

Gain dependent pulse regimes transitions in a dissipative dispersion-managed fibre laser

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Abstract: It is found that three distinct pulse regimes can be switched in a dissipative dispersion-managed (DM) fibre laser. A simulation based on nonlinear Schrödinger equation shows the transitions between Hyper-Gaussian similaritons, parabolic similaritons, and dissipative solitons in the same laser for the first time, by solely controlling the gain saturation energy. It is also shown that such transitions exist in a wide dispersion range from all-normal to slightly net-normal dispersion. This work demonstrates that besides dispersion and filter managements gain saturation energy can be a new degree of freedom to manage pulse regimes in DM fibre lasers, which offers flexibility in designing ultrafast fibre lasers. Also, the result indicates that in contrast to conservative soliton lasers whose intensity profiles are unique, dissipative DM lasers show diversity in pulse shapes. The findings not only give a better understanding of pulse shaping mechanisms in mode-locked lasers, but also provide insight into dissipative systems.

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OCIS Codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers.

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1. Introduction

Passively mode-locked fibre lasers have been extensively studied since their first realization in 1992 [1, 2], as they are not only scientifically interesting but also can be an attractive source for practical applications. These lasers can work on different regimes mainly determined by dispersion. Solitons[3, 4] are formed when anomalous dispersion is balanced by nonlinearity in a laser. When a laser has all-normal or strong net-normal dispersion, solitons do not exist, however interplay between gain, loss, dispersion and nonlinearity can also generate stable pulses. In contrast to soliton lasers, these lasers are highly dissipative as dissipative effects such as spectral filtering play an important role in the pulse formation[5]. The resulting dissipative solitons (DSs) in these lasers can have peak power and energy at least an order of magnitude greater than those of solitons which are limited by the soliton area theorem or peak power clamping in saturable absorber (SA) [6]. Solitons propagate nearly unchanged inside a cavity, naturally meeting the self-consistent condition of a laser. DSs are not static and experience changes especially in normal-dispersion components, as a result, spectral filtering is required to reverse these changes. Spectral filtering can be realized by introducing a filter inside a laser directly, or from the spectral filtering effect of SA as DSs are highly chirped temporal shortening also cuts away the blue and redshifted spectral components in pulse wings. Besides DSs, amplifier similaritons which rely on a local nonlinear attractor can also be generated in normal-dispersion fibre lasers[7]. They were firstly observed in an amplifier[8]. A normal-dispersion amplifier can shape pulses to be parabolic similaritons independent of input pulse profiles. Similaritons which have linear chirp can tolerate large nonlinear phase without wave breaking. A filter is generally needed to ensure similariton propagation in a similariton laser; otherwise the limited gain bandwidth disrupts the self-similar evolution[7]. The amplifier similaritons can be decoupled from average cavity parameters; for instance, they can be generated even in anomalous-dispersion regime[9], as they rely on a local nonlinear attractor. In contrast, the formation of passive similaritons[10] which evolve self-similarly in passive fibres and are reversed by a dispersive delay line, depends on average cavity parameters[11]. In addition to parabolic similaritons, it was found recently that Hyper-Gaussian (HG) similaritons can be stimulated in a nonlinear attractor when the amplifier gain is small[12]. The existence of HG similariton in a laser is yet to be demonstrated.

Although various pulse regimes are discovered in mode-locked lasers, their coexistence in a single set of cavity parameters, i.e., a single laser was rarely observed. A prior study demonstrated that soliton and similariton can be emitted at different positions of the same laser [13]; another experiment showed that Gaussian-like pulses, similaritons and DSs can be switched in a laser by carefully adjusting the gain saturation energy (pump power) [14]; a corresponding numerical study is yet to be demonstrated. Recently, a numerical study showed that passive similaritons and stretched DSs which evolve mostly monotonically in each segment as in a self-similar laser but the variation of the pulse duration is reversed, coexist in the same laser [11]; also, transition between Gaussian pulses and similaritons was implied in another numerical study [15].

Here, we show that three different pulse regimes including HG similaritons, parabolic similaritons and DSs can be targeted in a single laser by solely controlling the gain saturation energy, through the results of numerical simulations. **The numerical results agree qualitatively with prior experimental observations.** To the best of the author's knowledge, here for the first time the existence of an HG similariton in a laser cavity is confirmed, following its discovery in an amplifier [12]. It is also found that such transition exists in a large dispersion range. **The influence of the gain profile is also studied.** Coexistence of distinct pulse regimes in a single laser allows us to reveal the relations between them and compare them. A roadmap to access desired pulse regime becomes clear in a dissipative DM fibre laser, which is crucial for the design and applications of ultrafast fibre lasers.

