All-Optical Kerr Synchronization of a Dissipative Kerr Soliton Microcomb to an Optical Reference

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Abstract: We demonstrate Kerr-mediated all-optical synchronization of a dissipative Kerr solition with an external master laser in a single microring resonator. It enables passive frequency division for optical clock metrology applications.

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Numerous optical metrology applications have been rendered accessible using optical frequency combs (OFCs), primarily because of their capacity to create a phase-coherent bridge between microwave and optical frequencies [1]. On-chip OFC integration – typically produced by periodic extraction of a dissipative Kerr soliton (DKS) inside a microring – has significantly reduced power consumption [2], while their compact size and low production costs [3] make them attractive for a wide array of applications. However, stabilizing an on-chip OFC is exceptionally challenging and creating a fully-integrated chip-scale optical clock has yet to be demonstrated. The power of a few comb teeth can be increased by orders of magnitude by so-called dispersive waves (DW) for cavity modes are almost phase-matched with the DKS by employing dispersion engineering unique to photonics platforms [4]. These DWs can be tuned to be harmonic for octave-spanning operation, but their powers remains low due to the intrinsic efficiency of the DKS/pump conversion. Multi-external driving of a DKS has been demonstrated as a promising approach for high power spectral extension [5], yet the system presents multiple carrier-envelope offsets (CEOs). To this extent, metrology applications with integrated frequency combs are still highly challenging to implement, whether for optical clocks or optical synthesizers, which we will emphasize in this work.

Here, we show that DW creation offers close to phase velocity matching resonances with the DKS, which, in addition to widening the comb bandwidth, may be used to synchronize the DKS to an external optical reference inside the same resonator where the DKS is generated. Hence, like Huygens' coupled pendulum experiment [fig. 1(a)], first-order synchronization of a DKS' group and phase velocities to an external on-resonance master laser is made achievable by the coupling supplied by the same nonlinear effect that enables the DKS, namely the Kerr effect inside a single microring. Here, we introduce an individual control of a single comb tooth that, in contrast to earlier work on synchronization between various DKSs [6], enables tuning of

