# Measurement of the intensity dependent refractive index using complete spatio-temporal ultrashort pulse characterization

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The complete knowledge of an optical pulse before and after its passage through a given material allows the evaluation of the properties of the material.

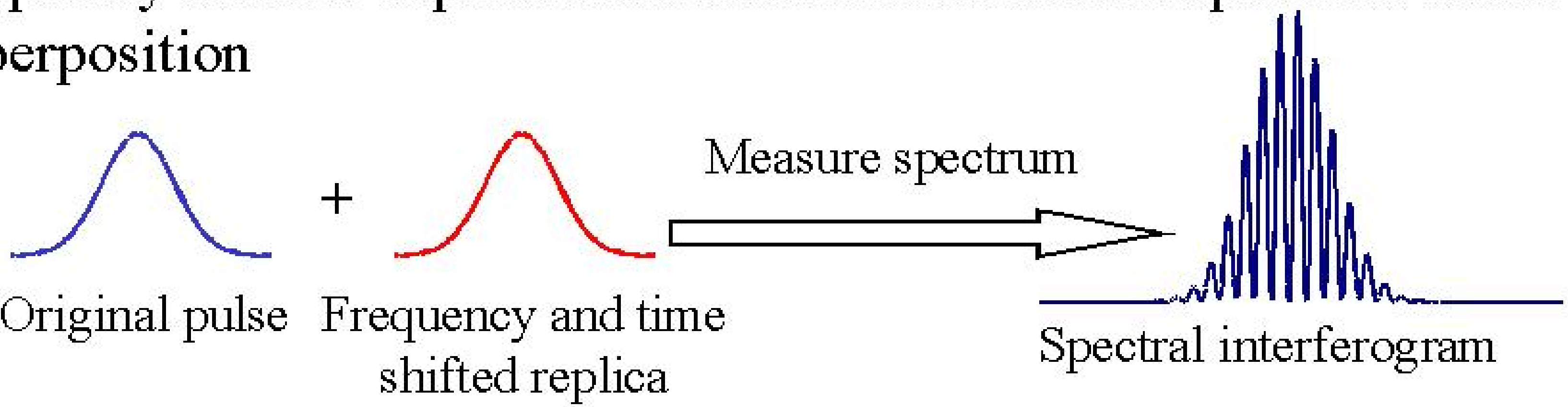
Kerr effect: $n = n_0 + n_2 I$

The intensity dependent refractive index affects the phase of the optical pulse.

The complete characterization of the optical pulse is performed with a technique based on Spectral Phase Interferometry for Direct Electric field Reconstruction (SPIDER): a space-time SPIDER

# SPIDER: complete characterization of ultrashort optical pulses

Experimental principle: to characterize a pulse, interfere it with a frequency-shifted replica of itself and measure the spectrum of the superposition



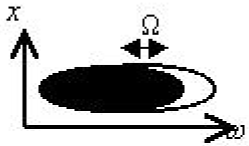

SPIDER is a shearing interference technique; the spectral interferogram contains the derivative of the phase with respect to frequency:

$$\phi(\omega+\Omega)-\phi(\omega)\approx\Omega\frac{\partial\phi}{\partial\omega}$$ provides the desired complete characterization

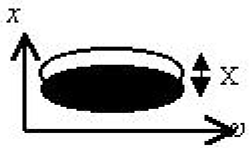
C. Iaconis and I.A. Walmsley, Opt. Lett. **23**, 792 (1998)

# Space-time SPIDER

A spectrally resolved spatial shearing **plus**
a spatially resolved spectral shearing