2. Simulation model

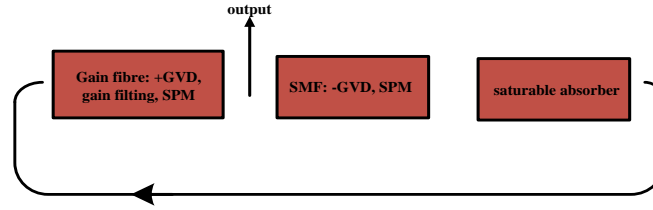


Fig. 1. Schematic of the dissipative DM fibre laser.

The laser setup is shown in Figure 1 including **gain Erbium-doped fibre (EDF)**, output coupler, single-mode fibre (SMF) and SA, which is similar to a realistic laser [14]. Simulation is performed with commercially available software based on the split-step Fourier method[16]. Pulse propagation within the fibre sections was modelled with a standard modified nonlinear Schrödinger equation for the slowly varying pulse envelope:

$$\frac{\partial A}{\partial z} = -\frac{1}{2}(i\beta_2) \frac{\partial^2 A}{\partial \tau^2} + i\gamma |A|^2 A + gA$$

Here, the gain in EDF is described by $g = g_0 \exp(-E_p / E_s)$, where $g_0 = 23/\text{m}$ corresponds to the small signal gain, **which is non-zero only for the gain fibre**, E_p and E_s are the pulse energy and the gain saturation energy. E_s can be changed by pump power in experiment. **The gain is taken to have a Gaussian shape with a bandwidth of 40 nm.** β_2 is second-order group-velocity dispersion (GVD) dispersion. The EDF (OFS) has normal dispersion, the GVD of which is $0.0634 \text{ ps}^2/\text{m}$; SMF (Corning SMF-28) has negative GVD which is $-0.023 \text{ ps}^2/\text{m}$. γ is **nonlinear fibre coefficient**. The nonlinear parameters of EDF and SMF are 0.0066 and $0.00165 \text{ (Wm)}^{-1}$ respectively. **It is to note that nonlinear polarization rotation (NPR) was used to mode lock the laser in [14]. In the simulation, NPR is replaced by SA the transmission function of which is given by $T(\tau) = R_0 + \Delta R(1 - 1/(1 + P/P_0))$ where $R_0 = 10\%$ is the unsaturable reflectance, $\Delta R = 90\%$ is the saturable reflectance, P is the pulse instantaneous power, P_0 is the saturable power which is 400 mW .** The output coupling is 90% as the experiment. In the simulation, firstly, the lengths of EDF and SMF used are the same as the experiment [14], which are 2.5 and 4.7 m respectively to find the transitions between different pulse regimes, as well as the pulse evolution along the cavity. Then, the length of SMF is varied while that of EDF is fixed to find the dispersion range in which this transition behavior exists. The initial field conditions are the same for all the simulations here, which is a 1 ps sech pulse with energy of 10 pJ . **It takes around 100 round trips before the evolution of HG**

similariton stabilizes, and about 300 round trips to form stable parabolic similaritons and DSs. Unless otherwise notified, the parameters used in the simulation are the ones mentioned above.

3. Results

3.1 Transitions between different pulse regimes

It is well known that normal-dispersion gain fibre can work as a nonlinear attractor which forces pulses of different initial shapes to form amplifier similaritons[8, 17]. However, it was shown recently that the dimensionless saturation energy $\eta_s = \gamma E_s / \sqrt{g_0 \beta_2}$ has to be greater than some critical value to generate amplifier similariton in a nonlinear attractor[12]. The input pulses converge to a new type of self-similar linearly chirped pulses in the nonlinear attractor, when η_s is smaller than the value, which means nonlinearity in the amplifier plays a minor role here. The pulse shape is a product of Gaussian and super-Gaussian function and was termed as HG similaritons[12]. The dimensionless saturation energy depends on E_s which is the gain saturation energy. Therefore, by scaling E_s it is possible to see switching between HG and amplifier similaritons in a laser.

