A Highly-Integrated Optical Frequency Synthesizer Based on Phase-locked Loops

Mingzhi Lu[1], Hyun-Chul Park[1], Eli Bloch[2], Leif A. Johansson[1], Mark J. Rodwell[1], and Larry A. Coldren[1,3]

[1]*Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA, 93106, USA.*
[2]*Department of Electrical Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel.*
[3]*Department of Materials, University of California, Santa Barbara, CA, 93106, USA.*
mlu@ece.ucsb.edu

Abstract: The first highly-integrated optical synthesizer is realized by photonic integration and optical phase-locking technique. Preliminary results show >160 GHz output frequency range and a relative frequency accuracy as defined by the RF signal.
OCIS codes: (250.5300) Photonic integrated circuits; (060.2840) Heterodyne; Optical phase-locked loop; optical frequency synthesis

Frequency synthesis is widely used in many electronic systems. By using a synthesizer, arbitrary RF frequencies that are coherent to a single reference signal are generated. High frequency RF signals are therefore obtained with a similar phase noise to that of a crystal oscillator or other low noise sources. The coherent RF tone generated by RF synthesis enables RF signal up/down-conversion and coherent detection, and is the core technology for numerous applications, including radio receivers, mobile telephones, satellite receivers, GPS systems, radar, etc. Although RF frequency synthesizers are widely used commercially, its counterpart, an optical synthesizer is far from mature. In this paper, the first highly-integrated optical frequency synthesizer is proposed and demonstrated.

For a typical RF synthesizer architecture, a phase-locked loop (PLL) is usually the key element. Frequency dividers and multiplexers in the PLLs are key components for generating a signal with a different frequency from the reference. However, in the optical domain, efficient and integrated frequency dividers and multiplexers are not available. Moreover, the demanded frequency range is relatively small compared to the absolute optical frequency. Using dividers and multiplexers for optical synthesis is not realistic. In this work, the first integrated optical frequency synthesizer is achieved by phase-locking a tunable CW laser to an optical comb, which is generated from a narrow linewidth reference laser [1][2].

The basic idea of this integrated synthesizer is explained in Fig. 1 [1]. The continuous-wave laser A is a single fixed-wavelength narrow-linewidth laser, which is used as the reference laser in this system. Stable and narrow-linewidth comb lines are then generated from this fixed-wavelength laser through modulators. The comb lines are then used as the reference for the heterodyne optical phase-locked loop (OPLL). A RF frequency f_{RF2} is applied on the electronic IC (EIC) of the OPLL to introduce a frequency offset, which is $f_{RF2}/2$ [3]. By tuning the slave laser mirror and phase section currents as well as f_{RF2}, the slave laser can phase-lock the frequency of $f_i \pm f_{RF2}/2$, where i=1,2,3,4… As long as the heterodyne OPLL offset frequency range is larger than half of the comb line spacing, the optical synthesizer can cover all the frequencies within the comb range. Moreover, the SG-DBR linewidth will be the same as CW laser A, because of the linewidth 'cloning' of OPLL [4]. Importantly, switching between frequencies can be achieved much more quickly and accurately (Hz-level) than with freely-running tunable lasers, and thermal effects over a few degrees are not an issue, because of the rapid (submicrosecond or even nanosecond) phase locking.

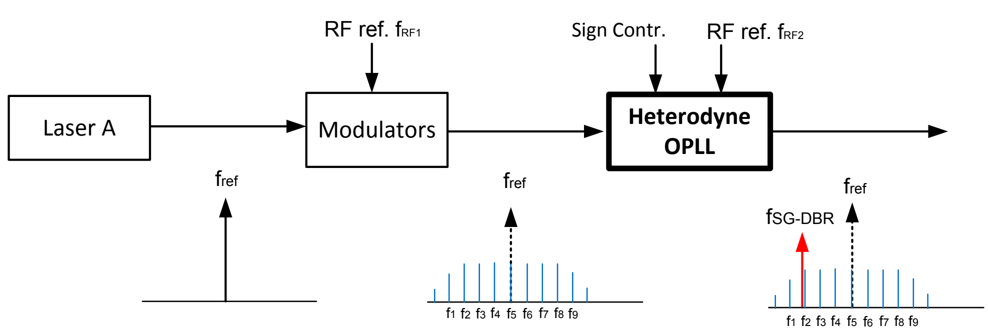

Fig. 1. The architecture of the optical frequency synthesizer.