Spectral shear: obtain $$\frac{\partial \phi(x,\omega)}{\partial \omega}$$



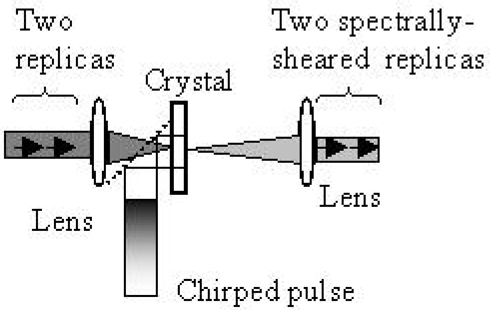

Spatial shear: obtain $$\frac{\partial \phi(x,\omega)}{\partial x}$$

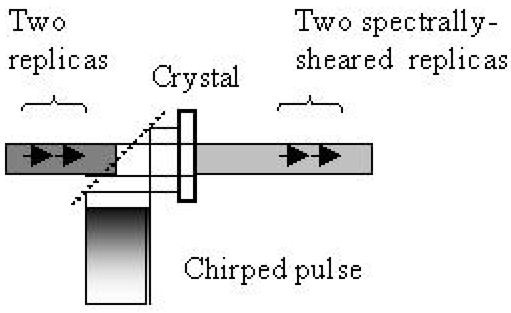
Reconstruct the spatio-spectral phase from the two independent phase gradients.

C. Dorrer et al., Opt. Lett. **27**, 548 (2002)

# Record the interference pattern in an imaging spectrometer

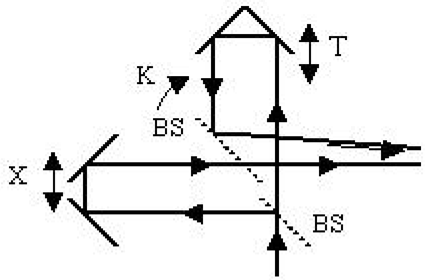
## Spectral shear: upconvert two replicas with a chirped pulse





## Spatial shear: shear two replicas using a Michelson interferometer




## We study the propagation of a pulse in 1.25 cm of SF59 glass

| | |
|---|---|
| **Pulse properties** | Wavelength $\lambda$ = 819 nm;<br>Energy E = 21 $\mu$J<br>Peak intensity $I_0 = 5.9\times10^9$ W/cm$^2$ |

| | **Input pulse** | **Output pulse** |
|---|---|---|
| Spatial FWHM | $\delta = 0.21$ cm | $\delta = 0.21$ cm |
| Temporal FWHM | $\tau = 65$ fs | $\tau = 200$ fs |

The pulse broadens considerably in time; it does not broaden in space.

# Contributions to the phase

Diffraction $\Delta\phi_{diffr} \sim \frac{1}{4\pi}\frac{\lambda z}{\delta^2} \sim 10^{-3}\, rad$

Dispersion $\Delta\phi_{disp} \sim \frac{1}{2}\frac{\beta_2 z}{\tau^2} \sim 0.5\, rad$

