Optical Synthesis Using Kerr Frequency Combs

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***Abstract*— An InP-based photonic integrated circuit was demonstrated for offset locking an on-chip broadly tunable laser to a heterogeneously integrated optical frequency comb oscillator based on a crystalline whispering gallery mode resonator. The optical tuning within 60nm band is demonstrated. The locked laser has excellent spectral purity, sub-kHz linewidth, and good frequency stability.**

Keywords*— photonic integrated circuits, integrated optics, optical phase-locked loop, heterodyne, optical frequency comb, optical microresonator, whispering gallery mode, self-injection locked semiconductor laser

I. INTRODUCTION

Synthesizers are key capabilities in time and frequency applications. The advent of optical techniques in these fields has made a number of important capabilities possible, so optical synthesis, required in optical frequency control, is under intense development in several laboratories around the world. Many coherent optical systems can be realized by using optical phase-locked loops (OPLLs), a key element of optical synthesis, as the key building blocks. These include optical atomic clocks, light detection and ranging (LIDAR), fiber sensing, optical tomography and terahertz wave generation. High-performance, low-power and compact photonic integrated circuits (PICs) are needed to support these technologies. PIC-based OPLLs were actively studied recently [1,2]. The demonstrated PICs consumed as high as ≥0.5 W [3] of power and their footprint exceeded 2.3 mm^2 [4]. An improvement of these parameters is needed in designing compact and low-power systems.

We here report on a compact, low-power coherent optical system involving a 60-nm-tunable LO laser, couplers and photodetectors integrated monolithically, as well as an integrated Kerr optical frequency comb (OFC) generator operating as a frequency reference. The heterodyne OPLL transfers the phase noise of a reference frequency comb to the generally noisy LO laser, within the loop bandwidth. Therefore, having an excellent LO is a prerequisite of success in realization of a high performance OPLL. We demonstrate the offset locking of the on-chip Y-branch laser to the OFC unit, making it an important step forward towards an eventual demonstration of a chip-scale, low-power, ultra-stable optical frequency synthesizer.

We found that the geometrical size and the electrical power consumption for the PICs can be improved significantly by a careful design [5]. The inherent advantages of chip integration can be enhanced in this way, and the system can be made much smaller. This is attractive since the small-sized PICs enable a short OPLL loop delay, which results in a larger loop bandwidth.

II. EXPERIMENT

Schematic of the experimental setup is shown in Fig. 1. It included two separate integrated components: an optical receiver chip and a frequency comb.

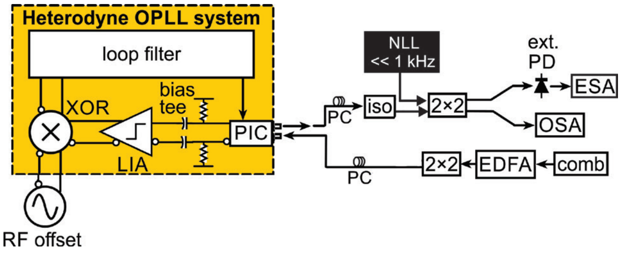

Figure 1: Experimental setup. The heterodyne OPLL system monitors the performance of the Y-branch laser. (ESA: electrical spectrum analyzer, OSA: optical spectrum analyzer, PC: polarization controller, iso: isolator and ext. PD: external photodiode, and EDFA: erbium-doped fiber amplifier, LIA: limiting amplifier, PIC: photonic integrated circuit

A. Broadly tunable laser and the receiver

The Y-branch laser in the full back-end PIC has a three times smaller cavity compared to standard sampled-grating distributed Bragg reflector. With short gain and mirror sections as well as a highly-reflecting back cleaved/HR-coated mirror, the device requires low current, and therefore lower drive power. The short cavity design was made by shortening the gain section and introducing zero-length back mirror through high-reflection coating, replacing the standard long back mirror. The emission wavelength is tuned via Vernier effect and was designed for high efficiency at 30º C ambient. The tuning range of the laser is measured to be 60 nm without changing the temperature, covering the entire C-band of optical communication. The laser shows good single-mode working

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performance with a side-mode suppression ratio of > 45 dB across the whole tuning range. No long absorber section or integrated booster preamplifier was included in this design so that the power consumption and chip-size could be reduced further. The output and input waveguide cleaved facets were coated with anti-reflection coating to suppress parasitic reflection. The laser is integrated into the receiver depicted in Figure 2.

