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Letter

All-polarisation-maintaining modified figure-of-8 fibre laser as a source of soliton molecules

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Abstract
The conditions are identified, under which a figure-of-eight all-polarisation-maintaining fibre laser with two independently pumped active media, each in one of the two cavity loops, generates soliton molecules with adjustable number of solitons in the molecule. The soliton count in the molecule may be reproducibly set between 2 and 6 by adjustment of the ratio of the pump powers of the active media. The average duration of the autocorrelation function of a single soliton is 11.6 ps, the repetition rate of the pulse train is 14.19 MHz, and its average spectral width is 10 nm. An analysis of the map of the mode-locked regimes set by different ratios of the pump source powers has shown that there exist two separate areas, one corresponding to generation of noise-like pulses and the other, to generation of soliton molecules. We believe that our findings will extend the application area of soliton molecules and will further bring a new insight into understanding of soliton molecule formation inside fibre cavities.

Keywords: mode-locked fibre laser, soliton molecules, dissipative solitons, nonlinear amplifying loop mirror

(Some figures may appear in colour only in the online journal)

1. Introduction

Soliton molecules (SM) attract significant fundamental and practical interest [1–5]. Previous decades of research revealed a plethora of soliton molecule types including: SM with independently evolving phase and flipping phase, group-velocity-locked vector SM [6], etc. Formation of such structures was demonstrated inside fibre cavities having both normal and anomalous dispersion at spectral regions 1 μm [7], 1.5 μm [8], 2 μm [9]. From the practical point of view, SM may be leveraged to increase capacity of telecommunication channels [10, 11].

Most of experimental fibre lasers make use of polarisation-insensitive fibre components, thus giving rise to nonlinear polarisation evolution (NPE). The presence of the NPE effect greatly enriches dynamics of soliton molecule formation and therefore brings new insights into nonlinear processes occurring within fibre cavities.

On the other hand, NPE-based lasers, while being a useful test-bed for fundamental research, suffer from a significant limitation in the practical aspect. Environmental influence on the net birefringence of the fibre laser cavity greatly disturbs mode-locking state. It is also well-known in the research community that polarisation controllers must be readjusted after some time to maintain mode-locked state [12].

These issues significantly limit the area of practical application of fibre lasers generating soliton molecules. One of the promising solutions is to build a fibre laser based

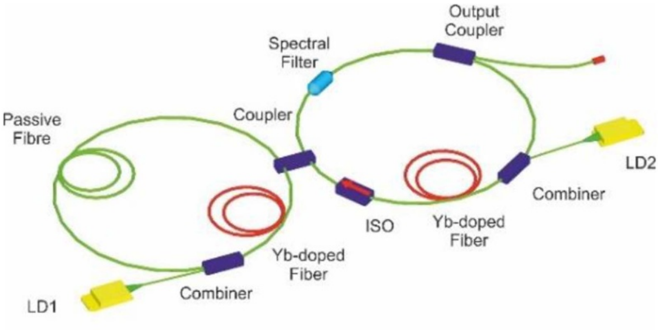

Figure 1. Schematic diagram of the figure-8 fibre laser with stretches of active Yb-doped fibre within both loops of the cavity.

on polarisation-maintaining (PM) elements. The work [13] demonstrates a linear cavity with PM Yb-doped fiber that produces SM with independently evolving phase. However, their experimental setup also includes discrete volumetric elements such as a diffraction grating that negate the advantages of the all-fiber configuration.

Here we demonstrate a figure-8 fibre laser built with polarisation-maintaining elements [14] for SM generation. In comparison with a classic realisation of the figure-8 geometry, we added a second stretch of active fibre. Independent electronically-driven gain control of the two active fibres provides a convenient way to adjust properties of mode-locked states via pumping laser diodes [15]. In the following, we present the results of our experimental studies of the proposed fibre laser configuration.

2. Experimental installation

Our figure-8 mode-locked fibre laser cavity consists of two fibre loops,—unidirectional (main) and bidirectional (NALM) ones,—connected to each other through a 40/60 coupler (figure 1). Both loops comprise 2.5-m long amplifying sections of double-clad Yb-doped fibre with absorption of 3.9 dB m^{-1} at 978 nm. The main loop also includes a 70% output coupler and a high-power Faraday isolator that ensures unidirectional propagation. Active fibres are pumped through fibre beam combiners by independently controlled multimode laser diodes each with the optical power of up to 4 W at 978 nm. All fibre inside the cavity, both passive and active, maintains polarisation.

