Soliton control by a weak dispersive pulse

Luca Tartara

Department of Electrical, Computer and Biomedical Engineering, Università degli Studi di Pavia, via Ferrata 5, 27100 Pavia, Italy (luca.tartara@unipv.it)

Received October 27, 2014; revised January 15, 2015; accepted January 15, 2015; posted January 16, 2015 (Doc. ID 225687); published February 5, 2015

A detailed experimental investigation about the propagation of a fundamental soliton interacting with a weak dispersive pulse at an optical event horizon is presented. The results show that the soliton is either redshifted or blueshifted depending on the wavelength of the dispersive pulse. As a consequence of such a wavelength shift, the soliton is either stretched or compressed. The results thus demonstrate the possibility of controlling the propagation of an intense optical pulse by means of a less powerful pulse.

OCIS codes: (190.4370) Nonlinear optics, fibers; (190.5530) Pulse propagation and temporal solitons; (320.7110) Ultrafast nonlinear optics.

http://dx.doi.org/10.1364/JOSAB.32.000395

1. INTRODUCTION

All-optical control of light draws a great deal of interest as it paves the way to the realization of ultrafast logical circuits. Cubic nonlinear materials naturally lend themselves to performing manipulation of light by light because of the dependence of the refractive index on the intensity of the propagating optical field originating from the Kerr effect. Particularly waveguiding structures provide ideal media for nonlinear interactions for their capability of confining the optical radiation for long propagation lengths. The recent advent of microstructured optical fibers has then offered new intriguing opportunities thanks to their high nonlinear coefficients along with tailorable dispersion characteristics [1]. The most investigated mechanism relies on the cross-phase modulation experienced by a dispersive pulse, defined as a weak signal pulse propagating in the normal dispersion regime, by means of an intense pump pulse usually being a soliton-like pulse. Nishizawa and Goto have demonstrated the trapping of a dispersive pulse by a Raman-shifting soliton pulse [2]. As the soliton is progressively shifted to longer wavelengths because of intrapulse scattering, the wavelength of the dispersive pulse gets shorter and shorter fulfilling the group-velocity-matching condition forced by the high index wall induced by the soliton. The effect of the soliton approaching the zero dispersion wavelength (ZDW) has been studied by Hill *et al.* [3]. Efimov *et al.* have carried out an experimental investigation of the interaction of a soliton with a dispersive continuous wave (CW) highlighting some peculiar characteristics related to intrapulse stimulated Raman scattering [4]. A detailed theoretical study of the reflection of a dispersive pulse on the high index wall induced by a Raman soliton has been provided by Gorbach and Skryabin [5]. Beginning from the work of Philbin *et al.* [6], the focus of research has moved to the case of a not-evolving soliton. In such a work the blueshift of a CW dispersive signal by a fundamental soliton not experiencing Raman self-frequency shift is demonstrated. Moreover the authors interpret this phenomenon as the fiber-optical analogue of a white-hole event horizon opening the way to new exciting research opportunities covering different areas of physics. Subsequently the redshift of a CW dispersive signal has been demonstrated as well [7] and a detailed investigation of the phenomenon has been performed both theoretically and experimentally [8]. Other interesting features of such a kind of interaction have been theoretically investigated by Lobanov and Sukhorukov obtaining a critical value for the group-velocity mismatch [9]. Demircan *et al.* have carried out an in-depth numerical study in the case of the interaction between two ultrashort pulses rather than a soliton and a CW signal [10]. They have focused their attention on the effect of the nonlinear interaction on the soliton and have demonstrated that its wavelength and duration are modified as a result of the reflection of the dispersive pulse. In such a way the properties of an intense optical pulse can be varied according to the parameters of a weaker pulse thus leading to a novel proposal for an all-optical transistor. However, experimental results about this mechanism are still lacking.