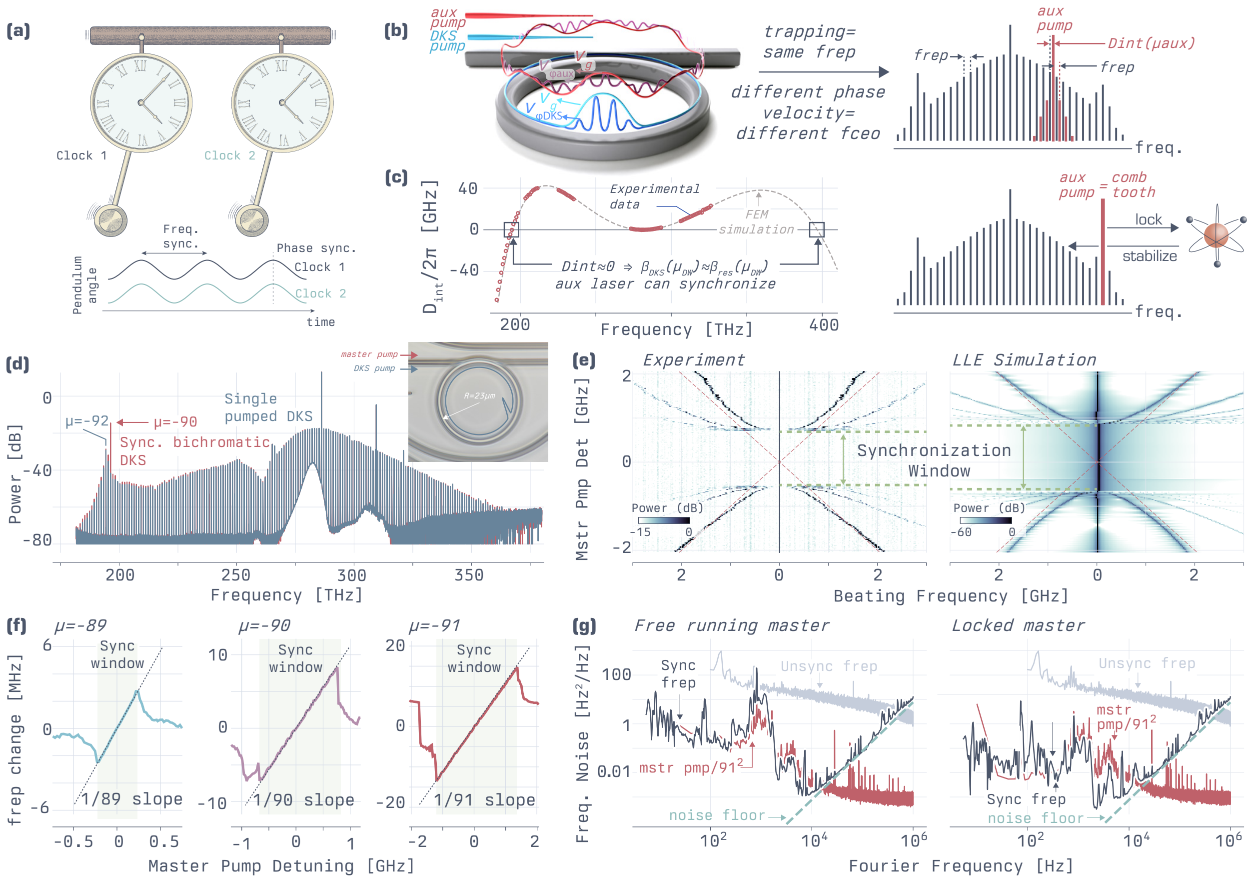

Fig. 1. **(a)** Huygens' experiment of coupled pendulums yielding phase and frequency synchronization. **(b)** Bichromatically driven DKS. The cross-phase modulation traps both wave components yielding the same repetition rate. However the phase velocities are different due to the resonator dispersion, creating an interleaved comb. **(c)** Higher order dispersion allows for D_{int} zero-crossing, yielding close-to phase-matched DKS azimuthal component with the cavity resonance. The phase velocity mismatch between the DKS and the auxiliary laser becomes small enough that synchronization can occur. The auxiliary laser becomes master of the follower DKS as it becomes an OFC comb tooth, which once locked can passively stabilize the DKS. **(d)** Obtained microcomb from the Si_3N_4 microring (inset) pumped at 284 THz with DW at $\mu = -92$ modes away from the pump. The master laser can be injected at several modes around this DW. **(e)** CEO shift measurement with master pump detuning: when there is no synchronization, the difference of phase velocity can be detected as a beat between the two CEOs of the composite comb (colormap). Under synchronization, a single CEO is present and there is an absence of a beat frequency. The LLE model accurately reproduces the experimental results. **(f)** Frequency division: detuning of the master laser leads to a change of the OFC repetition rate, scaling with difference of mode number between the pump and the master laser. **(g)** Noise synchronization: Under synchronization, the repetition rate frequency noise is synchronized to the master laser frequency noise at $\mu = -91$, with a suppression due to noise division scaled by the square of the mode spacing between the pump and the master laser. Locking the master laser (right) reduces low frequency noise.

the repetition rate and CEO frequency of the DKS while frequency dividing the stability of the master laser onto the repetition rate.

An OFC is obtained from a DKS through its periodic extraction at each round trip into a bus waveguide, creating a fixed pulse train which, by Fourier relationship, produces the OFC. Therefore, the DKS group velocity translates into the OFC repetition rate while its phase velocity translates into the CEO. Usually, under bichromatic pumping in a single resonator, the Kerr effect through cross-phase modulation is strong enough to trap the wavepacket components to obtain a single group velocity, thus a single repetition rate [7,8]. The interplay between the microring dispersion and the dispersion-less nature of the DKS, for which the auxiliary laser must be sent on resonance, results in an offset in phase velocity between each wave packet component. It is represented in the OFC as various CEO frequencies [5,8] that are directly related to the integrated dispersion (D_{int}) at the auxiliary laser mode [fig. 1(b)]. Even if spectral extension is possible [5], its use in an integrated optical clock is restricted due to the higher number of frequencies that must be locked for metrology applications. Broad spectral extension typically occurs for large D_{int} at the auxiliary laser mode, resulting in a large shift between CEO frequencies. However, the integrated microring's higher-order dispersion terms also enable D_{int} zero-crossing and the creation of DWs. Here, the normalized DKS azimuthal components μ are almost resonant and, as a result, nearly phase-matched to the cavity resonance. This attribute may enable synchronization inside the same resonator of the group and phase velocity between the DKS and the on-resonance auxiliary laser. This is in contrast to the spectral extension case where the phase velocity mismatch must be minimized. Consequently, the DKS properties – repetition rate and CEO – are now tied to the external auxiliary laser, functioning as a master, as it essentially becomes a comb tooth of the OFC [fig. 1(c)]. As a result, by utilizing an extra-stable leader master, such as one locked to the two-photon transition of a Rubidium atom, its stability can be directly transferred to the pinned comb tooth and further divided onto the repetition rate. By eliminating the need for active feedback to connect the comb to the atomic element, a passive microcomb optical clock may now be possible.

