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# Deterministic generation of Kerr soliton microcomb in coupled microresonators by a single shot pulsed trigger

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## ABSTRACT

We demonstrate the generation of Kerr frequency combs with controllable intracavity soliton states by seeding the single continuous wave (CW) driven two coupled nonlinear microresonators with a pulsed trigger. The stable one-, two-, or three-soliton frequency comb can be realized deterministically simply by adjusting the pulse intensity of the trigger signal. Numerical simulations show that the generation of the mode-locked soliton frequency combs is robust without going through any instability or chaotic states. These results provide a means for the deterministic and controllable generation of optical Kerr frequency combs on integrated chips.

**Keywords:** Microresonator, optical frequency comb, Kerr effect, pulse trigger

## 1. INTRODUCTION

Microresonator-based optical frequency combs (microcombs) can be generated on a monolithically integrated chip, which is promising for compact broadband coherent light sources and desirable for practical applications ranging from spectroscopy to ultrafast optics and metrology[1-3]. Several approaches have been proposed for the generation of intracavity solitons[4-7]. The fast pump frequency scanning scheme[4] was first demonstrated for the generation of optical Kerr frequency combs, which allows the intracavity field to reach soliton operation by sweeping the pump frequency from the blue to the red detuning region. Soliton microcombs can also be generated using the thermal tuning method[5] by varying the current (or voltage) applied to the microheater to control the cavity resonance wavelength. In addition, the "power kicking"[6] and the auxiliary photothermal compensation scheme[7] have been proposed and exploited as well. The above methods inevitably require precise tuning of either the pump frequency or the operation temperature and the intracavity field undergoes the modulation instability (MI) state, which becomes technically difficult in practice and severely limits the microcomb applications. Thus, it remains a challenge to control the soliton states and to deterministically generate the desired single soliton state. Recently, two coupled microresonators have also been used to achieve soliton microcomb generation by tuning the coupling coefficient, which offers more flexibility and possibilities compared to a single nonlinear microresonator[8]. The soliton region in the two coupled cavities can be shifted to the blue-detuned side.

In this paper, we adopt a pulsed triggering scheme to control the intracavity soliton states of Kerr microcombs based on two coupled nonlinear microresonators. The temporal and spectral evolution dynamics of single-soliton microcomb formation are numerically investigated. We find that the generation of the mode-locked soliton states can be controlled by varying the power of the triggering pulse. We also find that the average powers of the one-, two-, and three-soliton microcombs are 6.020 W, 6.422 W, and 6.783 W, respectively. The rest of the paper is organized as follows. Section 2 introduces the scheme and theoretical model of the deterministic generation of soliton microcombs. Section 3 reports the numerical results, including the temporal and spectral profiles and the evolution of the intracavity average power for Kerr soliton generation. Section 4 concludes the paper.

## 2. MICROCOMB GENERATION SCHEME AND THEORETICAL MODEL

### 2.1 Scheme of deterministic microcomb generation

Figure 1 shows the scheme for the deterministic generation of Kerr soliton microcombs. The two coupled microresonators are externally driven by a single CW pump beam. The central frequency of the input CW laser is fixed and blue detuned with respect to the nearest main cavity resonance frequency. The soliton microcombs are excited by a trigger pulse. In addition, the phases of the soliton combs are intrinsically synchronized because they are generated by the same single pulse trigger. Such coherently seeded comb lines initiate the Kerr comb generation process and avoid the random pulse build-up due to modulation instability (MI). Thus, a single shot pulse can deterministically trigger the single-soliton state without going through MI or chaotic states. Neither the pump frequency nor the cavity resonance need to be tuned.