In this paper, a detailed experimental investigation on the evolution of a soliton pulse reflecting a weaker dispersive pulse is presented. The change of the properties of the soliton are studied as a function of the parameters of the dispersive pulse. In such a way previously unconsidered features of the nonlinear interaction can be investigated and discussed.

2. THEORETICAL FRAMEWORK AND NUMERICAL MODELING

When a dispersive pulse is reflected at the optical event horizon formed by a soliton propagating at a slightly different group velocity, it is shifted at a different wavelength [6]. Depending on the input wavelength of the dispersive pulse, the frequency can either increase or decrease. However, also the soliton is affected by the strong interaction made possible by the optical event horizon [10]. Because of energy conservation, also the soliton wavelength has to change. More precisely, its shift is the opposite of the shift of the dispersive pulse so that when one pulse is blueshifted, the other pulse is redshifted and vice versa. As a consequence the soliton experiences a different value of dispersion and so has to adjust its duration following the conditions required for soliton-like propagation. The scenario is similar to the one occurring in a dispersion-varying fiber, be it a dispersion-decreasing fiber [11] or a dispersion-increasing fiber [12]. In such fibers indeed the soliton-like pulse undergoes a change of its width following the change of the value of dispersion. If the dispersion increases, the pulse is stretched, while if the dispersion decreases, the pulse is compressed. It appears thus possible to tune the properties of an optical pulse by means of a weaker pulse.

This mechanism has also been checked by means of a numerical model based on the nonlinear Schrödinger equation:

$$\frac{\partial A}{\partial z} - \sum_{n\geq 2} \frac{i^{n+1}}{n!}\beta_n \frac{\partial^n A}{\partial T^n} = i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial T}\right)A\cdot\int_{-\infty}^{+\infty} R(T')|A(z,T-T')|^2 \mathrm{d}T', \quad (1)$$

where A is the complex envelope of the propagating field evaluated in a frame of reference traveling at the group velocity of the soliton, z is the spatial coordinate along the fiber, β_n are the dispersion coefficients, γ is the nonlinear coefficient, T is the time coordinate, ω_0 is the soliton angular frequency, and R is the Raman response of the fiber. Details on the solving techniques can be found in [13].

In Fig. 1(a) the evolution along the fiber of a fundamental soliton at the wavelength of 790 nm launched along with a weaker dispersive pulse is shown. The properties of the fiber are the same as the one used in the experiments and will be given in the following paragraph. The dispersive pulse leads the soliton at the input by 400 fs and is centered at the wavelength of 592 nm so that it propagates at a slightly slower group velocity than the infrared pulse. Initially the two pulses do not overlap in time so that the dynamics of the evolution of the soliton are mainly ruled by the Raman effect decelerating the pulse. This is proved by the slight delay acquired in the reference frame moving at the initial group velocity. However the dispersive pulse shown in Fig. 1(b) is progressively approached by the soliton and as soon as it overlaps its leading edge it experiences a strong nonlinear effect due to cross-phase modulation [10]. As a result the group velocity of the soliton noticeably increases as the reversed slope of the trajectory shows. In the frequency domain the pulse has to shift to a different wavelength, namely the wavelength corresponding to the new value of the group velocity. This is confirmed by the spectrum at the output, which turns out to be centered at 787 nm.

