Nonlinear Pulse Shaping and Polarization Dynamics in Mode-Locked Fibre Lasers

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ABSTRACT

We review our recent progress on the study of new nonlinear mechanisms of pulse shaping in passively mode-locked fibre lasers. These include a mode-locking regime featuring pulses with a triangular distribution of the intensity, and spectral compression arising from nonlinear pulse propagation. We also report on our recent experimental studies unveiling new families of vector solitons with precessing states of polarization for multi-pulsing and bound-state soliton operations in a carbon nanotube mode-locked fibre laser with anomalous dispersion cavity.

Keywords: Dynamics of nonlinear optical systems, mode-locked fibre lasers, pulse shaping, pulse propagation and temporal solitons.

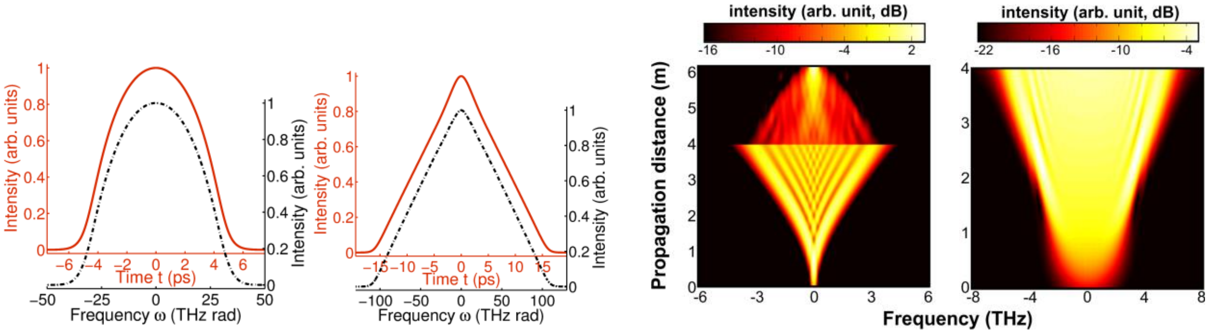
1. INTRODUCTION

Rapid recent progress in passively mode-locked fibre lasers is closely linked to new nonlinear regimes of pulse generation [1], namely, dissipative solitons in all-normal-dispersion cavities, and self-similar pulse (similariton) propagation in passive [2] and active [3-6] fibres. These are fundamentally different from the previously known soliton and dispersion-managed soliton (stretched-pulse) regimes. From a purely scientific point of view, fibre lasers provide convenient and reproducible experimental settings for the study of a variety of nonlinear dynamical processes. The nontrivial interplay between linear and nonlinear effects in a fibre cavity can be used to shape the pulses and pulse dynamics and, hence, lead to different mode-locking mechanisms. Therefore, this research area is interesting in its own right. Despite substantial research in this field, qualitatively new phenomena are still being discovered. In this paper, we review our recent results and advances in the area, by presenting a novel type of nonlinear pulse-shaping regime in a mode-locked fibre laser leading to the generation of linearly chirped pulses with a triangular temporal intensity profile [7], and a new concept of a fibre laser architecture supporting self-similar pulse evolution in the amplifier and nonlinear spectral pulse compression in the passive fibre [8].

Polarization dynamics in lasers have been intensively studied for more than two decades in the context of various applications. Implementation of mode-locking techniques in fibre lasers results in suppression of the stochastic polarization dynamics typical of spontaneous mode-locking, and so regular dynamics in the form of dissipative solitons have been observed [9-11]. The state of polarization (SOP) of these vector solitons was either rotating with a period of a few roundtrips or locked. In this work, we present a complete experimental characterization of new families of vector solitons with precessing SOPs for multi-pulsing and bound-state soliton operations on a time scale of 40-40000 roundtrips in a carbon-nanotube mode-locked fibre laser operating at anomalous dispersion [12].

2. NONLINEAR PULSE SHAPING AT NORMAL DISPERSION

Similaritons are asymptotic, parabolic-shaped pulse solutions of the nonlinear Schrödinger equation with normal dispersion (ND) in the quasi-classical limit, which convert nonlinear phase into a linear frequency chirp. Self-similar evolution of a pulse in the passive fibre of a laser has been observed [2]. In such laser, a short segment of gain fibre decouples gain filtering from the nonlinear evolution in the long passive fibre, and the chirp accumulated in the passive fibre is compensated by anomalously dispersive delay. In the ND regime of a passive fibre, starting from a conventional initial field distribution, aside from parabolic waveforms it is possible to generate other advanced field distributions such as flat-top- and triangular-profiled pulses with a linear chirp [13]. Such pulse waveforms represent transient states of the nonlinear pulse evolution in the fibre medium and can be associated with an intermediate asymptotic regime of the pulse propagation. We have recently exploited intermediate asymptotic evolution in a practical laser system [7]. We have demonstrated the possibility of pulse shaping in a mode-locked fibre laser using control of the intra-cavity propagation dynamics by adjustment of the normal net dispersion and integrated gain. The existence of two distinct steady-state solutions of stable single pulses in different regions of the system parameter space has been shown: the previously known self-similar parabolic pulse and a pulse with a triangular temporal form and a linear chirp (Fig. 1a). Similarly to the similariton regime, the triangular pulse regime features a monotonic nonlinear evolution in the passive fibre segment of the laser, though the scales of temporal and spectral broadening are larger. The main difference with the similariton regime is that the chirp is changed from normal at the end of the gain fibre to anomalous at the entrance of the passive fibre by the dispersive delay. The anomalous chirp at the entrance of the passive fibre is consistent with our findings on triangular pulse generation in single-pass fibre systems [13,14].



