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Multicolor interband solitons in microcombs

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Abstract

In microcombs, solitons can drive non-soliton-forming modes to induce optical gain. Under specific conditions, a regenerative secondary temporal pulse coinciding in time and space with the exciting soliton pulse will form at a new spectral location. A mechanism involving Kerr-induced pulse interactions has been proposed theoretically, leading to multicolor solitons containing constituent phase-locked pulses. However, the occurrence of this phenomenon requires dispersion conditions that are not naturally satisfied in conventional optical microresonators. Here, we report the experimental observation of multicolor pulses from a single optical pump in a way that is closely related to the concept of multicolor solitons. The individual soliton pulses share the same repetition rate and could potentially be fully phase-locked. They are generated using interband coupling in a compound resonator.

Introduction

Dissipative solitons (DSs) in optical microresonators are self-reinforcing, localized wave packets generated through the double balance between propagation loss and nonlinear gain, as well as cavity dispersion and nonlinearity. In optical microresonators, various mechanisms for DS generation have been reported, including Kerr DSs in a $\chi^{(3)}$ medium¹, DSs in optical parametric oscillators², Pockels DSs in a $\chi^{(2)}$ medium^{3,4}, and optomechanical DSs⁵. Solitons can also drive non-soliton-forming modes to induce optical gain. A secondary temporal pulse coinciding in time and space with the exciting soliton pulse can then form. The secondary pulse is not necessarily phase-locked with the exciting pulse, but is synchronized with its repetition rate. Stokes solitons are an example of this multicolor pulse behaviour in which the gain is provided by the Raman interaction⁶.

Also, a new class of complex solitary wave has been theoretically proposed in optical microresonators⁷ with connection to observations in related physical systems^{8,9}, and referred to as multicolor solitons. The multicolor

soliton landscape features dispersive waves originating from a primary soliton. These waves coherently pump another soliton (or several other solitons) via Kerr parametric gain at a different optical frequency (or several optical frequencies). The newly generated solitons coincide with the primary soliton in the temporal domain and share the same group velocity with the primary soliton. The occurrence of this phenomenon requires that the dispersive waves are phase-matched, as well as that the local group velocity is matched between the primary soliton's frequency and the dispersive wave's frequency. These combined dispersion requirements do not naturally exist in usual optical microresonators, and several engineered device structures have been numerically simulated to support such dispersion^{7,10,11}. Several related works use additional pump(s) to generate a secondary soliton (or non-solitonic microcombs) at a different color^{12–14}. However, no experimental demonstrations of multicolor solitons with a single pump (as proposed in ref. ⁷) have been implemented to our knowledge.

Here, we report an experimental observation that is closely related to multicolor cavity solitons¹⁵. The required dispersion is achieved in a three-coupled-ring (3CR) microresonator and controlled via differential heater tuning of the rings. When the primary soliton is generated from a continuous wave (CW) pump laser, it can spontaneously trigger the formation of another soliton (hereafter referred to as the secondary soliton) at a

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different carrier frequency and in a certain cavity-laser detuning regime. The secondary soliton is experimentally confirmed to be a femtosecond pulse that shares the same group velocity with the primary soliton. In contrast to the original multicolor soliton proposal⁷, the multicolor solitons observed here exist on distinct frequency bands (i.e., interband), and thus do not naturally share the same optical phase. However, feedback control of the pump laser is experimentally demonstrated to stabilize the relative optical phase between the two solitons. The central carrier frequency difference of the two solitons at different colors can also be tuned electrically by differential heater tuning of the 3CR, ranging from 0.5 THz to 1.5 THz. The results enrich the soliton family and can be used to extend the spectrum of the soliton. Also, the control and tuning capabilities of the multicolor solitons are potentially useful for high-coherence THz-wave generation.

Results

Generation of multicolor interband solitons

The device used in this work is a three-coupled-ring (3CR) microresonator (Fig. 1a,b)^{16,17}. The scheme of multicolor interband solitons generation is illustrated in Fig. 1a. A primary soliton (red) is first generated by pumping the microresonator with an amplified CW laser at ν_p . The primary soliton induces Kerr parametric gain and an effective potential well due to cross-phase-modulation (XPM) at its temporal location. The secondary soliton (blue) forms with a threshold behaviour, through the double balance between parametric gain and cavity loss, as well as XPM and local anomalous dispersion (detailed in Materials and Methods). The solitons reside in different dispersion bands of the coupled resonators. Moreover, supermodes are delocalized across the structure rather than in a single ring (see Supplement). An idler sideband (orange) is also formed as a result of the

