



Gigahertz-repetition-rate soliton microcombs

MYOUNG-GYUN SUH  AND KERRY VAHALA*

T. J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA

*Corresponding author: vahala@caltech.edu

Received 4 December 2017; accepted 8 December 2017 (Doc. ID 314893); published 18 January 2018

Soliton microcombs with repetition rates as low as 1.86 GHz are demonstrated, thereby entering a regime more typical of table-top combs. Low rates are important in spectroscopy and relax requirements on comb processing electronics. © 2018

Optical Society of America under the terms of the [OSA Open Access Publishing Agreement](#)

OCIS codes: (140.4780) Optical resonators; (190.4390) Nonlinear optics, integrated optics; (190.5530) Pulse propagation and temporal solitons.

<https://doi.org/10.1364/OPTICA.5.000065>

Since their invention, frequency combs have revolutionized a wide range of applications including spectroscopy, time standards, microwave generation, and laser ranging [1]. Conventional frequency combs are table-top devices and emit ultrashort pulses at repetition rates (i.e., comb line spacing) that typically lie between 100 MHz to 10 GHz [1]. An important recent development has been soliton mode-locking in miniature, high- Q microresonators [2–6]. Compared to earlier microcombs [7], soliton microcombs are stable, offer reproducible spectral envelopes and generate short pulses. Moreover, several conventional comb applications have been demonstrated using soliton microcombs including dual-comb spectroscopy [8,9], dual-comb distance measurement [10,11], and optical frequency synthesis [12].

Because of their small size, soliton microcombs have much higher pulse repetition rates (typically, tens of GHz to several THz) than those of conventional mode-locked laser combs. The small size also enables low parametric oscillation threshold [13] and overall low operating power on account of the associated small mode volume. However, while higher repetition rates (>10 GHz) are useful in certain applications [7,10,14], lower repetition rates (<10 GHz) are desirable to resolve narrower spectral lines [8], to create amplified high-peak-power pulses for continuum generation [15], and to enable use of low-power signal processing electronics [1]. Here, we report soliton microcombs with repetition rates as low as 1.859 GHz, which is substantially lower than other rates reported to date and which also overlaps with rates for conventional frequency combs. The latter feature suggests that soliton microcombs can provide many functions offered by conventional table-top comb technology.

To maintain low threshold and operating power in the lower repetition rate (and larger mode volume) devices, we use

ultra-high quality factor silica wedge disks [16]. The thickness of the silica disk is ~ 8 μm , the wedge angle is typically in the range of 10–40 deg and the soliton repetition frequency is determined by the disk diameter (D) which is controlled with precision 1:20,000. These resonator design parameters can be adjusted to control resonator dispersion, minimize avoided-mode-crossings and (for the rates <11 GHz) avoid stimulated Brillouin scattering [16]. In the experiment, a continuous-wave fiber laser at 1550 nm is amplified by an erbium-doped fiber amplifier and coupled into the microresonators via a tapered fiber coupler [17]. Stable soliton generation uses the capture-lock method [18].

Typical experimental parameters for the soliton microcombs are summarized in Table 1. The intrinsic quality factors (Q_0) of 4.358 GHz and 1.859 GHz soliton microcomb devices are relatively lower because their large size (large exposure field) required use of contact photolithography during microfabrication. Other devices are fabricated using 10:1 projection photolithography (1 cm^2 field). The lower finesse (F) of the larger devices also indicates fabrication-induced differences. Using a larger-field projection tool [16] would improve Q factor, resulting in reduced threshold power (P_{th}) and operation power (P_{pump}) for the lowest-rate devices. Figure 1 shows the optical and electrical spectra of the soliton microcombs with three different repetition rates (f_{rep}) below 10 GHz. The squared hyperbolic secant envelope (dashed red curve in upper panel) indicates single soliton states with 200 fs–300 fs pulse width, which can be further compressed by increasing operation power. The Fig. 1 lower-panel zoom-in spectra and the upper-panel electrical spectra (insets) verify soliton line spacing and repetition rate. The line contrast in the optical spectra decreases as the soliton line spacing approaches 0.02 nm, the spectrum analyzer resolution.

