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Soliton microcombs in optical microresonators with perfect spectral envelopes

Mulong Liu^{1†}, Ziqi Wei^{2,3†}, Haotong Zhu^{1†}, Hongwei Wang⁴, Xiao Yu⁵, Xilin Han⁵, Wei Zhao^{6*}, Guangwei Hu^{4*} and Peng Xie^{3,5*}

We theoretically and experimentally investigate thermal dynamics involved soliton microcomb generation in silicon oxynitride microresonators. Importantly, auxiliary laser heat balance scheme with flexible thermal manipulation is introduced to circumvent thermal instability and the intra-cavity temperature can be tuned from 60 °C to 41.5 °C via the commercial thermoelectric controller. As a result, various perfect soliton states with ultra-smooth spectral envelopes are observed on a well-designed and fabricated microresonator with homogeneous sidewall and thickness where spatial modes interaction and distortion are eliminated. The pre-reported spectral abrupt jumps due to mode hybridization are completely avoided and solitons tail oscillation vanishes simultaneously. This reported ideal coherent comb source without residual temporal and spectral noise will facilitate practical applications such as spectroscopy, ranging and astrocomb calibration.

Keywords: perfect solitons; thermal dynamics; auxiliary laser heat balance; Raman effect

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Introduction

Since last decade, microresonator-based optical frequency combs (i.e. *microcombs*) have attracted significant attentions due to their unprecedented advantages of ultra-high repetition rates, wide bandwidth and high compactness^{1,2}. Microcombs are promising for extensive applications including optical clocks³, coherent communications⁴, precise spectroscopy^{5–7}, accurate ranging^{8–10}, quantum optics¹¹, etc. A myriad of material platforms have been successfully demonstrated for efficient microcomb generation¹², including complementary metal-ox-

ide semiconductor (CMOS)-compatible microresonators such as Si₃N₄^{13–15}, silicon¹⁶, silica^{17,18} and silicon oxynitride¹⁹, as well as other platforms like CaF₂ and MgF₂ crystallines^{20,21}, AlN^{22,23}, AlGaAs²⁴ and diamond²⁵. CMOS-compatible materials are of particular importance in advancing microcomb technology, owing to their compatibility with semiconductor processing and their ability to integrate with other photonic devices platform. Silicon oxynitride, as a CMOS-compatible materials, has been widely used in the fabricating of high-quality factor optical resonators due to its relatively low

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nonlinear losses¹⁹. However, the influence of silicon oxynitride microresonator on the performance and dynamics of soliton microcombs remains an open question. Soliton microcombs, relying on the double balance between cavity loss and parametric frequency conversion on one hand, as well as anomalous dispersion and Kerr nonlinearity on the other, exhibit outstanding features of low frequency and amplitude noise and high coherence which are essential for practical applications.

However, during the transition into a steady soliton state, the dramatic intracavity power drop can result in the pump frequency shifting out of cavity resonance through the thermo-optical effect, thus introducing the difficulties to deterministically capture solitons in experiments. The specific technical approaches are required according to distinct thermal and nonlinear properties for different platforms. To date, the rapid forward frequency-tuning²⁶, forward and backward frequency-scanning²⁷, power-kicking²⁸, thermal tuning²⁹, Euler bends³⁰ and auxiliary-laser-based methods^{31,32} are exploited for single soliton generation based on materials with relative low (e.g. MgF_2 ³³, silica³⁴ and LiNbO_3 ³⁵) and high (e.g. Si_3N_4 ³⁶ and AlN ²³) thermal-optical coefficients. With these advanced experimental techniques, soliton microcomb generation now has been extended from the telecom band³⁷ to the visible³⁸ and mid-infrared band³⁹, along with a few proof-of-concept demonstration of applications^{40,41}. However, certain techniques face significant limitations in soliton microcomb generation due to relatively high operational complexity. For instance, rapid forward frequency-tuning demands extremely precise scanning speed⁴², power-kicking necessitates meticulous regulation of pump power²⁸, and conventional auxiliary-laser-based methods are difficult to flexibly control the temperature of microresonators⁴³. Therefore, it is of great significance to realize the adiabatic process in a simpler and more accessible way.

