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Dynamic sideband generation in soliton fiber lasers

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Abstract

We show numerically that when a soliton circulating in the laser cavity experiences dynamical bifurcations, extra sets of sidebands appear in the soliton spectrum. The new sidebands have clearly different characteristics to those of the conventional soliton sidebands, indicating that there exists a new mechanism of sideband generation in the lasers.

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Sideband generation in soliton spectrum of the mode-locked fiber lasers is a well-known phenomenon [1–4]. It is a result of constructive interference between the soliton and the dispersive waves. When a soliton circulates in a laser cavity, it periodically experiences perturbations caused by the cavity components and emits dispersive waves. After one round trip propagation in cavity if the phase difference between the soliton and the dispersive waves is a multiple of 2π, then a sideband is generated in the soliton spectrum. The generated sidebands have well-defined frequencies, which are determined by the cavity dispersion and length [3]. Jones et al. [5] have also reported sideband generation in stretched-pulse fiber lasers. Although, sideband generation in the lasers still has the same physical mechanism, due to the pulse stretching and compression inside the cavity, the sidebands are not as obvious as those generated in lasers with everywhere negative cavity dispersion. In this letter, we report on a new type of sideband generation in the soliton fiber lasers passively mode-locked by the nonlinear polarization rotation (NPR) technique [6]. We show numerically that soliton period-doubling and/or -tripling bifurcations could result in the generation of new sidebands in the soliton spectrum. And furthermore, the new sidebands have clearly different characteristics to those of the conventional soliton sidebands.

Our numerical study was motivated by the recent experimental observation of soliton deterministic dynamics in a dispersion-managed fiber laser [7]. It was shown that under strong soliton intensity, the cavity nonlinearity of the fiber laser could lead to soliton period-doubling and period-tripling bifurcations. In particular, the optical spectra of the period-doubled solitons exhibited extra spectral structures as compared with those of the solitons without period-doubling bifurcations. To understand the experimental results we have numerically studied soliton dynamics in soliton fiber lasers and numerically revealed soliton period-doubling bifurcations and route to chaos [8]. Our numerical simulations further showed that the appearance of the soliton deterministic dynamics is caused by the nonlinear laser cavity property. It is another intrinsic feature of soliton fiber lasers. Our previous numerical simulations have focused on the soliton fiber lasers with dispersion-managed cavity, where due to the pulse stretching and compression

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inside the cavity, fine structures of the soliton sidebands are not clear. Using exactly the same laser model and the numerical calculation technique as reported in [8], we have further simulated the soliton dynamics in non-dispersion managed fiber lasers and revealed again the soliton period-doubling, period-tripling and period-doubling route to chaos. Solitons obtained in these lasers have sharp sidebands. Therefore, details of the soliton sideband variation under soliton bifurcations could be investigated.

Our numerical simulations are based on the coupled Ginzburg–Landau equations of the following form:

$$\begin{aligned}\frac{\partial u}{\partial z} &= \mathrm{i}\beta v - \delta\frac{\partial v}{\partial t} - \frac{\mathrm{i}}{2}\kappa''\frac{\partial^2 u}{\partial t^2} + \mathrm{i}\gamma\left(|u|^2 + 2|v|^2\right)u \\ &\quad + \frac{\mathrm{i}\gamma}{3}v^2u^* + \frac{g}{2}u + \frac{g}{2\Omega_g^2}\frac{\partial^2 u}{\partial t^2} \\ \frac{\partial v}{\partial z} &= -\mathrm{i}\beta u + \delta\frac{\partial u}{\partial t} - \frac{\mathrm{i}}{2}\kappa''\frac{\partial^2 v}{\partial t^2} + \mathrm{i}\gamma\left(2|u|^2 + |v|^2\right)v \\ &\quad + \frac{\mathrm{i}\gamma}{3}u^2v^* + \frac{g}{2}v + \frac{g}{2\Omega_g^2}\frac{\partial^2 v}{\partial t^2},\end{aligned} \tag{1}$$

where u and v are the two normalized slowly varying pulse envelopes along the slow and the fast axes of the optical fiber, respectively. $2\beta = 2\pi\Delta n/\lambda$ is the wave-number difference, and $2\delta = 2\beta\lambda/2\pi c$ is the inverse group-velocity difference. κ'' is the dispersion parameter, γ is the nonlinearity of the fiber. g is the gain coefficient for EDF and Ω_g is the gain bandwidth. For the undoped fiber, g is taken as 0. The EDF gain is saturated by the total light energy in the cavity as described by

$$g = g_0 \Bigg/ \left[1 + \frac{\int(|u|^2 + |v|^2)\mathrm{d}t}{E_s}\right], \tag{2}$$

where g_0 is the small signal gain and E_s is the saturation energy. In the frequency domain, g has a spectral profile of

