Soliton Formation with Controllable Frequency Line Spacing Using Dual-pump in Microresonator

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Abstract: We propose a method for controllable frequency line spacing soliton formation in microresonator using two continuous wave (CW) pumps with multi free spectral range (FSR) spacing.

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Temporal solitons have excellent properties such as broadband, low-noise frequency spectra, and small line-to-line amplitude variations [1] and can persist their shape in temporal profile. In microresonator, temporal cavity solitons have been experimentally observed by scanning through the cavity resonance [2]. Phase modulating the driving field has also been used to generate cavity solitons in microresonator [1]. We propose another method for controllable frequency line spacing soliton formation in microresonator using two CW pumps with multi FSR spacing. The results of numerical simulation of Lugiato-Lefever equation (LLE) show that only two steps are needed for soliton formation, and only two fixed value of detuning is needed, thus without tuning speed problem. Specifically, we demonstrate that single-FSR or multi-FSR solitons can be generated by changing the frequency spacing of two CW pumps.

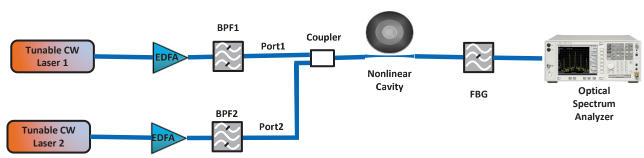

Fig. 1. Schematic illustration of the structure under study. Two CW pumps are amplified and filtered seperately, then combined by a coupler. The combined pumps are coherently added to the lightwave circulating in the resonator through a coupler with power transmission coefficient θ. After filtering the pump frequency using a fiber bragg grating (FBG), the generated spectrum is detected by an optical spectrum alanyzer.

We consider a structure shown in Fig. 1. To study the evolution of the field inside the resonator, we use the generalized mean-field Lugiato-Lefever equation [3] expressed by Eq(1),

$$T_R \frac{\partial E(t,\tau)}{\partial t} = (-\alpha - i\delta_0 + iL \sum_{k\geq 2} \frac{\beta_k}{k!} (i\frac{\partial}{\partial \tau})^k)E + i\gamma L \mid E \mid^2 E + \sqrt{\theta} E'_{\mathrm{in}}. \tag{1}$$

Here $E(t,\tau)$ is the amplitude of the intracavity field, t is the slow time describing the evolution of the field, while τ is the fast time describing temporal field within the cavity in a frame. T_R is the roundtrip time of the field, α, γ represent the total linear cavity losses and nonlinear coefficient respectively. δ_0 measures the frequency detuning between the laser carrier and cavity resonance frequencies. β_k is the k-th order dispersion coefficient, L is the cavity length, E'_{in} is the input field. Parameters are taken from the 226 GHz FSR Si_3N_4 microresonator in [4]. For simplicity, only second-order dispersion is considered. In the first step, a single CW pump with power $P_{\mathrm{in}1} = 0.755$W is coupled through port1 to excite frequency combs, pumping at 1550nm and the detuning $\delta_0 = -0.0045$. After several ns comes to the second step, we set the detuning δ_0=0.05 and introduce another CW pump f_m away from the first laser with power $P_{\mathrm{in}2}$=0.0755W through port2. Two fields are combined by a coupler with ratio $\alpha_1 = 0.5$ and coherently coupled into the resonator, thus the dual-pump input field can be written as the following equation,

$$E_{\rm in}^{'}=\sqrt{\alpha_1 P_{\rm in1}}+\sqrt{(1-\alpha_1)P_{\rm in2}}\exp(-2i\pi f_m\tau). \tag{2}$$

We first consider the situation of f_m = FSR. Fig. 2(a) shows the evolution of the temporal and frequency profile of intracavity field from simulation time t=0 to 625ns. Starting from a weak initial field [1], the temporal pulses are generated into nearly equidistributed pulses in the first step which corresponds to modulation instability(MI), and correspondingly the spectrum is dominated by "primaray" comb lines separated by multiple FSRs [5] due to cascaded four wave mixing (FWM). From the begining of the second step at t = 25 ns, the number of pulses decreases suddenly, and the spectrum broaden evidently. The number of pulses continues to decrease in the coming period of time, and the spectrum exhibit periodic broad fluctuations, and eventually lead to the generation of a single cavity soliton with broadband and smooth spectrum.

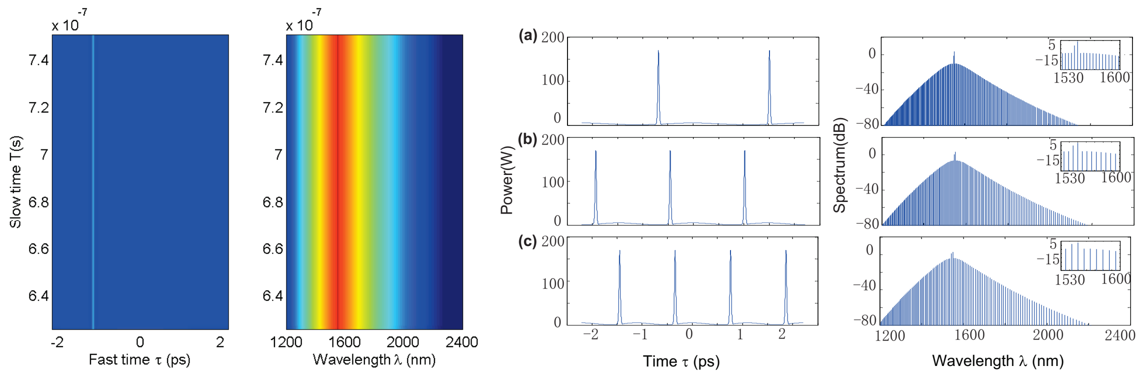

Fig. 2. (a) shows the temporal (left) and frequency (right) profile of the route to a steady state soliton within a Si_3N_4 microresonator with 200 μm diameter and quality factor $Q=3*10^5$. FSR = 226GHz; γ = 1 $W^{-1}m^{-1}$; $\alpha=\theta=0.009$; f_m = FSR. (b), (c), (d) demonstrate the generated solitons with f_m = 2FSR, 3FSR, 4FSR correspondingly.

Then we consider the situation of f_m equivalent to multiple FSRs. Using the same parameters and following the same steps. The generated temporal profile and spectrum of the steady state intracavity field are shown in Fig. 2(b), (c), (d) corresponding to f_m = 2FSR, 3FSR, 4FSR respectively. We can see that f_m has a close relationship with the generated soliton number. Assume f_m to be equivalent to N FSR, then we can get N solitions per roundtrip with equidistance in temporal domain, correspondingly, the smooth spectrum with mode spacing equivalent to N FSR forms in the spectrum. Thus multi-FSR solitons can be generated by changing the frequency spacing between two pumps.

In conclusion, we have proposed a new approach to the formation of controllable frequency line spacing solitons, and numerically studied the evolution of intracavity field using LLE. The demonstrated technique offers a simpler way of generating solitons compared to the scanning detuning method, since there is no tuning speed problem. We also find that by introducing a second pump with frequency N FSR away from the first pump at proper time, multi-FSR solitons with N FSR comb spacing can be generated.

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