Optical Phase Lock Loop as High-Quality Tuneable Filter for Optical Frequency Comb Line Selection

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(Invited Paper)

***Abstract*—This paper describes an optical phase lock loop (OPLL) implemented as an ultraselective optical frequency comb line filter. The OPLL is based on a photonic integrated circuit (PIC) fabricated for the first time through a generic foundry approach. The PIC contains a distributed Bragg reflector (DBR) laser whose frequency and phase are stabilized by reference to an optical frequency comb generator. The OPLL output is a single-mode DBR laser line; other comb lines and noise at the output of the OPLL filter are attenuated by >58 dB below the peak power of the OPLL-filter output line. The OPLL bandwidth is up to 200 MHz, giving a filter quality factor greater than 1,000,000. The DBR laser can be tuned over 1 THz (8 nm), enabling different comb lines to be selected. Locking to a comb line with a frequency offset precisely selectable between 4 and 12 GHz is also possible. The coherence between the DBR laser and the comb lines is demonstrated by measurements of the heterodyne signal residual phase noise level, which is below −100 dBc/Hz at 5 kHz offset from the carrier. The OPLL-filter output can be up to 6 dB higher than the peak power of the comb line to be isolated by the filter. This optical gain is a unique characteristic which can significantly improve the SNR of communication or spectroscopy systems. This OPLL is envisaged to be used for high purity, tuneable microwave, millimetre-wave, and THz generation.**

***Index Terms*—Microwave photonics, optical filters, optical frequency comb, optical phase lock loop, photonic integration, THz signal generation, tuneable millimetre-wave source component.**

I. Introduction

MICROWAVE Photonics is an interdisciplinary research field that looks into developing new, and optimising existing, ways of using photonic devices for generation, manipulation, distribution and detection of microwave, millimeter-wave (mm-wave) and terahertz (THz) signals [1], [2]. The advantages of photonics include: i) the ability to transport microwave signals over long distances with little penalty in the optical domain, ii) immunity to electromagnetic interference (EMI), iii) the wide bandwidth of opto-electronic components, and iv) frequency agility of optical components. The above characteristics lead to extreme configurability of photonic-based systems – a feature which cannot be easily achieved if using conventional microwave components. It makes microwave photonics attractive and in demand for many applications in microwave, mm-wave and also THz frequency systems, for instance high resolution frequency domain spectroscopy [3]–[5], coherent communication [6], and astronomy [7], [8].

Microwave photonics combines the two technologies allowing for microwave signals to be distributed across a long distance using optical fibers which are much lighter and more flexible and, most importantly, which introduce much lower signal loss than conventional coaxial cables. The bandwidth of the transmission links and individual components in the optical domain can be a few orders of magnitude greater than that of microwave counterparts. Similarly, the frequency tuning range of optical sources, in particular semiconductor lasers, is much wider than microwave oscillators. Nonetheless, in order to bring the benefits of photonics into the RF domain, suitable opto-electronic converters are required. Photomixers, such as photodiodes and photoconductors, are used to convert two optical waves at slightly different wavelengths into a heterodyne electrical signal at the frequency corresponding to the frequency difference of the two optical signals. Generation of high frequency signals in the THz range has been demonstrated using this heterodyning technique and the bandwidth of opto-electronic converters is usually a limiting factor for further frequency increase. This technique can also produce, as do conventional RF mixers, spurious tones and higher order mixing products, which need to be filtered out at some stages in the system. Although heterodyning two lasers can be used to generate a broadly tuneable RF signal, the spectral quality of this signal is largely dependent on the linewidth and frequency (wavelength) stability of the two lasers. Compact semiconductor lasers, for instance, may have a linewidth in the range of tens of MHz, and their emission wavelength stability may be affected by their thermal dependence and/or mode changes, which would be directly translated to frequency instabilities of the heterodyne signal. For applications that require

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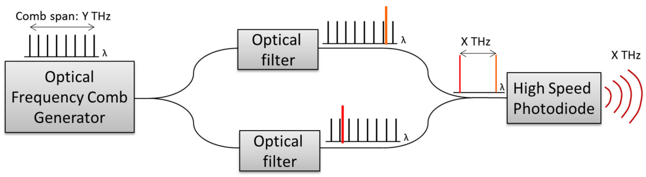

Fig. 1. Schematic representation of component arrangement for photonic generation of microwave, mm-wave and THz signals.

a narrow linewidth microwave source with a stable absolute frequency, the phase coherence between optical tones must be maintained. This can be achieved through direct or external modulation of a single laser if a signal of a few tens of GHz is to be generated, the frequency limit being set by laser or external modulator bandwidth. To generate an high quality signal at mm-wave or THz frequency, one would need a fully stabilized dual wavelength source, which could be obtained through selecting two lines from an optical frequency comb generator (OFCG). In that regard, Section II of this paper provides a short summary of available OFCGs reported in the literature. Key to an OFCG based system is the use of high quality optical filters as seen in the configuration presented in Fig. 1. While passive optical filters are available commercially and are widely researched, one could alternatively use an independent laser (slave laser) source that could be phase stabilized using optical injection locking (OIL) [9] or an optical phase lock loop (OPLL) [10]. This approach enables frequency tracking and the provision of optical gain within the filter. Both optical phase locking techniques allow the relative phase difference between the slave laser and comb line to be minimized, effectively acting as an optical filter.

