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Toward Hz-level Optical Frequency Synthesis Across the C-band

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Abstract: By using a stable comb as an input reference to an integrated heterodyne optical-phase-locked-loop consisting of a coherent receiver photonic IC with a widely-tunable laser, high-speed feedback electronics, and an RF synthesizer, accurate optical frequencies across multiple comb lines can be generated. Initial results will be presented.
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Beginning with a single stable optical reference tone, it has been shown that a broad comb of lines with similar stability and linewidth can be generated. This has been done by phase locking one line of a mode-locked InP-based photonic IC laser to such a reference with an integrated high-bandwidth optical phase-locked loop (OPLL) [1]. Variations of the mode-locked laser (MLL) also contained a gain-flattening filter that broadened the optical comb into the multi-terahertz range [2]. This comb source is then used as a reference for a second heterodyne OPLL, which contains a widely-tunable laser that can be tuned across the C-band [3,4]. Tuning between comb lines is accomplished with a tunable RF synthesizer for offset locking. Two techniques of offset locking have been demonstrated: (a) the RF was applied to an optical modulator following the tunable laser and an optical sideband was used for locking [5]; (b) the RF was applied to an electronic mixer following optical detection in the heterodyne receiver and the RF difference frequency used for locking [6]. Figure 1 illustrates this system. In this case the MLL is also actively mode locked with a fixed f_{RF1} for more stability. The tunable frequency f_{RF2} is varied from a low value to at least half of the comb line spacing for full wavelength coverage.

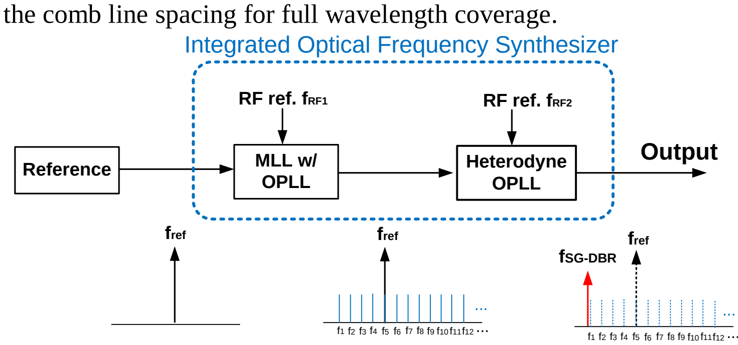

Fig. 1. Integrated optical frequency synthesizer system. The components within the dashed box could be on one chip, although initially they have been separate.

Figure 2 gives a schematic of the integrated MLL/OPLL using a ring MLL geometry along with results. Results from both a ring and linear MLL are shown, but only the linear MLL included the OPLL in the fabricated chips. The actively mode-locked ring MLL had about 70 useful comb lines spaced by 29.6 GHz. The electrical spectrum after detection shows a frequency deviation in the mode-spacing of < 10 Hz across ~2 THz with no phase locking. The linear MLL (24 GHz comb) after phase locking to a Rock laser (~200 Hz linewidth) shows no measurable center frequency deviations relative to the reference Rock laser (line is phase locked), but has a phase error variance of <0.12 rad^2 (integrated from 1 kHz to 10 GHz) and a relative linewidth for adjacent lines across the spectrum < 1 kHz. That is, the phase locked optical waves 'wiggle' back and forth a small amount, but never deviate by any significant fraction of π radians in phase from their proper value—standard deviation is < 20° over time periods of hours.

An alternative to the MLL/OPLL approach for stable comb generation is to use a self-referenced comb that does not require a reference tone. This involves the generation of an octive-wide comb, usually by nonlinear interactions in a high-Q resonator. A line from the low frequency end is frequency-doubled and phase-locked to a line on the high frequency end of the same frequency by adjusting the parameters of the resonator. At this point the comb is 'self-referenced' and very stable [7].