Indeed, such transition was observed in the simulation. First, the simulation was run under small gain saturation energy and HG similariton was found. As an example, Fig. 2 (a) shows a typical HG pulse intensity (red solid) when E_s is 0.3 pJ; Hyper-Gaussian (green dashed) and Gaussian (blue) fitting are also shown for comparison in the figure. As seen, the pulse is much closer to Hyper-Gaussian fitting. HG similariton has reduced pulse wings due to the contribution of super-Gaussian function. Linear chirp of HG similariton is also confirmed. Fig. 2 (a) also shows the pulse chirp (black solid) and a linear fit (pink dashed); it can be seen that the chirp is linear across the pulse though some deviations are present in the wings. The corresponding spectral profile (black solid) and Gaussian fitting (red dashed) are shown in Fig. 2 (b). For HG similaritons, the pulse duration increases monotonously in the gain fibre[12]. To confirm this, the pulse duration and spectral bandwidth evolution of HG similariton in each segment of the laser are also studied, as shown in Fig. 3 (a). As it can be seen, the pulse duration (black) increases in EDF, and is compressed by SMF; it differs from stretched pulses which stretch and compress twice per cavity round-trip[18]. The spectral bandwidth follows nearly the same evolution in the cavity as seen in the blue curve. As mentioned, nonlinearity in the amplifier plays a minor role in HG similariton generation. To further confirm this, nonlinearity is set to be zero in EDF, and HG similariton can still be observed.

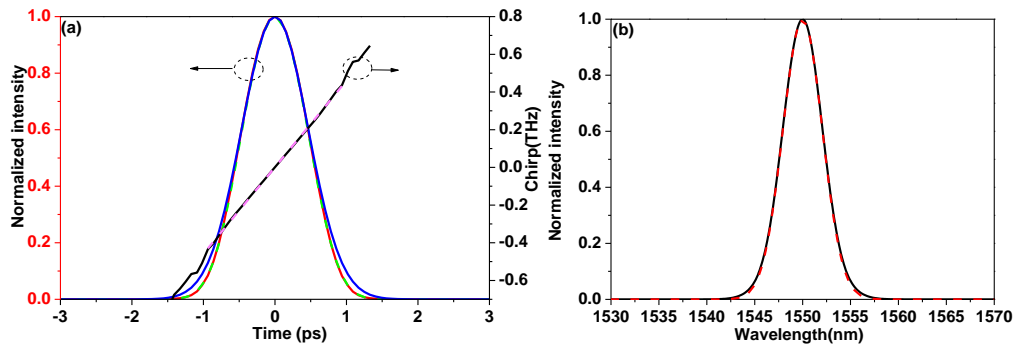


Fig. 2. (a) The temporal profile of the HG similariton obtained in simulation (red solid) with Hyper-Gaussian (green dashed), Gaussian (blue solid) fit and the pulse chirp (black solid) with linear fit (pink dashed); (b) the spectrum of HG similariton (black solid) and Gaussian fitting (red dashed).

In addition to the HG similariton, the amplifier similariton was also observed by solely increasing E_s in accordance with the discussion above, while other parameters were kept the same as before in the simulation. Fig. 4 (a) shows the temporal intensity of the amplifier similariton (red) and parabolic fit (green), when E_s is 1.7 pJ which is ~ 6 times of that for HG similariton generation. It can be seen that the pulse is well fitted by parabolic function. The pulse shape can also be characterized via a measure of its kurtosis [15, 19]. For example, Gaussian pulse shape has a pulse kurtosis of 0, and parabolic one has a value of -0.86. Here, the pulse kurtosis has an exact value of -0.86. Linear chirp of the pulse is also confirmed, which can be from the black curve in Fig. 4 (a) and its linear fitting (pink dashed). Fig. 4 (b) shows the corresponding spectrum. Fig. 3 (b) shows the pulse duration and spectral bandwidth evolution inside the laser. Both of them increase monotonically in the EDF, which are characteristics of an amplifier similariton fibre laser[7, 11].