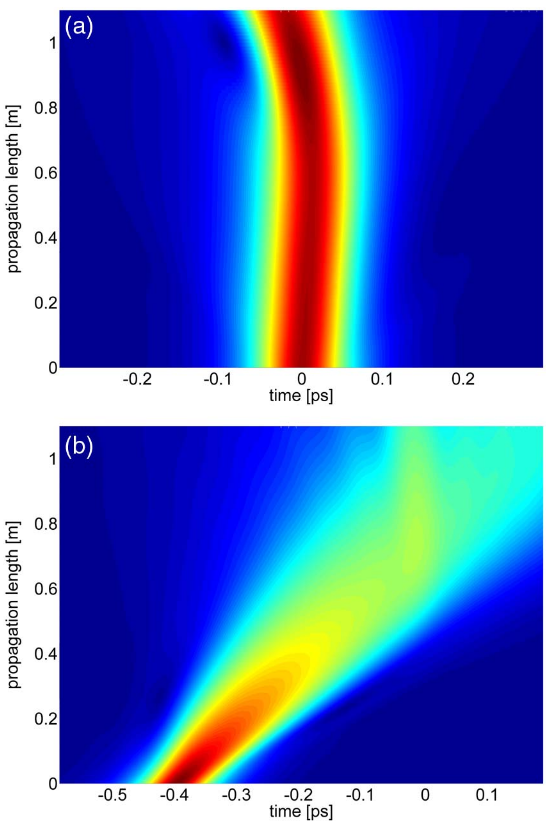

Fig. 1. Propagation of (a) a fundamental soliton and of (b) a dispersive pulse.

3. EXPERIMENTAL RESULTS

As pointed out in [10] a proper dispersion profile is required for an efficient reflection of the dispersive pulse and therefore the properties of a microstructured fiber can be conveniently exploited. The dispersion of the used fiber is shown in Fig. 2. The ZDW is 700 nm so that in the region around 800 nm readily accessible by titanium:sapphire lasers the dispersion is anomalous and a soliton-like pulse can be easily generated. The wavelength of the dispersive pulse has to lie around the group-velocity-matched (GVM) wavelength, which is in the orange-red region of the spectrum. In order to have two pulses at the desired wavelengths, a titanium:sapphire laser system made up by a seed oscillator (Tsunami, Spectra Physics) and a regenerative amplifier (Titan, Quantronix) is employed. The output pulse is centered at 790 nm and has a full-width-half-maximum (FWHM) duration of 70 fs as revealed by an autocorrelation measurement. After a beam splitter two pulses are available: one can be directly used as a soliton, while the other one acts as a pump for an optical parametric generator (TOPAS, Light Conversion).

The pulse out of the parametric generator can be tuned from 1150 to 1600 nm so that the visible portion of the spectrum around 620 nm can be accessed by frequency doubling in a thin beta barium borate crystal. The FWHM pulse width of the visible pulse lies between 80 and 85 fs depending on the wavelength. After an independent power control, the two

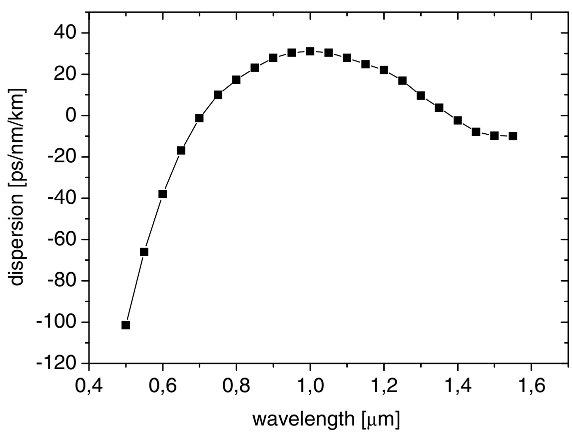

Fig. 2. Dispersion curve of the used fiber.

beams are spatially recombined by a dichroic mirror in order to have a perfect spatial overlap for an efficient coupling into the fiber. The temporal overlap is adjusted by means of a motorized delay line mounted on the path of the visible pulse. An aspheric lens couples the two beams into the 1.1-m long fiber span mounted on a three-axis piezoelectric translation stage. The output radiation is collected by a microscope objective and its properties are measured in the time domain by an autocorrelator and in the frequency domain by an imaging spectrometer. The energy of the infrared pulse is first adjusted at the maximum value at which neither temporal nor spectral distortions are recorded at the output when the dispersive pulse is not copropagating. The corresponding time-bandwidth product is 0.32 so that the generation of a fundamental soliton can be assumed. The corresponding peak intensity is about 2 GW/cm^2 considering an effective area of 2 μm^2 in the wavelength range of interest. Higher intensities of the infrared pulse would lead to the onset of supercontinuum generation hindering the observation of the expected phenomena. When also the dispersive pulse is coupled into the fiber, the soliton pulse undergoes an evolution, which depends on the wavelength, the power, and the time delay of the weaker dispersive pulse, which is coupled into the fiber along with it.

