# Dark and bright pulse passive mode-locked laser with in-cavity pulse-shaper


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**Abstract:** We demonstrate the integration of a spectral pulse-shaper into a passive mode-locked laser cavity for direct control of the output pulse-shape of the laser. Depending on the dispersion filter applied with the pulse-shaper we either observe a bright or dark “soliton-like” pulse train. The results demonstrate the strong potential of an in-cavity spectral pulse-shaper as an experimental tool for controlling the dynamics of passively mode-locked lasers.





**OCIS codes:** (060.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (190.5530) Pulse propagation and temporal solitons; (190.4380) Four-wave mixing.


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## 1. Introduction

Passive mode-locked lasers have been the subject of considerable research interest for several decades. In general they rely on nonlinear processes to achieve the mode-locking and thus can yield ultra-short pulses and ultra-high repetition rates, that are not achievable with active mode-locking techniques which are limited by the bandwidth of the mode-locking electronics. For this reason they have found applications in a variety of fields ranging from terahertz generation [1], to metrology [2] to nonlinear spectroscopy [3]. Recently, passive mode-locked fibre lasers that take advantage of self-similar propagation and all-normal cavity dispersion have received significant attention, due to their ability to strongly improve the output pulse energy of these lasers [4, 5, 6, 7], promising relatively cheap and compact high pulse energy sources. Another intriguing aspect of passive mode-locked lasers is their ability to yield repetition rates in excess of hundreds of GHz [8, 9, 10], a fact which can prove advantageous for pulse sources for optical time-division multiplexing, the generation of THz radiation and spectroscopy applications. In addition to their use as pulse sources for applications in numerous fields, passive mode-locked lasers are of interest from a fundamental standpoint, as a model to study the dynamics of dissipative systems and effects such as soliton explosions [11] and soliton molecules [12] have been observed in mode-locked laser systems.

Passively mode-locked fibre lasers thus far have been relatively limited in terms of their reconfigurability. In general if a different output pulse-shape, a different pulse-width or repetition rate is desired it involves a significant change to the cavity, often this means a total redesign

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of the cavity to the new output parameters. A higher degree of control over the output parameters of passive mode-locked lasers to adjust the laser for different experimental requirements is therefore highly desirable.

Spectral pulse-shaping [13] is a technique which employs spectral filtering of phase and intensity to create a desired temporal field distribution from the output of a mode-locked laser. It has been highly successful for applications in a number of fields [14, 15]. However as it is placed outside of the laser cavity its control of the laser field is limited; the repetition rate of the laser remains fixed, the bandwidth of the filtered spectrum is determined by the bandwidth of the input spectrum and manipulation of the in-cavity dynamics of a laser is not possible.

We recently demonstrated the inclusion of a pulse-shaper into the cavity of a passive mode-locked fibre laser [16], allowing us to tune the repetition rate and wavelength of the laser between 40 and 640 GHz and 1540 nm and 1560 nm respectively. In this paper we show, that by taking advantage of the phase filtering ability of the in-cavity pulse-shaper we can directly control the laser dynamics in order to vary the output pulse-shape. By applying various parabolic phase profiles to the filter we are able to precisely change the cavity dispersion of the laser, yielding unprecedented control over the shape of the output pulse-train. With appropriate dispersion values we can create either dark or bright output pulses as well as optimize the pulse width. These results are particularly significant in light of the recent interest in "dark soliton" lasers [17, 18]. Our results present the first mode-locked laser which can be tuned to emit either dark or bright pulses, demonstrating the strong potential of in-cavity pulse-shaping as an experimental tool for controlling the dynamics of passively mode-locked lasers.

The mode-locking mechanism in our experiment is a close relative of the modulation instability laser [19, 20, 21], so-called dissipative four-wave mixing (DFWM). It relies on spectral filtering and fiber-nonlinearity [22] to yield a pulse train with the repetition rate and center wavelength determined by the spectral filter. Thus by combining this mode-locking technique with a reconfigurable spectral filter it is possible to tune both the wavelength and repetition rate. A further advantage of this mode-locking technique is that it greatly facilitates mode-locking at very high harmonics which let to several publications achieving hundreds of GHz [23, 24, 25]. In this article we take advantage of the capability of our in-cavity pulse-shaper to perform dispersion trimming [26]. This allows us to precisely control the cavity dispersion of the laser, enabling the variation of the output pulse-shape.

