

High-Power Picosecond Pulsed Kerr Soliton Microcombs

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Dissipative Kerr solitons in optical microresonators offer unparalleled platforms for ultralow-noise, high-repetition rate frequency comb generation with a compact form and driven by a continuous-wave laser. However, despite their attractive properties suited for practical applications, fundamental limitations regarding their output power and conversion efficiency still remain crucial problems that must be overcome. Here we discover unexplored operation regimes of Kerr soliton microcombs yielding high power and a picosecond pulse width by exploiting the strong mode interaction in birefringent crystalline microresonators. We demonstrate experimentally single-soliton microcombs with average powers of up to 24 and 38 mW as well as an improved conversion efficiency with a double-digit percentage and a microwave soliton repetition rate as low as 15.5 GHz. The observations are in agreement with numerical analyses based on the Lugiato-Lefever equation. The presented results not only facilitate novel applications and an architecture based on microresonator frequency combs, but also contribute to a further understanding of soliton physics.

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Introduction—Optical frequency combs generated in Kerr microresonators have attracted significant attention thanks to their self-confined mechanisms with a monochromatic continuous-wave (CW) pump laser [1–3]. Dissipative Kerr soliton (DKS) microcombs realized by balancing dispersion and Kerr nonlinearity, as well as dissipation and parametric gain, offer a compact and coherent connection between optical and microwave frequencies [4–6]. DKSs have already shown exceptional capabilities in various applications, including optical clocks [7,8], radar and LiDAR systems [9,10], optical communications [11,12], frequency synthesis [13], and low-noise microwave oscillators [5,14–16]. An unfortunate limitation of DKSs is the extremely low conversion efficiency of the pump power to the power of the comb lines. This is mainly because a DKS is sustained with an effectively red-detuned pump frequency, leading to most of the pump power being transmitted, namely, not being coupled to the

microresonator. As a result, with single-DKS microcombs generated in an anomalous group-velocity dispersion (GVD) regime, the comb lines typically carry less than a few percent of the input pump power [17–19].

The conversion efficiency of single-soliton microcombs is primarily determined by multiple parameters such as the loss, coupling coefficient, input power, pump detuning, and dispersion coefficient of Kerr resonators [12,17,18,20,21]. In addition to the careful engineering of these parameters, efforts have been made to improve the conversion efficiencies of soliton Kerr combs by utilizing pulsed pumping [22,23], external gain cavities [24,25], and other microcomb states [26–28]. Recently, coupled cavity systems that enable arbitrary control of a single resonance mode have offered a pathway to obtaining highly efficient single-soliton microcombs [29,30].

However, finding a simple and efficient method of obtaining DKSs with a high output power and a high conversion efficiency remains a huge challenge; furthermore, the soliton conversion efficiency is inversely proportional to the comb spacing [17,18]. This trade-off critically imposes the need for the highly efficient driving of soliton microcombs with a microwave-rate repetition frequency.

In this Letter, we demonstrate high-power, high-conversion-efficiency DKS microcombs by exploiting

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the strong mode interactions inherent to ultrahigh-Q magnesium fluoride (MgF_2) crystalline microresonators. The local dispersion profiles induced at a branch of anti-mode crossings (AMXs) help us obtain highly efficient single-soliton microcombs with average powers of up to 24 and 38 mW while maintaining an electrically detectable repetition rate of 15.5 GHz. An approximate theoretical analysis validates our experimental observations and reveals the existence of a region of high-power DKS with a picosecond pulse width. We also show that the presence of resonant radiation boosts the conversion efficiency by up to 28% and the comb line power in addition to the pump frequency. Our results pave the way for exploring undiscovered physical dynamics of DKS microcombs, as well as potential applications that demand high comb power and spectral density with significant low-noise properties.