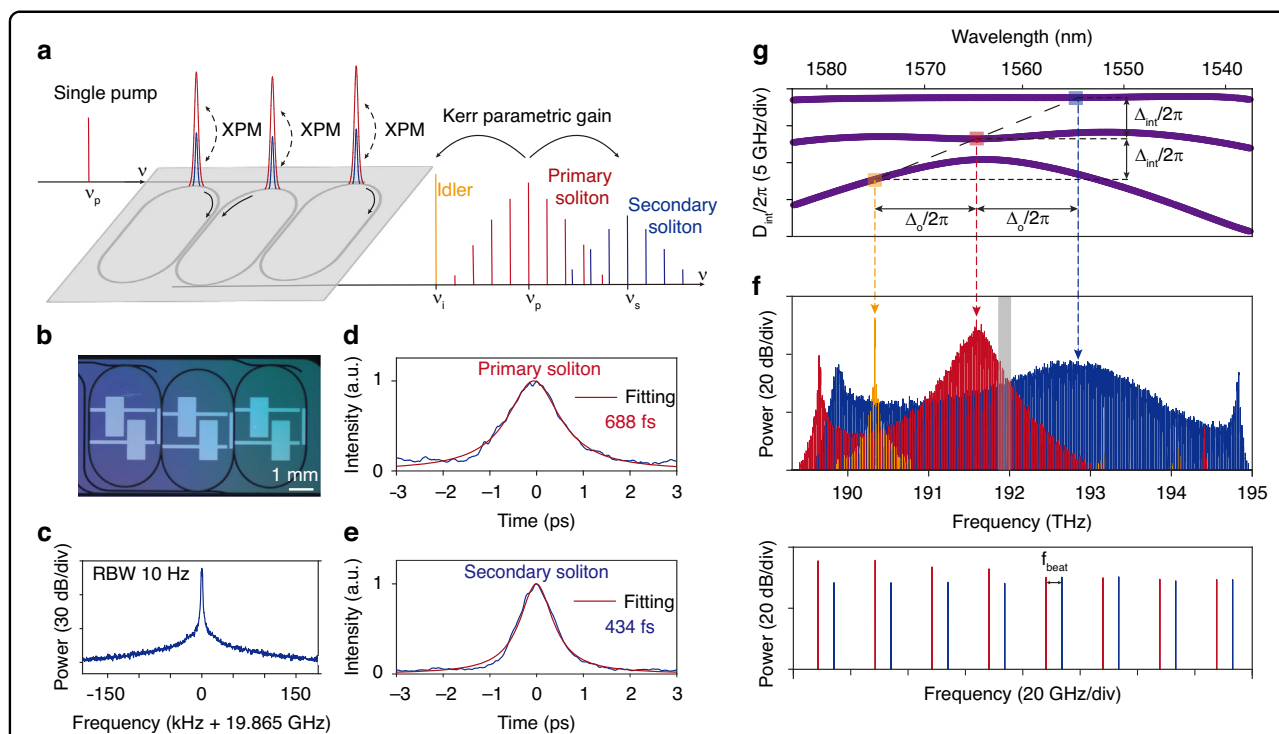


Fig. 1 Generation of the multicolor interband solitons. **a** Conceptual illustration of multicolor interband soliton generation. The primary soliton is generated at the carrier frequency ν_p from a single CW pump. The secondary soliton emerges at a different carrier frequency ν_s (which coincides with the primary soliton in the time domain), accompanied by generation of a four-wave-mixing idler sideband at ν_i . The primary and secondary soliton trap each other to synchronize in the temporal domain via Kerr cross-phase-modulation (XPM). **b** Photograph of the three-coupled-ring device used in this study. **c** RF spectrum of detected pulse train (10 Hz resolution bandwidth). **d, e** Measured autocorrelation traces (blue) and their Lorentzian fitting curves (red) for the primary and secondary solitons. Inferred full-width at half-maximum optical pulse widths are marked. **f** Optical spectrum of multicolor interband solitons. The red, blue and orange spectral lines represent the primary soliton, secondary soliton and idler sideband, respectively. The lower panel is a zoom-in view of the gray shaded area in the upper panel, showing two different sets of comb lines corresponding to two solitons. The frequency spacing between adjacent comb lines is denoted by f_{beat} . **g** Dispersion spectrum for the generation of the multicolor interband solitons. The three-coupled-ring microresonator has three dispersion bands, and is pumped at a mode on the middle band (red). One mode on the upper band (blue) and one mode on the lower band (orange), together with the pumped mode, satisfy the phase-matching condition for parametric oscillation, as indicated by the black dashed line. The secondary soliton and idler sideband are generated near these two modes

four-wave-mixing between the primary and secondary soliton, which cannot yield a soliton due to local normal dispersion in this case, but nonetheless enables phase-matching of the process. It is further noted that the phenomenon is distinct from pulse-triggered or phase-modulation-induced seeding methods for soliton formation, which externally drive soliton formation^{18,19}.

The fact that the secondary soliton shares the same group velocity (repetition rate) is confirmed by the repetition rate measurement using a fast photodetector and an electrical spectral analyzer (Fig. 1c). One single high signal-to-noise ratio (SNR) tone is observed via photo-detection. The temporal pulse nature of the two solitons is confirmed by the auto-correlation measurement (Fig. 1d,e) with the setup detailed in Materials and Methods. The primary soliton features a 688 fs full-width at half-maximum temporal duration, while that of the secondary soliton is 434 fs.

Optical spectra of the generated multicolor solitons are presented in Fig. 1f. The spectra are measured by collecting the output from the bus waveguide coupled to the middle ring (which serves as an effective drop port), and measuring the output using a high resolution optical spectrum analyzer (APEX AP2083A, ~ 10 MHz frequency resolution). In Fig. 1f, the comb lines from the primary soliton are colored in red, while those of the secondary soliton (idler) are in blue (orange). As a modification to the multicolor solitons proposed in ref. ⁷, the carrier-offset frequencies of the two solitons are not necessarily the same. The lower panel of Fig. 1f is a zoomed-in view of the overlapping region between two solitons, indicated by gray shade in the upper panel. Two sets of comb lines separated by a frequency of f_{beat} are observed. The results indicate that no fixed phase relationship between the primary and secondary soliton is guaranteed. However, servo control of the pump laser is possible to force the phase-locking, which will be detailed later.

Dispersion condition for multicolor interband solitons generation

The generation of multicolor solitons requires specific dispersion conditions. In this case, it is addressed by on-demand electrical tuning of the dispersion^{17,20}. The resonator dispersion spectrum that supports the optical spectrum in Fig. 1f is shown in Fig. 1g. The width of the waveguide is chosen to support only the fundamental TE mode for individual rings. Three hybrid mode families are formed, giving rise to three bands in the dispersion spectrum, whereas the mode coupling strength can be found in the Supplement. The primary soliton is pumped at an anomalous dispersion window ($D_{2,p}/2\pi = 374$ kHz) on the middle band near 1565 nm.

To generate the multicolor solitons (secondary soliton), it is first necessary to phase-match to the dispersive waves

on the other bands. Here, interband phase-matching of parametric oscillation is achieved between the three dispersion bands. The parametric process involves two photons from the middle (pumped) band (frequency ν_p close to the cavity resonance at frequency $\nu_{p,c}$), and one photon from each of the upper and lower bands (whose frequencies ν_s, ν_i are near the corresponding cavity resonance with frequencies $\nu_{s,c}$ and $\nu_{i,c}$), respectively, such that

$$\nu_{s,c} + \nu_{i,c} \approx 2\nu_{p,c} \quad (1)$$

with the integrated dispersion at these modes $D_{\text{int},p}, D_{\text{int},s}, D_{\text{int},i}$ satisfying

$$D_{\text{int},s} + D_{\text{int},i} \approx 2D_{\text{int},p} \quad (2)$$

for resonant excitation (phase matching). The phase-matched frequency is indicated by the black dashed line in Fig. 1g. On the dispersion spectrum, the three modes that are phase-matched are equally-spaced both horizontally and vertically, with spacing $\Delta_o/2\pi, \Delta_{\text{int}}/2\pi$ respectively, as a result of eqns. (1)(2) (instead of appearing as a zero-value crossing in D_{int}).

