Ultrahigh-Q MgF_2 crystalline microresonator for soliton comb generation

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***Abstract*—Dissipative Kerr soliton comb with repetition rate of ~ 27 GHz and spectral range of 60 nm is generated in a magnesium fluoride microresonator with ultrahigh quality (Q) factor approaching one billion.**

***Keywords*—MgF_2 crystalline microresonator, active capture method, optical frequency comb, Kerr soliton comb**

I. INTRODUCTION

Optical frequency comb has been regarded as a kind of revolutionary light source with the unprecedented frequency precision. It is usually considered as a cornerstone for the field of dual-comb spectroscopy [1], ultrafast distance measurement [2], optical clock [3], coherent communications [4], optical frequency synthesizer [5], and so on. Recently, Kerr frequency comb based on four-mixing wave (FWM) in high-Q resonator has attracted great interests with the intriguing features of miniature size and low power consumption. In particular, Kerr soliton comb manifests itself by virtue of ultrahigh repetition, low phase noise, and broadband coherence [6]. To date, optical microresonators with various materials including silica (SiO_2), silicon nitride (Si_3N_4), lithium niobate ($LiNbO_3$) and magnesium fluoride (MgF_2), have been reported for the generation of soliton comb [7-10]. Among these materials, MgF_2 is insensitive to the ambient humidity and temperature, which improves the stability of Kerr soliton. They also have a high nonlinearity, small absorption constant from the ultraviolet to mid-infrared band. Because of these shining points, it has been considered as an ideal material for the generation of stable dissipative Kerr soliton comb [11-15]. However, most of works are implemented by controlling the pump laser scan rate to generate soliton combs. This passive method is unable to capture specific soliton state, and the solitons easily disappear due to the drift of cavity-pump detuning [16].

In this work, we demonstrate the active capture and stabilization of dissipative Kerr soliton in MgF_2 crystalline microresonator by utilizing power kicking method and servo control. The MgF_2 crystalline resonator with diameter about 3 mm is fabricated, and the Q factor of 927.5 million is obtained via fine polishing process. The single soliton comb with repetition rate about 27 GHz from 1520 nm to 1580 nm are also generated when the pump power is ~ 23 dBm. In addition, we also observed the optical spectra of two- and three-soliton states. This active capture method promotes the on-demand stable soliton generation in MgF_2 crystalline resonator.

II. SOLITON COMB GENERATION

A. *EXPERIMENTAL SETUP*

Figure 1(a) describes the experimental setup of soliton comb generation. A continuously tunable fiber laser at ~ 1550 nm is amplified by a erbium-doped fiber amplifier (EDFA) to pump resonator. The frequency of laser is finely scanned through a triangle wave generated from an arbitrary function generator (AFG). Then, a band pass filter (BPF) is used to filer the noise of EDFA. An acousto-optic modulator (AOM) is exploited to control the power of pump laser, which is driven by a 55 MHz sine wave from AFG. A fiber polarization controller (FPC) is used to adjust the polarization state to obtain the optimal coupling efficiency. At the output port, the optical comb and transmission is separated by a fiber Bragg grating filter (FBG). Subsequently, comb power is divided into two parts through a coupler with ratio of 90:10. A fraction of soliton comb power (90%) is recorded by an optical spectrum analyzer (OSA), and another part is monitored in real time by a low-noise photodetector (PD) and sent to servo control box. When the servo controller detects the photocurrent, an error signal is generated by subtracting the setpoint. Here, the MgF_2 microresonator with diameter about 3 mm is fabricated via an ultra-precision machining device, as shown in the inset of Fig. 1(a). To fabricate the crystalline microresonator, a MgF_2 crystal sample is fixed on a spindle, which drives the crystal to rotate at high speed to obtain a MgF_2 microresonator with an ultra-smooth surface by a precision chemical polishing process [17]. The Q factor of MgF_2 resonator is 927.5 million, as shown in Fig. 1(b).

