Optimization of supercontinuum generation in photonic crystal fibers for pulse compression

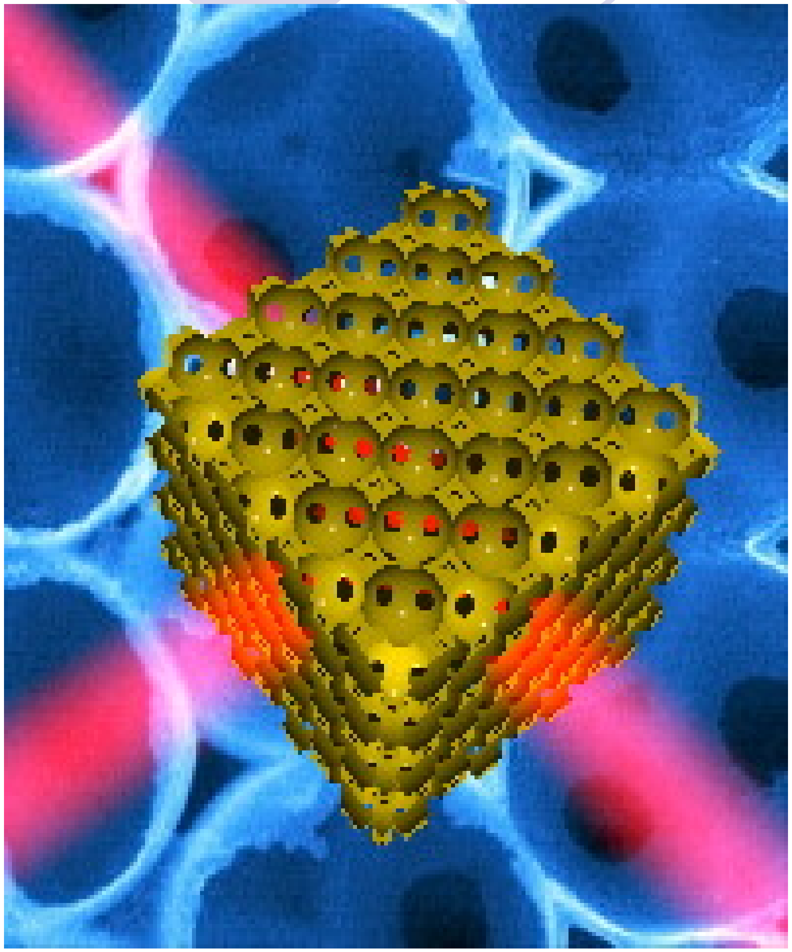
Noah Chang

Herbert Winful,Ted Norris

Center for Ultrafast Optical Science

University of Michigan

What is Photonic Crystal?