We want to emphasise the major role of spectral filtering in generation of soliton molecules inside the given fibre laser cavity. Operation of the same laser without spectral filter was presented in our previous work where we did not observe generation of soliton molecules at the same ranges of pumping powers [16]. To achieve generation of soliton molecules we have implemented a 5-nm spectral filter that is twice as narrow as a typical spectral width of a soliton molecule.

3. Results

To study all possible pulsed regimes of our laser cavity, we consistently changed the powers of both pumping diodes in the range from 4 to 0.5 W in the following order. At a fixed power of the LD1, we gradually reduced the power of the LD2 from 4 to 1 W with a step of 0.03 W and measured the parameters of the output radiation at each power step. Then the power of LD1 was reduced by 0.03 W, and the procedure was repeated until LD1 power became equal to 0.5 W. The laser output radiation was measured by autocorrelator A.P.E pulseCheck, optical spectrum analyser Yokagawa AQ637, and radio-frequency spectrum analyser Tektronix RSA306B. Radio-frequency spectrums were measured at the vicinity of

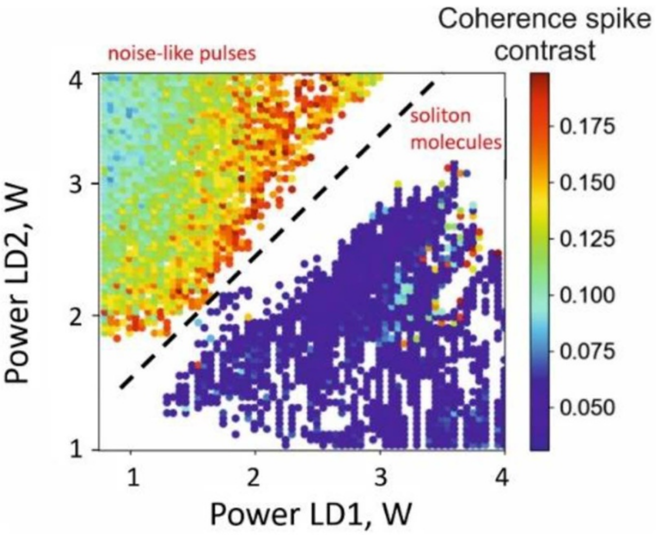

Figure 2. Coherence degree map of pulsed regimes depending on injection current of the pumping laser diodes.

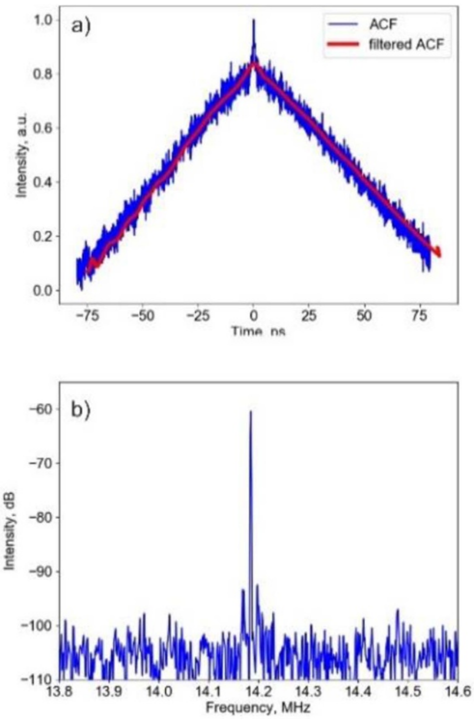

Figure 3. (a) Autocorrelation function and (b) radio-frequency spectrum in the vicinity of the fundamental mode of noise-like pulses.