With further optical loss reduction through fabrication process optimization, < 1 GHz repetition rate operation is

Table 1. Experimental Parameters for Soliton Generation

f_{rep} (GHz)	D (mm)	Q_0 ($\times 10^6$)	F ($\times 10^3$)	P_{th} (mW)	P_{pump} (mW)
33 ^a	2.0	180	31	2.2	>23
22.10 ^a	3.0	300	34	1.8	>17
14.61 ^a	4.5	340	26	1.7	>13
9.355 ^a	7.0	670	32	1.2	>25
4.358 ^b	15.0	380	8.6	6.7	>300
1.859 ^b	35.0	460	4.4	14.5	>415

^aProjection lithography.

^bContact lithography.

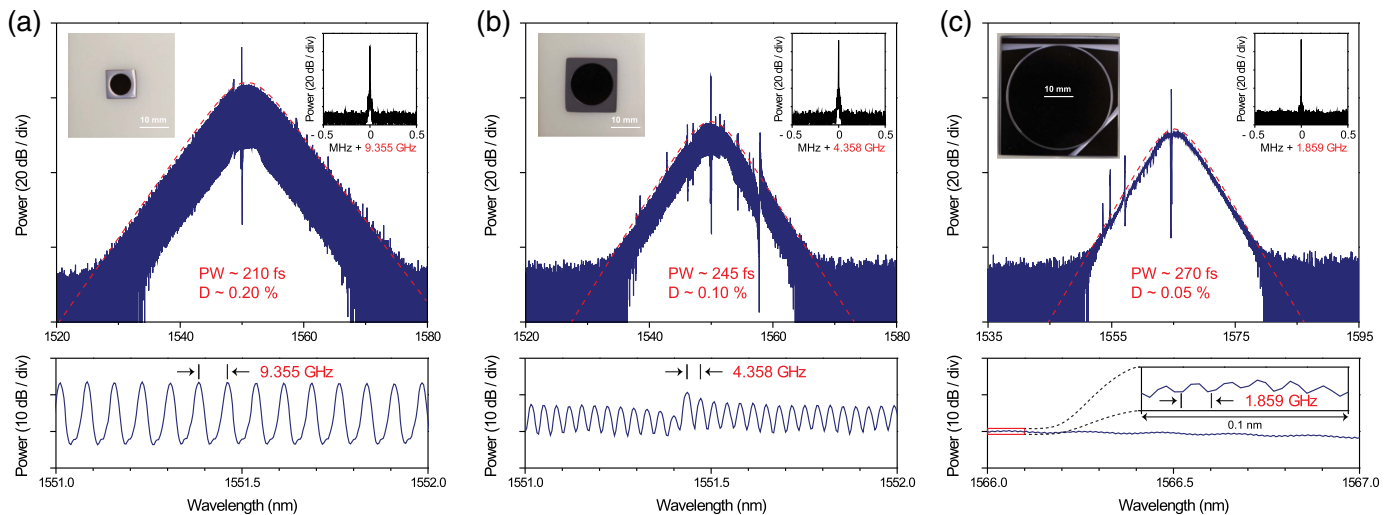


Fig. 1. Soliton microcomb optical spectra at repetition rates: (a) 9.355 GHz, (b) 4.358 GHz, and (c) 1.859 GHz. Upper panel shows optical spectra. Lower panel shows zoom-in spectra of comb lines (resolution is 0.02 nm). Insets: Electrical spectra of the detected soliton pulse streams (resolution bandwidth is 500 Hz) and top-view of microresonators. PW, pulse width; D, duty cycle.

feasible, thereby allowing soliton microcomb operation at precisely controlled rates extending from hundreds of MHz to multiple THz. Moreover, pulse-driven soliton generation [19] is possible at the low rates demonstrated here and can reduce operating power. To reduce footprint in low-repetition-rate designs, spiral resonators [20] could potentially be used. Also, the recent demonstration of silicon-nitride waveguide-coupled silica-ridge resonators can allow these silica soliton microcomb devices to be integrated with other on-chip optical components [21].

Funding. Defense Advanced Research Projects Agency (DARPA) (HR0011-16-C-0118, W911NF-16-1-0548).

Acknowledgment. This work was supported by DARPA under the SCOUT and ACES programs. The authors also thank the Kavli Nanoscience Institute.

