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

Grégory Moille,[1,2,*] Jordan Stone,[1,2] Michal Chojnacky,[1,3] Curtis Menyuk,[4] and Kartik Srinivasan[1,2]

[1]Joint Quantum Institute, NIST/University of Maryland, College Park, MD, USA; [2]Microsystems and Nanotechnology Division, NIST, Gaithersburg, MD, USA; [3]Sensor Science Division, NIST, Gaithersburg, MD, USA; [4]University of Maryland at Baltimore County, Baltimore, MD, USA; [*]gmoille@umd.edu

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

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Optical frequency combs (OFCs) have opened up a wide range of optical metrology applications, principally due to their ability to create a phase-coherent bridge between microwave and optical frequencies [1]. Among them are optical clocks, in which a frequency comb serving as a clockwork divides the frequency of an optical atomic transition coherently to achieve state-of-the-art stability [2]. Conventional architectures need an octave-spanning comb with one of the comb teeth actively locked to the laser stabilized to the atomic transition to stabilize the comb carrier-envelope offset (CEO) [fig. 1(a)]. With battery power consumption [3] and foundry fabrication for low production costs [4], both leveraging on-chip OFC integration using a dissipative Kerr soliton (DKS) inside a microring, significant milestones for portable optical clocks have been achieved. However, because of the required electronics' size, complexity, and power requirements, the active stabilization of the comb presents the primary barrier to full integration.

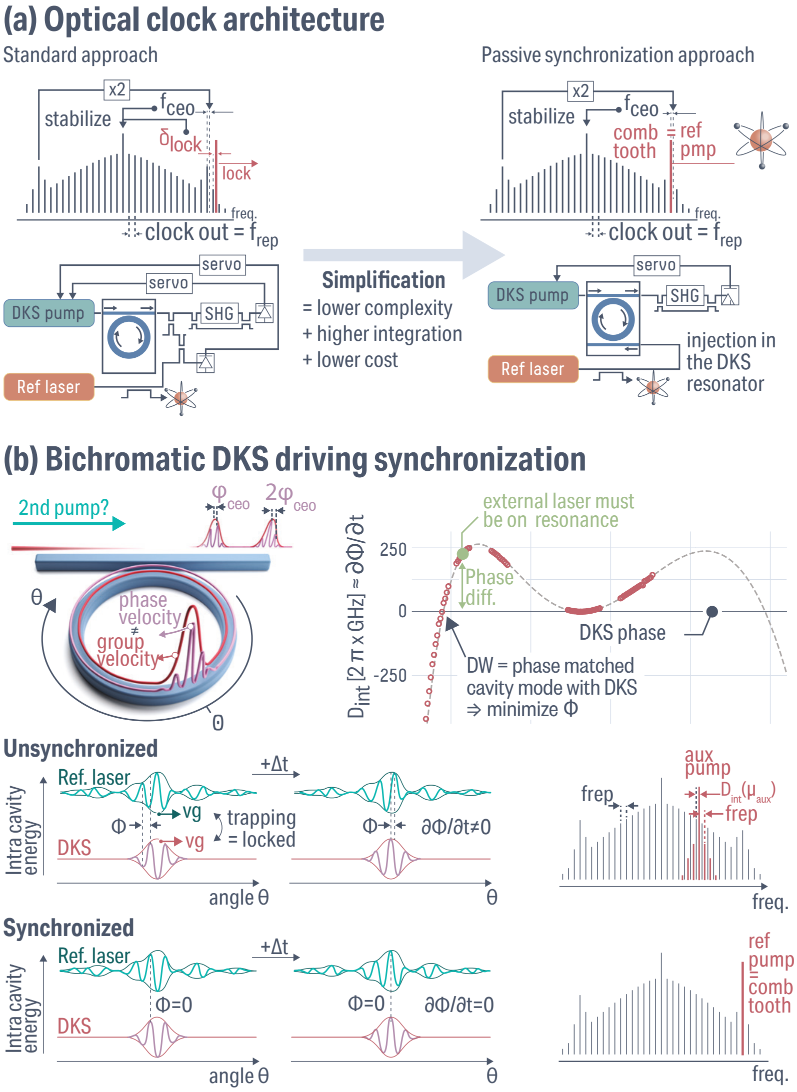

Fig. 1. (a) Current and proposed new optical clock architecture. The reference becoming a comb tooth through passive synchronization allows for a drastic simplification of the clock. (b) Principle of bichromatic DKS driving and synchronization. A DKS presents a group and phase velocity. To synchronize the system, the phase slip – related to D_{int} at the secondary pumped mode – must be minimized. This condition is achieved close to the dispersive wave (DW).