Beyond these encouraging progresses, certain challenges to further improve the performance of soliton microcombs still remain, especially for those with high thermal constant considering the continuously emerging new platforms. For instance, researchers quench thermorefractive effects of AlGaAs by cryogenic cooling temperatures to 4–20 K for soliton microcomb generation. Its thermorefractive value in room-temperature is an order of magnitude larger than that of Si_3N_4 and SiO_2 , and AlN by more than two orders of magnitude⁴⁴. In addition, soliton properties in microresonator of previous

reports are, generally, not "perfect" regarding temporal and spectral profile. For example, under the interaction of high-order nonlinearity and mode crossing, a spike will appear in the spectra envelope showing the soliton tail oscillation in the time domain, which will induce additional noise. To solve the chronic drift of solitons in the cavity, the phase modulation of the pump in the frequency domain⁴⁵ and Raman effect via balancing with the high-order dispersion are sought⁴⁶. These elaborate approaches to control the soliton generation dynamics leads to recent development of perfect soliton crystals (PSCs), which are composed by a number of dissipative Kerr solitons equally distributed around the resonator^{47,48} via regulating the comb line spacing. The PSC with intrinsic low redundant noise of individual solitons in temporal domain and no abrupt drop or jump on spectra could promise the applications in astronomical spectrometers⁴⁹ and optical fiber communications⁴, which remains under explored.

Here, we explore the thermal influence on soliton microcomb generation in silicon oxynitride materials platform. We found that the strong thermal effect prohibits the soliton microcomb generation under single pump frequency scanning scheme. Therefore, we employ a novel auxiliary-laser-assisted tuning method combined with precise and flexible thermal regulation via a thermoelectric controller (TEC), applied to a sophisticated design and processing silicon oxynitride microresonator with smooth sidewall and uniform thickness, thereby generate stable Kerr solitons. Eliminating the influences of other modes or mode distortion and sustaining the pure fundamental mode field, various perfect soliton states with favored smooth spectral envelope are accessible promptly by adjusting auxiliary light. Our perfect soliton state features the completely vanishing spectral discontinuities caused by avoided-mode-crossing (AMX) effects^{13,50,51}, and shows no oscillating background waves, residual noise or radiation loss induced by high-order-dispersion (HOD) and/or AMX, which are crucial for highly accurate fast distance acquisitions. The corresponding ideal coherent microcombs avoid intensity jumps and radiation loss important for practical applications including spectroscopy, quantum optics, astronomy and others.

Theory and simulation

The Lugiato-Lefever equation (LLE) including second-order dispersion, Raman and thermal effects is used to

describe the spectral-temporal dynamics of frequency comb generation^{27,52} in our material platform. Thermal effects are included by calculating and considering the intra-cavity power induced additional detuning and the generalized LLE can be written as,

$$T_R \frac{\partial E}{\partial t} = - \left(\frac{\alpha + \kappa}{2} + iL \frac{\beta_2}{2} \frac{\partial^2}{\partial \tau^2} + i(\delta_0 + \delta_T) \right) E + \sqrt{\kappa} E_{in} + i\gamma L \left(|E|^2 + \tau_R \frac{\partial |E|^2}{\partial \tau} \right) E, \quad (1)$$

$$\frac{d\delta_T}{dt} = -\frac{\delta_T}{\tau_0} + \zeta P, \quad (2)$$

where $E(t, \tau)$ is the envelope of field within the resonator, t and τ correspond to the slow time and the fast time, respectively, T_R is the round-trip time, E_{in} is the pump field, δ_0 is the laser detuning and δ_T is the thermal detuning. Equation (2) describes the thermal dynamics, where P is the average intracavity power and ζ describing the shift of the detuning in response to the average intracavity power depends on the thermal-optical coefficient of the material and the absorbed power converted to heat, τ_0 is the thermal response time measured to be submicrosecond in previously fabricated microresonators. Since τ_0 also depends on the design of the cavity, and it is set as 100 ns to reduce simulation time. Some parameters of the silicon oxynitride microresonator used for calculations to investigate the different soliton generation dynamics are as follows: the round-trip loss α is given as 0.006; the power transmission coefficient κ is 0.00147; the total cavity length L is set to 3.72 mm; the second order dispersion β_2 is $-37 \text{ ps}^2 \text{ km}^{-1}$; the Raman shock time $\tau_R = 2.7 \text{ fs}$; the nonlinear coefficient $\gamma = n_2 \omega / c A_{eff}$ is 0.11 (Wm)^{-1} with the nonlinear refractive index n_2 and the effective mode area A_{eff} ⁵³.