REFERENCES

- S. A. Diddams, *J. Opt. Soc. Am. B* **27**, B51 (2010).
- T. Herr, V. Brasch, J. Jost, C. Wang, N. Kondratiev, M. Gorodetsky, and T. Kippenberg, *Nat. Photonics* **8**, 145 (2014).
- X. Yi, Q.-F. Yang, K. Y. Yang, M.-G. Suh, and K. Vahala, *Optica* **2**, 1078 (2015).
- V. Brasch, M. Geiselmann, T. Herr, G. Lihachev, M. Pfeiffer, M. Gorodetsky, and T. Kippenberg, *Science* **351**, 357 (2016).
- C. Joshi, J. K. Jang, K. Luke, X. Ji, S. A. Miller, A. Klenner, Y. Okawachi, M. Lipson, and A. L. Gaeta, *Opt. Lett.* **41**, 2565 (2016).
- P.-H. Wang, J. A. Jaramillo-Villegas, Y. Xuan, X. Xue, C. Bao, D. E. Leaird, M. Qi, and A. M. Weiner, *Opt. Express* **24**, 10890 (2016).
- T. J. Kippenberg, R. Holzwarth, and S. Diddams, *Science* **332**, 555 (2011).
- M.-G. Suh, Q.-F. Yang, K. Y. Yang, X. Yi, and K. J. Vahala, *Science* **354**, 600 (2016).
- M. Yu, Y. Okawachi, A. G. Griffith, N. Picqué, M. Lipson, and A. L. Gaeta, "Silicon-chip-based mid-infrared dual-comb spectroscopy," arXiv:1610.01121 (2016).
- P. Trocha, D. Ganin, M. Karpov, M. H. Pfeiffer, A. Kordts, J. Krockenberger, S. Wolf, P. Marin-Palomo, C. Weimann, S. Randel, W. Freude, T. J. Kippenberg, and C. Koos, "Ultrafast optical ranging using microresonator soliton frequency combs," arXiv:1707.05969 (2017).
- M.-G. Suh and K. Vahala, "Soliton microcomb range measurement," arXiv:1705.06697 (2017).
- D. T. Spencer, T. Drake, T. C. Briles, J. Stone, L. C. Sinclair, C. Fredrick, Q. Li, D. Westly, B. R. Ilic, A. Bluestone, N. Volet, T. Komljenovic, L. Chang, S. H. Lee, D. Y. Oh, M.-G. Suh, K. Y. Yang, M. H. P. Pfeiffer, T. J. Kippenberg, E. Norberg, L. Theogarajan, K. Vahala, N. R. Newbury, K. Srinivasan, J. E. Bowers, S. A. Diddams, and S. B. Papp, "An integrated-photonics optical-frequency synthesizer," arXiv:1708.05228 (2017).
- T. Kippenberg, S. Spillane, and K. Vahala, *Phys. Rev. Lett.* **93**, 083904 (2004).
- P. Marin-Palomo, J. N. Kemal, M. Karpov, A. Kordts, J. Pfeifle, M. H. Pfeiffer, P. Trocha, S. Wolf, V. Brasch, M. H. Anderson, R. Rosenberger, K. Vijayan, W. Freude, T. J. Kippenberg, and C. Koos, *Nature* **546**, 274 (2017).
- J. M. Dudley, G. Genty, and S. Coen, *Rev. Mod. Phys.* **78**, 1135 (2006).
- H. Lee, T. Chen, J. Li, K. Y. Yang, S. Jeon, O. Painter, and K. J. Vahala, *Nat. Photonics* **6**, 369 (2012).
- M. Cai, O. Painter, and K. J. Vahala, *Phys. Rev. Lett.* **85**, 74 (2000).
- X. Yi, Q.-F. Yang, K. Youl, and K. Vahala, *Opt. Lett.* **41**, 2037 (2016).
- E. Obrzud, S. Lecomte, and T. Herr, *Nat. Photonics* **11**, 600 (2017).
- H. Lee, M.-G. Suh, T. Chen, J. Li, S. A. Diddams, and K. J. Vahala, *Nat. Commun.* **4**, 2468 (2013).
- K. Y. Yang, D. Y. Oh, S. H. Lee, Q.-F. Yang, X. Yi, and K. Vahala, "Integrated ultra-high-Q optical resonator," arXiv:1702.05076 (2017).