Optica High-brightness Sources and Light-driven Interactions Congress 2022 (EUVXRAY, HILAS, MICS)

Dissipative Kerr Solitons Burst in Microresonator and Time-frequency Analysis

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Abstract: This paper establishes a Kerr soliton burst system by the double-pump method, which supports a single soliton state for over one hour. The soliton is analyzed by short-time Fourier transform to get the time-frequency spectrum. © 2022 The Author(s)

1. Introduction and Methods

Optical frequency combs (OFC) are discrete and equispaced lines in the frequency domain with numerous applications. When the third-order parametric amplification and cavity losses, as well as the self-phase modulation (SPM) and cavity dispersion, are double-balanced, broadband dissipative Kerr solitons (DKSs) can be triggered [1]. Compared with the femtosecond laser or fiber resonator, the microresonator fabricated by SiN or similar optical material has a higher repetition frequency, better quality factor, and is easier to integrate. In this paper, we design an integrated ring resonator based on the Lugiato-Lefever equation (LLE) [2],

$$\frac{\partial \psi(\theta,\tau)}{\partial \tau} = -(1+i\zeta_0)\psi + i\frac{1}{2}\frac{\partial^2 \psi}{\partial \theta^2} + i|\psi|^2\psi + f \tag{1}$$

where f represents dimensionless pump field intensity. Consider the cavity's second-order dispersion, set the second-order dispersion coefficient D_2, then the total dispersion parameter $\beta = -2D_2/\kappa$. According to the model in Fig. 1 (a), we simulate in COMSOL Multiphysics® to design a microresonator structure with the anomalous group velocity dispersion (GVD) region.

The ring resonator should be swept from the blue-detuned side to the red-detuned side for soliton burst. However, the red-deturned region is usually unstable, and the pump laser frequency is hard to maintain at the status due to thermal effect [3]. We set up a dual-pump experiments scheme as shown in Fig. 1 (c), which includes two lasers (TSL-770 and PPCL-300) as the primary and auxiliary pump. The two lasers are pumped into the resonator through two optical circulators and tuned in two resonances simultaneously [4, 5]. Then fix the wavelength of the auxiliary pump and finely tune the primary pump from blue-detuning towards red-detuning. The optical power in the microresonator is stable due to the opposite evolution process of the primary pump and auxiliary pump.

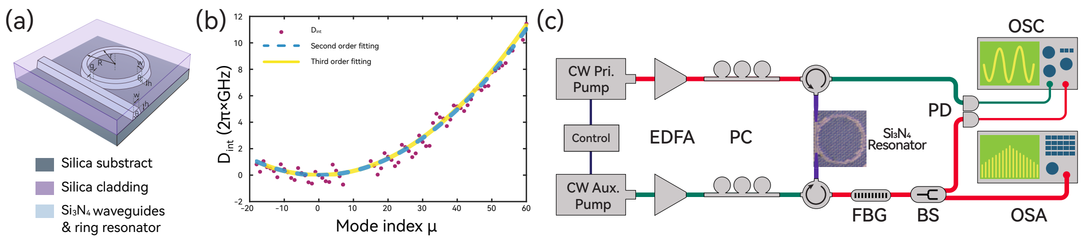

Fig. 1. Microresonator design and experiments scheme. Optical spectrum of multi-soliton and single soliton are generated by dual pump methods. (a) Models for microresonator simulation; (b) Simulation results of the designed ring resonator dispersion characteristics; (c) Dual pump experiments scheme for soliton generation.

2. Experiments and Results

The integrated microresonators are fabricated in 800nm-thick low-stress Si_3N_4 film by Ligentec, and a typical Q-factor around 1.65×10^6 is obtained. Two fiber lenses are used to couple the laser into the waveguide with coupling loss about 1.5dB. The measured free spectral range (FSR) of the ring resonator is around 94.45 GHz and

