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Probe-controlled soliton frequency shift in the regime of optical event horizon

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Abstract: In optical analogy of the event horizon, temporal pulse collision and mutual interactions are mainly between an intense solitary wave (soliton) and a dispersive probe wave. In such a regime, here we numerically investigate the probe-controlled soliton frequency shift as well as the soliton self-compression. In particular, in the dispersion landscape with multiple zero dispersion wavelengths, bi-directional soliton spectral tunneling effects is possible. Moreover, we propose a mid-infrared soliton self-compression to the generation of few-cycle ultrashort pulses, in a bulk of quadratic nonlinear crystals in contrast to optical fibers or cubic nonlinear media, which could contribute to the community with a simple and flexible method to experimental implementations

OCIS codes: (190.7110) Ultrafast nonlinear optics; (190.5530) Pulse propagation and temporal solitons; (320.5520) Pulse compression.

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1. Introduction

Optical event horizon has attracted great interests soon after its proposal [1], which refreshes the understanding of nonlinear interactions of light, especially for the classic topic of the two-color pulse collision [2–5]. Physically, based on the cross-phase-modulation (XPM) effect, an optical event horizon is formed when an intense pump light which gives rise to a strong refractive index barrier so a weak probe light hits the barrier will be velocity inversed as well as frequency shifted, just named in the optical analogue of physics behaviors at an event horizon [1]. Such phenomena were also understood in terms of the four-wave mixing effect [6].

Recent discussions [7–12] on temporal pulse collision and mutual interactions in the regime of optical event horizon are mainly involving an intense solitary wave (i.e. a fundamental soliton (FS)) in the anomalous dispersion range, and a dispersive probe wave (DW) in the normal dispersion range. Then, in such a soliton-probe collision, the FS will maintain its shape during the propagation but get perturbed by DW via the XPM effects, while the DW mainly evolves with temporal broadening and the pulse fraction overlapped with the FS is strongly impacted. The DW fraction will be retorted back when hitting on the event horizon (the energetic FS). The two-pulse collision process has been demonstrated not only in optical fibers to the application of wavelength conversions, light controls [13], pulse compressions as well as supercontinuum generations [14, 15], but also in nonlinear crystals as one of the most recent updates [16].

In this paper, we further investigate the probe-controlled soliton frequency shift in the regime of optical event horizon. We study the frequency shift of idler wave caused by the soliton frequency shift. In addition, we apply such flexibly bi-directional soliton frequency shift scheme to the excitation of the soliton spectral tunneling (SST) effects and therefore a bi-directional SST is proof-of-concept investigated, in a dispersion landscape with multiple zero dispersion wavelengths (ZDWs). In return, the regime of optical event horizon is demonstrated robust since it is still valid in a complicated dispersion circumstance. Moreover, we also investigate the soliton self-compression in the probe-controlled frequency shift scheme, with the soliton pulse being pushed towards the ZDW. We point out such a soliton self-compression is effectively adiabatic and could lead to the high-quality compression in the few-cycle regime. We highlight such pulse compression schemes not only with the application in the few-cycle pulse generations in near- and mid-infrared, but also with the implementation in a quadratic nonlinear crystal in contrast to commonly known optical fibers as well as cubic nonlinear media, which is a complementary to the experimental implementation of optical event horizon.

2. Typical two-pulse collision process and XPM-induced frequency chirp

Typical two-pulse collision process in the regime of optical event horizon is illustrated in Fig. 1 by using a generalized nonlinear Schrödinger equation (GNLSE) [17]:

$$\frac{\partial A(z,T)}{\partial z} = \mathscr{F}^{-1}\left(D(\omega)\tilde{A}(z,\omega)\right) + i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial T}\right)A(z,T)\int_{-\infty}^{+\infty} R\left(T-T'\right)\left|A\left(z,T'\right)\right|^2 dT', \tag{1}$$

Considering two hyperbolic secant pulses as pump FS $A_1(0,T) = \sqrt{P_1}\mathrm{sech}(T/T_2)$, and probe DW $A_2(0,T) = \sqrt{P_2}\mathrm{sech}[(T-T_d)/T_2]$. By properly locating (delaying or advancing) the FS with respect to the DW, efficient blue-shift or red-shift of FS is achievable and controllable [13]. Moreover, such a probe induced soliton frequency shift is corresponding to the soliton temporal entrapping by the probe wave, where the soliton always has a trend to temporal shift towards the probe wave, by either speeding up or slowing down its group velocity.

