Optical Frequency Synthesis by Offset-Locking the Tunable Local-Oscillator of a Low-Power Integrated Receiver to a Microresonator Comb

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Abstract: *A power-efficient and highly-integrated photonic system, producing low phase-noise coherent optical signal with a wavelength range of 23 nm in the C-band, is presented. The system includes novel InP-photonic integrated coherent receiver circuits that consume record-low (approximately 184 mW) electrical power.*

Keywords: Photonic integrated circuits, heterodyne, microcavities, resonators.

Recently, highly-integrated optical phase-locked loops (OPLLs) have been demonstrated for a number of potential applications including coherent optical communications, light detection and ranging (LiDAR) and frequency metrology [1]. Another particularly interesting application is an optical frequency synthesis (OFS) for which OPLL-based offset locking is recently considered to be one of the most attractive techniques. There have been extensive ongoing research efforts to develop low-cost, compact, robust and power-efficient OFS systems using this OPLL-based technology.

Such OFS systems based on a heterodyne-OPLL technique have been demonstrated by numerous research groups [2-5]. On the way towards achieving chip-scale and highly power-efficient OFS systems, the goal is to keep the total power consumption of the entire system at a watt-level. Given the fact that photonic integrated circuits (PICs) with a widely-tunable local oscillator (LO) laser consumes most of the electrical power to realize heterodyne-OPLL within an OFS system, we report on the development of a compact and low-power coherent receiver PIC and its use in OPLLs for frequency synthesis in this work.

A microscope image of the processed InP-chip with a dimension of 1.9 mm × 0.8 mm is shown in Fig. 1(a). InP-based PICs include a Y-branch laser with a tuning range of over 60 nm, a 2 × 2 MMI coupler, a pair of photodetectors (PDs) and input waveguide for coupling light from the reference source. Microresonator-based optical frequency comb (OFC), serving as a master oscillator (MO) which our LO laser within PICs to be phase-locked to, was utilized in this study. InP-PICs have a short gain section for the laser, with no semiconductor optical amplifiers is incorporated, allowing low

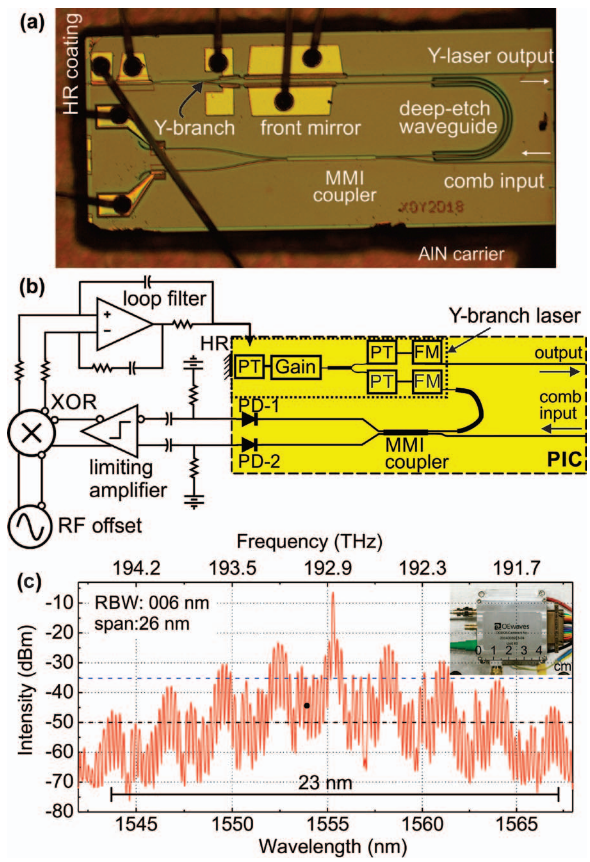

Fig. 1: a) A microscope image of the fully-processed InP-based photonic integrated receiver circuit, b) schematic diagram of the heterodyne OPLL, and c) optical spectrum of the Kerr frequency comb with a span of 23 nm.

power consumption. It only consumes ~184 mW of electrical power for its full operation. Commercial-off-the-shelf (COTS) electronics were employed to construct the OPLL system for offset locking. The system was assembled by closely connecting the InP-PIC, COTS electronic ICs and loop filter discrete components on an AlN carrier via wirebonding. The photonic receiver generates the mixed output of LO and MO signals and produces an error signal fed into the electronic circuits that tune the phase of the LO in order to match that of the MO, as schematically illustrated by the system architecture in Fig. 1(b). Overall, our heterodyne OPLL consumes 1.3 Watts of electrical power and it can offset lock up to 17.4 GHz offset frequencies [6].