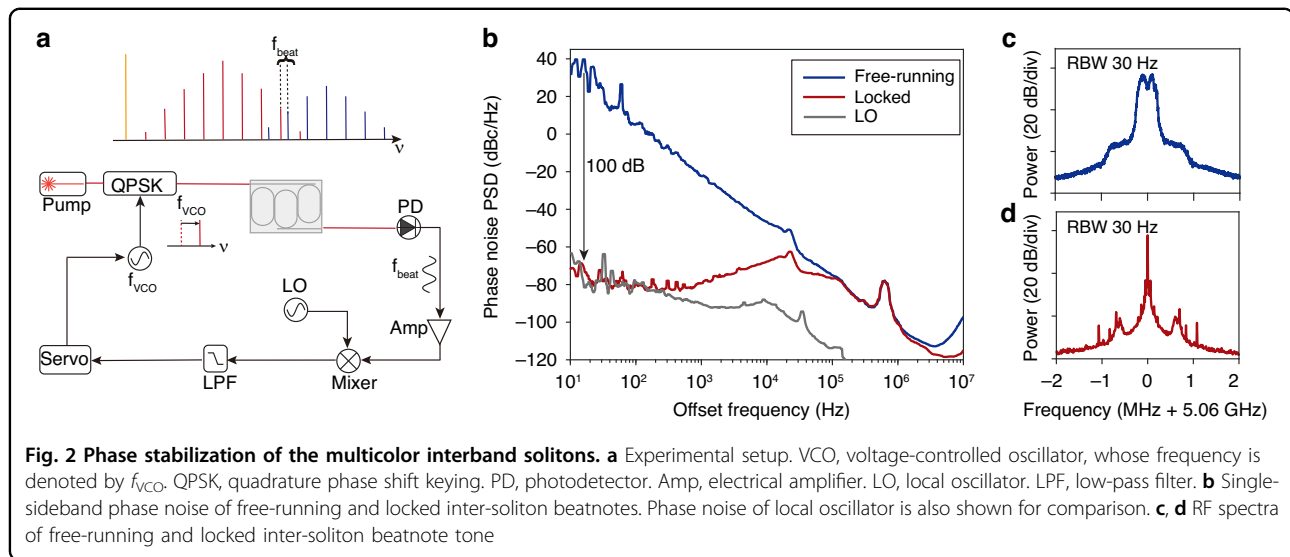
The second requirement for the generation of the multicolor solitons is the group velocity matching of the primary and secondary solitons, so as to synchronize (and trap) the propagation of the two solitons along the resonator. Experimentally, the FSRs of the middle and upper band at $\nu_{p,c}$ and $\nu_{s,c}$ are measured to be near 19.86 GHz with a slight difference of ~ 1 MHz. The upper band simultaneously features local anomalous dispersion ($D_{2,s}/2\pi = 39$ kHz), suitable for bright soliton mode-locking. On the lower dispersion band, normal dispersion around the phase-matched mode does not support soliton formation, resulting in a sharp spectral peak.

Servo phase-locking of the multicolor interband solitons

Different from the multicolor solitons proposed in the ref. ⁷, the multicolor interband solitons do not phase-lock as a result of the frequency offset between the dispersion bands. It is therefore not a direct coherent extension of the microcomb. Here, we show that the phase-locking can be achieved by servo control of the pump laser. Given that the repetition rates of the primary and secondary solitons are always the same, after the phase-locking, the secondary soliton can be viewed as a coherent extension of the primary soliton.

Experimental setup for f_{beat} locking is illustrated in Fig. 2a. A fiber laser is frequency-shifted by a quadrature phase shift keying (QPSK) driven by a voltage-controlled oscillator (VCO). The sideband from the QPSK (whose frequency is higher than the pump by the VCO frequency) is used to pump the multicolor interband solitons, followed by optical amplification. The microcomb output is





amplified by an Erbium-doped fiber amplifier (EDFA) and directed to a fast photodetector, producing a beatnote signal f_{beat} at around 5 GHz. The beatnote is electrically amplified and mixed with a 5 GHz stable local oscillator (LO), generating an error signal. The servo output controls frequency of the VCO, which shifts the f_{beat} by controlling the pump line frequency ν_p in Fig. 1a. Phase noise of the locked f_{beat} is measured by a commercial phase noise analyzer (R&S FSWP) as presented in Fig. 2b in red, while that of the free-running f_{beat} is plotted in blue for comparison. Phase noise of locked f_{beat} is 100 dB lower than the free-running case at 10 Hz frequency offset, and follows the LO phase noise (gray) at low offset frequencies (< 100 Hz). RF spectra of the free-running and locked f_{beat} tone are presented in Fig. 2c,d, respectively. Note that the f_{beat} locking is compatible with the simultaneous locking of f_{rep} , for full phase stabilization between any of the comb lines of the multicolor solitons, which is detailed in Methods.