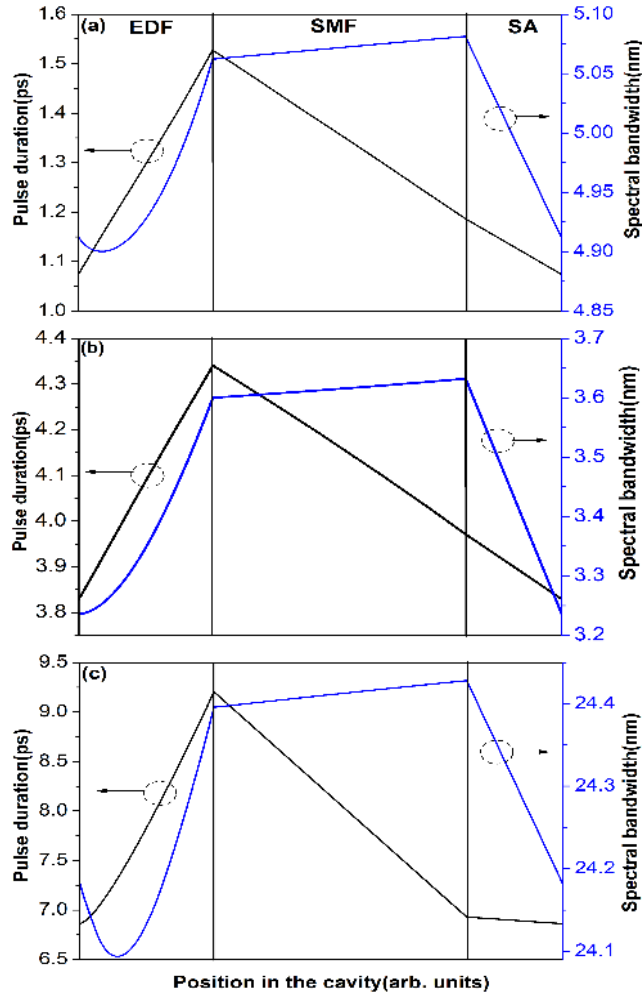


Fig. 3. Evolution of the pulse duration (black) and spectral bandwidth (blue) of HG similariton (a), parabolic similariton (b) and DS (c).

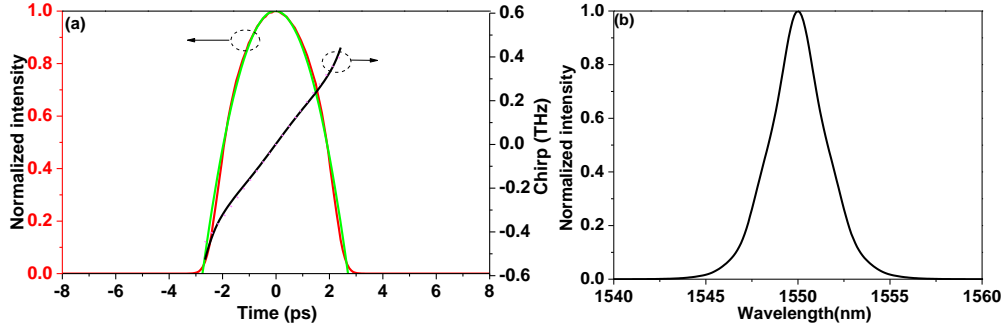


Fig. 4. (a) the temporal profile of the parabolic similariton obtained in simulation (red solid) with parabolic fitting ((green solid)), and the pulse chirp (black solid) with linear fit (pink dashed); (b) its spectrum.

When the gain saturation energy is increased, the pulse gradually deviates from parabolic shape and the spectrum becomes more squared; finally, DS regime is accessed which is characterized by its unique spectral shape that is steep at edges and has a dip in the top [5]. Fig. 5 (a) shows an example of DS spectrum at a gain saturation energy of 38 pJ. Evolution of pulse duration and spectral bandwidth of DS is shown in Fig. 3 (c). As it can be seen, in the first segments of the EDF, gain filtering effect dominates and the spectral bandwidth decreases. Owing to increasing peak power, SPM becomes dominant, leading to spectrum broadening in the rest of EDF. Similar spectrum evolution was also observed in Ref. [20]. Such evolution is very different from that of parabolic similariton: the spectral bandwidth of the parabolic similariton is much smaller than the gain bandwidth of EDF, thus gain filtering has negligible effect. Therefore, transition from the amplifier similariton to DS is due to the gain filtering effect. An infinite bandwidth of gain is required for amplifier similariton generation in a nonlinear attractor [17]. The bandwidth of EDF can be treated as infinite when the pulse spectral width is small. However, when the spectral width of similariton approaches the gain bandwidth of EDF by harder pumping, similariton generation is challenged and DS is generated instead. If the gain bandwidth of EDF is increased, amplifier similariton can exist under higher pump power, which was also confirmed by the simulation. Therefore, the maximum spectral bandwidth of similariton is limited by the gain bandwidth of EDF, which in turn restricts the minimum duration of the dechirped pulse; however it can be increased by Raman gain [21] or adding a separate nonlinear segments in a similariton laser [22].