Experimental results—We begin by considering the crystallographic property of an MgF_2 crystal used as a cavity platform in this Letter. A single-crystal MgF_2 is an optically uniaxial crystal in which incoming light experiences different refractive indices depending on the propagation direction. Such unique behavior is known as optical birefringence, and it should be carefully considered in the design of optical components. With microresonator fabrication, z -cut crystals are usually employed to avoid optical birefringence [4,31,32] with the result that transverse-electric (TE) and transverse-magnetic (TM) modes show greatly different but constant refractive indices as seen in Figs. 1(b) and 1(c). In contrast, the refractive index of the TM mode varies while propagating along the circumference of an x -cut resonator due to the broken optical rotational symmetry. This unique index can be expressed by [33]

$$\frac{1}{n^2(\lambda, \theta)} = \frac{\cos^2 \theta}{n_o(\lambda)^2} + \frac{\sin^2 \theta}{n_e(\lambda)^2}, \quad (1)$$

where $n_o(\lambda)$ (~ 1.3705) and $n_e(\lambda)$ (~ 1.3819) are the refractive indices of ordinary and extraordinary rays at 1550 nm, respectively, obtained from Sellmeier equations, and θ is the angle between the wave vector and the optic axis. As shown in Fig. 1(c), the refractive index of TM polarization oscillates between n_o and n_e while the refractive index of TE polarization remains constant in x -cut resonators.

To confirm the impact of the birefringent property on the microresonator dispersion, we measure and analyze the mode structures for each polarization in z -cut and x -cut resonators. Because tapered fiber coupling is unfit for the polarization-resolved measurement, we utilize a prism coupling system for the dispersion measurement, where we use a Glan-Thompson polarizer to deterministically control the polarization of the input light. The measurement is performed with the calibrated fiber interferometer method [34]. Figures 2(a) and 2(b) show a dispersion

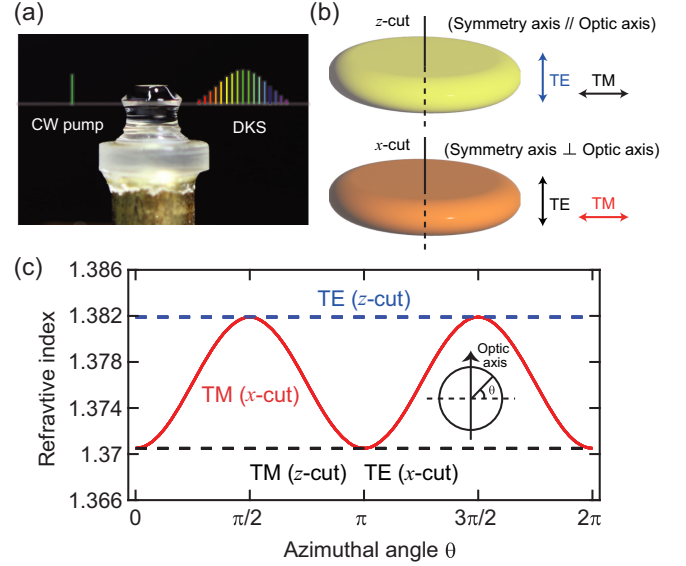


FIG. 1. Birefringent properties in MgF_2 microresonators. (a) Photograph of an MgF_2 microresonator with illustration of Kerr solitons pumped by continuous-wave light. (b) Schematics of the relationship between a cavity symmetry axis and an optical axis for z - and x -cut resonators. (c) Refractive indices for TE and TM modes along the circumference at 1550 nm. The refractive index of TM polarization (solid red line) oscillates between n_o and n_e while the refractive index of TE polarization remains constant (dashed black line) in x -cut resonators. The TE mode (dashed blue line) and TM mode (dashed black line) show constant but different indices in z -cut resonators.

mode map of a z -cut MgF_2 resonator, and Figs. 2(c) and 2(d) depict the fitted results of a representative mode family, yielding the equidistant free-spectral range (FSR) ($D_1/2\pi$) and $D_2/2\pi$ in relation to group velocity dispersion β_2 , as $D_2 = -cD_1^2\beta_2/n$. Similarly, Figs. 2(e)–2(h) show a dispersion mode map and fitted results in an x -cut MgF_2 cavity. Typical GVD values of MgF_2 resonators fall within the range of approximately $\beta_2 \approx -2$ to -10 ps²/km, and the variations result from the presence of spatial higher-order modes that undergo different geometric dispersions.

