Towards visible soliton microcomb generation

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Frequency combs have applications that extend from the ultra-violet into the mid-infrared bands. Microcombs, a miniature and often semiconductor-chip-based device, can potentially access most of these applications, but are currently more limited in spectral reach. Here, we demonstrate mode-locked silica microcombs with emission near the edge of the visible spectrum. By using both geometrical and mode-hybridization dispersion control, devices are engineered for soliton generation while also maintaining optical Q factors as high as 80 million. Electronics-bandwidth-compatible (20 GHz) soliton mode locking is achieved with low pumping powers (parametric oscillation threshold powers as low as 5.4 mW). These are the shortest wavelength soliton microcombs demonstrated to date and could be used in miniature optical clocks. The results should also extend to visible and potentially ultra-violet bands.

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Soliton mode locking\textsuperscript{1–5} in frequency microcombs\textsuperscript{6} provides a pathway to miniaturize many conventional comb applications. It has also opened investigations into new nonlinear physics associated with dissipative Kerr solitons and Stokes solitons\textsuperscript{7}. In contrast to early microcombs\textsuperscript{5}, soliton microcombs eliminate instabilities, provide stable (low-phase-noise) mode locking, and feature a highly reproducible spectral envelope. Many applications of these devices are being studied, including chip-based optical frequency synthesis\textsuperscript{8}, secondary time standards\textsuperscript{9}, and dual-comb spectroscopy\textsuperscript{10–12}. Also, a range of operating wavelengths is opening up by use of several low-optical-loss dielectric materials for resonator fabrication. In the near-infrared (IR), microcombs based on magnesium fluoride\textsuperscript{1}, silica\textsuperscript{2,13}, and silicon nitride\textsuperscript{3} are being studied for frequency metrology and frequency synthesis. In the mid-IR spectral region silicon nitride\textsuperscript{16}, crystalline\textsuperscript{17}, and silicon-based\textsuperscript{18} Kerr microcombs, as well as quantum-cascade microcombs\textsuperscript{19}, are being studied for application to molecular fingerprinting.

At shorter wavelengths below 1 µm microcomb technology would benefit optical atomic clock technology\textsuperscript{20}, particularly efforts to miniaturize these clocks. For example, microcomb optical clocks based on the D1 transition (795 nm) and the two-photon clock transition\textsuperscript{21} (798 nm) in rubidium have been proposed\textsuperscript{9,22}. Also, a microcomb clock using two-point locking to rubidium D1 and D2 lines has been demonstrated\textsuperscript{23} by frequency doubling from the near-IR. More generally, microcomb sources in the visible and ultra-violet bands could provide a miniature alternative to larger mode-locked systems such as titanium sapphire lasers in cases where high power is not required. It is also possible that these shorter wavelength systems could be applied in optical coherence tomography systems\textsuperscript{24–26}. Efforts directed toward short wavelength microcomb operation include 1 µm microcombs in silicon nitride microresonators\textsuperscript{27} as well as harmonically generated combs. The latter have successfully converted near-IR comb light to shorter wavelength bands\textsuperscript{28} and even into the visible band\textsuperscript{29,30} within the same resonator used to create the initial comb of near-IR frequencies. Also, crystalline...
resonators and silica microbubble resonators have been dispersion-engineered for comb generation in the 700 nm band. Finally, diamond-based microcombs afford the possibility of broad wavelength coverage. However, none of the short wavelength microcomb systems have so far been able to generate stable mode-locked microcombs as required in all comb applications.

A key impediment to mode-locked microcomb operation at short wavelengths is material dispersion associated with the various dielectric materials used for microresonator fabrication. At shorter wavelengths, these materials feature large normal dispersion that dramatically increases into the visible and ultraviolet bands. While dark soliton pulses can be generated in a regime of normal dispersion, bright solitons require anomalous dispersion. Dispersion engineering by proper design of the resonator geometry offers a possible way to offset the normal dispersion. Typically, by compressing the waveguide dimension of a resonator, geometrical dispersion will ultimately compensate a large normal material dispersion component to produce overall anomalous dispersion. For example, in silica, strong confinement in bubble resonators and straight waveguides has been used to push the anomalous dispersion transition wavelength from the near-IR into the visible phase matching to ultra-violet dispersive waves. However, to compensate the rising material dispersion this compression must increase as the operational wavelength is decreased, and as a side effect, highly confined waveguides tend to suffer increased optical losses. This happens because mode overlap with the dielectric waveguide interface is greater with reduced waveguide cross-section. Consequently, the residual fabrication-induced roughness of that interface degrades the resonator Q factor and increases pumping power (e.g., comb threshold power varies inverse quadratically with Q factor).

