Synchronization of microresonator optical frequency combs

Jae K. Jang[1,*], Alexander Klenner[1], Xingchen Ji[2,3], Yoshitomo Okawachi[1],
Michal Lipson[3], and Alexander L. Gaeta[1]
[1]*Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA*
[2]*School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA*
[3]*Department of Electrical Engineering, Columbia University, New York, NY 10027, USA*

[*]*Author e-mail address: jj2837@columbia.edu*

Abstract: We experimentally demonstrate passive synchronization of two modelocked microresonator optical frequency combs separated by a path exceeding 20 m of optical fiber. We show that the output temporal cavity solitons can be coherently combined.

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Spontaneous synchronization of coupled nonlinear oscillators is a ubiquitous phenomenon that has been observed in many branches of science, including biology, neuroscience, engineering and physics [1]. In the context of optical physics, extensive studies of this phenomenon have been performed on networks of coupled lasers which have led to the demonstration of their collective phase locking [2] and coherent beam combining [3]. These results have subsequently been extended to the technology of modelocked laser-based optical frequency combs which has resulted in coupled combs with near-identical line spacing. An alternative platform for optical frequency comb generation is based on driven passive nonlinear microresonators [4]. It combines merits of the more conventional laser-based comb technology [5] with additional benefits such as spatial compactness and potential for on-chip integration [6]. Although single microresonator systems have been intensively studied over the past decade [4,6-12], the dynamics of coupled microresonators remain unexplored, and only very recently have there been preliminary numerical results showing evidence of frequency-locking among interacting microresonator combs [11].

Here we report the first demonstration of synchronization of two microresonator-based frequency combs, separated by over 20 m of optical fiber. Such a system offers not only a powerful platform for studying synchronization physics, but can also be used to coherently combine the outputs of multiple modelocked microresonator combs and to synchronize multiple wavelength division multiplexed sources [13,14].

A schematic of our experiment is shown in Fig. 1. We employ two silicon nitride microresonators with waveguide dimension of 730×1500 nm on two independent chips. A single tunable continuous-wave (CW) laser serves as the pump source for both microresonators. Its output is amplified with an erbium-doped fiber amplifier and split into two beams of equal intensity. Each beam is coupled to the integrated bus waveguide of a microresonator with a lensed fiber. We access the cavity soliton-based coherent frequency comb state [8-10] by electrically tuning the integrated microheaters on chips, as detailed in [12]. The output of one microresonator is collected and a small fraction (<1%) is combined with the CW pump field of the second microresonator. This combined field, which contains a portion ("synch signal") of the first ("master") microresonator comb signal, drives the second ("slave") microresonator. The sync signal goes through several passive fiber components whose cumulative length is over 20 m of optical fiber.

Figure 2 shows our experimental results on the synchronization behavior for our system. All results for the synchronized case are plotted in blue while the results of the unsynchronized case are plotted in red. Figure 2(a) and (d) show the optical spectra of the slave comb measured with an optical spectrum analyzer (OSA). In addition, we measure the *combined* optical spectra [Fig. 2(b) and (e)] with a high resolution (10 MHz) OSA, which allows us to resolve individual comb lines. We observe fringes in the synchronized case in Fig. 2(a) and attribute it to stationary interference between the slave comb and the sync signal which encompasses a fraction of the master comb. This is

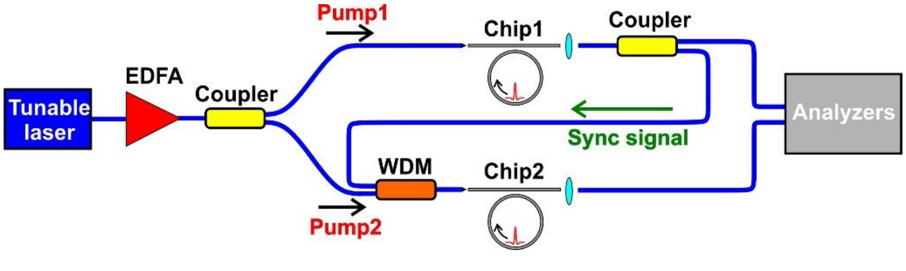

Fig. 1. A simplified schematic of our experimental set-up. EDFA: erbium-doped fiber amplifier, WDM: wavelength division multiplexer.

