

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. 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 applications possible, so optical synthesis supporting optical frequency control is under intense development in several laboratories around the world. Many coherent optical systems can be realized by using optical phase lock loops (OPLLs) as key elements of optical synthesis. These include optical atomic clocks, light detection and ranging (LiDAR), fiber optic sensing, optical tomography and terahertz wave generation. High-performance, low-power and compact photonic integrated circuits (PICs) -based OPLLs are important for enabling these applications and have been actively studied recently [1,2]. These demonstrated PICs consumed as high as ≥ 0.5 W [3] of power and their footprint exceeded 2.3 mm^2 [4]. Further improvement of these parameters is needed in designing compact and low-power systems.

In this paper we report on an experimental realization of an OPLL-based optical synthesizer. The device includes a compact, low-power coherent optical system involving a 60-nm-tunable LO laser, couplers and photodetectors monolithically integrated on a standard InP/InGaAsP material platform, 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 for success in realization of a high performance

OPLL. We demonstrate the offset locking of an on-chip Y-branch laser to the OFC unit, making this an important step forward towards the future 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 with a careful design [5,6]. 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.

To create the optical synthesizer we utilized an OPLL involving commercial-off-the-shelf parts. This loop required usage of an optical amplifier to achieve locking to low power frequency comb lines. To show that the entire system can be placed on a chip we designed an OPLL with a trans-impedance amplifier (TIA) increasing the sensitivity of the system significantly. No optical amplification is needed when TIAs provides high electrical gain with minimal noise.

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.

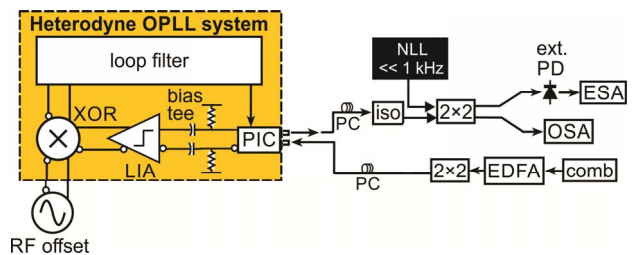


Figure 1: Experimental setup. The heterodyne OPLL system monitors the performance of the Y-branch laser. (ESA: electrical spectrum analyzer, OSA: optical spectrum analyzer, PC: polarization controller, iso: isolator and ext. PD: external photodiode, and EDFA: erbium-doped fiber amplifier, LIA: limiting 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 reflective 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 30° 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 performance with a side-mode suppression ratio of > 45 dB across the entire 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.

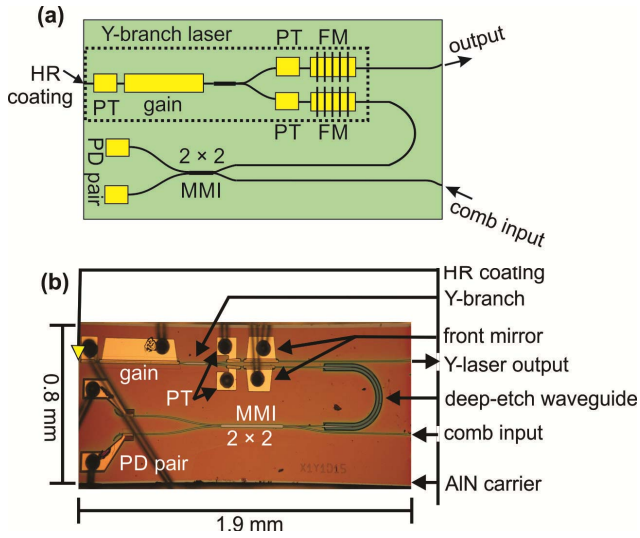


Figure 2: (a) Functional schematic of the photonic integrated receiver circuit composed of a Y-branch laser, two MMI couplers, and a balanced photodetector pair, (b) microscope image of the PIC mounted on a separate aluminium-nitride (AlN) carrier and wirebonded. (HR: high reflection, MMI: multimode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

B. Kerr frequency comb oscillator

We used an OFC generator consisting of a semiconductor laser pumping a crystalline MgF₂ 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 is the residual light from the pump laser. The RF signal generated by the 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 was observed. The 3-dB bandwidth 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 (see Fig. 4). The variations can be linked to the 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 difficult task. We utilized the frequency combs with the smoothest envelope.