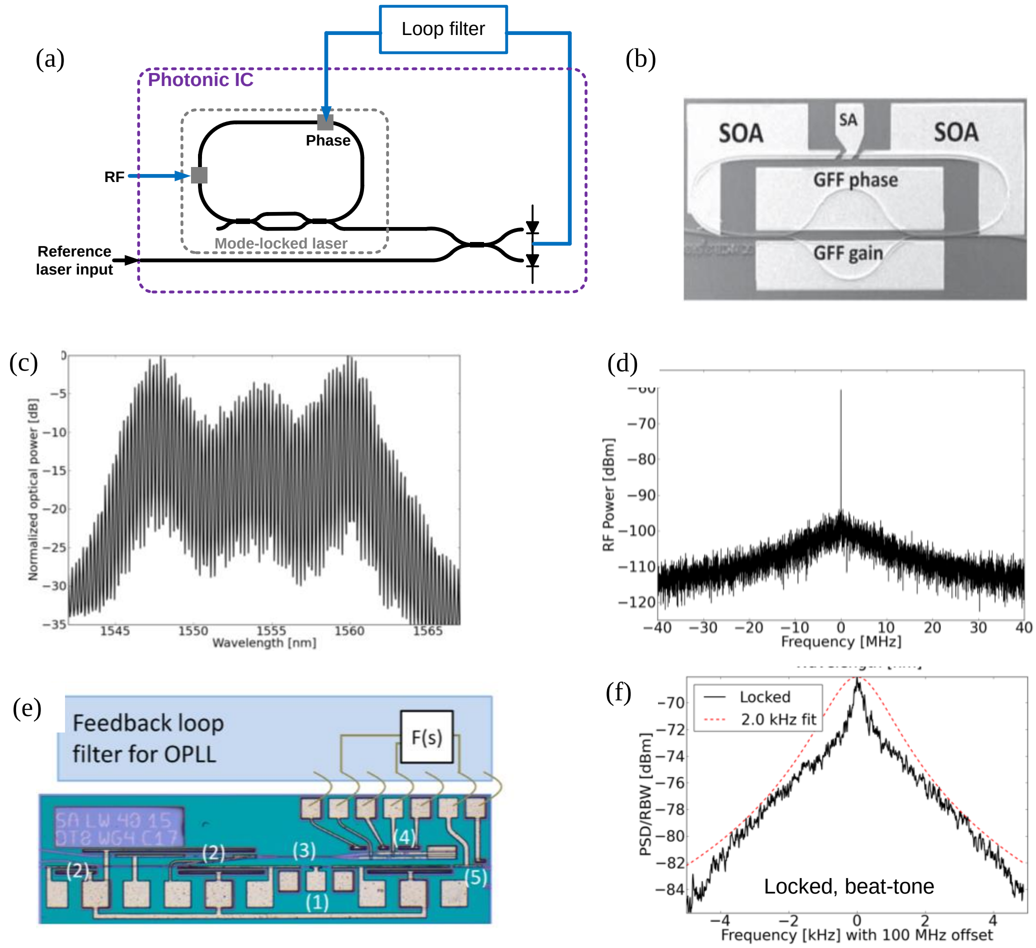

Fig. 2. (a) Comb generator schematic and results consisting of a MLL with OPLL. The double coupler geometry shown in the schematic can be used for gain flattening. RF is applied to an intensity modulator for active mode locking; the OPLL feedback is applied to a phase modulator to dynamically adjust the lasing frequency. (b) Photo of ring MLL with gain flattening filter (GFF). (c) Optical output of ring MLL. (d) Detected electrical spectrum of ring MLL. (e) Linear MLL/OPLL. (f) Detected electrical spectrum of linear MLL/OPLL. [1,2]

Figure 3 gives a schematic of the second heterodyne OPLL that accepts the input from the comb generator and provides a tunable optical output between comb lines. As mentioned in the first paragraph above the offset locking is achieved either with a tunable RF input to (a) an optical modulator following the integrated widely-tunable laser (SGDBR) or (b) an electronic mixer following detection in the feedback electronics. In either case, the procedure is to acquire lock to the difference frequency between the comb line and the RF line, and then tune the RF from a low value up to at least half way to the next comb line, where one can then use the opposite side band from the modulator or mixer from the next comb line and tune the RF down to near that next comb line.

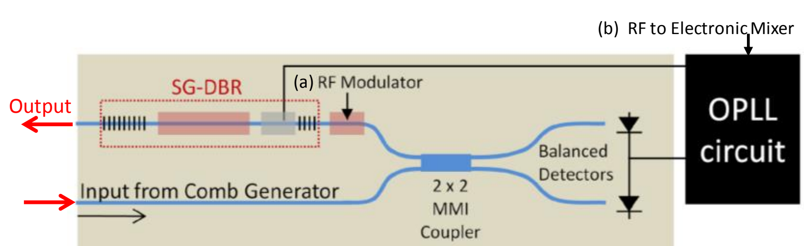

Fig. 3. Heterodyne OPLL with tunable RF offset locking of a widely-tunable laser to the generated comb.

The SGDBR also needs to be adjusted so that its center frequency is moved to the next comb line to repeat the process in order to avoid mode-hops. Then the process can be repeated across the entire comb. As shown in Fig. 2 relatively flat, strong combs extending over half of the C-band have already been accomplished, and it is anticipated that full C-band will be possible with these techniques.

The first experiments performed used a double modulator pulse carving configuration following an external-cavity laser with a ~100 kHz linewidth to generate a 40 GHz comb for use with the coherent receiver PIC and OPLL circuit illustrated in Fig. 3 [8]. The results are summarized in Fig. 4, where tuning across four comb lines is illustrated for a total of ~ 160 GHz. In this case a 4-photodiode I-Q coherent receiver was also employed instead of the simple 2-photodiode geometry illustrated in Fig. 3. Although the SGDBR laser unlocked had a linewidth >5 MHz, once locked, its linewidth 'cloned' that of the external cavity laser at ~100 kHz. No retuning of the SGDBR was used in order to illustrate how much tuning could be accomplished by only tuning of the phase tuning section from the feedback circuit.

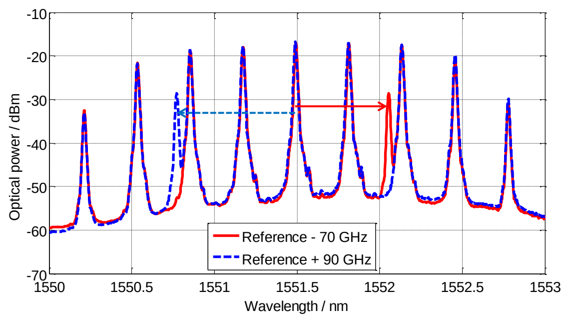

Fig. 4. Superposition of comb input and two output spectra from an optical spectrum analyser. Actual linewidths here ~ 100kHz. The initial locking was to the central line at 1551.5 nm. Then, the SGDBR was tuned -70 GHz and +90 GHz to the output lines shown by using a 26 GHz synthesizer and tuning the sum and difference frequencies formed with the nearest comb lines to and away from them. [8]

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