Repetition rate tuning of soliton in microrod resonators

Rui Niu\textsuperscript{1,3}, Shuai Wan\textsuperscript{1,3}, Shu-Man Sun\textsuperscript{1,3}, Tai-Gao Ma\textsuperscript{1,3}, Hao-Jing Chen\textsuperscript{1,3}, Wei-Qiang Wang\textsuperscript{2,4}, Zhizhou Lu\textsuperscript{2,4}, Wen-Fu Zhang\textsuperscript{2,4}, Guang-Can Guo\textsuperscript{1,3}, Chang-Ling Zou\textsuperscript{1,3}, Chun-Hua Dong\textsuperscript{1,3,†}

\textsuperscript{1}Key Laboratory of Quantum Information, CAS, University of Science and Technology of China, Hefei, Anhui 230026, P. R. China
\textsuperscript{2}State Key Laboratory of Transient Optics and Photonics, Xi’an Institute of Optics and Precision Mechanics (XIOPM), Chinese Academy of Sciences (CAS), Xi’an 710119, China
\textsuperscript{3}CAS Center For Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China and \textsuperscript{4}University of Chinese Academy of Sciences, Beijing 100049, China

(Dated: September 19, 2018)

The coherent temporal soliton in optical microresonators has attracted great attention recently. Here, we demonstrate the dissipative Kerr soliton generation in a microrod resonator, by utilizing an auxiliary-laser-assisted thermal response control. By external stress tuning, the repetition rate of the soliton has been controlled over a large range of 30 MHz. Our platform promises precise tuning and locking of the repetition frequency of coherent mode-locked comb in the microresonator, and holds great potential for applications in spectroscopy and precision measurements.

Benefiting from the strongly enhanced nonlinear optics effects in high-quality (Q) factor whispering gallery (WG) microresonators, frequency combs have been observed in various experimental platforms via cascaded nonlinear processes [1–5]. In 2014, it was demonstrated that the coherent frequency comb, which is called temporal soliton state, can be generated spontaneously by the competition of Kerr nonlinearity, continuous laser driving and dissipation in a crystalline WG microresonator [6, 7]. The dissipative Kerr soliton (DKS) offers broadband low-noise frequency comb in frequency-domain, or the femtosecond pulse train in the time-domain. Such DKS attracted great attention immediately [8], and has been realized in various material and photonic platforms [9–12], and has also been extended to different frequency bands [13–16]. The DKS in microphotonic cavities has the merits of scalability, stability, portability and low power consumption, thus it holds great potentials for applications in ultrahigh data rate communication [17], high precision optical ranging [18, 19], dual-comb spectroscopy [20], low-noise microwave source [21], optical clock [22] and astronomical spectrometer calibration [23].

Although great progress has been achieved on the proof-of-principle demonstration of applications of soliton microcombs, there are still many practical challenges when comparing the soliton microcomb with the commercial products based on bulky optics and fiber optics counterparts. For instance, in the scenarios of time-keeping and precision spectroscopy [24], the stabilization of the repetition rate ($f_{\text{rep}}$) of the soliton microcombs is essential. However, the $f_{\text{rep}}$ varies from resonator to resonator, and is also sensitive to environment temperature and pump power. Therefore, the efficient tuning of the $f_{\text{rep}}$ is on demand for soliton microcombs. In the past few years, though the $f_{\text{rep}}$ of incoherent frequency comb in microcavities has been effectively tuned by various methods, such as thermal tuning [25], mechanical tuning [26] and pump frequency tuning [27], their applications in soliton microcomb have not been demonstrated yet.

In this letter, we experimentally demonstrate the effective tuning of the repetition rate of DKS in a microrod cavity. By introducing an auxiliary laser to excite the mode that is excluded from soliton microcomb generations [28–30], the cavity thermal response is effectively adjusted and the switching to the DKS can be stably achieved. Based on such a controlling approach, we realized the DKS in the microrod under different external bias stress, and successfully tuned the repetition rate $f_{\text{rep}}$ of the soliton microcomb over 30 MHz. Our platform allows the stabilization of the device temperature by the auxiliary laser, precise and fast tuning of the $f_{\text{rep}}$, thus making it potential for locking soliton microcomb.