MgF_2 resonators usually support multiple mode families, resulting in deviations from ideal parabolic dispersion curves (i.e., a large shift of mode frequencies) due to mode interactions as seen in Fig. 2. The large difference in the D_1 of two different polarizations is clearly attributed to the birefringent property. We note that the ratio of D_1 in two polarization modes ($D_1^{\text{TM}}/D_1^{\text{TE}} = 1.0074$) agrees with the ratio of n_o and n_e ($n_e/n_o = 1.0083$) with an error of only 0.09% in z -cut resonators. While the TM mode in x -cut resonators experiences a periodic change in refractive index, the ratio of D_1 , that is $D_1^{\text{TM}}/D_1^{\text{TE}} = 0.9957$, also shows good agreement with a ratio of 0.9959, which is derived from a simple assumption of the average value of two indices, i.e., n_o divided by $(n_o + n_e)/2$, with an error of 0.02%. Another important aspect is that strong mode interactions are more likely to be present in x -cut resonators

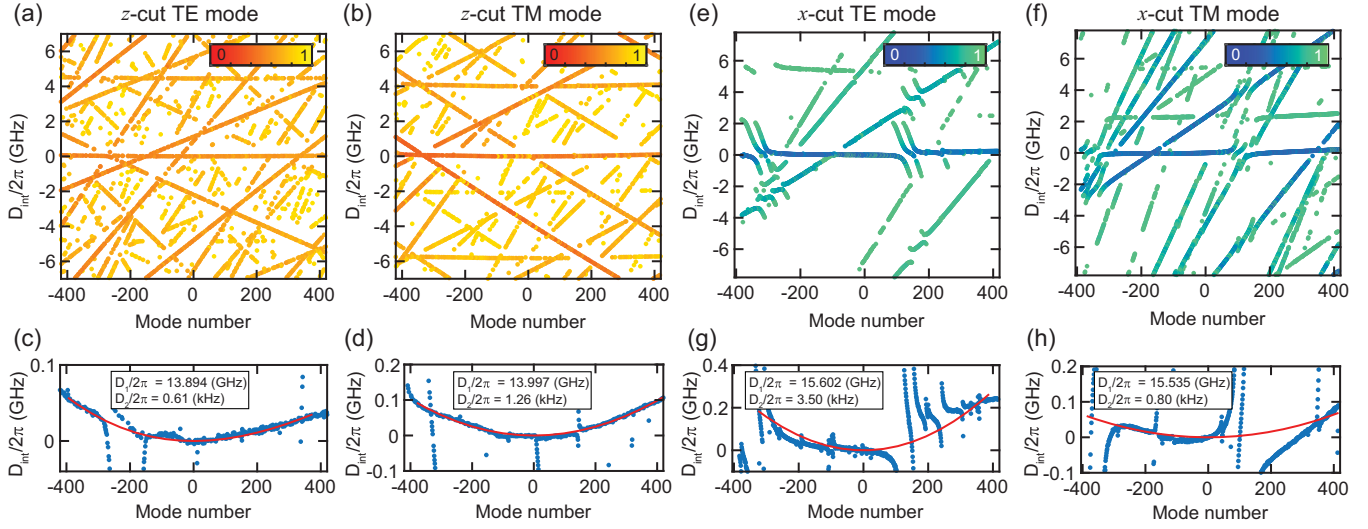


FIG. 2. Measured mode structures and the integrated dispersion of the selected mode family for z -cut and x -cut resonators. The color bar indicates the depth of transmission. The FSR and dispersion are extracted from the measurement data by polynomial fitting. (a),(c) z -cut TE mode, (b),(d) z -cut TM mode, (e),(g) x -cut TE mode, (f),(h) x -cut TM mode. The large difference between the FSRs of the same resonator is attributed to birefringence. The overall dispersion β_2 mostly falls within the range of approximately $\beta_2 \approx -2$ to -10 ps²/km, whereas strong AMXs are more prominent in the x -cut resonators.

than in z -cut resonators. While we witnessed such a prominent birefringent effect on dispersion profiles, we recall that there are very few studies regarding microcomb formation in x -cut MgF₂ resonators. This is mainly because the birefringence causes unwanted strong mode interactions between orthogonal polarization modes [35] that could prevent soliton formation when it occurs in the vicinity of the pump mode [36]. Otherwise, the shifted mode frequencies introduce asymmetric distortions or spikes in a soliton spectrum [37–39], which affect the phase noise performance of soliton microcombs via non-linear coupling [40].

