

Soliton glasses in Fabry-Perot resonators

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Abstract: We study novel soliton glass frequency combs to a modified Lugiato-Lefever Equation (LLE) that include cross-phase modulation within a Fabry-Perot resonator. Soliton glasses are characterized by stable, spatially locked, phase-locked, and randomly spaced soliton pulses.

Microresonator frequency combs have been the subject of increasing interest in recent years and can be applied to a variety of different fields, including timekeeping [1], opto-mechanics [2], microwave generation [3], and communications [4]. Microresonator combs are generated by dissipative solitons that are created by the simultaneous balance of nonlinearity and dispersion, as well as gain and loss [5]. Microresonators have small form factors, often in a ring resonator configuration, that may be integrated onto chips and operate at low powers. Fabry-Perot resonators are another geometry that can generate frequency combs [6,7]. In this paper, we report a computational study of frequency combs from Fabry-Perot resonators. We found novel multiple-soliton solutions, which are stable, phase-locked and have randomly spaced pulses. We refer to these solutions as soliton glasses since they congeal from a chaotic multi-soliton solution as the frequency is red-detuned. Once they form, they are highly stable in the presence of a sizable noise level, corresponding to 1% of the total power. They reliably form with the same pump and final detuning value; however, the placement of the solitons is random, and the number of solitons varies within a small range around a mean. We observed these soliton glass solutions in the anomalous dispersion region with a dispersion value near zero. These novel solutions to the Fabry-Perot resonators with the cross-phase term added yield broad spectra with numerous comb lines that are spaced apart by a single free-spectral range (FSR), which makes them attractive for applications such as microwave generation.

The Lugiato-Lefever equation (LLE) is commonly used to simulate the evolution of the field ψ within microresonators over time. Fabry-Perot resonators differ from ring resonators in that they exhibit cross-phase modulation. The LLE may be modified to account for the cross-phase modulation by the addition of a nonlinear term, $2i\psi\langle|\psi|^2\rangle$, where the bra-ket notation represents the spatial average of $|\psi|^2$ as shown in the following FP-LLE [5]:

$$\frac{\partial\psi}{\partial\tau} = -(1 + i\alpha)\psi + i|\psi|^2\psi - \frac{\beta}{2}\frac{\partial^2\psi}{\partial\theta^2} + F + 2i\psi\langle|\psi|^2\rangle, \tag{1}$$

where α is the detuning, β is the normalized dispersion, and F is related to the pump power. It has previously been shown that Fabry-Perot resonators can support conventional solutions to the LLE such as single soliton pulses and Turing rolls [5]. However, the soliton glass solutions that we report here have not previously been reported. A combination of nearly flat dispersion at the center wavelength, a large bandgap, and high finesse that is available on modern-day, on-chip Fabry-Perot resonators makes the generation of soliton glasses technologically feasible.

We focus our study on the Fabry-Perot LLE in the anomalous regime with $\beta = -2.4 \times 10^{-5}$ in Eq. (1), so that the dispersion curve is almost flat. In the simulation, the detuning α is a ramp function from 0 to 10, after which the detuning value is clamped at 10. The normalized input power F is 2.76. The center wavelength is 1530 nm. The round-trip length of the cavity is 30 mm, and the FSR is 4.4 GHz. The field is initialized using Gaussian-distributed random noise. Figure 1(a) shows the absolute value squared of the field, $|\psi|^2$, for the soliton glass solution as a function of space. The $-\pi$ to π in the θ-axis corresponds to $-L/2$ to $L/2$ where L is the length of the Fabry-Perot cavity [5]. In this study, the soliton glass contains around 52 pulses that are locked in space respect to each other. The exact number of pulses depends on the random seed used to initialize the simulation and varies between 39–63. We ran 50 simulations with different random noise seeds and half of our computational results exhibit the same glass characteristics. In the other cases, we obtain a continuous wave. Hence, the detuning may need to be swept a few times in order to obtain a soliton glass solution. Figure 1(b) shows the root-mean-square (RMS) error as a function of normalized time which spans over 10's of microseconds in real time. The RMS error in Fig. 1(b) is defined as RMS $= \{\mathrm{avg}[(|\psi_{n+1}(\theta)|^2 - |\psi_n(\theta)|^2)^2]\}^{1/2}$, where avg[ ] represents the average, and *n* represents the index of the time step in the simulation. Figure 1(b) shows two distinct regions. During the detuning sweep and using the ramp that was previously described, the field builds up from white noise, during which time the number of solitons changes and they move randomly until the solution congeals and a steady state is reached at a normalized time, τ, of about 2000, which in this case correlates to about 75 μs of real time. The RMS converges to a value higher than machine error due to the inclusion of quantum noise. Figure 1(c) shows the intracavity, normalized power spectrum in dBc for the soliton glass, corresponding to the spatial domain signal shown in Fig. 1(a). The frequency comb that is generated has lines that are spaced apart by a single FSR at 4.4 GHz and a power per line that is above -40 dBc for most lines.