B. *Active capture of soliton states*

The soliton state is formed as the pump laser is scanned from the blue detuned region to the red detuned region. The specific process is as follows. First, the laser locates in the blue detuned region, where the four-wave mixing comb is generated. Then, as the laser frequency moves toward red detuned region, the intracavity power suddenly drops, and comb power exhibits "step-like" features, which is soliton step, as displayed in Fig. 1(c). It is observed that the soliton step is only about 0.5 ms, which is mainly because the cavity-pump detuning moving out of the range of soliton presence. Therefore, the laser frequency is needed to be controlled by a servo control box based on the measured soliton power to achieve the stabilization of soliton states.

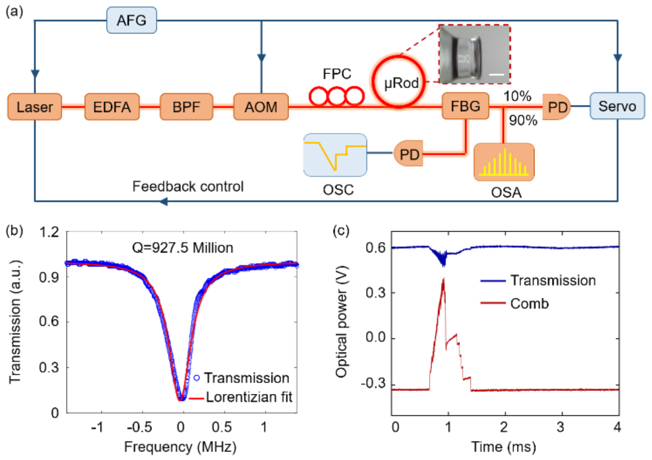

Fig. 1. (a) Experimental setup. EDFA: erbium-doped fiber amplifier, BPF: band pass filter, AOM: acousto-optic modulator, AFG: arbitrary function generator, FBG: fiber Bragg grating filter, FPC: fiber polarization controller, OSA: optical spectrum analyzer, OSC: oscilloscope, PD: photodetector. Inset: optical microscope images of microresonator. Scale bar: 1 mm. (b) The mesured transmission spectrum of MgF_2 microresonator. (c) Evolution of comb power as the laser frequncey sweeps from blue side to red side.

Figure 2(a) demonstrates the capture and locking of soliton step, where the red line represents soliton power, and a Mach-Zehnder interferometer (MZI) signal (blue) line is the reference of pump laser tuning. It is fabricated according to [18], including two 50:50 bi-directional couplers and a 5 m long fiber. The free spectral range (FSR) of MZI is determined to be 39.5 MHz after calibration by the hydrogen cyanide (HCN) standard gas chamber. The stable generation of soliton comb contains four stages. Herein, power kicking method is used to capture soliton step, and the servo controller is used for the stabilization of soliton. Firstly, the laser frequency is finely scanned from blue detuning region to resonance, resulting in the generation of FWM comb (Stage I). Subsequently, the laser frequency is no longer scanned and the power is reduced via AOM, resulting in blue shift of cavity mode. As a result, the pump laser frequency locates in the red side of resonant mode, where solitons are possibly formed (Stage II). Then, servo controller is triggered by AFG to control the laser frequency to ensure the setting value equal to soliton power (Stage III). It is worth mentioning that this method will compensate the cavity-pump detuning drift, thus soliton state can be stabilized in a long time (Stage IV). Figure 2(b) demonstrates the generated single soliton comb when the laser power is ~ 23 dBm, which exhibits a se^{2}ch spectral envelope with the spectrum ranging from 1520 nm to 1580 nm. Because of the interaction between different spatial modes, several dispersive waves are generated to break up the spectral envelope, i.e. spikes in the comb spectrum [19]. The inset of Fig. 2(b) exhibits that the repetition rate of single soliton comb is about 27 GHz. Figure 3 shows the frequency comb spectra of two- and three-solitons states. It deserves to be mentioned that the repetition rate of soliton comb can be regulated to suit different application scenarios by fabricating microresonator with different diameter.