Figure 1(a) shows the home made microrod resonator and the associated mechanical tuning setup. The microrod cavity is fabricated from a fused silica rod, where the surface is deformed by heating the rod with a focused CO\textsubscript{2} laser beam and simultaneously rotating it [26, 31]. This microrod resonator for frequency comb applications was firstly studied by P. Del’Haye [26, 31, 32], promising an efficient approach to control the $f_{\text{rep}}$. By placing such a rod in our setup, its length and the stress in the material can be changed by applying a voltage to the piezoelectric transducer (PZT). An enlarged photo of the fabricated cavity is shown in Fig. 1(b). There are two taper regions, while the protrudent region in between is a WG cavity providing the confinement potential in the vertical direction of the microrod. The electric field intensity distribution of a typical fundamental WG modes is shown in Fig. 1(c), with the cavity cross-section profile taken from experimental data. The simulation result indicates that light is confined at the equator, and the energy is very close to the surface. When a voltage is applied to the
FIG. 1. (a) The setup for the mechanical tuning of microrod, where a PZT (green block) is used to compress the microrod. (b) The photo of the microrod cavity, with a diameter of about 1.2 mm. (c) The optical microscopy picture of microrod cavity and the corresponding optical mode profile of the whispering gallery modes by numerical simulation. (d) Schematic of the experimental setup of repetition rate tuning. EDFA: erbium-doped fiber amplifier. TF: tunable filter. FPC: fiber polarization controller. DSO: digital oscilloscope. OSA: optical spectrum analyzer. ESA: electrical spectrum analyzer. EOM: electro-optic modulator.

PZT, the material refractive index changes due to the stress and the cavity geometry changes due to the strain, both lead to the changes of resonance frequency and free spectral ranges (FSR). For a DKS microcomb, the repetition rate directly depends on the FSR of the modes close to the pump laser wavelength \( \Delta_{\text{FSR}} = 55.6 \text{ GHz} \), and the intrinsic \( Q \) factors of WG modes are about \( 2 \times 10^8 \). A typical transmission spectrum of the high-Q WGM by sweeping the laser wavelength is plotted in Fig. 2(a), indicating a narrow linewidth of about MHz. Here, the laser power is very low to avoid the thermal effect induced bistability. It is worth noting that the lineshape of the resonance showing a ringing feature, which is a hallmark of ultrahigh-Q resonance, as light could be stored inside the cavity for a long duration of about \( \tau = Q/\omega \) and interfere with the transmitted sweeping laser [33].

In principle, our microrod resonator allows the formation of DKS as long as the group velocity dispersion of the resonances is anomalous around the working wavelength and the power of pump laser exceeds the threshold [6, 7]. Therefore, the microrod resonator is fabricated to satisfy the condition of anomalous dispersion at the telecom wavelength, and the input power of the laser is amplified by an erbium-doped fiber amplifier (EDFA, upto 5 Watt). However, as demonstrated in other experimental platforms [34, 35], in practical the thermal effect prevents us from directly generating the DKS by simply sweeping the pump laser wavelength. To reconcile this challenge, we adopt the thermal response control scheme by using another auxiliary laser that couples the traveling wave WG resonator in the counter-clockwise (CCW) direction [28], as depicted by the red circuits in Fig. 1(d). The light in CW (pump and generated comb) and CCW (auxiliary laser) directions are separated by two circulators [29, 36], with the polarization of each laser is controlled.

FIG. 2. (a) The typical optical mode spectrum at 1546 nm which is measured at sweeping speed 2.6 MHz/\( \mu \)s. The red line represents the theoretic fitting result with \( Q_0 = 2 \times 10^8 \). (b) Schematic of auxiliary-laser-assisted thermal response control method. (c) Experimental transmission of pump (blue) and auxiliary (red) lasers, the pump laser settles on a low-noise soliton step. (d) Optical spectrum of single DKS, the red line shows the spectral sech\(^2\) envelope.
by the fiber polarization controllers (FPCs). And then the transmission data and optical spectrum are recorded by the digital oscilloscope (DSO) and the optical spectrum analyzer (OSA), respectively.

Figure 2(b) illustrates the mechanism of the auxiliary-laser-assisted DKS generation [28–30]. Firstly, the pump and auxiliary laser are settled at blue-detuning side of the cavity mode. In the experiment, pump power and auxiliary power were set at about 800 mW. When the auxiliary laser drop out of a cavity mode, the cavity cools down rapidly and the resonance blue shifted, effectively scanning the pump to reach the DKS state. Figure 2(c) shows the actual experimentally dynamics of pump laser and auxiliary laser, the green region means that the auxiliary laser launches a “kick” to the pump, only the latter one triumphantly pushed the pump to the DKS state, while the success rate mainly depends on the detuning of pump and auxiliary lasers. By applying such a thermal response control method, we eventually reached single soliton state, as shown in Fig. 2(d).

