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Cancellation of Raman self-frequency shift for compression of optical pulses

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Abstract

We study to which extent a fiber soliton can be manipulated by a specially chosen continuous pump wave. A group velocity matched pump scatters at the soliton, which is compressed due to the energy/momentum transfer. As the pump scattering is very sensitive to the velocity matching condition, soliton compression is quickly destroyed by the soliton self-frequency shift (SSFS). This is especially true for ultrashort pulses: SSFS inevitably impairs the degree of compression. We demonstrate numerically that soliton enhancement can be restored to some extent and the compressed soliton can be stabilized, provided that SSFS is canceled by a second pump wave. Still the available compression degree is considerably smaller than that in the Raman-free nonlinear fibers.

1 Introduction

The generation of ultrashort few-cycle optical pulses with a controlled waveform followed by the generation of ultra-broadband continua is an important topic in modern nonlinear optics. Different approaches have been suggested [3, 15, 9, 17, 5] resulting in the impressive spread of pulse spectra, ranging from the ultraviolet into the terahertz regime. In what follows we report on the modified pulse compression scheme originally suggested in [6, 2]. The scheme is based on cross-phase modulations between the compressed soliton and one or several pump waves [7, 14, 18]; it is schematically illustrated in Fig. 1. Here, a fiber soliton creates a nonlinear perturbation of the refractive index, the pump wave is scattered at this perturbation and transfers its energy and momentum to the soliton, which is then compressed. This kind of interactions can be understood as an optical analogue of the event horizons [10, 8] and quantified using adiabatic approach and quantum mechanical scattering theory [4, 11].

More specifically, to compress a soliton with carrier frequency ω_a one first looks for a frequency ω_b leading to matched group velocities, such that

$$\beta'(\omega_a) = \beta'(\omega_b), \tag{1}$$

where the group velocity is $v_g = 1/\beta'$, and $\beta'(\omega)$ denotes the first derivative of the wavenumber k given by the dispersion law $k = \beta(\omega)$. Typically $\omega_{a,b}$ belong to opposite sides of the zero-dispersion frequency ω_{ZDF} at which β'' vanishes (Fig. 2). A pump wave with a slightly shifted carrier frequency $\omega_b + \Omega$ is then scattered at the soliton. The soliton frequency is blue-shifted, accompanied by the solitons compression, resulting in a significant increase in the peak power (Fig. 3). The increase can be optimized by a careful choice of the offset Ω, as quantified in [12], also cf. Fig. 6.

As an example, Fig. 3 shows an interaction of a dispersive pump pulse reflected at a soliton, resulting in a nearly tenfold increase of soliton's peak power. Yet, these calculations ignore the Raman scattering.

Raman scattering manifests itself in the soliton self-frequency shift (SSFS), a continuous red-shift of the carrier frequency that applies to any few-cycle fiber soliton with the exception of the Raman-free gas-filled fibers [1]. The SSFS clearly destroys the group velocity matching condition (1) and suppresses soliton amplification. In temporal domain the impairement of the velocity-matching condition

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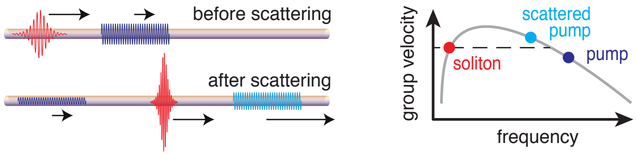

Figure 1: An optical soliton (red) serves as a scatterer for the velocity matched pump wave (blue) and experiences an increase in peak power.

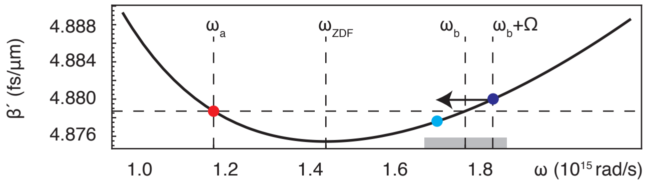

Figure 2: A typical dispersion profile (bulk fused silica) for which a soliton (red point) is effectively compressed by a group velocity matched pump wave (blue point). The pump must belong to the gray domain, which provides a nearly perfect scattering and maximizes energy/momentum transfer. The soliton frequency shift (not shown) is considerably smaller than that of the pump.