Conversely, the intensive deviation of mode frequencies induced by AMXs gives rise to a unique mode profile, where one branch of the distorted curves exhibits strong local anomalous GVD. Figure 3(a) shows the induced local dispersion observed in x -cut resonators, and such local modes are numerically fitted to obtain local $D_2/2\pi$ values as shown in Figs. 3(b)–3(e). Compared with the moderate overall dispersion ($\beta_2 < -10$ ps²/km), leading to a broad soliton spectrum [32,36,41,42], the local anomalous dispersion is two or more orders of magnitude stronger than the overall dispersion, namely $\beta_2 \approx -1000$ to -2000 ps²/km. The essential key to obtaining high-power Kerr soliton microcombs with a higher conversion efficiency is the use of such *local* dispersion by comparison with *overall* dispersion. According to approximate analytical solutions of the Lugiato-Lefever equation (LLE) [43], we find that the average soliton power and the maximum comb line power are proportional to $|\sqrt{\beta_2}|$ and $|\beta_2|$, respectively. The LLE also yields the laws regarding the conversion

efficiency (CE) as [17,18] $CE = \eta \sqrt{\theta |\beta_2| / (\gamma P_{in})} D_1$, where η is the coupling ratio (i.e., the ratio of the total Q-factor to the external Q-factor), θ is the power coupling coefficient, γ is the Kerr coefficient, and P_{in} is the CW pump power. This formula indicates that strong dispersion scales up the conversion efficiency by a factor of the square root of the GVD value, and thus we can expect a high conversion efficiency exceeding a double-digit percentage, which is substantially higher than the nominal efficiency of DKSs in an anomalous dispersion. It should be noted that the conversion efficiency is typically limited to less than 1% in DKSs with microwave repetition rates [20] due to the proportional relationship between the FSR and CE.

With this guideline in mind, we pump high-Q modes in an x -cut MgF₂ resonator with an FSR of 15.5 GHz. The loaded linewidth of the pump mode is narrower than 1 MHz (i.e., $Q > 2 \times 10^8$). Here we employ tapered fiber coupling to allow us to access a sufficient number of mode families and achieve flexible adjustment of the fiber-resonator coupling rate. Scanning the pump laser frequency with an excitation power of ~ 200 mW, we observe a distinct single step in the transmission light, namely direct evidence of the emergence of soliton microcombs as shown in Fig. 3(f). The noteworthy difference is the height of the step is located closer to the modulation instability (MI) state, implying a higher soliton power compared with conventional single-soliton states. Figures 3(g) and 3(h) show optical spectra of MI states and a single-soliton state, respectively. Both the average power (23.8 mW) and the maximum line power (5.1 mW) are significantly higher

