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Emission of multiple dispersive waves from a single Raman-shifting soliton in an axially-varying optical fiber

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Abstract: We provide the experimental demonstration of the generation of multiple dispersive waves from a single soliton propagating in the vicinity of the first zero-dispersion wavelength of an axially-varying optical fiber. The fiber is designed such that the Raman-shifting soliton successively hits three times the longitudinally evolving zero-dispersion wavelength, which results in the emission of three distinct dispersive waves at different fiber lengths. These results illustrate how suitably controlled axially-varying fibers allow to tailor the soliton dynamics in a very accurate way.

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1. Introduction

The propagation of a fundamental soliton in the vicinity of the zero-dispersion wavelength (ZDW) of an optical fiber results in the emission of a dispersive wave (DW) across the ZDW [1, 2], caused by the perturbation of the soliton by third (or higher) order dispersion [3, 4]. This resonant process occurs providing that the spectral tail of the soliton leaks sufficiently far into the normal dispersion region [3, 5]. If so, the frequency of the DW is ruled by a phase-matching relation involving the dispersion and nonlinear properties of the fiber and the soliton characteristics:

$$\frac{\beta_2}{2}\Omega^2 + \frac{\beta_3}{6}\Omega^3 = \frac{\gamma P}{2} \tag{1}$$

where β_2 and β_3 are the second and third-order dispersion terms, $\Omega = \omega_S - \omega_{DW}$ is the frequency separation between the soliton at ω_S and the DW at ω_{DW}, P is the soliton peak power and γ is the fiber nonlinear parameter. This relation indicates that the process of DW emission can be harnessed through an appropriate control of the fiber dispersion. If this control is longitudinal (using axially-varying optical fibers), then the dynamics of the soliton, and therefore of the DW generation, can be tailored.

A number of numerical studies have examined this situation. C. Milián *et al.* have investigated the propagation of a soliton in a continuously tapered optical fiber [6]. They have designed their fiber such that the ZDW follows the soliton redshift due to intrapulse Raman scattering. In this way, the soliton spectrum keeps overlapping with the normal dispersion region all along its redshift. This results in the continuous emission of DWs which can be seen as a polychromatic DW. Based on this concept, F. R. Arteaga-Sierra *et al.* have extended this study to the case of an optical fiber with a sequentially-increasing ZDW with fiber length [7]. They have shown that multiple and discrete DWs can be generated if the soliton hits the ZDW several times during its Raman-induced redshift.

From an experimental point of view, there is to our knowledge only one related work reported very recently by some of us [8]. In this study, the emission of multiple DWs from a frequency-locked soliton has been observed recently near the second ZDW of a dispersion oscillating fiber (DOF) [8]. In this configuration, the Raman-induced soliton self-frequency shift (SSFS) is cancelled by the emission of the first DW [9], and a second DW is observed as a result of the oscillating ZDW hitting the frequency-locked soliton.

Our aim here is to demonstrate experimentally the possibility of emitting multiple DWs from a single Raman-shifting fundamental soliton using an axially-varying optical fiber. Our experiment involves a fiber designed in such a way that the first ZDW reaches three times the Raman-shifting soliton along its redshift. As a consequence, three distinct DWs are emitted at three different fiber lengths, resulting in a multi-peak spectrum at the blue edge of the soliton, as numerically predicted in [7].

2. Principle and experiments

The concept of our experimental demonstration is sketched in Fig. 1(a). It involves a fundamental soliton (represented in red in Fig. 1(a)) experiencing a redshift through Raman-induced SSFS and propagating in a DOF. The longitudinal evolution of the DOF is designed such that its ZDW (black dotted line in Fig. 1(a)) oscillates with fiber length and hits several times the redshifting soliton. The amplitude of ZDW variation increases along the fiber so that it hits the soliton which experiences a Raman-induced redshift. At the locations where this happens (blue star markers in Fig. 1(a)), the soliton spectrum significantly overlaps with the normal dispersion region so that it seeds the generation of a DW (represented in blue in Fig. 1(a)) at the phase-matched frequency given by Eq. (1). This results in the generation of multiple DWs following the number of matching points between the ZDW and the soliton.

