



# Experimental Demonstration of Self-Oscillation Microcomb in a Mode-Splitting Microresonator

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Self-oscillation and bifurcation as many-body dynamics solutions in a high-Q microresonator have induced substantial interest in nonlinear optics and ultrafast science. Strong mode coupling between clockwise (CW) wave and counterclockwise (CCW) wave induces mode-splitting and optical self-oscillation in the optical cavity. This study experimentally demonstrates the self-oscillation microcomb formation in a microresonator with strong backward Rayleigh scattering. When a pump laser sweeps across a resonance, both spontaneous symmetry breaking (SSB) and self-oscillation phenomenon are observed. The breathing soliton and stable soliton state can switch to each other through careful tuning of the pump detuning. Our experiments provide a reliable scheme for breather soliton microcomb generation. Meanwhile, the rich physics process enhances the comprehension of nonlinear optics in a cavity.

**Keywords:** microresonator, mode splitting, optical frequency comb, self-oscillation, optical soliton

## INTRODUCTION

Optical Rayleigh backscatter is one widespread phenomenon in the optical system. In a microresonator, the Rayleigh backscatter can induce mode splitting and rich nonlinearities due to the linear coupling between CW and CCW propagating waves [1–3]. Meanwhile, the nonlinear coupling between CW and CCW waves can induce spontaneous symmetry breaking, self-switching of counterpropagating waves, and spontaneous chiral symmetry breaking, which have been experimentally demonstrated in ultrahigh-Q whispering-gallery-mode (WGM) microresonators [4–6]. The intrinsic mechanism is the different nonlinear phase shifts between the counterpropagating waves due to the cross-phase modulation (XPM) and self-phase modulation (SPM), which have been modeled based on the coupled-mode theory or coupled Lugiato–Lefever equations (LLEs) [7].