The graph of Fig. 3(a) reports the output pulse width most differing from the input one recorded at each dispersive wavelength. Such results have been recorded at the maximum power of the dispersive pulse being one fourth of the soliton power. The time delay of the dispersive pulse has to be set positive for wavelengths longer than about 612 nm and negative for shorter wavelengths so that at the input the dispersive pulse lags behind the soliton pulse in the former case while the soliton pulse lags behind the dispersive pulse in the latter case. The interpretation of such results is as follows: the wavelength of 612 nm has to be regarded as the GVM wavelength so that a dispersive pulse at a shorter wavelength and coupled into the fiber with a negative delay is progressively approached by the soliton and is finally reflected at the leading edge of the soliton itself. As a consequence the visible pulse is redshifted and thus the infrared pulse is blueshifted. The new soliton wavelength corresponds to a lower value of dispersion so that the pulse is compressed in the time domain just like in a dispersion-decreasing fiber. If the dispersive pulse is at a longer wavelength and initially lags behind the soliton, the scenario is reversed. As soon as the visible pulse overlaps the trailing edge of the infrared pulse, it is reflected and shifted to a shorter wavelength. The soliton then shifts to a longer wavelength with a higher value of dispersion and is thus spectrally compressed like in a dispersion-increasing fiber.

The wavelength shift corresponding to the pulse width shown in Fig. 3(a) is given in the plot of Fig. 3(b). The data confirm the blueshift of the soliton for dispersive wavelengths shorter than the GVM wavelength and the redshift for longer wavelengths. The variation of dispersion which can be estimated by the wavelength shift does not fully account for

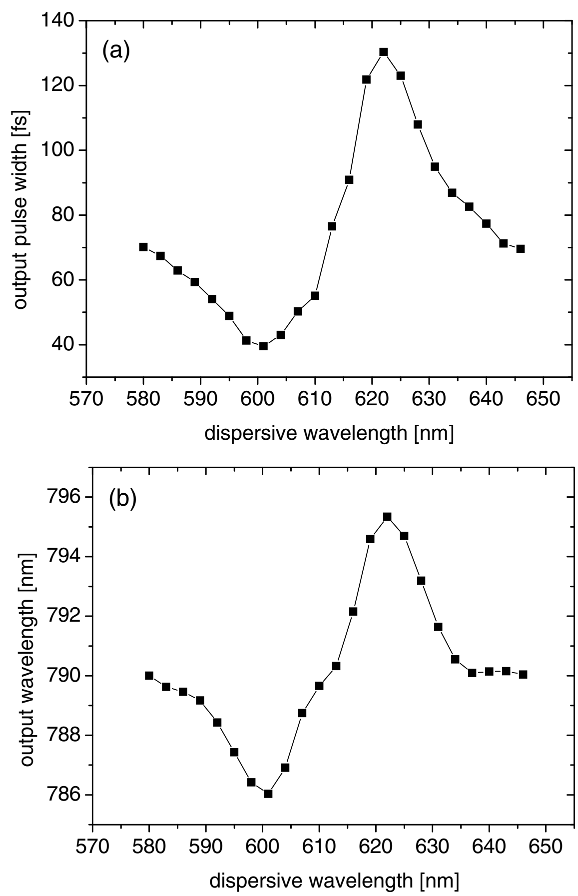

Fig. 3. (a) Output pulse width and (b) wavelength of the soliton pulse as a function of the wavelength of the dispersive pulse.

