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Optical Dual-Comb Vernier Division of an Octave-Spanning Kerr Microcomb

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Abstract: We measure the repetition rate of a 900 GHz octave-spanning soliton microcomb based on Vernier dual-comb frequency division implemented with two silicon nitride microresonator combs fabricated on the same wafer.

Optical frequency combs (OFC) are an integral tool in frequency metrology and atomic clocks. To be useful for such applications, the OFC's carrier offset frequency and repetition rate need to be stabilized. The push towards integrating such OFC sources has resulted in a string of impressive demonstrations of on-chip octave-spanning dissipative Kerr solitons based on silicon nitride (SiN) microresonators [1–3].

Thus far, all reported octave-spanning Kerr combs based on on-chip integrated sources have repetition rate frequencies that are inaccessible to electronics. To address this challenge, a second comb with a smaller repetition rate (f_{rep_2} ca. 20 GHz) was introduced to optically divide a THz-FSR octave-spanning comb [1]. As conceptually illustrated in Fig. 1a, assuming both rings are pumped with the same laser and are subsequently locked at a second locking point, the THz comb repetition rate can be divided down to f_{rep_2}. Alternatively, the main comb's repetition rate can be divided using a secondary large repetition rate microring with a small difference (δf_{rep}) in repetition rate [4]. If the resonances of both rings are aligned such that they can share a common pump, then due to the Vernier effect, the combs' sidebands walk off until they finally overlap again $M_2 \times f_{rep_2}$ modes away from the pump. At this point, the overlap beat note ($f_{overlap}$) can be photodetected and locked. Subsequently, the beat frequency between the combs' first sideband pairs is measured (i.e. δf_{rep}). An optically divided version of the main comb's repetition rate can then be found as $f_{rep_1} = M_2 \cdot \delta f_{rep} \pm f_{overlap}$. The Vernier approach relaxes the requirements of getting a microcomb with a photodetectable repetition rate (which requires exceptionally high Q values to offset the intensity drop caused by the large mode volume) and results in higher signal to noise ratio beat notes that are useful for the feedback control loops.

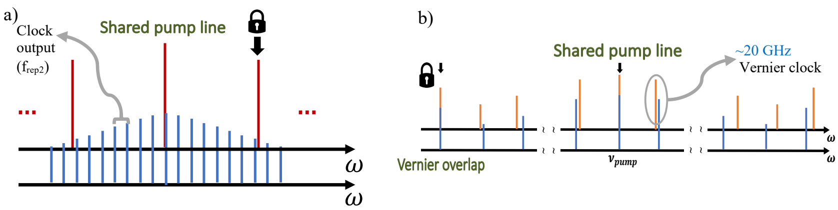

Fig. 1. Comparison of optical dual-comb schemes for the readout of microcomb THz repetition rates. a) Conventional dual-comb division [1]. b) Vernier dual-comb division [4].

Here we report a Vernier measurement of an octave-spanning Kerr comb using two $\sim$ 900 GHz solitons. The solitons are generated from devices fabricated on the same SiN wafer using an optimized subtractive process [5]. To support octave-spanning solitons via dispersion engineering, we have targeted a SiN wafer thickness of 740 nm and a ring-width of 1.64 μm and 1.62 μm for resonators 1 and 2, respectively. Both ring 1 and ring 2 include a pulley coupling section and feature high intrinsic Qs of 4×10^6 and 2.2×10^6, respectively. To align the devices' resonances, we rely on platinum micro-heater deposited on top of the ring waveguide to enable thermal tuning of resonances and offset frequency [6]. The integrated heater on device 2 is utilized to shift the resonance frequency by $\sim$ 250 GHz with an electrical power consumption of $\sim$ 180 mW. A continuous-wave laser at $\sim$1548.3 nm is sent to a carrier suppressed single-sideband modulator driven by a voltage-controlled oscillator (VCO) to control its frequency and is subsequently split into two branches. Each branch contains a SiN coupling stage preceded by an optical amplifier. A single fast ramp to the VCO is sufficient to generate solitons in both devices. After the microrings, a set of beam splitters and wavelength-division multiplexing (WDM) filters are used to suppress the pump, combine the combs, and demultiplex different wavelength bands.