The key building block of this system, the heterodyne OPLL [5], has the structure shown in Fig. 2, including three parts: a photonic IC (PIC), an EIC and a loop filter built of discrete components. The PIC is based on the InGaAsP/InP integration platform, and it is composed of a widely-tunable sampled-grating DBR (SG-DBR) laser, a star-coupler-based 90-degree hybrid, four high-speed uni-travelling-carrier (UTC) photodetectors, and transmission lines [6]. The SG-DBR laser covers a 40 nm spectral range, and the UTC photodetectors have a 35 GHz 3-dB RF bandwidth. The EIC is based on Teledyne's 500-nm InP HBT technology, and has a working frequency higher than 50 GHz. TIAs, a single-sideband mixer (SSBM) and a phase/frequency detector are integrated. The details of this EIC can be found in [3]. The loop filter electronics ensures the loop property. In this case, a dual-path type II loop is used. The size of the whole OPLL system is ~ 10x10 mm^2. The designed loop bandwidth is ~ 500 MHz.

The details of test setup are shown in Fig. 3. First, an optical comb is generated from the reference laser by applying modulations using a phase modulator (PM) and a Mach-Zehnder modulator (MZM), both of which are driven by 40 GHz RF signals that are generated from active frequency doublers. The output of the MZI is amplified by an Erbium-doped fiber amplifier (EDFA), and then propagated through a long fiber where the comb is flattened due to nonlinear effects. An optical filter with a 2.4-nm FWHM bandwidth is used to filter out the amplified spontaneous emission (ASE) noise. The comb is then coupled into the PIC as the reference for the OPLL as shown in Fig. 3.

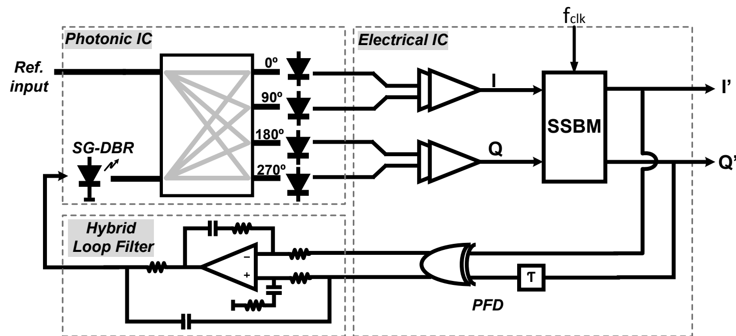

Fig. 2. The architecture of the heterodyne OPLL.

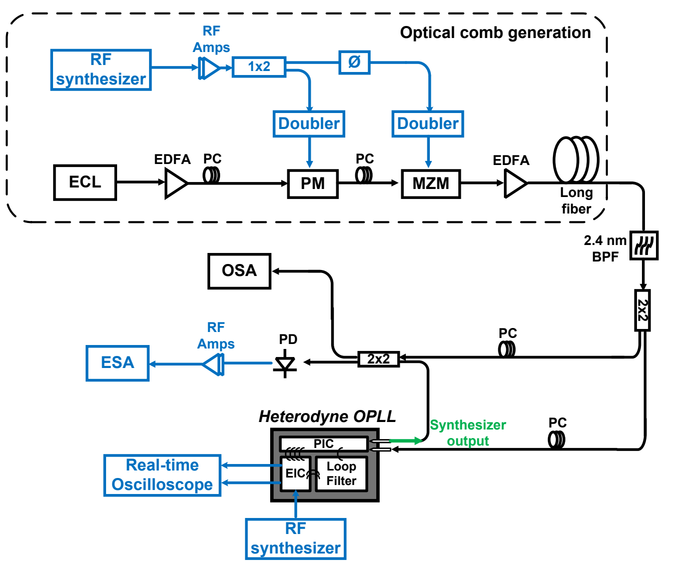

Fig. 3. The test setup of the optical synthesizer. The blue lines indicate RF connection, and the black lines are optical fiber connections. (ECL: external cavity laser, ESA: electrical spectrum analyzer, OSA: optical spectrum analyzer.)

The measurement indicates a 25 GHz offset locking range of the heterodyne OPLL, which means that this optical synthesizer can cover the whole frequency spectrum within the comb range as long as the line spacing is no larger than 50 GHz. A 40 GHz comb spacing is chosen in this case.

We have successfully phase locked the SG-DBR laser to the comb lines. Fig 4(a) shows the optical spectra when the SG-DBR laser locks to two of the comb lines, respectively, with a 10 GHz offset. The electrical spectra are shown in Fig. 4(b) & (c) as well. As we can see, the RF beating tones show that the offset frequency is exactly 10 GHz, which is +90 GHz and -70 GHz from the reference laser frequency. That is, >160 GHz range is covered. The narrowness of the RF tones on the ESA also verifies the coherence between the SG-DBR laser and the reference laser. To the best of our knowledge, this is the first time that a prototype of a real optical synthesizer has been demonstrated.