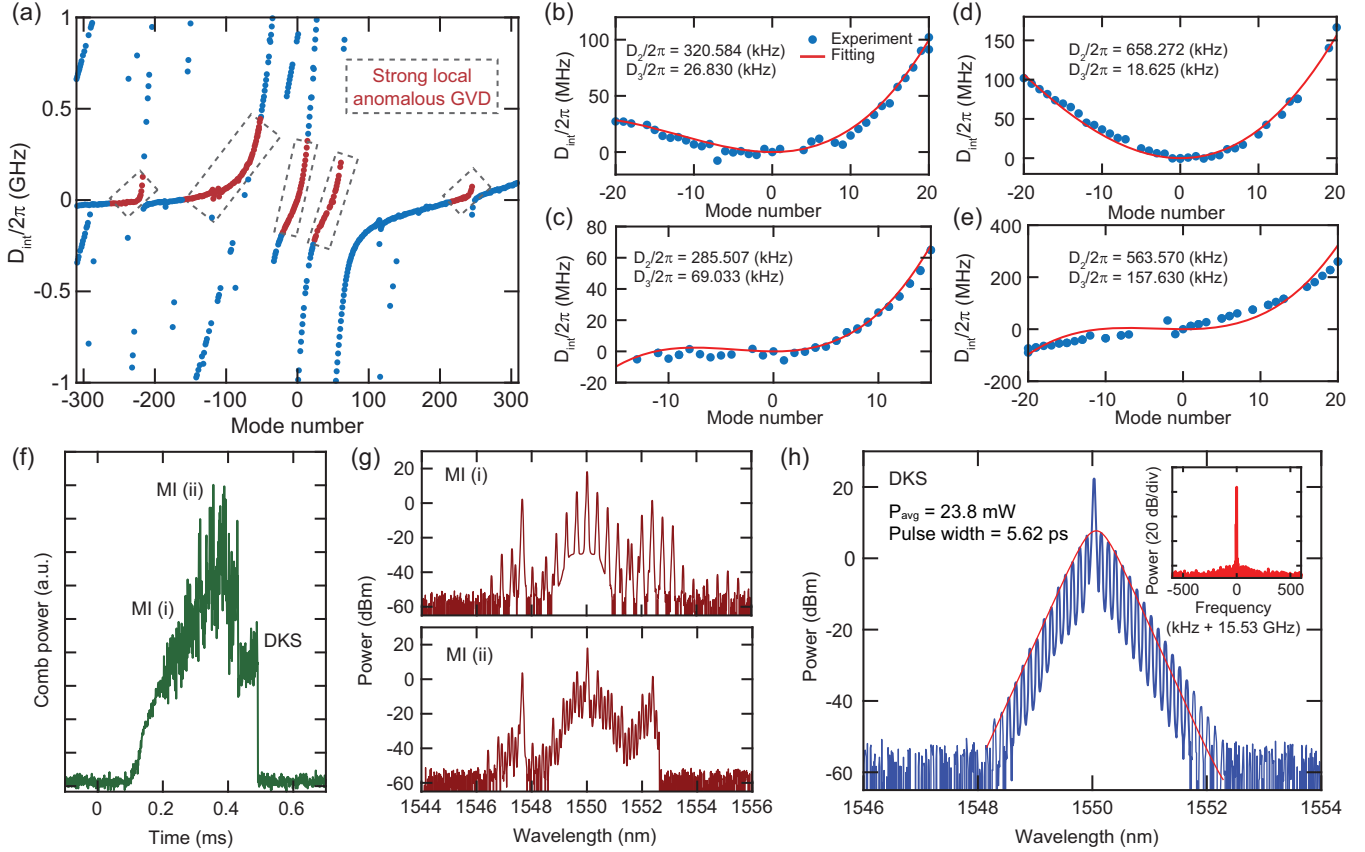


FIG. 3. High-power (HiP) DKS formation in an MgF₂ microresonator with an FSR of 15.5 GHz. (a) Measured integrated dispersion in which the induced local anomalous dispersion regimes are shown with red circles. (b)–(e) The representative local strong anomalous GVD observed in *x*-cut resonators. The local dispersion exhibits strong β_2 with four-digit values, i.e., greater than $-1000 \text{ ps}^2/\text{km}$. (f) Monitored comb power associated with a soliton step. (g) Optical spectra of MI states. The spectrum evolves from a Turing pattern comb to an MI comb. (h) Measured spectrum of a single-DKS state with an average power of 23.8 mW and a CE of 13.8%. The inset shows the soliton beat note signal with a 100-Hz resolution bandwidth.

than those of conventional DKSs; hence, we refer to this type of DKS as a high-power (HiP) DKS for clarity. The observed HiP DKS yields a high conversion efficiency of 13.8% defined as the ratio of the total power of the comb lines excluding the residual pump power that exceeds the soliton envelope to the input power. The square of a hyperbolic secant function yields a pulse width FWHM (pulse duration) of 5.62 ps (3.19 ps). In the resulting spectra, the pump laser is stabilized to the resonance with the Pound–Drever–Hall technique to counteract the fluctuation of the pump detuning [32,44,45], and the soliton state is maintained unless the servo control is turned off. This technique also allows us to estimate the cavity dispersion because the GVD value is determined uniquely by the pulse width and the controlled detuning of 2.7 MHz, yielding $D_2/2\pi = 522 \text{ kHz}$ ($\beta_2 = -1582 \text{ ps}^2/\text{km}$). This is comparable to the fitted values of the local anomalous dispersion induced on the AMX. Theoretical analyses regarding the trade-off between the strong GVD and the spectral bandwidth are provided in Appendix A.

Finally, we report the rich dynamics of HiP solitons by analogy with conventional DKSs. The optical spectra observed in different MgF₂ resonators are shown in Fig. 4 wherein HiP solitons are generated along with a dispersive wave (DW) emission. The local dispersion induced on AMXs tends to exhibit highly asymmetric profiles, thus effectively working as higher-order dispersion [see Figs. 3(d) and 3(e)]. This leads to a DW emission as well as a spectral recoil while sustaining high output powers. With the aid of the strong DWs, the conversion efficiency of the spectrum in Fig. 4(a) reaches 28% with an average power of 37.8 mW, which constitutes significant records for DKSs generated from a single anomalous dispersion microresonator. We would like to stress that in principle, HiP solitons can be generated not only in *x*-cut resonators but also in *z*-cut resonators, provided that a strong AMX accidentally occurs without birefringence. Indeed, we can encounter the spectrum presented in Fig. 4(b) in *z*-cut resonators although it is not often observed.