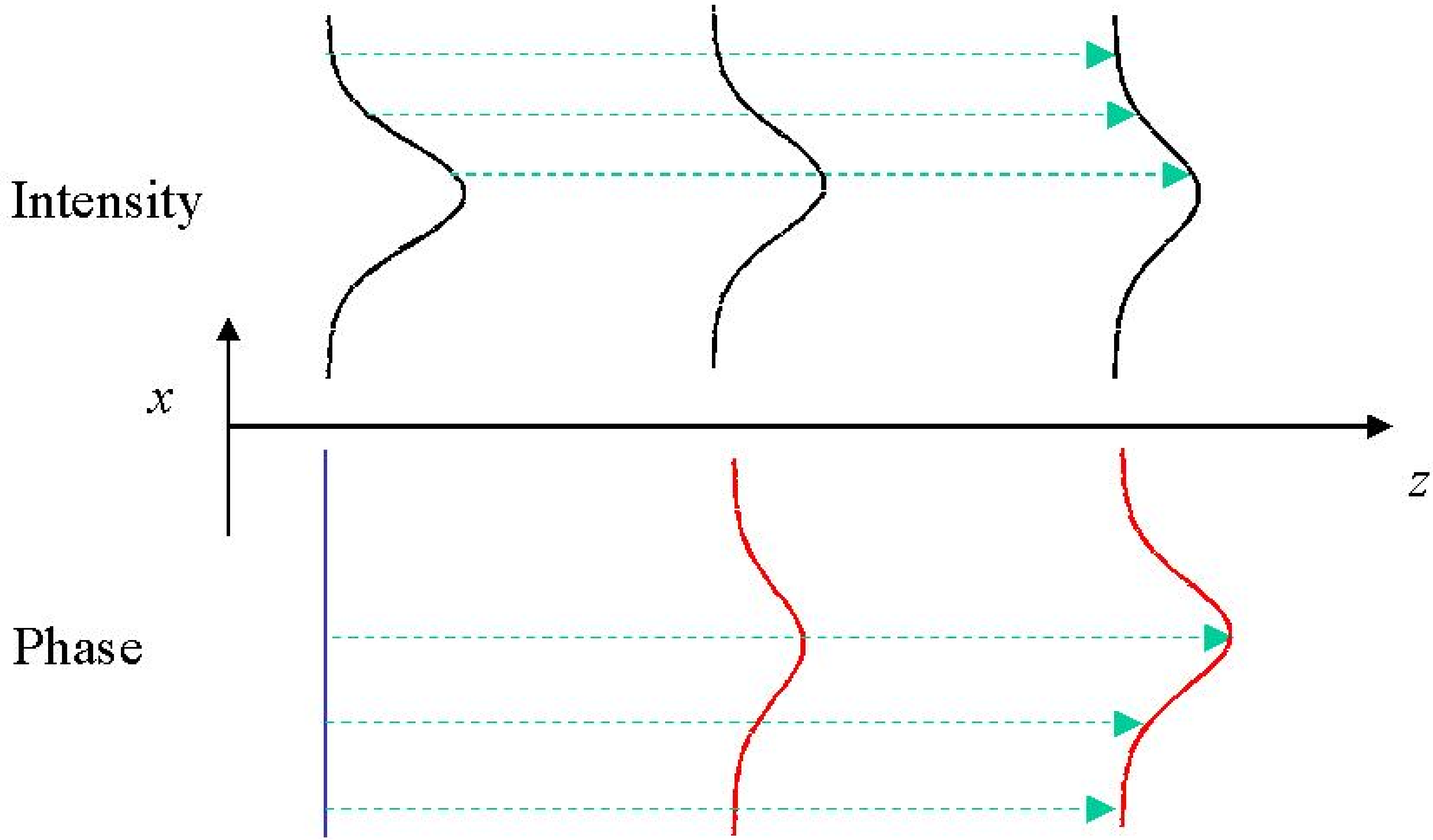
Nonlinearity $\Delta\phi_{NL} \sim \frac{2\pi}{\lambda} I_0 n_2 z \sim 3\, rad$

The nonlinear phase is comparable to the phase given by dispersion. It is somewhat difficult to distinguish the NL phase from the dispersive phase, when looking at the temporal domain.