We employ an integrated microring with $RR = 23$ µm ring radius and $RW = 830$ nm built of 670 nm thick Si_3N_4 embedded in SiO_2 and linked to a bus waveguide in a pulley-like manner for coupling strength control at the DKS pump and the external laser frequencies. We create a single DKS state with a repetition rate of approximately 997 GHz using a continuous-wave pumping power of around 180 mW at 286 THz (1048 nm), presenting a DW at $\mu = -92$ (the mode number μ is indexed to the pump mode μ=0), corresponding to ≈ 194 THz (1544 nm) [fig. 1(d)]. We use a continuously tunable laser centered at $\mu = -90$ and has about 2 mW of power on-chip to first test the synchronization between the DKS and the external laser. Out of synchronization, the obtained OFC should present two interleaved comb components, each with a different CEO, induced by the phase velocity mismatch in the resonator [5,8]. Experimentally, a beat note should be recorded in the electrical domain between the two components with a linear dependence with the master external laser detuning [fig. 1(e)]. However, the linear trend turns parabolic once the laser is adjusted sufficiently close to the synchronization window, as Appleton witnessed in his triode oscillator synchronization experiment [9]. With only around 2 mW of on-chip power for the master laser, we show an absence of beat – the synchronization signature as the external laser becomes a comb tooth – over a range of about 1.75 GHz of master laser tuning range. Using the Lugiato Lefever equation model under multi-driving field [10] from the *pyLLE* freeware, we can reproduce such behavior very accurately by periodically extracting the DKS every-round trip (reproducing the experiment) and probing the frequency difference in CEO between the comb components.

In the synchronized state, with the master laser acting as a comb tooth of the OFC, any frequency tunings allow for fine-tuning of the repetition rate thanks to the frequency division between the pump and the master laser. By electro-optically (EO) modulating two neighboring comb teeth to form an EOcomb driven at about 17.4 GHz and spanning across the DKS repetition rate, we frequency down-converts the close to 1 THz OFC repetition rate to measure and demonstrate this unique feature. One can observe that within the synchronized window, the OFC repetition rate follows a linear trend with the master laser detuning [fig. 1(f)] by scanning the master laser frequency around various modes μ. Furthermore, we demonstrate that the slope of this linear trend matches the mode difference between the DKS pump and the master laser. It is noteworthy that adjusting the repetition rate will affect the CEO frequency. As a result, it can be tuned to make nonlinear interferometer CEO detection in an octave-spanning microcomb easier.

Lastly, we investigate the behavior of the repetition rate noise in synchronization with a master laser. We assess the frequency noise of the OFC while synchronized and unsynchronized using the same EOcomb technique that was used previously. The thermo-refractive noise, a significant component of the frequency noise, dominates in the unsynchronized case [fig. 1(g), gray data]. In contrast, in the synchronized case, this repetition rate noise is highly suppressed [fig. 1(g), blue data] and synced to the master laser frequency noise after accounting for the frequency division factor that scales with the square of the master laser's mode number [fig. 1(g), red data]. When the master laser is either free-running or locked to a 10 MHz Mach-Zehnder interferometer, the repetition rate noise exhibits the same noise pattern as the master laser, a further indication of synchronization and resulting frequency noise division behavior.

To conclude, we have demonstrated that a single microring resonator can simultaneously produce and synchronize a DKS to a master reference, enabling frequency division and transfer of the master laser stability onto the OFC. Our research offers a new perspective on the DKS nonlinear dynamics and a path for integration of microcomb-based optical clocks.

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