In the first stage, relatively stronger thermal effects with $\zeta = -1 \times 10^4 \text{ (Ws)}^{-1}$ is used for simulation. The laser detuning is linearly tuned from -0.004 to 0.056 in $0-1600 \text{ ns}$ and held at 0.056 in $1600-3500 \text{ ns}$. It is found that stochastic solitons annihilate or survive in all 30 scans as seen from Fig. 1(a). The different colored curves represent the evolution of intracavity energy under the different pump powers. On the one hand, the Kerr comb starts to form into soliton states around the end of the laser tuning. With the power drop in the soliton transition, thermal detuning increases (becomes less negative) and total detuning decreases, exceeding the soliton existence region. Consequently, solitons annihilate due to thermal-induced resonance blueshift. On the other hand,

the presence of thermal chaos also allows distinct routes to soliton formation. For instance, in some scans the comb remains in the chaotic state with a blue-detuned pump over the full time scanning. Therefore, a weak thermal effect with $\zeta = -5 \times 10^3 \text{ (Ws)}^{-1}$ is chosen for the next stage to trigger soliton state. The laser detuning is linearly tuned from -0.004 to 0.043 and hold at 0.043 in remain time to induce soliton generation. Different soliton states can be obtained as shown in Fig. 1(b). Intra-cavity soliton number, closely associated with the power in the cavity, will not affect total detuning significantly for weak thermal effects here thus leading to solitons survive in all 20 scans. These results show that, the generated solitons can either survive or annihilate due to thermal dynamics when the pump laser is scanned from blue to red detuning region and then stop at a fixed wavelength. In previous frequency-scanning experiments²⁷, the soliton steps are tens of nanoseconds making it difficult for soliton generation and stabilization, which is expected to be the strong thermal influences and needed to be overcome. In order to balance the blue detuning caused by thermal effects in microcavity, here auxiliary laser assisted tuning method is applied to different soliton states capturing. The bi-chromatic pump method is widely used for dual-comb spectroscopy⁵⁴ and quantum informatics⁴⁰. The basic principle of solitons generation in the microresonator is demonstrated by comparing Fig. 1(c) and Fig. 1(d). As manifested in Fig. 1(c) and Fig. 1(d), soliton pulses cannot be excited in the microresonator when there is only one CW pump, but they can be excited when a TE pump and a TM pump are existed simultaneously.

Experimental setup and principle

The experimental setup is built as shown in Fig. 2(c) to verify whether auxiliary laser assisted tuning method can play an effective role in soliton capture experiments. The key element is a microresonator with a 49 GHz free spectral range made of silicon oxynitride glass. Such material system is well established and used in on-chip nonlinear optics^{55,56} and repetition-rate-multiplicable pulsed laser sources⁵⁷. In addition, this platform is different from LiNbO₃ which relies on the unique photorefractive merit^{58,59}. Figure 2(a) and 2(b) shows physical drawing and scanning electron microscope image of the microresonator. Pump light (TE polarization) centered at 1562.2 nm and auxiliary light (TM polarization) are simultaneously injected into the bus waveguide from two different

