Self-Adaptive Transition of Laser Mode-Locking States via Online Dispersion Engineering over a Wide Range

Authors: Zha, Zimin, Sun, Suwan, Wu, Kailin, Shi, Zhiming, Li, Zilong, Chu, Yongyuan, Guo, Hairun, Guo, Hairun

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Abstract

We demonstrate dispersion-engineered dissipative soliton mode-locked lasers, by means of intracavity spatial light modulation (SLM). The inline cavity GVD control of wide range (-0.28 ps^2 ~ 0.06 ps^2) in the laser cavity is realized, by which we achieve continuous and stable switching of traditional solitons, dispersion-managed solitons, and dissipative solitons. A transient process of pulse-adaptive reconstruction is observed during the switching of different solitons. Transitions of soliton dispersive waves from Kelly sidebands, and transformation to quartic solitons have been observed via tuning the high-order dispersion coefficients. W-shaped solitons are demonstrated under negative second-order dispersion and positive fourth-order dispersion.

Full Text

Preamble

Self-Adaptive Transition of Laser Mode-Locking States via Online Dispersion Engineering Over a Wide Range

ZIMIN ZHA[1], SUWAN SUN[1], KAILIN WU[1], ZHIMING SHI[1], YONGYUAN CHU[1], ZILONG LI[1],[2], AND HAIRUN GUO[1],*

[1]Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai, China

[2]School of Engineering and Materials Science, Queen Mary University of London, Mile End, Bethnal Green, E1 4NS, London, United Kingdom

hairun.guo@shu.edu.cn

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We demonstrate dispersion-engineered dissipative soliton mode-locked lasers using intracavity spatial light modulation (SLM). By achieving inline cavity GVD control over a wide range ($-0.28\ \mathrm{ps}^2 \quad 0.06\ \mathrm{ps}^2$), we realize continuous and stable switching among traditional solitons, dispersion-managed solitons, and dissipative solitons. A transient process of pulse-adaptive reconstruction is observed during soliton switching. Transitions of soliton dispersive waves from Kelly sidebands and transformations to quartic solitons are observed by tuning higher-order dispersion coefficients. W-shaped solitons are demonstrated under negative second-order dispersion and positive fourth-order dispersion.

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Introduction

Nonlinear systems with periodic variations of nonlinearity and dispersion appear in various physical problems and engineering applications. Solitons represent one of the most widely studied forms of excitation in nonlinear systems [1]. As localized structures that can be understood as self-reinforcing waves, they propagate while maintaining their shape—a remarkable property achieved by balancing diffusive and focusing effects. In optics, solitons arise from the linear and nonlinear interaction of light and matter, and the soliton effect significantly improves mode-locked laser performance, enabling direct generation of optical pulses with ultrashort durations well below 100 fs [2]. Considerable engineering and technical efforts have been invested in developing solid-state, fiber, and semiconductor lasers [3], while fiber lasers that achieve mode-locking at moderate energy scales are widely used in optical frequency combs [4–6], medical imaging, ophthalmology, and other applications [7–9].

During soliton propagation, the interplay between dispersion and nonlinear effects plays a crucial role in shaping pulses and manipulating photodynamics. Stable pulse generation relies on careful laser design to achieve compensation among various effects. As a platform for soliton pulse implementation, fiber lasers excel in flexible design, offering unprecedented ability to engineer cavity dispersion through the selection and length of fiber components, which leads to many new pulse behaviors and laser operation mechanisms, such as dispersion-managed solitons and dissipative solitons [10–12].

Different dispersion environments bring not only pulse energy selectivity but also the ability to generate, control, and manipulate ultrashort light pulses and special waveforms. Therefore, precise control of cavity dispersion is essential. In typical cases, once the laser is constructed, the cavity becomes difficult to reconfigure due to its fixed parameters. To achieve a higher degree of control over pulse dynamics in the laser cavity, flexible dispersion tuning and editing of the cavity environment are critical. The use of grating pairs [13] or a Martinez-type stretcher [14, 15] with an adjustable mechanical slit inserted inside the cavity is a commonly employed method. However, these approaches make the laser system complex and lack the precision of filters. Moreover, due to mechanical constraints, these schemes may provide a fixed, non-tunable dispersion value that yields hysteretic dispersion changes and may be difficult to edit across a wide range that continuously spans several dispersion regions. Recently, several online methods for regulating intracavity dispersion have been developed, including spatial light modulation techniques [16]. The modulation of spectral amplitude and phase to obtain designed optical waveforms has been widely used in many fields [17–20].