This paper focuses on a laser locking technique which can be implemented to isolate a single line from an OFCG with closely spaced (<15 GHz) optical comb lines. The OPLL can be considered to be a highly selective optical frequency comb line filter, since it allows the slave laser to acquire the spectral characteristics of the reference comb line, while attenuating all the other lines. Moreover, the slave laser frequency can be interpolated between the comb lines with a precisely defined frequency offset from one of them. The characteristics of the OPLL and its performance are described in Section III. The filtering properties of the OPLL are described in Section IV.

In the arrangement presented in Fig. 1, two OPLL filters are used to provide two highly coherent tones separated by hundreds of GHz which, if heterodyned on a photodiode, would generate a high frequency, broadly tuneable signal. Moreover, an optical modulator could be added after one of the optical comb line filters, allowing for data transmission at carrier frequency beyond 250 GHz [11].

The process of acquiring spectral characteristics through phase locking may also be advantageous in applications where, for instance, the spectral characteristics of an ultra-stable master laser needs to be transferred onto a number of inexpensive diode lasers [12]. The OPLL, as presented in this paper, would also find applications in coherent communication [11], LIDAR and clock signal distribution.

TABLE I
OVERVIEW OF OPTICAL FREQUENCY COMB GENERATORS

	Span (THz)	Spacing (GHz)	Power (dBm)
FM Laser	2	24.5	-40
Hybrid modelocked laser	2	29.5	-5
Monolithic passively mode-locked ring laser	1.08	10	-2
Quantum dash mode-locked laser	1.6	24	-10
Laser modulated by cascade of PM and IM	0.38	10	-20
Fibre mode-locked laser	>6	0.05 - 1	-40 — -20
Fibre re-circulating loop	2-4	10 - 24	-40 — -10
OFCG based FWM processes in highly nonlinear fibres	4-15	10, 25	-30
μ ring resonators	37	875	0

II. OPTICAL FREQUENCY COMB GENERATOR

Several semiconductor and fibre-based optical frequency comb generators (OFCGs) have been developed over the years. FM lasers [13], hybrid mode-locked lasers [14], monolithically integrated passively mode-locked ring lasers [15], [16] and quantum dash mode-locked lasers [17] are some examples of thermally stable, monolithic semiconductor based OFCGs with fixed comb line spacing. Among the fibre-based systems, a single-mode laser modulated by a cascade of phase and intensity modulators driven by tailored RF waveforms has been shown to generate a very uniform optical comb over a span of 380 GHz [18], while OFCGs based on fibre mode-locked lasers are capable of generating comb lines over a span of >6 THz [19], with line spacing from 27 MHz [20] to 1 GHz [21]. Further, fibre re-circulating loop OFCGs have been demonstrated with a span from <2 THz [22], [23] to >4 THz [24]. For this particular comb, the phase noise of the heterodyne between two successive comb lines has also been measured up to 90 GHz, and is −80 dBc/Hz at an offset frequency of 10 kHz [23]. OFCGs realized through four wave mixing (FWM) processes in highly nonlinear fibres have produced comb lines over a much broader span [25], [26], however, these generally require high optical input powers in the 400 mW to 1500 mW [26] range. Similarly, comb line generation over a wavelength range of nearly 300 nm has been demonstrated through nonlinear mechanisms in micro-resonators [27], with a line spacing of 875 GHz. Characteristics of various type of OFCGs are summarized in Table I.

The optical frequency comb generator used as a reference source for the OPLL described in this paper was generated using a dual-drive Mach-Zehnder modulator (MZM) [28] yielding 19 optical coherent lines separated by equal frequency intervals of 15 GHz. The comb has a span of 285 GHz, within the −15 dB envelope, and its output was amplified by an Erbium-doped fibre amplifier to boost the power of each optical line. The laser

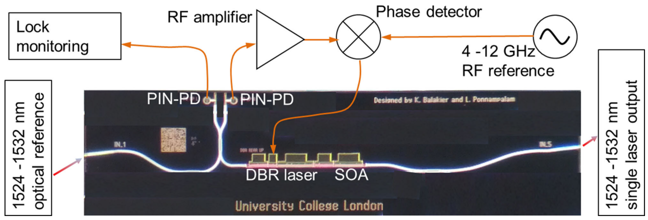

Fig. 2. Schematic representation of the OPLL that includes a photograph of the 2 mm × 6 mm InP-based photonic integrated circuit.