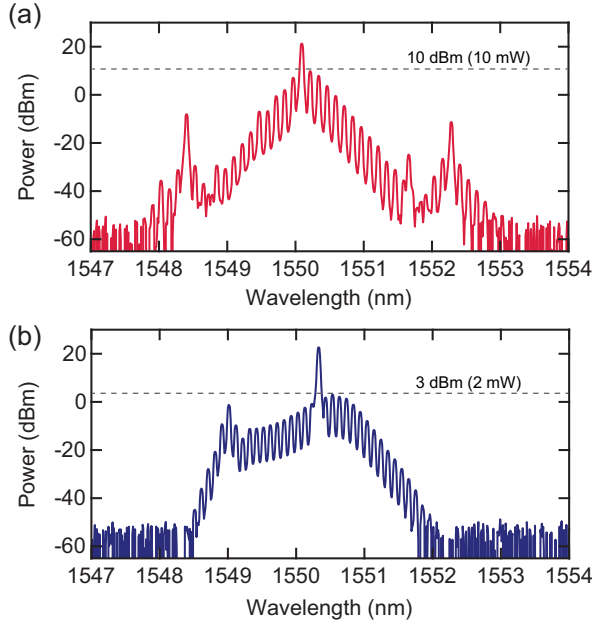


FIG. 4. Optical spectra of soliton microcombs accompanied by dispersive wave emission. (a) Optical spectrum with average power of 37.8 mW and conversion efficiency of 28%. The FSR corresponds to 15.5 GHz, and the comb line power reaches 10 mW at the top of the soliton envelope. (b) Observed optical spectrum in a z -cut resonator with an FSR of 12.6 GHz. The average power and the conversion efficiency are 8.3 mW and 7.5%, respectively.

Discussion—In summary, we have demonstrated HiP DKS microcombs in MgF_2 crystalline microresonators, enabled by the strong spatial mode interaction inherent to ultrahigh-Q microresonators. A strong AMX is stimulated by utilizing the optical birefringence in x -cut MgF_2 resonators that are usually unfavorable for soliton generation but are now employed to enhance both the output comb powers and the conversion efficiency. We theoretically investigated the range in which such soliton states exist, and the results confirmed our experimental observations. Finally, the HiP DKS exhibits a CE of 28% and an average power of 37.8 mW with a pulse width of several picoseconds. The maximum comb line power reaches 10 mW, which represents a substantial power per line for a DKS generated in CW pumped anomalous dispersion microresonators.

A high output power, in return for a narrow bandwidth, offers opportunities for novel microcomb applications as well as new possibilities for traditional applications [46]. In particular, the demonstrated HiP microcombs with microwave-rate repetition frequencies enable direct and efficient optical-to-electrical (OE) conversion without optical amplification, yielding a high signal-to-noise ratio (SNR), low-noise microwave generation [5,14]. This unique feature also enables efficient microwave generation, where the optical signal can be split into multiple branches while still maintaining strong radio frequency (rf) output. The details

of microwave generation and characterization are provided in Appendix B. Beyond microwave photonics, the high output power is also useful for laser processing and seeding applications [47], and the limited bandwidth can simplify dual-comb spectroscopy by suppressing aliasing effects [48]. While larger line spacings are generally preferred in optical communications, high-power comb lines can still be advantageous for applications that require only a few channels with high optical SNRs, such as coherent carrier supply or short-reach interconnects [49]. The mechanism presented here can be applied to the dispersion engineering of integrated platforms and is not limited to the telecom band [50,51]. Our findings provide important guidelines for balancing the soliton comb power with the soliton repetition rate. With further investigation in the future, we believe that this new type of Kerr soliton, the HiP DKS, will play an essential role in practical microcomb-based applications.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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End Matter