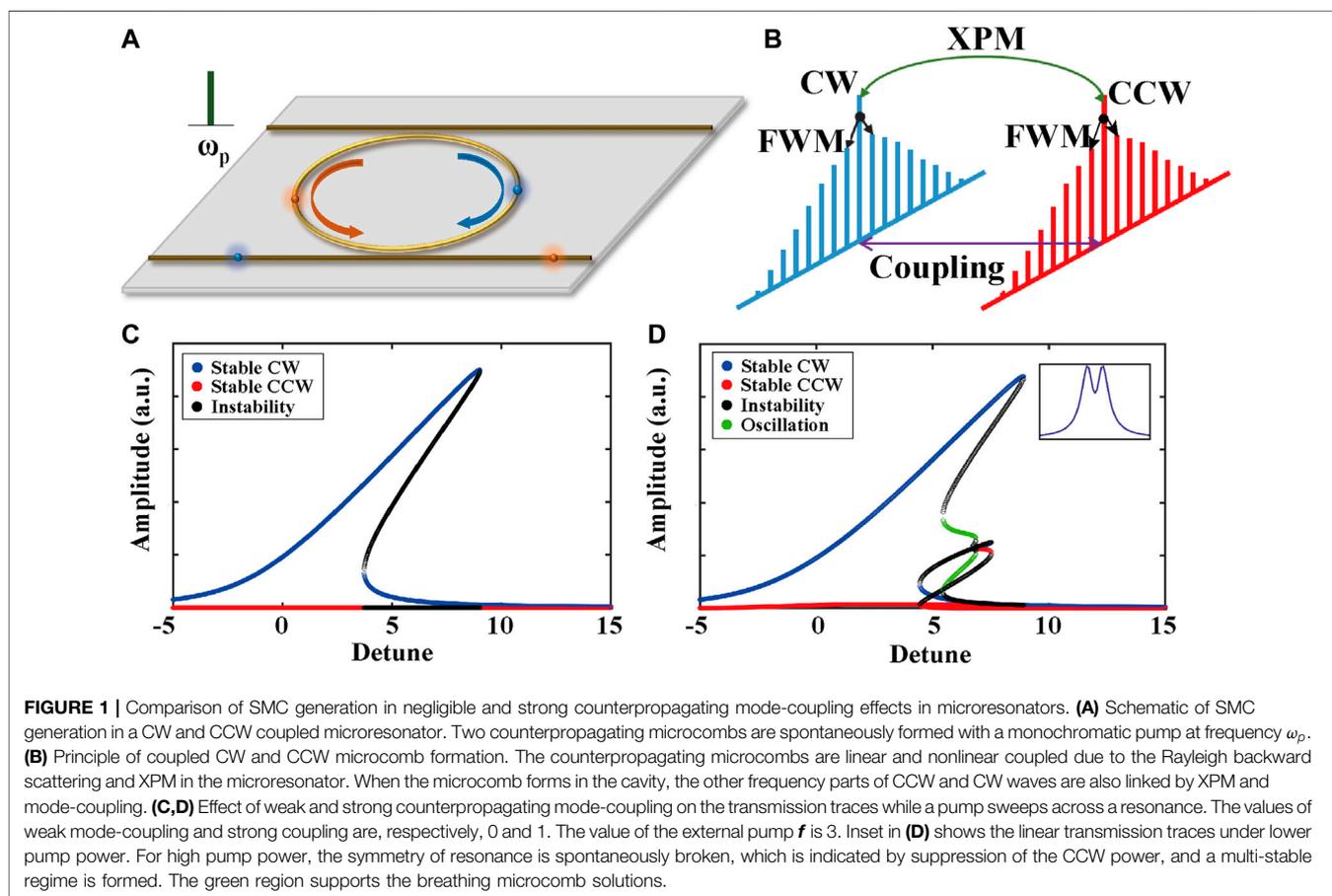
The optical field is greatly enhanced in a high-Q microresonator, which induces a low threshold four-wave mixing (FWM) for the microcomb formation [8]. The states of microcombs rely on the detuning of the continuous wave pump laser. To date, both stable solitons [9, 10] from soliton crystals [11–13] to soliton molecules [14, 15] and breathing solitons [16–19] have been discovered. Stable soliton microcombs (SMCs) [20–23] have become novel integrated broadband coherent optical sources that have shown great application prospects in a series of areas, such as dual-comb spectroscopy [24–26], ranging system [27, 28], high-speed communication systems [29, 30], and optical computing [31–33]. Breather soliton is a special soliton state with periodic energy exchange