Thermal tuning of the multicolor interband solitons

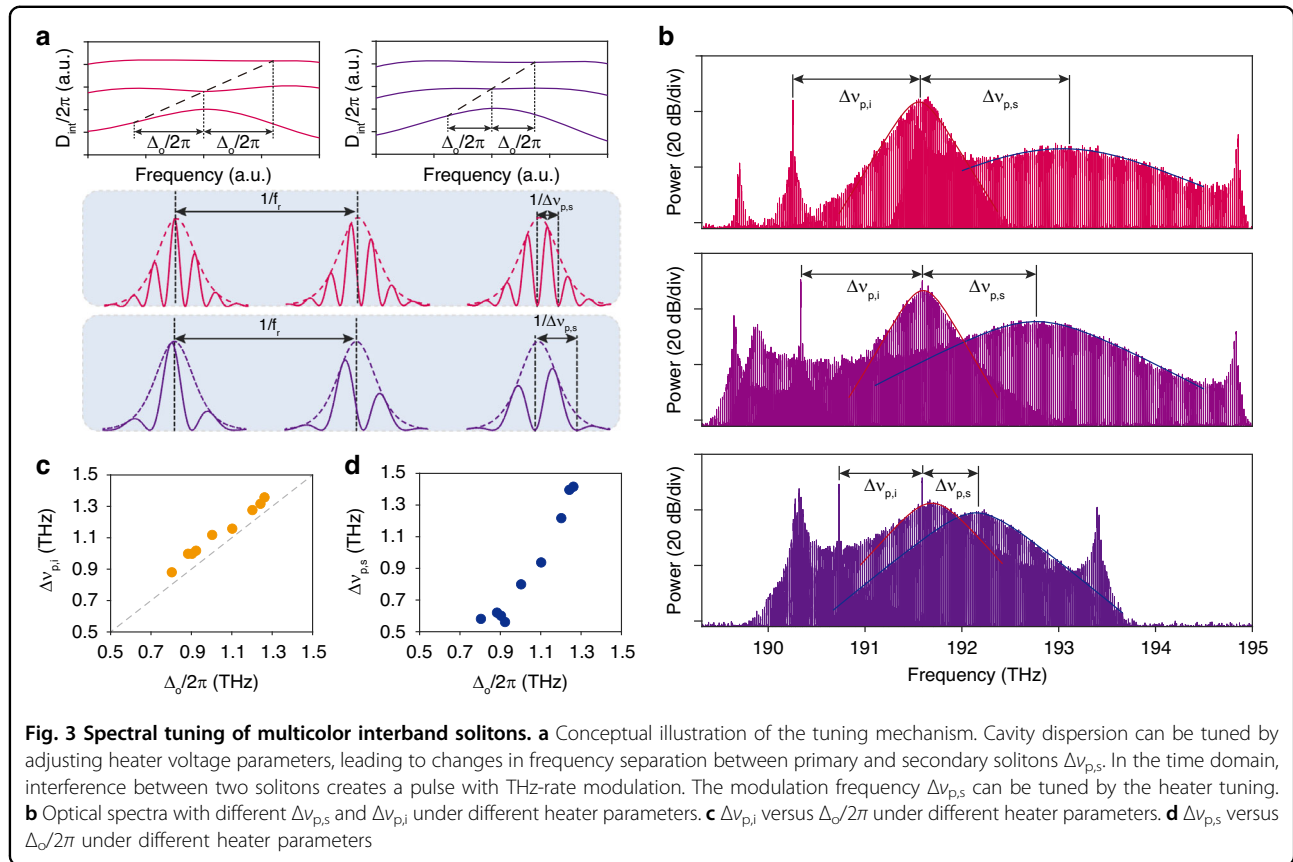
Electrical tuning of the frequency separation between the two solitons is demonstrated via differential temperature tuning between the three rings. The tuning scheme is illustrated in Fig. 3a. Temperature of three rings in the cavity is independently controlled by electrical heaters. Resonator dispersion curve is tuned efficiently by adjusting heater voltage parameters^{17,20}. In Fig. 3b, three optical spectra measured at different heater parameters are shown. Here, the primary soliton is fitted by the $sech^2$ envelope, while fitting details of the secondary soliton are in Materials and Methods.

When the dispersion is modified, the phase-matched frequency of the dispersive wave is actively tuned (while the pump frequency is fixed). The idler sideband is

expected to emerge at the phase-matched mode, and the frequency separation between the pump soliton spectral center and the idler sideband $\Delta\nu_{p,i}$ is predicted to be $\Delta_o/2\pi$. In Fig. 3c, measured values of $\Delta\nu_{p,i}$ versus $\Delta_o/2\pi$ (derived from dispersion measurements) are plotted. As the central wavelength of the secondary soliton mostly follows the phase-matched wavelength, the frequency separation between the pump and the secondary soliton spectral center $\Delta\nu_{p,s}$ is also actively tuned. Measured values of $\Delta\nu_{p,s}$ are presented in Fig. 3d. The observed $\Delta\nu_{p,i} \neq \Delta\nu_{p,s}$ is explained in Materials and Methods.

Discussion

While the focus of this report is to establish and study the interband multicolor-soliton mechanism, a potential application of multicolor interband solitons is terahertz wave generation. The frequency separation between two solitons $\Delta\nu_{p,s}$ falls within THz range, and in the time domain the interference between two solitons creates a THz modulation in optical intensity. In the time domain, after averaging out optical frequency oscillations, temporal optical intensity distribution features pulses with THz-band carrier. Pulse repetition rate is still f_{rep} and carrier frequency is $\Delta\nu_{p,s}$, which is tunable. By converting the optical wave into terahertz waves using photoconductive process²¹ or optical rectification²², a THz-band frequency comb is generated, where the central frequency is $\Delta\nu_{p,s} \sim 0.5 - 1.5$ THz, and the repetition rate is $f_{rep} \approx 20$ GHz. The scheme combines a THz-band carrier frequency (defined by $\Delta\nu_{p,s}$) with a microwave-rate repetition frequency (defined by f_{rep}). This configuration is particularly beneficial for THz time-domain spectroscopy and dual-THz-comb systems, where lower repetition rates



provide finer spectral resolution and denser RF beat-notes while remaining compatible with high-SNR photodetection and WDM multiplexing.

In conclusion, a new type of soliton closely related to the phenomenon theoretically predicted in the reference⁷ is experimentally demonstrated. A secondary soliton is generated from a primary soliton via Kerr parametric gain and trapped by the potential well created by cross-phase-modulation from the primary soliton. The two solitons have different central frequency, but coincide in time and share common repetition rate. The two-soliton microcomb can be fully referenced to RF sources and has good tunability through dispersion tuning of the three-coupled-ring microresonator. The new physics also enriches understanding of cavity nonlinear soliton dynamics and points out a possible method of soliton generation and spectrum extension. The present span (< 5 THz) is constrained by the intrinsic normal dispersion, but could be further optimized using another waveguide geometry²³. Specifically, the waveguide geometry (e.g., width and height) should be precisely engineered to minimize the amount of group velocity dispersion over a broader wavelength coverage. This microcomb system is also potentially useful as a chip-based terahertz comb source.

