a phase/frequency detector. The loop filter is built on a common Aluminium Nitride carrier, using a voltage feedback operational amplifier as an active filter and integrator. The beat signal from the on-PIC photodetectors are finally negatively fed back to the SG-DBR laser phase section through the EIC and the loop filter.

The loop delay for the closely integrated hybrid PIC-EIC-LP circuits is approximately 200 ps, in which 40 ps is from the PIC, >100 ps is from the EIC and 50 ps from the loop filter and interconnections.

The PIC is fabricated with a centered-QW structure, and quantum well intermixing is used to define active and passive areas. UTC photodetector layers are regrown by MOCVD after active/passive definition. Surface ridge waveguides are used for all devices on chip. A star coupler is chosen as a 90-degree hybrid, where in-phase and quadrature signals are generated. Microstrip transmission lines are also integrated. The details about the PIC design and fabrication can be found in [10]. Measurements show the full functionality of the PIC. The SG-DBR laser covers 40 nm, and UTC photodetectors have a RF bandwidth of 35 GHz [10]. A picture of the photonic IC is shown in Fig. 2.

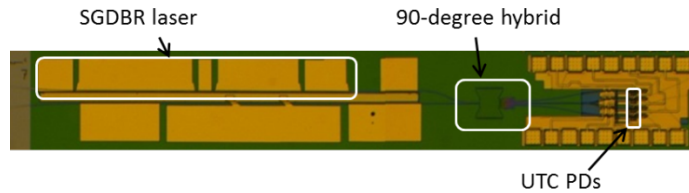


Fig. 2. A microscope picture of the PIC.

The EIC is fabricated at Teledyne Scientific using 500 nm InP-HBT technology. The unit gain frequency is 300 GHz. The working frequency of the designed EIC is up to 50 GHz.

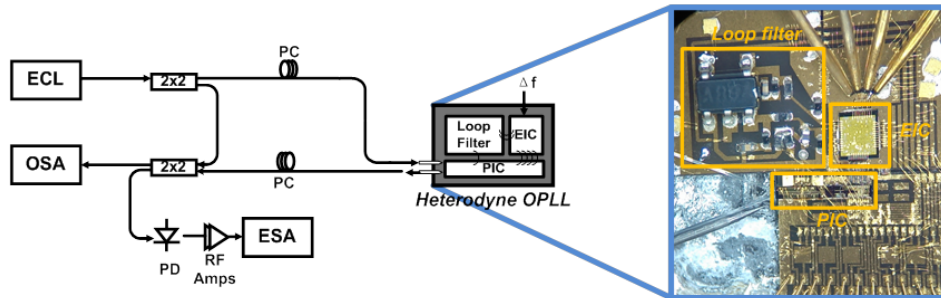
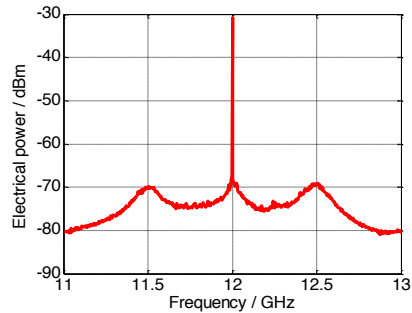


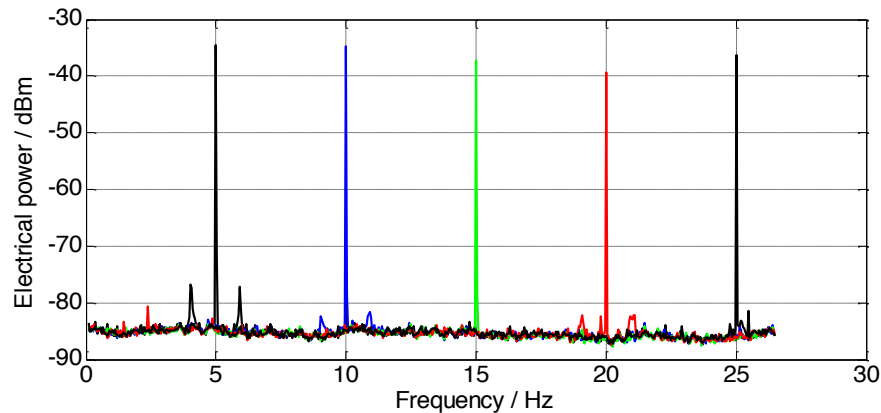
Fig. 3. The schematic of the OPLL test setup and a microscope picture of the heterodyne OPLL. (ECL: external cavity laser, OSA: optical spectrum analyzer, ESA: electrical spectrum analyzer, PC: polarization controller.)

Schematics of the OPLL test bed can be found in Fig. 3 and a microscope picture is also shown. The designed loop bandwidth is around 500 MHz. Using lensed fiber, the reference laser (an Agilent widely-tunable laser) signal was coupled into the PIC, and the SG-DBR laser signal was coupled out from the back mirror for monitoring purposes. The optical spectrum of the SG-DBR laser and the reference laser was measured by an optical spectrum analyzer (OSA) and their beat tone measured by an electrical spectrum analyzer (ESA) via a high speed photodetector. The offset locking frequency is defined by RF signal generator frequency, which is twice of the desired offset frequency of this heterodyne OPLL [9].

The experiment shows phase locking between the on-PIC SG-DBR laser and the incoming reference laser. The beating tone of the locked lasers is shown in Fig. 4 with an offset frequency of 12 GHz. According the Fig. 4, the closed loop bandwidth is around 500 MHz, which is in accordance with our design, and the phase noise within 500 MHz is well suppressed. By only tuning the RF signal generator frequency, frequency pull-in and phase locking are achieved at the same time. As long as the desired locking frequency is within a laser cavity mode spacing, by turning on the OPLL, the SG-DBR laser output frequency will be pulled towards the desired frequency, and it will finally be phase locked automatically. Total pull-in and locking times are sub-microsecond. The maximum offset frequency that we achieve in this experiment is 25 GHz, as limited by the RF synthesized signal generator, since the SSB mixer requires double the offset frequency [9] and only a 50 GHz signal generator is available for this experiment. A series of electrical spectra are shown in Fig. 5, where the offset frequencies vary from 5 GHz to 25 GHz.



**Fig. 4. Beating tones of the two lasers when the offset frequency are 12 GHz, measured with 100 kHz resolution bandwidth.**



**Fig. 5. Shows the beating tones of the two lasers when they are phase locked at various frequency offsets: 5 GHz, 10 GHz, 15 GHz, 20 GHz, and 25 GHz. The resolution bandwidth is 100 kHz.**

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