Observation of a two-stage soliton breakup

Dmitriy Krylov, Suzanne Sears, and Keren Bergman
Department of Electrical Engineering, Princeton University, J303 E-Quad, Olden Street, Princeton, NJ 08544
Tel.: (609) 258-2971 Fax: (609) 258-0463 e-mail: krylov@ee.princeton.edu

J. Nathan Kutz
Department of Applied Mathematics, University of Washington, Box 352420, Seattle, Washington 09195-2420

Abstract: We experimentally demonstrate a two-stage breakup of a pre-chirped soliton optical pulse in optical fiber. Each stage accepts a single input pulse and produces two independent pulses. The stages are cascaded to produce a one-to-four breakup.

OCIS codes: (060.5530) Pulse propagation and solitons; (060.4370) Nonlinear optics, fibers

With the recent developments in design of dispersion-managed soliton communication systems and chirped pulse systems, it has become increasingly important to understand the fundamental limits on the chirped pulse propagation in optical fibers. It has been recently reported that a combination of high chirp and high peak power relative to the anomalous dispersion parameter can lead to complex propagation dynamics. The theory [1], supported by computational evidence [2], states that a symmetric perturbation to the soliton optical pulse, such as strong chirping, would disrupt the familiar periodic propagation of a high-order soliton and result in an irreversible breakup. For a sufficiently strong chirp, a high-order N-soliton pulse can be completely decomposed into an ordered train of N fundamental solitons. Recently, we have reported an experimental verification of such a breakup of a chirped high-order soliton pulse [3]. It has been postulated that as the ejected pulses move further away from the center, they act as independent solitons. In this paper we experimentally demonstrate that the pulses emerging from the breakup are indeed independent solitons and can be injected into a second breakup stage. If the experimental parameters are chosen carefully, the breakup process can be repeated. If in the first stage an initial soliton breaks up into two, then each of the resulting solitons also breaks up into two pulses in the second stage, and we get a four-pulse structure.

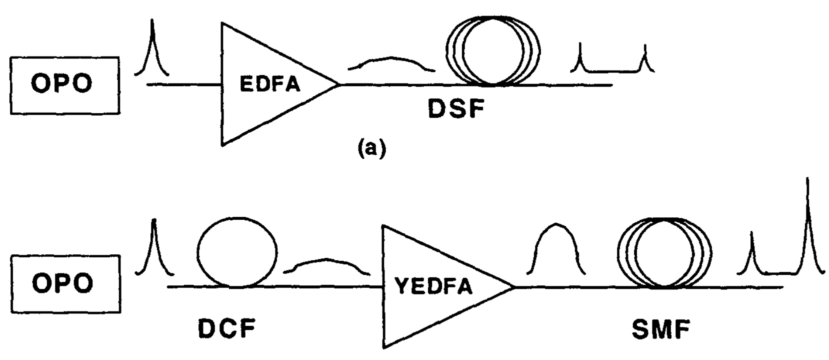

Fig. 1. Experimental configuration of (a) The first breakup stage that includes an optical parametric oscillator (OPO), erbium-doped fiber amplifier (EDFA), and dispersion-shifted fiber (DSF); and (b) the second breakup stage which includes the OPO, dispersion compensated fiber (DCF), Yb/Er-doped fiber amplifier (YEDFA), and single-mode fiber (SMF).

The first step in designing such an experiment is to create two stages, each of which independently breaks up an input optical pulse into two. Each stage in turn consists of several components that provide the necessary chirp and amplification to the input pulse and then a section of anomalous optical fiber where the actual breakup can occur. The next and the most crucial step is to pick the components in such a way that the output of the first stage can be fed into the second stage to produce the desired result.

The experimental setup is shown in Figure 1. The first stage, as shown in Figure 1(a), is another implementation of the experiment reported in [3] and is operated in such a way as to produce a two-pulse breakup. A Spectra-Physics Opal optical parametric oscillator (OPO) provides a train of 160-fs (FWHM) sech-shaped transform limited optical pulses at a repetition rate of 82MHz and centered at a wavelength of λ_0=1550nm. The light is coupled into an erbium-doped fiber amplifier (EDFA) that is 20m long and has a normal dispersion parameter D=−25ps/(nm km). The optical pulses that emerge from the amplifier have a temporal width of 6ps (FWHM) and a spectral (3dB) bandwidth of 20nm, indicating that they are strongly chirped. The pulses are then sent to a 400m section of Corning LEAF dispersion-shifted fiber (DSF) which has a dispersion zero at 1520nm (D=3.0 ps/(nm-km) at 1550nm). Since the breakup produces ultra-short pulses, the time-domain behavior is measured via an auto-correlation. Figure 2(a) shows the auto-correlation trace taken at the output of the DSF with 8mW of average power coming out of the EDFA with the auto-correlation amplitude in arbitrary units plotted versus time. This is a typical auto-correlation of two pulses separated by about 7 picoseconds. Note that the side peaks are about half the size of the central peak, which indicates that the two pulses are roughly equal in height.

The second stage in its stand-alone configuration also takes the OPO pulses at the input, as shown in Figure 1(b). The light with an initial average power of 5mW is coupled into a 1.7m section of dispersion-compensated fiber (DCF) with a strong normal dispersion parameter of D=−102ps/(nm km). This provides the chirp necessary for the breakup to occur. The optical power is then boosted by another optical amplifier (YEDFA) that uses 4m of co-doped Yb/Er gain fiber with anomalous dispersion parameter of D=20ps/(nm km). The pulses are then sent into a 100m section of the single-mode fiber (SMF) with anomalous dispersion parameter of D=15ps/(nm km). The dispersion in the breakup component is higher in this case than in the first stage, but the YEDFA saturates at 70mW and provides a sufficiently large gain to reach the high-order soliton regime. Figure 2(b) shows the auto-correlation trace taken at the output of the SMF with 40mW of average power coming out of YEDFA. Again we see the two-pulse structure with the separation of about 7 picoseconds. Note that the side peaks are smaller than half the size of the central peak, indicating that the two pulses are not equal in height in this case. Numerical simulations that include Raman effects confirm the observation that for high peak powers the energy gets transferred from one pulse to the other, resulting in asymmetry [3,4].

