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A Highly Integrated Optical Phase-locked Loop for Laser Wavelength Stablization

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Abstract—**A highly integrated optical phase-locked loop (OPLL) has been applied to stabilize the semiconductor laser wavelength for the first time. Preliminary results show that the slave laser is stably phase-locked to a reference laser within 2.2 K temperature fluctuation.**

Keywords-coherent; optical frequency synthesis; optical phase-locked loop; wavelength stablization.

Coherent fiber optic communication is receiving a lot of interest recently. [1] However, whether used for long-haul or short-haul communication (e.g. PON), coherent receivers have high requirements on LO laser performance, such as narrower linewidth, and better wavelength stability. A lot of work has been done to stabilize the laser wavelength. For the commercialized laser module, a temperature-controlled external cavity is commonly applied. By locking the laser wavelength to the cavity through a photodetector and feedback circuits, the laser wavelength can be controlled within hundreds of MHz range. Work has also been done using optical injection phase-locked loop (OIPLL) [2]. By applying an OIPLL, the slave laser can stably injection lock to the reference laser or comb lines without an offset frequency.

Research on OPLL's started more than 50 years ago, but has proven to be difficult, mainly because of the loop delay and therefore the limited loop bandwidth. Although the loop bandwidth has been improved from MHz range to 200-300 MHz range [3,4] because of photonic integration, it is still not enough to maintain stable locking with small perturbations. A 0.2 K temperature change will easily make the OPLL lose locking. Therefore, it is not feasible to stabilize laser frequency using existing OPLLs.

In this paper, we propose and demonstrate an optical phase-locked loop with phase/frequency detection [5]. By incorporating both a phase detector and a frequency detector, the loop pull-in range and hold-in range become much larger compared to a traditional optical phase-locked loop with only a phase detector. Therefore, this OPLL is much easier to get phase locked and also more resistive to temperature fluctuation. The architecture of the system is shown in Fig. 1. Reference laser and slave tunable laser are mixed in a 90 degree hybrid. The in-phase and quadrature signals are then generated and detected by four high-speed photodetectors. Trans-impedance limiting amplifiers, a single-sideband mixer, a phase/frequency detector (PFD) and an active loop filter are used in the electronic feedback path.

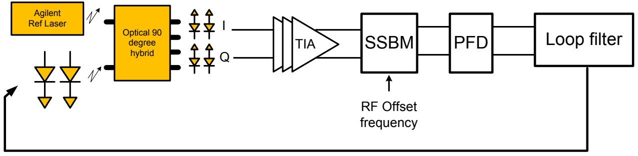

Fig. 1. The architecture of the optical phase-locked loop.

The system is composed of three blocks: a photonic integrated circuit (PIC), an electronic integrated circuit (EIC) and a loop filter (LF).

On the PIC, a widely-tunable sampled-grating distributed Bragg reflector (SG-DBR) laser, a star-coupler-based 90 degree hybrid, four quantum well photodetectors and four microstrip transmission lines were integrated [5]. A centered quantum well InGaAsP/InP integration platform was chosen to integrate all these optical components monolithically. The EIC is composed of limiting amplifiers, a digital single-sideband mixer and a phase/frequency detector as shown in Fig. 1. The phase/frequency detector is based on an RF delay line and an XOR gate [6], which is basically a quadri-correlator frequency detector. The EIC was fabricated using Teledyne's standard 500nm HBT fabrication line, and the f_{max} of each transistor is 300 GHz. The details about the EIC are discussed elsewhere [6]. Loop filter was built on an AlN carrier using an operational amplifier and discrete surface-mount components.

The photonic IC, the electronic IC and a loop filter are closely interconnected via wire bonding, and the size of the whole OPLL is within one or two centimeter square. The test setup as well as the picture of the OPLL is shown in Fig. 2. We used a 100 kHz-linewidth Agilent external-cavity tunable laser as the reference laser and coupled into the PIC using a lensed fiber. The SG-DBR laser was coupled it out through the back mirror for monitoring purpose. The frequency of the free running SG-DBR laser drifts within hundreds of MHz range, and the linewidth is also much wider than that of the reference laser.

The open-loop response was first measured. By fixing the beating tone of the two lasers at 6 GHz and sweeping the RF offset frequency, the output of the PFD was shown in Fig. 3. The frequency detection curve crosses zero volt point around 12 GHz, which is double of the locking frequency as designed.