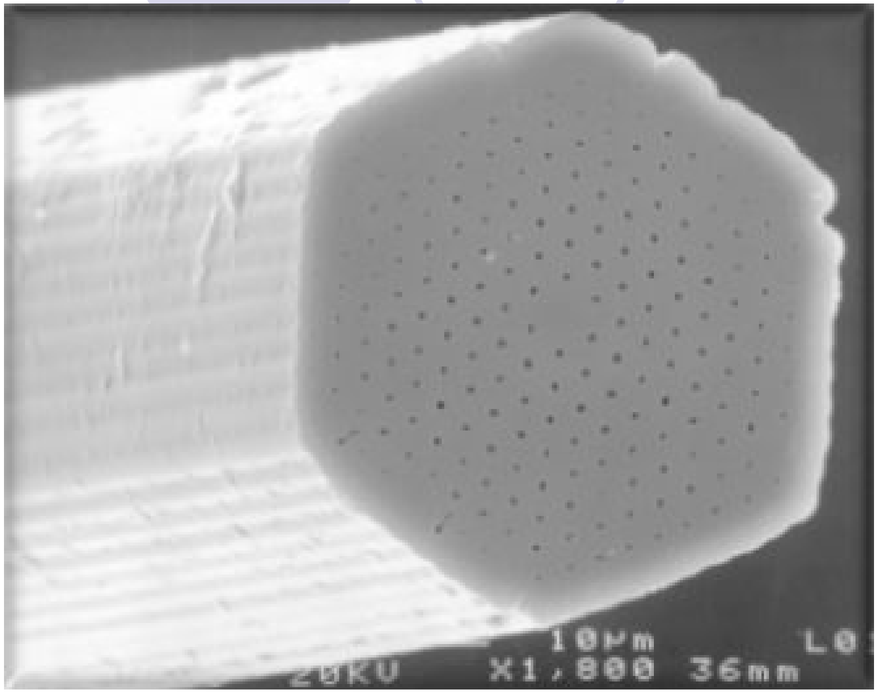


A microstructured material is one that is structured on the scale of the optical wavelength. A diffraction grating is a simple example. If the structure is periodic - regularly repeating - then the material is called a "photonic crystal". This is analogous to a normal crystal in which atoms or groups of atoms are arranged in a repeating pattern, except that the repeat period is on a much larger scale.

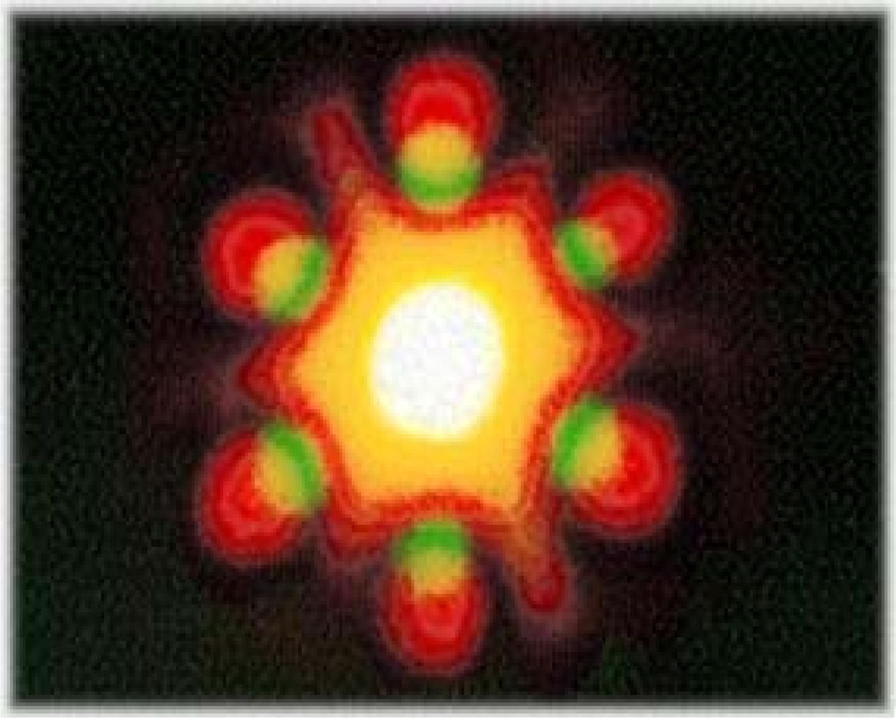
(**SEM image of a silicon inverse opal. This three-dimensional Photonic Crystal consists of a fcc close-packed lattice of air spheres (diameter 600 nm) that are coated with silicon (about 23% by volume) and exhibits a complete photonic band gap centered at 1.46 μm with a gap-to-midgap ratio of 5%. The inset shows the theoretical modelling of the structure.**)

http://www-tkm.physik.uni-karlsruhe.de/~kurt/GroupPage/framtest.html

Photonic Crystal Fiber (PCF)



