Kerr effect -- self-focusing

When an intense laser beam enters a nonlinear material, the electric field of the beam can induce a change in the refractive index of the material that is proportional to the intensity of the beam. This nonlinear effect is called the Kerr effect. The total refractive index of the material is the sum of the refractive index, n_0, with no laser beam present and the term n_2I, where n_2 is the second-order nonlinear refractive index and I is the intensity of the beam.

$$n = n_0 + n_2I$$

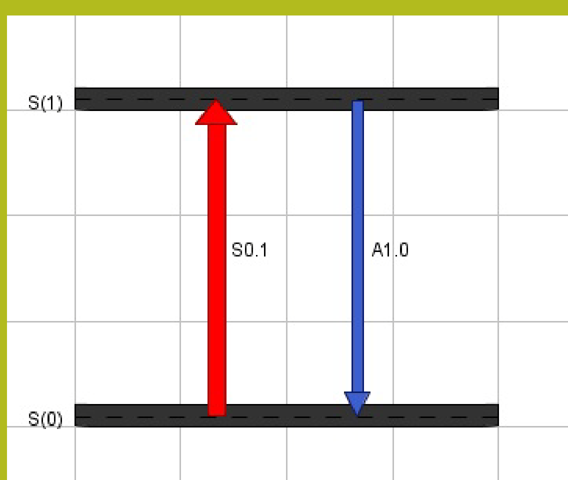
The change in refractive index can be positive or negative. Values of n_2 are generally small (e.g. 2×10^{-16} cm^2 W^{-1} for silica), so that high beam intensities are required to have a significant effect. In the time domain, the Kerr effect by itself leads to a phase shift and frequency shift, but no self-focusing or de-focusing. However, if the refractive index change is positive, the Kerr effect combined with diffraction can lead to self-focusing of the laser beam since the center of the beam will have higher intensity and a higher refractive index change than the edges of the beam. The index changes are equivalent to having a positive gradient index lens.

The SimphoSOFT® mathematical model includes both the Kerr effect and diffraction, which allows a user to accurately analyze photo-activated materials and optimize their performance at high laser intensities. By using SimphoSOFT one can pre-screen a target material to avoid dangerous levels of intensity at the center of the pulse, or conversely, to emphasize the high intensity, depending on the goal.

Example SimphoSOFT simulation of beam self-focusing: Kerr effect along with diffraction

SimphoSOFT allows defining a nonlinear index of refraction, n_2, for the host material (the value used in this example is provided in one of the properties tables below). The diffraction term is included to the propagation model by default (but could be turned OFF for some cases, including the one where self-focusing is not observed). The sample is composed of molecules dispersed in a host material, which in this example is silica. The molecules have two energy states for optical transitions: singlet states S(0) and S(1) (other singlet states and vibrational states will be ignored). The molecular absorption cross-section is very small for this example and insignificant. The host material has a positive nonlinear refractive index n_2.

Screenshot of SimphoSOFT® M-CAD with 2-level energy level diagram of the molecules



The energy level diagram includes one-photon absorption (S0.1 on the diagram) and fluorescence (A1.0).

- One-photon absorption (1PA) cross-section in the example 2-level model: 1×10^{-20} cm^2 from S(0) to S(1).
- Relaxation time for the example 2-level model: 1 ns from S(1) to S(0)

The absorption cross-section is very small in this example and it does not contribute to the self-focusing effect.

Other sample properties	
Molecular dopant density (concentration) in the host material	3.0×10^{18} molecules/cm^3
The host material linear refractive index	$n_0 = 1.4$
Host material linear absorption	$\alpha = 0$ cm^{-1}
Host material nonlinear refractive index	$n_2 = 2.0 \times 10^{-16}$ $cm^2 W^{-1}$
Sample length	10 mm

Laser properties	
Pulse energy	40 μJ
Pulse radius (HW1/e2M)	56.8 μm
Pulse FWHM	1 ps
Wavelength	780 nm

Numerical Setup parameters		
Temporal domain	$10 \times T_0$	
Radial domain	$5 \times R_0$	
Propagation domain	10 mm	1.09 L_{df}
# Time samples	512	
# Radial samples	64	
# Propagation samples	512	
Diffraction	On	

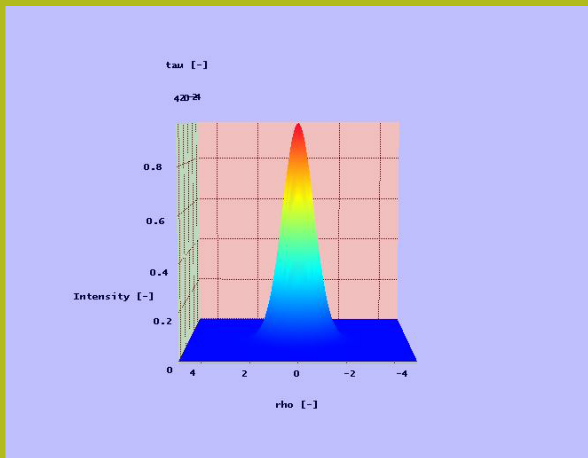
For this example, the diffraction length L_{df} is 9.096 mm for the given laser wavelength and radius. The 10 mm sample length corresponds to 1.09 L_{df}.

