Effect of Self-phase Modulation on the Pulse Bandwidth

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Here, I want to correct the widespread understanding that self phase modulation (SPM) (from the Kerr effect) always broadens the spectrum of a pulse. The broken time-reversal symmetry already shows that this can not be the case.

The basic message is: **When SPM acts on a pulse, this may make the pulse spectrum broader or narrower, or leave it unaffected, depending mainly on the chirp of the pulse.**

The reason for this is the following: it is true that SPM generates additional frequency components, but this must be considered in the picture of amplitudes, not intensities: **The amplitude contributions from SPM interfere with those amplitudes which are already present in the pulse.** If this interference is constructive in the wings of the spectrum, the spectrum will become broader. However, the interference can also be destructive, and the effect will then be that the pulse spectrum gets narrower.

General experience, resulting e.g. from simulations of pulse propagation, suggests:

SPM with a positive value of n_2 increases the bandwidth of positively chirped (i.e., up-chirped) pulses and decreases the bandwidth of negatively chirped pulses. (Note that the chirp itself can be influenced by SPM; apply the rule just to thin pieces of the material where the chirp stays about constant.)

I illustrate this with several examples:

1. Consider soliton transmission in a fiber with SPM and GDD. For simplicity, assume that there is no loss and that fundamental soliton pulses are injected. These unchirped solitons keep their temporal and spectral shape, although they experience more and more dispersion as they travel down the fiber. The new frequency components from SPM are always 90° out of phase of the already existing components and thus do not change the spectral intensities.
2. Consider a second-order soliton: upon propagation, its width in the temporal and spectral domain oscillate. This demonstrates that SPM can increase or decrease the bandwidth, depending on the pulse.
3. Consider an initially unchirped pulse which enters a medium with positive SPM (i.e., with positive n_2). To first order in the propagation distance, this only changes the phases of the temporal and spectral profile and thus introduces some positive chirp. Therefore, as a second-order effect we obtain a broadening of the spectrum. (This does not happen during soliton transmission because the negative GDD prevents the generation of a positive chirp.)

4. Consider a negatively chirped pulse which enters a medium with positive SPM. This makes the pulse longer and reduces its spectral width. This kind of nonlinear spectral compression has been demonstrated in various experiments.
5. Consider a soliton mode-locked laser where the pulse bandwidth is constantly reduced by the finite gain bandwidth. In steady state, there must be an effect to compensate for this. This can be a modulator or a saturable absorber, but it can also be SPM. For the latter to work the pulse must develop a positive chirp. Indeed one can observe in simulations that the chirp of the intracavity pulse increases when the resonator losses are increased, which increases the effect of gain filtering.