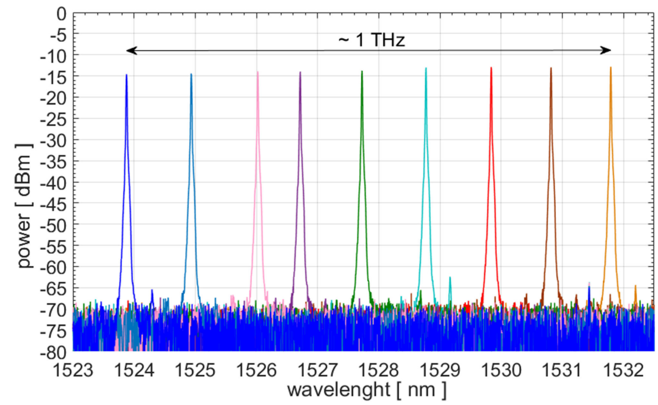

Fig. 3. Optical spectra of the DBR laser tuning range.

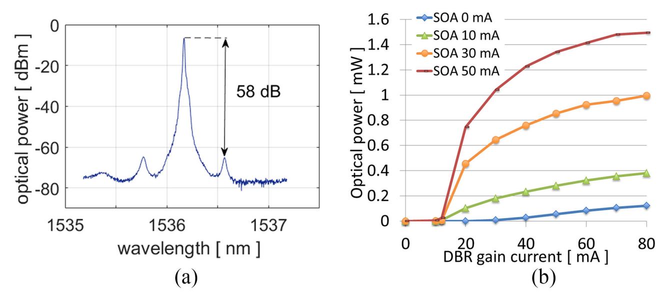

Fig. 4. Optical spectrum of the DBR laser measured with resolution of 0.01 nm (laser gain current of 100 mA and SOA currents of 50 mA) (a) and optical output power for different laser gain and SOA currents (b).

used as the reference for the OFCG has a full width half maximum (FWHM) linewidth of 10 kHz and operates at 1533.13 nm wavelength.

III. Optical Phase Lock Loop

Realising an OPLL based on a semiconductor laser offers a significant advantage due to its compactness. However, the relatively broad, MHz-range linewidth of diode lasers presents a particular challenge to the OPLL realisation due to the linewidth – delay trade-off [10], [29]. In order to stabilize a laser with a linewidth of 1.2 MHz, the delay within the opto-electronic feedback loop must be less than two nanoseconds to achieve a phase error variance of less than 0.03 rad^2. Such a short delay requirement imposes the need for photonic integration, which allows for several photonic components to be fabricated monolithically on a single chip reducing the length of optical interconnections to a few millimetres length. Nowadays, even complex photonic circuits can be fabricated through generic foundries, which also allow a selection of designs from different users to be allocated and processed on a single wafer using a common fabrication process [30], [31]. This can lead to a significant reduction in the fabrication cost, reduced lead-time and increased yield compared to custom research-based fabrications. The drawbacks of the foundry process come, similarly to its advantages, from the generic and universal nature of the fabrication process, which may compromise the performance of some photonic devices.

The heterodyne optical phase lock loop (OPLL) is a feedback control system built to stabilise the phase of a slave laser to an external reference (master) laser with absolute but adjustable frequency offset. A schematic representation of an heterodyne OPLL is shown in Fig. 2. When the OPLL is in operation, the phase of the heterodyne signal generated by the external reference and the on-chip slave laser on the photodiode is compared with the RF reference local oscillator using a phase detector. The baseband phase error signal, which corresponds to the phase difference between the lasers, is fed back into the phase section of the slave laser to correct its operation point in accordance with the reference tone phase and frequency. A more detailed description of the OPLL design and operation principles, and typical performance of this particular OPLL, are given in [10], [32].

The OPLL discussed in this paper is based on an n-doped InP chip fabricated using a generic foundry fabrication process at Oclaro Technologies, UK. The key component of the OPLL system is a photonic integrated circuit (PIC) containing a slave distributed Bragg reflector (DBR) laser, PIN photodiode (PIN-PD) and various optical passive interconnections (waveguides, couplers/splitters etc.), all of which form part of the OPLL [32]. Additionally, a semiconductor optical amplifier (SOA) was included after the DBR laser output to boost the optical power level before it is coupled to the on-chip waveguide and into an optical fibre. The PIC dimensions are 2 mm × 6 mm, and its photograph has been included in Fig. 2. The PIC is combined with off-the-shelf RF components (RF amplifier, double-balanced mixer acting as a phase detector, RF reference synthesiser) to create an heterodyne OPLL [32]. The electronic part of the feedback loop is represented schematically in Fig. 2.