## 2. Experiment

The laser setup is depicted in Fig. 1. It consists of a ring cavity with a commercial erbium-

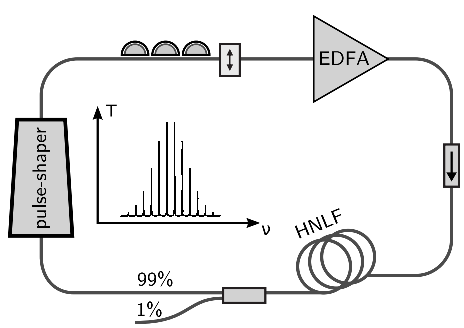


Fig. 1. Experimental setup. EDFA: erbium-doped fiber amplifier, HNLF: highly nonlinear fiber.

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doped fiber amplifier (EDFA) as the gain medium. 33 m of highly nonlinear fiber (HNLF) provide the nonlinearity for the four-wave mixing which enables the mode-locking. The pulse-shaper (Finisar WaveShaper) functions as the spectral filter exhibiting a Fabry-Perot (FP) type transfer function with a Gaussian envelope (inset in Fig. 1) and an optical isolator ensures the unidirectional operation of the ring. The wavelength and repetition rate of the laser are controlled by changing the free spectral range (FSR) and center wavelength of the FP and Gaussian bandpass filter functions inside the pulse-shaper. An additional parabolic spectral phase filter in the pulse-shaper adds a specific amount of group-velocity dispersion to the cavity. By varying the curvature of this filter we can precisely control the overall cavity dispersion of the laser. In all the presented experiments the FSR and bandwidth of the bandpass filter were kept constant at 160 GHz and 2.5 times the FSR respectively and only the curvature of the parabolic phase filter was varied. The output of the laser is characterised with an optical spectrum analyser (OSA) and a second-harmonic generation frequency resolved optical gating (SHG-FROG) device.

Figure 2 illustrates the effect of the pulse-shaper dispersion variation on the output of the laser. The top and middle and bottom rows depict the OSA traces, FROG spectrograms and

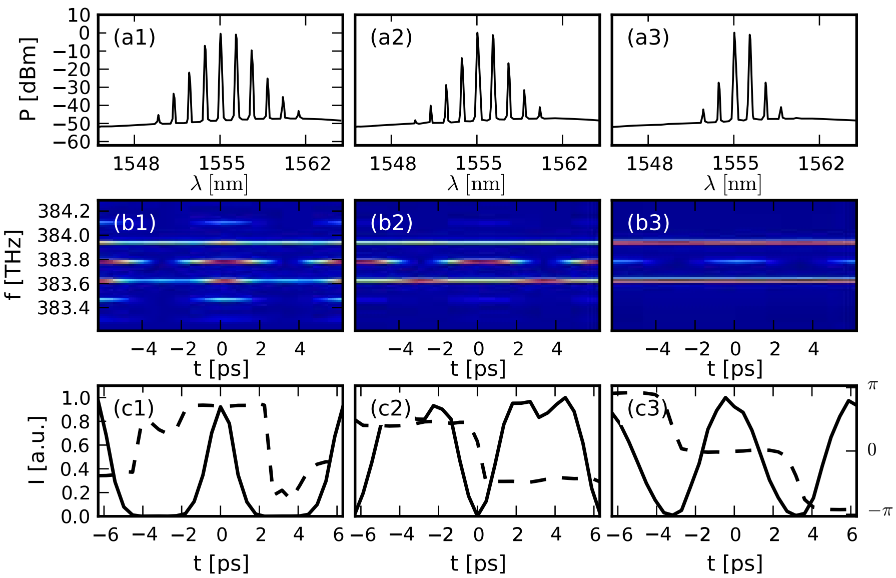


Fig. 2. (a) Optical spectra, (b) FROG spectrograms and (c) recovered field intensity (solid) and phase (dashed) for dispersion values (1) $\beta_2 L = 0.4$ ps$^2$, (2) $\beta_2 L = 0.5$ ps$^2$ and (3) $\beta_2 L = 0.8$ ps$^2$.

recovered fields of the laser for pulse-shaper dispersion values of (1) $\beta_2 L = 0.4$ ps$^2$, (2) $\beta_2 L = 0.5$ ps$^2$ and (3) $\beta_2 L = 0.8$ ps$^2$ respectively. It should be noted that the value for the overall cavity dispersion is not known, due to the dispersion of the EDFA, which is only known to be slightly normal, and an unknown length of standard SMF inside the pulse-shaper. However as the cavity contains about 15-20 m of standard SMF (the exact value is unknown due to the length inside the pulse-shaper), some normal dispersion EDF and 30 m of slightly anomalous dispersion HNLF ($\lambda_0 \approx 1551$ *nm*), the average dispersion of the cavity should be between $-0.3$ and $-0.6$ ps$^2$. The optical spectra and FROG spectrograms clearly reveal a change of the output pulse-shape when the dispersion is varied across the point of zero average dispersion.

