Soliton Crystals in a High-Q MgF_2 Microresonator

Heng Wang[1], Bing Duan[2], Chang Li[2], Yong Zhang[1], Daquan Yang[2], Chuan Wang[3,*]

[1]*School of Science, Beijing University of Posts and Telecommunications, Beijing, 100876,China*
[2]*School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, 100876,China*
[3]*School of Artificial Intelligence, Beijing Normal University, Beijing, 100875, China*
** Email: wangchuan@bnu.edu.cn*

Abstract: Based on the power-kicking method, the soliton crystals and multiple solitons in high-Q magnesium fluoride microresonator are observed. Under constant pump, they could be obtained with different defects deterministically that occurred by the wavelength tuning.

1. Introduction

The generation of dissipative Kerr solitons (DKSs) in nonlinear optical microresonators has been demonstrated in various platforms, and the low-noise DSKs are now used in many applications. Recently, soliton crystals (SCs), as a novel concept, have attracted intensive attention. When the solitons are matched to the maxima of the modulation of the intracavity continuous-wave(CW) mode induced by avoiding mode crossing(AMX), it leads to a tightly regular arrangement of DSKs in the microresonator (usually called the perfect soliton crystals, PSCs) or an almost regular arrangement (SCs with defects) [1]. The soliton crystal state was first discovered in a silica microresonator [2] and subsequently demonstrated in other materials such as Si_3N_4 [1], $LiNbO_3$ [3], and AIN[4].

In this report, the high-Q MgF_2 microresonators with anomalous dispersion are fabricated. Based on the power-kicking method, we generate multiple soliton states and soliton crystal states in the microresonator. Furthermore, we maintain the same final pump power and then by slowly tuning the pumping wavelength, the soliton modes are observed gradually red-shift to cross with the neighboring modes. This may lead to the degradation of the crystal steps into multiple-soliton steps. Compared with the previous work, we can actively capture multiple soliton states or soliton crystals with different defects at different wavelengths without changing the power. To our knowledge, this is the first demonstration of soliton crystals in a high-Q MgF_2 microresonator.

2. Experiment observation and active capture of soliton crystals and multiple solitons

As shown in the inset of Fig. 1(a), using precision machining with hand fine polishing we fabricated a high-Q MgF_2 microresonator with a diameter of about 2.7 mm and an FSR of about 26 GHz, which has a maximum loaded Q (Q_{load}) factor of about 5.7×10^8 [5]. As shown in Fig. 1(b), the quality factor of the mode used in the experiment is around 1550.22 nm. Exploiting the Mach-Zehnder interferometer (MZI) that has been calibrated for free-spectral range (FSR), along with a narrow linewidth fiber laser, we precisely measured its load Q factor (Q_{load}) up to 1.32×10^8 and intrinsic Q (Q_{int}) factor up to 1.75×10^8, which allowed us to obtain multiple solitons and soliton crystals with relatively low power. The simplified experimental setup diagram is shown in Fig. 1(a). The acousto-optic modulator (AOM) is used to control the pump power amplified by erbium-doped fiber amplifier (EDFA), arbitrary function generator (AFG) generates a signal to the AOM to increase the power to extend the soliton steps, photodetector (PD) detects the soliton step power and sends it to servo, and finally servo captures and maintains the multi-soliton or soliton crystal states.

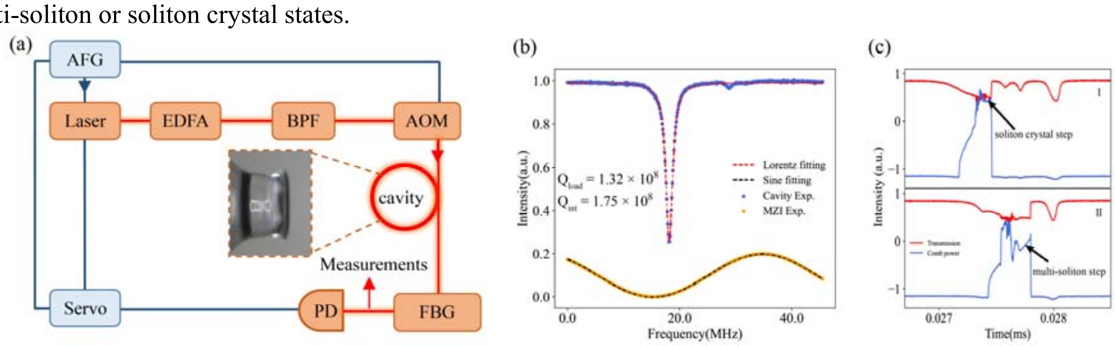

Fig. 1. (a) Experimental setup. AFG, arbitrary function generator; EDFA, Erbium-doped fiber amplifier; AOM, acousto-optic modulator; FBG, fiber Bragg grating filter; PD, photodetector; Inset is the image of the MgF_2 microresonator. (b) Resonance profile of soliton mode near 1550.22 nm with Lorentz fitting and the black dashed line is the fitted curve of MZI with a calibrated FSR of 39.521 MHz. (c) I and II show the soliton crystal steps and the multiple soliton crystal steps, respectively; the blue line is the comb power and the red line is the transmission spectrum.