A. DBR Laser

The DBR laser integrated on the PIC can be tuned continuously over an 8 nm range (from 1532 nm to 1524 nm), by adjusting the current applied to the laser Bragg gratings. The tuning range is presented in Fig. 3. The static tuning sensitivity when adjusting the currents to both of the gratings is on average 37 GHz/mA. The laser operates in a single mode across the 1 THz range with a side-mode suppression ratio up to 58 dB, as seen in Fig. 4(a)).

The optical output is coupled out of the chip using a simple cleaved single mode fibre. Up to 0 dBm optical power was measured at the output when the DBR laser gain section and the integrated SOA were driven with 100 mA and 50 mA currents, respectively. The chip output power measurements are presented against DBR laser gain bias currents for different SOA currents in Fig. 4(b).

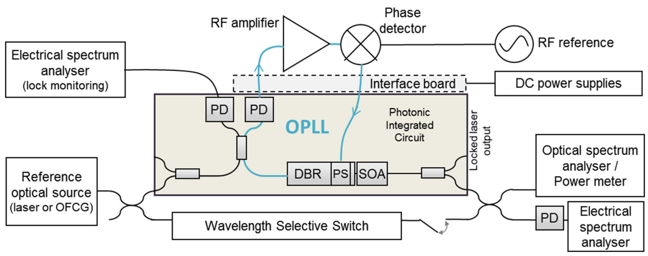

Fig. 5. Schematic of the experimental arrangement.

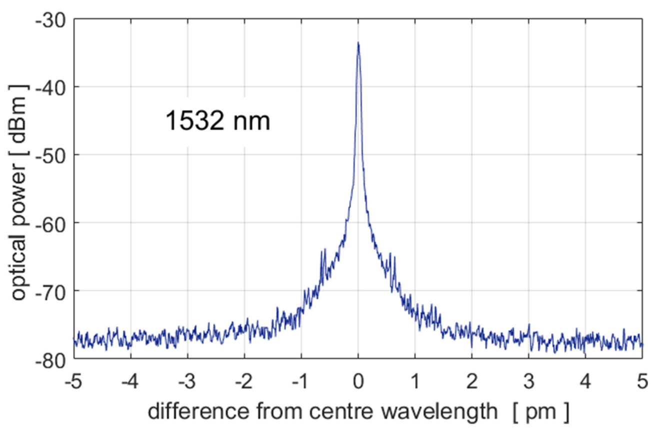

Fig. 6. Optical spectrum of locked DBR laser centered at 1532 nm. (resolution = 0.04 pm).

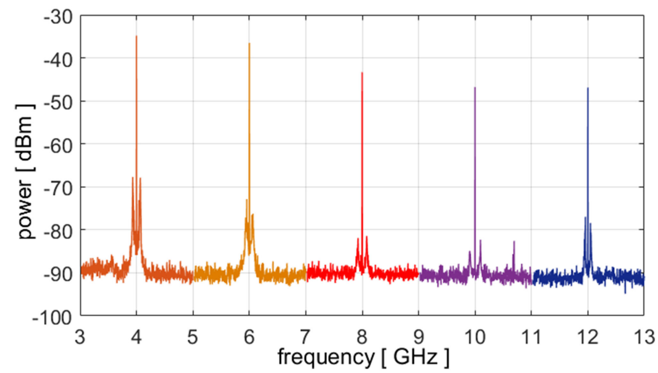

Fig. 7. Heterodyne beat-notes between DBR lasers and external reference laser measured at integrated PIN-PD (RBW = 500 kHz, VBW = 100 kHz).

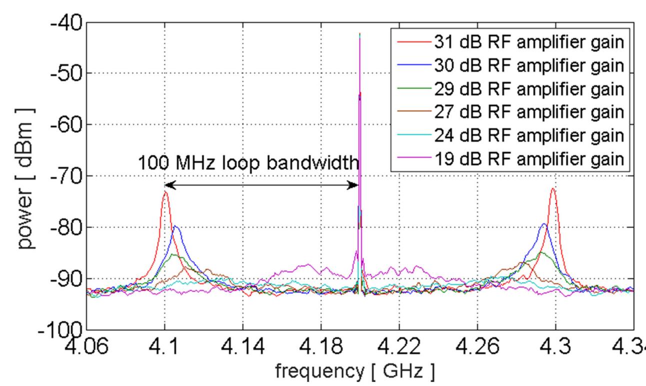

Fig. 8. Electrical spectra of the phase-locked heterodyne measured at different RF amplifier gains (RBW = 100 kHz VBW = 10 kHz).

IV. OPLL Locking and Tuneability

The experimental assembly used to phase stabilize the DBR laser to the external reference optical tone (single laser or optical comb line) is presented schematically in Fig. 5. The heterodyne OPLL phase locks the integrated DBR laser to the reference optical tone with a variable offset frequency.