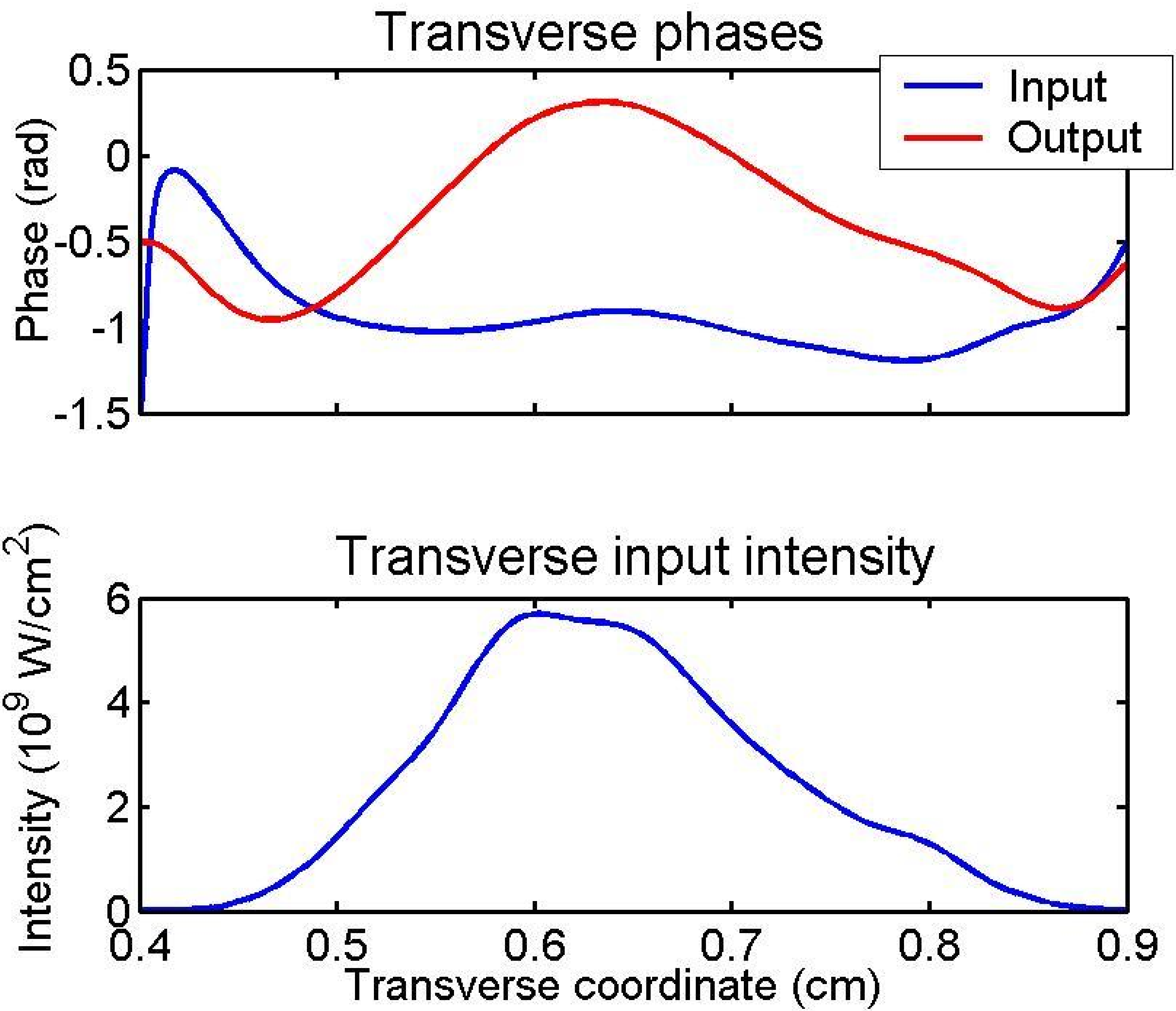
Phase differences along the transverse direction depend on the nonlinearity in a straightforward way:

$$\phi(x) = \frac{2\pi}{\lambda} n_2 \int_0^z I(z', x)\, dz'$$

# No diffraction: propagation along straight lines




Phase $\qquad \phi(x) = \frac{2\pi}{\lambda} n_2 \int_0^z I(z', x) dz'$ along each line



Transverse phases
Input
Output
Phase (rad)
0.5
0
-0.5
-1
-1.5
Transverse input intensity
Intensity (10^9 W/cm^2)
6
4
2
0
0.4
0.5
0.6
0.7
0.8
0.9
Transverse coordinate (cm)