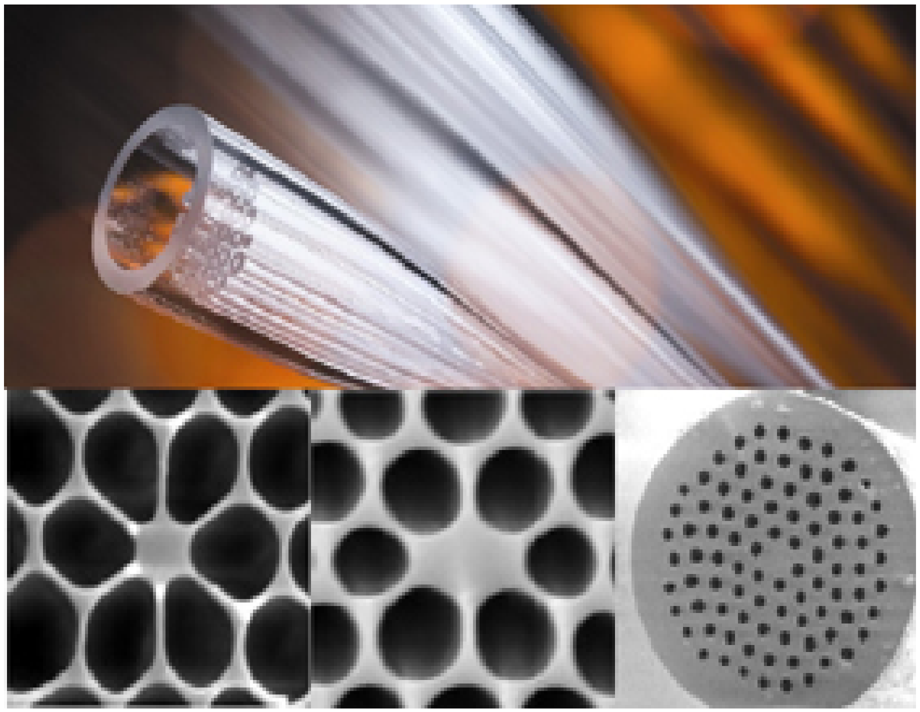
An SEM image of a photonic crystal fibre. Note the periodic array of air holes, and the central defect (a missing hole) that acts as the fibre's core. The fibre is about 40 microns across.



A photograph of the far field pattern emerging from a photonic crystal fibre. The fibre was carrying red light from a helium-neon laser and green light from an argon ion laser.

http://www.bath.ac.uk/physics/groups/opto/pcf.html

Commercially Available Crystal Fiber A/S



The top is a preform and the bottom are each section of Highly nonlinear PCF, polarization maintaining PCF and Large mode area PCF from the left.

Specifications

1. Small core highly nonlinear PCF:
- Small core diameter (1.7µm, 2.0µm)
- High nonlinearity
- Zero dispersion in visible wavelength region
- Bending insensitive

2. Highly nonlinear polarization maintaining PCF:
- High polarization retention
- Small core dimension
- Zero dispersion in visible wavelength region
- Bending insensitive

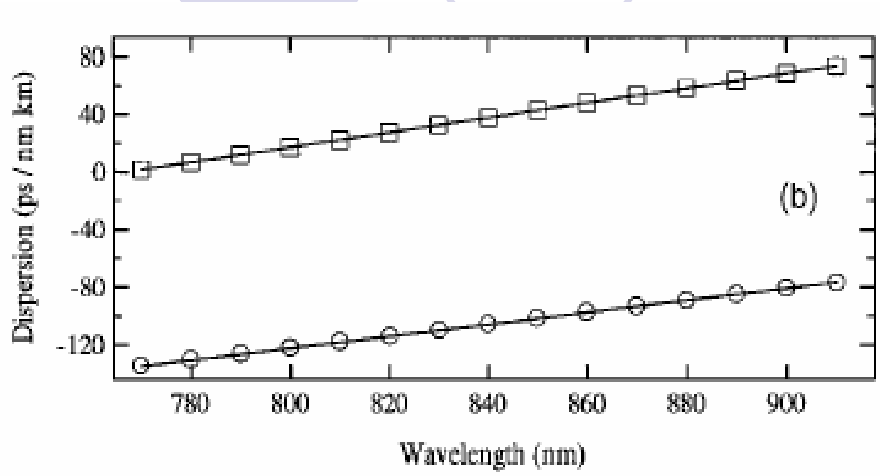
3. Large mode area PCF:
- Large core (15µm, 20µm)
- Low loss
- High power level without nonlinearity