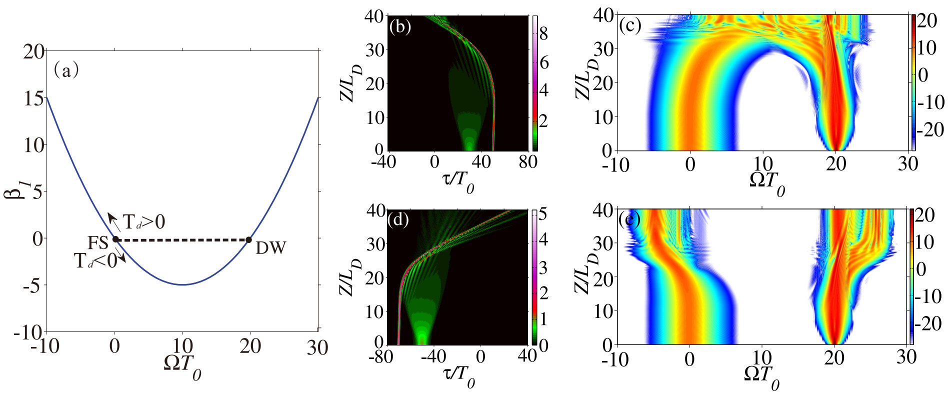

Fig. 1. Simulation of two-pulse collision by using fiber dispersion coefficients ($\overline{\beta}_1$ =0, $\overline{\beta}_2$ = -1, $\overline{\beta}_3$ = 0.1) at the FS and the nonlinear coefficients are set to 1. Raman effect is not included. (a) Corresponds relative group delay $\beta_1 = 1/V_{g1}$. (b,c) Temporal and spectral evolution of pulse collision when $T_d = -20$, and FS has a process of spectral blue-shift. (d,e) $T_d = 20$, FS has a process of spectral red-shift. FS is centred at 0 and DW is centred at 20, $P_1 = 4, P_2 = 1, T_1 = 0.5, T_2 = 4$.

To understand the soliton frequency shift better, we derive the expression of probe-induced soliton frequency shift from the XPM-induced frequency chirp by using the coupled nonlinear Schrödinger equations (CNLSEs) of two pulses [17]. In the propagation moment where z = L: Assuming two pulses at identical group velocities, the XPM-induced frequency chirp of FS is well approximated by:

$$\delta\omega(T) = -\frac{\gamma_1 L}{\pi}\frac{\partial}{\partial T}\left|A_2(L,T)\right|^2. \tag{2}$$

γ_1 is the nonlinear parameters of FS. Equation (2) suggests that the frequency chirp working on the FS qualitatively depends on the pulse intensity profile of the DW. And consistent with what is illustrated by Fig. 1, soliton frequency shift is mainly dominated by P_2 and T_d (has little to do with T_d, because at the moment of collision happening, the pulse duration of the DW is approximately twice as the initial time delay T_d). Such frequency chirp corresponds to a spectral shift by properly locating the FS with respect to the DW. It is emphasized that it is exactly in the regime of optical event horizon that such interaction is effectively enhanced, since the probe DW is long in temporal duration and is of high coherence, and the intense soliton could always maintain the wave packet when being frequency shifted.

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3. The frequency shift of idler wave and SST effects during the collision process

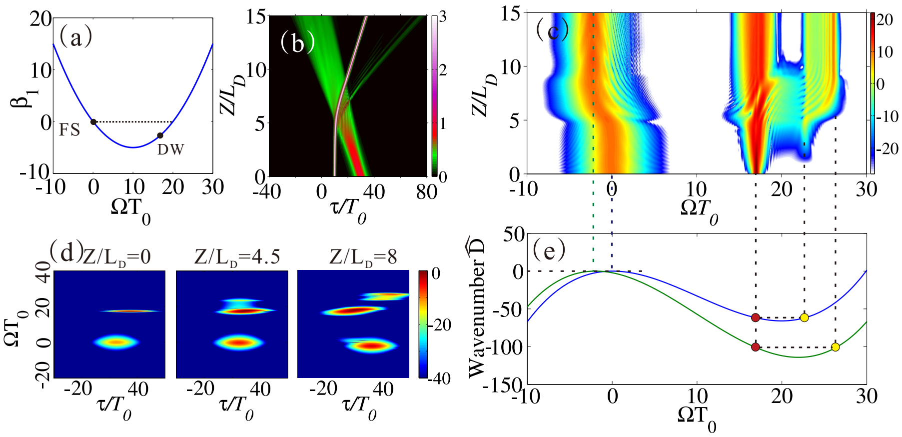

Fig. 2. (a) Two-pulse collision with group velocity mismatch (input FS is centred at 0 and DW is centred at 17). (b,c) Temporal and spectral evolutions with same parameters of Fig .1(d,e). (d) spectrograms at different propagation lengths. (e) Wavenumber $\hat{D}(\omega-\omega_s) = \sum_{k\geq 2}\beta_k/k!\cdot(\omega-\omega_s)$.