# Numerical evaluation of $n_2$

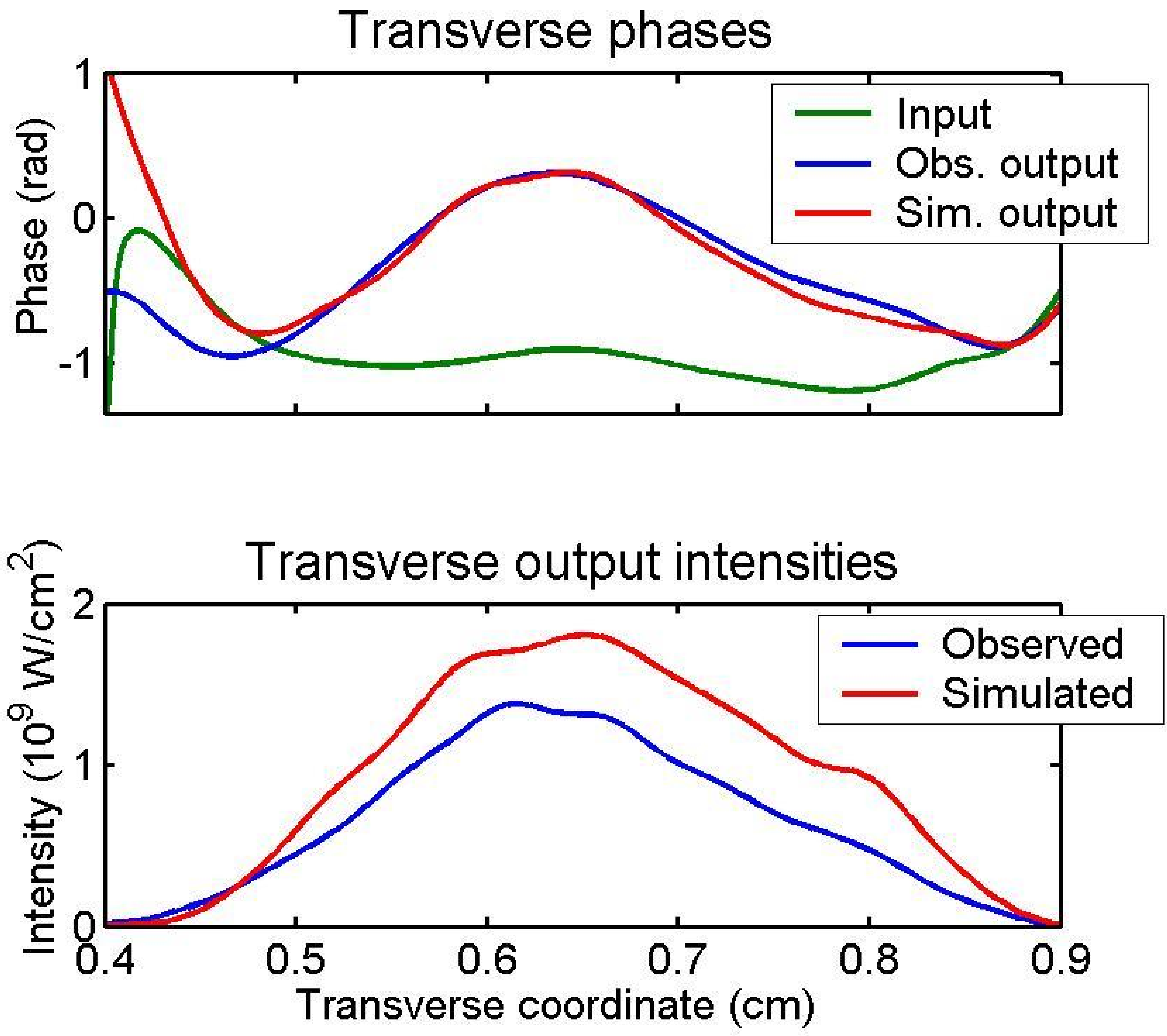
Solve the (2+1)-D nonlinear Schrödinger equation; this includes dispersion, diffraction and nonlinearity

Look for the value of $n_2$ which gives the least-squares fit between the observed and simulated transverse phases.

Result of this calculation: $n_2 = 50 \times 10^{-16}\, cm^2 / W$

Friberg at al., IEEE J. Quant. El., 23, 2089 (1987) $n_2 = 68 \times 10^{-16}\, cm^2 / W$ @ 1 $\mu$m

Rivet et al, Opt. Comm., 181, 425 (2000) $n_2 = 40 \times 10^{-16}\, cm^2 / W$ @ 800 nm


Transverse phases
Phase (rad)
1
0
-1
Input
Obs. output
Sim. output
Transverse output intensities
Intensity (10^9 W/cm^2)
2
1
0
Observed
Simulated
0.4
0.5
0.6
0.7
0.8
0.9
Transverse coordinate (cm)

Analysis of the method: it is necessary to solve the NL Schrödinger equation

Suppose one calculates the NL phase, $\phi(x) = \frac{2\pi}{\lambda} n_2 \int_0^z I(z', x) dz'$ ,