http://www.rikei.co.jp/dbdata/products/producte249.html

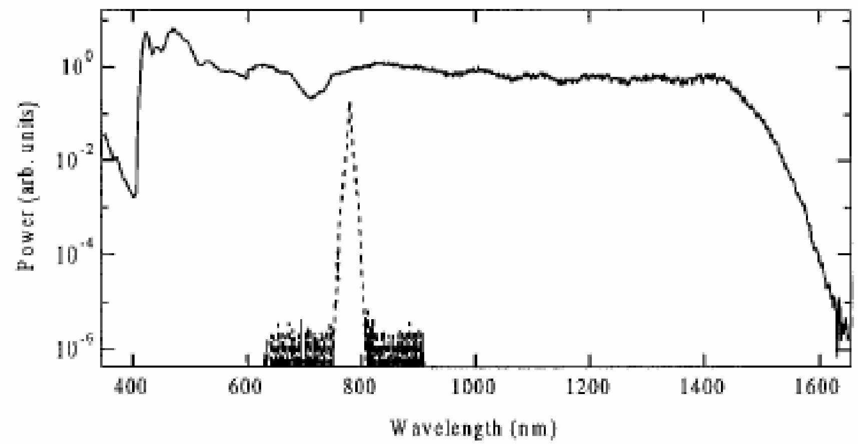
Application of PCF

- *Supercontinuum generation*
- Four-wave mixing
- Raman amplification
- All optical switching based on XPM
- Ultrahigh power/Ultrashort pulse delivery
- Mode filtering
- Photonic crystal fiber coupler
- Tunable devices with micro-fluids in PCF

SC Generation from PCF



Measured GVD of PCF (squares) and a standard single-mode fiber (circles).



Optical spectrum of continuum generated in a 75-cm section of PCF. The dashed curve shows the spectrum of the initial 0.8nJ 100-fs pulse

Advantages to generate SC with PCF:

(1) Zero-dispersion wavelength shifted to visible wavelength ⟶ pulse not broadened too much along propagation distance