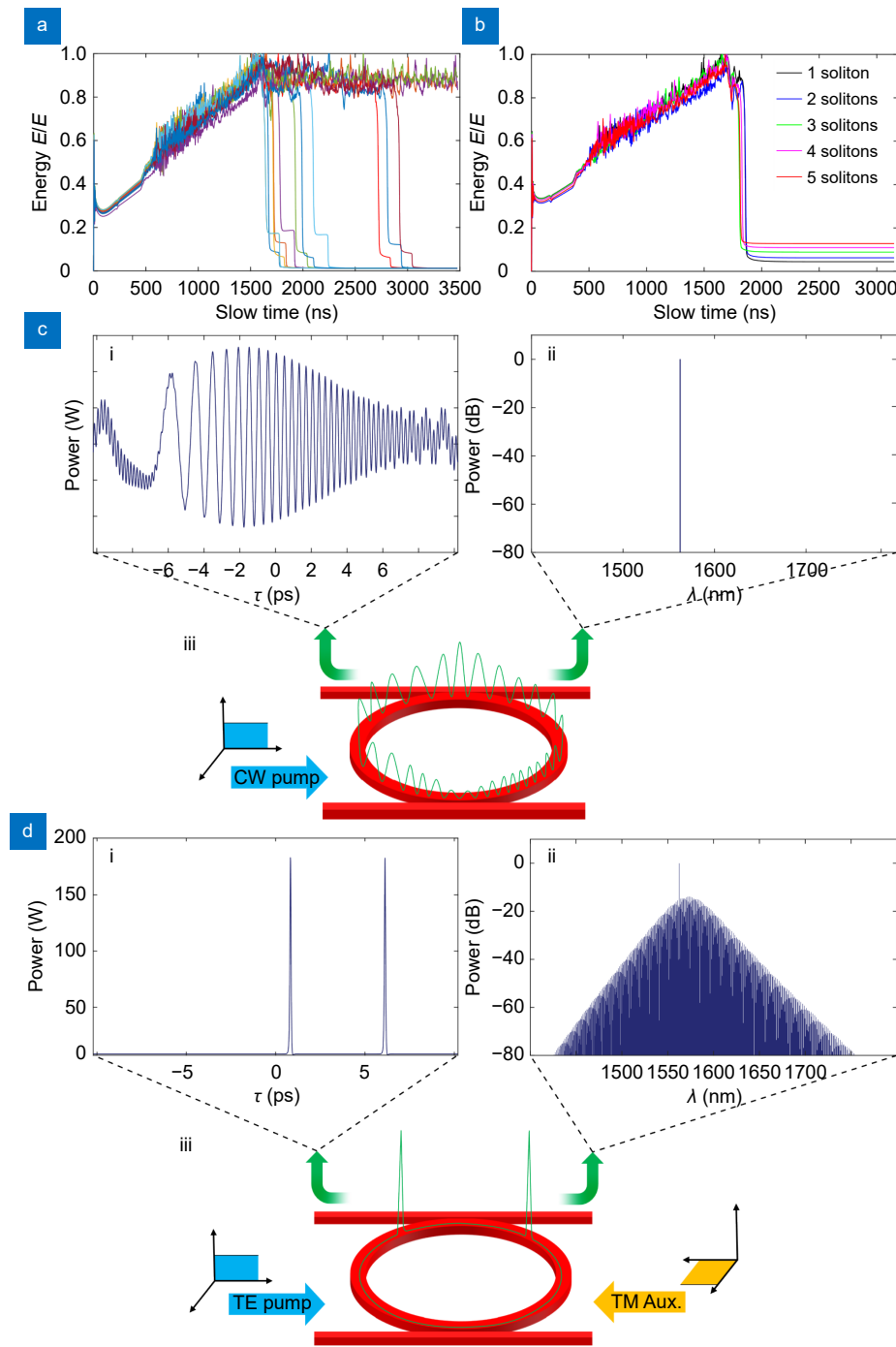


Fig. 1 | The influences of thermal effects on soliton formation and auxiliary laser assisted tuning method. **(a)** For strong thermal effects of $\zeta = -1 \times 10^4 \text{ (Ws)}^{-1}$, intracavity energy evolution reflects soliton annihilation or in chaotic regime. Different color represents distinct microcomb routes and determined by intracavity energy instability. **(b)** For weak thermal effect of $\zeta = -5 \times 10^3 \text{ (Ws)}^{-1}$ solitons can always survive in all 20 scans. Calculated temporal profile **(c-i)** and spectral profile **(c-ii)** of chaotic state with only one pump. **(c-iii)** Schematic diagram of chaotic state with only one pump. Calculated temporal profile **(d-i)** and spectral profile **(d-ii)** of two solitons state with heat balance scheme. **(d-iii)** Schematic diagram of two solitons state with heat balance scheme.

directions after through the fiber polarization controller and erbium-doped fiber amplifier. The circulator is used to isolate the reversely transmitted light. The thermoelectric controller (TEC) enables precise temperature regula-

tion, allowing for adjusting the resonant peak of microresonators. The microresonator pigtailed with a standard fiber array with coupling loss of about 2.5 dB per facet is then packaged into a standard 14 pins butterfly