Here, we present a crucial development in the integration of microcomb clockworks. Instead of actively locking the reference laser to the microcomb, we passively synchronized the DKS to this reference through nonlinear interaction by directly injecting the reference laser into the same resonator that produces the DKS microcomb [fig. 1(a)]. As the group and phase velocities of the reference laser exactly match those of the DKS, it is possible to passively impart the stability of the atomic transition onto the microcomb. In order to create such a system, it is crucial to remember that DKSs have two fundamental characteristics: group velocity and phase velocity, which correspond to the microcomb's repetition rate and CEO frequency, respectively [fig. 1(b)]. The group velocity of the various "colors" in the microring – one being the DKS, the other being the secondary pump – is always locked through nonlinear-trapping of the respective envelope [fig. 1(b)], resulting in an equal repetition rate regardless of the secondary pumped mode [5, 6]. However, the reference laser must be sent on resonance for efficient power transfer to the microring. The intrinsic dispersion of the cavity yields a constant phase slip between the DKS and the secondary pump color such that $\partial\Phi/\partial t \neq 0$ with $\Phi = \varphi_{\mathrm{ref}} - \varphi_{\mathrm{dks}}$, yielding a CEO frequency offset between the two comb component [6, 7]. In order to synchronize the different "colors", defined by $\partial\Phi/\partial t = 0$, it is helpful to recall the Adler equation [8] and notice that synchronization happens with a lower coupling strength for $\Phi = 0$. Recalling the integrated dispersion $D_{\mathrm{int}}(\mu) = \omega_{\mathrm{res}} - (\omega_{\mathrm{pmp}} + \omega_{\mathrm{rep}}\mu) \equiv \Phi/t$ with μ the azimuthal mode number relative to the pumped one, its zero crossing allows for dispersive wave (DW) creation that increases the comb bandwidth through resonant interactions [9], but such zero crossing(s) also present the lowest phase difference. Thus, we show that we can accomplish nonlinear synchronization and turn the reference laser into a DKS microcomb tooth by injecting the reference laser close to the DW condition.

We employ an integrated microring with $RR = 23$ μm ring radius and $RW = 830$ nm ring width built of 670 nm thick $\mathrm{Si_3N_4}$ embedded in $\mathrm{SiO_2}$ and linked to a bus waveguide in a pulley-like manner for coupling strength control at the DKS pump and the reference laser frequencies. We create a single DKS state with a repetition rate of ≈ 997 GHz using a continuous-wave