$$g(\omega) = g_p\left[1 - \left(\frac{\omega - \omega_0}{\Omega_g}\right)^2\right], \tag{3}$$

where g_p is the peak gain and ω_0 is the peak gain frequency. A soliton formed in the fiber laser is the result of mutual interaction among the effects caused by cavity dispersion, fiber nonlinearity, laser gain, and cavity boundary condition. To faithfully simulate the soliton features, one also needs to take into account the laser cavity effect including the actions of the various cavity components, such as the polarization controllers and polarizer. In our simulation, we used the so-called pulse-tracing technique to model the pulse shaping in the cavity [9]. We start our simulation with an arbitrary initial weak pulse and then follow the circulation of the pulse in the cavity. The pulse propagation in the various pieces of fiber is described by the coupled GLEs (1), and the actions of the discrete cavity components are modeled by multiplying their 2×2 transfer matrices with the light field when the pulse encounters them in the cavity. The coupled GLEs were numerically solved with the standard split-step method. Numerically we found that as far as the laser parameters are appropriately selected, a steady state soliton operation can always be obtained, and furthermore, almost all soliton features observed in experiments can be reproduced, including the soliton period-doubling route to chaos.

We have numerically carefully investigated the extra soliton sideband generation associated with the soliton period-doubling bifurcations. Fig. 1 shows a comparison between the soliton spectra obtained before and after a soliton period-doubling bifurcation. Initially the soliton is in a conventional soliton period-1 state, after the bifurcation it jumps into a soliton period-2 (P2) state. In obtaining the result we have used the following laser parameters: cavity length $L = 6$ m, which consists of 1 m dispersion shifted fiber (DSF) with dispersion parameter $\kappa''_{DSF} = -2\ \mathrm{ps}^2/\mathrm{km}$, 4 m erbium-doped fiber (EDF) with dispersion parameter $\kappa''_{EDF} = -10\ \mathrm{ps}^2/\mathrm{km}$ and 1 m standard single mode fiber (SMF) with dispersion parameter $\kappa''_{SMF} = -18\ \mathrm{ps}^2/\mathrm{km}$, $\kappa''' = 0.1\ \mathrm{ps}^3/\mathrm{km}$, $\Omega_g = 20$ nm, $\gamma = 3\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$, gain saturation energy $P_{sat} = 1$ nJ, fiber beat length $L_b = \mathrm{L}/4$, cavity linear phase delay bias ph $= 1.5\pi$, and the orientation of the intracavity polarizer to the fiber fast axis $\psi = \pi/8$. The pump strength G was used as the control parameter.

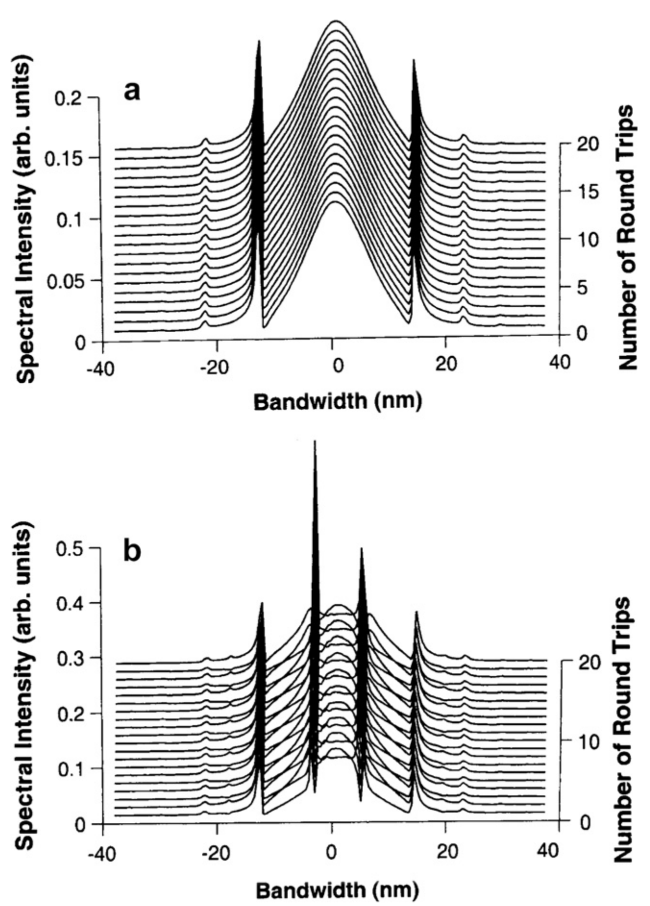

Fig. 1. Soliton spectral evolution with cavity round-trips numerically calculated. (a) P1 state, $G = 335$. (b) P2 state, $G = 345$. The P2 state is formed from the P1 state after a period-doubling bifurcation.