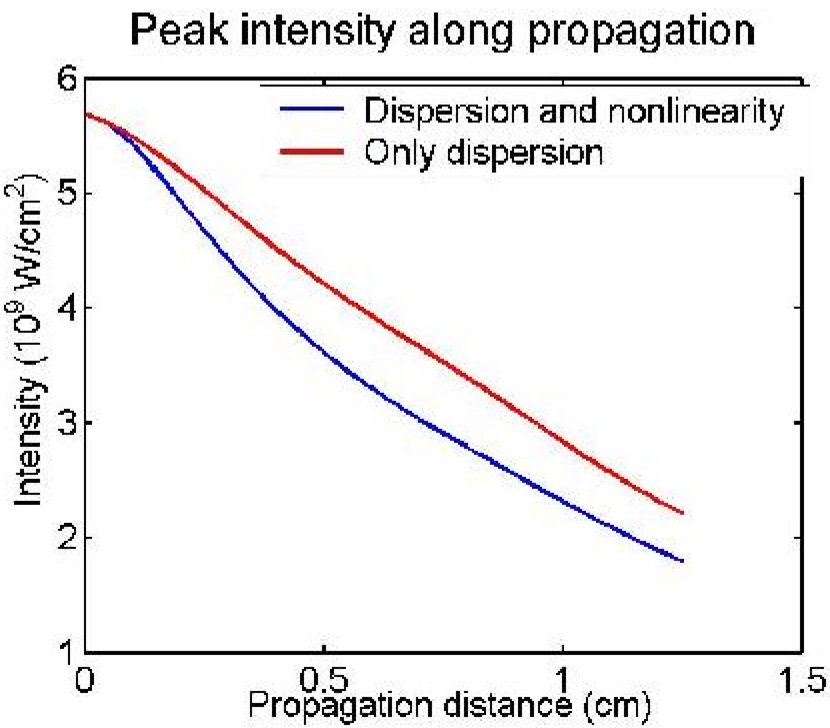
using an approximated expression for the intensity $I(z, x)$ obtained by neglecting nonlinearity in the propagation equation.

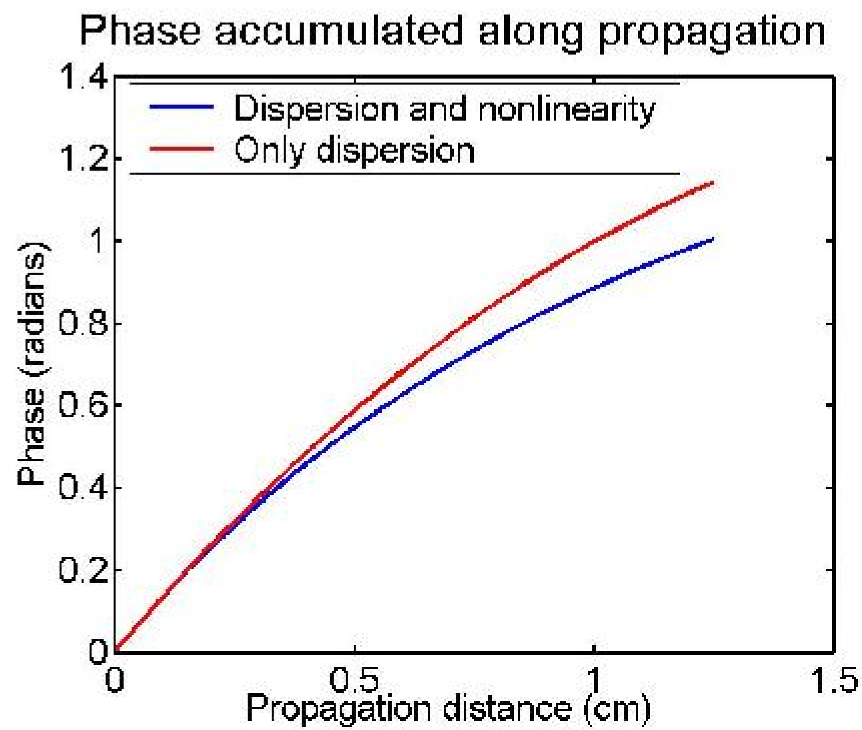
In this case the value of $n_2$ that achieves the best fit between measured and calculated transverse phases is $n_2 = 32 \times 10^{-16} cm^2 / W$