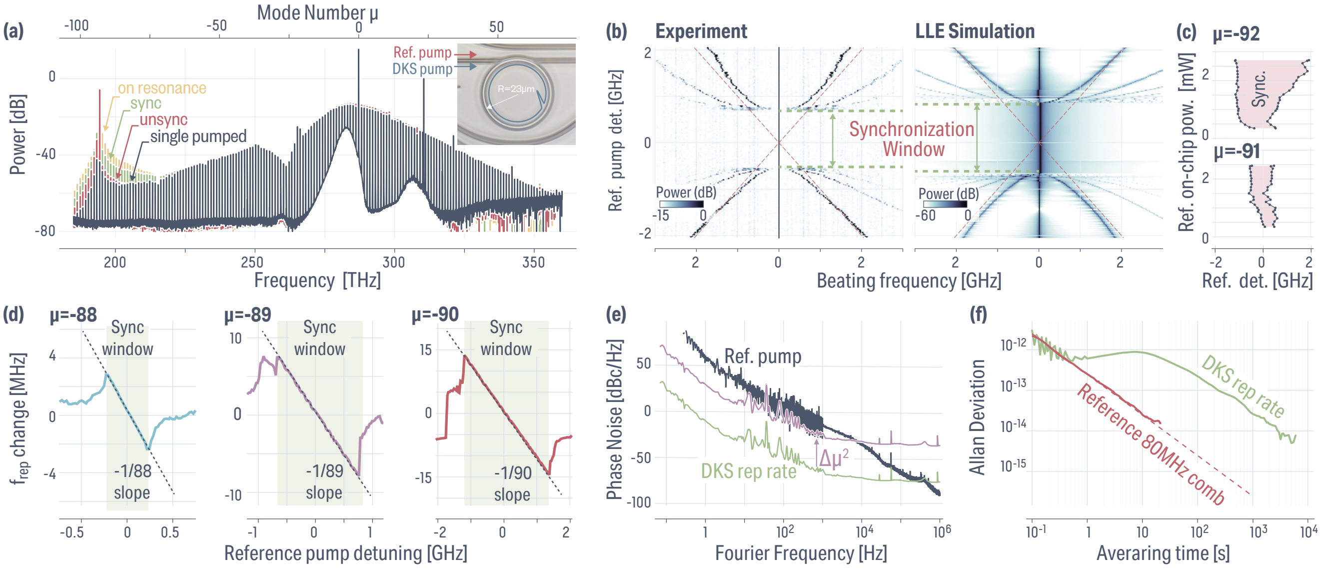

Fig. 2. (a) Microresonator DKS OFC obtained under single pumping (dark blue) and with the reference pump on resonance (yellow), synchronized to the DKS (green) and unsynchronized (red). (b) CEO frequency offset measurement (left) and simulation (right) against the reference laser detuning. The region presenting an absence of a beat is where the reference laser becomes a comb tooth, and therefore demonstrating synchronization. (c) Synchronization region as a function of reference laser power and detuning for two different modes. (d) Disciplining of the OFC repetition rate to the reference laser tuning for different modes and with a fixed main pump. The slope of the repetition rate change against the detuning of the reference laser matches the frequency division factor. (e) Phase noise of the reference pump (dark blue) against the DKS repetition rate phase noise under synchronization (green). In purple we show the scaled repetition rate phase noise according to the frequency division factor. (f) Long term fractional frequency stability measurement through the Allan deviation exhibits a $1/\tau$ slope at long averaging time, highlighting the phase locking to the reference 80 MHz fiber comb. The fiber comb repetition rate is the main source of microwave noise in our system, and its noise is due to its imperfect locking to a reference Rb frequency standard.

pumping power of ≈ 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. 2(a)]. We use a continuously tunable laser centered at $\mu = -92$ and with ≈ 2 mW of on-chip power to act as the reference laser to first test the synchronization. Out of synchronization, the obtained OFC should present interleaved comb components, each with a different CEO, induced by the phase slip in the resonator [6, 7]. Experimentally, a beat note should be recorded in the electrical domain between the two components with a linear dependence with the reference external laser detuning [fig. 2(b)]. However, the linear trend turns hyperbolic once the laser is adjusted sufficiently close to the synchronization window. We show an absence of the beat note – the synchronization signature as the external laser becomes a comb tooth – over a range of ≈ 1.75 GHz of reference laser tuning. 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. We demonstrate that, as expected, the locking window is power dependent [fig. 2(c)] and that multiple modes around the DW exhibit synchronization behavior. In the synchronized state, with the reference laser acting as a comb tooth of the OFC, any reference laser frequency shift allows for fine-tuning of the repetition rate thanks to the frequency division between the pump and the reference laser, assuming the former is fixed. By measuring the repetition rate using an electro-optic comb apparatus [11], one can observe that within the synchronized window, the OFC repetition rate follows a linear trend with the reference laser frequency [fig. 2(d)]. We demonstrate that the slope of this linear trend matches the mode difference between the DKS pump and the reference laser, in accordance with the frequency division principle. 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 noise and stability of this potential clockwork [fig. 2(e)-(f)]. Using a 80 MHz stabilized fiber frequency comb spanning across the two pumps, we are able to phase-lock the main and reference pump to a common reference. The obtained phase noise of the repetition rate of the synchronized microcomb presents a division from the reference pump phase noise according to the OFC comb spacing between the two pump ($\Delta\mu$) of our clockwork. We measure the long term stability of the repetition rate over three uninterrupted hours and demonstrate division by a factor $\Delta\mu$ from the stability of the two pinned pumps to the fiber frequency comb, with a $1/\tau$ behavior indicative of phase stability with the reference. It is important to point out that the main source of microwave noise arises from the repetition rate of the fiber comb, and we show that our DKS OFC reproduce this stability once scaled to its repetition rate. Although the short term stability presents a different behavior, environmental disturbance has not been particularly mitigated, and the behavior is consistent with previously observed stability of a microcomb clockwork [2].

To conclude, we have demonstrated that a single microring resonator can simultaneously produce and synchronize a DKS to a reference, enabling frequency division and transfer of the reference 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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