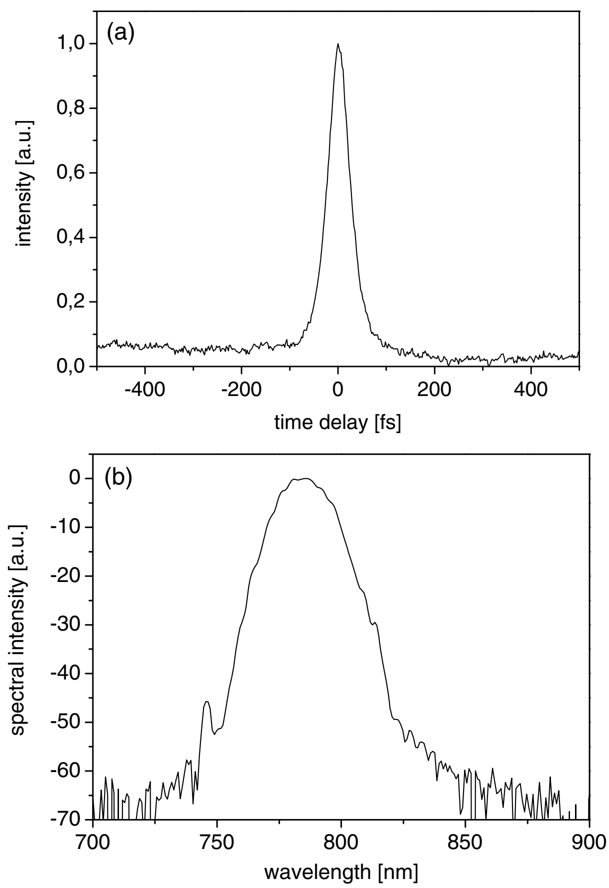

Fig. 4. (a) Soliton autocorrelation trace and (b) spectrum plotted in a logarithmic scale for a dispersive wavelength of 601 nm.

the change of the pulse width according to a simple adiabatic model. The main reason for this discrepancy arising also in numerical models [10] is to be ascribed to the abrupt change of the wavelength as shown by the numerical simulation of Fig. 1. As the wavelength shift takes place on a propagation length being comparable to the soliton period, the adiabatic model cannot be regarded as valid. Moreover, the wavelength shift here described is effective only in the presence of a strong enough higher-order dispersion [10], which is also a condition making the adiabatic model void. Both the spectra and the autocorrelation traces reveal no severe distortion in the pulse. In order to have a deeper verification of soliton-like propagation, the resulting time-bandwidth product has been evaluated finding a mean value of 0.335 very close to the transform limit for an ideal hyperbolic secant shape. The autocorrelation trace and spectrum in the case of maximum soliton compression are given in Fig. 4.

As the nonlinear interaction at an optical event horizon takes place either on the trailing edge of the soliton pulse or the leading edge, the time delay plays a crucial role [10,14]. An investigation of the dependence of the output pulse width on the delay has been carried out at the two dispersive wavelengths of 601 and 622 nm corresponding to the maximum compression and stretching of the soliton, respectively. The power of the dispersive pulse has been kept constant at the same value as the previously shown data. The results are shown in the graphs of Fig. 5.

In the first case the dispersive pulse propagates at a slower group velocity than the soliton pulse. That is the reason why no interaction takes place for a positive delay long enough. On the other hand, the pulse compression is effective when the dispersive pulse initially leads the soliton pulse. The dispersive pulse in fact is progressively approached by the soliton pulse along the fiber and as soon as it overlaps the leading edge of the soliton the interaction is effective. When the two pulses overlap in time to some extent ever since the input of the fiber, the efficiency of the process here described is reduced as the reflection of the dispersive pulse originating the compression of the soliton occurs just at the leading edge of the soliton. For the longer dispersive wavelength, the data can be easily interpreted keeping in mind that the sign of group velocity mismatch is reversed in comparison with the case of the shorter wavelength. As a consequence the nonlinear interaction is effective only when the dispersive pulse is coupled into the fiber after the soliton so that it can catch it up until it is reflected on the trailing edge. On the contrary, if the soliton pulse lags behind the dispersive pulse, no interaction can occur since the dispersive pulse travels at a higher group velocity.