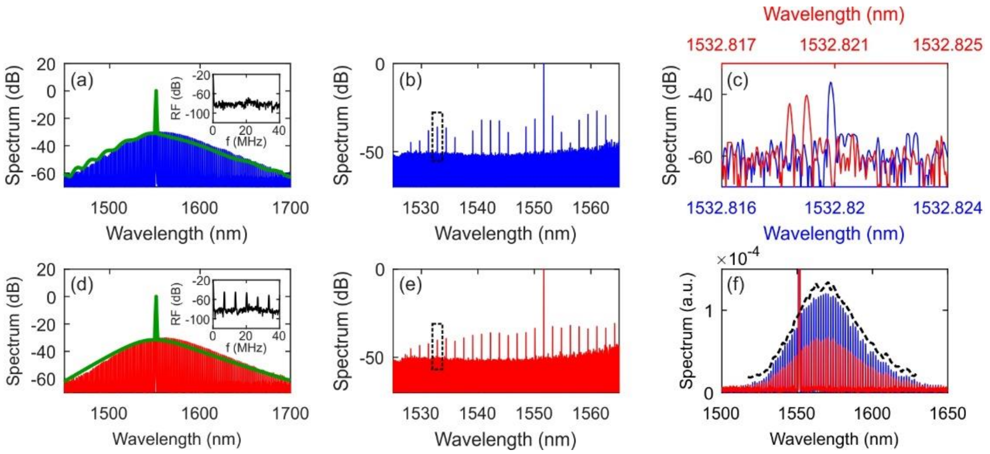

Fig. 2. Plots (a) and (d) show the experimental optical spectra (blue and red) of the slave microresonator output when it is synchronized and unsynchronized, respectively, to the master microresonator. The green curves are the simulated spectra and the insets show the complementary RF beat-note measurements. Plots (b) and (e) are the combined optical spectra measured using a high-resolution optical spectrum analyzer, corresponding to (a) and (d), respectively. Plot (c) shows the zoomed-in traces of (b) and (e) near the 12th blue-detuned comb lines [dashed boxes in (b) and (e)] relative to the pump. The red trace has been numerically displaced by 0.001 nm for clarity. (f) Comparison of the incoherent intensity sum (red) and the coherently combined spectrum (blue), with black dashed curve showing the theoretically expected level.

confirmed both by the complementary radio-frequency beat-note measurements [insets of (a) and (d)] and by the round-trip averaged spectra (green curves) from numerical simulation based on the Lugiato-Lefever equation [8], which are in good agreement with the experiment. Our simulation quantitatively reproduces the interference fringes that manifest during synchronization. It also reveals that the disappearance of the fringes in the absence of synchronization in Fig. 2(d) is due to a relative drift of the circulating cavity solitons in the two microresonators. In the case of synchronization, the combined spectrum in Fig. 2(b) exhibits clear fringes reminiscent of a multiple cavity soliton state in microresonators [12], which indicates that the relative positions of the intracavity solitons are stably locked, *i.e*. the repetition rates are equal. Outside the synchronization regime, the fringes vanish and the spectral envelope becomes smooth, as in Fig. 2(e). Figure 2(c) presents the zoomed-in plots, extracted from Fig. 2(b) and (e) (black boxes), of the 12th comb lines which are blue-detuned relative to the pump. The blue trace corresponding to synchronized combs only exhibits a single comb line, in contrast to the unsynchronized case in the red trace showing two distinct lines. Finally, we investigate the possibility of coherent comb combining by interfering the two comb outputs with a beam splitter. The red curve in Fig. 2(f) shows the incoherent intensity sum of the individual combs through the splitter. In comparison, the blue curve corresponds to the measured combined spectrum when the combs are synchronized. As expected, the spectral power of the coherently combined spectrum is approximately double that of the incoherent sum. The black dashed curve shows the theoretically expected coherent sum of the individual spectra, which is in good agreement with our experimental data. These results provide the first experimental demonstration of synchronization between two microresonator combs, which in this case are separated by an optical path length of > 20 m.

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