A reference laser with less than 10 kHz linewidth was used in all the experiments in this paper. As a consequence of phase locking, the DBR laser (which in its free running mode has a −3 dB linewidth of 1.25 MHz [32]) acquires the lineshape corresponding to the convolution of the optical and RF reference tones. The FWHM linewidth of the RF reference is 10 Hz (measured with 10 Hz resolution bandwidth) and therefore can be considered negligible relative to the kHz-scale linewidth of the master laser. This linewidth improvement of the DBR laser cannot be assessed in the optical domain (Fig. 6) as the measurement is limited by the 10 MHz frequency resolution of the optical spectrum analyser.

In order to assess the quality of locking in detail, the heterodyne signal generated by the two optical tones spaced by the offset frequency must be observed in the electrical domain with kHz resolution bandwidth or less. Spectra from the electrical spectrum analyser demonstrating beat signals at frequency offsets ranging from 4 GHz to 12 GHz are shown in Fig. 7. The roll-off in the frequency response of the PIN-PD and other electrical connections (e.g., wirebonds) can be observed in Fig. 7, where the power of the 12 GHz heterodyne signal is smaller than that of the 6 GHz tone, as measured and demonstrated in [32] for different bias voltages.

This drop in RF power is observed only on the integrated lock-monitoring PIN-PD and is compensated by the adjustment of the variable gain amplifier within the feedback loop. Indeed, the optical output power of the chip is not dependent on the RF offset between the master and slave lasers. The RF amplifier allows the power of the phase error signal within the loop to be precisely adjusted. These changes, according to OPLL theory [33], have an effect on the OPLL bandwidth which can be observed and measured on the electrical spectra of the heterodyne signal, as demonstrated in Fig. 8.

Fig. 8 demonstrates how varying the RF amplifier gain from 19 dB to 31 dB results in the loop bandwidth changing from approximately 20 MHz to 100 MHz. As defined in [33] and [34] the loop bandwidth is indicated by the offset of the side peaks from the heterodyne carrier. As the loop gain increases (as a result of increasing the gain of the RF amplifier), the phase noise close to the carrier frequency is suppressed, the offset frequency of the side peak increases and eventually the power of the side peaks rise [33], [34].

When the loop is in operation, the laser wavelength can be controlled with Hz-level precision by fine tuning the frequency of the RF reference synthesizer. The RF offset tuning range is currently limited by the phase detector operation range (specified for 4–12 GHz) and could be further increased by replacing

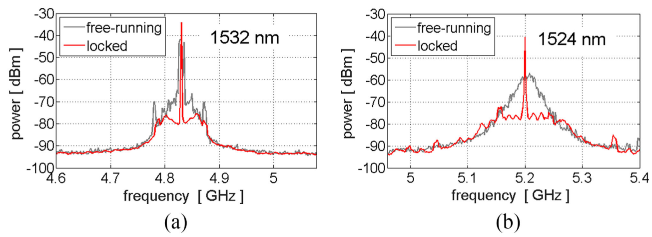

Fig. 9. Locked (continuous red line) and free-running (dashed grey line) heterodyne signals generated by lasers at 1532 nm and 1524 nm (RBW = 200 kHz, VBW = 10 kHz).

this component with one with a broader operational bandwidth. The other device limiting the higher offset frequency locking is the PIN-PD on the PIC, whose frequency response decreases by 6 dB at 12 GHz [32].

However, a frequency offset between the two optical tones greater than 12 GHz may not be required in many applications. For instance, when the OPLL is used to select one of the multiple lines of the optical comb, the highest frequency offset does not need to be larger than half of the frequency spacing between the OFCG lines [33]. It is worth noting that most of the broad span combs, as can be seen in Table I, have their lines separated by less than 24 GHz, which is often limited by the modulator bandwidth and the driving synthesizer. Therefore, locking the laser with up to 12 GHz offset from any comb line is sufficient to access all the wavelengths in between the comb lines, ultimately allowing for continuous tuning of the microwave photonic signal.

Fig. 3 demonstrates that the wavelength range of eight nanometres can be accessed by applying a combination of control currents to the grating and phase section of the DBR laser. This continuous wavelength tuning translates into continuous tuneability of the microwave, mm-wave and THz signals. However, changing the grating currents has also an effect on the laser linewidth which increases from its minimum value of 1.25 MHz (measured when grating currents is 0 mA) to tens of MHz for higher currents. This lineshape change is due to the presence of additional electrical noise in the tuning currents of DBR grating of the laser [35], [36]. The consequence of this broadening is a phase and frequency jitter of the free running heterodyne signal, as seen in Fig. 9 (dashed line). Despite the increased linewidth of the laser, the OPLL can still successfully control and phase-lock the DBR laser to the reference laser (continuous line Fig. 9).