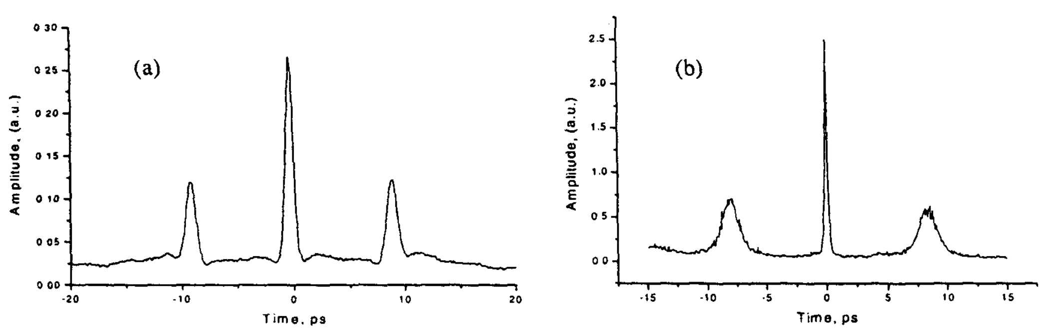

Fig. 2. Auto-correlation traces of (a) the first stage and (b) the second stage 1-to-2 breakup.

The next step is to cascade the two stages. The output of the first stage, as shown in Figure 2(a), with the average power of 8mW is sent through the second stage as described above. The two pulses are chirped in the DCF and then sent into the YEDFA. The gain of the YEDFA is adjusted so that the average power going into the 100m of SMF is 65mW. This way, each of the pulses from the first stage has sufficient chirp and peak power for the breakup to occur as it propagates in the SMF. Figure 3 shows the autocorrelation trace taken at the output of SMF and is the main result of this paper.

The trace is slightly asymmetric due to polarization fluctuations, but four peaks on each side of the central large peak are clearly visible. This auto-correlation trace qualitatively corresponds to the cartoon of the pulse train in time domain that is shown in the inset of Fig. 3. The interpretation is that each of the two almost identical pulses from the first stage has been independently affected by the setup in the second stage and has undergone an independent breakup producing a pair of pulses that are unequal in height. The resulting four-pulse structure would in fact produce a nine-peak auto-correlation such as shown in Figure 3.

In conclusion we experimentally demonstrated a two-stage breakup of a prechirped high-order solitons in anomalous optical fibers. Each of the two stages independently takes a single-pulse input and produces a two-pulse output. The resulting pulses act as independent solitons, and the two stages can be cascaded to observe a one-to-four pulse evolution. Each of the two resulting pulses from the first stage acts as an independent entity and can be broken up again to produce a four-pulse structure.

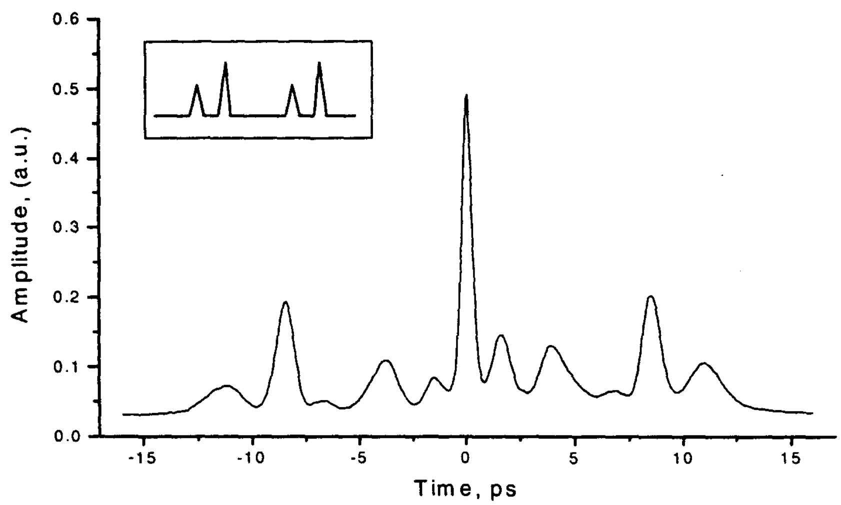

Fig. 3. Auto-correlation trace of the 2-stage 1-to-4 soliton breakup. Inset: reconstruction of the pulse train in time domain.

References.

[1] J.C. Bronski, "Semiclassical eigenvalue distribution of the Zakharov-Shabat eigenvalue problem," Physica D **97,** 376-397 (1996)

[2] J. C. Bronski and J.N. Kutz, "Numerical simulation of the semi-classical limit of the focusing nonlinear Shrodinger equation," Phys. Lett. A **256,** 325-336 (1999).

[3] D. Krylov, L. Leng, K. Bergman, J.C. Bronski, and J.N. Kutz, "Observation of the breakup of a prechirped N-soliton in an optical fiber," Opt. Let. **24,** 1191-1193 (1999).

[4] S. Sears, M. Soljiacic, M. Segev, D. Krylov, and K. Bergman, "Cantor set fractals from solitons," Phys. Rev. Lett., **84,** 1902-1905, (2000)