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Octave-spanning microcombs generation with controllable intracavity soliton states

Feng Ye[1], Zihao Cheng[2], Dongmei Huang[2,3], Xuanyi Liu[4], H. Y. Fu[4], P. K. A. Wai[2,5], Qian Li[1,*]

[1]School of Electronic and Computer Engineering, Peking University, Shenzhen 518055, China
[2]The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen 518057, China
[3]Photonics Research Centre, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
[4]Tsinghua Shenzhen International Graduate School and Tsinghua-Berkeley Shenzhen Institute, Tsinghua University, Shenzhen 518055, China
[5]Department of Physics, Hong Kong Baptist University, Kowloon Tong, Hong Kong
**Corresponding author e-mail address: liqian@pkusz.edu.cn*

Abstract: We propose a monolithically integrated scheme to efficiently generate robust octave-spanning microcombs with controllable intracavity soliton states using a single CW pump.

1. Introduction

Soliton Kerr frequency combs (microcombs) in microresonators provide a multi-wavelength laser source with coherent and evenly-spaced frequency lines, which is a powerful technique in various fields containing LIDARs, coherent telecommunication and quantum key distribution [1-6]. Various approaches have been adopted to intracavity solitons formation [1-4]. Nevertheless, it is still challenging to control soliton states in microresonators due to thermo-optic instability. Different soliton states can be accessed by backward tuning of the CW laser after the generation and stabilization of a multi-soliton state. [2]. But the backward tuning method is limited by the response time of lasers or heaters, and not all multi-soliton states can be switched to a lower soliton number upon backward tuning [3]. Besides, a single-soliton microcomb can be deterministically excited by seeding the CW-driven microcavity with a single-shot of energetic sub-picosecond pulse offered by a high-performance pulsed laser [4]. The demand for additional pulsed laser source adds extra cost, and its fixed output pulse is inconvenient for tuning. The methods mentioned above inevitably require additional instruments or a complicated experimental process, which goes against the full integration of the microcomb system and strongly limits the microcomb applications. To our knowledge, the fully integrated approach for stable controlling the soliton states number of excited soliton microcomb has not been reported. In this paper, we develop a monolithically integrated scheme to control the soliton states of the intracavity soliton microcomb based on a microring-resonator combined with a Mach–Zehnder modulator (MZM). An effective pulse shaper is realized by adjusting the pulse width and intensity of the signal on the MZM. As a result, the octave-spanning solitons microcombs are straightforwardly achieved in the dispersion-engineering LN waveguide with controllable soliton states number by using a single CW pump.

2. Comb generation scheme and theoretical model

The thin-film lithium niobate (LN) platform is considered. The LN microresonator has a free spectral range (FSR) of 226 GHz and a radius of 100 μm. Since a single shot of pulse is injected into microresonator with a CW pump after pulse shaper enabling, the light field inside the microcavity is not fixed but varies significantly. Consequently, the Ikeda map is more suitable for modeling the evolution of the optical field in the cavity [5],

$$\psi^{(m+1)}\left(z=0,T\right)=\sqrt{\theta}\psi_{in}^{(m)}\left(T\right)+\sqrt{1-\theta}e^{-i\delta_0}\psi^{(m)}\left(z=L,T\right), \tag{1}$$

$$\frac{\partial\psi^{(m)}\left(z,T\right)}{\partial z}=-\frac{\alpha_0}{2}\psi^{(m)}+i\sum_{k\geq 2}\frac{i^k\beta_k}{k!}\frac{\partial^k\psi^{(m)}}{\partial T^k}+i\gamma\left(1+iT_s\frac{\partial}{\partial T}\right)\left|\psi^{(m)}\right|^2\psi^{(m)}, \tag{2}$$

where $\psi^{(m+1)}(z,T)$ is the slowly-varying envelop of the optical field in the m-th roundtrip, T is the time delay, α_0= ~0.82 dB/cm is the linear loss coefficient, θ=0.0019 is the coupling coefficient, β_k is the k-th order dispersion coefficient, γ=1 /W/m is the nonlinear coefficient, δ_0=0.0205 is the detuning between the CW pump frequency and the closest l-th order resonant frequency, $L = 2\pi r$ is the roundtrip length, T_s is the optical shock time constant. A hyperbolic-secant pulse centered at 1550 nm is loaded in the microresonator from the MZM. It can be numerically expressed as $\psi_{in}^{(m)}\left(T\right)=\psi_{cw}+\sqrt{P_0}\,\mathrm{sech}\left[\left(T\right)/T_0\right]$ where ψ_{cw}, P_0 and T_0 represent the CW pump field, the peak power and duration of the pulse, respectively.

3. Simulation results and discussion

Figure 1 shows the soliton microcomb generation scheme involving an MZM as the pulse shaper and a microring as the resonator. The modulation signal with the expected pulse shape can be carved from the input CW laser by adjusting the electrical signal on MZM. Figure 1(b) shows the group-velocity dispersion (GVD) for the fundamental transverse electric mode of the LN waveguide with bottom width W=1500 nm, rib thickness H_{rib}=350 nm, slab thickness H_{slab}=450 nm and sidewall angle θ=70°. The calculated integrated dispersion β_{int} for the 1550-nm pump is depicted in Fig. 1(b). According to the phase-matching condition [1], the dispersive wave can be generated at around 1195 nm and 2655 nm.