Phase locking at the most extreme operational wavelength and precisely defined frequency offsets is presented in Fig. 9 at offset frequencies of exactly 4.8 GHz and 5.2 GHz, when the lasers are operating at around 1532 nm and 1524 nm, respectively. As expected, a large reduction in linewidth and increase in the peak power can be seen in the spectra of the phase-locked heterodyne signal compared to the signals generated by these lasers in the free running mode.

V. Comb Line Filtering

Tuneable optical filters with high selectivity are required to isolate only one comb line while effectively suppressing all the others, and in particular the adjacent lines. Although the quality of widely tuneable passive filters is improving as they are being investigated worldwide, the insertion loss remains significant, the bandwidth is in the GHz-range, and the transmission spectra of some integrated photonic-based filters are periodic [37]. Good quality optical filters based on bulk optics are commercially available offering insertion loss as small as 5–10 dB. The −3dB bandwidth (BW) of top-of-the-range filters is in the range of several GHz [38], [39]. The GHz-range BW, and finite roll-off of the filter profile may still result in several comb lines spaced by <15 GHz being passed, even through ultra-selective filters. Photonic integrated optical filters are also being extensively investigated offering an obvious advantage of compact size [40]. These, however, suffer from higher insertion losses and limited tuning range due to the periodic frequency response of ring-based filters and slow tuning time due to thermal actuators in the ring resonators [41], [42]. A high loss through the optical filter may become a significant restriction, in particular if the peak power per comb line is low, and high optical power is required on the photodetector generating mm-wave and THz signals. To avoid the use of multiple optical power amplification stages, laser locking techniques offer an attractive alternative to passive optical filters.

To demonstrate the OPLL performance as a highly selective optical comb line filter, the output of the entire comb (described in Section II) was coupled using a lensed fibre into the waveguide on the PIC. The optical spectrum of the comb at the input of the OPLL, and the single optical line of the phase-locked DBR laser at the output of the OPLL are presented in Fig. 10, demonstrating attenuation of optical noise and adjacent optical comb lines to below –60 dBm (measured with 10 MHz resolution bandwidth). This exceptional filtering capability is due to the PIC component layout which ensures that none of the optical input signals is present at the OPLL output. As a result, the suppression of optical noise and other comb lines by over 50 dB is achieved (limited by the suppression of the DBR laser sidebands).

To assess the quality of phase locking in more detail, the heterodyne signal generated by the integrated and external photodiodes was observed on the electrical spectrum analyser (indicated in Fig. 5). At the output of the integrated PIN-PD several beat-notes could be observed, as presented in Fig. 11.

In Fig. 11a) several tones can be identified, including the DBR beating with the three closest comb lines resulting in the 4.2 GHz (also presented in Fig. 11b)), 10.8 GHz and 19.2 GHz signals. The 15 GHz beat between all comb lines is also visible. Lastly, the second harmonic of the 4.2 GHz heterodyne signal is present at 8.4 GHz, indicating some nonlinearity in the characteristics of the PIC-PD. Despite all the multiple RF tones detected, the OPLL could successfully phase lock the DBR laser at exactly the frequency offset defined by the reference RF synthesizer. The measurements at the output of the PIN-PD enable additional information on the feedback loop performance and dynamics of the loop to be obtained, for instance the dependence of the loop bandwidth on the RF gain in the feedback circuits, as seen in Fig. 8.

In order to examine the quality of the DBR laser optical output as well as the stability of the locking, the heterodyne signal must also be measured on the external PD. To this end the optical frequency comb was split into two optical paths, as shown

