Frequency Comb and Ultrashort Pulse Generation in a Normal-Dispersion FP Microresonator with Bandpass Filtering

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Abstract: Frequency comb and ultrashort pulse generation in a normal-dispersion Fabry-Perot microresonator with bandpass filtering are demonstrated. The spectral filtering introduces different cavity dynamics and can support 371-fs pulse and parabolic spectral shape.

Microresonator based dissipative Kerr soliton (DKS) generation has attracted significant attention because it has very compact size, high repetition rate and ultrashort temporal pulse with low noise [1]. However, this technique is limited to the microresonators with anomalous dispersion. Due to the lack of modulational instability (MI) on the bistable upper branch, the normal-dispersion microresonators are difficult to generate stable Kerr combs [2]. The mode-locked state is also hard to achieve since the nonlinearity cannot be balanced by normal dispersion. Nevertheless, normal-dispersion mode-locked state is of particular interests since waveguide dispersion in visible and near IR is mostly normal [3]. Recently, it has been shown theoretically and experimentally that dark soliton and platicons can be generated in normal-dispersion microresonator by the method of mode coupling and pump tuning [2, 4]. However, mode-locked ultrashort pulses are more desirable. Ref. [5] achieve mode-locked ultrashort pulse generation in a normal-dispersion Si_3N_4 mircoring resonator with the assistance of wavelength-dependent quality factors, but wavelength-dependent Q is not controllable during the fabrication.

In this work, we propose a new approach to achieve frequency comb and ultrashort pulse generation in a normal-dispersion Fabry-Perot (FP) microresonator. The key difference compared to the conventional normal-dispersion microresonators is that a bandpass filter (BPF) is incorporated to the FP cavity. The spectral filtering of this BPF can enhance the self-amplitude modulation, and helps to shape and stabilize the intracavity pulses. Frequency comb and mode-locked ultrashort pulse generation is obtained with a synchronized pulsed pump and wavelength tuning. The pulse duration can be down to 371 fs (FWHM) and the spectrum shows a parabolic profile. Simulation is based on modified FP Lugiato-Lefever equation (FP-LLE). A detailed comparison with the normal-dispersion FP microresonator without BPF is also performed.

The proposed structure is shown in Fig. 1(a). The FP microresonator adopts a 1-cm long highly nonlinear fiber (HNLF) with normal dispersion and single mode transmission. The two end facets of HNLF are polished and coated with high-reflective (HR) coatings. The two HR coatings are designed for bandpass filtering, i.e., only the spectrum near a center wavelength can be reflected, as shown in Fig. 1(b). The reflection spectrum $\theta_{filter}(\lambda)$ of the BPF HR coatings is described by its center wavelength λ_c = 1560 nm, bandwidth $\Delta\lambda$= 20 nm, transition region λ_{tr}= 6 nm and stopband suppression A_0 = 20 dB. A linear coupling loss of θ_c = 0.002 is also added to the coatings. Therefore, the total reflection of the BPF HR coatings is given by $\theta_{coupling} = \theta_c + \theta_{filter}(\lambda)$. A synchronized pulsed pump is chosen to drive the microresonator.

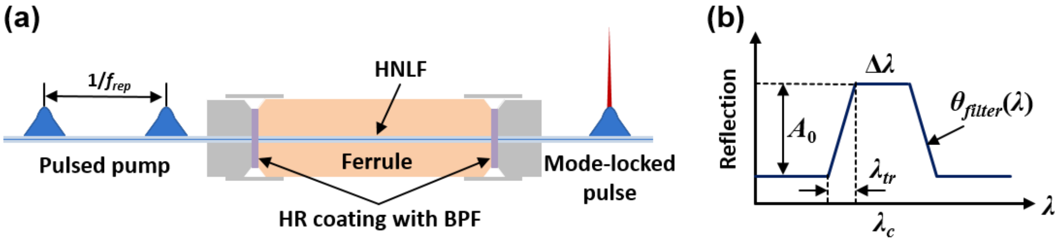

Fig. 1. (a) Proposed structure of normal-dispersion microresonator with BPF. (b) Reflection spectrum of BPF HR coatings.

The modified FP-LLE is describe in Eq. (1), where E is the field envelope inside the cavity, α is the intracavity loss, δ_0 is the pump-resonance detuning, P_{cav} is the average power accumulated in the cavity, and $\theta_{coupling}$ is the coupling loss per roundtrip. The normal-dispersion FP microresonator is characterized by a free spectral range (FSR) of 10 GHz, a group velocity dispersion of β_2=10 ps^2/km, a nonlinear coefficient of γ =12 W^{-1}km^{-1} and a resonance width of $\kappa/(2\pi)$ = 7 MHz, corresponding to an intracavity loss α = 0.002. The synchronized pulsed pump are composed of 41 spectral combs with equal phase and power, and the average power of pulsed pump is 75mW.

$$t_R \frac{\partial E(t,\tau)}{\partial t} = \left[-\frac{\alpha}{2} - \theta_{Coupling} - i\delta_0 - iL\frac{\beta_2}{2}\frac{\partial^2}{\partial \tau^2} + iL\gamma \cdot |E|^2 + 2iL\gamma P_{cav} \right] \cdot E + \sqrt{\theta_C} E_{in} \quad (1)$$

The modified FP-LLE is solved by split-step Fourier method. In order to illustrate the important role of bandpass filter in the proposed microresonator, we compare the intracavity pulse evolution with and without spectral filtering, while other simulation parameters remaining the same. Fig. 2(a) and 2(b) present the simulation results without BPF, while Fig. 2(c) and 2(d) show the results with BPF. The pump-resonance detuning in two cases are both initially set on the blue detuning of δ = -5κ and continuously increased to the red detuning of δ = 25κ. Such tuning process will cause the intracavity fields to evolve through all typical states in both microresonators. Four distinct spectral and temporal profiles at the detuning of 5κ, 10κ, 15κ and 20κ are summarized on the right-side panels of Fig. 2(a) and 2(c), and marked as I, II, III and IV.