Materials and methods

Theory of multicolor interband solitons generation

Here, the coupled rings are effectively replaced with a single cavity, and the three supermode families in Fig. 1g are viewed as independent transverse mode families. The assumption is validated in the Supplementary Information. The soliton dynamics in presence of parametric interaction is governed by^{14,24},

$$\begin{aligned} \frac{\partial}{\partial T} E_p = & -\left(\frac{\kappa_p}{2} + i\delta\omega_p\right)E_p + i\frac{D_{2,p}}{2}\frac{\partial^2}{\partial\phi^2}E_p + 2ig_{\text{FWM}}^*E_sE_iE_p^* \\ & + i(g_0|E_p|^2 + 2g_{\text{XPM}}|E_s|^2 + 2g_{\text{XPM}}|E_i|^2)E_p + F \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial}{\partial T} E_s = & -\left(\frac{\kappa_s}{2} + i\delta\omega_s\right)E_s - \Delta D_{1,s}\frac{\partial}{\partial\phi}E_s + i\frac{D_{2,s}}{2}\frac{\partial^2}{\partial\phi^2}E_s \\ & + i(g_0|E_s|^2 + 2g_{\text{XPM}}|E_p|^2 + 2g_{\text{XPM}}|E_i|^2)E_s \\ & + ig_{\text{FWM}}E_p^2E_i^* \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{\partial}{\partial T} E_i = & -\left(\frac{\kappa_i}{2} + i\delta\omega_i\right)E_i - \Delta D_{1,i}\frac{\partial}{\partial\phi}E_i + i\frac{D_{2,i}}{2}\frac{\partial^2}{\partial\phi^2}E_i \\ & + i(g_0|E_i|^2 + 2g_{\text{XPM}}|E_p|^2 + 2g_{\text{XPM}}|E_s|^2)E_i \\ & + ig_{\text{FWM}}E_p^2E_s^* \end{aligned} \quad (5)$$

Here, the slow-varying electric fields E_k ($k = p, s, i$ for primary soliton, secondary soliton and idler sideband



respectively, * denotes complex conjugate) are defined in the co-rotating frame of the primary soliton and normalized to photon number. The carrier angular frequencies are denoted by ω_k ($k = p, s, i$), respectively. ω_p equals the pump angular frequency. The choice of ω_s and ω_i is not deterministic, but to eliminate the phase factor in the four-wave-mixing (FWM) terms, it is forced that

$$\omega_s + \omega_i = 2\omega_p \quad (6)$$

We further define detuning $\delta\omega_k = \omega_{k,c} - \omega_k$ ($\omega_{k,c}$ is the corresponding cavity mode angular frequency, $k = p, s, i$), where

$$\delta\omega_s + \delta\omega_i - 2\delta\omega_p \equiv \omega_{s,c} + \omega_{i,c} - 2\omega_{p,c} \equiv \text{Constant} \quad (7)$$

Since the detunings need to be small for resonant excitation, a requirement for mode frequencies eqn. (1) arises. Furthermore, κ_k ($k = p, s, i$) is cavity loss rate, $\Delta D_{1,s} \equiv D_{1,s} - D_{1,p}$, $\Delta D_{1,i} \equiv D_{1,i} - D_{1,p}$, $D_{1,k}$, $D_{2,k}$ are first- and second- order cavity dispersion parameters, g_0 , g_{XPM} , g_{FWM} are effective nonlinear self-phase-modulation, cross-phase-modulation (XPM) and four-wave-mixing (FWM) coefficients respectively (for definition see Supplementary Information), and $F = \sqrt{\kappa_{\text{ext},p} P_{\text{in}} / \hbar \omega_p}$ is the pump term, where $\kappa_{\text{ext},p}$ is the external coupling rate and P_{in} is the on-chip input power.

Analytical analysis

Several approximations are made to derive the analytical solution of eqns. (3)(4)(5). We focus on near-threshold behaviour where the power of the secondary soliton and idler sideband is much lower than the primary soliton, that $|E_s|, |E_i| \ll |E_p|$. The primary soliton takes the unperturbed soliton form

$$E_p = A_p \text{sech}(B\phi) \quad (8)$$

The dynamics of E_s and E_i , with this E_p expression inserted, yields Schrödinger-type equations in a sech^2 potential well with parametric gain terms. The idler sideband is approximated as a continuous wave, while the secondary soliton exhibits ground-state solution as follows:

$$E_s = A_s \text{sech}^\gamma(B\phi) e^{-i\Delta\mu_s \phi} \quad (9)$$

$$E_i = A_i \quad (10)$$

The linear phase factor in E_s results from FSR mismatch of the primary and secondary soliton forming mode families. $\Delta\mu_s$ denotes a shift in secondary soliton central

mode from mode $\omega_{s,c}$. For γ and $\Delta\mu_s$ it is derived (detailed in the Supplementary Information),

$$\gamma(1 + \gamma) = \frac{4g_{\text{XPM}} D_{2,p}}{g_0 D_{2,s}} \quad (11)$$

$$\Delta\mu_s = \frac{\Delta D_{1,s}}{D_{2,s}} \quad (12)$$

Eqn. (12) indicates that the central mode of secondary soliton is shifted to where the FSR of the soliton forming mode aligns with the primary soliton.

Furthermore, a threshold behaviour is predicted. E_s and E_i compose a coupled linear system, where either exponential growth or decay can occur. The secondary soliton forms under exponential growth, when parametric gain overcomes cavity loss. By taking the inner product of both sides of eqns. (4)(5) with their respective eigenfunctions (9)(10), the equations reduce to a linear set of ordinary differential equations governing the evolution of E_s and E_i amplitudes, and the threshold condition is readily obtained. Setting $\Delta D_{1,s} = 0$ for simplicity of expression, its threshold condition is calculated to be

$$\begin{aligned} \frac{\kappa_s \kappa_i}{4} + \left(\frac{\delta\omega_s + \delta\omega_i}{2} - \frac{g_{\text{XPM}} \sqrt{2D_{2,p} \delta\omega_p}}{\pi g_0} - \gamma^2 \frac{D_{2,s}}{2D_{2,p}} \delta\omega_p \right)^2 \\ - \frac{2|g_{\text{FWM}}|^2 \delta\omega_p^2}{\pi g_0^2} \sqrt{\frac{D_{2,p}}{2\delta\omega_p}} \frac{\Pi(\gamma+2)^2}{\Pi(2\gamma)} = 0 \end{aligned} \quad (13)$$

