Deterministic Single Soliton Generation without Frequency Tuning in a Graphene-FP Microresonator

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Abstract: A novel microresonator based on Fabry–Pérot resonator and monolayer graphene has been proposed. This design allows deterministic single soliton generation without frequency tuning and has strong robustness under frequency and timing jitter.
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The generation of dissipative Kerr soliton (DKS) in high Q micro-resonators has attracted significant attention because it can obtain broadband optical frequency comb with low noise and ultrashort temporal pulses at very high repetition rate [1]. To obtain DKS, the pump laser should be tuned over the cavity resonance from blue side to the red side with an appropriate tuning speed [2]. However, due to phase/frequency noise induced by pump laser and thermal effects, the results of frequency tuning experiments are not deterministic (e.g. number of solitons). Some improvements based on pump tuning method have been proposed, such as synchronous pulse driving [3], backward pump tuning [4], feedback controls [5], and phase or amplitude modulation [6]. However, precision frequency tuning of pump laser is still a key step in DKS formation to boost nonlinear process and stabilize the operation in single soliton state.

In this work, we propose a novel Fabry–Pérot (FP) microresonator assisted by monolayer graphene which serves as an ultrafast saturated absorber (SA). This design enables the deterministic generation of single soliton without the requirement of pump frequency tuning process. The pulse shaping mechanism of SA helps to suppress the perturbation and stabilize the intracavity pulse. Therefore, driven by pulsed pump with a proper fixed frequency, the FP resonator can accumulate intracavity power, reach the parametric oscillator threshold and directly enter into single soliton state. The Lugiato-Lefever equation (LLE) applied for an FP microresonator is also developed for the first time and used to verify the feasibility of this novel structure.

The proposed structure is shown in Fig. 1(a). Compared with FP microresonator used in Ref. [3], the right facet of the microresonator is coated with highly anti-reflection (AR) coating, and the neighboring optical fiber facet is coated with high-reflection (HR) coating. Monolayer graphene is sandwiched between the right facet of the microresonator and the fiber connector. Thus, the SA induced pulse shaping mechanism is introduced into the microresonator. The power-dependent transmission of monolayer graphene can be expressed by $T(I)=1-(\alpha_0 - \alpha_{ns})/[1+(I/I_{sat})]-\alpha_{ns}$, where α_0 is the linear loss, α_{ns} is the nonsaturable loss, I is the instantaneous pulse power, and I_{sat} is the saturation power. In the following simulation investigation, the typical parameters of graphene are set as follows, I_{sat}=100 MW/cm^2, α_{ns}=1%, α_0=2.3%. The corresponding transmission curve is shown in the inset of Fig. 1(a). The transmission is set 99.99% for AR coating and the reflection is 99.99% for HR coating.

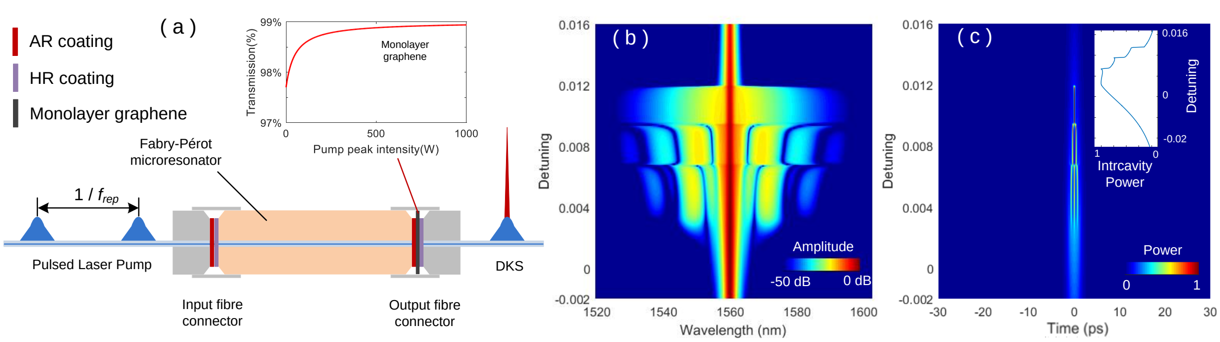

Fig. 1. (a) Schematic drawing of the proposed microresonator structure. Inset: Transmission curve of monolayer graphene. (b) Spectral and (c) temporal evolutions when pump frequency is tuned over the resonance. Inset of (c): evolution of intracavity power.

The LLE applied for FP microresonator is described in Eq. (1). Here, E is the field inside the cavity, α is the intracavity loss, δ is the frequency detuning, P_{cav} is the power accumulated in the cavity, and θ is the pump coupling loss. The LLE for FP microresonator is derived from the equivalent coupled mode equations in Ref. [3]. The LLE is more convenient to investigate the temporal power-dependent absorption induced by monolayer graphene.