Soliton crystals can only be excited at relatively low power. When the mode power is high, it usually leads to degradation of the soliton crystal steps into a multi-soliton state. Then, the waveform inside the microresonator is a typical multi-soliton state and is accompanied by a decrease in the number of solitons[1]. The SCs steps are clearly observed as shown in Fig. 1(c), we slowly tune the wavelength of the fiber laser while the resonant mode in (I) is gradually heated and then red-shifted due to the thermo-optical effect of the microresonator, which leads to mode crossing with the two modes on the right, eventually causing a change in the background potential field and the power of the mode in the microresonator [6, 7]. We observe that the SCs steps of (I) degenerate into the typical multiple soliton steps of (II). When servo captures a multi-soliton or soliton crystal, the final pump power is continuously monitored by a power meter and is always maintained at 117.8 mW. Thus, it is not required to change the pump power, and by finely tuning the laser resonant wavelength and controlling the target mode with respect to other mode distance changes, crossing or not, we can deterministically and actively capture multiple soliton states or soliton crystal states with different defects and vacancies (Schottky defects). As shown in Figure 2(a), we first observed the spectrograms of the Turing states (I) and the chaotic modulation instability (MI, II) states of the target mode. Slowly tuning the pump wavelength to near 1550.2256 nm, which requires constant attention to the drift state of the mode due to the thermo-optical effect, we eventually actively capture the multiple soliton state (III). Here (IV) and (V) are the results with different vacancies near 1550.2234 nm and 1550.2249 nm band, respectively, when no mode crossing is produced. (VI) is a soliton crystal with Frenkel defects obtained at 1550.2387nm, which results from the shift of a soliton in the time domain. Fig. 2(b) shows the RF spectra of the Turing states (I), MI states (II), and soliton crystal states(VI), respectively, where a significant reduction in noise can be observed when the soliton crystal state is generated.

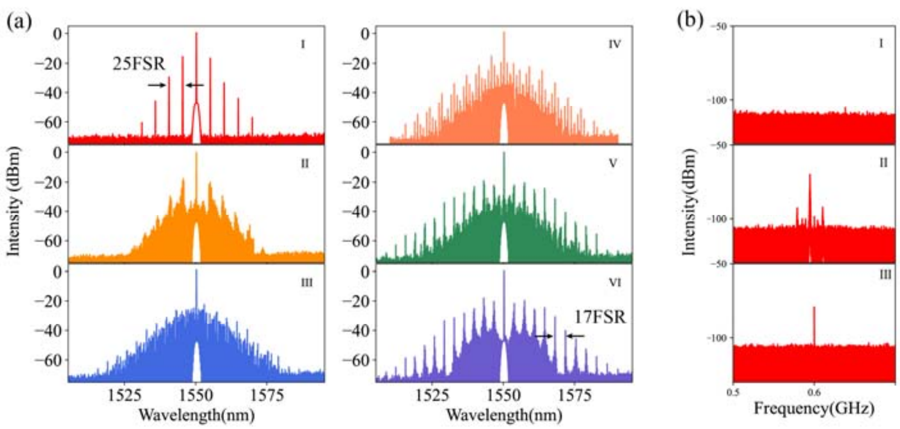

Fig. 2. (a) Measured optical spectra for frequency comb at (I) Turing states, (II) MI states, (III) multiple soliton states. (IV) and (V) are Soliton crystal states with vacancies, (VI) shows the soliton crystal states with Frenkel defects. (b) RF spectra of the Turing states, MI states, and soliton crystal states, respectively.

3. Summary

In summary, we demonstrate the deterministic capture of multiple-soliton states and soliton crystal states with different defects in a high-Q MgF_2 microresonator with constant pumping power and control the target mode shift by changing the pumping wavelength only. We believe that the PSC states are also deterministically accessible in subsequent experiments by optimizing the coupling position.

4. Acknowledgements

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5. References

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