Impact of Third Order Dispersion on Dissipative Soliton Resonance

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Abstract—Dissipative soliton resonance (DSR) is a promising way for high-energy pulse generation typically having a symmetrical square pulse profile. While this method is well known, the impact of third order dispersion (TOD) on DSR is yet to be fully addressed in the literature. In this article, the impact of TOD on DSR is numerically investigated under the frame of the complex cubic-quintic Ginzburg-Landau equation (CQGLE). Our numerical investigations indicate that DSR can stably exist under TOD with nearly the same pulse amplitude, but with a (significantly) different pulse duration. Depending on the value of chromatic dispersion, the pulse duration can be notably longer or shorter due to the presence of TOD. The TOD effect also alters the dependence of pulse duration on the nonlinear gain. Another impact of TOD on DSR is that the DSR exists with an asymmetric pulse profile, leading to steepening of one edge of the DSR pulse, while flattening of the other. Our results indicate that TOD has a critical role for realizing DSR in mode-locked lasers and it should be taken into consideration during design and development of DSR-based lasers.

Index Terms—Dissipative soliton resonance, third-order dispersion, mode locking, high-energy laser.

I. INTRODUCTION

Dissipative soliton resonance (DSR) effect has attracted wide attention since it was first predicted as a promising way for high energy pulse generation in 2008 [1]–[6]. Quite different from other kinds of stationary pulse regimes, the DSR shows distinctive advantage of wave-breaking-free effect with a square-shaped pulse characterized by flat-top and steep pulse edges, where the pulse energy infinitely increases through expanding pulse duration without altering the pulse amplitude [7]–[11]. Not only the unlimited pulse energy is attractive, but also its distinct square pulse shape is promising for applications such as the efficient optical parametric oscillators with square pulse pump [12]–[15]. Near linear chirp distribution across the flat-top region of DSR allows for the efficient compression of pulse duration outside the laser oscillator. Owing to these advantages, the formation mechanism and existence condition of DSR have been thoroughly discussed numerically and theoretically [7], [16], [17], inspiring a number of experimental reports in the frame of mode-locked fiber lasers [2], [5], [6]. CQGLE) as a phenomenological description of mode-locking dynamics averages the effects of discrete laser cavity components over one round trip [18], and thus being widely adopted to explore the universal behavior of DSR. With this model, it turns out that DSR can be stably formed in both anomalous and normal chromatic dispersion regimes[7], [19], [20], and remains robust in laser models with parameter management [21]. The numerical investigation of DSR in this framework also guides the practical design of DSR by relating the parameters of the CQGLE with realistic ring laser cavity [22].

In the aforementioned investigations, the DSR has been studied however without considering the effect from high order dispersion (HOD). Particularly, mode-locked fiber laser with a long cavity length could easily accumulate a high amount of TOD, which can result in asymmetry of pulse profile [23], [24], pulse broadening or compression [25], [26], and impair soliton stability [27]. Complex pulse regimes such as soliton pulsating and erupting [28], [29], and even chaotic pulse regimes can be introduced by TOD effect [30]. Appropriate TOD can eliminate soliton explosions through compensating self-steepening effect [31]. Fourth order dispersion has also been investigated in terms of soliton stability, soliton splitting [32], [33], pure-quartic soliton formation [34], etc. Inspired by these complex roles of HOD, a fascinating question arises on how is DSR affected by...
HOD effect. If the pulse profile of DSR can be reshaped without impairing its wave-breaking feature, it will provide higher freedom for potential applications.

In this paper, we thoroughly investigate the performance of DSR in the frame of CQGLE by introducing TOD effect. The simulation result shows that, depending on the amount and sign of chromatic dispersion, the TOD effect can lead to a significant expansion or reduction of the pulse duration of DSR. Besides, TOD also alters the pulse edge steepness of DSR.