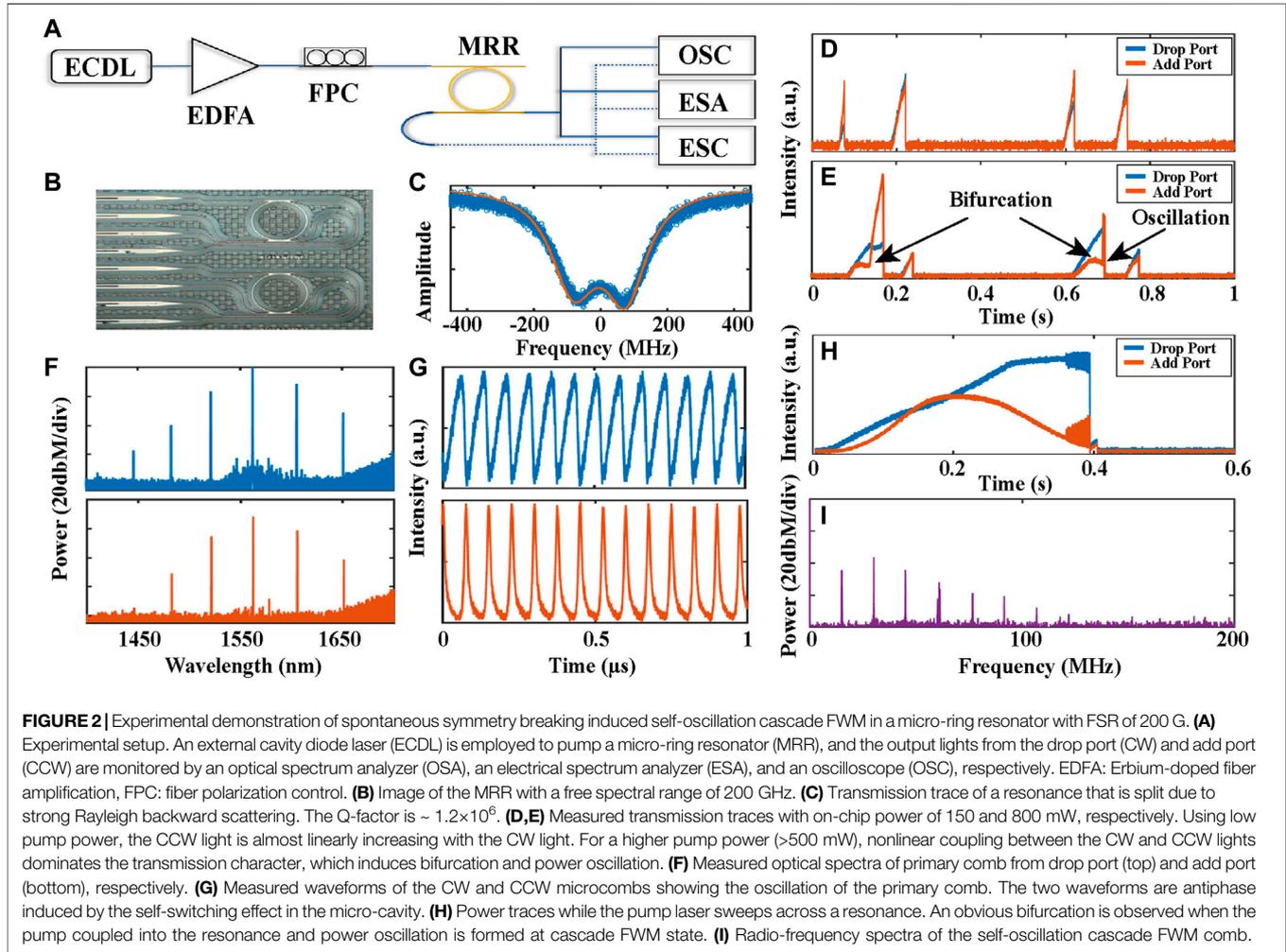
between the SMC and pump laser [16, 17] or another optical cavity mode [34, 35], which shows rich dynamics in cavity soliton physics. Recently, other types of soliton oscillations are also experimentally or theoretically studied. For example, forced oscillation is studied in a synthesized soliton crystal generation experiment due to the moving offset between the potential field and solitons [36]. In a counterpropagating Kerr soliton generation experiment, a relative motion between the counterpropagating solitons is observed due to the slight pump frequency difference [37]. Breather soliton *via* high-order dispersion is also theoretically studied [38]. Besides, self-oscillation performance and symmetry breaking *via* XPM or dual cavity are also demonstrated [39, 40]. For a microresonator with backward Rayleigh scattering, the interplay between counterpropagating waves introduces another degree of freedom affecting the microcomb formation [7]. A recent theoretical study shows a new type of soliton oscillation due to Rayleigh scattering instability [41]. The breathing frequency coincides with the Rayleigh scattering doublet splitting. A series of theoretical studies concern the generation of SMC in mode-splitting microresonators. All the studies show rich, dynamic processes in microresonators when the Rayleigh scattering is considered. However, there is still no experimental observation of mode-splitting induced breathing oscillations in an on-chip micro-ring resonator.

In this study, the dynamics of self-oscillation microcomb is studied based on the strong backward Rayleigh scattering. The CCW wave is suppressed while a high-power pump laser sweeps across the blue-detuned regime, which is regarded as SSB due to XPM between the counterpropagating waves. Once the pump laser enters the red-detuned regime, the power of counterpropagating waves inversely changes. The interplay of counterpropagating waves provides a novel mechanism for oscillated microcomb formation. Our results not only highlight the richness nonlinear dynamics for cavity physics research but also take the merits of simplicity for oscillated microcomb and breather soliton observations.