(2) Very small effective core area ⟶ nonlinearity increased by over 20 times

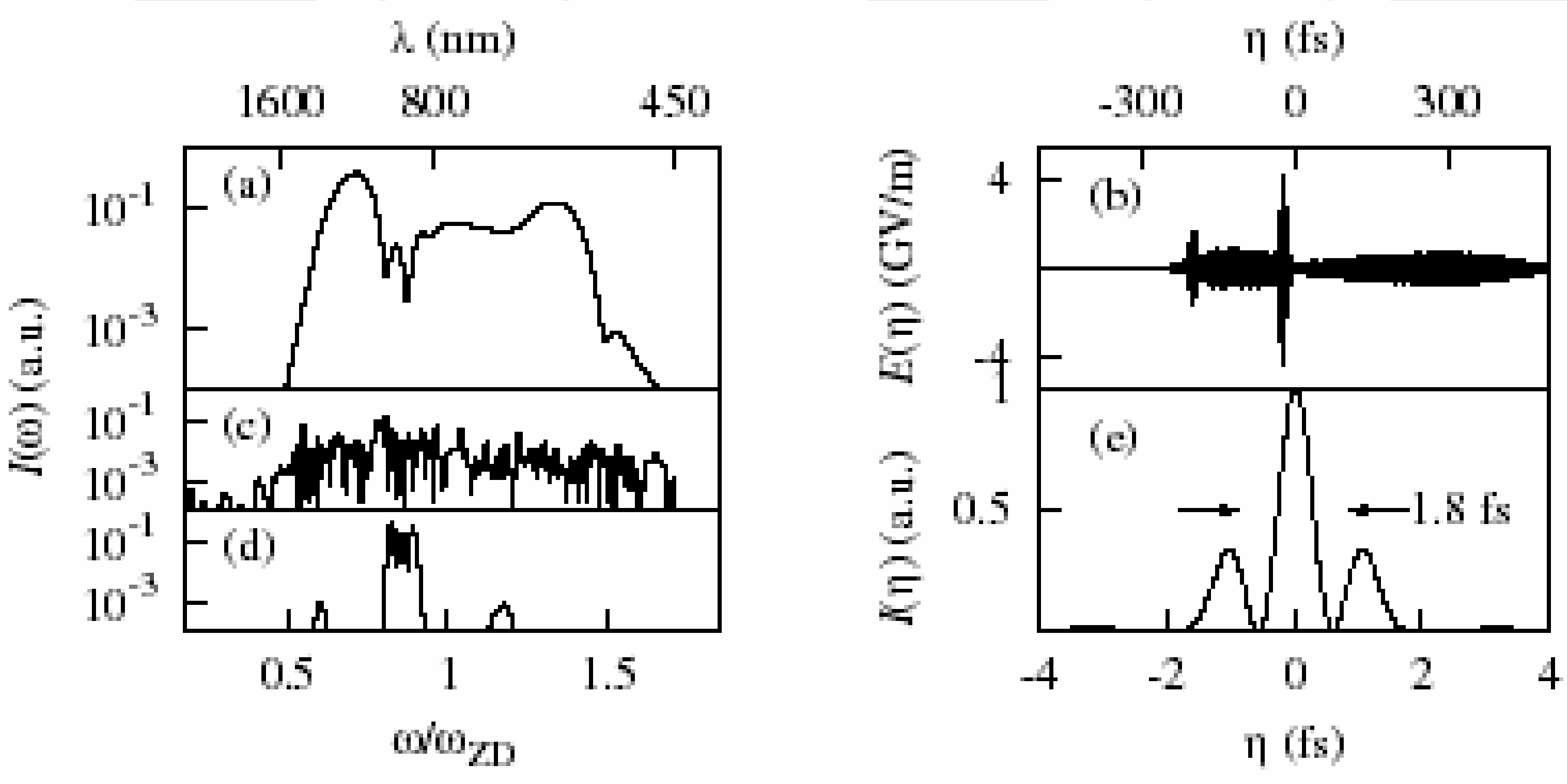
(3) All wavelength single mode

<u>*Jinendra K. Ranka etc., Optics Letters, vol. 25, 25(2000)*</u>

Application of Supercontinuum

- *Single/sub cycle pulse by compression*
- Optical coherence tomography
- Optical frequency metrology
- Optical source for WDM/DWDM communication system
- Wideband tunable wavelength conversion