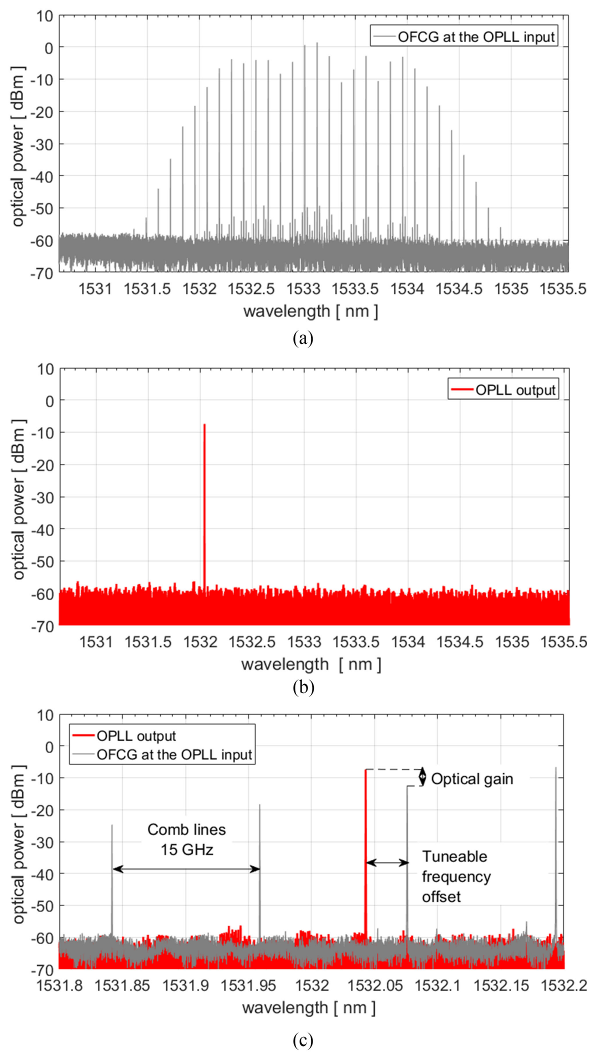

Fig. 10. Optical spectra of (a) the optical frequency comb at the OPLL input, (b) the DBR laser at the OPLL output, and (c) the comparison of OPLL input and output. Measured with RBW = 10 MHz.

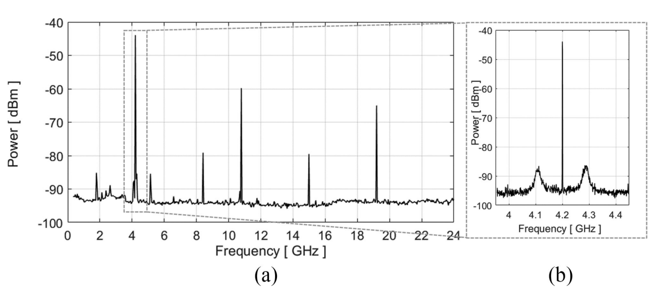

Fig. 11. Electrical signals obtained by heterodyning DBR laser and entire OFCG on the monitoring PIN-PD integrated on PIC (RBW = 200 kHz VBW = 10 kHz).

schematically in Fig. 5. To avoid an increased residual phase level of the heterodyne due to the length difference between the two optical paths an additional section of optical fibre was added to one of them. The OPLL was used to select one line of the comb, while the next but one consecutive line was isolated out by a configurable wavelength selective switch with 10 GHz FWHM bandwidth. The two optical tones were then combined

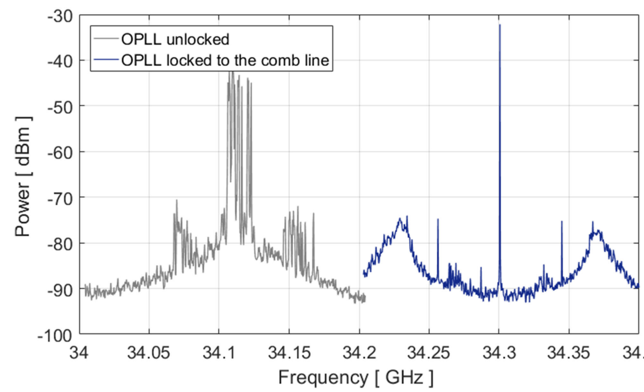

Fig. 12. Electrical spectra of the free running and phase locked heterodyne signals measured at the external photodiode (RBW = 50 kHz, VBW = 3 kHz).

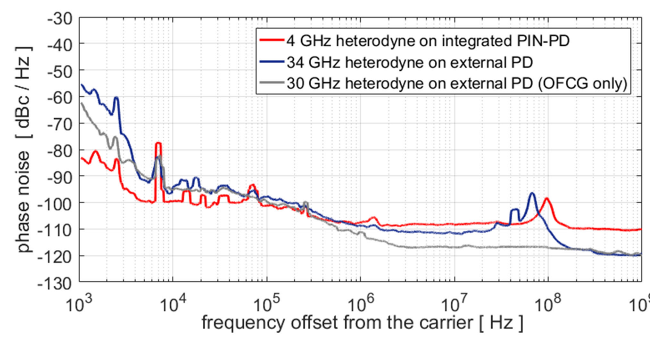

Fig. 13. SSB phase noise measurement of the phase locked heterodyne signals at 4 GHz and 34 GHz.

together on an external 65 GHz BW photodiode and the heterodyne signal was measured at the spectrum analyser demonstrating a high purity, 34.3 GHz signal (30 GHz spacing between two comb lines and 4.3 GHz frequency offset introduced by OPLL) as seen in Fig. 12. The improvement in spectral purity and frequency stability of the heterodyne signal generated when the OPLL operated in the locked and unlocked conditions is evident. Moreover, the frequency of the phase-locked heterodyne can be tuned with Hz-level precision simply by adjusting the frequency of the RF reference applied the OPLL.

Subsequently, the coherence between the comb line used as the optical reference for the OPLL and the phase-stabilised DBR laser was assessed by measuring the phase noise of the heterodyne signals. Fig. 13 shows the single sideband (SSB) phase noise measurements of the 4 GHz and 34 GHz heterodyne signals measured on the integrated PIC-PD and external photodiode, respectively. The beat-note between two comb lines separated by 30 GHz was also measured and is included in Fig. 13 for reference.

