Thermal control of Kerr microresonator soliton comb via an optical sideband

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Abstract: We demonstrate the thermal control of a microresonator soliton comb via an optical sideband, in which the detuning is passively fixed, enabling the robust and frequency-tunable soliton comb as well as the phase noise reduction. © 2022 The Author(s)

Introduction
A dissipative Kerr soliton comb (soliton comb) generated from a high-Q microresonator is very sensitive to thermal effect owing to a small mode volume of the microresonator. The thermal effect is prominent in the generation and phase noise of a soliton comb. When a soliton comb is generated, a sudden drop of intracavity power induces the resonance frequency shift, which makes it difficult to access a soliton comb. The phase noise of the repetition frequency of the soliton comb is also limited by the thermal effect via the thermal exchange between a microresonator and surrounding. The undesirable thermal effect has been mitigated by using an independent single-frequency CW laser as an auxiliary light, which is placed on the blue side of the resonance [1, 2]. In ref [3], the independent CW laser is replaced with an optical sideband generated from an electro-optic modulator (EOM), although the reduction of the phase noise is not shown.

In this report, more advantages of the use of an optical sideband as an auxiliary light are unveiled. In addition to the generation of a soliton comb as demonstrated in [3], the phase noise reduction is observed. Moreover, we show that the large “effective” soliton existence range, owing to the perfectly correlated frequency motion between the pump and auxiliary light, is also applied to scan the frequency of the soliton comb without introducing a microheater.

Experiments
Figure 1(a) shows the experimental setup. A single-frequency CW laser (called master CW laser) is separated and used as a pump (the red path in Fig. 1(a)) and auxiliary (the blue path in Fig. 1(a)) light. The auxiliary light is input into a dual-parallel Mach-Zehnder modulator (DP-MZM), which is operated in the carrier-suppressed single-sideband (CS-SSB) mode, generating a sideband-based (S-B) auxiliary light. The optical power of the S-B auxiliary light (Paux) in the experiments is 100 mW at the largest. The pump and S-B auxiliary light after passing through an optical circulator is coupled into a Si3N4 microresonator (Q ~ 4.8 × 105 and free spectral range ~ 1 THz) from the opposite side. When the transient comb power and phase noise of the soliton comb are measured, the

Figure 1. (a) Schematic of the experimental setup. DP-MZM: dual-parallel Mach-Zehnder modulator, NF: notch filter, PD: photodetector, OSC: oscilloscope, OSA: optical spectrum analyzer. (b) The working principle of the thermal control via sideband-based (S-B) auxiliary light. The rule (i): when Vaux decreases (increases), the intracavity power of the S-B auxiliary light (Paux) is increased (decreased), causing the decrease (increase) of Vres. The rule (ii): when Vres decreases (increases), Paux is increased (decreased), pushing Vres to be the original frequency. (c) Transient dynamics of the comb power from the pump (red) and S-B auxiliary (blue) light.
residual pump light is rejected by a notch filter (NF). The phase noise of the repetition frequency of the soliton comb ($L_{\text{rep}}$) is measured in the optical domain by using a two-wavelength delayed self-heterodyne interferometer (TWDI) [4]. In the experiments, the S-B auxiliary light is located at the blue side of the resonance frequency as shown in Fig. 1(b). In this situation, as shown in route (ii) in Fig. 1(b), when the resonance frequency ($v_{\text{res}}$) is changed, the S-B auxiliary light counteracts the frequency shift by the change of the intracavity power of the S-B auxiliary, pushing $v_{\text{res}}$ to be the original frequency. The blue shift of $v_{\text{res}}$ caused when a chaotic comb transitions to a soliton comb is mitigated by the S-B auxiliary light, allowing to access a stable soliton comb. In Fig. 1(c), a soliton comb is generated at around 25 ms, showing the increase (decrease) of the intracavity power of the pump (S-B auxiliary) light. Due to the counter-interaction, a soliton comb is generated with a 100 % success probability (100 success in 100 tries). Route (ii) is also applied to the reduction of $L_{\text{rep}}$. $L_{\text{rep}}$ with the S-B auxiliary (the blue curve in Fig. 2(a)) is more than 20 dB lower than $L_{\text{rep}}$ without the S-B auxiliary light (the red curve in Fig. 2(a)). Also note that the tolerable range of the frequency of the master CW laser ($V_{\text{master}}$) to have optimum phase noise reduction is about 9 times larger than the case with the use of an independent CW laser as an auxiliary light (will be shown in the talk).

Another benefit of the use of the S-B auxiliary light is the extension of the “effective” soliton existence range, which is defined as to how large $V_{\text{master}}$ can be swept without losing the soliton comb [3]. The extension of the “effective” soliton existence range is obtained by route (i) in Fig. 1(b). When $V_{\text{master}}$ increases (decreases), $V_{\text{res}}$ is also increased (decreased), at the same time, due to the pushing force from the S-B auxiliary light, which originates from the decrease (increase) of intracavity power of the S-B auxiliary light. The pushing force reduces the change of the detuning between the pump light and resonance frequency, extending the “effective” soliton existence range. As shown in Fig. 2(b), when $P_{\text{aux}}$ is 100 mW, the “effective” soliton existence range with the S-B auxiliary light (the blue circles in Fig. 2(b)) is 18 times larger than the range without the S-B auxiliary light (the red squares in Fig. 2(b)). The autonomous tracking of $V_{\text{res}}$ via $V_{\text{master}}$ also enables the scanning of the soliton comb. Figure 2(c) shows the scan range of the soliton comb at different frequency scan rates. The scan range is more than 10 GHz up to the scan rate of 200 Hz. However, the scan range gradually decreases when the scan rate is further increased owing to the photothermal response of the microresonator (the red curve in Fig. 2(c)).

![Figure 2](image)

**Figure 2.** (a) The relative phase noise with (blue) and without (red) the S-B auxiliary light. The black curve is the measurement noise floor. (b) Effective soliton existence range of the method with the S-B auxiliary light (blue) and independent auxiliary laser (red). (c) The frequency scan range of the soliton comb at different scan rates (blue) and photothermal response of the microresonator (red).

**Conclusion**

In conclusion, we showed that the S-B auxiliary light not only enabled the access to a soliton comb, but also reduced the phase noise of the soliton comb and extended the “effective” soliton existence range. The phase noise reduction of more than 20 dB was observed in a wide range of frequency offsets with a large tolerable range of $V_{\text{master}}$. Moreover, the “effective” soliton existence range was extended by 18 times owing to the perfect frequency correlation between the pump and S-B auxiliary light, which allowed the frequency scanning of the soliton comb with the scan range of more than 10 GHz. The demonstrated thermal control method would be a versatile way for low phase noise soliton comb and massively parallel frequency-modulated CW Lidar [5] operated in harsh environments.

**References**

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