To validate the DKS microcomb generation in our experiments, we characterized the output frequency combs in detail by resuming the optical spectrum and the radio frequency (RF) beat note of comb lines. Limited by the detection range of our detector and electrical spectrum analyzer (ESA), we used an electro-optic modulator (EOM) modulated with frequency of $\Omega = 20$ GHz to down convert the beat note signal to less than 20 GHz. Based on the preknowledge about the range of FSR in our cavity, we can exactly determine the $f_{\text{rep}} = f_{\text{rep}}' + 2\Omega$ while $f_{\text{rep}}'$ is the measured frequency in ESA. Typical results for different microcomb states achieved in our system are plotted in Fig. 3. When the pump was blue detuned, the microrod frequency comb exhibited low-noise primary comb state, the corresponding RF signal of primary comb state was too large to be detected due to the limited modulation depth of EOM (Fig. 3(a)). When we precisely increased the pump laser wavelength, the high-noise modulation instability (MI) state was achieved with single FSR spacing while RF noise signal bandwidth was about 10 MHz, as shown in Fig. 3(b). Then, we carefully scanned the auxiliary laser to precisely control the effective pump detuning, thus realize the switching to soliton state with high probability. For a typical multi-soliton state in Fig. 3(c), the RF noise background is reduced by about 20 dB and the noise peak bandwidth is also reduced by 20 dB (to 100 kHz) comparing to the MI state.

Since our system has the advantages of fast and convenient adjustment of the structure, we demonstrate a mechanism for tuning the repetition rate precisely through applying a mechanical force along the vertical direction of the microrod. In our experiment, we applied voltages on the PZT, and adjusted the microrod frequency comb exhibited low-noise microcomb under different PZT voltages. (b) The RF beat note with different PZT voltages. (c) The dependence of RF beat note frequency with the different applied PZT voltage. (d) The variation of the RF frequency for pump detunings at the different applied PZT voltage.
ferent voltage on PZT. Due to the limited resolution of OSA (0.02 nm), the offset of the comb lines for different voltages is hardly distinguished. Therefore, the tuning of $f_{\text{rep}}$ can only be accurately inferred from RF spectra, as shown in Fig. 4(b). Through increasing the applied voltage step by step, the repetition rate variation was recorded and shown in Fig. 4(c), which indicates the repetition rate reduces by nearly 30 MHz with the voltage applied to 80 V, and the decreasing rate get slower after 40 V. The nonlinear slope of the $f_{\text{rep}}$ tuning may attributed to the nonlinear response of the PZT. The adjustable range of the repetition rate is mainly restricted by the acceptable voltage of PZT (120 V at most) for the moment. It is also known that the repetition rate of DKS also changes with the pump detuning, which might also be used for $f_{\text{rep}}$ tuning. To test this pump detuning-based $f_{\text{rep}}$ tuning method, we studied the $f_{\text{rep}}$ at each voltage after reaching soliton state by slightly changing the pump detuning. As shown in Fig. 4(d), at each voltage the repetition rate varies 300 kHz at most, which is much less than the variation caused by the PZT. As a consequence, the repetition rate can be precisely changed over a range of 30 MHz, which is two orders larger than the pump-detuning approach.

In conclusion, by introducing an auxiliary-laser-assisted thermal response control, the generation of the DKS in an ultra high Q microrod resonator is demonstrated successfully. And the tuning of the repetition rate of the DKS in a microrod resonator is demonstrated by external stress tuning. The repetition rate of the soliton state can be precisely tuned over a broad band of 30 MHz. Benefitting from the advantage of precisely and fast tuning of repetition frequency of DKS in the microresonator our platform can lock the repetition rate stably, and provides a promising candidate for applications such as metrology, spectroscopy and spectrometer calibration.

This work was supported by the National Key Research and Development Program of China (Grant No.2016YFA0301303), National Natural Science Foundation of China (Grant No.61575184, 11722436, 11874342 and 91536219), and Anhui Initiative in Quantum Information Technologies (AHY130000), the Fundamental Research Funds for the Central Universities. W.Q.W., Z.L. and W.F.Z. acknowledge the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB24030600). This work was partially carried out at the USTC Center for Micro and Nanoscale Research and Fabrication.

[1] T. J. Kippenberg, R. Holzwarth, and S. a. Diddams, “Microresonator-based optical frequency combs,” Science 332, 555–9 (2011).