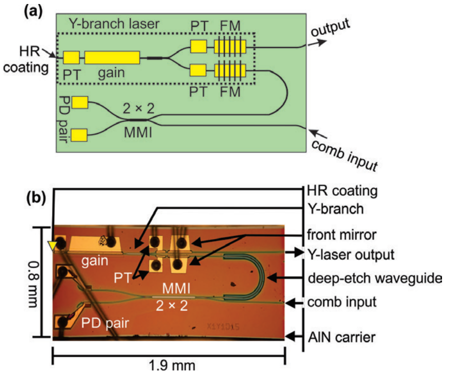

Figure 2: (a) Functional schematic of the photonic integrated receiver circuit composed of a Y-branch laser, two MMI couplers, and a balanced photodetector pair, (b) microscope image of the PIC mounted on a separate aluminium-nitride (AlN) carrier and wirebonded. (HR: high reflection, MMI: multimode interference, PT: phase tuner, FM: front mirror, PD: photodetector), (c) Schematic of the Kerr frequency comb generator.

B. Kerr frequency comb oscillator

W used an OFC generator consisting of a semiconductor laser pumping a crystalline MgF_2 resonator with a mode spacing of 25.5 GHz. The unit was packaged in a 12 cc form factor and its fiber-coupled output was sent to an optical spectrum analyzer (OSA). The measured optical spectrum with a 50-dB span of 23nm is shown in Fig. 3(a). The strongest central line at 1555.27nm originates from residual light from the pump laser. The RF signal generated by beat frequency of the comb lines on a fast PD integrated in the packaged unit was measured to distinguish between chaotic and coherent regimes of the frequency comb. An exceptionally high spectrally pure RF line with the coherent comb was observed. The 3-dB width of the RF beat tone at 25.7 GHz is <100 Hz, limited by the resolution bandwidth (RBW) of the electronic spectrum analyzer, ESA. The phase noise of the repetition rate of the OFC, as well as the pump light, is shown at Fig. 3d.

Depending on the initial conditions, the OFC unit produces frequency combs varying in shape. The variations can be linked to the generation of different number of optical pulses within the WGMR. While all the realized solutions are intrinsically stable and suitable for LO stabilization, the solution corresponding to the single pulse localized in the resonator is advantageous as it does not have any envelope structure. Changing of the power of the comb lines makes the offset locking to some of the modes of the OFC a hard task. We tried to utilize the frequency combs with the smoothest envelope.

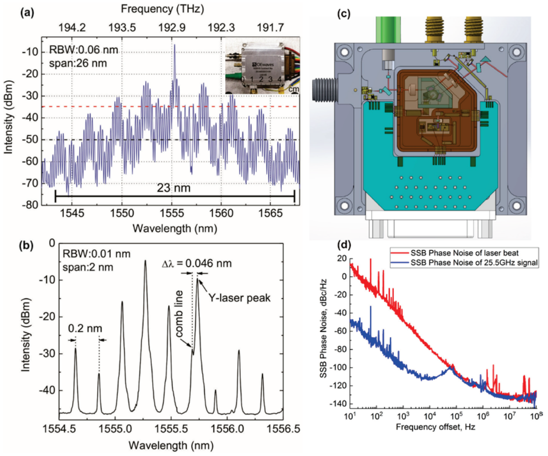

Figure 3: (a) Optical spectrum of a stabilized Kerr frequency comb generated in the unit, as shown as inset. The comb spans 23 nm defined as the width where the intensity ≥ -50 dBm (black dotted line) and has a line spacing of 0.2 nm, yielding more than 115 lines. The optical output comb power exiting the fiber is 100 μW obtained after subtracting from the pump laser power, meaning only ~0.5 μW per comb line is achieved in the wavelength range of 1542 nm-1568 nm. The horizontal (red) dashed line denotes the 0.5 μW per comb line power level, and (b) optical spectrum when Y-branch laser is offset--locked to the comb at 1555.69 nm with a wavelength difference of 0.046 nm. (c) Schematic of the frequency comb unit. (d) Single sideband phase noise of the laser and the comb repetition rate of the comb unit. The laser phase noise is measured by beating the laser with a similar device at a fast photodiode.

III. CONCLUSION

A miniature and low power photonic coherent synthesizer with an integrated broadly tunable laser and an integrated Kerr frequency comb oscillator are developed and utilized. Low noise optical lines could be produced by tuning the laser across the comb span and locking it to any of the comb lines. In this way, the higher power laser reproduced the characteristic noise of the comb. The demonstrated PIC synthesizer is promising for reduction of the total power consumption to watt-level in a highly integrated package.

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