The measured optical spectra are shown in Fig. 2a. The main soliton (device 1) has an octave-spanning spectrum covering 960 nm to 2080 nm. The spectrum of the readout soliton (device 2) is broad enough to observe

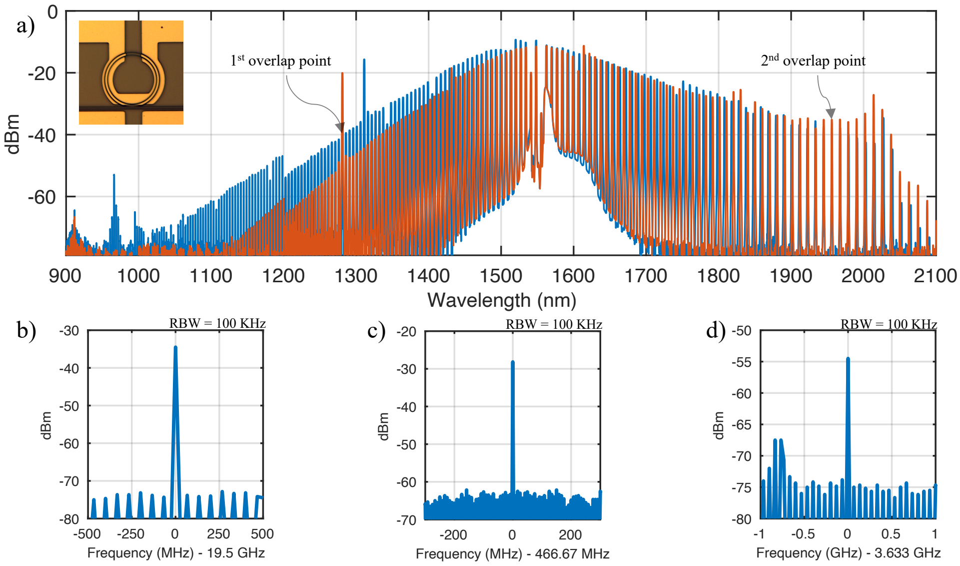

Fig. 2. a) Optical spectra of the main octave-spanning soliton (shown in blue) and the readout soliton (orange). The spectra were split and measured using short-wavelength ($\leq 1.2\ \mu m$) and long-wavelength optical spectrum analyzers. The inset shows a sample microresonator from the wafer. b) The measured δf_{rep} RF beat note. c) The overlap RF beat note. d) Electro-optic measurement of the repetition rate. The modulators are driven by a 17 GHz sinusoid.

two comb-line pairs overlapping at 1281 nm and 1956 nm, respectively. By detecting the beat between the first sideband pairs, we measure a frequency repetition difference $\delta f_{rep} = f_{rep_1} - f_{rep_2}$ of 19.5 GHz. Using WDMs, we separate the short-wavelength comb lines below 1.5 μm and detect the overlap beat at 1281 nm using a transimpedance amplified photodetector, and measure a beat note frequency of 466.67 MHz. The main comb repetition rate then is $f_{rep_1} = 46 \cdot \delta f_{rep} \pm f_{overlap}$, which gives either 897.467 GHz or 896.533 GHz. The $M_2 = 46$ factor and the sign ambiguity (i.e. $\pm f_{overlap}$) can be determined from the optical spectra traces. Alternatively, they can be determined by detecting the beat frequency between the sideband pair adjacent to the overlap point, or by dithering the repetition rate and measuring the change in $f_{overlap}$ and δf_{rep}.

To verify the repetition measurement results based on the Vernier division, we measure the main soliton repetition rate using electro-optic downconversion. Two adjacent comb lines are band-pass filtered and sent to a tunable electro-optic (EO) frequency comb generator driven at 17 GHz [7]. The imparted sidebands overlap midway between the two comb lines. We filter and amplify the overlapping EO sidebands before photodetecting them and measure a frequency of 3.633 GHz (see Fig. 2d). By dithering the EO modulation frequency, we determine the repetition rate to be 53×17 GHz $-$ 3.633 GHz $=$ 897.367 GHz. Note that these beat notes are not measured simultaneously and both soliton repetition rates were free-running and not locked, which may contribute to the difference between the Vernier and EO f_{rep_1} measurement. We note that in Fig. 2d, a broadened peak at 2.8 GHz slightly above the noise floor is observed. More investigation is needed to determine whether it arises from the soliton itself or the measurement apparatus.

In conclusion, we fabricate two large repetition rate microring resonators and generate dual solitons simultaneously with a single pump to perform an initial Vernier frequency division demonstration. In the future, we plan to lock the overlap beat and test the coherent division of the Vernier scheme.

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