(without dispersion one would obtain $n_2 = 20 \times 10^{-16} cm^2 / W$ ;

the full calculation gives $n_2 = 50 \times 10^{-16} cm^2 / W$ )

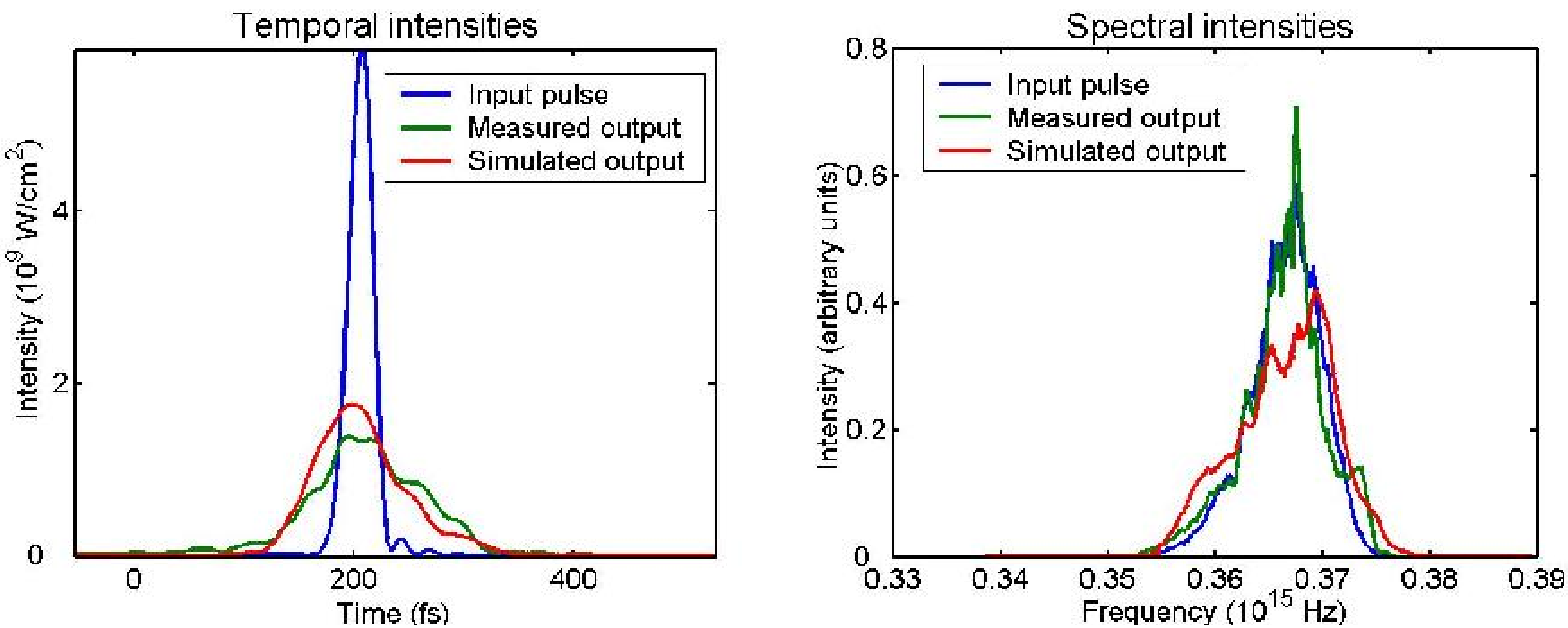
The approximated propagation that neglects nonlinearity overestimates the pulse intensity;
it therefore overestimates self-phase modulation




Increasing nonlinearity spreads the pulse;
therefore self-phase modulation is not linear in $n_2$

# Check other pulse properties to validate our fit




In the time domain the agreement is acceptable
In the spectral domain there are differences.

# Advantages of the method

- Conceptually simple
- No assumptions on the pulse shape
- It is possible to separate clearly refractive nonlinear effects from absorptive nonlinear effects

# Acknowledgements

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http://www.optiscitrust.org/