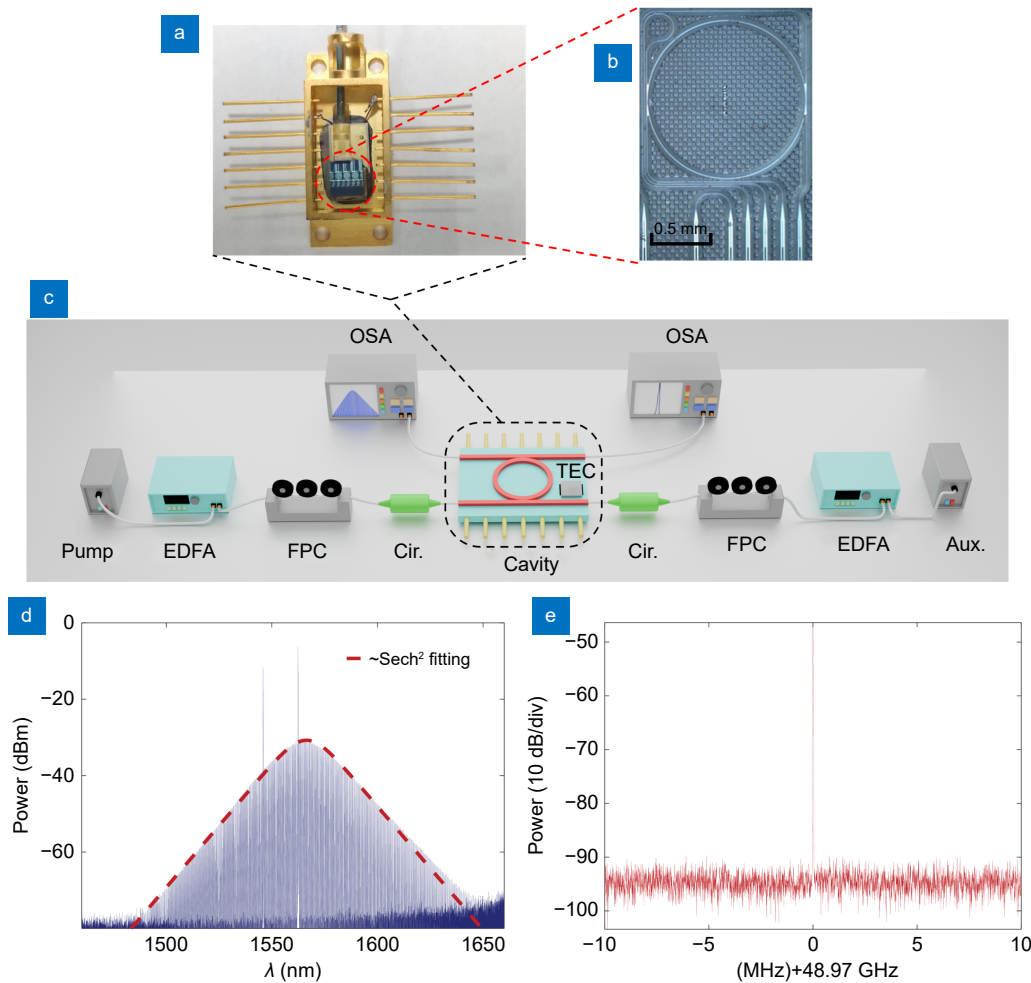


Fig. 2 | Experimental setup and single perfect soliton. (a) Physical drawing of a microresonator. (b) Scanning electron microscope image of the microresonator. (c) Experimental setup for perfect soliton generation. ECDL, external cavity diode laser; EDFA, erbium-doped fiber amplifier; FPC, fiber polarization controller; Cir., circulator; TEC, thermoelectric controller; OSA, optical spectrum analyzer. The zoom in of the chip shows a scanning-electron micrograph of the waveguide cross-section. (d) Low-noise single soliton state (blue curve) with a sech^2 fitting spectral profile (red dashed curve). (e) Microwave beat note of the photo-detected soliton.

package with a commercial TEC.

In this system, the auxiliary laser operating in the blue detuning regime at one cavity mode is to balance the intracavity heat flow and actively stabilize different soliton states. In detail, the c.w. pump laser counter-propagates in the microcavity and works at a different cavity mode, thus heats the cavity and red-shifts all cavity resonances. While the red-shifted resonances displace the auxiliary laser from its own cavity mode, in turn cooling the cavity. By properly setting the pump power and temperature of TEC (equally to varying the detuning of pump and auxiliary lasers), the heat flow induced by dual pump tends to balance out each other. Therefore, the pump laser can scan across the entire cavity resonance linewidth without thermal dragging. Furthermore, adjusting injection power of auxiliary laser or precise tem-

perature control through TEC can be used to suppress the minimal power fluctuations and maintain power stability during stable solitons. Stable soliton states can be generated with high repeatability by implementing the auxiliary laser heating scheme.