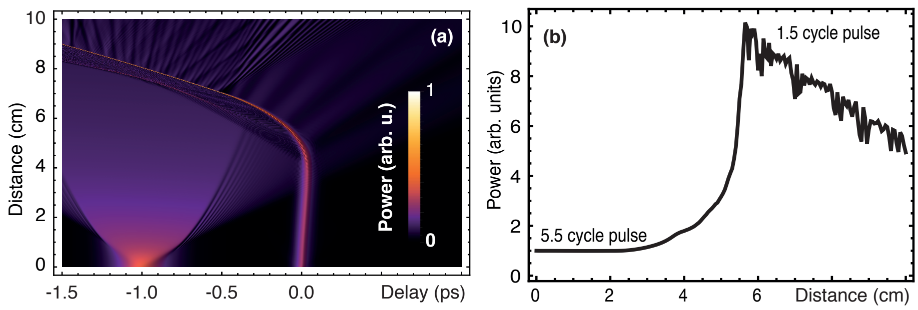

Figure 3: (a) A dispersive wave packet (left pulse, 540 nm, at half maximum (FWHM) 176 fs, and initially 2 times initial soliton power, bulk silica dispersion) is reflected/scattered at a fundamental soliton (right pulse, 2800 nm, 53 fs FWHM). The Raman scattering is artificially switched off. (b) The gain of the soliton peak power is approximately by a factor 10.

becomes obvious. The Raman scattering bends the soliton trajectory away from the pump (Fig. 4b). Fig. 5a shows a more extreme, yet typical case. The soliton “avoids” an interaction altogether, though both pulses started close together. The initial parameter values for the pulses must be chosen so as to generate any collision at all.

To overcome the SSFS effect and force compression of a frequency-shifted soliton, one has to use a considerably more powerful pump wave [6]. Moreover, the pump frequency offset Ω has to be adjusted so as to match the group velocity condition (1) precisely at the scattering point and with the yet unknown soliton carrier frequency [2]. This procedure is sophisticated, and it comes as no surprise that experimentally observed pulse compression rates were considerably below the theoretical predictions [16].

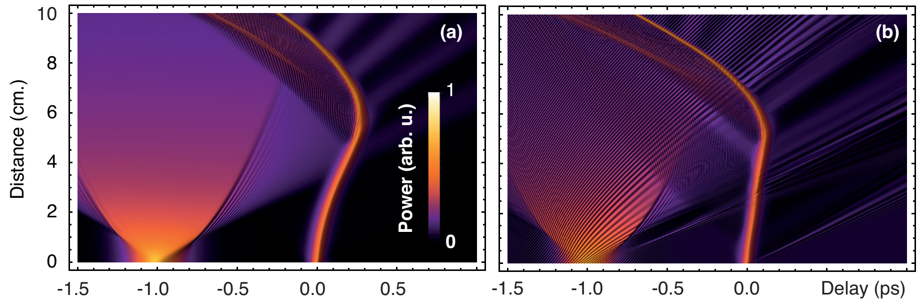

Figure 4: (a) A dispersive wave packet (left pulse, 540 nm, FWHM 176 fs) is reflected/scattered at a fundamental soliton (right pulse, 2800 nm, FWHM 53 fs, fused silica). The Raman scattering is switched on. The soliton follows a curved trajectory. It tends to avoid the pump wave and peak power only rises by a factor 2. (b) The soliton trajectory is straightened by an additional low-amplitude continuous pump wave (487 nm, 2% of the initial soliton peak power). The final soliton peak power is 25% larger then in (a) but still much smaller then that in the Raman-free calculation shown in Fig. 3.