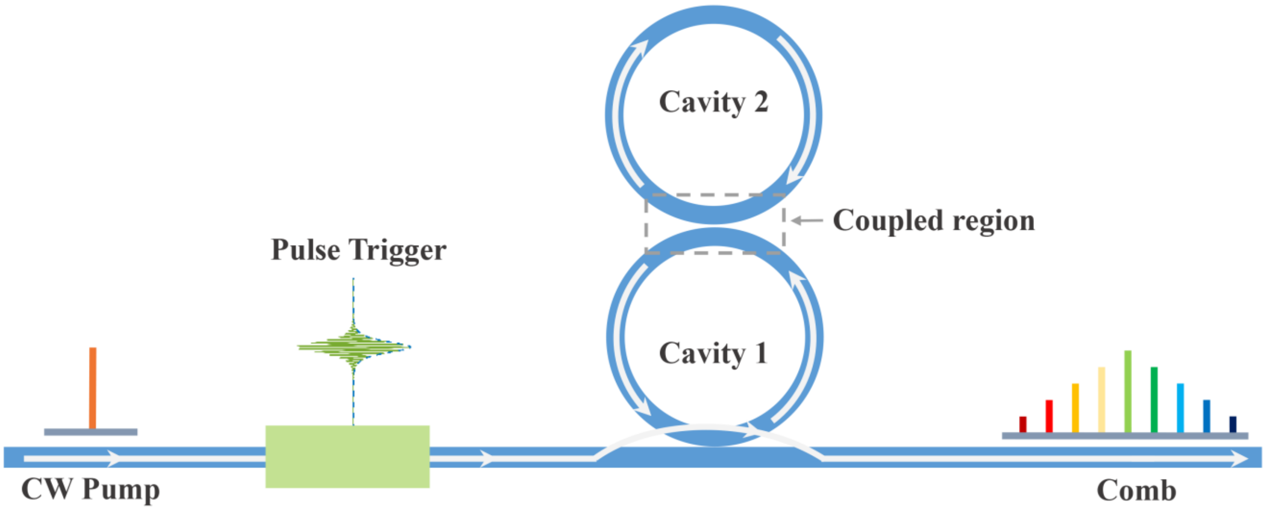


Figure 1. Schematic diagram of the deterministic Kerr soliton microcomb generation. Cavity 1 is the main cavity and Cavity 2 is the auxiliary cavity.

### 2.2 Theoretical model

The nonlinear passive cavity dynamics in the two coupled microresonators and the corresponding microcomb generation can be described by the coupled Ikeda map[5]

$$\frac{\partial E_{1/2}(z,\tau)}{\partial z} = -i\delta k_{01/02} E_{1/2} - \frac{\alpha_{1/2}}{2} E_{1/2} - i\frac{\beta_{21/22}}{2}\frac{\partial^2 E_{1/2}}{\partial \tau^2} + i\gamma_{1/2}\left|E_{1/2}\right|^2 E_{1/2}, \tag{1}$$

$$E_{1/2}(0,\tau) = i\sqrt{\theta_c} E_{2/1}(L,\tau) + \sqrt{1-\theta_c} E_{1/2}(\frac{L}{2},\tau), \tag{2}$$

$$E_1 = i\sqrt{\theta} E_F + \sqrt{1-\theta} E_1. \tag{3}$$

The injected CW pump and the single shot pulse during the m-th round trip are given by

$$E_F^{(m)} = E_{CW} + \sqrt{P_0}\,\mathrm{sech}(T/T_0). \tag{4}$$

where $z$ is the distance, $\tau$ is the time, and $i$ is the imaginary number. $E_j$, $\delta k_{0j}$, $\alpha_j$, $\beta_{2j}$, and $\gamma_j$ represent the optical fields, wave vector of the pump laser, power loss per unit length, second order dispersion coefficient, and nonlinear coefficient of the main cavity ($j$=1) and the auxiliary cavity ($j$=2), respectively. $L$ is the round-trip length of one cavity, $E_F$ is the amplitude of the pump laser, $\theta$ is the power coupling coefficient between the straight waveguide and the main cavity and $\theta_c$ is the power coupling coefficient between the two cavities. $E_{CW}$ is the amplitude of the single CW pump laser, $P_0$ and $T_0$ are the peak power and duration of the trigger pulse, respectively. In this paper, we use $Si_3N_4$ coupled microresonators as an example, and the main parameters are listed in Table 1.