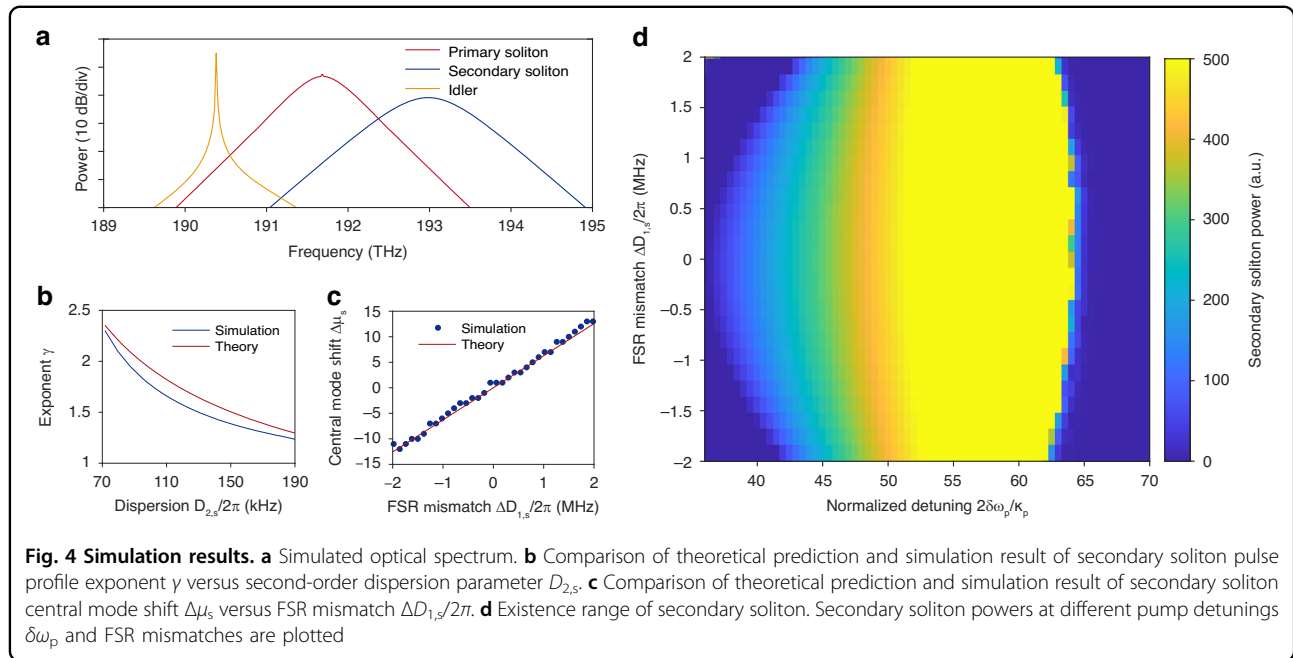
where $\Pi(t) \equiv \int_{-\infty}^{\infty} \text{sech}^t x dx$.

Numerical simulation

To confirm that the proposed mechanism enables multicolor interband solitons, numerical simulations are performed based on full coupled LLEs eqns. (3)–(5) using split-step Fourier transform method. For each dispersion band, 1024 modes are involved in the model.

In the simulation, the system is seeded by a single primary soliton. The results are summarized in Fig. 4. Simulated spectrum in Fig. 4a displays good similarity to experimental data in Fig. 1. The conclusions drawn from analytical model are also validated. To verify eqn. (11), dispersion parameter $D_{2,s}$ is tuned and exponent γ is determined by spectrum fitting at each $D_{2,s}$. The analytical and numerical results are consistent (Fig. 4b). For eqn. (12), the central mode shift of the secondary soliton $\Delta\mu_s$ obtained from simulation and eqn. (12) are plotted together at different FSR mismatches $\Delta D_{1,s}$ in Fig. 4c, also showing good agreement. Besides, it is numerically verified that XPM is essential to stable mode-locking of the secondary soliton (see Supplementary Information).

Simulation parameters are listed as below. For Fig. 4a, $\omega_p = 2\pi \times 191.68$ THz, $Q_{\text{int}} = 75 \times 10^6$, $Q_{\text{ext}} = 200 \times 10^6$,



$\delta\omega_p = 22.5\kappa_p$, $\delta\omega_s = \delta\omega_i = 12.5\kappa_p$, $\Delta D_{1,s} = 0$, $\Delta D_{1,i} = 2\pi \times 31.8$ MHz, $D_{2,p} = 2\pi \times 353$ kHz, $D_{2,s} = 2\pi \times 159$ kHz, $D_{2,i} = -2\pi \times 154$ kHz, $g_0/2\pi = 4.33 \times 10^{-3}$ Hz, $g_{\text{XPM}}/2\pi = 1.73 \times 10^{-3}$ Hz, $g_{\text{FWM}}/2\pi = 1.73 \times 10^{-3}$ Hz, $P_{\text{in}} = 300$ mW. Loss rates are derived by $\kappa_{\text{ext},p} = \omega_p/Q_{\text{ext}}$, $\kappa_k = \kappa_{\text{int}} + \kappa_{\text{ext}} = \omega_p/Q_{\text{int}} + \omega_p/Q_{\text{ext}}$ ($k = p, s, i$). For Fig. 4b, $\Delta D_{1,s}$ is fixed at 0. For Fig. 4c,d, $D_{2,s}$ is fixed at $2\pi \times 159$ kHz.

Threshold behaviour of the secondary soliton generation

Threshold behaviour is observed both experimentally and numerically, which is typical for parametric processes and predicted by the theory. When the pump laser scans across the mode from blue-detuned regime to red-detuned regime, a single primary soliton is generated at first, and the secondary soliton and idler sideband emerge when pump detuning reaches a certain threshold. Optical spectra below and above threshold detuning are shown in Fig. 5b.

Measured and simulated soliton steps of primary and secondary solitons are also shown separately in Fig. 5d. The measurement setup is detailed in Fig. 5a. The comb output is amplified by an erbium-doped fiber amplifier (EDFA) and equally split into two routes. Each route is directed to an optical waveshaper to filter out primary/secondary soliton only, and then detected by a photodetector (PD). The PD signals are received by an oscilloscope to monitor soliton power. Analogous to simulation result, the measurement also verifies the sequenced generation of primary and secondary solitons, indicating the existence of threshold detuning. In the numerical model, when pump detuning is slowly ramped, existence of threshold is observed explicitly (Fig. 5c).

Normalized threshold detuning $2\delta\omega_p/\kappa_p$ calculated from eqn. (13) with simulation parameters is 33.8, close to simulation value 35.7.