II. NUMERICAL MODEL

The CQGLE with TOD can be expressed as in [7], [29], [31], [35]
\[
\begin{align*}
\frac{i\psi_z}{D} + \frac{D}{2} \psi_{tt} - i \beta_3 \psi_{ttt} + |\psi|^2 \psi + v |\psi|^4 \psi \\
= i \delta \psi + i \beta_3 \psi_{ttl} + i \beta_3 |\psi|^2 \psi + i \mu |\psi|^4 \psi
\end{align*}
\] (1)

where the normalized optical envelope \( \psi = \psi(t, z) \) is a complex function of retarded time \( t \) and propagation distance \( z \). \( z \) is normalized to the cavity round-trip number. \( \psi_z \) is the first-order \( z \)-derivative, and \( \psi_{tt} \) and \( \psi_{ttl} \) are the second-order and three-order \( t \)-derivatives, respectively. Left side of (1) contains the conservative terms: \( D \) is the averaged cavity chromatic dispersion, with \( D > 0 \) (\( D < 0 \)) in the anomalous (normal) chromatic dispersion regime, respectively. \( \beta_3 \) is TOD of laser cavity, and the sign of \( \beta_3 \) is consistent with sign of cavity TOD. \( v \) accounts for the quintic reactive Kerr nonlinearity. Right side of (1) represents all the dissipative effects: \( \delta < 0 \) is the linear loss. \( \beta > 0 \) donates spectral filtering. \( \epsilon \) represents the nonlinear gain. \( \mu < 0 \) counts for saturation of the nonlinear gain.

The complex equation in (1) was numerically solved using the split-step Fourier method. Note that the performance of the DSR is strongly related to the seven parameters. As an example, the parameters used in the simulation are implemented based on the parameters in Ref. [7]: where DSR exists around the upper boundary of the stable soliton solution in the two dimensional parameter space \( (D, \epsilon) \) by setting four optimal parameters as \( \delta = -0.05, \beta = 0.4, \nu = -0.08, \) and \( \mu = -0.05 \). In this work, the TOD effect is considered and we focus on analyzing the performance of DSR in the remaining three dimensional parameter space \( (\beta_3, D, \epsilon) \).

III. SIMULATION RESULTS

A. Impact of \( \beta_3 \) on DSR with constant \( (D, \epsilon) \)

We first investigate the performance of DSR at the point of \( (D=-2.5, \epsilon=0.239677) \) with \( \beta_3 = 0.2 \). Stable soliton solution is obtained in this case. Figure 1(a) shows the pulse evolution as a function of round-trip number \( z \), where the pulse stably operates with an inclined evolution trace. The slope is proportional to the strength of \( \beta_3 \). Due to this phenomenon, we move the pulse peak to \( t = 0 \) when the pulse is close to boundary of time window during the evolution, this ensures the correct simulation within the numerical time window. Figure 1(b) shows the corresponding pulse profile, where the pulse duration and amplitude are \( T_{\text{pulse duration}} = 42.4 \) and \( |\psi|_{\text{max}} = 2.1 \), respectively. The pulse profile exhibits a square shape with an approximate flat-top structure (strictly speaking, the flat-top is still a weak convex shape). In order to facilitate comparison, the pulse is translated along lateral axis so that the pulse peak is located at \( t = 0 \) (the figures below are the same). A typical feature is that both edges of the pulse show different steepness. The rise time, which is defined as the time duration from 5% to 95% of the pulse peak, is used to describe the steepness of pulse edges. In the case of \( \beta_3 = 0.2 \) (solid line), the rise times of leading and trailing edges of the pulse are \( T_{\text{rise time leading edge}} = 12.7 \) and \( T_{\text{rise time trailing edge}} = 23.8 \), respectively. As a comparison, Fig. 1(b) also shows the DSR with \( \beta_3 = 0 \) (the dashed line), where the pulse amplitude is nearly the same for the two pulses. Due to the symmetrical pulse profile at \( \beta_3 = 0 \), the rise times are \( T_{\text{rise time leading edge}} = T_{\text{rise time trailing edge}} = 17.7 \), which is between the leading and trailing edges of the DSR with \( \beta_3 = 0.2 \). This phenomenon suggests that TOD steepens the leading pulse edge but stretches the trailing pulse edge of DSR. In addition, the DSR with zero TOD shows different pulse duration of \( T_{\text{pulse duration}} = 30.0 \), indicating the dependence of pulse duration on TOD.