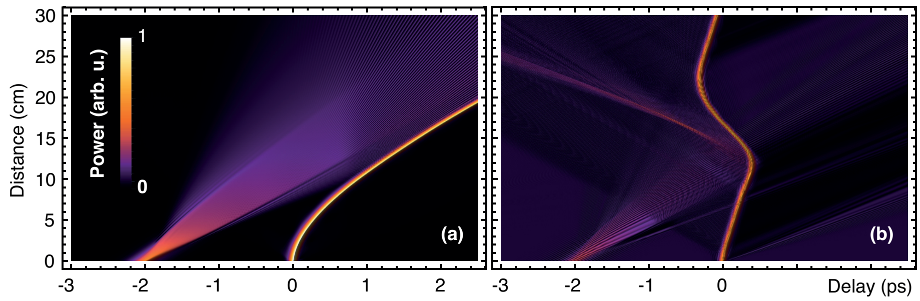

Figure 5: (a) Due to Raman scattering the soliton trajectory (right pulse, 2800 nm, FWHM 53 fs) bends away from the dispersive pulse (left pulse, 504 nm, FWHM 176 fs, 5% of the initial soliton peak power). (b) The soliton trajectory is straightened by an additional low-amplitude continuous pump wave (487 nm, 1.2% of the initial soliton peak power) and interaction with the main pump wave is forced. Soliton peak power is temporarily amplified by a factor 1.3.

2 Compression schemes

In this contribution we suggest and investigate two options to facilitate compression of fiber solitons despite the negative impact of Raman scattering. The first option is to restore the velocity matching condition by compensating the SSFS with the scattering of a second pump wave. The second option is to adjust the pump peak power to force compression.

2.1 First construction using two pump waves

Starting with the first procedure, we apply a combination of two pump waves. Both pump waves evolve almost independently of each other and serve different purposes: the main pump pulse compresses the soliton, similar to the Raman-free case (Fig. 4a). The second pump is chosen to cancel out the effects of the SSFS. It is an almost invisible low-amplitude continuous wave that precisely compensates SSFS and yields a soliton that propagates along the fiber with almost no changes until the main pulse can reach it (Fig. 4b).

The main pump wave is chosen to provide the most efficient compression of the initial soliton following

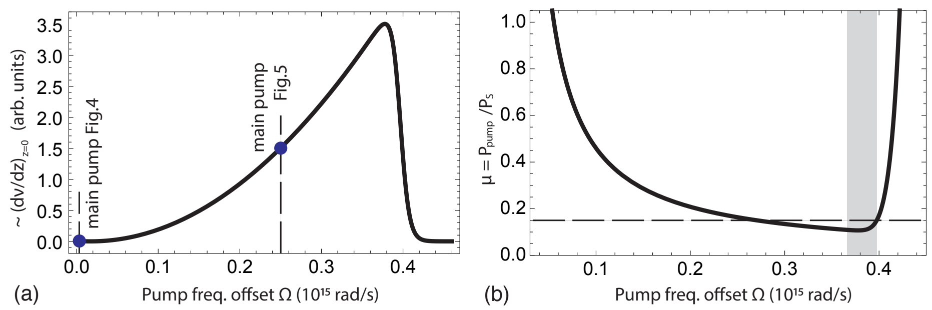

Figure 6: (a) Interval of initial pump frequencies for an effective interaction with a soliton of initial carrier frequency $\omega_a = 0.67$ PHz (2800 nm wavelength) and FWHM of 53 fs. The maximum of the curve indicates the frequency for the strongest initial influence on the soliton. (b) Pairs of initial pump frequency and amplitude for cancelling the SSFS for a soliton as in (a). The shaded region indicates the parameter region for a stable compensation.