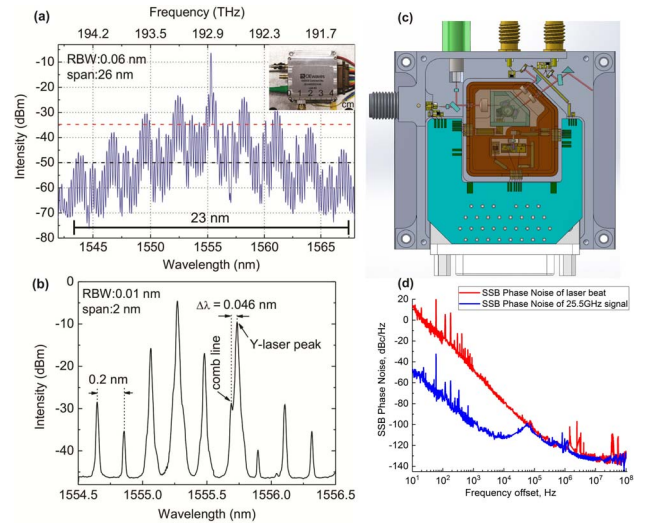


Figure 3: (a) Optical spectrum of a stabilized Kerr frequency comb generated by the OFC generator, as shown as inset. The comb spans 23 nm defined as the width where the intensity ≥ -50 dBm (black dotted line) and has a line spacing of 0.2 nm, yielding more than 115 lines. The optical output comb power exiting the fiber is 100 μ W obtained after subtracting the pump laser power, meaning only ~ 0.5 μ W per comb line is achieved in the wavelength range of 1542 nm-1568 nm. The horizontal (red) dashed line denotes the 0.5 μ W 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.

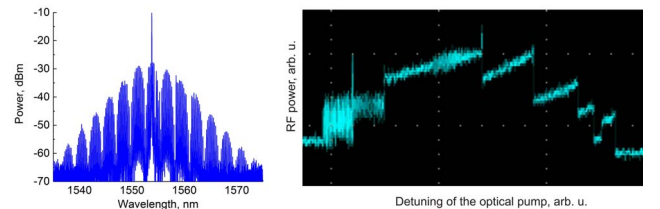


Figure 4: Illustration of the multi-stability of the Kerr frequency comb (compare with the spectrum in Fig. 3a). Left: Another type of Kerr comb frequency spectrum emitted by the oscillator. Right: An oscilloscope trace illustrating the RF power generated by the frequency combs emitted by the oscillator on a fast photodiode. The observed power jumps correspond to different comb regimes.

C. Heterodyne OPLL System

In the OPLL system reported here, a SiGe based commercial-off-the-shelf (COTS) limiting amplifier with 30-dB differential gain was used (Fig. 5). This gain is equal to 31.6 in linear units, indicating that offset phase-locking can be achieved using error signals with a peak to peak magnitude of approximately 10 mV. This corresponds to 0.2 mA required beat current in 50 Ω common mode logic system. In fact, this beat current is produced by beating optical comb-line power of 10 μ W with the given 1 mW LO power. Please note that the responsivity of the on-chip PDs is assumed to be 1 A/W. The beat current I_{beat} can be calculated by the following expression:

$$I_{beat} = 2\sqrt{I_{REF}I_{LO}}$$

$$I_{beat} = 2\sqrt{0.01(mA)\times 1(mA)}$$

$$I_{beat} = 0.2mA$$

where, I_{REF} and I_{LO} are the photocurrents in the on-chip PD resulting from the optical power of the reference comb line and on-chip LO, respectively.

Hence, the minimum input optical comb line power required for the offset locking is experimentally measured to be about 10 μ W.

