Optical Synchronization of a Photonic Crystal Resonator to a 10 GHz Chip-Scale Mode-Locked Laser PIC

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Abstract: We present an optical frequency division technique to transfer the timing stability of a stabilized Photonic Crystal Resonator Comb (~200 GHz repetition rate) to a chip-scaled mode-locked laser (~10 GHz repetition rate). © 2022 The Author(s)

1. Introduction

Interest in developing chip-scale optical frequency comb technologies has grown tremendously in the past decade. In particular, the study of nonlinear physical phenomena on integrated platforms has lead to the discovery of soliton microcombs on integrated microresonators. High-Q microresonators can support various patterns and stationary states in intracavity fields such as the low-noise dissipative Kerr soliton (DKS). The DKS has already been utilized in a variety of applications such as optical frequency synthesis [1] and optical communications [2] due to its low phase noise nature with perfectly equidistant comb lines. More recently, research in comb generation in normal dispersion resonators has shown significant advantages normal dispersion combs offer in terms of efficiency and ease of operation. Here, we utilize normal dispersion tantalum pentoxide (Ta_2O_5 or tantala) based Photonic crystal resonators (PhCR)[3]. The PhCR rings have a sinusoidal modulation of the inner waveguide walls to create a bandgap for one of the frequency modes. This bandgap enables a frequency shift of the mode excited by the pump laser, which unconditionally satisfies phase matching for the normal dispersion resonator. These resonators do not require any fast wavelength sweeping methods to excite low-noise comb states as they avoid the generation of modulational instability comb states.

Microresonator combs need to be fabricated at high free spectral ranges (FSR) in the 100s of GHz or even THz regimes to generate large comb bandwidths. The FSR of these combs cannot be directly detected and controlled via commercial photodetectors. Additionally, these THz combs have the potential for generating octave spanning spectra which can be self-referenced using f-2f stabilization. Alternatively, semiconductor-based mode-locked lasers (MLL) which have low FSRs in the GHz regime can be directly detected and controlled. These MLLs have the disadvantage that it can be challenging to generate a coherent octave required for f-2f stabilization due to low peak power pulses. The low cavity Qs as well as the low optical powers can also make axial mode linewidths much broader as compared to the microresonator comb lines which inherit linewidths from the pump laser. In this paper we take advantage of the merits of both technologies, namely the low-noise of the microcomb and the robustness of the FSR detection offered by MLLs via a technique known as harmonic injection locking [4]. These two systems are linked by injecting two tones derived from the PhCR comb into the MLL. This technique transfers the phase stability of the primary laser (PhCR comb) to the axial modes of the secondary laser (MLL) and results in a perfectly phase locked output from the MLL with a reduction in phase noise of the detected RF signal at the output. This also optically divides the wide spacing of the injected tones into the microwave regime of the repetition rate of the MLL (f_{REP}). The ν_{REP} will therefore be an exact integral multiple of f_{REP}, i.e., $\nu_{REP} = n \times f_{REP}$.

2. Experimental Setup

Fig. 1 shows the schematic diagram of our experimental setup. We use a tantala based photonic crystal resonator with an FSR~200 GHz. The comb is generated by pumping the PhCR with a tunable external-cavity diode laser. The pump wavelength is controlled and detuned via an external piezo modulation input to the laser to generate the comb. The comb generation does not require any fast frequency sweeping so slow piezo tuning is sufficient. The excess pump power is filtered using an add/drop DWDM filter. The comb is then amplified and split into two paths. The first path is input into an electro-optic division (EO division) chain consisting of two phase modulators (PM) driven by a modulation frequency f_{EO}. The EO division generates two nearly overlapping optical tones separated by a low frequency difference near the midpoint of adjacent comb lines. These two tones are isolated by a waveshaper (WS-2) for each pair adjacent comb lines and photodetected. This electro-optic beat signal is mixed with another signal from a ultra low-noise (ULN) quartz oscillator with a frequency of f_{LO} to generate an error signal which is fed into a servo