Minimizing material dispersion provides one way to ease the impact of these constraints. In this sense, silica offers an excellent material for short wavelength operation, because it has the lowest dispersion among all on-chip integrable materials. For example, at 778 nm, silica has a group velocity dispersion (GVD) equal to 38 ps²/km, which is over five times smaller than the GVD of silicon nitride at this wavelength (>200 ps²/km). Other integrable materials that are also transparent in the visible, such as diamond and aluminum nitride, have dispersion that is similar to or higher than silicon nitride. Silica also features a spectrally broad low-optical-loss window so that optical Q factors can be high at short wavelengths. Here, we demonstrate soliton microcombs with pump wavelengths of 1064 and 778 nm. These are the shortest soliton microcomb wavelengths demonstrated to date. By engineering geometrical dispersion and employing mode hybridization, a net anomalous dispersion is achieved at these wavelengths while also maintaining high optical Q factors (80 million at 778 nm, 90 million at 1064 nm). The devices have large (millimeter-scale) diameters and produce single soliton pulse streams at rates that are both detectable and processable by low-cost electronic circuits. Besides illustrating the flexibility of silica for soliton microcomb generation across a range of short wavelengths, these results are relevant to potential secondary time standards based on transitions in rubidium. Using dispersive-wave engineering in silica it might also be possible to extend the emission of these combs into the ultra-violet as recently demonstrated in compact silica waveguides.
Soliton generation at 1064 nm. Dispersion simulations for TM modes near 1064 nm are presented in Fig. 2a and show that TM modes with anomalous dispersion occur in silica resonators having oxide thicknesses less than 3.7 μm. Aside from the thickness control, a secondary method to manipulate dispersion is by changing the wedge angle (see Fig. 2a). Both thickness and wedge angle are well controlled in the fabrication process. Precise thickness control is possible because this layer is formed through calibrated oxidation of the silicon wafer. Wedge angles between 30° and 40° were chosen in order to maximize the Q factors. The resonator dispersion is characterized by measuring mode frequencies using a scanning external-cavity diode laser (ECDL) whose frequency is calibrated using a Mach–Zehnder interferometer. As described elsewhere, the mode frequencies, \( \omega_m \), are Taylor expanded as \( \omega_m = \omega_0 + \mu D_2/2 + \mu^2 D_3/6 \), where \( \omega_0 \) denotes the pumped mode frequency, \( D_2/2\pi \) is the FSR, and \( D_3 \) is proportional to the GVD, \( \beta_2 \) (\( D_2 = -\beta_2\partial^2/\partial n_0^2 \), where \( c \) and \( n_0 \) are the speed of light and material refractive index). \( D_3 \) is a third-order expansion term that is sometimes necessary to adequately fit the spectra (see discussion of 778 nm soliton below). The measured frequency spectrum of the TM1 mode family in a 3.4 μm thick resonator is plotted in Fig. 2b. The plot gives the frequency as relative frequency (i.e., \( \omega_m = \omega_m - \omega_0 \)) to make clear the second-order dispersion contribution. The frequencies are measured using a radio-frequency calibrated Mach–Zehnder interferometer having a FSR of approximately 40 MHz. Also shown is a fitted parabola (red curve) revealing \( D_2/2\pi = 3.3 \) kHz (positive parabolic curvature indicates anomalous dispersion). Some avoided mode crossings are observed in the spectrum. The dispersion measured in resonators of different thicknesses, marked as solid dots in Fig. 2a, is in good agreement with numerical simulations.