Appendix A: Theoretical analyses—HiP DKSs attained by strong anomalous GVD sacrifice the spectral bandwidth as a fundamental trade-off [12]. Analytical solutions of the LLE feature distinct differences in soliton operation regimes as plotted in Fig. 5(a). A GVD

greater than $-100 \text{ ps}^2/\text{km}$ leads to picosecond pulse widths (green shaded region) in contrast to the femtosecond pulse widths of the conventional DKS regime (pink shaded region). Figure 5(b) shows a contour map for the maximum comb line power as a

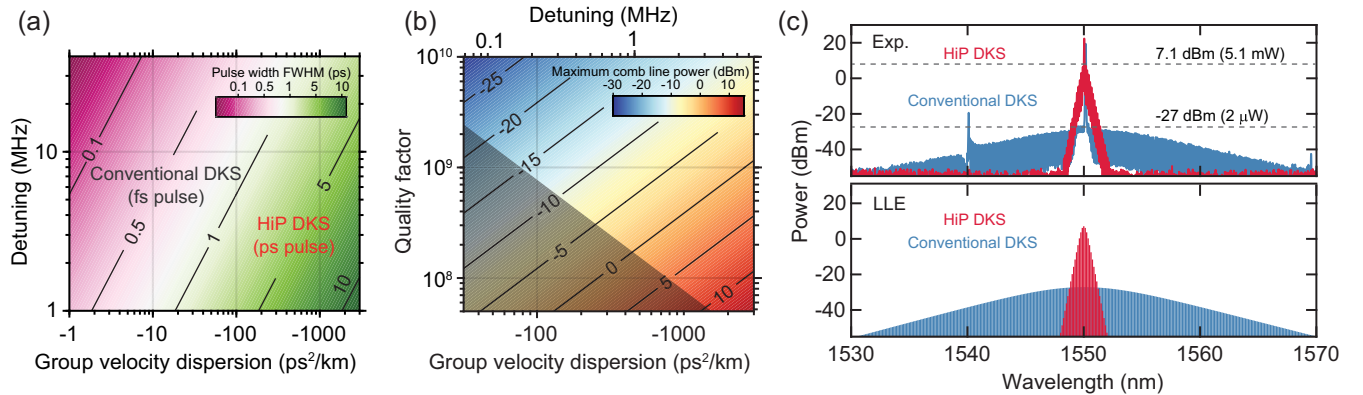


FIG. 5. Comparison of HiP DKSs with conventional DKSs in MgF_2 microresonators. (a) Contour map clarifying soliton pulse widths as a function of GVD and detuning. (b) Contour map for maximum power per comb line. The calculation assumes a soliton pulse width of 5 ps, an FSR of 15.5 GHz, and a coupling ratio $\eta = 0.7$ (slightly over-coupling). (c) Optical spectra of DKSs obtained experimentally and in a numerical simulation with different GVD values ($\beta_2 = -2000 \text{ ps}^2/\text{km}$ for the HiP DKS and $\beta_2 = -3.0 \text{ ps}^2/\text{km}$ for the conventional DKS). The pulse width FWHM of the HiP DKS (conventional DKS) corresponds to 5.5 ps (282 fs).