In this Letter, we apply inline dispersion engineering in an NPR mode-locked fiber laser with spatial optical modulation. Continuous and stable switching from negative to positive dispersion is achieved, and we observe that switching between different soliton pulses operating in different dispersion regimes undergoes an adaptive reconstruction process that gives rise to an environmental stability-related chaotic state in the time domain. Furthermore, higher-order dispersion engineering is achieved. By changing both third-order dispersion (TOD) and fourth-order dispersion (FOD) components, we observe transitions in soliton dynamics, including the emergence of soliton dispersive waves, the appearance of quartic solitons, and the formation of w-shaped solitons.

Experimental Setup and Results

The experiment is based on a mode-locked fiber laser with nonlinear polarization rotation (NPR), as shown in the schematic setup in Fig. 1(a). The overall cavity length is 10.94 m, including 2.2 m of Erbium-doped fiber as the gain medium. The net cavity dispersion is approximately -0.2375 ps^2. Unlike conventional NPR mode-locked fiber lasers, a spatial light modulation module (Finisar WaveShaper4000A) is connected inside the cavity, which is programmable for engineering cavity loss and phase spectral profile: $(\omega) = \mathrm{L}$. Thus, we can set the phase mask within the bandwidth of spectral pulse shaping at its frequency resolution of 10 GHz to manipulate the cavity dispersion environment.

In the initial state (i.e., when the SLM is fully transparent with no phase change), adjusting the polarization controller appropriately implements a soliton mode-locked laser by launching a pump power of 200 mW, characterized in both temporal and spectral domains as shown in Fig. 1(b-d). An external trigger signal with frequency consistent with the laser repetition rate was used when measuring the DFT spectrum to maintain signal tracking. Due to the presence of spatial light modulators, there is additional dispersion, and the second-order dispersion at this time is estimated through dispersion compensation to be approximately -0.2739 ps^2. Specifically, the laser spectrum is centered at approximately 1563.12 nm with a 3-dB bandwidth of about 3.1 nm (Fig. 1(g)), and a stable output pulse sequence with an interval of about 88 ns is obtained. The radio frequency spectrum of the pulse sequence is also characterized (Fig. 1(d)), where the fundamental frequency tone is 14.1 MHz and the signal-to-noise ratio (SNR) exceeds 62 dB.

The second-order dispersion value in the cavity was adjusted by setting different phase masks while keeping the pump power and polarization controller angle constant. When the cavity GVD was set at -0.0551 ps^2, the dispersion-managed soliton operating in the near-zero dispersion region was immediately obtained. A Gaussian spectrum with a 3-dB bandwidth of approximately 21.44 nm (Fig. 1(j)) was obtained while spectral sidebands were eliminated. Moreover, the dispersion-managed soliton could be obtained within a certain dispersion interval of about -0.0824 ps^2 -0.004 ps^2, and slight adjustment of the polarization controller angle would not destroy the soliton state.

While the near-zero dispersion-managed soliton was operating, we could change the intracavity second-order dispersion to achieve dissipative solitons operating in the net-normal dispersion region. Meanwhile, the filter bandwidth also required proper control, as DSs need additional amplitude modulation beyond saturable absorber action. A Gaussian spectral profile was programmed on the filter because the default rectangular profile is similar to the shape of the DS spectrum. Fig. 1(k) shows the DS spectrum obtained for a net GVD of 0.0543 ps^2 and a filter bandwidth at FWHM of 0.4 THz. The spectrum exhibits steep edges, and its bandwidth is limited to about 7.79 nm (3-dB bandwidth), all of which are viewed as characteristic features of DSs.

Because the dispersion adjustment in the experiment was real-time and immediate, when experimental parameters were set on the platform, continuous dispersion modification was carried out without changing any platform settings (such as pump power or polarization controller angle), allowing us to record the dynamic process of soliton switching in real time. As shown in Fig. 1(e) at around 10,000 roundtrips and in Fig. 1(f), there was a chaotic state at the moment of switching, where the soliton pulse underwent an adaptive reconstruction process. The duration of the entire chaotic state was mainly related to the environmental stability of the laser, and this process did not occur if the dispersion was slowly changed within a single region, as shown from 0 to 9,900 roundtrips in Fig. 1(e), corresponding to the spectra in Fig. 1(g-i).