The experimental setup for generation of 1064 nm pumped solitons is shown in Fig. 2c. The microresonator is pumped by a continuous wave (CW) laser amplified by a ytterbium-doped fiber amplifier (YDFA). The pump light and comb power are coupled to and from the resonator by a tapered fiber. Typical pumping power is around 100 mW. Solitons are generated while scanning the laser from higher frequencies to lower frequencies across the pump model. The pump light is modulated by an electro-optic phase modulator (PM) to overcome the thermal transient during soliton generation. A servo control referenced to the soliton power is employed to capture and stabilize the solitons. Shown in Fig. 2d are the optical spectra of solitons pumped at 1064 nm. These solitons are generated using the mode family whose dispersion is characterized in Fig. 2b. Due to the relatively low dispersion (small \( D_2 \)), these solitons have a short temporal pulse width. Using the hyperbolic-secant-squared fitting method (see orange and green curves in Fig. 2d), a soliton pulse width of 52 fs is estimated for the red spectrum. By increasing the soliton power (blue spectrum) the soliton can be further compressed to 44 fs, which corresponds to a duty cycle of 0.09% at the 20 GHz repetition rate. Finally, the inset in Fig. 2d shows the electrical spectrum of the photo-detected soliton pulse stream. Besides confirming the repetition frequency, the spectrum is very stable with excellent signal-to-noise ratio (SNR) greater than 70 dB at 1 kHz resolution bandwidth.

Soliton generation at 778 nm. As the operational wavelength shifts further toward the visible band, normal material dispersion increases. To generate solitons at 778 nm an additional dispersion engineering method, TM1–TE2 mode hybridization, is therefore added to supplement the geometrical dispersion control. The green band region in Fig. 1b gives the oxide thicknesses and wavelengths where this hybridization is prominent. Polarization mode hybridization is a form of mode coupling-induced
dispersion control$^{22,38,39,54}$. The coupling of the TM1 and TE2 modes creates two hybrid mode families, one of which features strong anomalous dispersion. This hybridization is caused when a degeneracy in the TM1 and TE2 effective indices is lifted by a strong anomalous dispersion. This hybridization is caused when a

To verify this effect, resonators having four different thicknesses ($\theta = 40^\circ$) were fabricated and their dispersion was characterized using the same method as for the 1064 nm soliton microresonator using a tapered microfiber. The amplified light is sent into a periodically poled lithium niobate (PPLN) device for second-harmonic generation. The frequency-doubled output pump power at 778 nm is coupled to the microresonator using a wedged angle mirror with a wedge angle $\theta = 90^\circ$. The TM1 and TE2 modes cross each other without hybridization.

Moreover, the tuning of this component occurs over a range of larger oxide thicknesses for which it would be impossible to compensate material dispersion using geometrical control alone. To project the application of this hybridization method to yet shorter soliton wavelengths, Fig. 3g summarizes calculations of second-order dispersion at a series of oxide thicknesses. At a thickness close to 1 micron, it should be possible to generate solitons at the blue end of the visible spectrum. Moreover, wedge resonators having these oxide film thicknesses have been fabricated during the course of this work. They are mechanically stable with respect to stress-induced buckling$^{36}$ at silicon undercut values that are sufficient for high-Q operation.

For soliton generation, the microresonator is pumped at 778 nm by frequency-doubling a CW ECDL operating at 1557 nm (see Fig. 4a). The 1557 nm laser is modulated by a quadrature phase-shift keying (QPSK) modulator for frequency-kicking$^{57}$ and then amplified by an erbium-doped fiber amplifier (EDFA). The amplified light is sent into a periodically poled lithium niobate (PPLN) device for second-harmonic generation. The frequency-doubled output pump power at 778 nm is coupled to the microresonator using a tapered fiber. The pump power is typically about 135 mW. The soliton capture and locking method was again used to stabilize the solitons$^{35}$. A zoom-in of the TM1 mode spectrum for $t = 1.47 \mu m$ with a fit that includes third-order dispersion (red curve) is shown in Fig. 4b. The impact of higher-order dispersion on dissipative soliton formation has been studied$^{58,59}$. In the present case, the dispersion curve is well suited for soliton formation. The optical spectrum of a 778 nm pumped soliton formed on this mode family is shown in Fig. 4c. It features a mode-family branches. The polarization mode hybridization produces a strong anomalous dispersion component that can compensate normal material dispersion over the entire band. Moreover, the tuning of this component occurs over a range of larger oxide thicknesses for which it would be impossible to compensate material dispersion using geometrical control alone.
We have demonstrated soliton microcombs at 778 and 1064 nm using on-chip high-Q silica resonators. Material-limited normal dispersion, which is dominant at these wavelengths, was compensated by using geometrical dispersion through control of the resonator thickness and wedge angle. At the shortest wavelength, 778 nm, mode hybridization was also utilized to achieve anomalous dispersion while maintaining high optical Q. These results are the shortest wavelength soliton microcombs demonstrated to date. Moreover, the hybridization method can be readily extended so as to produce solitons over the entire visible band. The generated solitons have pulse repetition rates of 20 GHz at both wavelengths. Such detectable and electronics-compatible repetition rate soliton microcombs at short wavelengths have direct applications in the development of miniature optical clocks and potentially optical coherence tomography.