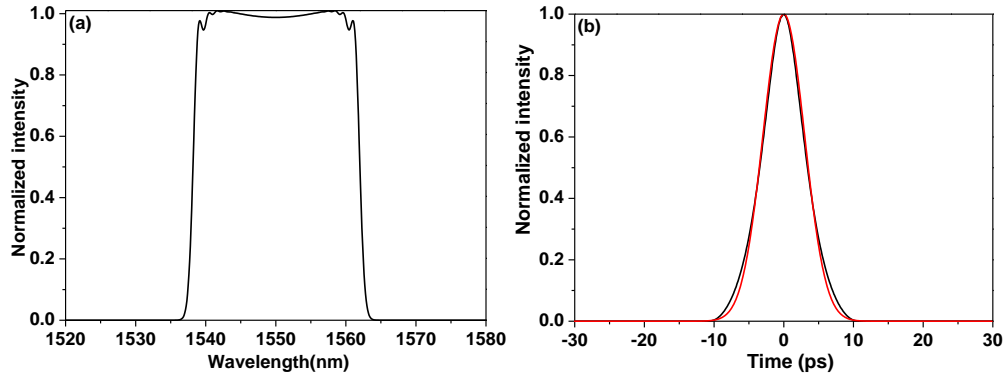


Fig. 5. (a) the spectrum of DS; (b) its temporal intensity (black) and Gaussian fitting (red).

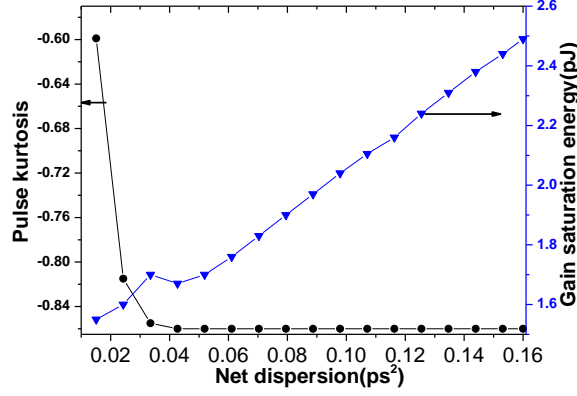


Fig. 6. Pulse kurtosis (black circles) and the corresponding gain saturation energy (blue triangle) under net dispersion variation.

3.2 Transitions dependence on dispersion

It is of great importance to know the dispersion range in which such transition happens. This was studied by varying the length of SMF from 7.1 to 0 m (0 m corresponding to all-normal dispersion) at intervals of 0.4 m which corresponds to dispersion variation from -0.0033 to 0.16 ps² at intervals of ~ 0.01 ps². The length of EDF and SA parameters were kept the same as the previous values while the gain saturation energy was changed. It was found that this behavior exists in a large dispersion range. In the dispersion regimes where parabolic similaritons exist, HG similariton and DSs can be found by decreasing and increasing gain saturation energy respectively. Fig. 6 (black circles) shows that pulse kurtosis with an exact value of -0.86 can be found in the dispersion range from 0.043 to 0.16 ps². It means that parabolic similaritons exist in this dispersion range, which is also confirmed by checking their intensity profiles. Fig. 6 (blue triangle) shows the corresponding gain saturation energy required for obtaining the pulse kurtosis in the figure. The gain saturation energy required for generating parabolic similaritons increases as the dispersion becomes stronger. As seen in the figure when the net dispersion is decreased from 0.043 ps², an exact value of -0.86 is no longer possible, which means parabolic similaritons do not exist in this dispersion range (0.015 - 0.034 ps²). This is due to the fact that smaller dispersion gives rise to wider spectrum which challenges amplifier similariton formation in the nonlinear attractor. However, DSs and HG similaritons can still exist in this range. Further decreasing the net dispersion to -0.0033 ps² corresponding to 7.1 m SMF will access the well-known stretched-pulse (DM soliton) regime where the pulse compresses and stretches twice per cavity round-trip, which features DM soliton evolution. In fact, DM soliton appears at a dispersion of 0.0013 ps² corresponding to 6.9 m SMF. Parabolic similaritons and DSs are no longer possible when DM solitons are observed.