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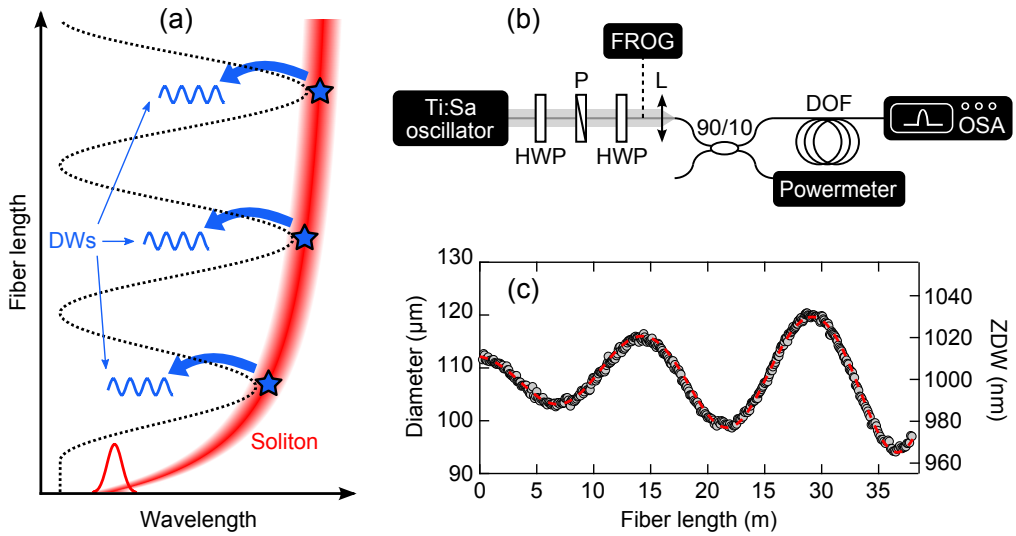

Fig. 1. (a) Scheme of the concept of multiple DWs generation from a single Raman-shifting soliton. The black dotted line depicts the ZDW and star markers represents locations where DWs are generated. (b) Experimental setup. HWP: half-wave plate; P: polarizer; L: lens. (c) Evolution of the fiber outer diameter (markers, left axis) as a function of length measured during the fiber draw process. Right axis: corresponding simulated ZDW (red dashed line).

Figure 1(b) shows the experimental setup used to demonstrate this concept. The pump laser is a Ti:Sa oscillator delivering linearly polarized femtosecond pulses. A series of half-wave plates and polarizer are used to simultaneously adjust the pump power and rotate the linear polarization state. The pulses are then injected into a polarization maintaining (PM) 90/10 coupler whose 90 % output port is spliced to a DOF with aligned neutral axes. The 10 % output port was used to monitor the pump power and to ensure that the power launched in the DOF remained constant during the cutback experiments presented hereafter. The pulses at the coupler input were fully characterized using a frequency-resolved optical gating (FROG) system. They have a near transform-limited gaussian shape with a full width at half maximum (FWHM) duration of 180 fs. We estimated the pulse properties at the DOF input (i.e. at the coupler output) by taking into account the coupler length of 0.7 m and its dispersion value at 1030 nm. We found that their duration increases to 410 fs at the coupler output and the chirp parameter C (defined as in [10]) is $+3.7$.

The DOF used in this experiment was drawn from a PM photonic crystal fiber (PCF) preform. Figure 1(c) shows the evolution of its outer diameter (left axis) recorded during the fiber draw process. It follows an amplitude modulated sine shape with a period of 15 m and an amplitude linearly increasing at a rate of 10 %. The dotted red line corresponds to the ZDW of the neutral axis of interest here simulated from the PCF structure with a finite element commercial mode solver. The ZDW is 1011 nm at the DOF input and reaches 1021 nm and 1030 nm at respectively 14 m and 29 m, where it will hit the redshifting soliton.

The experimental conditions were initially determined using numerical simulations of the generalized nonlinear Schrödinger equation (GNLSE) [11]. More precisely, knowing the dispersive and nonlinear DOF properties as well as the duration and chirp of the pump pulses, their peak power and wavelength were adjusted so that the fission of the input pulse generates a fundamental soliton with a subsequent Raman-induced SSFS allowing to reach the successively increasing ZDW of 1021 nm and 1030 nm at 14 m and 29 m, respectively. From this