[2] P. Del’Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, “Optical frequency comb generation from a monolithic microresonator,” Nature 450, 1214–1217 (2007).

[3] Y. K. Chembo, “Kerr optical frequency combs: theory, applications and perspectives,” Nanophotonics 5, 214–230 (2016).

[4] X. Guo, C.-L. Zou, H. Jung, Z. Gong, A. Bruch, L. Jiang, and H. X. Tang, “Efficient Generation of a Near-visible Frequency Comb via Cherenkovlike Radiation from a Kerr Microcomb,” Phys. Rev. Appl. 10, 014012 (2018).

[5] A. Pasquazi, M. Peccianti, L. Razzari, D. J. Moss, S. Coen, M. Erkintalo, Y. K. Chembo, T. Hansson, S. Wabnitz, P. Del’Haye, X. Xue, A. M. Weiner, and R. Morandotti, “Micro-combs: A novel generation of optical sources,” Phys. Rep. 729, 1–81 (2018).

[6] T. Herr, V. Braisch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, “Temporal solitons in optical microresonators,” Nat. Photonics 8, 145–152 (2014).

[7] T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, “Dissipative Kerr solitons in optical microresonators,” Science 361, eaan8083 (2018).

[8] A. M. Weiner, “Frequency combs: Cavity solitons come of age,” Nat. Photonics 11, 533–535 (2017).

[9] W. Wang, Z. Lu, W. Zhang, S. T. Chu, B. E. Little, L. Wang, X. Xie, M. Liu, Q. Yang, L. Wang, J. Zhao, G. Wang, Q. Sun, Y. Liu, Y. Wang, and W. Zhao, “Robust soliton crystals in a thermally controlled microresonator,” Opt. Lett. 43, 2002 (2018).

[10] Z. Gong, A. Bruch, M. Shen, X. Guo, H. Jung, L. Fan, X. Liu, L. Zhang, J. Wang, J. Li, J. Yan, and H. X. Tang, “High-fidelity cavity soliton generation in crystalline AlN micro-ring resonators,” Opt. Lett. 43, 4366 (2018).

[11] Q.-F. Yang, X. Yi, K. Y. Yang, and K. Vahala, “Stokes solitons in optical microcavities,” Nat. Phys. 13, 53–57 (2017).

[12] D. C. Cole, E. S. Lamb, P. Del’Haye, S. A. Diddams, and S. B. Papp, “Soliton crystals in Kerr resonators,” Nat. Photonics 11, 671–676 (2017).

[13] V. Braisch, M. Geiselmann, T. Herr, G. Lihachev, M. H. P. Pfeiffer, M. L. Gorodetsky, and T. J. Kippenberg, “Photonic chip-based optical frequency comb using soliton Cherenkov radiation,” Science 351, 357–360 (2016).

[14] Q. Li, T. C. Briles, D. A. Westly, T. E. Drake, J. R. Stone, B. R. Ilic, S. A. Diddams, S. B. Papp, and K. Srinivasan, “Stably accessing octave-spanning microresonator frequency combs in the soliton regime,” Optica 4, 193 (2017).

[15] S. H. Lee, D. Y. Oh, Q.-F. Yang, B. Shen, H. Wang, K. Y. Yang, Y.-H. Lai, X. Yi, X. Li, and K. Vahala, “Towards visible soliton microcomb generation,” Nat. Commun. 8, 1295 (2017).

[16] M. H. P. Pfeiffer, C. Herkommer, J. Liu, H. Guo, M. Karpov, E. Lucas, M. Zervas, and T. J. Kippenberg, “Octave-spanning dissipative Kerr soliton frequency combs in $\text{Si}_3\text{N}_4$ microresonators,” Optica. 4, 684 (2017).

[17] P. Marin-Pulomo, J. N. Kemal, M. Karpov, A. Kordt, J. Pfeifle, M. H. P. Pfeiffer, P. Trocha, S. Wolf, V. Brasch, M. H. Anderson, R. Rosenberger, K. Vijayan, W. Freude, T. J. Kippenberg, and C. Koos, “Microresonatorbased solitons for massively parallel coherent optical communications,” Nature 546, 274–279 (2017).
[18] P. Trocha, M. Karpov, D. Ganin, M. H. P. Pfeiffer, A. Kordts, S. Wolf, J. Krockenberger, P. Marin-Palomo, C. Weimann, S. Randel, W. Freude, T. J. Kippenberg, and C. Koos, “Ultrafast optical ranging using microresonator soliton frequency combs,” Science 359, 887–891 (2018).

