Mitigation of self-phase modulation by sinusoidally time varying phase

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The propagation of intense ultra-short optical pulses in a Kerr medium such as an optical fibre still remains a critical issue for the performance of many optical systems such as beam delivery, optical communication or pulse amplification systems. This is because the self-phase modulation (SPM) of the propagating pulse usually causes a broadening of the pulse spectrum that is typically accompanied by an oscillatory structure covering the entire frequency range. Several strategies have been proposed and successfully deployed to counteract the deleterious effects of SPM in fibre-optic systems. These include spatial or temporal scaling to reduce the impact of nonlinearity via the use of very large mode area fibres or chirped pulse amplification. A different class of approaches relies on the exploitation of the peculiar properties of parabolic shaped pulses and self-similar evolution, the use of other types of pre-shaped input pulses, and the compensation of nonlinear phase shifts with third-order dispersion. However, none of these last techniques preserves the pulse temporal duration.

A simple technique to compensate the nonlinear phase due to SPM and related spectrum broadening of nanosecond or picosecond optical pulses consists in using an electro-optic phase modulator to impart the opposite phase to the pulses. This method, which emulates the use of a material with a negative nonlinear index of refraction, has proved successful in fibre-optic and free-space optical telecommunication applications using phase-shift keying systems and in the generation of high-peak-power nanosecond pulses.

We have recently experimentally demonstrated that for Gaussian shaped input pulses, the use of a simple sinusoidal drive signal for the phase modulator with appropriate amplitude and frequency is sufficient to reduce the nonlinear spectrum broadening to a large degree, and to significantly enhance the spectral quality of the pulses while their temporal duration remains unaffected. In this paper, we present a comprehensive analysis of the SPM-mitigation method involving the use of a sinusoidal phase modulation. Most of the previous works are primarily experimental in nature and have not discussed the sensitivity of the technique to the initial pulse characteristics.

First, we recall the concept of our method and overview our proof-of-principle experiment. Next, we derive an exact closed formula for the rms spectral width of an initially Gaussian pulse after undergoing SPM and with the corrective phase applied, which confirms the substantial reduction of the SPM-induced spectrum broadening attainable with the phase compensation. Then, we describe the impact of the initial pulse shape and duration on the effectiveness of the technique through numerical simulation of the governing equation. We show that for hyperbolic secant pulses, optimisation of the parameters of the modulating sinusoid through a scan of the amplitude-frequency space outperforms the parameter choice based on simple analytic guidelines. By varying the initial pulse duration across an order of magnitude, we highlight the significant differences in performance between pre- and post-propagation compensation schemes, and show that remarkable SPM mitigation is attainable even in the presence of non-negligible fibre dispersion.

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The propagation of intense ultra-short optical pulses in a Kerr medium such as an optical fibre remains a critical issue for many optical systems. This is because the self-phase modulation (SPM) of the propagating pulse usually causes a severe broadening of the pulse spectrum that is typically accompanied by an oscillatory structure. Several strategies have been proposed and successfully deployed to counteract the deleterious effects of SPM in fiber-optic systems, including spatial or temporal scaling to reduce the impact of nonlinearity. Other approaches rely on the exploitation of the peculiar properties of parabolic shaped pulses and self-similar evolution. However, none of these last techniques preserves the pulse temporal duration.

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