## PRINCIPLE

**Figure 1A** shows the microcomb formation in a microresonator with strong Rayleigh backscatter. **Figure 1B** shows the basic principle of microcomb generation with Rayleigh backscatter. Previous reports mainly focus on the case of weak Rayleigh backscatter, which has little influence on the SMC formation and survival. As a comparison, when a microresonator with strong backward Rayleigh scatter is pumped, part of the pump power is backward scattered and forms a CCW optical field in the microcavity. The counterpropagating fields experience an



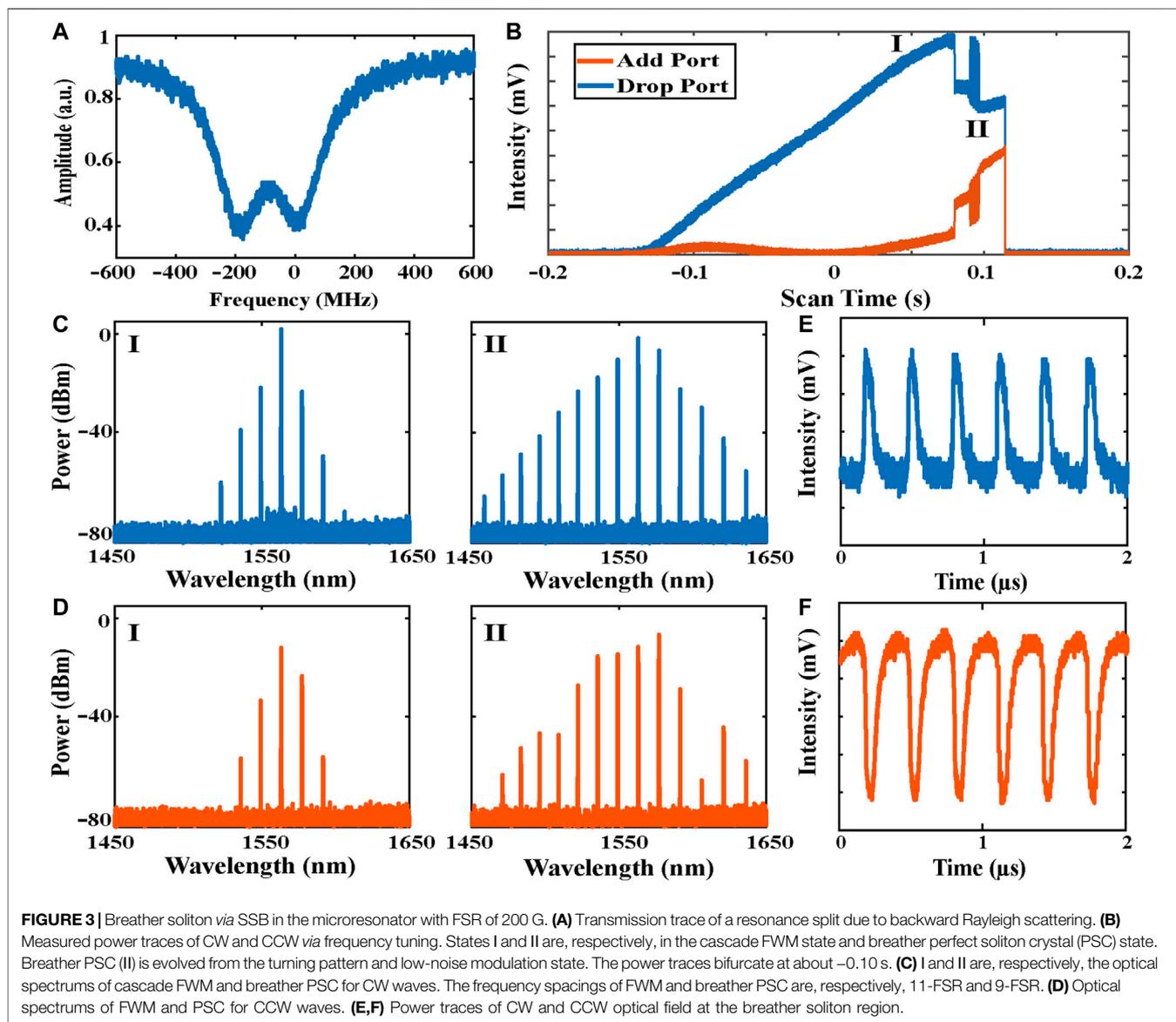


additional phase shift due to the XPM, which causes a larger frequency shift on the resonances and suppresses the CCW wave power increase when the pump locates at the blue-detuned regime. Hence, a strong SSB would be formed. Once the pump laser enters the red-detuned regime or frequency domain between two resonance modes, the power of counterpropagating waves will inversely change. Two counterpropagating microcombs will co-exist in the cavity. By considering the strong Rayleigh backscatter effect, the dynamics of microcomb formation can be modeled using the coupled normalized LLE:

$$\begin{aligned} \frac{dA_{cw}}{dT} = & -(1 + i\delta\omega)A_{cw} + iGA_{ccw} + id_2 \frac{\partial^2}{\partial\phi^2} A_{cw} + 2iA_{cw}P_{ccw} + f \\ & + iA_{cw}A_{cw}A_{cw}^* \end{aligned} \quad (1)$$

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where  $A_{cw,u}$  and  $A_{ccw,u}$  are the CW and CCW optical fields, respectively, and  $\delta\omega$  represents the normalized detuning between the pump and resonance. The normalized coupling rate between the CW and CCW fields is  $G$ .  $d_2$  describes the normalized second-order dispersion coefficient.  $P_{cw}$  and  $P_{ccw}$  are the averaged intra-cavity power for CW and CCW optical waves, respectively. In order to demonstrate the self-oscillation phenomenon, the cavity stability is analyzed firstly. We only consider the pump mode and neglect the cavity dispersion. The value of external pump  $f$  is 3. When the backward Rayleigh scattering is negligible and the value of  $G$  is 0, a standard bistable curve can be obtained while a high-power pump sweeps across a resonance, as shown in **Figure 1C**. By adding a dimension of the counterpropagating mode-coupling effect and