3.3 The influence of the gain profile

The above results are obtained by using Gaussian gain profile. This profile has been used widely to model the gain profile of active fibres in the simulation study of passively mode-locked fibre lasers, and it shows validity in the field. Nevertheless, further simulations were performed to investigate the influence of the gain profile, by using parabolic and Lorentz gain shapes while the gain bandwidths are the same as that used in the Gaussian gain. Table 1 shows the pulse parameters and the gain saturation energy needed to access different pulse regimes under different gain profiles. As seen in the table, there are nearly no differences in HG or parabolic similariton regime between different gain profiles. The spectral widths of HG or parabolic similaritons is less than 5 nm, which is almost an order of magnitude smaller than that of the gain bandwidth (40 nm), therefore, the gain shape has no effect on the formation of

HG or parabolic similaritons. However it influences the parameters of DSs, as the spectral width of DSs shown in Tab. 1 (>20 nm) approaches the gain bandwidth. Unlike HG and parabolic similaritons, the simulation shows that (not shown here) the DS duration decreases as the gain saturation energy increases: as DSs are largely chirped, the pulse front and tail contain redshifted and blueshifted spectral components respectively, and the limited gain bandwidth of EDF works as a filter (or in other words, gain filtering) to cut these spectral components resulting in shortening the pulse duration. This relationship was experimentally observed in a DS fibre laser, as shown in Fig. 4 of Ref. The Lorentz profile has much stronger wings than Gaussian and parabolic ones, which means it has weaker gain filtering effect than the other two. As a result, the DS has longer temporal duration when Lorentz gain profile is used, as seen in Tab. 1. Thus, it can be concluded that such transitions do not depend on the gain profile while it only influences the parameters of DSs.

Tab. 1. The pulse parameters and the gain saturation energy needed to access different pulse regimes under different gain profiles

Gain profile	HG similaritons			Parabolic similaritons			DSs		
	Pulse width (ps)	Spectral width (nm)	E_s (pJ)	Pulse width	Spectral width	E_s	Pulse width	Spectral width	E_s
Gaussian	1.073	4.913	0.3	3.827	3.236	1.7	6.860	24.184	38
Parabolic	1.085	4.895	0.3	3.903	3.150	1.7	9.295	23.293	45
Lorentz	1.103	4.865	0.3	4.007	3.407	1.7	18.626	21.923	75

4. Discussion

As shown, three different pulse regimes exist in a dissipative DM fibre laser. The output of the laser depends strongly on the gain saturation energy. The laser emits HG similaritons when nonlinearity is weak in the gain fibre, which means nonlinearity does not account for its formation; when nonlinearity comes to play by increasing the gain saturation energy, the well-known nonlinear attractor effect shapes the pulse to form parabolic amplifier similaritons; then self-similar evolution is disrupted as the spectral bandwidth approaches the gain bandwidth of the gain fibre and DS is generated instead. These numerical results confirm previous experimental findings [14]. In [14], Gaussian-like pulses were found under low pump power; similaritons and DSs were observed when the pump power was increased. In the simulation, gain saturation energy plays the same role as pump power in experiments. Similar to the experiment, the simulation also shows that the HG similariton is generated under small gain saturation energy and parabolic similaritons and DSs are formed when the gain saturation energy is increased. Although the Gaussian-like pulse is assumed to be DM solitons (stretched pulses) in [14], here the simulation confirms that the pulse is actually the HG similariton as discussed above (Section 3.1). This versatile laser can find applications where pulse shape manipulation is needed. For example, in optical communications, pre-processing for the input signal into a particular DM system is essential to obtain the exact periodic DM soliton [23]. Power and pulse duration can be easily controlled. However, modulating the pulse shape is complicated and often involves expensive optical elements. For practical DM systems it is important to achieve DM soliton pulse evolution from a wide variety of input pulse forms. Although spectral filter plays an important role in amplifier similariton [7] and DS generation[5], as shown here, it is not necessary in a dissipative DM fibre laser. SA can work as a filter as temporal shortening of large-chirp pulses also induces filtering effect, which can be seen in the spectral bandwidth evolution in Fig. 3. Therefore, the laser configuration is simplified.

5. Conclusion

In conclusion, we have reported the coexistence of different mode-locking regimes in dissipative DM fibre lasers by a numerical study. Different pulse regimes can be easily accessed by pump power scaling. Distinctive pulse regimes are guided by different mechanisms which are clearly revealed by the numerical results. The dispersion range supporting this switching behavior is also studied, which is found to be from all-normal to slightly net-normal dispersion. The work not only presents the relations between different pulse regimes, but also proposes a promising functional ultrafast fibre laser in which multi-shape pulses are available.

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