Fig. 13 demonstrates good agreement between the spectral characteristics of the beat-note generated by two comb lines and those generated by one comb line and the DBR laser. The OPLL can supress the phase noise of the heterodyne signal to a level below −100 dBc/Hz at offsets from the carrier greater than 6 kHz. The increase in the phase noise at the lower frequency offsets from the carrier can be explained by the temperature dependence of and imperfect length matching between the two optical paths through which the optical tones propagate. The increased phase noise level for the 4 GHz signal at the higher offset is noise-floor limited due to the lower power of the signal generated by the integrated PIN-PD.

The measured phase noise level is lower than that of the phonically generated signal used in the 10-Gb/s transmission link at 120 GHz carrier [43]. To demonstrate that this OPLL can be used for high-data-rate coherent communication applications, a wireless link with a carrier frequency tuneable between 229 GHz and 244 GHz was successfully demonstrated and described in [11].

A. Q Factor

Considering the OPLL as an ultra-selective band pass filter, its spectral selectivity is strongly dependent on the loop bandwidth, which can be adjusted in the range from 40 MHz to 200 MHz (20 MHz and 100 MHz on each side of the laser tone), as shown in Fig. 8. In general, loop bandwidth is dependent on the loop gain (adjusted with the RF amplifier) and phase-error propagation delay present in the loop, as well as the limitations imposed by the loop stability criteria [44].

The OPLL-filter quality (Q) factor can be defined as the ratio between the laser operation frequency and the loop bandwidth. The value of the Q factor of this OPLL-based microwave photonic filter can be therefore estimated to be in the range of 1×10^6 to 5×10^6, which is amongst the highest reported in the literature [45]–[47] for optical frequencies.

B. Optical Gain

The entire comb with a total optical power of $\sim$14 dBm was coupled using a lensed fibre into the waveguide on the PIC. It is estimated that before the comb signal reached the active area of the photodetectors, it was reduced by 12 dB, mostly due to fibre-to-chip coupling, two MMI coupler/splitters, and waveguide loss. The entire comb spectrum results in up to -1.2 mA of DC photocurrent (depending on the photodiode reverse bias) being generated at each PIN-PD. Nonetheless, the peak power of the single comb line used as reference for phase locking was -13 dBm, which would correspond to about 2 μA of DC photocurrent. It should be noted that the laser power at the output of the chip is up to 0 dBm (depending on the SOA current and chip-to-fibre coupling). The power amplification of about 6 dB (demonstrated in Fig. 10) is another unique characteristic of the OPLL which demonstrates its advantage over conventional passive ultra-selective filters; the latter suffering from a typical insertion loss of 5–10 dB.

VI. Conclusion

The presented OPLL demonstrates a good example of a system where a foundry fabricated PIC and commercial, off-the-shelf (COTS) electronics have been used to build an opto-electronic feedback loop capable of phase stabilising the semiconductor laser to the optical reference with offset frequency setting resolution of 1 Hz. The OPLL centre wavelength operation range is limited only by the tuning range of the DBR laser, which is 1 THz. The residual phase noise of the heterodyne signal generated by these two optical tones was reduced to the level of -100 dBc/Hz at 6 kHz offset from the carrier frequency.

The OPLL was designed with the objective of eliminating any noise and adjacent comb lines present in the optical input signal at the output of the OPLL. The demonstrated out-of-band rejection was up to 58 dB (when measured on optical spectrum analyser with 0.01 nm resolution) and is limited by the sidebands of the DBR laser. Such suppression is expected from the highest quality optical filter, hence the OPLL can be considered as an ultra-selective optical comb line filter with quality factor exceeding 10^6. Moreover, the OPLL can offer unique characteristics that can be particularly important if we consider optical combs with low power and fixed frequency spacing between the lines. First, the OPLL allows for tuneable frequency offset of up to 12 GHz from the selected comb line. Secondly, an optical gain can be offered, meaning that optical power can be greater at the output than at the input of the OPLL. This is particularly important for systems that require high SNR.

Despite the excellent filtering capabilities, the OPLL-based filter has also some drawbacks. Notably, the presence of active components on the PIC creates the need to consider the power consumed by this filter, hence its implementation should be based on the functional requirements of the application. The bandwidth of the OPLL-filter is not broadly tuneable and remains in the range of 40 MHz to 200 MHz. It should, however, be mentioned that any optical filter with such a narrow bandwidth would require an additional wavelength-locking mechanism, to ensure that the power of the filtered signal is not compromised by the wavelength drift of the input source or filter. In the case of the OPLL-filter, once the phase locking has been acquired, tracking of the input signal is automatically achieved by the loop, within its hold-in range. The hold-in range of this first order loop is of 200 MHz, which could be increased further by introducing a loop filter with an integrator function.

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