Optical Frequency Synthesis by Offset-Locking to a Microresonator Comb

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Abstract: We report on the experimental demonstration of a chip-scale microresonator comb enabled optical frequency synthesizer using an agile and highly-integrated heterodyne optical phase-locked loop with InP-based photonic integrated circuit and commercial-off-the-shelf electronic components.

OCIS codes: (250.5300) Photonic integrated circuits; (060.5625) Radio frequency photonics; (060.2840) Heterodyne (140.0140) Lasers and laser optics; (140.3600) Lasers, tunable; (140.3945) Microcavities; (230.5750) Resonators

In recent years, chip-scale and low-power optical frequency synthesizers (OFSs) based on self-stabilization of full-octave microresonator combs are being increasingly investigated for various ultra-high-precision applications in which micro-Hertz levels of stability are sought [1]. However, for many practical applications, including optical spectroscopy [2], optical communication [3], light detection and ranging (LiDAR) [4], and some types of frequency metrology, stabilities in the few Hertz range would be very attractive. In this work, we report on the experimental demonstration of a continuously-tunable, microresonator-enabled, ultra-compact OFS near 1550 nm achieved by using a heterodyne optical phase-locked loop (OPLL) [5].

Figure 1(a) illustrates the basic concept of a compact and chip-scale OFS. A microresonator-based optical frequency comb (OFC) was used as an ultra-stable and narrow linewidth source, serving as a master oscillator (MO) [6]. The comb lines are then used as the reference for the heterodyne OPLL. A RF frequency from a tunable RF synthesizer is applied to feedback electronic circuits of the OPLL to introduce a frequency offset, defined by the frequency difference between the master laser and the local oscillator (LO) laser. By tuning the phase section current of the LO laser as well as f_{RF}, the LO is phase-locked to the comb lines. In order for an OFS to synthesize any arbitrary frequency between comb lines, the heterodyne OPLL offset frequency range must be at least half of the comb's free spectra range (FSR). Also for such continuous tuning, the FSR of the comb must be less than the slave laser's mode-hop free tuning range.

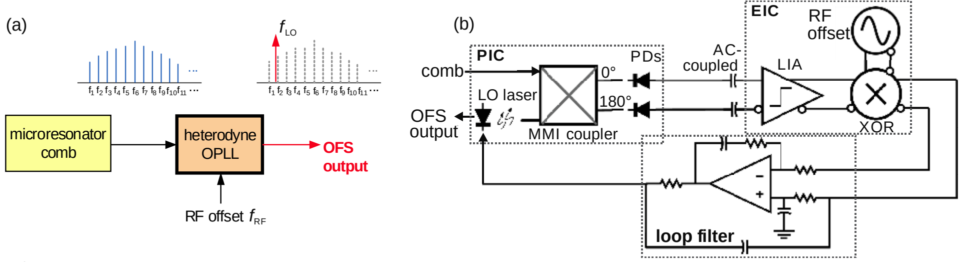

Fig. 1. (a) Optical frequency synthesizer (OFS) system, showing two main building blocks – a comb source and a heterodyne OPLL. The optical spectra are also plotted at the output of each block, and (b) system architecture of the heterodyne OPLL. (MMI: multimode interference, LIA: limiting amplifier, PIC: photonic integrated circuit, EIC: electronic integrated circuit, and PDs: photodiodes)

The heterodyne OPLL, serving as a core building block of an OFS is displayed in Fig. 1(b). This system is composed of a photonic integrated circuit (PIC) and feedback electronic circuits. The latter is composed of electronic ICs (EICs) and a loop filter. Injected single comb line as a MO and sampled-grating distributed Bragg reflector (SG-DBR) as a LO in a PIC oscillate at different frequencies, producing a RF beatnote at this offset frequency on the balanced photodetector pair. The beat signal is then amplified by the limiting amplifier (LIA) to make the system insensitive to intensity fluctuation from the PIC. A phase detector (logic XOR gate in this case) compares the phase of the beat signal with a reference signal from a tunable RF synthesizer, thus generating the baseband phase error signal. This is then fed back through the loop filter to control the LO laser's phase and hence lock the phase of the LO to a single comb line.

The heterodyne OPLL board was assembled by soldering both PIC and EIC on top of the AlN carriers. The loop filter as a part of the feedback electronic circuits was also built on the same carrier using discreet components and an operational amplifier. The PIC, EIC, and loop filter were placed together closely using wirebonds. The carriers were carefully designed to decrease the loop delay as much as possible. A photograph of such an OPLL system and its zoomed-in version are shown in Fig. 2(a) and (b), respectively. The experimental setup is shown in Fig. 2(c). Using lensed fibers, the microresonator comb output was coupled into the PIC for offset locking. The SG-DBR laser was coupled out from the back mirror to beat with the comb off-chip for verifying phase-locking.