With pulse energy 40 μJ and pulse length 1 ps, the power becomes: 40 μJ/1 ps = $4 \times 10^{-5}/10^{-12} = 4 \times 10^{7}$ Watts = 40 MW. Note that the minimum critical power, P_{cr}, for observing self-focusing in silica is expected to be $P_{cr} = 1.836 \times \lambda^2/(4\pi n_0 n_2)$ or approximately 3 MW for the values given in the above tables, Reference (1).

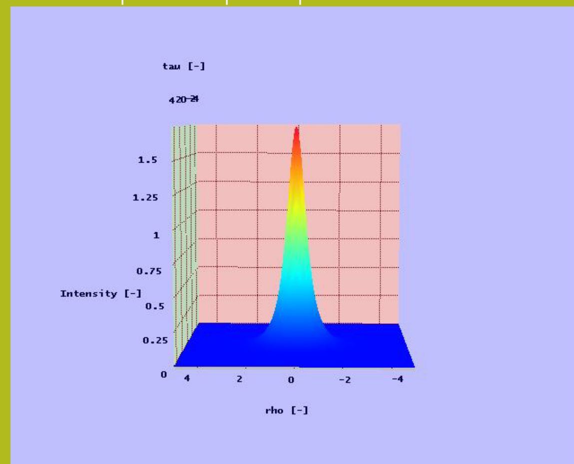
Results of SimphoSOFT calculations with Kerr and diffraction: intensity almost doubled at the sample exit

Kerr effect -- self-focusing

Pulse shape at sample input

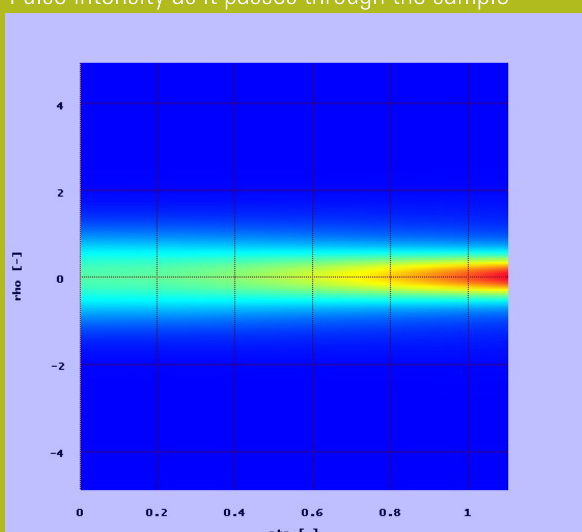


Pulse shape at sample output

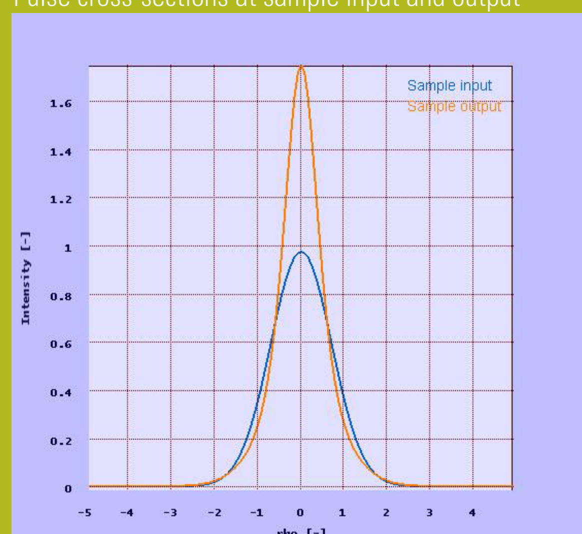


The pulse at the sample output is narrower and has nearly twice the peak intensity as the pulse at the sample input. This example illustrates the importance of including the Kerr effect and diffraction for some types of optical materials. Both functions are built-in features of SimphoSOFT. SimphoSOFT allows users running very detailed analysis on the nonlinear beam distortion, which can be extremely important for optically thick samples (with propagation distance of several L_{df}).

Pulse intensity as it passes through the sample



Pulse cross-sections at sample input and output



References:
(1) G. Fibich and A. Gaeta, Optics Letters 25, 335-337 (2000).

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