The OPLL submount temperature is controlled by a thermoelectric temperature controller. The free-running SG-DBR laser shows 13.68 GHz/K temperature tuning sensitivity.

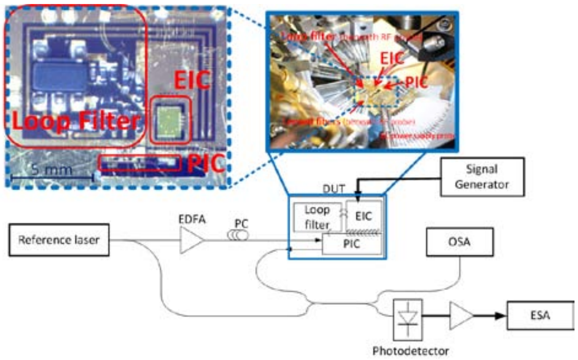

Fig. 2. The schematic of the OPLL test setup is shown in the lower part of this figure. Thinner lines indicate fiber connections and thicker lines show the RF cable connections. Pictures of the OPLL are also shown.

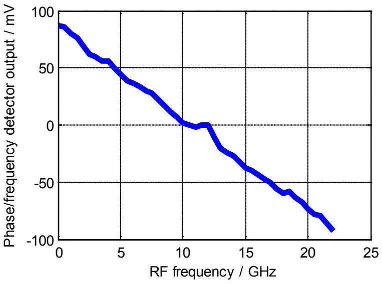

Fig. 3. Frequency detector open- loop response curve. The two lasers are offset by 6 GHz.

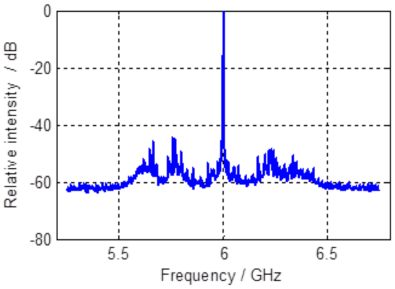

Fig. 4. The beating tones of the two lasers when the offset frequency is 6 GHz, measured with 5 kHz resolution bandwidth.

The electrical spectrum analyzer data of the beating between the reference and the locked slave laser is shown in Fig. 4, where the offset frequency is 6 GHz. By changing the RF reference frequency, we continuously shifted the SG-DBR frequency within the range from -9.5 GHz to -1.5 GHz, and also from 1.5 GHz up to 7.5 GHz with phase locking to the reference laser, respectively. [5] The phase-locked SG-DBR laser has the same wavelength stability as the Agilent reference laser and the linewidth has also been greatly improved as indicated in Fig. 4. After phase locking the on-PIC SG-DBR laser to a reference laser with 6 GHz frequency offset, we tuned the submount temperature. The original submount temperature was set at 12°C. Typically a change in temperature leads to material dielectric index changes, therefore causing a wavelength shift of the laser. In this case, the feedback loop changes the current injected to the laser phase section accordingly to compensate for the temperature-dependent index change, keeping the laser wavelength stable and in lock. While tuning the temperature from 11.9 °C to 14.1 °C, the OPLL kept in locking status. The wavelength of the locked SGDBR is line narrowed and held constant for temperature changes up to 2.2 K--whereas an unlocked laser would drift by > 30 GHz. The measured voltage on the laser phase tuning diode is shown in Fig. 5. By applying the IV curve of the phase tuning diode, the temperature and current relation can be obtained (Fig. 5). At 11.8 °C and 14.2 °C, cavity mode hopping was observed so the OPLL lost locking at those temperatures.

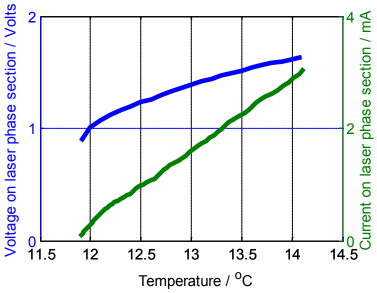

Fig. 5. DC voltage measured on the phase-locked SG-DBR laser phase tuning diode at different submount temperature. Current is obtained from the IV curve of the laser phase tuning diode.

In conclusion, by adopting a phase/frequency detector in the OPLL system, large frequency pull-in and hold-in ranges have been achieved. The wavelength of the locked SG-DBR laser is resistant to temperature fluctuations up to 2.2 °C.

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