Vibrational Kerr solitons in an optomechanical microresonator

Jia-Chen Shi¹, Qing-Xin Ji¹, Qi-Tao Cao¹, Yan Yu¹, Wenjing Liu¹, Qihuang Gong¹,², Yun-Feng Xiao¹,² *

¹State Key Laboratory for Mesoscopic Physics and Frontiers Science Center for Nano-ophotelectronics, School of Physics, Peking University, 100871, Beijing, China
²Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China

yfxiao@pku.edu.cn

Abstract: We theoretically demonstrated the existence of Kerr soliton microcombs in an optomechanical microresonator. Interestingly, an exotic vibrational Kerr soliton state is found, which is modulated by a self-sustained mechanical oscillation with a red-detuned pump. © 2022 The Author(s)

1. Introduction

Chip-integrable microresonator-based frequency combs have attracted much interest in recent years. In particular, dissipative Kerr soliton (DKS) microcombs, based on Kerr nonlinearity in microcavities, have attracted increasing interest recently as an approach to optical clock, LIDAR, telecommunications, optical computations as well precision spectroscopy. Besides, DKSs have also been employed as an entity for investigating nonlinear physics, accompanied with various novel phenomena including breathing soliton, soliton crystals, and soliton bursts [1].

Very recently, other cavity-enhanced nonlinear effects are introduced for manipulation of the soliton microcombs, promoting performance of combs and revealing novel nonlinear phenomena. These effects provide strategies for manipulating microcomb properties, e.g., frequency extension through second harmonic generation and noise reduction through Brillouin scattering [2, 3]. However, the ubiquitous optomechanics in microcavities, a powerful platform to manipulate photons and phonons ranging from classical to quantum regime, is still elusive for Kerr soliton microcombs [4].

Fig. 1. (a) Illustration of a DKS in a WGM optomechanical microresonator. (b) Schematic diagram of coupled optical modes $\psi_n$ interacting with a single dissipative mechanical mode with displacement $x(\tau)$. FWM: four-wave-mixing. (c) Numerically simulated phase diagram of the coupled system. Without the optomechanical (OM) interaction, the soliton exists in the region between the two black curves, where the shaded region denotes the breathers. With the OM interaction, soliton exists in the colored regions, with breathing DKS, stationary DKS, and OMVS. (d) Upper panel: temporal DKS profiles for $\Delta = 8.5$, $f = 3$ (marked as the star). Lower panel: dynamical evolution of OMVS over a normalized slow time versus azimuthal angle $\phi$ over a single round trip.

2. Results

In this work, we theoretically demonstrate the existence of robust DKSs in a strongly coupled optomechanical microresonator. Interestingly, counterintuitive to the empirical fact of phonon cooling under red-detuning, an exotic
The soliton state is found with periodical oscillation modulated by the mechanical resonance. Moreover, by analysis using Lagrangian method, it is revealed that the oscillation is attributed to the extra mechanical gain from the soliton through optical spring effect.

As shown in Fig. 1(a), a whispering gallery mode (WGM) optomechanical microresonator is adapted for DKS generation, where the cavity boundary vibrates due to the enhanced light-radiation pressure [4]. Under a red-detuned pump input, the cavity modes $\psi_n$ forming the soliton combs couple to each other through Kerr four-wave-mixing (FWM), and interact with a single mechanical mode, as illustrated in Fig. 1(b). The evolution of this coupled system is described by Lugiato-Lefever equation incorporated with optomechanical coupling [4].

In absence of the optomechanical effects, the existence of the soliton states depends on both the continuous wave (CW) pump intensity $f$ and the frequency detuning $\Delta$, and these solitons can be classified into stationary solitons and breathing solitons, i.e., breathers, which exhibits periodic oscillations [5], as shown in Fig. 1(c). Once strong optomechanical coupling is introduced, by solving equations with typical experimental parameters, it is found that single DKS still exists within certain regions, of which all the boundaries redshift compared with the case without optomechanical effects. In the optomechanical microcavity, a new type of soliton state emerges, characterized by a temporal oscillation in its intensity, which is referred to as the optomechanically vibrational soliton (OMVS), as shown in Fig. 1(d).

Notably, in conventional optomechanical systems, the self-sustained mechanical oscillation oscillator is well-known to exists only with the blue-sideband drive, whereas in our system, it is enabled with the drive at the red sideband. Interestingly, once the DKS is generated, the intracavity soliton pulse can shift part of the mode resonance to the red side of the input laser, forming an additional resonance by the Kerr effect, i.e., the $S$-resonance [6]. The pump laser is effectively blue-detuned to this new resonance, which thus introduces extra gain to the mechanical oscillator by releasing phonons through the enhanced stokes process as shown in Fig 2(a). In this case, the total loss of the mechanical resonator, including both the intrinsic and the optomechanical loss induced by the anti-Stokes process, can be compensated by the gain from the $S$-resonance, enabling the self-sustained mechanical oscillation, as illustrated in Fig. 2(b).

References

1. T. J. Kippenberg and A. L. Gaeta, and M. Lipson and M. L. Gorodetsky, “Dissipative Kerr solitons in optical microresonators,” Science 361, eaan8083 (2018)
2. A. W. Bruch and X. Liu and Z. Gong and J. B. Surya, and M. Li and C.-L. Zou and H. X. Tang, “Pockels soliton microcomb,” Nat. Photon. 15, 21–27 (2021)
3. Y. Bai and M. Zhang and Q. Shi and S. Ding and Y. Qin and Z. Xie and X. Jiang and M. Xiao, “Brillouin-Kerr soliton frequency combs in an optical microresonator,” Phys. Rev. Lett. 126, 063901 (2021)
4. M. Aspelmeyer and T. K. Kippenberg and M. L. Gorodetsky and T. J. Kippenberg, “Cavity optomechanics,” Rev. of Mod. Phys. 86, 1391 (2014)
5. E. Lucas and M. Karpov and H. Guo, “Breathing dissipative solitons in optical microresonators,” Rev. of Mod. Phys. 8, 736 (2017)
6. H. Guo and M. Karpov and E. Lucas and A. Kordts and M. H. Pfeiffer and V. Brasch and G. Lihachev and V. E. Lobanov and M. L. Gorodetsky and T. J. Kippenberg , “Universal dynamics and deterministic switching of dissipative Kerr solitons in optical microresonators,” Nat. Phys. 13, 94–102 (2017)