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This is confirmed by the field which is recovered from the FROG spectrograms using the principle components generalized projections (PCGP) algorithm [27, 28] with a constraint given by the experimental optical spectrum (the error was below $8 \times 10^{-4}$ in all cases). The output pulses change from a low duty cycle bright pulse-train (c1) to a train of dark pulses (c2) to an output similar to a sinusoidal beating (c3). The pulses exhibit characteristics similar to a train of solitons, i.e. a $\pi$-phase shift in between bright pulses and across the pulse for dark pulses. It should be noted that some of the recovered pulses display subpulsing and peak power variations, it is not clear if these are artefacts of the recovery or caused by supermode noise in the laser [29].

## 3. Simulations

To further understand the laser behaviour we performed numerical simulations with a model based on the generalized nonlinear Schrödinger equation (GNLSE) [29]:

$$\frac{\partial}{\partial \zeta}U + i\kappa \frac{\partial^2}{\partial \tau^2}U = i|U|^2 U + \frac{G}{1+\frac{Q}{I_S}}U - \frac{\alpha}{2}U \quad (1)$$

Here $\kappa = \frac{\beta_2 f^2 L}{2}$ is the normalised second order dispersion, with $f$ being the repetition rate and $L$ the cavity length. $Q$ is the average power, $I_S$ the saturation power, $G$ the cavity gain and $\alpha$ the propagation loss parameter. Cavity gain and gain saturation were kept constant at $G = 0.8$, $\alpha = 0.4$ and $I_S = 1.1$ while the second-order dispersion $\kappa$ was varied from -0.5 to 0.5. We used the split-step Fourier algorithm in a cavity configuration to simulate the laser. Once per round-trip the field is multiplied by a loss term of $l = \sqrt{1-0.25}$ accounting for the localised loss due to the output coupler and the pulse shaper, and by a spectral filter corresponding to a FP-filter with a mirror reflectivity of 0.9 multiplied with a Gaussian bandpass filter at 2.5 times the FSR of the FP-filter. Note that we did not account for supermode noise in the system (20 cavity modes per FSR) [29].

Figure 3(a) depicts the duty cycle of the output pulse train as a function of normalised dispersion $\kappa$. The figure clearly demonstrates the pulse-shape transition from dark to bright pulses

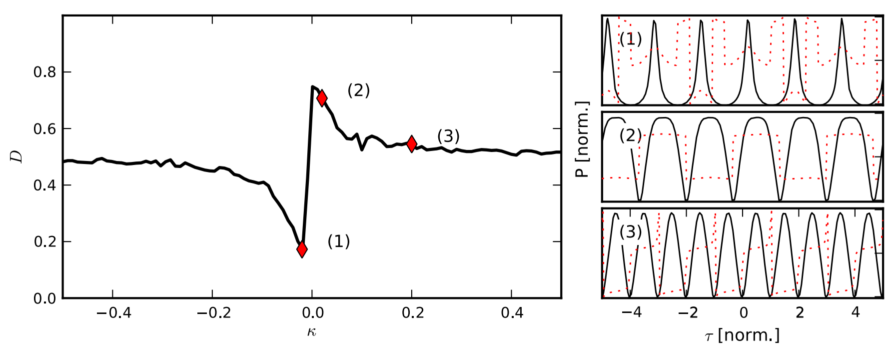


Fig. 3. (a) Duty cycle as a function of normalized dispersion $\kappa$. (b) Field intensity (solid), and phase (red, dotted) for the points 1,2,3 indicated in (a).

around the zero-dispersion point of the cavity. At high anomalous dispersion the duty cycle is very close 0.5, which gradually decreases before a transition at zero-dispersion to a duty cycle of $\approx 0.8$, corresponding to dark pulses. Upon further increasing the dispersion the duty cycle slowly decreases again approaching a value of 0.5. Note that we subtracted any cw-background

