Cancellation of Raman Self-frequency Shift for Compression of Optical Pulses

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***Abstract*—We study how an optical fiber soliton can be manipulated and compressed by interactions with a properly prepared group velocity matched pump wave (waves). The pump wave is scattered at the soliton, which is then accelerated, compressed, and may even reach a nearly single-cycle regime. Unfortunately, the pump wave scattering is efficient only in a narrow frequency window and the scattering process is easily destroyed by the soliton self-frequency shift. The latter inevitably violates the velocity matching condition. We demonstrate numerically that soliton enhancement can be to some extent restored if soliton self-frequency shift is previously canceled by an additional pump wave. Still the available compression degree is considerably smaller than that in the Raman-free nonlinear fibers.**

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 [1]–[5] resulting in the impressive spread of pulse carrier wavelengths, ranging from the ultraviolet into the terahertz regime. In what follows we report on the modified pulse compression scheme originally suggested in [6], [7]. The scheme is based on cross-phase modulations between the compressed soliton and one or several pump waves [8]–[10]; 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 [11], [12] and quantified using adiabatic approach and quantum mechanical scattering theory [13], [14].

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

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

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 latter experiences 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 [15].

An exemplary calculation presented in Fig. 3 demonstrates a nearly tenfold increase of soliton's peak power due to the pump degradation, but ignores the Raman scattering. The latter

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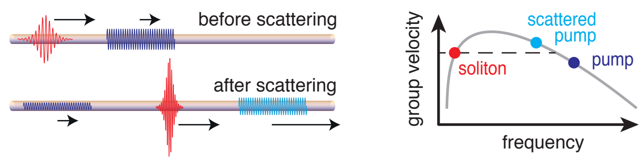

Fig. 1. An optical soliton (red) serves as a scatterer for the velocity matched pump wave (blue) and experiences an increase in the peak power.

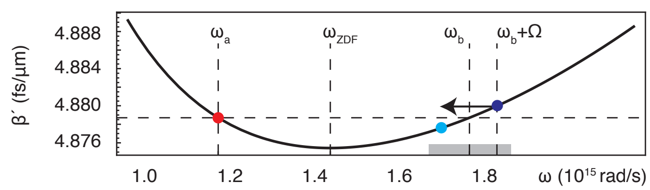

Fig. 2. A typical dispersion profile (bulk fused silica) for which a soliton (red point) is effectively compressed by a group velocity matched pump wave (blue point). The pump must belong to the gray domain, the latter provides a nearly perfect scattering and maximizes energy/momentum transfer.

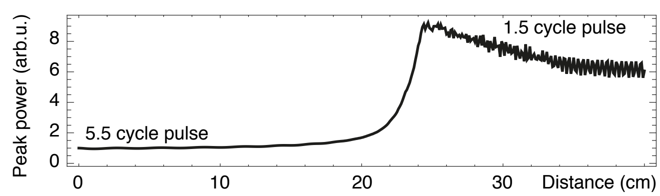

Fig. 3. A fundamental soliton (2800 nm, 53 fs at half maximum (FWHM), bulk silica dispersion) is subject to an approximately tenfold increase of its peak power due to interaction with a low-intensity (2% of soliton's initial power) pump wave at 525 nm.

manifests itself in the soliton self-frequency shift (SSFS), a permanent decrease of the carrier frequency that applies to any few-cycle fiber soliton with the exception of the Raman-free gas-filled fibers [16]. SSFS clearly destroys the group velocity matching condition (1) and suppresses soliton amplification.

To overcome the SSFS effect and to force compression of a frequency-shifted soliton one has to use a considerably more powerful pump wave [6]. Moreover, one has to adjust the pump frequency offset Ω such that the group velocity matching condition (1) is satisfied precisely at the scattering point and with the yet unknown soliton carrier frequency [7]. This is a sophisticated procedure and it is not surprising that experimentally observed pulse compression rates were considerably below the theoretical predictions [17].

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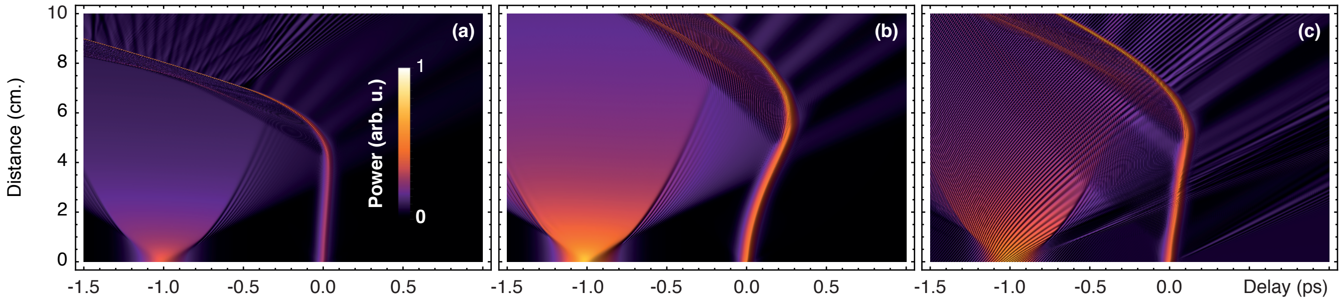

Fig. 4. (a) A dispersive wave packet (left pulse, 540 nm, FWHM 176 fs) is reflected/scattered at a fundamental soliton (right pulse, 2800 nm, FWHM 53 fs, fused silica). The Raman scattering is artificially switched off. The soliton gains an approximately tenfold increase in the peak power. (b) The Raman scattering is switched on. The soliton intrinsically follows a curved trajectory. It tends to avoid the pump wave and experiences only a twofold increase in the peak power. (c) Soliton's trajectory is straightened by an additional low-amplitude continuous pump wave (487 nm, 2% of the initial soliton peak power). The final soliton's peak power is 25% larger then in (b) but still much smaller then that in the Raman-free calculation (a).

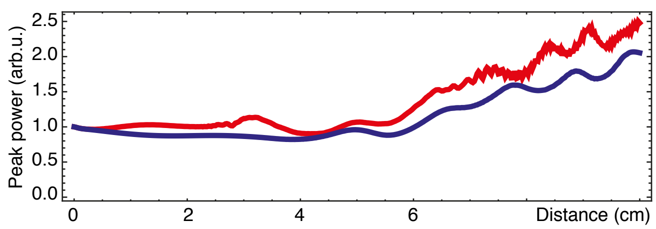

Fig. 5. The relative peak power of the compressed fundamental soliton for the calculations shown in Fig. 4b (blue) and Fig. 4c (red). Cancellation of the SSFS leads to an approximately 25% increase of the final peak power.

In this contribution we suggest and investigate another option to compress fiber solitons despite of the SSFS effect. Namely, we apply a combination of two pump waves. The main pump compresses the soliton, similar to the Raman-free case, which is shown in Fig. 4a. The Raman scattering changes soliton trajectory, such that the soliton "avoids" the pump (Fig. 4b). To repair soliton behavior we apply an additional, second pump, which is an almost invisible low-amplitude continuous wave that precisely compensates SSFS, as quantified in [18]. The compensation is stable and yields a soliton that propagates along the fiber with almost no changes (Fig. 4c for $0 < z < 5$ cm). The main pump wave is chosen to provide the most efficient compression of the initial soliton following [15]. Both pump waves evolve almost independently of each other and serve different purposes: the first pump cancels the SSFS and the second pump compresses the soliton. The pulse compression resulting from the two pump waves is more pronounced than that from a single pump (Fig. 5) but still considerably smaller than in a Raman free fiber (cf. Fig. 3).

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