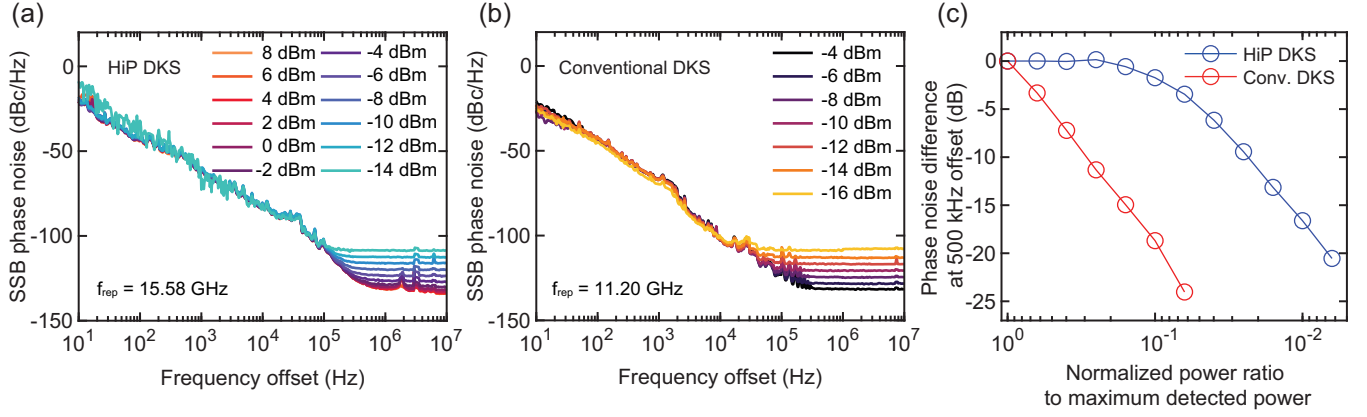


FIG. 6. (a),(b) SSB phase noise spectra under different detected powers for the HiP DKS and the conventional DKS. (c) The variation of the phase noise at a 500 kHz offset as a function of the soliton power normalized to the maximum detected power.

function of the Q-factor and GVD parameters with an FSR of 15.5 GHz and a pulse FWHM of 5 ps. The map reveals the specific region where the comb line power exceeds 5 dBm with a Q of ~ 100 million and an anomalous GVD stronger than -1000 ps²/km. The gray shaded region corresponds to an area where solitons no longer exist that is given by the bistability condition. HiP solitons are only accessible if these conditions are met, but it is a challenge to realize such a strong anomalous GVD with standard geometric dispersion engineering [34]. We believe that the intrinsic properties of ultrahigh-Q crystalline resonators that contain many spatial modes have revealed this specific existence region with the aid of the strong AMX. Figure 5(c) contrasts the optical spectra of HiP and conventional DKSs, showing that our experimental results are in agreement with an LLE simulation. While strong anomalous dispersion limits the spectral span, broader bandwidth can be achieved by operating at higher pump powers and detunings [12,20] and can be further enhanced through mode engineering or DW assistance [37,52].

Appendix B: Characterization of microwave signals—One attractive application of high-power microcombs is photonic microwave generation, as their high average power is highly beneficial for direct and efficient OE conversion. Here we characterize the microwave single-sideband (SSB) phase noise of HiP DKSs and conventional DKSs with microwave-rate repetition frequencies. A HiP DKS with a repetition rate of 15.58 GHz was generated in an *x*-cut resonator, and a conventional broadband DKS with a repetition rate of 11.2 GHz was generated in a *z*-cut resonator. The phase noise was measured using a phase-noise analyzer (FSWP26, Rohde and Schwarz) after photodetection with a high-speed InGaAs photodiode (1414, Newport). To highlight the benefit of the high soliton comb power, no optical amplification was employed prior to

photodetection. An electrical amplifier with a gain of approximately 20 dB was used to ensure the minimum required microwave input power to the analyzer. All other experimental conditions were kept identical.

Figures 6(a) and 6(b) show the SSB phase-noise spectra of the HiP DKS and the conventional DKS when the input power to the photodetector was gradually varied using a variable optical attenuator. The average powers of the HiP DKS and the conventional DKS were 17.7 mW and 0.5 mW, respectively. After residual pump rejection and passage through several fiber branches, the available comb power was reduced to some extent. For the HiP soliton, the comb power was further attenuated to avoid exceeding the maximum input level of the detector (~ 10 dBm). As the comb power was gradually reduced by the attenuator, a plateau region appears in the phase-noise spectra at high offset frequencies, indicating the shot-noise limit.

Figure 6(c) shows the variation of the phase noise at a 500-kHz offset as a function of the soliton power normalized to the maximum detected power, i.e., 8 dBm for the HiP DKS and -4 dBm for the conventional DKS. For the HiP DKS, the phase noise remains almost unchanged even when only a 10% fraction of the comb power is used for photodetection, whereas a ~ 20 dB degradation is observed for the conventional DKS. This power margin for OE conversion is clearly attributed to the high average comb power, highlighting the advantage of HiP DKSs over conventional soliton combs for power-efficient, low-noise microwave generation. This feature offers microwave generation, where the optical signal can be split into multiple branches while still maintaining low-noise rf signals. It should be noted that the calculated shot-noise floor is approximately -150 dBc/Hz for ~ 1 mW input [14]. We therefore expect that measured DKS microcombs are affected by other noise sources, such as laser noise, detuning noise, and dispersive-wave-induced noise, which have been intensively studied in recent works [5,38].