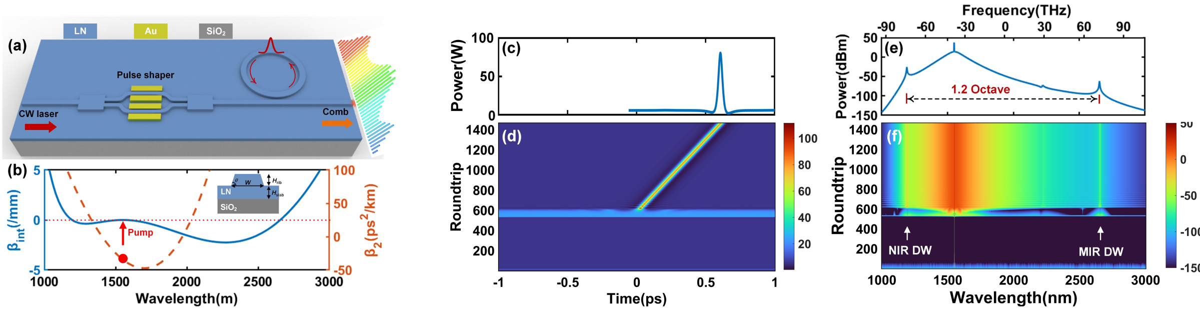

Fig. 1. (a) Schematic diagram of the octave-spanning soliton microcomb generator. (b) Integrated dispersion and second-order GVD. (c)-(d) Temporal and (e)-(f) spectral optical fields of output and evolution.

We simulate the optical pulse propagation inside the microcavities in terms of Eqs. (1)-(2). CW pump power is selected as $|\psi_{cw}|^2 = 1$ W . A single shot modulation with T_0 = 50.2 ps and P_0 = 4 W is modulated by the pulse shaper. Then the pulse launches into microring resonator at the 266th roundtrip and maintains for 533 roundtrips. As shown in Figs. 1(c)-1(d), cavity solitons cannot form spontaneously before pulse injection. After the 50.2-ps pulse involved in the resonator as external perturbations, the intracavity power is prominently enhanced. We observe the deterministic generation of stable femtosecond cavity solitons. Resonant supercontinuum and efficient microcomb generation are simultaneously achieved by bridging the fields of CW-driven resonant and pulse-driven non-resonant nonlinear optics [6]. During the co-propagating process between the CW pump and a pulse shot, a coherent 1.2 octave-spanning spectra is formed as shown in Figs. 1(e) and 1(f). Near-infrared (NIR) and mid-infrared (MIR) dispersive waves can also be clearly observed. To further demonstrate this approach, we tune the power and pulse duration of the picosecond pulse. As a result, two-soliton and three-soliton states are obtained in Fig. 2 after injecting the picosecond pulse with T_0 = 49 ps, P_0 = 4.2 W and T_0 = 51 ps, P_0 = 3.9 W, respectively. The excited soliton states in the cavity can be efficiently controlled by the modulation signal. Soliton microcombs still access 1.2 octave-spanning bandwidth which is the key requirement of self-referenced frequency (f-2f) microcombs, served as an excellent candidate for precision metrology.

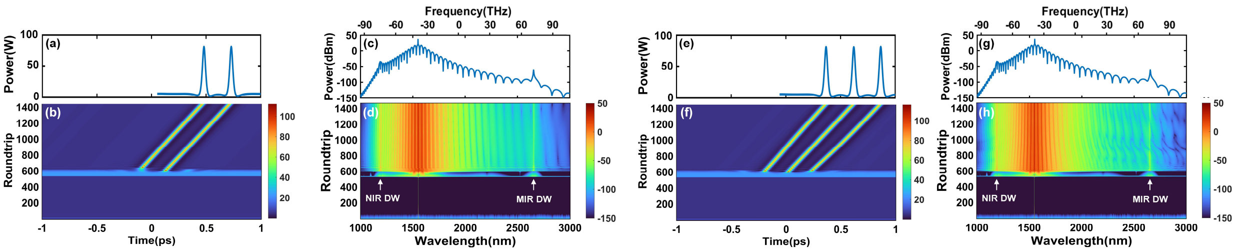

Fig. 2. (a)-(d) Two-soliton and (e)-(h) three-soliton microcomb generation including the temporal and spectral optical fields of output and evolution.

4. Conclusion

In conclusion, we proposed a monolithically integrated scheme for generating an octave-spanning microcombs with controllable intracavity soliton states. The robust single-, two- or three-soliton microcomb can be built up in the cavity by altering the modulation signal and only using a single CW pump. This solution bridging the fields of CW-driven resonant and pulse-driven non-resonant nonlinearity will enable the on-chip soliton microcomb generation with manipulating soliton states and coherent supercontinuum generation with high efficiency.

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Reference

[1] V. Brasch, et. al., Science **351**, 357–360 (2016).
[2] H. Guo, et. al., Nat. Phys. **13**, 94–102 (2016).
[3] M. H. P. Pfeiffer, et. al., Optica **4**, 684-691 (2017).
[4] Z. Kang, et. al., Opt. Express **26**, 18563-18577 (2018).
[5] F. Li, et. al., Nanophotonics **5**(2), 292-315 (2016).
[6] M. H. Anderson, et. al., Optica **8**, 771–779 (2021)