

# Active photonic integrated filter for optical comb line selection

K. Balakier \*, H. Shams, M. J. Fice, L. Ponnampalam, C. S. Graham, C. C. Renaud and A. J. Seeds

Department of Electronic and Electrical Engineering,

University College London (UCL),

Torrington Place, London WC1E 7JE, United Kingdom

[\\*k.balakier@ucl.ac.uk](mailto:k.balakier@ucl.ac.uk)

**Abstract**—We report the first foundry-fabricated photonic integrated circuit (PIC) implemented as a high quality, tuneable, optical filter for optical frequency comb line selection and amplification. The PIC containing DBR lasers and photodiodes is integrated with low frequency electronics to create an optical phase lock loop (OPLL), which performs as highly selective optical filter with sub-GHz bandwidth and 50 dB out of band suppression. The OPLL output is a single tone coherent with the comb lines, whose optical power is higher than the reference line, and which can be offset from the reference line by an agile and precisely defined frequency.

**Keywords**—photonic integration circuit; microwave photonics; semiconductor tuneable lasers; optical phase lock loop; optical filtering.

## I. INTRODUCTION

The generation of broadly tuneable CW mm-wave and THz signal can be achieved by optical heterodyning of two optical tones which can be created by two independent lasers, one of which is tuneable [1]. This is a cost effective approach, however the spectral qualities of the mm-wave signal are poor and the frequency tends to drift in the range of 100 MHz/C. The frequency stability of the heterodyned signal can be improved if the lasers are monolithically integrated, but the spectral purity of the signal remains an issue. An alternative approach to high frequency synthesis relies on the selection of two optical lines out of an optical frequency comb which consists of multiple optical tones that are separated by 10-30 GHz and phase correlated. Highly selective and tuneable optical filters are required to isolate only two comb lines while suppressing all the others. Although the quality of the filters improves, the passband remains in the GHz-range level, the insertion loss is at least 6-10 dB, and the tuneability of some integrated photonic-based filters is limited [2]. A high loss through the optical filter may become a significant bottleneck, in particular if the peak power per comb line is low and a photodetector requires high optical power. To avoid the use of multiple amplification stages a laser locking technique can be implemented instead of passive optical filters. For instance, injection locking provides optical gain, however the homodyne nature of this technique limits the tenability of the mm-wave/THz signal if the comb line spacing is not agile [3]. The other approach to phase stabilize a laser in reference to one of the comb lines is the optical phase lock loop (OPLL) whose implementation as highly selective optical filter for comb line selection is demonstrated for the first time in this paper.

## II. OPTICAL PHASE LOCK LOOP

A heterodyne OPLL allows the phase and frequency of the semiconductor laser to be stabilized with reference to the incoming optical tone with an additional frequency offset defined by an external RF reference with Hz-level precision [4]. The OPLL presented in this paper consists of InP-based photonic integrated circuit (PIC) fabricated using a generic foundry process and off-the-shelf electronic components creating a negative feedback loop as presented schematically in Fig. 1a). The PIC contains distributed Bragg reflector (DBR) lasers, semiconductor optical amplifiers (SOA), PIN photodiodes (PIN-PD), and various optical interconnections integrated monolithically on the 2 mm x 6 mm chip area as seen on the photograph in Fig. 1b).

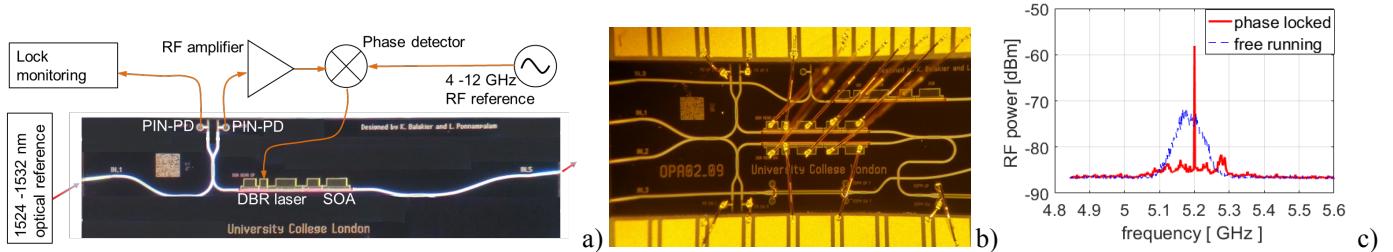


Figure 1 a) OPLL schematic, b) wirebonded PIC photograph c) electrical spectra of the free running and improved phase locked heterodyne signal generated by DBR and reference lasers on the PIN-PD integrated on the PIC.

The wavelength of the DBR laser can be tuned over an 8 nm range by adjusting the Bragg gratings current to match the wavelength of the selected optical comb line. Moreover, a short phase section (PS) of the laser is used to fine tune the laser operation point when the OPLL is in operation. The PS offers very fine tuning of the laser across 50 GHz with a tuning sensitivity

of up to 45 GHz/mA (depending on the phase section bias point). The laser operates in a single mode with a side-mode suppression ratio greater than 50 dB. Further, the DBR laser wavelength can be precisely controlled by adjusting the frequency of the RF reference synthesizer in the range from 4 GHz to 12 GHz.