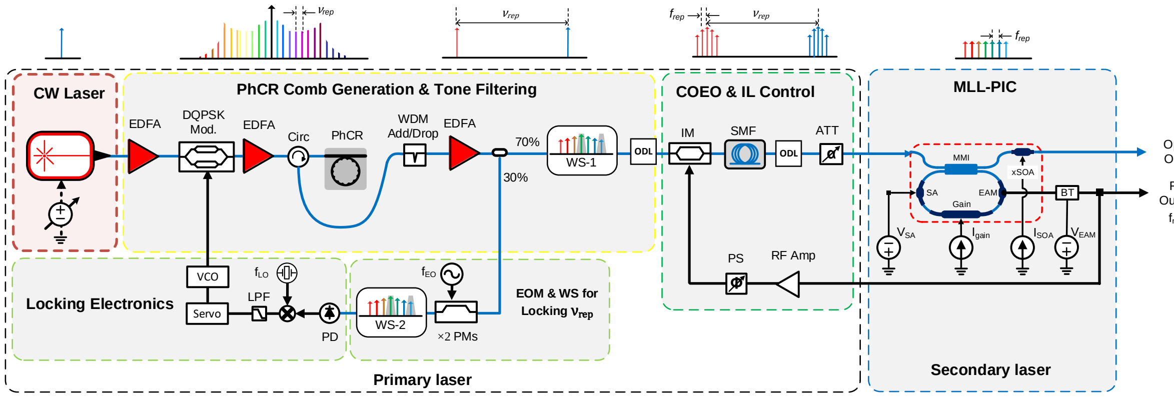

Fig. 1 Experimental setup - DQPSK: Differential quadrature phase shift keying modulator, Circ: Circulator, PhCR: Photonic Crystal Resonator, MLL-PIC: Mode-locked laser photonic integrated circuit, VCO: Voltage controlled oscillator, LPF: Low pass filter, WS: Waveshaper, IM: Intensity modulator, PM: Phase modulator, PS: RF Phase Shifter, ODL: Optical delay line, ATT: Optical attenuator, Blue lines are optical paths, Black lines are RF paths, Diagrams at the top of the figure depict spectra of CW laser, PhCR comb and MLL-PIC through the system. f_{EO}: modulation frequency, ν_{REP} : repetition rate of PhCR, f_{REP} : repetition rate of MLL-PIC, f_{LO} : frequency of low-noise quartz oscillator.

and used to lock the repetition rate of the comb. The output of the servo goes to a voltage controlled oscillator (VCO) which drives a DQPSK modulator in a single sideband suppressed carrier (SSB-SC) configuration. Tuning the pump using the SSB-SC configuration offers a greater bandwidth as compared to the piezo tuning of the laser and compensates for pump frequency drift and thermal fluctuations caused by the environment. The second path is input to another waveshaper (WS-1) to isolate two comb lines which are used for the harmonic injection locking. In this experiment we inject the comb lines spaced by ν_{REP} ~200 GHz into a MLL with a repetition rate f_{REP} ~10 GHz and demonstrate an optical frequency division factor of 20. The frequency f_{LO} of the ULN oscillator is 14.9145 MHz. The relations between the frequency terms required for harmonic injection locking which can be written as follows, $\nu_{REP} = 6\times f_{EO} - f_{LO}$ − (1) and $f_{REP} = \nu_{REP}/12$ − (2).

The secondary laser we use is an InP-based photonic integrated circuit (PIC) in a racetrack colliding-pulse MLL configuration [5]. It consists of a multimode interference coupler (MMI), a gain section, a saturable absorber, and an electro-absorption modulator. The MMI provides the input for the injected pulses and there is also a semiconductor optical amplifier (SOA) at the output port of the laser. In addition to the two tone injection locking, the laser is also operated in a coupled opto-electronic oscillator configuration (COEO). In this configuration the two tones from the PhCR comb are intensity modulated by the photodetected f_{REP} signal of the MLL-PIC before being injected. This additional COEO loop reduces noise of the MLL and increases coherence between axial modes spaced further apart. In the time domain, the COEO acts as a partial pulse picker to aid in pulse synchronization of the injected pulses to the MLL pulses.

3. Results

A compilation of the results is shown in Fig. 2. Fig. 2(a) shows an overlap of the pump suppressed platicon spectrum from the PhCR with the MLL spectrum over a span of 200 nm while Fig. 2(b) shows a zoomed in version with the MLL spectrum and individual PhCR comb lines visible. Fig. 2(c) shows the injected COEO modulated PhCR comb lines along with the MLL. Fig 2(d) shows the locked electro-optic beat note at f_{LO}. Fig. 2(e) shows the overlaid and centered f_{REP} signal before and after injection locking at a resolution bandwidth of 1 kHz. We can observe a 40 dB reduction in phase noise at 100 kHz offset from the center. Fig. (f) shows the ADEV plots for all cases – passive mode-locking, harmonic injection locking with and without the ν_{REP} lock as well as that of the low-noise quartz oscillator. It can be clearly seen that the timing stability of the harmonic injection locked with the ν_{REP} lock case follows the timing stability of the ULN oscillator. We observe an ADEV of $2\text{x}10^{-11}$ at 10s which corresponds to an rms deviation of 0.2 Hz in 10 GHz. Our RF synthesizers and RF spectrum analyzers are clocked to a GPS discipline oscillator to ensure the highest accuracy in measurements. A shift of 4.208 MHz of the repetition rate from 10.005729 GHz to 10.001521 GHz is observed after the MLL is injection locked as compared to the passive MLL state.