The sign of \( \beta_3 \) determines if the edge of the pulse is steepened or stretched. The simulation shows that the pulse profile at \( -\beta_3 \) is always a mirror inversion of the one at \( \beta_3 \) regarding the axis \( t = 0 \). For instance, Fig. 2(a) shows the pulse profiles at \( \beta_3 = \pm 0.2 \), where the minus TOD (\( \beta_3 = -0.2 \)) steepens the trailing edge and stretches the leading edge (the dot-dashed line), and their pulse profiles are mirror symmetric to each other regarding axis \( t = 0 \). Due to this phenomenon, the
following work only considers the cases of $\beta_3 > 0$. Figure 2(b) shows the rise times of leading and trailing pulse edges as a function of $\beta_3$ (the blue solid and dashed lines). The result shows that the TOD steepens the leading pulse edge but flattens the trailing pulse edge. For instance, at the case of $\beta_3 = 0.24$, $T_{\text{rise time, leading edge}} = 11.9$, and $T_{\text{rise time, trailing edge}} = 25.4$. Figure 2(b) also shows the corresponding variation of pulse duration (the red solid line), and it is found that $T_{\text{pulse duration}}$ continuously increases from 30.0 to 62.4 as $\beta_3$ goes from 0 to 0.24. Note that, when $\beta_3$ further increases, the pulse duration as it approaches the width of the numerical window and thus cannot be correctly simulated.

B. Rise time of pulse edge in the space of ($\beta_3, D, \varepsilon$) with constant pulse duration

In fact, the pulse edge steepness depends on not only the TOD ($\beta_3$) but also the chromatic dispersion ($D$) and nonlinear gain ($\varepsilon$). In order to illustrate this, we first simulate the steepness of pulse edges as a function of $D$ without considering TOD. Figure 3(a) shows the rise times of both pulse edges in the range of $-2.5 < D < 2.0$ with $\beta_3 \neq 0$, where their pulse durations are respectively maintained $T_{\text{pulse duration}} = 30, 25,$ and $20$ by appropriately setting the nonlinear gain ($\varepsilon$). It can be seen that, regardless of the pulse duration, the pulse with long pulse edges is formed in large normal dispersion region ($D \ll 0$). As $D$ increases, the rise time continuously decreases to a minimum value of 1.98 at $D \approx 0.3$, and then slowly increases again, indicating that DSR with steepest pulse edges can be obtained in near zero anomalous chromatic dispersion region. In the case of $\beta_3 \neq 0$, the rise time of pulse edges becomes different. For instance, Fig. 3(b) shows the rise times of pulse edges by setting $\beta_3$ to 0.015 for the curve with $T_{\text{pulse duration}} = 30$ in Fig. 3(a).
which is replotted in Fig. 3(b) to facilitate comparison. It can be seen that the leading (trailing) edge is obviously steepened (stretched) in large normal dispersion region. As $D$ increases, the difference of rise times in the cases of with/without TOD becomes weak gradually, and the leading (trailing) pulse edge is stretched (steepened) instead when $D$ is slightly greater than 0 (see inset of Fig. 3(b)).

The pulse edge steepness in Fig. 3(b) relies on both chromatic dispersion and TOD, as a result the individual contribution of TOD is unclear. Besides, since the DSR in the case of $D > 0$ and $\beta_3 = 0$ is already highly steep, the variation of pulse edge rise time caused by TOD cannot be clearly resolved in Fig. 3(b). Here, we use the relative change of rise time $\eta_{\text{rise time}}$ to quantitatively describe the impact of TOD on pulse edge steepness. It is defined by

$$\eta_{\text{rise time}} = \frac{T_{\text{risetime with TOD}} - T_{\text{risetime without TOD}}}{T_{\text{risetime without TOD}}}$$