Fig. 1(c) shows the optical spectrum of a stabilized Kerr frequency combs generated from a packaged and fiber-pigtailed unit developed in this study. The optical output comb power exiting the fiber obtained after subtracting from the pump laser power is 100 μW, meaning only ~0.5 μW per comb line (black dashed line) is accumulated in the wavelength range of 1542 nm-1568 nm. The comb spans 23 nm defined as the spectral region in which the frequency-comb envelope power exceeds -50 dBm (blue dashed line). It has a line spacing of 0.2 nm, yielding more than 115 lines. Considering the power consumption of the OFC unit, the OFS system consumes only 1.7 Watts, which is a major milestone towards achieving watt-level and chip-scale optical frequency synthesis. Details of the OFC's spectral characteristics will be presented at the conference.

The test setup is shown in Fig. 2(a). The comb output from the OFC unit was optically amplified by an erbium-doped fiber amplifier (EDFA) and finally coupled into the input waveguide of the PIC using a tapered lensed fiber. The Y-branch laser output through the front mirror at the right side of the PIC was outcoupled using a similar lensed fiber. An optical isolator was used at the laser output to reduce back reflections. To measure the OPLL tone, the output from the LO laser was mixed with the comb in an off-chip 2 × 2 coupler, detected via an external high-speed PD, and measured on the electrical spectrum analyzer (ESA). The other output of this coupler was connected to the optical spectrum analyzer (OSA) to measure the optical spectra of Y-branch laser and the comb output. A signal with a frequency equal to the beatnote frequency as a frequency offset was applied from the RF synthesizer to the XOR gate within the EIC.

After offset-phase locking the on-chip LO laser to a comb line, the LO laser `clones' the optical linewidth of the OFC which results in spectrally-pure optical output from the LO laser. Despite the Y-branch LO lasers has a quasi-continuous tuning range of 60 nm, any arbitrary optical frequencies with a spectral width of only 23 nm, limited by the comb span, can be generated by tuning the emission wavelength of our tunable LO laser.

The superimposed optical spectra of the Y-branch laser and the comb are shown in Fig. 2(b). The offset-phase locking of our LO laser to one of the comb lines is achieved with a wavelength separation of 0.046 nm. This is evidenced by the RF beating tone with an offset frequency is at 5.6 GHz measured by the ESA at the resolution bandwidth (RBW) of 3 MHz, as shown in Fig. 2(c). The beat-tone at 20.1 GHz generated between the locked Y-laser and the adjacent comb line is recorded. Also, the RF beatnote produced between the comb lines is observed at 25.7 GHz, as indicated in Fig. 2(c). The free running laser has 12 MHz instantaneous linewidth, whereas the relative linewidth of the locked beatnote is less than 100 Hz, revealing excellent relative spectral coherence between the on-chip LO laser and comb. More results relating to offset-locking as well as the purity of the OPLL beatnote will be shown at the conference.

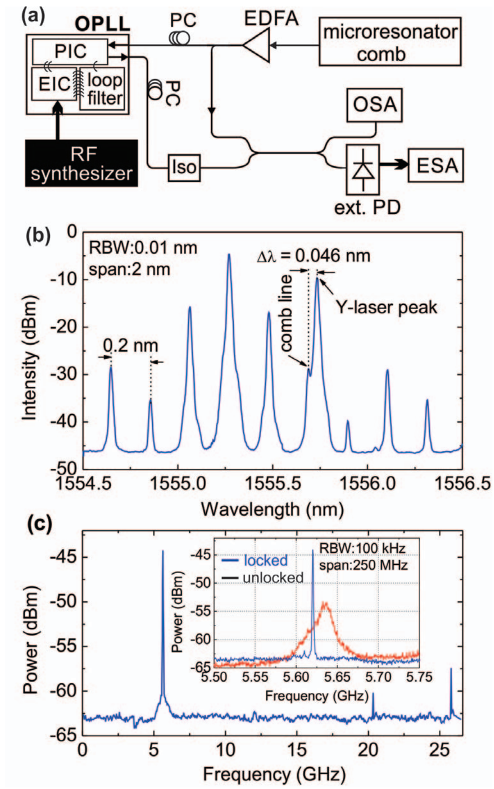

Fig. 2: (a) The test setup of the heterodyne OPLL system, (b) optical spectrum when Y-branch laser is offset-locked to the comb with a wavelength difference of 0.046 nm, and (c) RF spectrum of the locked beatnote at 5.6 GHz. RF spectra of the free-running and phase-locked Y-laser is shown as inset. (PC: polarization controller, iso: isolator and ext. PD: external photodiode, LIA: limiting amplifier)

This work was supported by DARPA-MTO under the DODOS Project, and National Science Foundation under Grant No. 1402935. A portion of this work was carried out in the UCSB nanofabrication facility, part of the NSF funded NNIN network.

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