In a regime of optical event horizon, the probe DW can experience a frequency conversion to an idler wave at ω_i, according to the resonance condition $\hat{D}(\omega_i-\omega_s) = \hat{D}(\omega_p-\omega_s)$ [6]. During the collision process, since the center frequency of the FS shifts, the phase-matched probe-idler pair is modified as well. Figures 2(b) and 2(c) show that the DW partly converts into new frequencies ω_i, termed the idler wave, and both the frequency of the FS and new idler wave ω_i shift during the collision process. Just as is shown in Fig. 2(e), the phase-matched probe-idler pairs change because the frequency of FS changes from 0 to 2, and the frequency of idler wave shifts from 22.6 to 26.3 correspondingly, generating a broadband idler wave. The evolution dynamics of the FS and the idler both shifting in the collision process can be confirmed from Fig. 2 (d), by employing the XFROG.

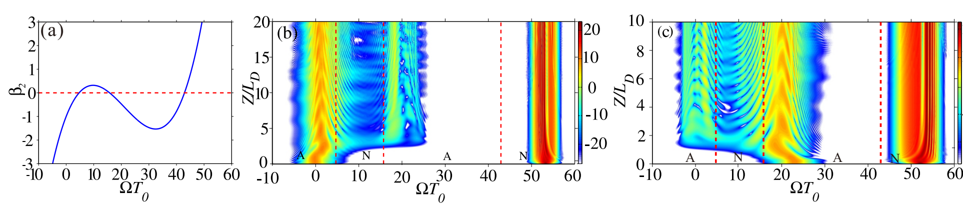

Fig. 3. Simulation by using fiber dispersion coefficients ($\overline{\beta}_1$ =0, $\overline{\beta}_2$ = -1, $\overline{\beta}_3$ = 0.3, $\overline{\beta}_4$ = -0.04, $\overline{\beta}_5$ = 0.0019) at the FS. (a) Group velocity dispersion (GVD) curve. (b) Blue side SST effect evoked by collision induced blue-shift of the FS. (c) Red side SST effect evoked by collision induced red-shift of the FS.

We promote the discussion of such soliton and probe interactions in another quite common dispersion landscape, i.e. in the presence of multiple ZDWs, which is already well implemented in photonic crystal fibers by means of dispersion engineering. In this case, we demonstrated that optical event horizon still works, giving rise to probe-induced soliton frequency shift. Classical SST effect is often interpreted as a soliton passing through a section of normal dispersion

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region, driven by the Raman induced frequency shift, which is always red-shifted and could balance the spectral recoil effect [18, 19]. But here we propose to make use of probe-induced soliton frequency shift, which could not only take the place of the Raman-induced soliton red-shift but also enable the SST to the short wavelength side. Under the condition of three ZDWs, Figures 3(b) and 3(c) display the spectrums of two-pulse collision causing blue/red shifting, accompanied with blue/red side SST effect at the FS. At the beginning, DW broadens both in time spectrum domain and then the launched soliton collides with the broadened DW and shifts to the blue/red side continually. By properly tailoring the dispersion profile and locating the FS, FS will shifts towards where the coupling is evoked, then partly couples from one anomalous dispersion regime to another, with a considerable efficiency.

4. Generation of few-cycle mid-infrared pulses in the BBO crystal

An important application of collision-induced FS spectral shift is found in pulse compression and supercontinuum generation (SCG), in which the FS is controlled by a small DW and shifted towards a zero dispersion wavelength, the soliton adiabatically changes its shape owing to the decrease of β_2 (leading to an increase in the soliton order), while the pulse width of soliton will decreae for keeping the soliton order unchanged. Particularly, in photonic crystal fibers of highly nonlinear materials (e.g. ZBLAN, and chalcogenide), such as the reported scheme provides the possibility of pulse compression and SCG in the mid-infrared (in the anomalous GVD regime) [15], while the controlling DW is located in the near-infrared that is of many choices with commercial laser systems.

Besides cubic Kerr materials, we point out that such scheme is also possible in quadratic nonlinear crystals since soliton formation could be implemented as well in those $\chi^{(2)}$ materials [20,21]. The idea of using $\chi^{(2)}$ crystals is to make use of the cascaded nonlinearity that is an equivalent cubic Kerr nonlinearity but stems from phase mismatched quadratic processes such as the second harmonic generation. With energy quickly converted between the fundamental wave and the second harmonic (in the phase mismatched cascading process), an intensity related nonlinear phase shift is introduced on the fundamental wave. Such cascaded quadratic nonlinearity is flexible controlled by the phase mismatch parameter, through e.g., the angle tuning in the birefringent configuration or quasi-phase-matching tuning in a non-critical configuration.