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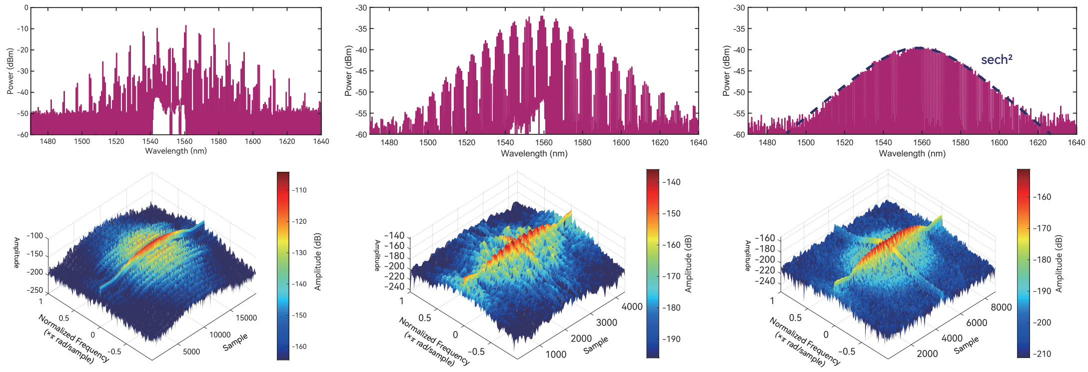
the anomalous dispersion characteristics in C-band is shown in Fig. 1 (b).The power of the primary laser is around 23dBm, while the auxiliary is 30dBm. Tuning the laser at the appropriate rate, the microresonator evolves through chaotic state and then enters the multi-soliton state. Finally set the primary and auxiliary pump wavelength as 1551.64 nm and 1557.26 nm, the envelop of single soliton is a complete and smooth sech^2 curve. We use FBG and digital algorithm to remove the four wave mixing spectral from auxiliary pump, the optical spectrum of chaostic comb, multi-soliton and single soliton are shown in Fig. 2 respectively.



(a) chaostic comb (b) multi-soliton (c) single soliton

Fig. 2. Optical spectrum and the time-frequency spectrum calculated by performing STFT on the auto-correlation function. (a) chaostic comb; (b) multi-soliton state; (c) single soliton state.

Most of the previous research of soliton is performed on the spectrum or the power spectrum. Since the repetition frequency of the integrated resonator is exceptionally high, it is difficult to characterize in the temporal domain directly. However, the theoretical simulation shows that in addition to periodic signals, the local characteristics of pulses are also worthy of attention during the time-domain evolution. We perform a short-time Fourier transform (STFT) to analyze the temporal information, simultaneously analyzing time and frequency domain [6], on the auto-correlation function obtained by Fourier transform on the power spectrum. We use a Kaiser function with a width of 256 as the window function of the STFT. The time-frequency spectrum is shown in Fig. 2. Due to the lack of coherence of the light pulses in the microresonator at the Chaotic state, they have a strip-like distribution along the time axis. There is only a significant peak along the frequency axis. In contrast, when entering the multi-soliton state, due to the coherence between the pulses, the short-time frequency spectrum along the time axis shows the coherence in the auto-correlation function. It has a continuous distribution along the frequency axis. The single soliton state has an envelope of sech^2 for the main component in the frequency axis direction. As coherence is optimal at this point, the analysis of the auto-correlation function is all concentrated. The single soliton state has an envelope of sech^2 for the main component in the frequency axis direction. As coherence is optimal at this point, there is only one peak along the time axis, resulting in a pure cross-shaped distribution on the time-frequency spectrum, which is significantly different from other stages and is a typical feature of the single soliton state.

In summary, this paper has conducted time-frequency research of the optical soliton generated by the integrated microresonator and its evolution process. We found that through the time-frequency analysis based on the short-time Fourier transform, the time-frequency spectrum of the single soliton state has a unique cross-shaped distribution, which may be used as a criterion for the DKS.

References

1. T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, "Dissipative kerr solitons in optical microresonators," Science **361**, eaan8083 (2018).
2. C. Godey, I. V. Balakireva, A. Coillet, and Y. K. Chembo, "Stability analysis of the spatiotemporal lugiato-lefever model for kerr optical frequency combs in the anomalous and normal dispersion regimes," Phys. Rev. A **89**, 063814 (2014).
3. C. Joshi, J. K. Jang, K. Luke, X. Ji, S. A. Miller, A. Klenner, Y. Okawachi, M. Lipson, and A. L. Gaeta, "Thermally controlled comb generation and soliton modelocking in microresonators," Opt. Lett. **41**, 2565–2568 (2016).
4. H. Zhou, Y. Geng, W. Cui, S.-W. Huang, Q. Zhou, K. Qiu, and C. Wei Wong, "Soliton bursts and deterministic dissipative kerr soliton generation in auxiliary-assisted microcavities," Light. Sci. & Appl. **8**, 50 (2019).
5. Y. Zhao, L. Chen, C. Zhang, W. Wang, H. Hu, R. Wang, X. Wang, S. T. Chu, B. Little, W. Zhang, and X. Zhang, "Soliton burst and bi-directional switching in the platform with positive thermal-refractive coefficient using an auxiliary laser," Laser & Photonics Rev. **15**, 2100264 (2021).
6. A. Volpato and E. Collini, "Time-frequency methods for coherent spectroscopy," Opt. Express **23**, 20040–20050 (2015).