Noise Reduction in Microresonators using Feedback-Controlled Phase Modulation

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Abstract: We numerically show that the impact of intrinsic noise on the soliton repetition-rate can be suppressed by phase-modulating the pump with its photodetected RF output, enabling effective noise suppression in a compact, chip-compatible architecture.

The generation of dissipative Kerr solitons (DKS) in microresonators enables the formation of optical frequency combs, termed microcombs, on chip-scale platforms such as silicon nitride and lithium niobate, making them attractive for compact, field-deployable, and mass manufacturable metrology systems [1, 2]. However, the small mode volume of microresonators gives rise to significant intrinsic cavity noise in the form of thermo-refractive fluctuations, which in turn perturb the DKS repetition rate f_{rep} [3]. Soliton trapping via phase modulation of the pump laser [4] and dual-pumping schemes [5] have been proposed as effective approaches to suppress the influence of this intrinsic noise on f_{rep}. These solutions, however, complicate the microcomb architecture by requiring either a low-noise RF signal generator for pump phase modulation or a second laser for dual-pumping, both of which are challenging to integrate on-chip. Recently, a scheme resembling an opto-electronic oscillator (OEO) was demonstrated using a platicon microcomb generated in a relatively large microresonator with a 10-GHz free spectral range (FSR) [6]. Although this approach yields low-noise microwave signals via photodetection, the dominant noise in this system originates from the electronic components rather than from intrinsic microresonator noise, owing to the large cavity mode volume and correspondingly low thermo-refractive fluctuations. The microwave noise spectrum remains essentially unchanged whether the microresonator is included or excluded, indicating that the microresonator does not exhibit the noise mechanisms relevant to low mode-volume, intrinsically noisy microresonators that are of interest in many practical applications.

Here, we propose and numerically study a fully integrated noise-reduction scheme for soliton microcombs by phase-modulating the pump laser using the photodetected DKS f_{rep} fed back as input to an electro-optic modulator (EOM), thereby eliminating the necessity of a low-noise external RF signal generator. Specifically, the repetition-rate beat between comb lines is detected on a photodetector; the resulting microwave signal drives the EOM that phase modulates the pump, forming a closed feedback loop [Fig. 1(e)]. We focus on how the impact of the dominant intrinsic noise on the microcomb is reshaped and suppressed by our proposed self-trapping mechanism. We model the soliton dynamics with the loss-normalized Lugiato-Lefever equation (LLE) modified to include pump phase modulation [7],

$$\frac{\partial \psi}{\partial \tau} = -(1+i\alpha)\psi + \left[\Delta\omega_{\mathrm{rep}}(\tau-\tau_{\mathrm{f}}) + n(\tau)\right]\frac{\partial \psi}{\partial \theta} - i\frac{\beta}{2}\frac{\partial^2 \psi}{\partial \theta^2} + i|\psi|^2\psi + F_0 e^{[i\delta_M \sin\theta]}, \quad (1)$$

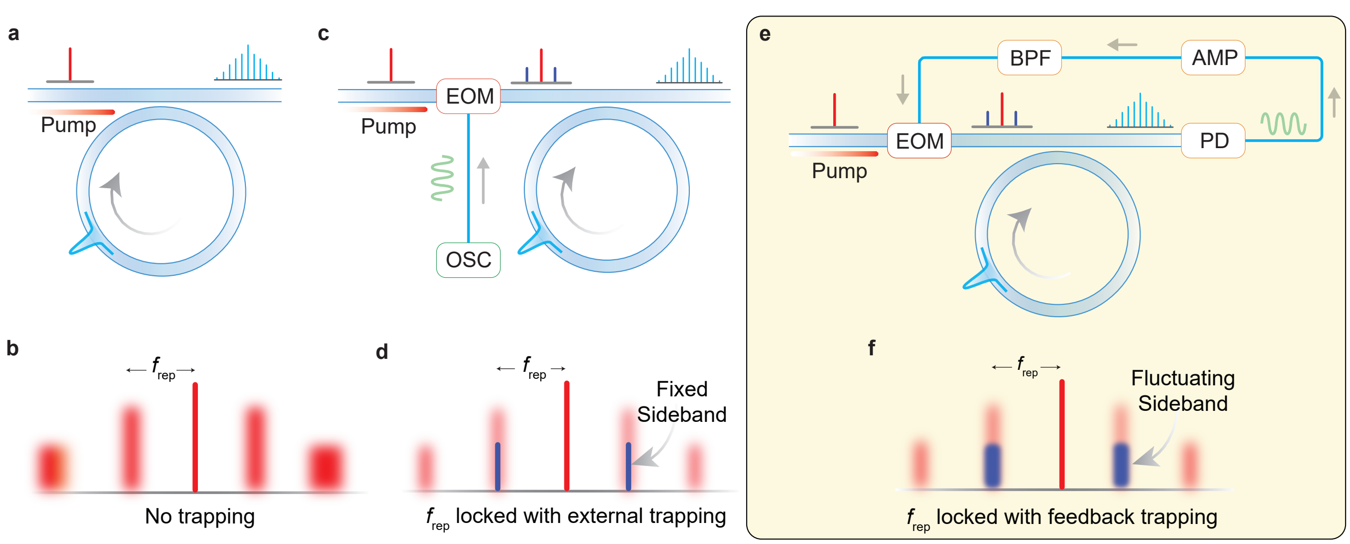

Fig. 1: (a) Soliton microcomb without trapping, (b) leading to timing jitter. (c) External trapping where the pump is phase modulated using an EOM driven by a low-noise RF oscillator. (d) The trapping generates pump sidebands that lock the soliton. (e) Proposed self-trapping setup where the comb repetition-rate beat detected on a photodetector drives the EOM in a feedback loop, (f) creating a trapping potential.