The PIC contains PIN-PDs that have  $-6\text{dB}$  bandwidth at 12 GHz and responsivity of 0.8 A/W. The PIC-PDs are implemented as part of the feedback loop as well as, for the first time, to control the quality of locking between DBR laser and the comb line.

The OPLL chip was designed so that none of the optical input signals is present at the PIC output, which results in exceptional filtering capabilities of sub-GHz passband and suppression of noise and other comb lines by over 50 dB. Moreover, the loop electronic circuit is designed to allow phase locking to a single comb line with the frequency offset tuneable across 8 GHz. The quality of the phase locking is assessed based on the spectral purity of the heterodyne signal generated by the DBR laser and the comb line on the photodiode. Figure 1c) represents the improvement in the spectral characteristics (increased peak power, FWHM linewidth reduced to less than 10 Hz) of the heterodyne signal when the loop is in operation.

The output power coupled from the PIC into the lensed fiber was measured to be up to 0 dBm when the DBR laser gain section and the SOA were driven with 100 mA and 50 mA currents, respectively.

### III. TOWARDS INTEGRATED PHOTONIC-BASED THZ OSCILLATOR

The greatest advantage of photonics-based millimeter/THz-wave signal generation is the possibility to output the continuously tunable and low-phase-noise signals while using only relatively low-frequency electronic and photonic components. Compact solutions for optical frequency comb generation (OFCG) as well as broad-bandwidth photodiodes have been demonstrated and are being improved. Photonic integrated optical filters are also investigated but suffer from high insertion losses or limited tuneability due to periodic frequency response of ring-based filters [2]. Good quality free-space optical filters are commercially available and although insertion loss can be smaller than 10 dB, the  $-3\text{dB}$  bandwidth (BW) remains in the range of several GHz, resulting in several comb lines being passed through the filter. Filtering capabilities of the top-of-the-range wavelength selective switch filter (10 GHz BW, 6 dB loss) and ultra-selective filter (6 GHz BW, 11 GHz loss) are presented in Figure 2a). The OPLL can be implemented as high quality optical filter capable of noise and other comb lines suppression by over 50 dB (Figure 2b). Moreover, the greatest advantage of the OPLL is that it provides coherent optical gain of 6 dB and enables tuneable frequency offset from the original wavelength of the selected comb line, as indicated in Figure 2c). These characteristics can significantly improve the performance of the future photonic-based mm-wave / THz oscillator both in terms of signal purity and continued tuneability.

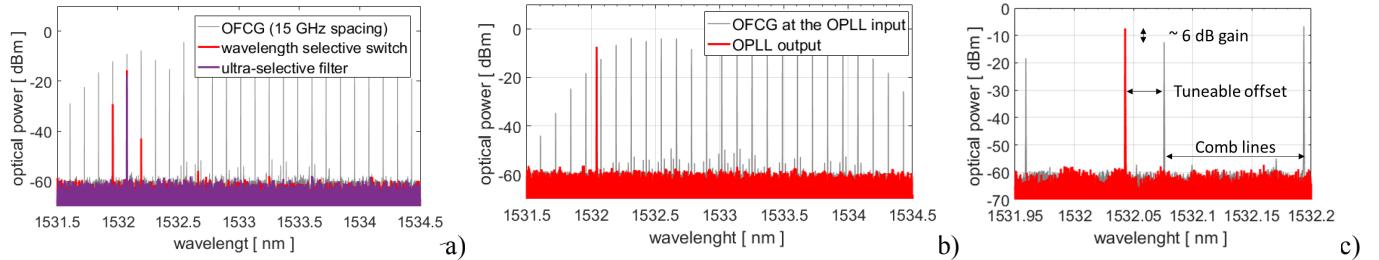


Figure 2 Optical spectra of the optical comb at the input to the optical filters and at the output of commercially available optical filters a) and optical filter based on the OPLL b) and c). Optical spectra were measured on high resolution (10 MHz) optical spectrum analyser.

The optical frequency comb used in this experiment has a free spectral range of 15 GHz. It was generated using a dual-drive MZM modulator followed by an Erbium doped fiber amplifier. The peak power of the line used as OPLL reference was  $-13\text{ dBm}$ .

### IV. CONCLUSIONS

In this work we present implementation of the OPLL as a comb line filter with sub-GHz optical bandwidth, suppression of noise and other comb lines of at least 50 dB, optical gain of 6 dB and continuous tuneability over 8 nm, and precisely defined (Hz-level) offset tuning from the reference line. This OPLL is based on low frequency electronic drive board and photonic circuits fabricated using generic foundry process, making it a compact, cost efficient, optical filter that could be integrated with other InP components. The OPLL has potential to become an important building block of future photonic-based mm-wave and THz oscillators.

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