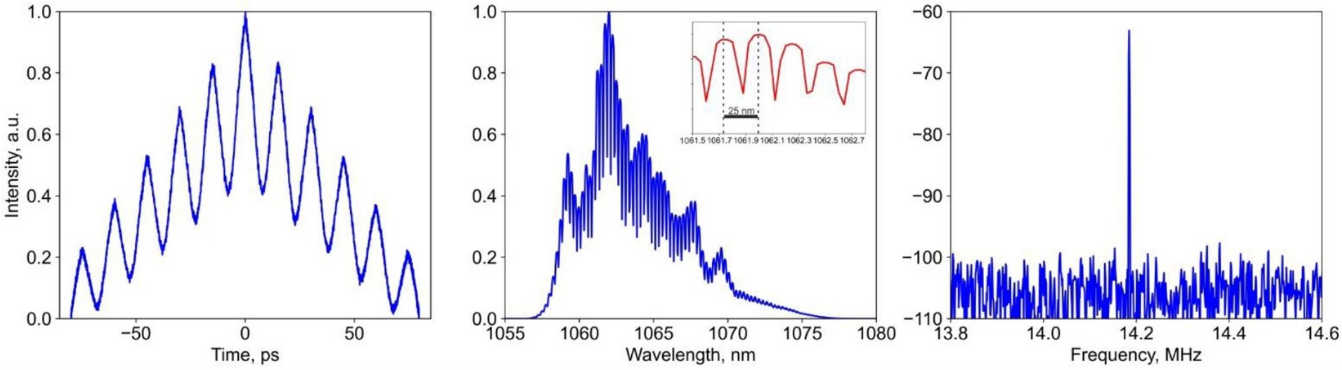

Figure 4. Example of generated soliton molecule. (a) Autocorrelation function, (b) optical spectrum, (c) radio-frequency spectrum.

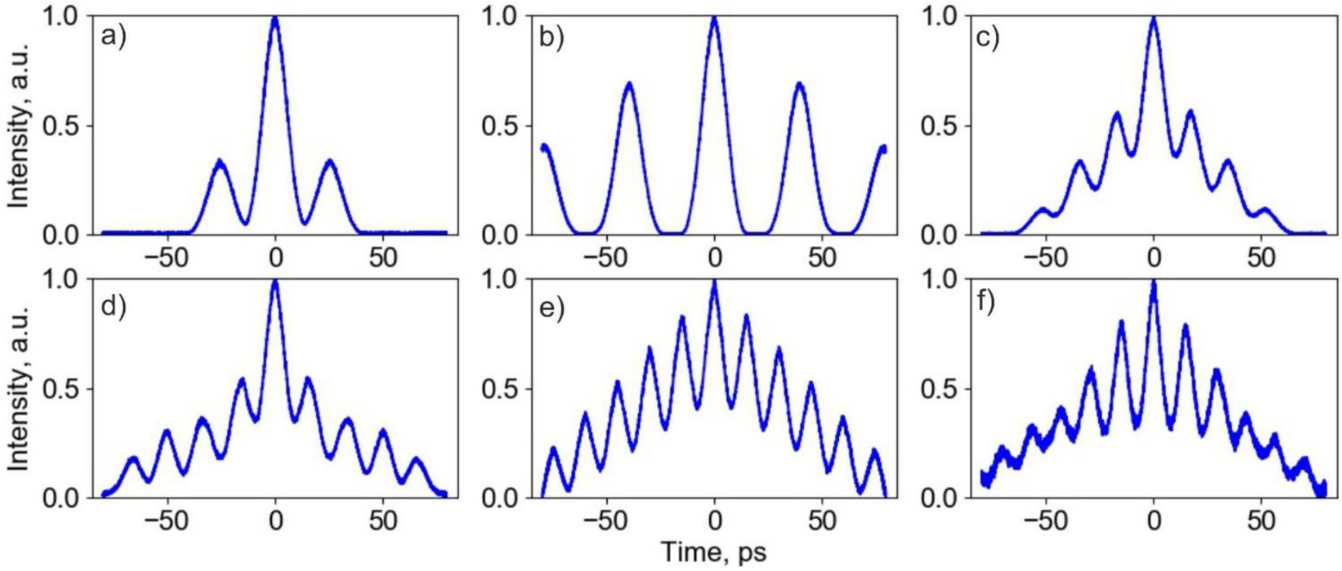

Figure 5. Possible states of soliton molecules generated in the modified figure-8 fibre laser.

fundamental mode 14.2 MHz with a span of 1 MHz and resolution 1.25 kHz.