[19] M.-G. Suh and K. J. Vahala, “Soliton microcomb range measurement,” Science 359, 884–887 (2018).

[20] M.-G. Suh, Q.-F. Yang, K. Y. Yang, X. Yi, and K. J. Vahala, “Microresonator soliton dual-comb spectroscopy,” Science 354, 600–603 (2016).

[21] X. Yi, Q.-F. Yang, K. Y. Yang, M.-G. Suh, and K. Vahala, “Soliton frequency comb at microwave rates in a high-Q silica microresonator,” Optica 2, 1078 (2015).

[22] S. B. Papp, K. Beha, P. Del’Haye, F. Quinlan, H. Lee, K. J. Vahala, and S. A. Diddams, “Microresonator frequency comb optical clock,” Optica 1, 10 (2014).

[23] E. M. Rainer, A. Harutyunyan, M. Anderson, M. Geiselmans, B. Chazelas, S. Kundermann, S. Lecomte, M. Cecconi, A. Ghedina et al., “A microphotonic astrocomb,” arXiv:1712.09526 (2017).

[24] S. T. Cundiff and J. Ye, “Colloquium: Femtosecond optical frequency combs,” Rev. Mod. Phys. 75, 325–342 (2003).

[25] X. Xue, Y. Xuan, C. Wang, P.-H. Wang, Y. Liu, B. Niu, D. E. Leaird, M. Qi, and A. M. Weiner, “Thermal tuning of kerr frequency combs in silicon nitride microring resonators,” Opt. Express 24, 687–698 (2016).

[26] S. B. Papp, P. Del’Haye, and S. A. Diddams, “Mechanical control of a microrod-resonator optical frequency comb,” Phys. Rev. X 3, 031003 (2013).

[27] S.-W. Huang, J. Yang, J. Lim, H. Zhou, M. Yu, D.-L. Kwong, and C. Wang, “A low-phase-noise 18 ghz kerr frequency microcomb phasedocked over 65 thz,” Sci. Reports 5, 13355 (2015).

[28] Y. Geng, M. Liao, H. Zhou, B. Wu, and K. Qiu, “Kerr frequency comb dynamics circumventing cavity thermal behavior,” in Nonlinear Opt., (OSA, Washington, D.C., 2017), p. NM1A.4.

[29] Y. Geng, X. Huang, W. Cui, Y. Ling, B. Xu, J. Zhang, X. Yi, B. Wu, S.-W. Huang, K. Qiu, C. W. Wong, and H. Zhou, “Terabit optical ofdm superchannel transmission via coherent carriers of a hybrid chip-scale soliton frequency comb,” Opt. Lett. 43, 2406–2409 (2018).

[30] Z. Z. Lu, W. Q. Wang, W. F. Zhang, S. T. Chu, B. E. Little, M. Liu, L. Wang, C.-L. Zou, C.-H. Dong, B. Zhao, and W. Zhao, “Thermally controlled dissipative kerr soliton switching in a micro-ring resonator,” In preparation.

[31] P. Del’Haye, S. A. Diddams, and S. B. Papp, “,” Appl. Phys. Lett. 102, 221119 (2013).

[32] L. D. Bino, J. M. Silver, M. T. M. Woodley, S. L. Stebbings, X. Zhao, and P. Del’Haye, “Microresonator isolators and circulators based on the intrinsic nonreciprocity of the kerr effect,” Optica 5, 279–282 (2018).

[33] C. Dong, C.-L. Zou, Jin-Ming Cui, Y. Yang, Z. Han, and G.-C. Guo, “Ringing phenomenon in silica microspheres,” Chin. Opt. Lett. 7, 299–301 (2009).

[34] H. Guo, M. Karpov, E. Lucas, A. Kordts, M. Pfeiffer, V. Brasch, G. Lihachev, V. Lobanov, M. Gorodetsky, and T. Kippenberg, “Universal dynamics and deterministic switching of dissipative Kerr solitons in optical microresonators,” Nat. Phys. 13, 94–102 (2017).

[35] X. Yi, Q.-F. Yang, K. Youl Yang, and K. Vahala, “Active capture and stabilization of temporal solitons in microresonators,” Opt. Lett. 41, 2037 (2016).

[36] Z. Shen, Y.-L. Zhang, Y. Chen, F.-W. Sun, X.-B. Zou, G.-C. Guo, C.-L. Zou, and C.-H. Dong, “Reconfigurable optomechanical circulator and directional amplifier,” Nat. Communications 9, 1797 (2018).