Table 1. Main parameters used in the simulation.

| Parameters | $Si_3N_4$ |
|---|---|
| Pump Wavelength $\lambda$ (nm) | 1550 |
| Propagation Loss $\alpha$ (dB/cm) | 1.2 |
| Radius $R$ (μm) | 1 |
| Free Spectral Range FSR (GHz) | 226 |
| Nonlinear Coefficient $\gamma$ ($W^{-1}m^{-1}$) | 1 |
| GVD Coefficient $\beta_2$ ($ps^2/m$) | 0.02 |
| Coupling Coefficient between the Straight Waveguides and the Main Cavity $\theta$ | 0.0025 |
| Coupling Coefficient between the Two Cavities $\theta_c$ | 0.0025 |

## 3. SIMULATION RESULTS AND DISCUSSION

The bistability region of the main cavity is determined numerically by considering the steady-state solutions of Eqs. (1)-(3), as shown in Fig. 2. The region between the solid black curves is available for the generation of soliton microcombs. The minimum pump laser power for soliton generation is determined by the power at the cusp of the soliton region. We choose a pump parameter of point A inside the soliton region, the corresponding detuning value and pump power are $-12.28\kappa$ and 3W, respectively, in Fig.2, to investigate the following pulse-triggered soliton formation.

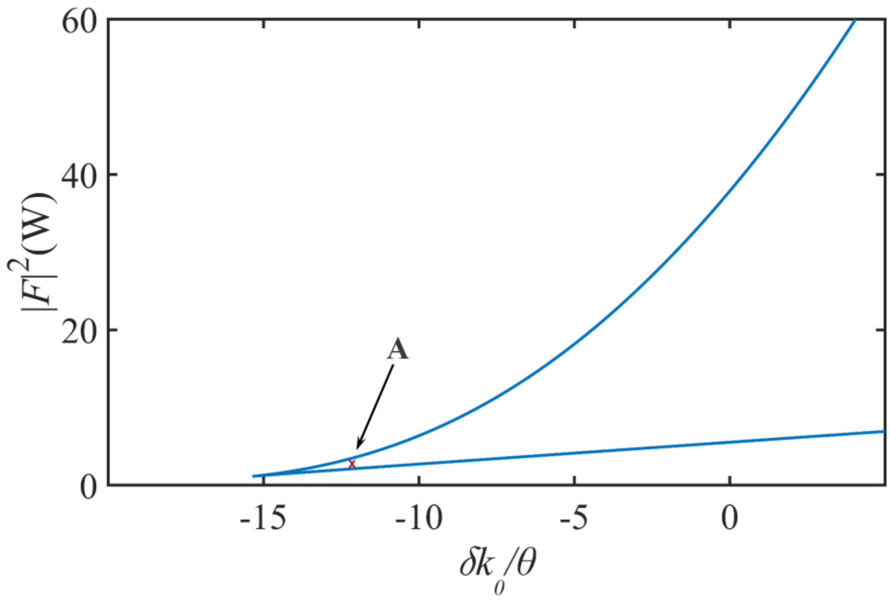


Figure 2. The bistability region of the coupled microcavities with $\kappa = \kappa_c$. The detuning and the corresponding pump power at point A are $-12.28\kappa$ and 3 W, respectively.

The numerical simulations of the detailed processes associated with the soliton formation in the two coupled microresonators are carried out based on Eqs. (1)-(4). The single CW pump is set in the blue detuning region with respect to the resonance of the main cavity, while the pulse width of the trigger signal is chosen to be 0.5 ps. The stable single-soliton state can be obtained when a single-shot pulse with a peak power of 2.8 kW is launched into the coupled microresonators at the 4000-th roundtrip [see Figs. 3(a) and 3(c)]. Figures 3(b) and 3(d) show the temporal and spectral evolution of the main cavity field. Two-soliton states [see Figs. 4(a) and 4(c)] and three-soliton states [see Figs. 4(b) and 4(d)] can also be obtained when the peak powers of the seeding picosecond pulse are $P_0$ = 3 kW and $P_0$ = 4 kW, respectively. Both the temporal and spectral profiles of the initial Gaussian pulse evolve to the soliton state, which forms a Kerr comb characterized by spectral lines with multiple FSR separations.