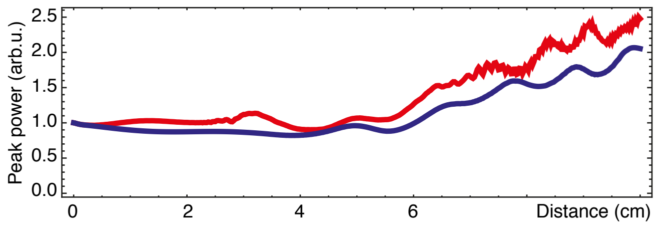

Figure 7: The relative peak power of the compressed fundamental soliton for the calculations shown in Fig. 4a (blue) and Fig. 4b (red). Cancellation of the SSFS leads to an approximately 25% increase of the final peak power.

[12]. Fig. 6a shows the z-derivative $d\nu/dz$ of the solitons frequency shift ν from initial carrier frequency ω_a at the beginning of the fiber vs. the initial pump frequency offsets Ω from ω_b. The curve indicates the initial impact of a pump with varying frequencies on the soliton. The maximal initial impact is expected at the peak of the curve. For the example shown in Fig. 4 Ω is chosen very close to ω_b, which ensures a longer interaction time and produces a strong soliton amplification over a longer propagation distance. The example in Fig. 5 uses an Ω closer to the frequency of maximal initial impact, producing a stronger amplification during a rather short interaction time.

The second pump pulse is quantified following [13]. Fig.6b indicates parameter pairs of pump power over initial soliton power $\mu = P_{pump}/P_s$ and Ω for which the soliton frequency stays unchanged, i.e. $d\nu/dz = 0$. The gray shaded region indicates parameter values for a stable SSFS cancellation.

The pulse compression resulting from the two pump waves is more pronounced than that from a single pump (Fig. 7) but still considerably smaller than in a Raman free case (cf. Fig. 3). For those cases as in Fig. 5, the trajectory of the soliton is stablilized by the second wave long enough to keep the velocity matching condition almost unimpaired. A collision of soliton and the main pump pulse is forced and results in a temporary soliton amplification of 30%. This is a huge advantage when setting up initial conditions also for experiments.

2.2 Construction using only one pump wave

A second option for compressing a soliton despite the SSFS uses just one pump wave. The pump peak power is adjusted to simply overpower Raman scattering. The main advantage over the previous work

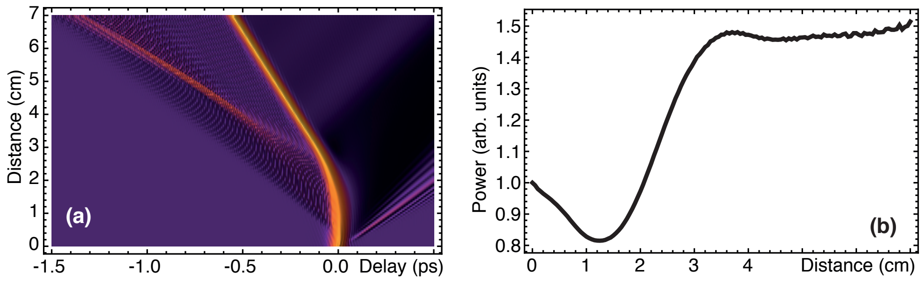

Figure 8: (a) Soliton (2800 nm, FWHM 53 fs) compressed by a continuous pump wave (504 nm, 5% initial solitons peak power). The soliton stabilizes at 2612 nm wavelength and (b) its peak power is amplified by a factor 1.5.

[6] is that the parameter pairs of Fig. 6b for SSFS-cancellation provide a guideline for suitable initial parameters. Again we choose Ω from the shaded region of stable compensation, but now together with a relative peak power μ which is higher than the suggested one for exact SSFS-cancellation. The soliton will be compressed over a short propagation distance and then stabilize, (Fig. 8). Final soliton frequency and peak power can be quantified using the theory provided in [11, 13].

3 Conclusion

We demonstrated how a fiber soliton can be effectively compressed despite the influence of Raman scattering. We can find a continuous pump wave to counteract SSFS and thereby forcing an interaction with a second pump pulse. Further a monochromatic pump wave can be chosen, which can compress a soliton and counteract the SSFS of the resulting soliton. The necessary parameters for both procedures can be chosen systematically using quantifications provided in [12, 13].

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