Accessing different soliton states in experiment

In experiments, the microresonator with a loaded Q-factor of 1.7×10^6 and dispersion of $-37 \text{ ps}^2 \text{ km}^{-1}$ is used for soliton generation. The platform is well established and used in large-scale integrated photonic circuits as well as on-chip soliton crystal generation⁶⁰ for its advantage of having a CMOS compatible process and high nonlinear performance. The delicately fabrication process of the microresonator ensure homogeneous waveguide sidewall

is similar as that used in Wang's research⁵⁷. Generally, residual fabrication-induced roughness of cross-section increases optical loss and degrades the resonator Q-factor, which is the primary reason contributing to significant fluctuations and imperfections in the spectral envelope of solitons. The pump and auxiliary laser wavelength are set as 1562.2 nm and 1545.4 nm with on-chip power of 32 dBm and 31.7 dBm, respectively. In this dual-pump scheme, the wavelength and power of the auxiliary laser can be adjusted to match different cavity resonances since the auxiliary laser only acts as a heat balancer. The resonances of the cavity shift toward shorter wavelengths with a decreasing operation temperature by tuning the TEC from 41.5 to 60 degrees Celsius. The microcavity first operates with a relatively high temperature and place the pump wavelength at the blue side of one resonance. Then the resonance is shifted toward the pump laser by reducing the temperature. In fact, pump laser is always coupled into the cavity through the fiber. Once the pump frequency is coupled into the cavity, the cavity will be heated due to the intra-cavity optical field enhancement. After tuning through the modulation instability combs and then the soliton crystal combs, one can increase the pump power to enhance intracavity energy, so the energy loss and cavity temperature can be balanced. With appropriate pump power, a step feature with a sharp power drop indicating soliton generation (Fig. 1(b)). Figure 2(d) shows the generated single soliton optical spectrum with electrical spectrum in Fig. 2(e). The second peak on the left side of the pump in Fig. 2(d) is the assistant pump light, which is important for bal-

ancing the energy and heat flow in the cavity. The dashed red curve is the fitted sech^2 profile which characterizes pure single soliton spectral profile and agrees perfectly with the experimental observations. Figure 2(e) reflects the equidistant distribution of single soliton spectral lines and each resonance peak has only one spectral line, which indicates that single soliton is generated in a low-noise state.

Figure 3(a–c) show experimental results of generated soliton states, wherein one, two and four solitons can be observed. The auxiliary laser component is filtered out here. It should be noted that the solitons formed here are perfect, meaning that they have exceptionally smooth spectra, without any spikes related to avoided-mode crossing as reported previously. This phenomenon is attributed to homogeneous sidewall of the microcavity avoiding different mode family interaction and unrelated to the incident light itself. In time domain, the beat between the pump and the spike region will lead to soliton tail oscillation and such jitter is unfriendly to precision measurement. Fortunately, the standard sech^2 shape spectrum of single soliton shown in Fig. 3(a) is in excellent agreement with the simulation result as shown in Fig. 3(d). Such a smooth spectral envelope with low redundant noise and unprecedentedly small line-to-line power variations are essential to applications in ranging, spectroscopy and astronomy. In our device, the obvious Raman-induced self-frequency shift (RSFS) manifesting itself as the spectral center redshift from the pump wavelength is also demonstrated^{53,61}. The shift induced by stimulated Raman scattering is 4.4 nm and the Raman