In the normal-dispersion microresonator without BPF, the platicon appears on the bistable upper branch when the pump is tuned across the resonance of cold cavity. As the detuning is increased, the platicon has broader spectral width, narrower pulse duration and higher pulse peak power, as shown in panels I~III of Fig. 2(a). A typical feature is the spectrum has two "cat ears". When the pump is tuned across the Kerr-shifted resonance, the intracavity field loses its mode-locking state, and drops to the lower branch of bistable curve, as shown in panel IV of Fig. 2(a). Due to the lack of MI on upper branch, intracavity pulse evolution in the normal-dispersion microresonator is very stable, which can be illustrated by Fig. 2(b). However, when the intracavity filtering is applied, the evolution process is completely different, as shown in Fig. 2(c). In panel I of Fig. 2(c), a mode-locked pulse is observed which has similar structure of platicon, but some smaller pulse patterns appear at the top of the flat-top pulse. This mode-locking state exists because the wings of platicon are still within the range of BPF. In panel II, as the detuning is tuned larger, the mode-locked platicon is lost since the two wings of the platicon spectrum are filtered out by the BPF, and the intracavity pulse evolves into a chaotic state. In panel III, further pump detuning causes pulse-liked noise to drop from upper branch to the lower branch in the bistable curve, and to evolve to a stable mode-locked ultrashort pulse with a pulse duration of 371 fs and a peak power of 372 W. It has a smooth spectral envelope, which can be fitted by parabolic curve, as shown in red-dotted line. In the last state in panel IV, the pump detuning is increased to 20κ, and the mode-locked ultrashort pulse can still be sustained with a pulse duration of 371 fs and a peak power of 492 W. The pulse duration is unchanged due to the unchanged spectrum bandwidth. The evolution of intracavity power is shown in Fig. 2(d). When the mode-locked pulse generated, the intracavity power drops suddenly and forms a step, which is similar to the soliton-steps of DKS in anomalous-dispersion microresonator.

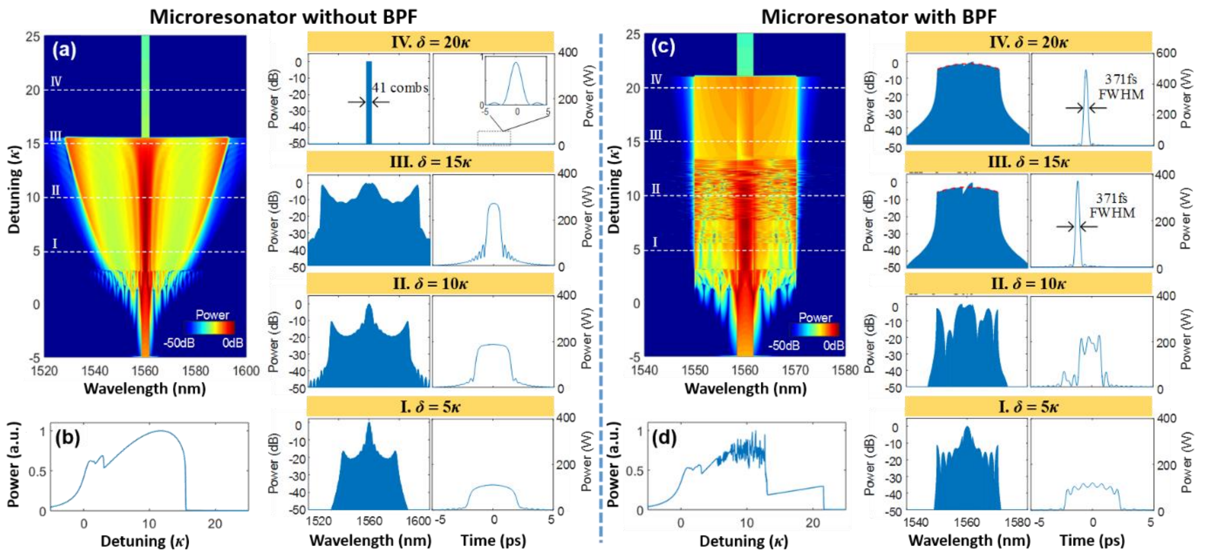

Fig. 2. (a) Normalized evolution of intracavity power and (b) spectral evolution simulation results in the absence of filtering characteristics in HR coating. (c) Normalized evolution of intracavity power and (d) spectral evolution simulation results when the HR coating contains filtering characteristics.

In summary, we report a novel normal-dispersion FP microresonator with bandpass filter. This design allows direct generation of mode-locked ultrashort pulse in normal-dispersion region. Moreover, we illustrate the important roles of bandpass filtering in the generation of mode-locked ultrashort pulse.

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