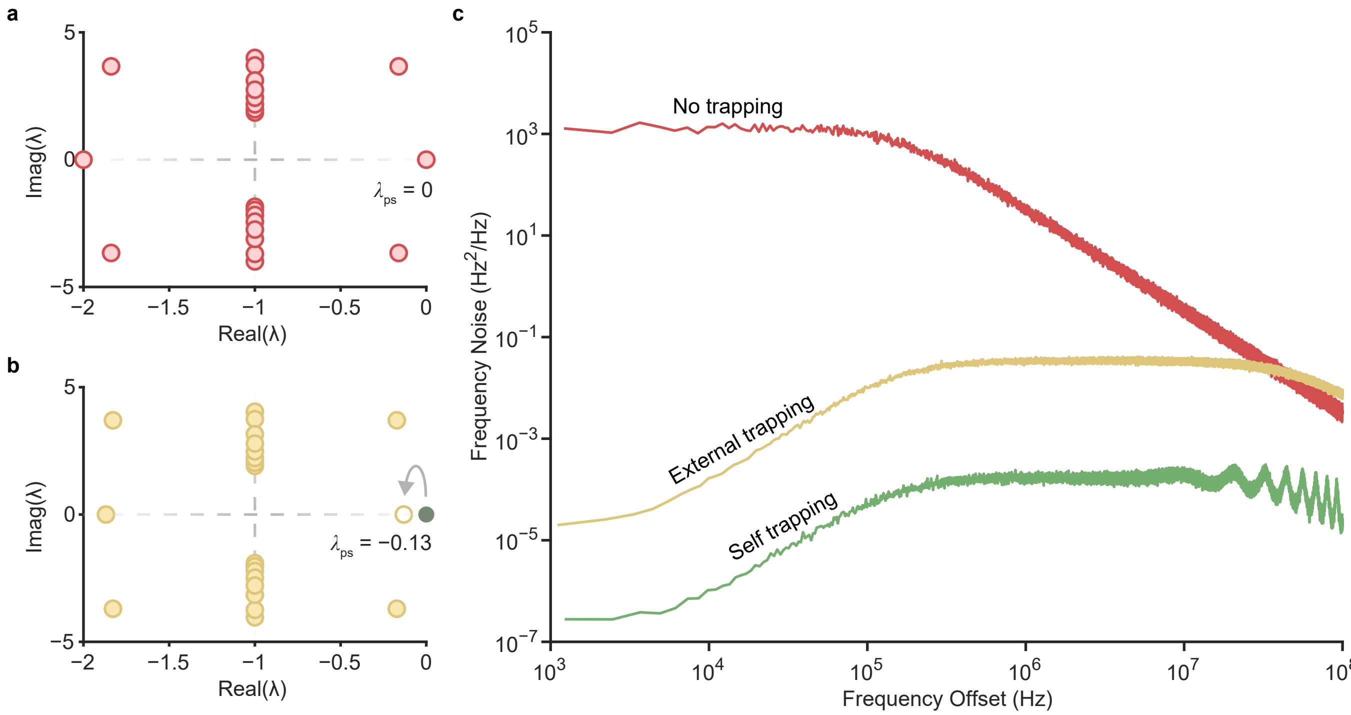

Fig. 2: (a) Dynamical spectrum of an untrapped soliton. (b) Eigenvalue spectrum with external and feedback trapping. (c) Frequency-noise PSD for three configurations presented in Fig. 1. LLE parameters: $\alpha = 3.2$, $\beta_2 = -0.2$, $F = 2.2$, $\delta_M = 0.65$, and $\tau_\mathrm{f} = 100$ ns.

where ψ is the normalized field envelope, α is the pump-resonance detuning, $\Delta\omega_\mathrm{rep}$ is the fluctuation in the DKS f_rep due to noise, τ_f is the feedback delay time, $n(\tau)$ is a white-noise source which we assume only impacts the cavity FSR, β_2 is the second-order dispersion parameter, F_0 is the pump amplitude, δ_M is the modulation depth, θ is the azimuthal coordinate, and τ is the normalized time. We track the soliton position during its evolution and compute the frequency-noise power spectral density (PSD) of the DKS f_rep. We first consider the microresonator system without pump phase modulation, where the DKS is not trapped. The dynamical spectrum, which is a plot of the eigenvalues that are obtained by linearizing Eq. 1 around its stationary solution [8], has an eigenvalue at zero [Fig. 2(a)], referred to as position-shifting eigenvalue λ_ps [5], which represents the translational invariance of the system. The f_rep noise PSD is shown in Fig. 2(c). Next, we consider a system where an external low-noise RF source is used to phase modulate the pump. The pump modulation traps the DKS, which results in λ_ps becoming negative [Fig. 2(b)], implying that perturbations to the soliton repetition rate damp. The f_rep noise is observed to be strongly reduced. Finally, we consider our proposed architecture where we close the feedback loop. The soliton pulse train is converted to an RF signal, amplified, filtered, and used to drive the EOM. With a modulation depth identical to the external RF source, the noise performance of the proposed scheme is significantly better than the externally driven setup, shown in Fig. 2(c). A short on-chip delay line introduces resonant peaks at high frequencies, but the noise remains lower than in the externally trapped case in the frequency range of interest for applications.

In summary, we numerically demonstrate an optoelectronic feedback scheme that self-traps soliton microcombs and substantially reduces their intrinsic repetition-rate noise in an integrated architecture. The approach achieves larger noise suppression than that obtained with an ideal external RF source while avoiding bulky RF references. A detailed theoretical treatment of the noise-reduction mechanism will be presented at the conference.

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