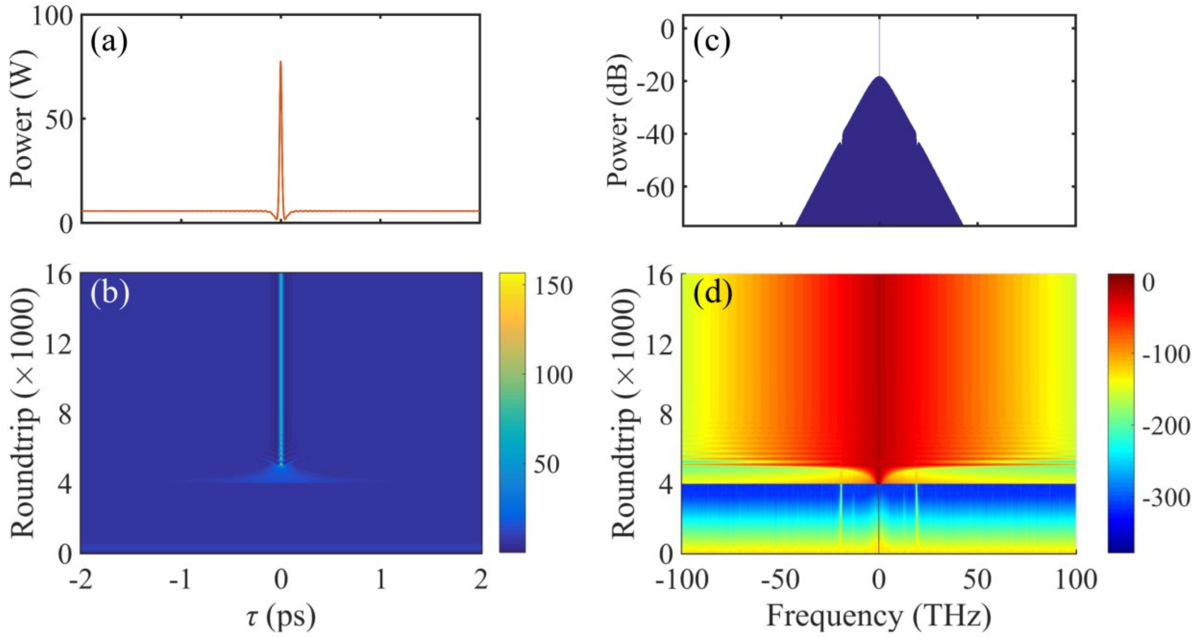


Figure 3. (a) Temporal waveform and (c) optical spectrum of the single-soliton microcomb. (b) Temporal and (d) spectral envelope evolution of the single-soliton microcomb.

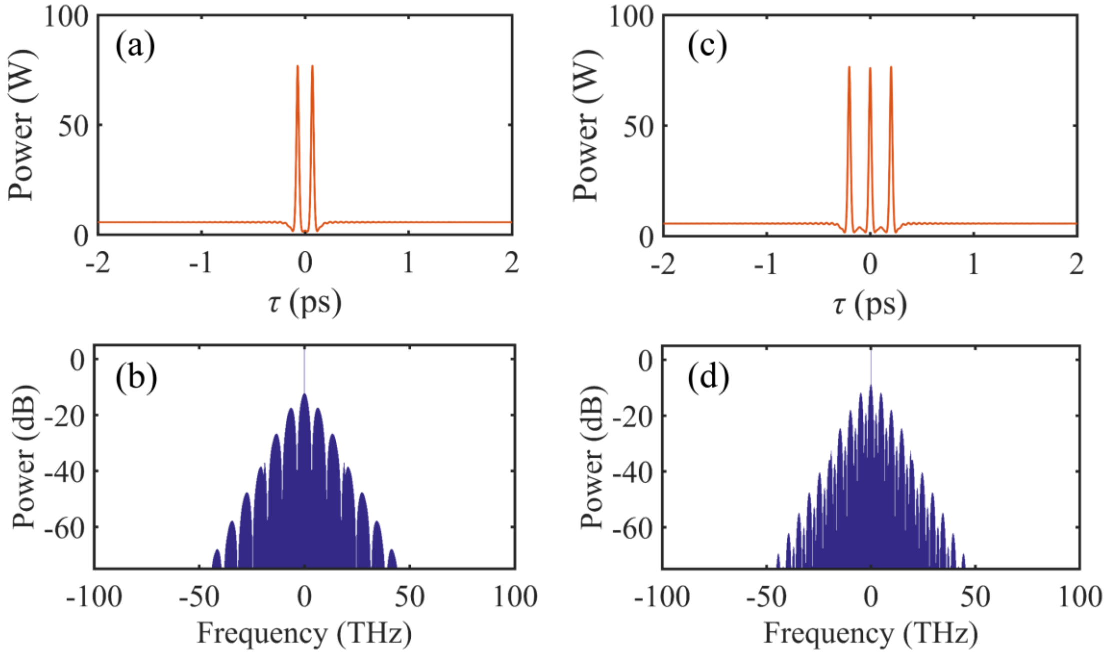


Figure 4. The (a) temporal waveform and (b) optical spectrum of the two-soliton state microcomb. The (c) temporal waveform and (d) optical spectrum of the three-soliton state microcomb.