As numerically investigated in [10], the wavelength shift of the soliton pulse increases when increasing the power level of the dispersive pulse because of energy conservation. Figure 6 shows the output pulse width and wavelength of the infrared pulse as a function of the power of the visible pulse at the

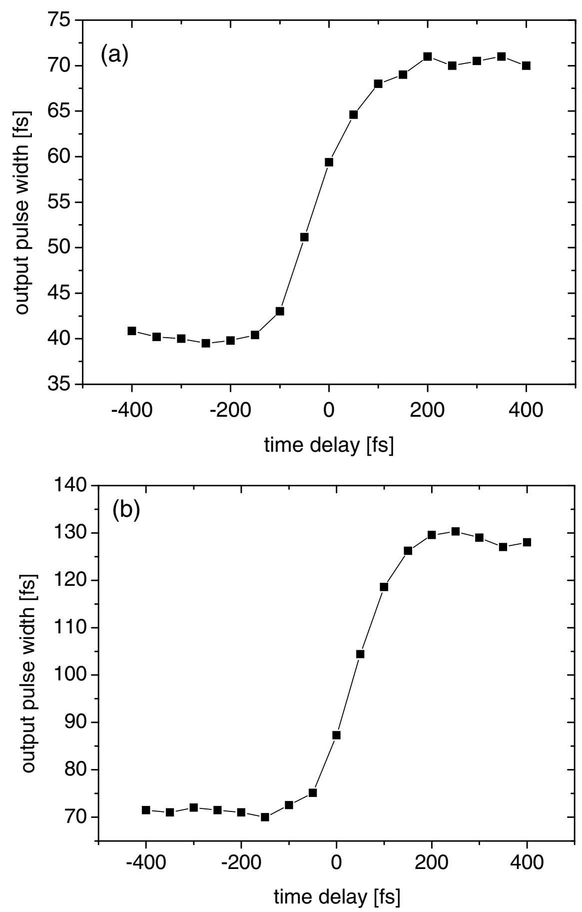

Fig. 5. Output pulse width of the soliton pulse as a function of the time delay of the dispersive pulse for the wavelengths of (a) 601 nm and (b) 622 nm.

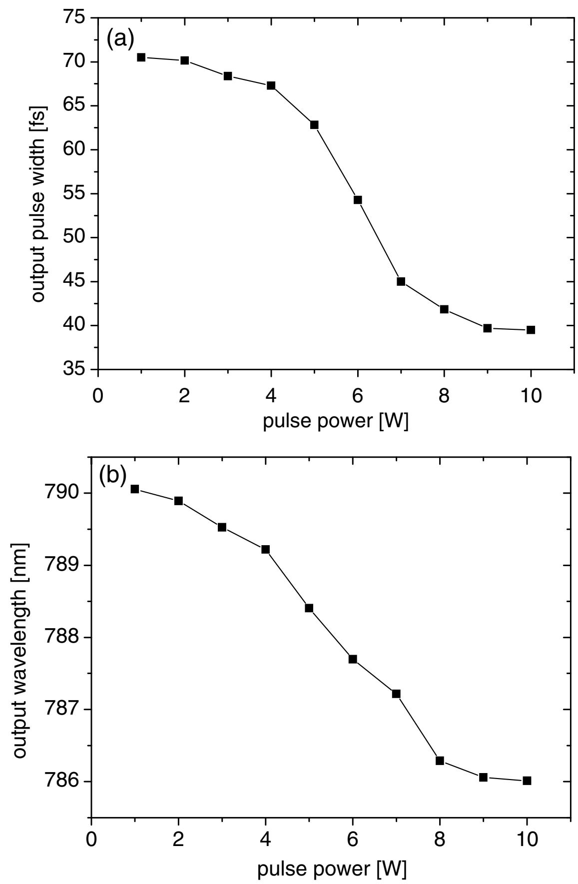

Fig. 6. (a) Output pulse width and (b) wavelength of the soliton pulse as a function of the power of the dispersive pulse at the wavelength of 601 nm.