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on the pulse trains for an accurate comparison. The field intensity and phase of the output pulse train at three different values of the dispersion as shown in Fig. 3(b) nicely confirm the notion of bright and dark pulses and the agreement with the experimentally recovered fields is very good. As in the experiment we see that the pulses exhibit a solitonic nature, i.e. a $sech^2$ intensity profile and a $\pi$-phase jump between pulses for the bright pulses and a $tanh^2$ profile and a $\pi$-phase jump in the middle of the dark pulses. To further compare the numerical with the experimental results we computed the spectrogram for the three different output fields from Fig. 3(b). The resulting spectrograms are shown in Fig. 4(b1)–(b3), for ease of comparison we

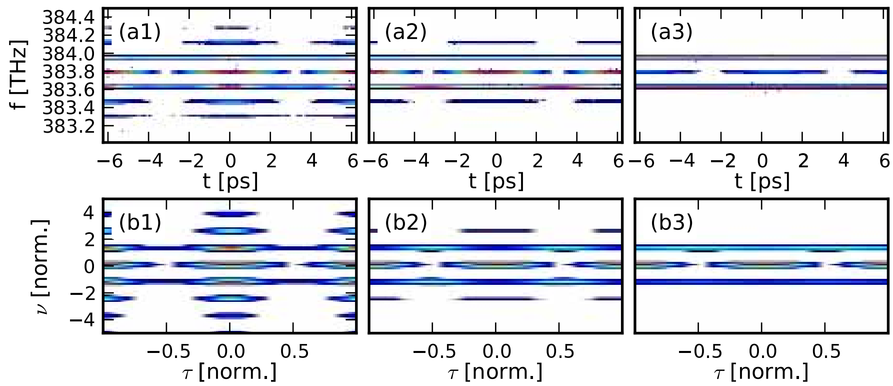


Fig. 4. Comparison of (a) experimental and (b) numerical FROG spectrograms for the dispersion values given in Fig. 2 and Fig. 3 respectively (spectrograms have been thresholded for better clarity).

have again included the experimental spectrograms [Fig. 4(a1)–(a3)] and plotted only above a threshold value. The qualitative agreement between experimental and simulated traces is very good. In particular we would like to point out a number of key features; The spectrograms for the bright pulses [(a1) and (b1)] show a number of higher harmonic frequency modes around the fundamental mode at the center of the frequency axis. Moreover all the maxima of the modes are aligned, i.e. they occur at the same time. This is the characteristic of a pulse train of short bright pulses, as seen in field intensity in Fig. 3(b1) and the recovered field in Fig. 2(c1). On the other hand the first-order harmonic modes around the central mode in the experimental spectrogram (a2) and the numerical one (b2) are $\pi$ out-of-phase with the fundamental modes along the time axis, i.e. the time of their maxima coincides with the minima of the fundamental mode. The next higher-order modes are again in-phase with the fundamental mode. This can be attributed to the pulses being dark pulses with a $\pi$ phase shift at the center of the pulses as displayed by the pulses in Fig. 3(b2) and 2(c2). The sinusoidal beating from Fig. 3(b3) and 2(c3) reveals itself in nearly constant first-order harmonics and a pulsed fundamental, which is reflected in the experimental spectrogram [Fig. 4(a3)]. It should be pointed out, that although we could not match the absolute cavity dispersion of the experiment, due to the uncertainty of the EDFA dispersion, the dispersion separation between (1), (2) and (3) is very similar for both experiment and simulations.

## 4. Discussion and conclusion

Our data demonstrates that we are able to experimentally control the output pulse-shape of the mode-locked laser by tuning the cavity dispersion using an in-cavity pulse-shaper. The laser can be tuned to exhibit either a dark or bright "soliton-like" pulse train. The experimental results are supported by numerical simulations which are in excellent agreement. Our results confirm that DFWM mode-locked lasers exhibit dark “soliton-like” pulses in the normal dispersion regime as shown in previous experiments [21, 30], or bright pulses in the anomalous dispersion regime [23]. Our results are of particular relevance with the recent reappeared interest in dark soliton lasers. This demonstration of pulse-shape variation via an in-cavity pulse-shaper is to the best of our knowledge the first demonstration of such a high degree of control over the output pulse-shape from a mode-locked laser. We believe that the concept of an in-cavity pulse-shaper holds great potential for achieving a high degree of control over the dynamics and the output of passive mode-locked lasers using other mode-locking mechanisms as well.

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