when the value of  $G$  is 1, the coupled LLEs have multi-solutions, as shown in **Figure 1D**. Compared with the lower pump power case (inset of **Figure 1D**), the CCW field is no longer increasing with the CW field under high power pump conditions, which proves the occurrence of SSB in a counter mode coupled microresonator. The optical fields show much more complex dynamics. A stability analysis shows that the coupled LLEs have stable and oscillatory solutions, which are respectively



corresponding to the stable and self-oscillation regime of the counterpropagating mode-coupling microresonator. The self-oscillation of the pump mode can induce oscillated microcomb formation, which provides a novel mechanism for breathing SMCs or self-oscillation microcomb generation.

## EXPERIMENT AND RESULTS

**Figure 2A** shows the setup of the experiment. The core device is a micro-ring resonator (MRR) with a free spectral range (FSR) of 200 GHz. **Figure 2B** shows the image of MRR, which is composed of a waveguide with a cross-section of  $2 \times 2 \mu\text{m}$ . The Q-factor of the MRR is  $1.2 \times 10^6$ , whose resonances are split due to the strong backward Rayleigh scattering, as shown in **Figure 2C**. In order to monitor the coupling effect between the two counterpropagating

waves in the MRR, the transmission power from the drop port (CW) and add port (CCW) are monitored simultaneously using a two-channel oscilloscope. When the power is about 150 mW, the powers of CW and CCW waves are monotonously increasing. **Figure 2D** shows the power traces while the pump sweeps across the resonances. There are no obvious nonlinear interactions between CW and CCW lights. When the on-chip pump power reaches 800 mW, a strong nonlinear coupling between CW and CCW waves occurs. Along with the pump detuning increase, there are obvious inflection points of the CCW power trace, as shown in **Figure 2E**. At this reflection point, the nonlinear coupling between the CW and CCW lights begins to dominate the optical field distribution, which induces power bifurcation of the counterpropagating waves. More interestingly, a rapid energy oscillation is observed. It is noted that microcomb is not formed at the self-oscillation region, where the CCW wave forms from

the backward Rayleigh scattering field rather than external injection.