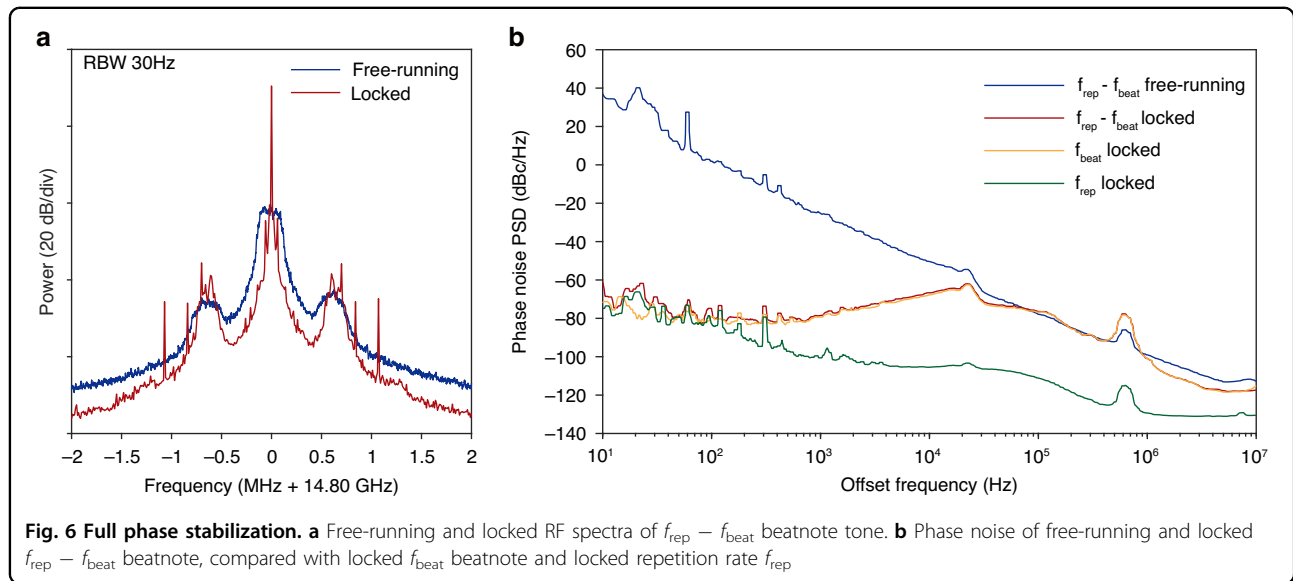
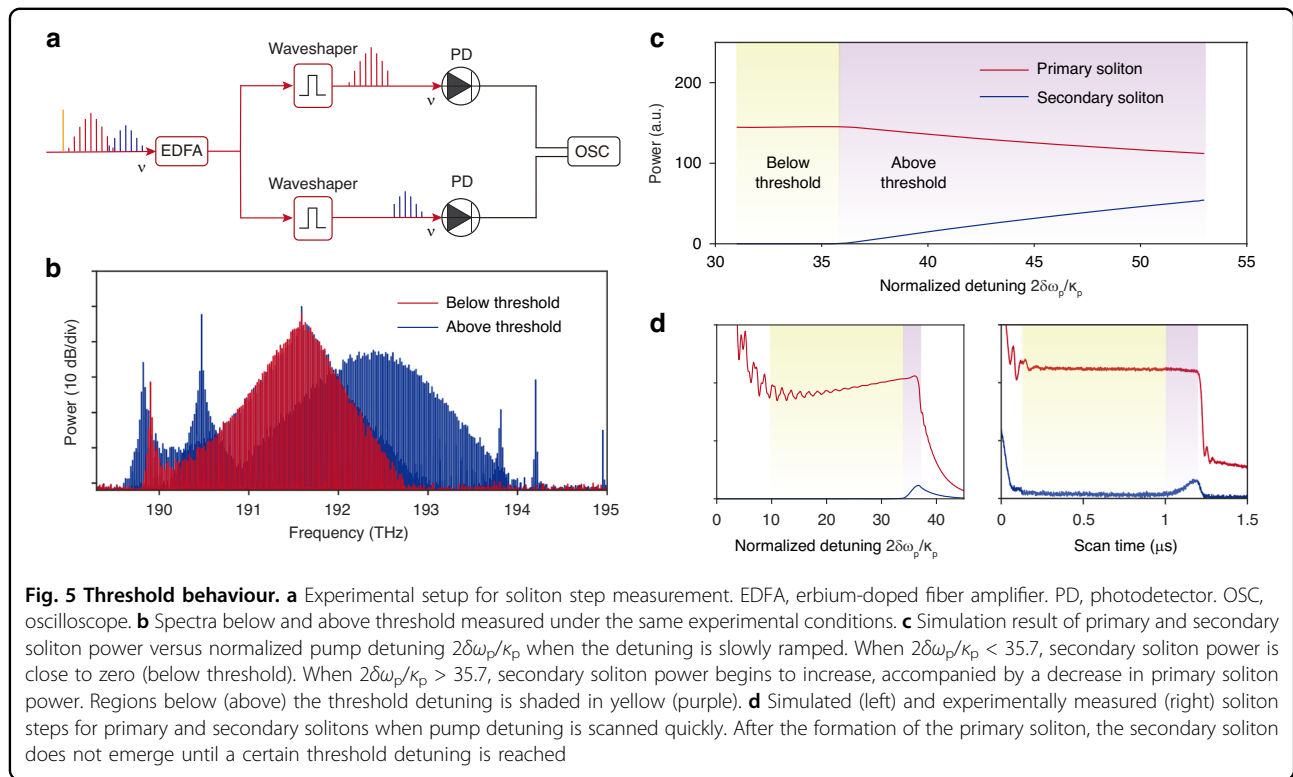
Furthermore, threshold behaviour in presence of FSR mismatch $\Delta D_{1,s}/2\pi$ is studied. Comb spectra are simulated under different FSR mismatches and pump detunings $\delta\omega_p$, and secondary soliton powers with respect to these parameters are plotted in Fig. 4d. Secondary soliton existence range is nearly symmetric with respect to $\Delta D_{1,s}/2\pi = 0$, and threshold pump detuning increases with FSR mismatch. The primary and secondary solitons simultaneously vanish when pump detuning exceeds the primary soliton existence limit.