(a)

(b)

Figure 1. (a) Solutions obtained at representative points of the parameter space of the parabolic and triangular pulse regimes in a passive similariton fibre laser cavity: temporal (red, solid curves) and spectral (black, dash-dotted curves) profiles of the pulse at the end of the passive fibre. Results adapted from [7]. (b) Evolution of the pulse spectral profile along an amplifier similariton fibre cavity with (left) and without (right) nonlinear spectral compression. Results adapted from [8].

Similaritons in the presence of gain constitute nonlinear attractors [15]. Amplifier similaritons have been stabilized in fibre oscillators [3-6]. In this case, the nonlinear attraction of the gain fibre is responsible for mode locking of the laser, and strong spectral filtering plays a supporting role by compensating both the broad pulse duration and bandwidth after the gain segment and, hence, facilitating the creation of a self-consistent cavity [4]. However, such filtering introduces high energy loss. We have recently proposed a new fibre laser design where the pulse-shaping mechanism is dominated by two nonlinear processes with distinctly different dynamics: similariton formation with nonlinear attraction in the gain fibre, and spectral compression arising from nonlinear propagation in the passive fibre [8]. In this design, a dispersive delay line imparts an anomalous chirp on the normally chirped pulse as produced by the amplifier. The anomalously chirped, large-bandwidth pulse is then spectrally compressed in a ND fibre. Indeed, for the anomalously chirped pulse entering the fibre, where the long and the short wavelengths are in the trailing and leading edges, respectively, the effect of self-phase modulation is to redistribute both the long and the short wavelengths toward the centre wavelength and, therefore, to spectrally compress the pulse instead of spectrally broadening it [16]. This results in a significant increase of the energy spectral density of the pulse (Fig. 1b), and nonlinear spectral compression benefits the laser's power efficiency by preventing strong spectral filtering from being highly dissipative. Moreover, the direct generation of transform-limited picosecond pulses from the laser is made possible. By varying the length of the passive fibre, period-doubling bifurcations [17] and chaotic pulse dynamics can also be observed in the system.

3. VECTOR SOLITONS WITH PRECESSING STATES OF POLARIZATION

In our experiment, we used an erbium-doped fibre ring-cavity laser passively mode-locked with carbon nanotubes [11,12], where we tuned an in-cavity polarization controller (PC) and the PC for the pump laser to obtain different polarization attractors. An in-line polarimeter measured normalized Stokes parameters s_1, s_2, s_3 and degree of polarization *DOP* which are related to the output powers of two linearly cross-polarized SOPs $|u|^2$ and $|v|^2$, and phase difference between them $\Delta\phi$ as follows:

$$S_0 = |u|^2 + |v|^2,\ S_1 = |u|^2 - |v|^2,\ S_2 = 2|u||v|\cos\Delta\phi,\ S_3 = 2|u||v|\sin\Delta\phi,\ s_i = \frac{S_i}{\sqrt{S_1^2 + S_2^2 + S_3^2}},\quad DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}, (i = 1,2,3). \tag{1}$$

With a pump current of 320 mA, multi-pulsing in the form of five-pulse soliton dynamics was observed. Multi-pulsing in the laser arises as a result of interplay between the laser cavities' bandwidth constraints and the energy quantization associated with the resulting mode-locked pulses [17]. DOP oscillations around the value of 30% indicated the presence of SOP oscillations faster than polarimeter resolution time (1μs), and the trace of these fast oscillations could be also found in the phase difference dynamics. As a result of the fast phase jumps between cross-polarized SOPs and slow SOP precessing, the polarization attractor at the Poincaré sphere comprises a polyline with an outline in the form of a circle. This attractor is located close to the equator at the Poincaré sphere which is an eigenstate for an isotropic laser [18]. Tuning the in-cavity PC led to increased anisotropy which, in turn, resulted in a polarisation-locked bound-state vector soliton. This type of soliton originates from a balance of repulsive and attractive forces between solitons caused by nonlinearity and dispersion, and can comprise two or more solitons with discrete and fixed pulse separation and phase difference [19]. This polarization-locked vector soliton can be shown as a fixed point in the Poincaré sphere. With a pump current increased to 355mA, the output dynamics took the form of a two-pulse second-harmonic mode-locking operation. DOP and phase difference were almost stabilized. This vector soliton can be related to a polarization attractor at the Poincaré sphere in the form of a limit cycle. In view of the unequal powers for two cross-polarized SOPs, this attractor also corresponds to the case of a strong anisotropy created by the in-cavity PC. By tuning the in-cavity PC, we could achieve combined tightly bound-state soliton and third-harmonic mode-locked operation (Fig. 2). In this case, the DOP was less than 20%, indicating an SOP alternation much faster than the polarimeter's resolution. The polarization attractor at the Poincaré sphere forms a circle.