Compared to LLE in general cases, the third phase term in Eq. (1) is caused by the nonlinear interactions between co- and counter-propagating fields. The correctness of this LLE has been confirmed by comparing the simulation results with the works reported in Ref. [3]. In the simulation of graphene-FP microresonator, we choose a microresonator length of 1.03 cm, corresponding to a free spectrum range (FSR) of 10 GHz near 1550 nm. The synchronous pulsed pump with peak power of 150 W and duration time of 1.5 ps is launched into the resonator.

$$t_R \frac{\partial E}{\partial t} = -\frac{1}{2}\alpha E - i\delta E + 2i\gamma L P_{cav} E + i\gamma L |E|^2 E - \frac{1}{2} i\beta_2 L \frac{\partial E^2}{\partial t^2} + \sqrt{\theta} E_{in} \tag{1}$$

The simulation results of spectral and temporal evolutions are shown in Fig. 1(b) and 1(c), when the detuning δ is scanned from -0.002 to 0.016. The change of intracavity power is shown in the inset of Fig. 1(c), and the curve has an obvious feature of soliton steps. The detuning region for single soliton state is 0.0095 to 0.0118.

Due to the pulse shaping mechanism induced by the graphene SA, the detuning frequency can be fixed to the single soliton region mentioned above, and a single soliton state can be directly obtained. The simulation results with a fixed detuning of 0.01 are summarized in Fig. 2. In Fig. 2(a)-2(d), it can be found that single soliton can be directly generated after 4200 roundtrips. There is no chaotic, breathing or multi-soliton states appearing in the soliton formation process. The saturable absorption of graphene allows the cavity to accumulate intracavity power and excite the DKS even with a fixed detuning pump. Fig. 2(e) shows the evolution of the intracavity power

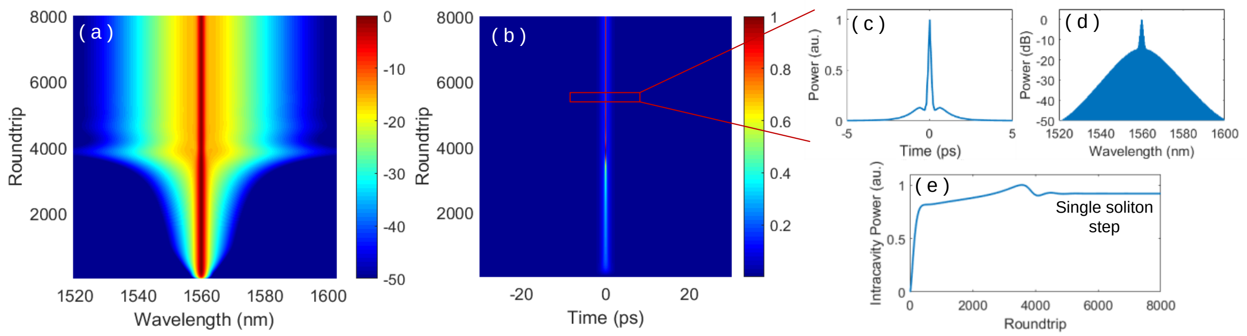

Fig. 2. (a) Spectral and (b) temporal evolutions when detuning δ=0.01. (c) Temporal, and (d) spectral profiles of single soliton state. (e) Intracavity power evolution of FP microresonator

Furthermore, the robustness of the device against frequency and timing jitter has also been investigated, and the simulation results are shown in Fig. 3. In Fig. 3(a), a detuning jitter of 0.09 with a duration of 1 ns is applied. The resonator can soon recover to its original single soliton state with the assistance of SA. Fig. 3(b) shows the state switching from single soliton to two soliton state when the pump frequency detuning shifts from 0.01 to 0.008. Fig. 3(c) reveals the resonator is insensitive to timing jitter. When pump pulse shifts 10 ps away from its original location, new soliton can be rebuilt following the pump pulse without the need of tuning frequency.

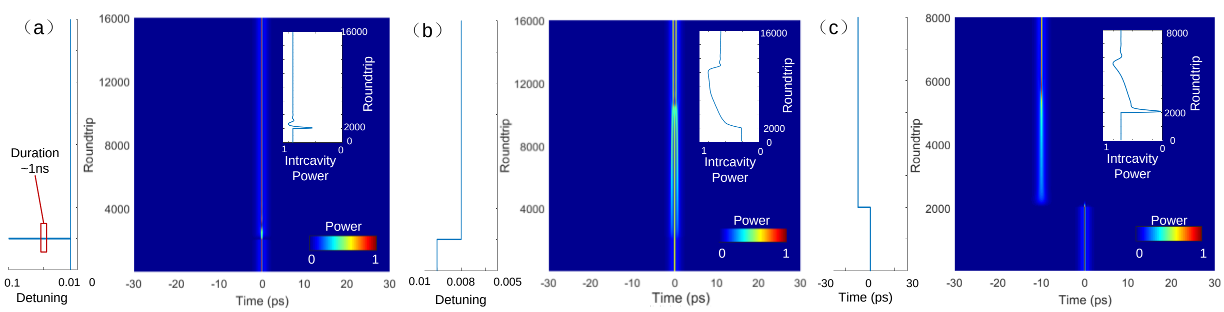

Fig. 3. (a) Temporal evolution when detuning has a jitter of 0.09 with 1-ns duration (10 roundtrip). (b) Temporal evolution from single soliton state to two soliton state when detuning shifts from 0.01 to 0.008. (c) Temporal evolution when pump pulse shifts 10 ps away.

In summary, we propose a novel microresonator based on monolayer graphene and FP resonator. This design allows deterministic single soliton generation without frequency tuning. Moreover, it has strong robustness to maintain the single soliton state under frequency and timing jitter.

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