The acquired map is presented in figure 2. Here we find two isolated regions that correspond to two different types of pulsed output: noise-like pulses and soliton molecules. A similar effect has also been reported in a figure-8 laser within the 1.5 μm region [17]. In our case, due to the all-PM configuration we are able to conveniently visualise these regions, because we have only two degrees of freedom.

The region above the dashed line in figure 2 corresponds to noise-like pulses. Figure 3. depicts the autocorrelation function and radio-frequency spectrum of the fundamental mode of noise-like pulses.

The autocorrelation function envelope is 88.75-ps wide, while the width of the coherence spike is 461 fs. Two spectral peaks on either side of the fundamental mode within the radio-frequency spectrum are related to power instability of noise-like pulses and significaty lower the contrast between maximum peak and background level down to 32 dB.

The region below the dashed line in figure 2 corresponds to soliton molecules. To distinguish noise-like pulses and soliton molecules, we calculate the coherence spike contrast under which we mean the ratio between the maxima of the unfiltered and filtered ACF. The signal processing procedure is as follows: for filtering the ACF and generating the ACF envelope (red curve in figure 3(a)), a low-pass 3-order Butterworth filter with 0.01π rad/sample cut-off frequency was used. The full-width half-maximum of the filtered ACF is used as a measure of pulse duration. We label as noise-like pulses with coherence spike contrast exceeding 0.1. A non-zero contrast value for stable mode-locked pulses comes from noise of the experimental autocorrelation function. We also filtered continuous wave and unstable regimes by the radio-frequency peak contrast.

It is worth noting that two stretches of gain fibre play different roles inside the laser cavity in addition to amplification. Adjusting the pump power of the Yb-doped fibre inside the nonlinear amplifying loop mirror modifies the saturation power of the loop [18], while adjusting the pump power of the second fibre varies accumulation of nonlinear phase of optical pulses due to the self-modulation effect. To succed in generation of stable soliton molecules, pumping powers should be matched.

Figure 4 presents an example of generated soliton molecules at pumping powers $P_{LD1} = 3.05$ W and

$P_{LD2} = 2.20$ W. Binding between solitons is confirmed by the presence of interference fringes in the optical spectrum of figure 4(b). Temporal separation between the solitons equal to $\tau = \frac{\lambda^2}{c\delta\lambda} = 15$ ps matches the predicted period of interference fringes $\delta\lambda = 0.25$ nm.

Adjusting the pumping powers of laser diodes allows convenient selection of the soliton count inside the molecule. Figure 5 shows the autocorrelation functions of soliton molecules generated in our experimental laser. The number of solitons $N_{soliton}$ inside the molecule may be caclulated as follows: $N_{soliton} = \frac{1}{2}(N_{peak} - 1)$, where N_{peak} is the number of autocorrelation function maxima. Thus, our proposed configuration provides for generation of soliton molecules with 2–6 coherent solitons inside. The number of peaks that we may detect with our measurement equipment was limited by the maximal scanning range of the autocorrelator. In figures 5(b) and (f) only part of the side peaks may be observed. The average power of the output molecules varied from 20 to 150 mW.

Acording to figure 5 temporal separation between solitons varies. Dependency of temporal separation against pumping powers is non-trivial and not continious. Increasing or decreasing pumping powers may lead to significant change of the form or number solitons inside soliton molecule. However, parameters of the soliton molecules are stable and reproducible after reseting absolute values of pumping powers.

4. Conclusions

In the present, we demostrate a modified configuration of figure-8 laser cavity used as a source of soliton molecules with the number of coherent solitons adjustable between 2 and 6. Leaving only polarisation-maintaning elements inside the laser cavity garantees a linearly polarised state insde and eliminates polarisation effects highly sensitive to evironmental perturbations. This also significantly simplifies control of mode-locked states. To generate a soliton molecule inside the modified figure-8 laser cavity, two conditions must be observed: (1) strong spectral filtration (2) a specified ratio between pumping powers of laser diodes. The mechanism of soliton formation under strong spectral filtration is a very important question that is not solved yet and will be addressed at our future investigations.

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