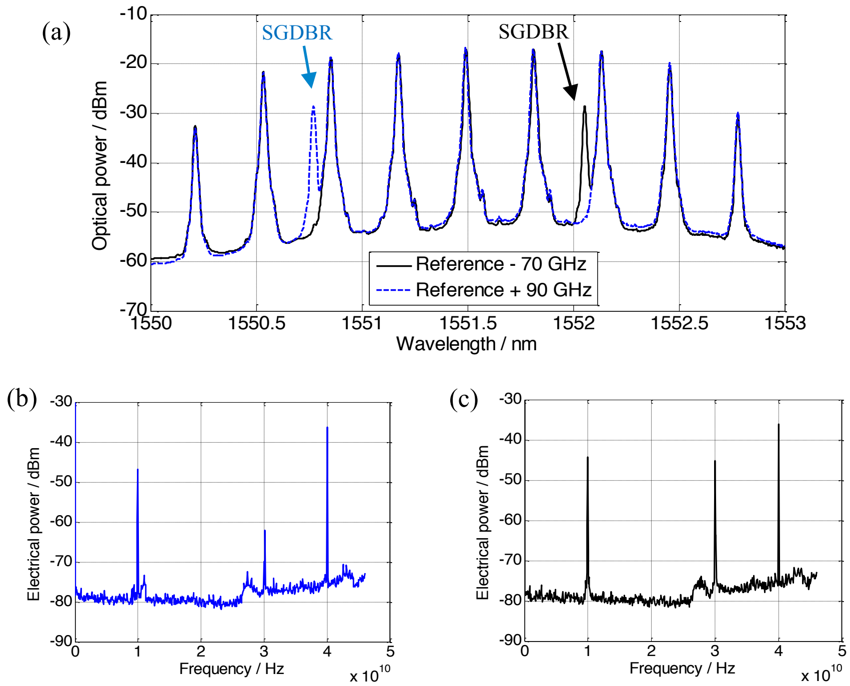

Fig. 4. Optical synthesizer measruement results. (a) optical spectra when the output is +90 and -70 GHz off the reference wavelength. The RBW is 0.01 nm. (b) and (c) RF spectra when the output is +90 and -70 GHz, respectively, measured on the ESA shown in Fig. 3. The RBW is 100 kHz.

Acknowledgement

This work was mainly supported by the DARPA CIPhER—PICO project. A portion of this work was done in the UCSB nanofabrication facility, part of the National Science Foundation (NSF) funded NNIN network. The EIC is fabricated at Teledyne Scientific and Imaging Company.

Reference:

[1] M. Lu, H. Park, J. S. Parker E. Bloch, A. Sivananthan, Z. Griffith, L. A. Johansson, M. J. Rodwell, and L. A. Coldren, “A Heterodyne Optical Phase-locked Loop for Multiple Applications," Optical Fiber Communication Conference, OW3D.1, 2013.

[2] R. J. Steed, L. Ponnampalam, M. J. Fice, C. C. Renaud, D. C. Rogers, D. G. Moodie, G. D. Maxwell, I. F. Lealman, M. J. Robertson, L. Pavlovic, L. Naglic, M. Vidmar, A. J. Seeds, "Hybrid Integrated Optical Phase-Lock Loops for Photonic Terahertz Sources," Selected Topics in Quantum Electronics, IEEE Journal of , vol.17, no.1, 2011.

[3] E. Bloch, H. Park, M. Lu, T. Reed, Z. Griffith, L. A. Johansson, L. A. Coldren, D. Ritter, and M. J. Rodwell, “A 1-20 GHz All-Digital InP HBT Optical Wavelength Synthesis IC," Microwave Theory and Techniques, IEEE Transactions on, Vol. 61, No. 1, 2013.

[4] M. Lu, H. Park, E. Bloch, A. Sivananthan, J. S. Parker, Z. Griffith, L. A. Johansson, M. J. W. Rodwell, and L. A. Coldren, "An Integrated 40 Gbit/s Optical Costas Receiver," J. Lightwave Technol. 31, 2244-2253, 2013.

[5] M. Lu, H. Park, E. Bloch, A. Sivananthan, A. Bhardwaj, Z. Griffith, L. A. Johansson, M.J. Rodwell, and L.A. Coldren, “Highly integrated optical heterodyne phase-locked loop with phase/frequency detection,” Opt. Express 20, 9736-9741, 2012.

[6] M. Lu, H. Park, E. Bloch, A. Sivananthan, J. S. Parker, L. A. Johansson, M. J. W. Rodwell, and L. A. Coldren, “Monolithic Integration of a High-speed Widely-tunable Optical Coherent Receiver," Photonics Technology Letters, Vol. 25, No. 11 (2013)