where $T_{\text{risetime with TOD}}$ and $T_{\text{risetime without TOD}}$ are the rise times of pulse edge with $\beta_3 = 0$ and $\beta_3 \neq 0$, respectively. $\eta_{\text{rise time}} > 0$ ($< 0$) corresponds to steepen (stretch) pulse edge, and its absolute value reflects the relative change of rise time. Figure 3(c) shows the calculated $\eta_{\text{rise time}}$ of Fig. 3(b) with $\beta_3 = 0.015$, and Fig. 3(d) shows $\eta_{\text{rise time}}$ of leading pulse edge with three different TOD of $\beta_3 = 0.005, 0.010, 0.015$. In both plots, $\eta_{\text{rise time}}$ varies as a function of chromatic dispersion and shows two peaks: one is at $D \approx -0.96$ and the other is at $D \approx 0.60$. When chromatic dispersion deviates from the two peaks, the absolute value of $\eta_{\text{rise time}}$ decreases gradually, indicating the weakened contribution of TOD on pulse edge steepness. Besides, $\eta_{\text{rise time}}$ in normal chromatic dispersion region is relatively higher when compared to the anomalous region. $|\eta_{\text{rise time}}|$ reaches the maximum value at $D \approx -0.96$. In the cases of $D \approx 0$ or $D \gg 0$, $\eta_{\text{rise time}}$ approaches to zero, indicating the less sensitivity of pulse edge steepness on TOD.

Figure 3 shows that, if one of the pulse edges is stretched, the other will be steepened. And in Fig. 2(b), the steepness of leading edge is continuously enhanced when $\beta_3$ increases from 0 to 0.24. These results seemingly imply that the DSR with an infinite steep pulse edge could be formed if TOD is strong enough. However, our numerous simulation results show that the pulse edge cannot be infinitely steepened by TOD, and both pulse edges turns to be stretched when $\beta_3$ exceeds a certain value. In order to clearly illustrate this, here we simulated the rise times of leading and trailing edges as a function of $\beta_3$ at two different parameter values of $(D=1.5, \varepsilon=0.44)$ and $(D=0, \varepsilon=0.408982)$, as seen in Figure 4(a) and 4(b), respectively. In Fig. 4(a), the rise times are $T_{\text{risetime leading edge}} = T_{\text{risetime trailing edge}} = 2.57$ at $\beta_3 = 0$. As $\beta_3$ increases from 0 to 0.2, $T_{\text{risetime leading edge}}$ always decreases, but $T_{\text{risetime trailing edge}}$ first decreases to a minimum of ~2.43 at $\beta_3 = -0.14$ and then starts to increase, suggesting that the pulse edge steepness cannot be infinitely enhanced by TOD. Figure 4(b) shows a similar phenomenon to Fig. 4(a). However, in this case, because the pulse edges at $\beta_3 = 0$ have a shorter rise time of ~2.17 and thus higher steepness, the leading pulse edge is only weakly steepened and then being continuously stretched, as seen the inset of Fig. 4(b).

C. The pulse duration of DSR in the space of $(\beta_3, D, \varepsilon)$

The pulse duration also depends on both TOD and chromatic dispersion. In order to illustrate this, the pulse duration as a function of $D$ is plotted in Fig. 5 with different TOD ($\beta_3 = 0, 0.005, 0.010, 0.015$). In this plot, the horizontal straight line without TOD corresponds to constant pulse duration of $T_{\text{pulse duration}} = 30.0$, and all other curves are simulated by adding different TOD to this curve. These curves show that, with constant TOD, the pulse duration strongly relies on
chromatic dispersion. Depending on the value of chromatic dispersion, the pulse duration becomes either shorter or longer when TOD is considered. In large normal dispersion region ($D < \sim -1.5$), the pulse duration ($T_{\text{pulse, duration}}$) is slightly increased by TOD. Decreasing of $T_{\text{pulse, duration}}$ occurs in the range of $\sim -1.5 < D < 0.05$. The most significant drop in pulse duration occurs at $D = -0.46$, where the pulse duration falls down from 30 to 5.6 as $\beta_3$ increases from 0 to 0.015. When $D > 0.05$, TOD always leads to longer pulse. In the vicinity of $D \approx 0.26$ as well as the region of $D \gg 0$, TOD leads to a dramatic increase of the pulse duration. This trend is particularly remarkable in the large anomalous dispersion region ($D \gg 0$).