The self-oscillation effect provides a novel mechanism for breathing microcomb formation. For microcomb generation in the microresonator, the on-chip power is boosted up to 1.0 W using a commercial EDFA and the polarization state is carefully tuned manually. **Figure 2H** shows the transmission traces of CW and CCW waves while the pump laser sweeps across a resonance of the MRR. The CW and CCW waves bifurcate at  $\sim 0.2$  s due to the strong XPM. Further increasing the pump detuning, a primary comb is formed, which accompanies strong power oscillation. **Figure 2F** and **Figure 2G** show the optical spectra and waveforms of CW and CCW waves, respectively. The CW and CCW waves oscillate out of phase. The optical state of the microcomb is the cascade FWM state. The oscillation is caused by the energy exchange between the CW and CCW waves, which is verified by the oscillation waveforms. **Figure 2I** shows the measured radio-frequency spectra, which indicates that the fundamental oscillation frequency is in the order of 10 MHz.

**Figure 3A** shows mode splitting at lower pump power, and the quality of the microresonator is 1.06 M. **Figure 3B** shows the output optical power traces of CW and CCW optical field while the on-chip power is amplified up to 1.0 W. **Figure 3C** and **Figure 3D** show the optical spectra of CW and CCW waves at different microcomb states, respectively. Power bifurcation phenomenon is observed at about  $-0.1$  s. With the increase in intracavity power, the primary comb is formed with a frequency spacing of 11-FSR (**Figure 3C(I)**). When the pump laser enters the red-detuning regime, the power of CW and CCW light changes inversely and keeps the intra-cavity optical power. Hence, the strong thermooptics effect is avoided for stable soliton microcomb formation. According to the stability analysis, there are stable and oscillation SMC states while the pump locates at the soliton existing regime. **Figure 3C(II)** presents the optical spectra of breathing perfect soliton crystals (PSC) after undergoing the stable soliton state. The oscillation perfect soliton crystal is caused by the energy exchange between the CW and CCW waves, which is proved by the antiphase oscillation of the measured optical power traces (**Figure 3E** and **Figure 3F**). The stable and breathing PSCs can be switched *via* slightly changing the pump detuning.

The mode-splitting effect provides another mechanism to realize intracavity thermal balance for stably accessing soliton microcomb states. As shown in **Figure 3B**, the power of the CCW wave increases while the pump enters the red-detuned regime, which compensates for the power decrease in the CW waves. Continuously increasing the pump wavelength, the breather PSC would evolve into the multi-soliton, as shown in the second soliton step in **Figure 3B**. In this region, the power of CW and CCW waves demonstrate the antiphase exchange.

The self-thermal balance mechanism assisted mode splitting extends the soliton existing range, and no special experimental technique is demanded for SMC generation. The mode-splitting

effect enriches the physics dynamics in microcomb generation. Both SSB and self-oscillation are observed due to the nonlinear interplay between two counterpropagating waves. The self-oscillation effect provides a novel mechanism for breathing SMC. Mode splitting could extend the breather soliton existence region.

## CONCLUSION

In conclusion, we have experimentally demonstrated the self-oscillation microcomb generation in a microresonator with mode splitting due to strong Rayleigh backscatter. Due to the strong nonlinear coupling between CW and CCW waves, the CCW light is suppressed while the pump laser locates at the blue-detuned regime. Once the pump enters the red-detuned regime, the exchange power between CW and CCW waves would occur and realize the self-oscillation performances, which induces the oscillation of microcombs, including cascade FWM state and SMCs. The study provides a new mechanism of breathing SMC generation, which enriches the cavity soliton physics.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

XW conceived the idea. XW, PX, YW, and WW performed the experiments and theoretical simulations. BL and SC designed and fabricated the microresonator. WZ and LW discussed the experimental results. WZ and WW supervised the whole project. All the authors contributed to the manuscript writing.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphy.2022.908141/full#supplementary-material>

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