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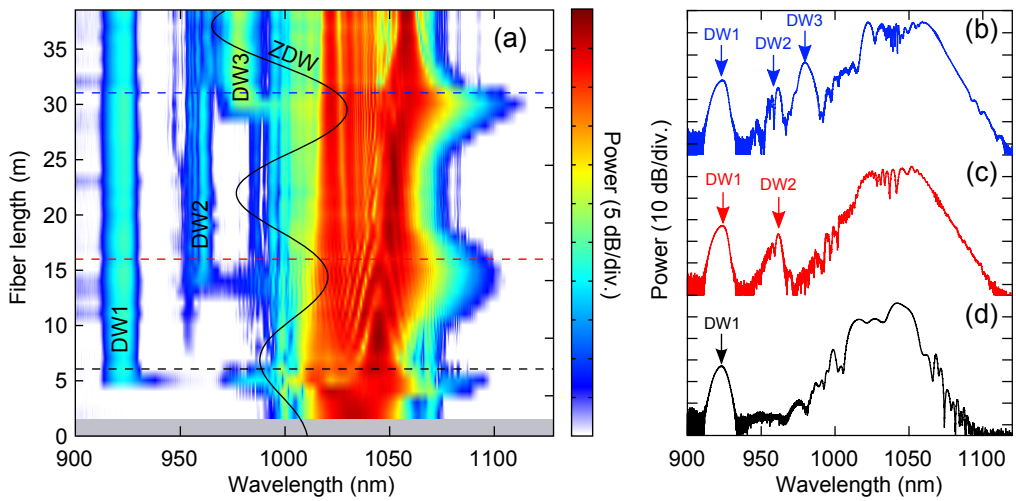

Fig. 2. (a) Evolution of the spectrum with fiber length showing the multiple emission of DWs (experiments). The black solid line depicts the ZDW plotted in Fig. 1(c). Dashed lines correspond to spectra plotted in the right panel. (b-d) Output spectra recorded for fiber lengths of 6 m (d), 16 m (c) and 31 m (b). Arrows depict the DWs.

preliminary step of numerical simulations, we found that a pump wavelength of 1030 nm and peak power of 46 W were suitable to reach this situation. Figure 2(a) shows the evolution of the spectrum as a function of fiber length measured with a cutback procedure, in which output spectra were recorded after successive cutbacks of 1 m. The input pump pulse breaks up at a length of about 5 m which leads to the ejection of a fundamental soliton, following the classical scenario of higher-order soliton fission [12]. At this point, a first DW, labeled DW1, is emitted at 923 nm due to the proximity of the soliton to the ZDW (depicted by the black line). After this point, the spectrum is only composed of a soliton and DW1, as shown in Fig. 2(d) for a fiber length of 6 m. The soliton experiences a redshift due to a combination of spectral recoil accompanying the DW emission [3] and Raman-induced SSFS. At around 14 m, the evolving ZDW reaches a local maximum value so that it comes close enough to the soliton to generate a second DW (labeled DW2) centered around 961 nm (see arrows in the spectrum measured at 16 m in Fig. 2(c)). DW2 is located at a different wavelength than DW1 because the soliton wavelength and the β_2 and β_3 values have changed, which modifies the phase-matching relation (1). The same scenario occurs once again at 29 m where a third DW, labeled DW3, is generated at 979 nm. From this length, the output spectrum (shown in Fig. 2(b) for a length of 31 m) exhibits three DWs located at different wavelengths for the reason explained above. The map of Fig. 2(a) shows that they have all three been emitted by the same fundamental soliton which is sequentially perturbed by the oscillating ZDW which comes close enough to the soliton to efficiently initiate the process of DW generation.

3. Numerical simulations and discussion

In order to get a deeper insight into this process, we performed numerical simulations using the GNLSE [11] by taking into account full dispersion curves as well as the Kerr and Raman nonlinear contributions (we used the Raman model from [13]). We found that higher-order dispersion terms β_n play a negligible role for $n \geq 4$. The DOF parameters and input pulse properties used for the simulations were the same as in experiments (duration of 410 fs, peak power of 46 W and chirp parameter of $+3.7$). Figure 3(a) shows the simulated evolution of the spectrum