Figure 5 also indicates that, with constant chromatic dispersion $D$, the pulse duration shows either a monotonous increase or decrease. For better clarity, two typical results are presented in Fig. 6. Figure 6(a) shows the pulse profiles of DSR with different TOD ($\beta_3 = 0, 0.005, \text{ and } 0.010$) at the point of ($D = 2.5, \varepsilon = 0.450522$), and Figure 6(b) shows the corresponding evolution of pulse duration as a function of $\beta_3$. In this case, $T_{\text{pulse, duration}}$ rapidly increases from 30.0 to 54.1 when $\beta_3$ slightly increases from 0 to 0.0235. A typical feature of Fig. 6(b) is that the rate of increase in pulse duration speeds up as $\beta_3$ increases. Remarkably, when $\beta_3 > \sim 0.023$, $T_{\text{pulse, duration}}$ rises sharply as a function of $\beta_3$. Similar trend is also presented from Fig. 2(b). When TOD leads to the decrease of pulse duration, the situation becomes slightly different. Figure 6(c) and 6(d) shows the simulation results at ($D = 0, \varepsilon = 0.408982$), where $T_{\text{pulse, duration}}$ continuously decreases from 30.0 to 4.4 when $\beta_3$ increases from 0 to 0.1.

In the above analysis, the role of TOD is only investigated for DSR with pulse duration $T_{\text{pulse, duration}} = 30.0$. However, the pulse duration of DSR is proportional to nonlinear gain $\varepsilon$. When $\varepsilon$ is small enough, the DSR will evolve into dissipative soliton regime, which is characterized by a Gauss pulse profile and small pulse energy relative to DSR [7]. Therefore, it is
important to know how the TOD alters the relationship between pulse duration and nonlinear gain. Figure 7(a) shows the evolution of the pulse duration $T_{\text{pulse duration}}$ as a function of nonlinear gain $\varepsilon$ under three different TOD ($\beta_2 = 0$, 0.005, and 0.010), where $D$ is set to 2.5. In this plot, regardless of the value of TOD, $T_{\text{pulse duration}}$ continuously increases with the increase of $\varepsilon$, and the increase speed ($\partial T_{\text{pulse duration}}/\partial \varepsilon$) is accelerated gradually. The pulse duration at $\beta_2 = 0$ is always longer than the case of $\beta_2 = 0$, and higher $\beta_2$ leads to longer pulse duration. The change ratio of pulse duration in term of TOD is described by using:

$$\eta_{\text{pulse duration}} = \frac{T_{\text{pulseduration with TOD}} - T_{\text{pulseduration without TOD}}}{T_{\text{pulseduration without TOD}}}$$

where $T_{\text{pulseduration with TOD}}$ and $T_{\text{pulseduration without TOD}}$ are pulse duration of soliton solution with $\beta_2 = 0$ and $\beta_2 \neq 0$, respectively. Figure 7(b) shows the variation of $\eta_{\text{pulse duration}}$ as a function of $\varepsilon$ under different TOD, where $\eta_{\text{pulse duration}}$ increases with the increase of $\varepsilon$, indicating that the pulse duration is increasingly dependent on TOD as nonlinear gain increases.

IV. CONCLUSION

In conclusion, we numerically investigate the impact of TOD on DSR in both anomalous and normal chromatic dispersion regions. The simulations demonstrate that TOD is an important factor for the pulse duration and thus pulse energy of DSR, regardless of the sign of TOD. In some chromatic dispersion region, TOD leads to rapid decreasing of pulse duration. However, when chromatic dispersion is appropriately set, TOD leads to a longer pulse duration and higher pulse energy. Particularly, in large anomalous dispersion region, even weak TOD can leads to dramatic increase in pulse duration. This perhaps answers the frequent reports of DSR generation based on mode-locked fiber lasers consisting of long anomalous chromatic dispersion fibers (hundred meters), which leads to the accumulation of a large amount of TOD [2], [6]. Under constant chromatic dispersion, the pulse duration is increasingly dependent on TOD as the nonlinear gain increases. Another notable effect is that TOD leads to an asymmetric profile of DSR. As a result, the leading and trailing pulse edges show different steepness. The edge steepness caused by TOD varies as a function of chromatic dispersion. In the vicinity of near zero anomalous chromatic dispersion, the DSR shows highly steepened pulse edges which is insensitive on TOD effect, but the pulse duration can be remarkably longer if TOD is introduced, which facilitates the generation of DSR with higher pulse energy and steeper pulse edges.

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