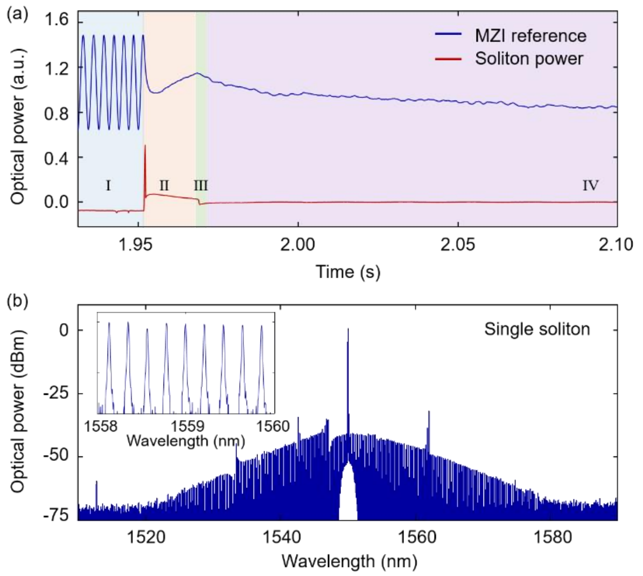

Fig. 2. (a) Illustration of the capture and locking of soliton step. I: Laser scanning; II: Power kicking; III: Locking engaged; IV: Soliton stabilized. (b) Single soliton comb with bandwidth ranges from 1520 nm to 1580 nm. Inset: Zoom in of the comb spetrum, demonstrating the repetition rate of ~ 27 GHz.

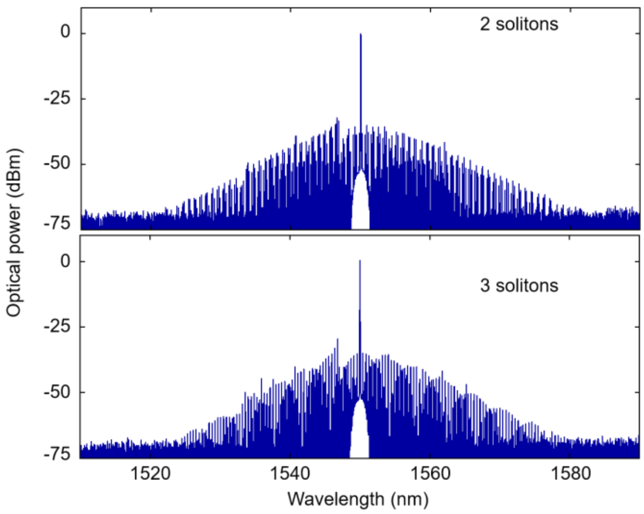

Fig. 3. Frequecy comb spectra of selected soliton states with two and three solitons.

III. SUMMARY

In conclusion, we achieve the soliton comb formation in MgF_2 microresonator based on an active capture method. The MgF_2 resonator with diameter about 3 mm is fabricated, and the *Q* factor approaches one billion through precision polishing process. Based on power kicking protocol, the single soliton comb with repetition rate about 27 GHz from the 1520 nm to 1580 nm is generated. Moreover, the different multiple soliton combs are also observed by capturing the specific soliton states. This work provides a promising platform for the ultrafast coherent optical communication, precision spectral measurement, ultrafast laser ranging, and optical atomic clock.

ACKNOWLEDGMENT

This work was supported by National Natural Science Foundation of China (11974058); Beijing Nova Program (Z201100006820125) from Beijing Municipal Science and Technology Commission; Beijing Natural Science Foundation (Z210004); and State Key Laboratory of Information Photonics and Optical Communications (IPOC2021ZT01), BUPT, China; and BUPT Excellent Ph.D. Students Foundation (CX2022114).

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