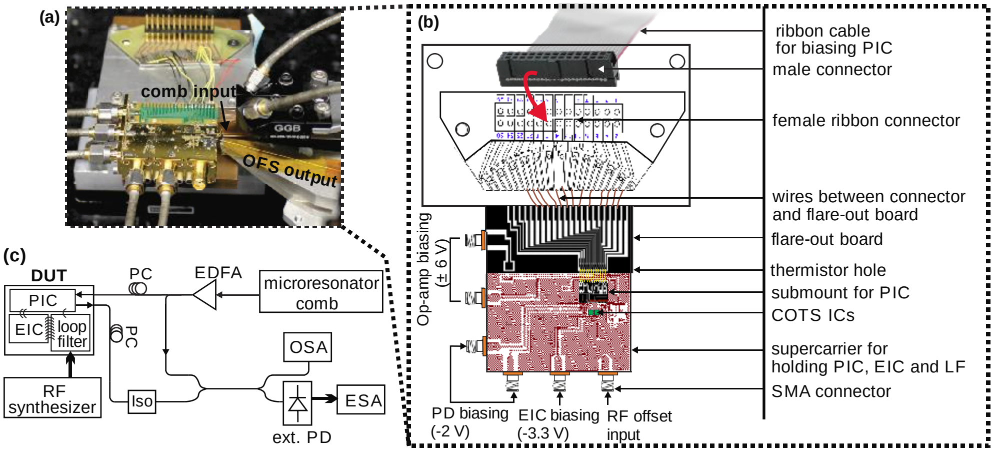

Fig. 2. (a) A photograph of the OPLL system, and its (b) zoomed-in version (lensed fibers and XYZ stages are not shown), and (c) the schematic of the test setup for monitoring the performance of the optical frequency synthesizer. Thinner lines show fiber connection and thicker lines show the RF cable connection. (ESA: electrical spectrum analyzer, EDFA: erbium doped fiber amplifier, OSA: optical spectrum analyzer, PC: polarization controller, ext. PD: external photodetector, iso: isolator)

We successfully phase-locked the SG-DBR laser to the optical frequency comb (OFC) using our heterodyne OPLL system. Under this locked condition, the superimposed optical spectra of comb output and laser are shown in Fig. 3(a) where the wavelength difference between comb peak and the nearest SG-DBR laser peak is 0.02 nm. The RF spectra of the beatnote at an offset frequency of 2.5 GHz, in cases of free-running and phase-locked, are shown in Fig. 3(b). In the locked case, the RF linewidth is reduced significantly, indicating the improved relative spectral coherence between the LO laser and the comb. Figure 3(c) shows the RF spectrum acquired with a higher span. Thus the on-chip SG-DBR laser is offset-locked across multiple comb lines by changing the current in mirror and phase sections of the SG-DBR laser and by applying the right RF offset frequency. Synthesizing an arbitrary optical frequency between two adjacent comb lines is achieved by tuning the RF offset source and the phase section current. In other words, an arbitrary optical frequency synthesis in the range from 1543 nm to 1568 nm (mainly limited by the output power level of the comb) is demonstrated using our presented OFS. Frequency switching of the on-chip laser to a point more than two dozen comb lines away (~5.6 nm) and simultaneous locking to the corresponding nearest comb line is also achieved in a time of ~200 ns. The synthesizer's performance characteristics relating to frequency switching and tuning resolution will be shown at the conference.

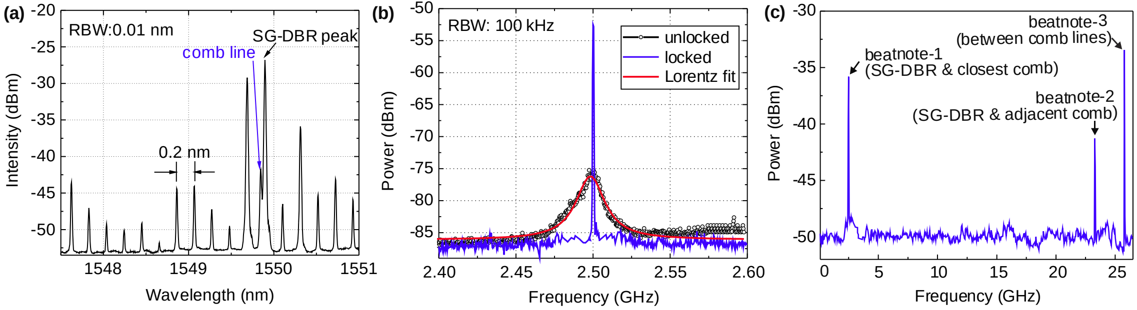

Fig. 3. (a) Optical spectra of comb at 1549.848 nm and LO laser when offset-locked to the comb, (b) the corresponding RF spectra, showing the measured linewidth of the free-running SG-DBR (LO) laser and phase-locked SG-DBR laser, and (c) RF spectrum of the locked beatnote between LO laser and comb at 2.5 GHz acquired with a higher span. The beatnote generated between LO laser and adjacent comb line at 23.2 GHz and the beatnote produced between comb lines at 25.7 GHz are also visible. The resolution bandwidth is 3 MHz.

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