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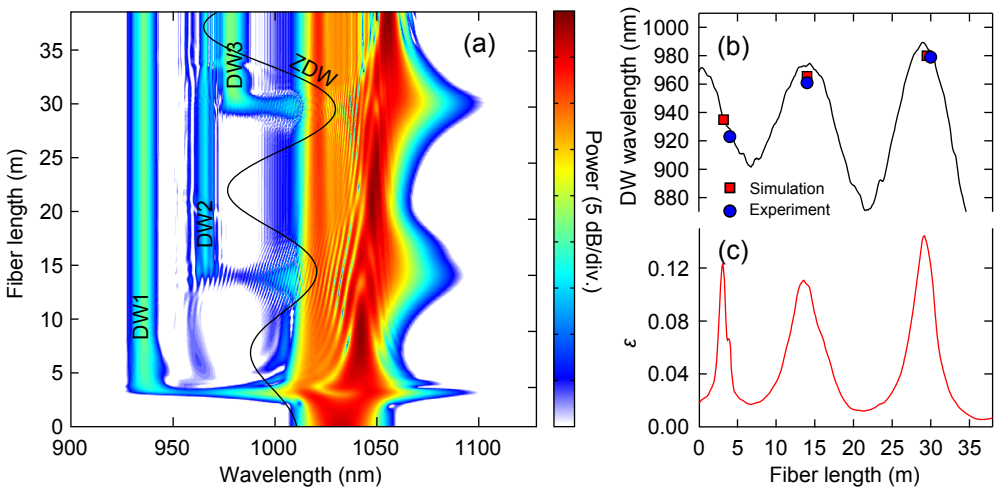

Fig. 3. (a) Simulated evolution of the spectrum with fiber length, correpsonding to the experiment of Fig. 2(a). The black solid line depicts the ZDW. (b) Longitudinal evolution of the phase-matched wavelength of DWs obtained from Eq. (1) from the simulated evolution of the soliton (black line). Markers correspond to the emission of DWs observed in simulations (red squares) and experiments (blue circles). (c) Evolution of the ε parameter (representing the spectral overlap between the soliton and the normal disperison regime) with fiber length.

with fiber length, corresponding to the experimental map of Fig. 2(a). The overall dynamics observed experimentally is very well reproduced both for the soliton and the three DWs. In order to quantify this, we plot in Fig. 3(b) the theoretical phase-matching curve obtained by solving Eq. (1), considering the simulated evolution of the soliton central frequency ω_S and peak power P, as well as the longitudinal evolutions of β_2, β_3 and γ. This curve oscillates with fiber length over about 100 nm, as a result of the oscillating dispersive and nonlinear properties of the DOF. Red squares and blue circles correspond to the emission of DWs observed respectively in numerical simulations and experiments. They are in good agreement with each other as well as with the theoretical phase-matching curve. The discrepancy in DW wavelength between simulations and experiments is presumably due to the uncertainty on the fiber properties. The slight difference in the fiber length at which DWs are emitted between simulations and experiments is attributed to the experimental resolution of the cutback (1 m). In order to understand why DWs are generated at these particular locations along the fiber, we plot in Fig. 3(c) the evolution of the ε parameter defined as:

$$\varepsilon = \frac{\beta_3(\omega_S)}{6T_0|\beta_2(\omega_S)|} \tag{2}$$

where T_0 is the pulse duration at $1/e$. The evolution of the ε parameter with fiber length is plotted in Fig. 3(b), by taking into account the longitudinal evolutions of β_2, β_3 and T_0 (extracted from numerical simulations) in Eq. (2). The ε parameter gives an estimation of the overlap between the tail of the soliton spectrum and the normal disperson regime. In presence of third-order dispersion, the soliton is considered to be stable for $\varepsilon < 0.04$ [1, 3], which means that DWs can be emitted for larger values. Physically, this means that the soliton spectrum has to overlap with the phase-matched wavelength located across the ZDW to initiate and seed the DW emission. Figures 3(b) and 3(c) indeed show that DWs are emitted in the regions where the

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ε parameter reaches its local maximum values (around 3.5 m, 14 m and 29 m in simulations). This suggests that the DW wavelength and emission location along the fiber can both be chosen through an appropriate longitudinal control of the phase-matching relation (1) and ε parameter of Eq. (2), which can be done by a suitable tailoring of the fiber longitudinal profile.

4. Conclusion

We have studied experimentally and numerically the dynamics of soliton propagation and generation of dispersive waves in a dispersion oscillating fiber. We have shown that a single fundamental soliton experiencing Raman-induced self-frequency shift can emit multiple dispersive waves (three in our case), as a result of the axially-varying properties of the fiber. They are generated at different phase-matching locations where the ε parameter (representing the spectral overlap of the soliton spectrum with the normal dispersion region) is maximized. This corresponds to the regions where the ZDW gets close enough to the soliton and eventually hits it.

Further engineering of the fiber longitudinal profile would allow to simultaneously tailor the phase-matching curve and ε parameter value and thus to control both the wavelength and emission location of dispersive waves along the fiber. This may lead to the observation of novel soliton/dispersive waves dynamics scenario.

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