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Solitonisation of Anderson localisation in Rogue-soliton generation

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Abstract: We unveil the relation between the linear Anderson localisation process and nonlinear modulation instability. Anderson localised modes seed the formation of solitary waves. Afterwards, optical-event horizon effects between dispersive waves and solitons produce an artificial collective acceleration that facilitates the collision of solitons, which could eventually lead to a rogue-soliton generation.

OCIS codes: 190.5530, 190.3100, 190.4410

1. Introduction

Modulation instability (MI) induced supercontinua via long pulses in solid-core optical fibres has been the subject of huge research in the recent years, after the evidence presented by Solli *et al.* that the output spectra contain statistically rare rogue events with large intensities and enhanced redshift. Depending on the initial input noise, a rogue soliton may appear inside the fibre after multiple soliton-soliton collisions [1]. In this work, we present new details on the dynamics that proceed the collision of solitons. In particular, we describe two different processes: solitonisation of Anderson localisation (AL), followed by optical-event-horizon (OEH) induced self-frequency redshift. The first process is the key element in generating solitons from the background noise, whereas the collision of different solitons is facilitated by the second process [2].

2. Anderson localisation and modulation instability

The propagation of intense pulses in optical fibres can be described in terms of the nonlinear Schrödinger equation [3]. Pure Kerr-nonlinearity results in a spatio-temporal modulation of the refractive index that will follow the variation of the pulse intensity. In the anomalous dispersion regime, the amplification of the background noise lead to a random temporal modulation of the refractive index that corresponds to an optical potential $U = \omega_0 \Delta n / c$, where $\Delta n(z,t) = n_2 |A|^2 / A_{\text{eff}}$, n_2 is the nonlinear refractive index in units of m^2/W, $A(z,t)$ is the pulse complex envelope, z is the propagation direction, t is the time-delay in a reference frame moving with the pulse group velocity, ω_0 is the pulse central frequency, c is the speed of light in vacuum, and A_{eff} is the effective optical mode area. The modes of this potential are the solutions of the following linear Schrödinger equation,

$$i\partial_z u_k - \frac{\beta_2}{2}\partial_t^2 u_k + U(z,t)u_k = 0, \tag{1}$$

where u_k is the complex amplitude of the mode with $k = 0,1,2,..$, and β_2 is the second-order dispersion coefficient. The slowly-varying envelope approximation implies that $\Delta n(z,t) \approx \Delta n(t)$ is frozen over short spatial z-intervals. Hence, Eq. (1) becomes the 1-D temporal analogue of the transverse-disorder Anderson waveguides [4], where linear temporal Anderson localised modes could be formed. Figure 1(a) depicts how the linear fundamental mode associated with a nonlinear superGaussian pulse is adiabatically compressed significantly due to AL until $z \approx 6$ m in a solid silica-core photonic crystal fibre. The temporal position of localisation is completely random, and it relies on the shape of the input noise. Since the temporal-induced potential is evolving, the localisation process is halted at that position, and the fundamental mode attempts to sustain at other places for few centimetres. These localised modes seed the emission of solitary waves as shown in panels (b,c), a phenomenon known as solitonisation of Anderson localisation [5].

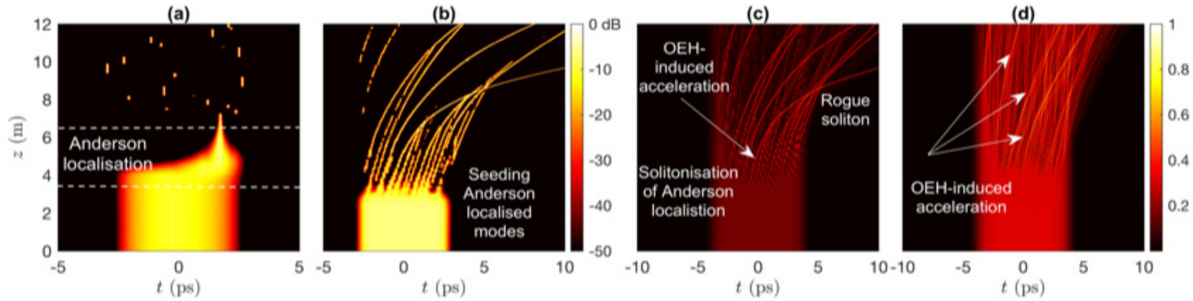

Fig. 1. (a) Temporal evolution of the ground Anderson state of the potential induced by a superGaussian pulse $A = \exp\left[-1/2\,(t/T_0)^{10}\right]$ with central wavelength 1060 nm, $T_0 = 3.63$ ps and input power 100 W inside the solid silica-core photonic crystal fibre of Ref. [7] with zero-dispersion wavelength located at 1055 nm in the presence of second-order dispersion and Kerr nonlinearity. (b,c) Temporal evolution of the first 20 Anderson eigenmodes on the top of each other and the superGaussian pulse in the presence of dispersion coefficients until the tenth-order, Kerr nonlinearity, Raman effect and self-steepening. Each linear mode in (c) is normalised such that its energy is unity. (d) Temporal evolution of the superGaussian pulse in the presence of second- and third-order dispersion, and Kerr nonlinearity.

3. Optical-event horizons

Beside AL, optical-event horizons (OEHs) [6] are also playing a major role in favouring soliton collisions. In the presence of third-order dispersion, a large pool of solitons and dispersive waves will form via MI, due to satisfying the phase matching conditions. Near the zero dispersion wavelength, the condition for the optical group-velocity event horizon between a leading soliton and a trailing dispersive wave can be easily met. The soliton-induced potential barrier impedes the flowing of the dispersive wave and reflect it back after collision. Interestingly, the collision can result in a soliton self-frequency redshift accompanied by a deceleration in the time domain even in the absence of Raman nonlinearity, as depicted in Fig. 1(d) that present the temporal evolution of the pulse inside the fibre. This deceleration is stronger for solitons at the leading edge, since they are trailed by a large number dispersive waves. Because of OEH-induced acceleration, solitons seeded by AL become very likely to collide. Finally, Raman nonlinearity allows the solitons to cluster in the time and frequency domains very quickly. This results in strong temporal overlap and close group velocities for the solitons, so they could strongly nonlinearly interact for a long distance, and a rogue-soliton is generated after exchanging energy between them, as shown in panel (c).

4. Conclusions

We have reported the missing ingredients of the generation of a rogue-soliton in optical fibres. We have found that the true origin of soliton generation during the modulation instability process is the temporal Anderson localisation effect. Optical-event horizon-induced acceleration facilitates soliton-soliton collisions. Rogue solitons are generated after strong temporal overlap between individual solitons with close group velocities, due to Raman nonlinearity. This work will potentially lead to novel routes for controlling of extreme nonlinear waves via linear-disorder optimisation.

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