To implement mid-IR pulse compression, we make use of the cascaded nonlinearity in a β-barium borate (BBO) crystal, in which optical analogy of the event horizon was recently investigated [16], cut for birefringent type-I interaction. We tune the phase mismatch parameter in the wavelength range by angle-tuning the crystal, so that the nonlinearity is positive signed matching the anomalous dispersion in the mid-IR to support soliton formations. We target at pulse compression at 2-μm out of Tm^{3+} doped fibers. The BBO crystal dispersion landscape implies that a 1.06-μm DW is suitable to induce the collision and control the soliton shift. Figures 4(c) and 4(d) show two-pulse collision in the BBO crystal and the soliton pulse is extremely compressed, shifting to the blue side simultaneously. A soliton pulse of 80 fs (50 GW/cm^2) at 2-μm is compressed to 14 fs (FWHM) during two-pulse collision with a probe DW (200 GW/cm^2) pulse of 100fs, accompanied with a over 1000-nm SCG. The peak intensity of soliton at z=38 mm is increased by over 10 times, as is showed in Fig. 4(e). Crystals usually have high threshold of thermal damage so they could handle high-energy and high-intensity pulses, overcoming the limitations for pulse energy and intensity in fibers. Moreover, the dispersion as well as the nonlinearity in a crystal is much larger than that in fibers, leading to an efficient pulse compression and SCG within a short propagation distance (usually in centimeters). Such a configuration could be easily implemented in a free space optics lab. The pulse collision even happens in a non-collinear scheme thanks to the short interaction length.

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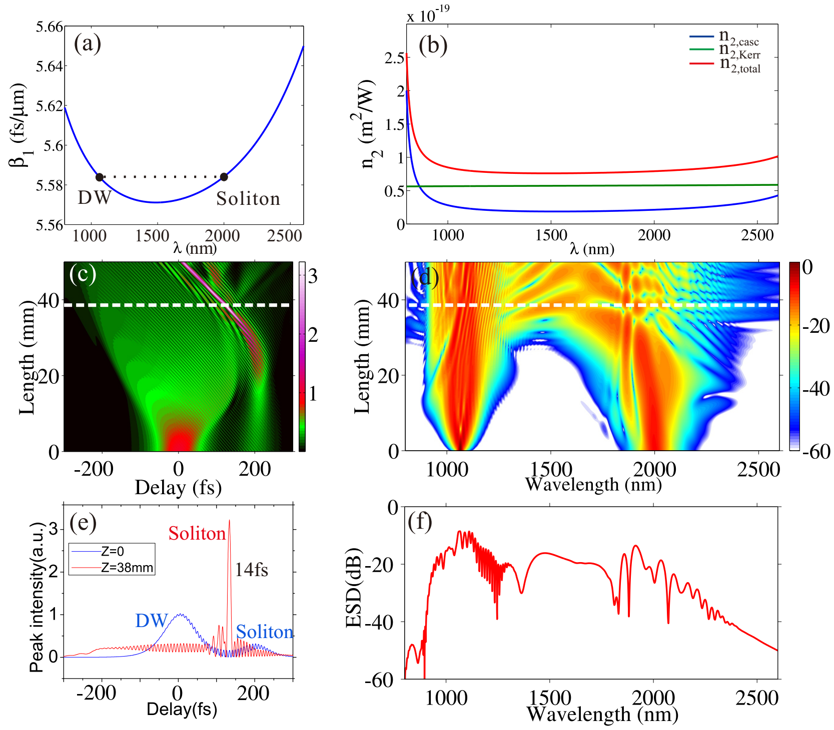

Fig. 4. Evolution of two-pulse collision in the BBO crystal ($\theta = 30^{\circ}$) by nonlinear wave equation in frequency domain (NWEF) [22]. (a) Relative group delay β_1. (b) n_2 of both the cascaded quadratic nonlinearity and the Kerr nonlinearity. (c) Temporal and (d) spectral evolution of two-pulse collision in the BBO crystal, the time delay between two initial pulses is -200 fs. (e) The envelope profile of the pulses at z= 0 and z= 38 mm. (f) The spectral profile of the pulses at z= 38 mm.

5. Conclusion

As a conclusion, we investigated the temporal pulse collision between an intense soliton and a weak dispersive probe wave, in the dispersion landscape with multiple ZDWs where the optical analogy of event horizon is valid. In such a regime, probe-controlled soliton frequency shift was discussed and applied to excite bi-directional SST effects to both blue and red wavelengths. Based on the understanding of soliton frequency shift, we further investigated the soliton self-compression with the pulse being pushed towards the ZDW. We numerically demonstrated such a compression scheme in a quadratic nonlinear crystal, in which a near-infrared 1-μm probe is controlling a mid-infrared 2-μm solitary pulse and gives rise to soliton compression to the few-cycle regime. Our proof-of-concept investigations based on crystals is complementary to previous discussions of the topic mainly in optical fibers.

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