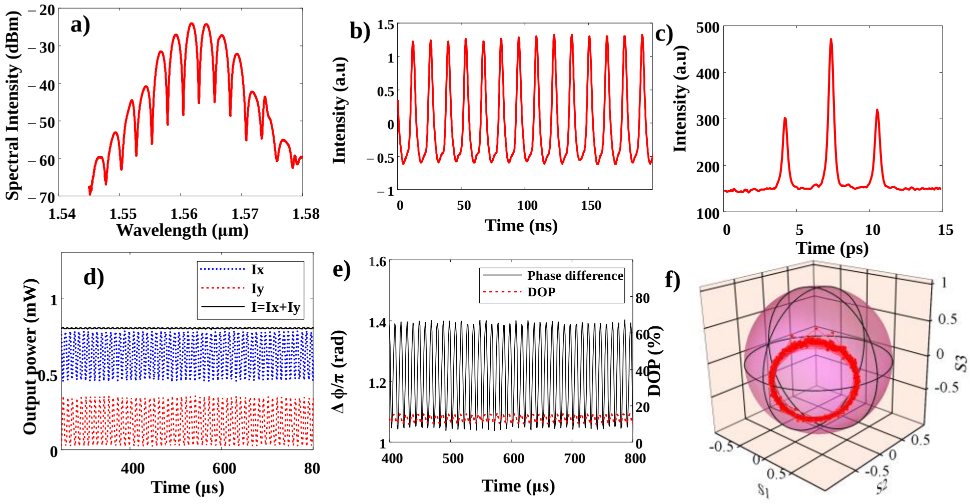


Figure 2. Vector soliton with slowly evolving SOP for combined tightly bound-state soliton and third-harmonic mode-locked operation. (a) Output optical spectrum, (b) single pulse train, (c) measured auto-correlation trace. Polarization dynamics in the time frame of 40-40 000 round trips (1μs -1ms) in terms of (d) optical power of orthogonally polarized modes I_x (solid line) and I_y (dashed line), total power $I=I_x+I_y$ (dotted line), (e) phase difference and DOP, and (f) Stokes parameters at Poincaré sphere. Parameters: pump current I_p=355mA, period T=13ns, pulse width T_p=383fs, output power $I\approx$ 0.8mW.

The phase difference dynamics observed in our experiment indicate the presence of coherent coupling between cross-polarized SOPs through the gain sharing and pump and in-cavity PCs [18]. It is well known from the theory of nonlinear coupled oscillators that weak coupling leads to a complex behaviour, and increasing the coupling produces stabilization of the behaviour, i.e. coupled attractors approach a stable steady state [20]. The coupling is determined by pump power, amplitude and phase anisotropy of the cavity caused by PCs. The complex polarization attractor for multi-pulse operation is the result of a weak coupling caused by isotropic cavity. Stabilization takes place with an increased amplitude and phase anisotropy in the cavity and leads to simpler attractors in the form of a fixed point or a limit cycle.

4. CONCLUSIONS

We have reviewed two recent examples of new nonlinear mechanisms of pulse shaping in mode-locked fibre lasers operating in the normal-dispersion regime. From a fundamental viewpoint, our results open new possibilities for studying nonlinear dynamical processes. From a practical viewpoint, triangular pulses are desired for various photonic applications, including time-domain add-drop multiplexing, wavelength conversion, and optical pulse doubling in frequency and time. The ability to generate highly-chirped parabolic pulses and transform-limited spectrally compressed picosecond pulses from a single device is attractive for applications. In particular, narrow-spectrum pulses are desired in applications requiring high spectral resolution such as in nonlinear vibrational microscopy. We have also reported on recent experimental findings on new types of vector solitons with slowly evolving SOPs on a time scale of 40-40000 round-trips for multi-pulsing and bound-state soliton operations in an anomalous-dispersion, carbon-nanotube mode-locked fibre laser. By unveiling the origin of new types of unique SOPs evolving on very complex trajectories, our experimental studies pave the way to new techniques in metrology, high-resolution femtosecond spectroscopy, high-speed and secure fibre optic communications, nano-optics (trapping and manipulation of nanoparticle and atoms), and spintronics (vector control of magnetization). Details and further developments of these approaches will be presented at the conference.

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