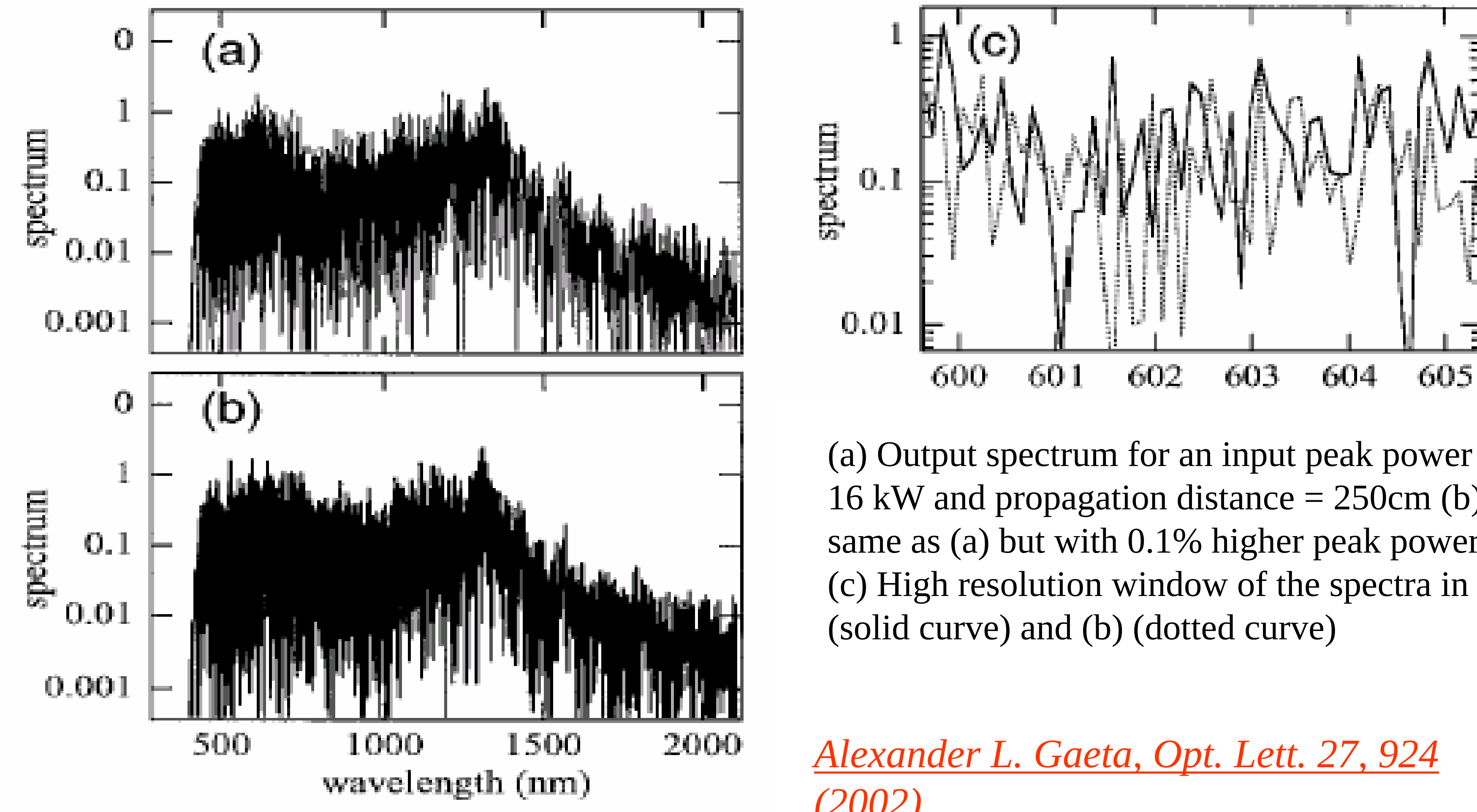
Pulse Compressed to Sub-cycle



Propagation length = 1.5 mm (a)(b), 9 mm (c)(e), 4.5 mm (d). (e) subcycle pulse compressed by a LC SLM (I=3.3 TW/cm^2,druation= 200 fs)

Husakou A. V. etc., Phys. Rev. Lett.,87,203901 (2001)