Experimental details

In the autocorrelation measurement, the comb output from the cavity is firstly amplified to 70 mW by an erbium-doped fiber amplifier (EDFA), and then directed to a waveshaper. The waveshaper is programmed as a band-pass filter that filters out either the primary or the secondary soliton, and in its passband, a quadratic dispersion is applied to compensate fiber dispersion. After filtering, the comb is again amplified to 300 mW by a second EDFA before sent into an autocorrelator. The data in Fig. 1d,e is measured when dispersion compensation is optimized so that the pulses display the smallest temporal widths.

Full phase stabilization is achieved by simultaneous locking of f_{rep} (by servo locking) and f_{beat} (by disciplining to a stable microwave synthesizer²⁵). It can be characterized by another inter-soliton beatnote with frequency $f_{\text{rep}} - f_{\text{beat}}$. The noise of this beatnote will be significantly





suppressed only when f_{rep} and f_{beat} are simultaneously stabilized. RF spectrum and phase noise data for the $f_{\text{rep}} - f_{\text{beat}}$ beatnote is plotted in Fig. 6. The phase noise of locked $f_{\text{rep}} - f_{\text{beat}}$ beatnote closely follows that of locked f_{beat} beatnote, while the noise of locked f_{rep} is below this level, indicating successful full phase stabilization. The two solitons form a coherent set of frequency comb with broader spectral range.

In Fig. 3b and Fig. 4b, consistent with the proposed theory, the secondary soliton spectra are fitted by an envelope with form

$$P(\nu) = |\text{FT}\{a \text{sech}^\gamma(bt)\}|^2 (\nu - \nu_s)^2 \quad (14)$$

where FT denotes Fourier transform, P is power, ν is frequency, t is time, and a, b, γ, ν_s are fitting parameters.

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Q.-X.J. and H.H. performed the measurements with assistance from J.Ge, M.G., and P.L. Analytical modeling and numerical simulation were performed by H.H., Y.Y., and Q.-X.J. The device is fabricated by W.J., J.Guo, and L.W. with assistance from A.F. and M.P. All the authors contributed to the writing of the manuscript. J.B. and K.V. supervised the project.

Data availability

The data that support the plots within this paper are available via figshare at <https://doi.org/10.6084/m9.figshare.31155208>. All other data used in this study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare no competing interests.

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References

- Herr, T. et al. Temporal solitons in optical microresonators. *Nat. Photonics* **8**, 145–152 (2014).
- Jankowski, M. et al. Temporal solitons in optical parametric oscillators. *Phys. Rev. Lett.* **120**, 053904 (2018).
- Bruch, A. W. et al. Pockels soliton microcomb. *Nat. Photonics* **15**, 21–27 (2021).
- Skryabin, D. V. Sech-squared Pockels solitons in the microresonator parametric down-conversion. *Opt. Express* **29**, 28521–28529 (2021).
- Zhang, J. et al. Optomechanical dissipative solitons. *Nature* **600**, 75–80 (2021).
- Yang, Q.-F., Yi, X., Yang, K. Y. & Vahala, K. Stokes solitons in optical microcavities. *Nat. Phys.* **13**, 53–57 (2017).
- Luo, R., Liang, H. X. & Lin, Q. Multicolor cavity soliton. *Opt. Express* **24**, 16777–16787 (2016).
- Akhmediev, N., Ankiewicz, A. & Soto-Crespo, J. Multisoliton solutions of the complex Ginzburg-Landau equation. *Phys. Rev. Lett.* **79**, 4047–4051 (1997).
- Braud, F., Conforti, M., Cassez, A., Mussot, A. & Kudlinski, A. Solitonization of a dispersive wave. *Opt. Lett.* **41**, 1412–1415 (2016).
- Moille, G., Li, Q., Kim, S., Westly, D. & Srinivasan, K. Phased-locked two-color single soliton microcombs in dispersion-engineered Si₃N₄ resonators. *Opt. Lett.* **43**, 2772–2775 (2018).
- Silvestri, C., Widjaja, J., Lin, A., de Sterke, C. M. & Runge, A. F. Theory of multicolor soliton microcombs. *Opt. Lett.* **50**, 2073–2076 (2025).
- Moille, G., Menyuk, C., Chembo, Y. K., Dutt, A. & Srinivasan, K. Synthetic frequency lattices from an integrated dispersive multi-color soliton. Print at <https://doi.org/10.48550/arXiv.2210.09036> (2022).
- Gao, M. D. et al. Multi-color solitons in coupled-ring microresonators. CLEO: Science and Innovations. (Optica Publishing Group, 2024).
- Menyuk, C. R., Shandilya, P., Courtright, L., Moille, G. & Srinivasan, K. Multi-color solitons and frequency combs in microresonators. *Opt. Express* **33**, 21824–21835 (2025).
- Hou, H. F. et al. Multicolor interband solitons in microcombs. CLEO: Fundamental Science. (Optica Publishing Group, 2025).
- Yuan, Z. Q. et al. Soliton pulse pairs at multiple colours in normal dispersion microresonators. *Nat. Photonics* **17**, 977–983 (2023).
- Ji, Q.-X. et al. Dispersive-wave-agile optical frequency division. *Nat. Photonics* **19**, 1–6 (2025).
- Jang, J. K., Erkintalo, M., Coen, S. & Murdoch, S. G. Temporal tweezing of light through the trapping and manipulation of temporal cavity solitons. *Nat. Commun.* **6**, 7370 (2015).
- Obrzud, E., Lecomte, S. & Herr, T. Temporal solitons in microresonators driven by optical pulses. *Nat. Photonics* **11**, 600 (2017).
- Ji, Q.-X. et al. Multimodality integrated microresonators using the moiré speedup effect. *Science* **383**, 1080–1083 (2024).
- Fattinger, C. & Grischkowsky, D. Terahertz beams. *Appl. Phys. Lett.* **54**, 490–492 (1989).
- Yeh, K.-L., Hoffmann, M., Hebling, J. & Nelson, K. A. Generation of 10 μ J ultrashort terahertz pulses by optical rectification. *Appl. Phys. Lett.* **90**, 171121 (2007).
- Liu, J. Q. et al. High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits. *Nat. Commun.* **12**, 2236 (2021).
- Crosignani, B. & Di Porto, P. Soliton propagation in multimode optical fibers. *Opt. Lett.* **6**, 329–330 (1981).
- Weng, W. L. et al. Spectral purification of microwave signals with disciplined dissipative Kerr solitons. *Phys. Rev. Lett.* **122**, 013902 (2019).