**Discussion**

We have demonstrated soliton microcombs at 778 and 1064 nm using on-chip high-Q silica resonators. Material-limited normal dispersion, which is dominant at these wavelengths, was compensated by using geometrical dispersion through control of the resonator thickness and wedge angle. At the shortest wavelength, 778 nm, mode hybridization was also utilized to achieve anomalous dispersion while maintaining high optical Q. These results are the shortest wavelength soliton microcombs demonstrated to date. Moreover, the hybridization method can be readily extended so as to produce solitons over the entire visible band. The generated solitons have pulse repetition rates of 20 GHz at both wavelengths. Such detectable and electronics-compatible repetition rate soliton microcombs at short wavelengths have direct applications in the development of miniature optical clocks and potentially optical coherence tomography. Also, any application requiring low-power near-visible mode-locked laser sources will benefit. The same dispersion control methods used here should be transferable to silica ridge resonator designs that contain silicon nitride waveguides for on-chip coupling to other photonics devices. Dispersive-wave generation at 758 nm was also demonstrated. It could be possible to design devices that use solitons formed at either 778 or 1064 nm for dispersive-wave generation into the visible and potentially into the ultra-violet as has been recently demonstrated using straight silica waveguides.

**Data availability.** The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.
References

1. Herr, T. et al. Temporal solitons in optical microresonators. Nat. Photonics 8, 145–152 (2014).
2. Yi, X., Yang, Q.-F., Yang, K. Y., Suh, M.-G. & Vahala, K. Soliton frequency comb at microwave rates in a high-Q silica microresonator. Optica 2, 1078–1085 (2015).
3. Nez, F., Biraben, F., Felder, R. & Millerioux, Y. Optical frequency determination of the hyperfine components of the 5S12-5D32 two-photon transitions in 87Rb. Phys. Rev. Lett. 113, 123901 (2014).
4. Okawachi, Y. et al. Bandwidth shaping of microresonator-based frequency combs via dispersion engineering. Opt. Lett. 39, 3535–3538 (2014).
5. Liu, Y. et al. Investigation of mode coupling in normal-dispersion silicon nitride microresonators for Kerr frequency comb generation. Optica 1, 137–144 (2014).
6. Ramelow, S. et al. Strong polarization mode coupling in microresonators. Opt. Lett. 39, 5134–5137 (2014).
7. Grudinin, I. S. & Yu, N. Dispersion engineering of crystalline resonators via microstructuring. Optica 2, 221–224 (2015).
8. Yang, K. Y. et al. Broadband dispersion-engineered microresonator on a chip. Nat. Photonics 10, 316–320 (2016).
9. Kippenberg, T. J., Holzwarth, R. & Diddams, S. A. Microresonator-based optical frequency combs. Science 332, 555–559 (2011).
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**Author contributions**
S.H.L., D.Y.O., Q.-F.Y., B.S., H.W. and K.V. conceived the experiment. S.H.L. fabricated devices with assistance from D.Y.O., B.S., H.W. and K.Y.Y. D.Y.O., Q.-F.Y., B.S. and H.W. tested the resonator structures with assistance from S.H.L., K.Y.Y., Y.H.L. and X.Y. S.H.L., D.Y.O., Q.-F.Y., B.S., H.W. and X.L. modeled the device designs. All authors analyzed the data and contributed to writing the manuscript.

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