We finally verify whether our measured frequencies satisfy the relations (1) and (2). f_{LO} is 14.9145 MHz and we modulate the electro-optic comb with an f_{EO} of 33.340888088 GHz. Substituting these values into (1), (2) we get a ν_{REP} = 200.030414028 GHz and a $f_{REP\text{-Calculated}}$ = 10.0015207014 GHz. However, we measure the f_{REP} of the MLL to be $f_{REP\text{-Measured}}$ = 10.001521 GHz. Comparing these two measured and calculated f_{REP} values gives a discrepancy of 0.2986 kHz which is well within the 1 kHz resolution bandwidth of the measurements.

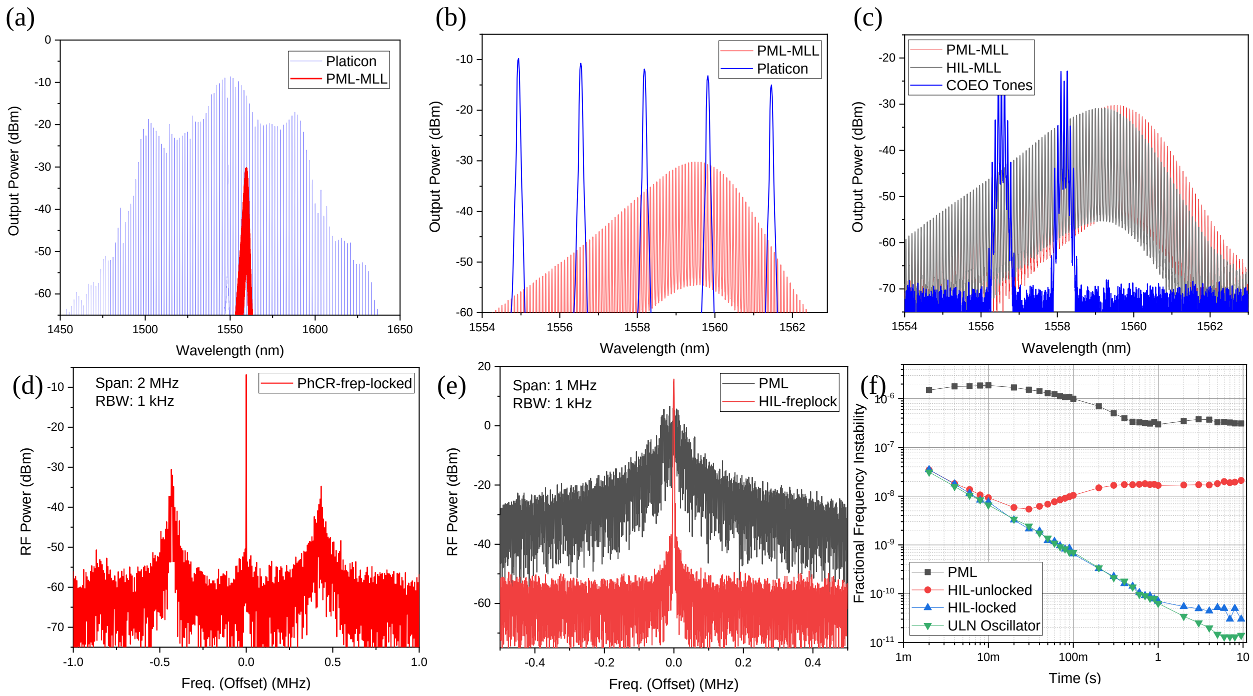

Fig. 2 (a) PhCR spectra and MLL spectra overlaid (b) Zoomed in MLL spectra with PhCR comb lines (c) Injected COEO modulated PhCR comb lines overlaid with MLL Spectra (d) Locked electro-optic beat of the comb at f_{LO} (e) f_{REP} beat (centered) before (gray) and after (red) injection locking (1 kHz RBW) (f) Fractional frequency instability (ADEV) plot for all cases – PhCR: Photonic Crystal Resonator, PML-MLL: Passive mode locked MLL, HIL-MLL: Harmonic Injection Locked MLL, ULN oscillator: Ultra low-noise quartz oscillator

Conclusion

We have presented an all-optical pulse synchronization of a photonic crystal resonator comb at 200 GHz FSR to a semiconductor MLL-PIC at 10 GHz. The technique utilizes electro-optic division locking the repetition rate of the comb. We demonstrate an optical frequency division factor of 20. In the future this frequency division factor can be increased to higher numbers through further stability improvements of the primary laser i.e., the PhCR comb. Furthermore, f_{CEO} locked octave spanning soliton combs could be utilized to realize a stable low repetition rate MLL frequency comb with absolute knowledge of both f_{REP} and f_{CEO}. This demonstration is important for applications which could potentially utilize microcombs combined with chip-scale MLLs as a bank of low-noise coherent oscillators for coherent links or as timing references in free-space telecom platforms.

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