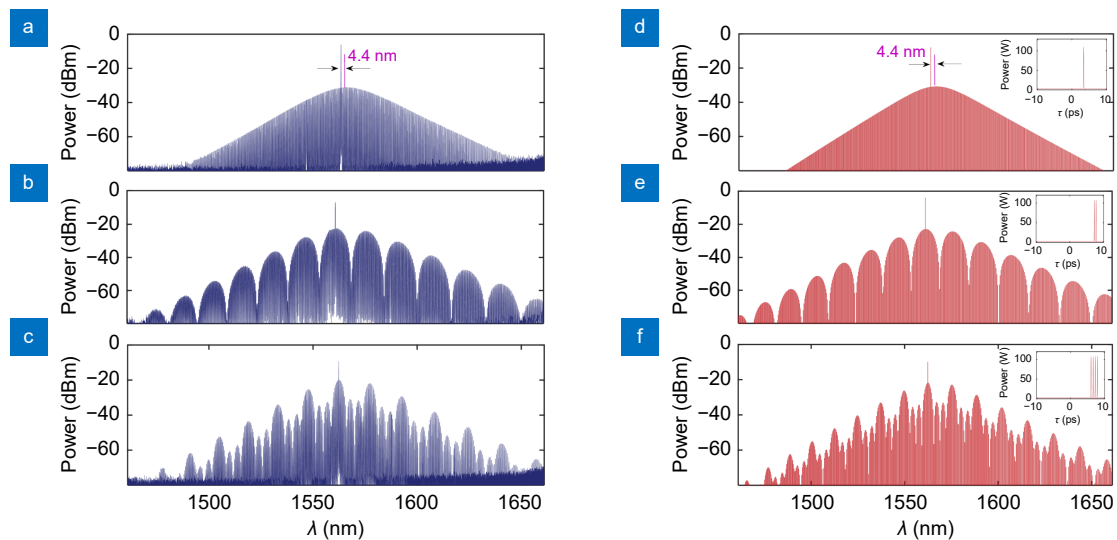


Fig. 3 | (a–c) Experimentally measured spectra for 1-, 2- and 4-soliton states, respectively. (d–f) Calculated different soliton states. Insets shows the corresponding temporal profile where oscillation is avoided.

shock time is inferred to 2.7 fs by comparing the spectrum of single soliton both in experiment and simulation.

Interestingly, it is further demonstrated that this scheme can suppress the thermal effect well and sequentially access stable different two soliton states flexibly through control the wavelength and power of auxiliary light as shown in Fig. 4. The generated spectra exhibit pronounced variations in the spectral envelope which arise from the interference of the Fourier components of the individual soliton. Figure 4(a–d) show four dual-soliton states obtained in experiments by first quickly adjusting the TEC from 5 k Ω to 2.5 k Ω to across the high noise state microcomb then carefully controlling tuning speed to acquire a low resistance around 2.2 k Ω for soli-

ton transition. Consequently, intracavity power reducing will result in different soliton distribution around resonator periphery. Final distance between two solitons depends on intracavity energy and heat balance. In our case, the resistance is tuned from 5 k Ω to 2.2 k Ω with the temperature adjustment from 60 to 44 degrees Celsius. The resistance used here should be larger than that of the single soliton regime because the energy of dual-soliton is about twice that of single soliton. The corresponding simulated spectra are shown in Fig. 5(a–d) and the insets depict the temporal profile. Simulation results match well with experimental structured spectra. Such perfect soliton states originate from the smooth waveguide side-wall itself and are different from the temperature

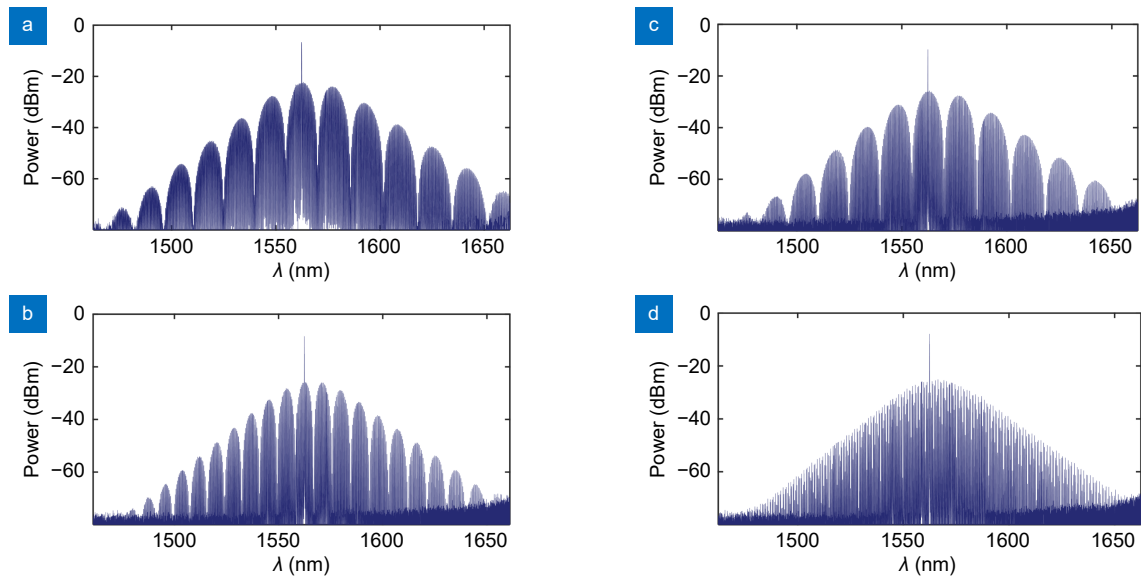


Fig. 4 | (a–d) Experimentally measured spectra of different two solitons states.