Single solitons also have comb lines spaced by a single FSR, but the power in each line is limited by the total power in the soliton, which is determined by the ratio of its duration to the round-trip time. On the other hand, cnoidal waves such as Turing rolls or soliton crystals can have a large power per line, but the lines are spaced multiple times the FSR away from each other, and the multiple is directly related to the number of peaks. By contrast, the soliton glass solution has a spectrum in which the lines have a bandwidth that is determined by the soliton duration, a power that is determined by the sum of all the solitons in the cavity, and where the comb lines are only one FSR away from each other.

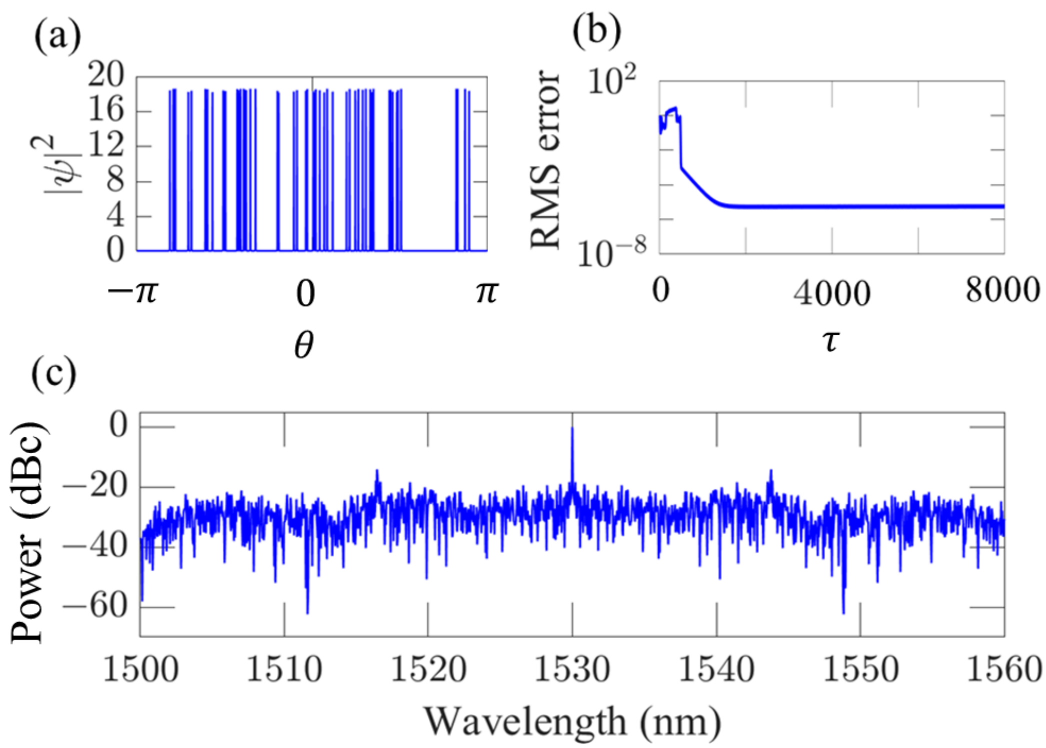

Fig. 1. (a) Soliton glass solution for the Fabry-Perot structure. (b) Convergence of the root-mean-square (RMS) error as a function of normalized time. (c) Normalized spectrum power as a function of wavelength for the soliton glass solution in (a).

In conclusion, we studied soliton glass frequency combs to the FP-LLE. We found novel soliton glass solutions, which are characterized by aperiodic spacing of locked soliton pulses. Soliton glass solutions yield broad spectra with lines spaced by a single FSR.

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