wavelength of 601 nm for a fixed time delay. At a low power the interaction turns out to be rather weak as the soliton pulse width and wavelength are almost unchanged. When increasing the power, the properties of the pulse change as a result of a strong nonlinear interaction. The data suggest a saturation of the compression for higher power levels. The combined action of self-phase modulation and normal dispersion lead to a major distortion of the pulse in such a way that only a smaller and smaller portion can interact with the soliton. Similar results have been obtained in the case of pulse stretching.

4. CONCLUSION

As a conclusion, it has been experimentally demonstrated that the properties of a soliton pulse can be tuned by means of a weak dispersive pulse. The pulse width and wavelength of the soliton change according to the wavelength, time delay, and power of the dispersive pulse. On the other side, the soliton retains its shape following the interaction with the less powerful pulse. These features make the results very promising for applications in the field of all-optical signal processing and computing.

REFERENCES

1. J. M. Dudley and J. R. Taylor, "Ten years of nonlinear optics in photonic crystal fibre," Nat. Photonics **3**, 85–90 (2009).
2. N. Nishizawa and T. Goto, "Pulse trapping by ultrashort soliton pulses in optical fibers across zero-dispersion wavelength," Opt. Lett. **27**, 152–154 (2002).
3. S. Hill, C. E. Kuklewicz, U. Leonhardt, and F. König, "Evolution of light trapped by a soliton in a microstructured fiber," Opt. Express **17**, 13588–13600 (2009).
4. A. Efimov, A. V. Julin, D. V. Skryabin, J. C. Knight, N. Joly, F. G. Omenetto, A. J. Taylor, and P. S. J. Russell, "Interaction of an optical soliton with a dispersive wave," Phys. Rev. Lett. **95**, 213902 (2005).
5. A. V. Gorbach and D. V. Skryabin, "Bouncing of a dispersive pulse on an accelerating soliton and stepwise frequency conversion in optical fibers," Opt. Express **15**, 14560–14565 (2007).
6. T. G. Philbin, C. E. Kuklewicz, S. Robertson, S. Hill, F. König, and U. Leonhardt, "Fiber-optical analogue of the event horizon," Science **319**, 1367–1370 (2008).
7. S. Robertson and U. Leonhardt, "Frequency shifting at fiber-optical event horizons: the effect of Raman deceleration," Phys. Rev. A. **81**, 063835 (2010).
8. A. Choudhary and F. König, "Efficient frequency shifting of dispersive waves at solitons," Opt. Express **20**, 5538–5546 (2012).
9. V. E. Lobanov and A. P. Sukhorukov, "Total reflection, frequency, and velocity tuning in optical pulse collision in nonlinear dispersive media," Phys. Rev. A. **82**, 033809 (2010).
10. A. Demircan, S. Amiranashvili, and G. Steinmeyer, "Controlling light by light with an optical event horizon," Phys. Rev. Lett. **106**, 163901 (2011).
11. S. V. Chernikov, E. M. Dianov, D. J. Richardson, and D. N. Payne, "Soliton pulse compression in dispersion decreasing fiber," Opt. Lett. **18**, 476–478 (1993).
12. H. P. Chuang and C. B. Huang, "Wavelength-tunable spectral compression in a dispersion-increasing fiber," Opt. Lett. **36**, 2848–2850 (2011).
13. I. Cristiani, R. Tediosi, L. Tartara, and V. Degiorgio, "Dispersive wave generation by solitons in microstructured optical fibers," Opt. Express **12**, 124–135 (2004).
14. L. Tartara, "Frequency shifting of femtosecond pulses by reflection at solitons," IEEE J. Quantum Electron. **48**, 1439–1442 (2012).