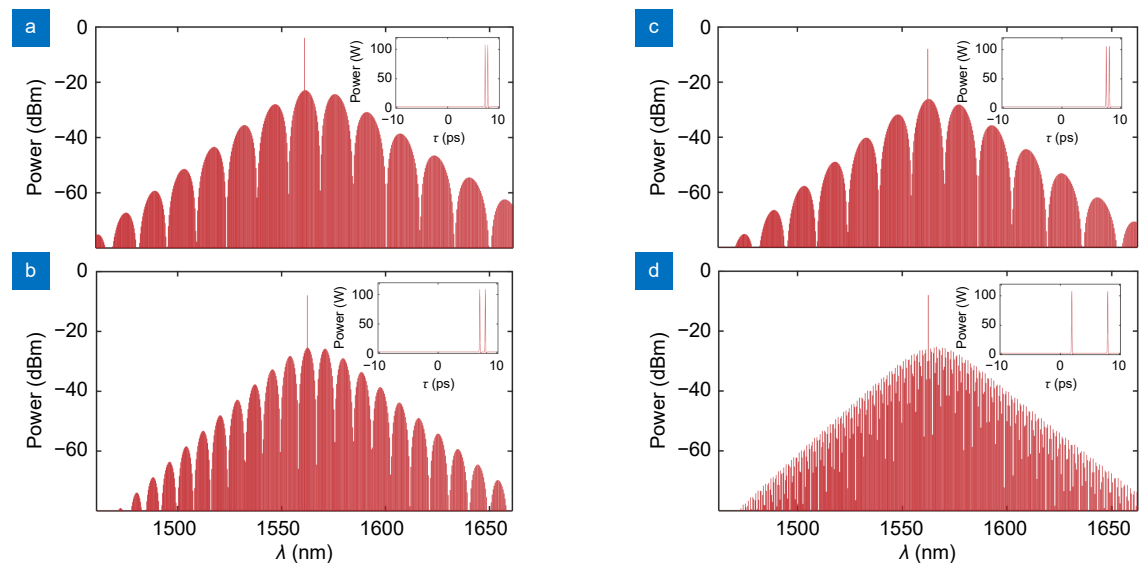


Fig. 5 | (a–d) Calculated spectra of different two-soliton states. Insets show corresponding temporal profile.

controlling induced AMX free microcombs, which relies on shifting the dispersive wave significantly to shorter wavelength with increasing temperature.

Conclusions

In summary, this work theoretically investigates thermal effect in silicon oxynitride microresonators based on the LLE model that incorporates thermal parameters. Simulations show that the generated solitons can either survive or annihilate due to thermal dynamics when the continuous pump laser is scanned from the blue to red detuning region. Therefore, the counter-propagating pump-auxiliary scheme possessing flexible thermal regulation is adopted to generate single soliton with favored smooth and standard sech^2 spectral profile. Furthermore, different multi-soliton states can be obtained easily by adjusting the TEC and auxiliary laser to balance the intracavity thermal instability. Thanks to our elaborate design and processing technology introducing uniform waveguide thickness and sidewall, the observed smooth spectra profile of solitons without any spike related to mode interaction as reported before paves the way for further frequency domain applications in spectroscopy, astronomy and telecommunications. The concomitant tail-oscillation-free temporal pulse in absence of absorption background can also accelerate soliton-based precision measurement like ranging and imaging. In future work, we will also investigate the generation of soliton microcombs with perfect spectral envelopes using auxiliary laser heat balance scheme in other material platforms.

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Author contributions

Mulong Liu proposed the idea and performed theoretical simulations. All authors contributed to experiments. Mulong Liu, Xiao Yu, and Xilin Han analyzed the data. All authors contribute to the manuscript. Wei Zhao, Guangwei Hu and Peng Xie supervised the project.

Competing interests

The authors declare no competing financial interests.



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