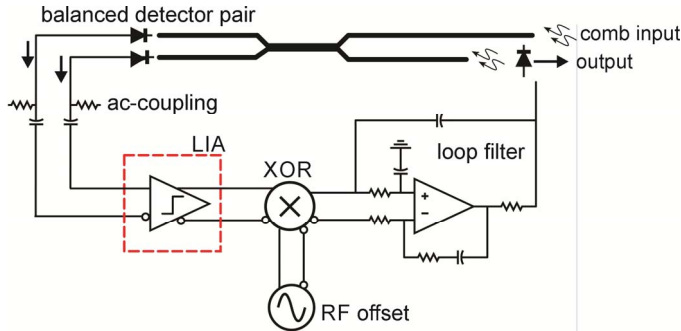


Figure 5: Schematic of the OPLL utilized in the optical synthesizer.

D. OPLL with improved sensitivity

Since the comb output power is not high for offset locking, an amplifier (the EDFA) is necessary to obtain adequate optical power levels in our presented OFS (see Fig. 1). For a fully chip-scale OFS, however, it is important to eliminate the EDFA and replace it with an on-chip semiconductor optical amplifiers. Furthermore, there is also an alternative way by which we could get rid of the EDFA. Instead of amplifying the power in the optical domain, we can increase the sensitivity of our electronic ICs so that the weak error signal generated by beating of the on-chip laser and low-power comb line on the balanced photodiodes can be handled by the feedback electronics. Specifically, the sensitivity of our OPLL system will be increased by using high-gain amplifiers with low noise figure so that on-chip lasers can be phase locked to a comb line without an EDFA. This also helps in reducing the OFS system power consumption further.

For this, we have designed a TIA with low noise, high gain and wide bandwidth using 130 nm SiGe HBT process (Fig. 6). This chip is designed for 80 dB voltage gain and 120 dB Ω transimpedance gain with 30GHz bandwidth. It has less than 10 pA/Hz^{1/2} input referred noise current up to 20 GHz with respect to 50 fF photodiode capacitance. These are the features that makes this application specific IC suitable for the frequency synthesis system.

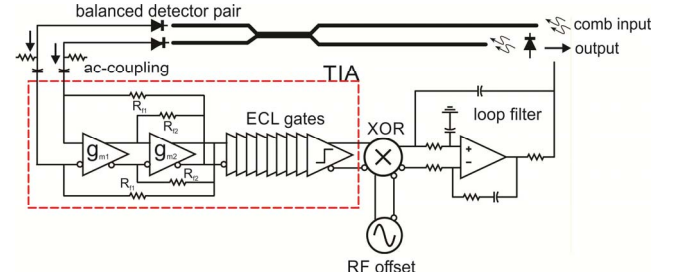


Figure 6: Schematic of the sensitive OPLL with low noise transimpedance amplifier.

As mentioned previously, each single harmonic of the optical frequency comb has only 0.5 μ W of power. After considering the fiber coupling loss of 6 dB and optical power splitting by 2 x 2 MMI, the on-chip comb power available for beating is about 60 nW, whereas the local oscillator's power is about 1 mW. Given the responsivity of the on-chip PDs is 1 A/W, the beat current resulting from between on-chip-laser and one of the comb lines is approximately 15 μ A in each PD, as shown in the following:

$$I_{beat} = 2\sqrt{I_{LO}I_{REF}}$$

$$I_{beat} = 2\sqrt{60(nA)\times 1(mA)}$$

$$I_{beat} = 15\mu A$$

This current needs to be amplified by the TIA and produce a logic output of 300 mV, which will drive the digital XOR gate. Thus, TIA should have at least the following gain.

$$Gain = \frac{300mV}{15\mu A} = 20k\Omega$$

$$Gain(dB\Omega) = 20 \log_{10} 20000 = 86$$

Our TIA has more than enough gain to lock the local oscillator to the optical frequency comb lines. Functional test of the TIA demonstrates 60 dB differential gain, with a proper DC restoration loop this gain can be as high as 80 dB as simulated.

This sensitivity can be improved to as low as 60 nW using the novel TIA design discussed here. When this is achieved, EDFA is no longer needed and the OFS system total power consumption will be much lower as well as it will be more compact and will be closer to a true chip scale OFS system with much less than 2 Watts of power consumption. Implementation of the compact structure is our current goal.

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. Low noise optical tone is produced on demand by tuning the laser across the comb span and phase locking it to any of the comb lines. In this way, the higher power laser reproduces the high spectral purity of the frequency 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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