Note that the soliton laser spectrum was not symmetric with respect to its center, as there could be intrinsic TOD or higher-order dispersion in the laser cavity. Therefore, we obtained a conventional soliton by compensating the higher-order dispersion present in the cavity. With 5.6 ps^3/km of added TOD, the soliton spectrum transformed into a symmetric structure. Increasing the cavity TOD caused the first-order sideband closest to the spectrum center to translate into a dispersive wave. As the TOD continued to increase, the sidebands became more compact and the dispersive wave grew stronger, followed by Kelly sidebands (Fig. 2(b)). Similar features were observed in the shape of the dispersion curve, as shown in Fig. 2(a). We then performed DFT analysis for the switching, shown in Fig. 2(c), obtaining the evolution of the Kelly sideband and dispersive wave. Fig. 2(d) shows the DFT spectra with certain characteristics extracted from the process at around 1,000 and 15,000 roundtrips.

It can be seen that with increasing TOD, the Kelly sideband translated into the dispersive wave. The spectrum first shrank, then the sidebands vanished, followed by competition between two spectral types. Finally, the dispersive wave became dominant at around 1550 nm. The entire evolution process experienced a certain time period, so we needed sufficient oscilloscope sampling time to achieve accurate sampling. Due to limitations in oscilloscope bandwidth and sampling rate, the number of sampling rounds was too large to obtain adequate range for DFT measurement. Thus, we sampled the spectra of each roundtrip separately using the history sampling pattern of the oscilloscope, then integrated them in order before data processing. In this way, we achieved sufficient spectral resolution and observed the fine spectral structures.

We conclude that due to the introduction of strong TOD, the dispersion distribution curve takes the shape of a third-order function that has an inflection point in the presence of distinct second-order dispersion. From the center to the inflection point, the intensities of the corresponding frequency components show a corresponding rise. Because it does not reach an FSR, the dispersion curve won't fold but instead forms a smooth bulge on the spectrum, appearing as a dispersion wave. We then increased the TOD value, and the variation in the dispersion distribution curve was also reflected in the shape of the output spectrum. That is, when the dispersion difference accumulated to an FSR, the intensity of the frequency component experienced a steep increase due to the curve's folding, and then sharply shaped Kelly sidebands appeared. Within some allowable error limits, the positions of the fundamental dispersion wave and the Kelly sidebands corresponded to the positions of the inflection point and the folding point, respectively.

Obviously, the above process caused an asymmetrical change of the spectral sidebands because the dispersion distribution curve was a monotonic function and the inflection point occurred only on one side. In fact, this effect can be applied to both sides of the spectrum, which requires the introduction of higher even-order dispersion to allow inflection points to exist on both sides of the dispersion curve. Thus, along with the existence of negative second-order dispersion, we introduced significant positive FOD to obtain a centrosymmetric dispersion distribution. As shown in Fig. 3, the first-order sideband took the shape of a dispersion wave, corresponding to the 'w' shape of the dispersion distribution curve (Fig. 3(a) and 3(b)). Other dispersion features were represented on the symmetrically distributed Kelly sidebands. When changing the sign of the FOD, the 'w' feature of the dispersion curve vanished, and both sides of the spectrum translated into Kelly sidebands (Fig. 3(c) and 3(d)). By this method, we could extract wavelength-dependent cavity dispersion in the gain band of the fiber cavity, which corroborates with the values introduced by the SLM.

Conclusion

In conclusion, we designed an NPR mode-locked fiber laser based on spatial optical modulation for dispersion engineering. Inline cavity GVD control over a wide range (-0.28 ps^2 0.06 ps^2) was realized, enabling continuous and stable switching among traditional solitons, dispersion-managed solitons, and dissipative solitons. A transient process of pulse-adaptive reconstruction is observed for different types of soliton switching within the same laser, corresponding to transient chaotic states in the time domain. Under wide-range control of higher-order dispersion (including TOD and FOD), we observed the emergence of dispersive waves and their evolution. Meanwhile, when positive FOD exists in the anomalous GVD region, w-shaped solitons were obtained. Our work provides a convenient method to operate over a wide range of dispersion, offering new insights for the study of soliton dynamics.

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