

Supplemental material

Observation of optical undular bores in multiple four-wave mixing

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Experimental procedure

Further details on the experiment set-up are given with reference to Fig. 3. The source is based on an external cavity laser (ECL Emcore diode) emitting at $\lambda_0 = 1555$ nm, first injected into a phase modulator (PM, Photline technologies) driven by a 100 MHz RF signal to enlarge the spectral linewidth in order to prevent any Brillouin back scattering in the fiber under test. The intensity modulation at 28-GHz is impressed by means of a 40-GHz bandwidth LiNbO₃ intensity modulator IM1 (Photline technologies). When the three-wave input is desired, IM1 is driven directly by a 28-GHz, whereas the dual-frequency beat-signal is synthesized by driving the modulator at its null transmission point by a 14-GHz half-frequency RF clock (Agilent synthesizer). This technique enables us to generate a twofold frequency carrier-suppressed initial 28 GHz beat-signal. In both case the RF signal that drives IM1 is used to trigger the optical sampling oscilloscope (OSO, EXFO picosolve) at the output of the fiber, thus achieving real-time observation of the dynamics. A programmable liquid-crystal-based optical filter (Finisar Waveshaper), centered on each of the dual pumps is then added in order to eliminate residual carrier component and half-repetition rate undesirable spectral bands. In order to increase the peak-power at the amplification stage, the modulated signal produced by IM#1 is then sliced into the time domain by means of a second 10-GHz bandwidth intensity modulator (IM#2, Photline technologies) driven by a programmable pulse pattern generator (PPG, Anritsu). The final signal consists in a burst of 8 periods of the initial 28-GHz modulation embedded into a 1:4 duty-cycle 7-GHz signal with 8-bit pattern. The resulting signal is amplified by means of an Erbium Doped Fiber Amplifier (EDFA, 3S Photonics) before injection into the 6-km long non-zero dispersion-shifted fiber (NZDSF) with dispersion $D = -2.5$ ps/nm km (slope $S = 0.07$ ps/nm² km), nonlinear Kerr coefficient $\gamma = 1.7$ W⁻¹ km⁻¹, and linear loss coefficient is

$\alpha = 0.2$ dB/km. A time-domain and a spectral mapping are then realized by monitoring the temporal profile on the OSO as well as the output spectra on the OSA (Yokogawa) as a function of injected power.

Numerical simulations

Simulations of the experiment are performed by integrating numerically the NLSE in dimensional units,

$$i \frac{\partial A}{\partial Z} - \frac{k''}{2} \frac{\partial^2 A}{\partial T^2} + |A|^2 A = 0, \quad (1)$$

where we make use of the retarded time $T = T_{lab} - k'Z$, T_{lab} being time in the lab frame and $k' = dk/d\omega$ the inverse group-velocity. Equation (1) can be easily rescaled into the dimensionless NLS equation of the paper [Eq. (2)] by introducing the variables $t = T/T_0$ and $z = Z/Z_0$, where $T_0 = (2\Delta f)^{-1}$ is the characteristic time associated with the input modulation, and $Z_0 = \sqrt{Z_{nl}Z_d}$ is the geometric mean between the two characteristic length scales of the problem, namely the nonlinear length $Z_{nl} = (\gamma P)^{-1}$ and the dispersion length $Z_d = T_0^2/k''$. Following this scaling, the dynamics turns out to depend on the value of a single parameter, namely $\varepsilon \equiv \sqrt{L_{nl}/L_d} = \Delta f \sqrt{4k''/\gamma P}$, which fixes the relative strength of dispersion and nonlinearity (the weaker the dispersion or the slower the modulation, the smaller ε). Here $\gamma = 2\pi n_{2I}/(\lambda_0 A_e)$ is the fiber nonlinear coefficient (n_{2I} and A_e are the nonlinear index (Kerr) coefficient, and A_e is the effective area of the fiber), whereas $k'' = d^2k/d\omega^2$ is the GVD, related to the dispersion coefficient as $D = -k''2\pi c/\lambda_0^2$. The maps in Fig. 4(c) and Figs. 5-6(d) are generated by integrating numerically Eq. (1) by means of the split-step algorithm, extracting the output at $Z = L$ for different input powers as done in the experiment. We have also assessed numerically the fact that the third-order dispersion in our experiment can be safely neglected.