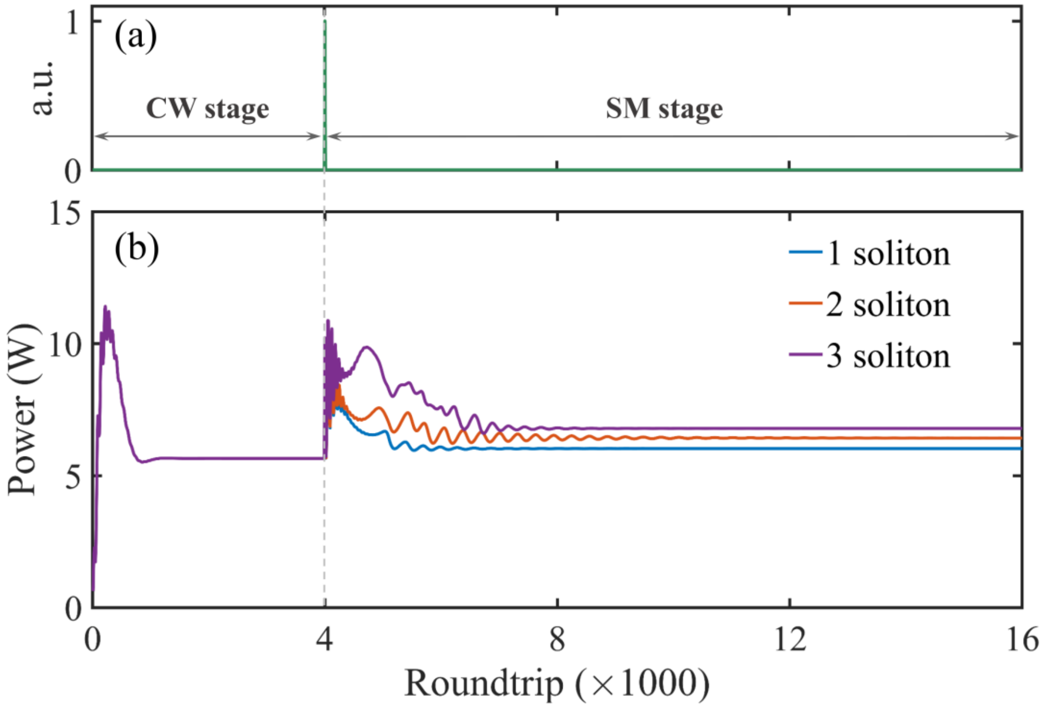


Figure 5. (a) A single shot pulse trigger is injected into coupled microresonators at the 4000-th roundtrip. SM: soloiton microcomb. (b) Evolution of the average intracavity in the formation of one-, two-, and three-soliton.

Figures 5(a) and 5(b) show the single pulse trigger signal and the corresponding evolution of the average intracavity power for the deterministic generation of Kerr soliton microcombs, respectively. A single shot pulse with a duration of 0.5 ps is launched at the 4000-th roundtrip to initiate the soliton microcomb (SM) stage. From Fig. 5(b), the average intracavity power undergoes a relaxation oscillation after the injection of the trigger pulse, and converges to a constant value. The final average powers of the one-, two-, and three-soliton microcombs are at 6.020 W, 6.422 W and 6.783 W, respectively, after about $1.2\times10^4$ roundtrips.

## 4. CONCLUSION

In conclusion, we have studied the deterministic generation of soliton microcombs in two coupled nonlinear microresonators using a pulse trigger. When the two coupled microresonators are pumped by a cw laser, Kerr soliton microcombs can be excited in the blue-detuned region of the main microcavity. We have shown by numerical simulation that the intracavity soliton states of the Kerr microcombs can be controlled by varying the intensity of the trigger pulse. The stable one-, two-, and three-soliton microcomb can be deterministically generated when the peak powers of the trigger picosecond pulse are 2.8 kW, 3 kW, and 4 kW, respectively. The use of a trigger signal to control the intracavity soliton states for soliton microcomb generation will facilitate practical applications of Kerr frequency combs.

## ACKNOWLEDGEMENT

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