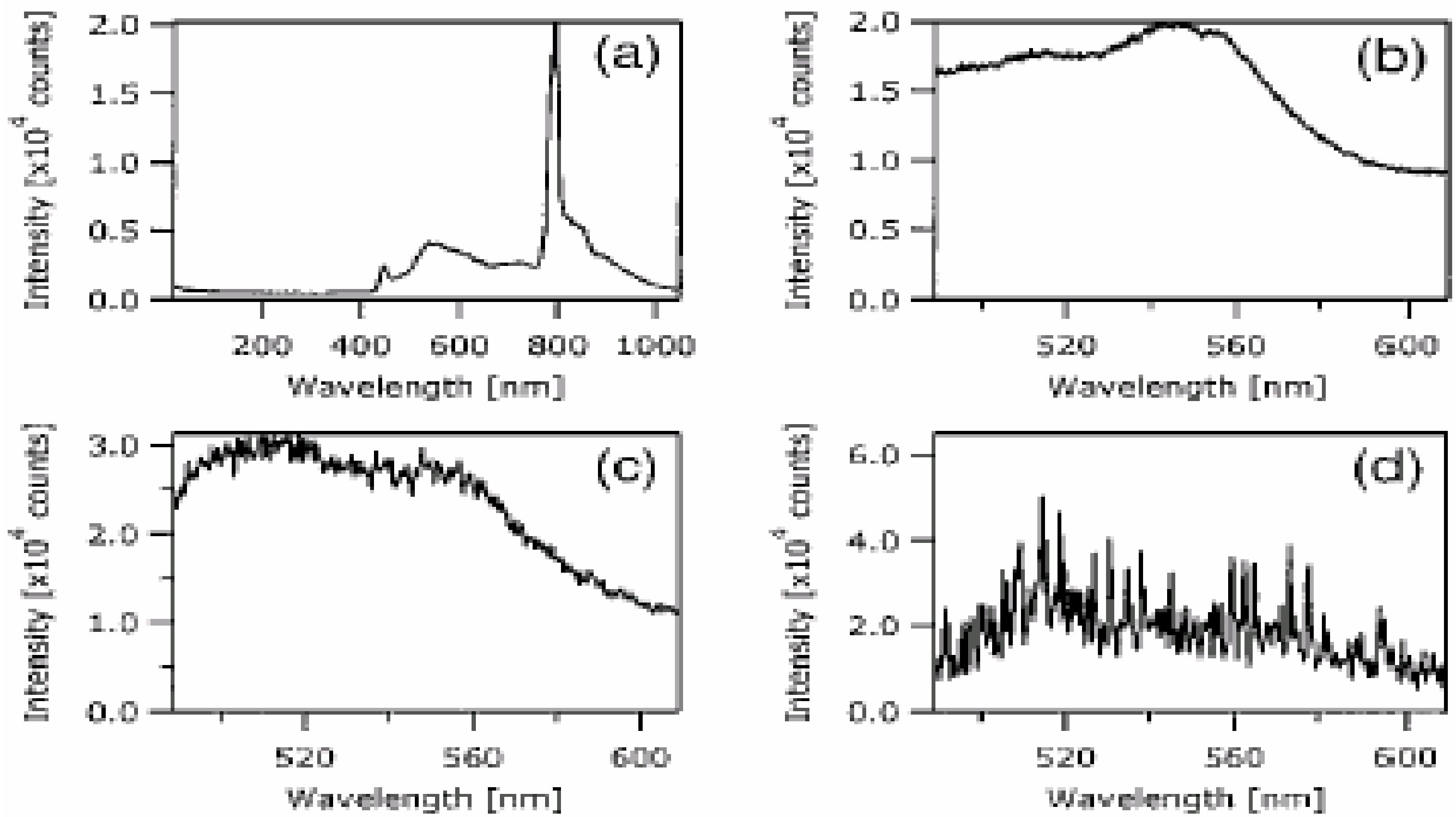
Fine structures of SC from simulation



(a) Output spectrum for an input peak power P= 16 kW and propagation distance = 250cm (b) same as (a) but with 0.1% higher peak power (c) High resolution window of the spectra in (a) (solid curve) and (b) (dotted curve)

Alexander L. Gaeta, Opt. Lett. 27, 924 (2002)

Structures Revealed by FROG



(a) Entire SC averaged over 10,000 pulses. Spectral section of the SC exposed for (b) 10,000 shots, (c) 100 shots and (d) a single shot. (input pulse duration = 30 fs, energy = 1 nJ, propagation distance = 16 cm)

Xun Gu etc., Opt. Lett., 27, 1174, (2002)

Compressible or not

Necessary conditions for compression to generate ultrashort pulse:

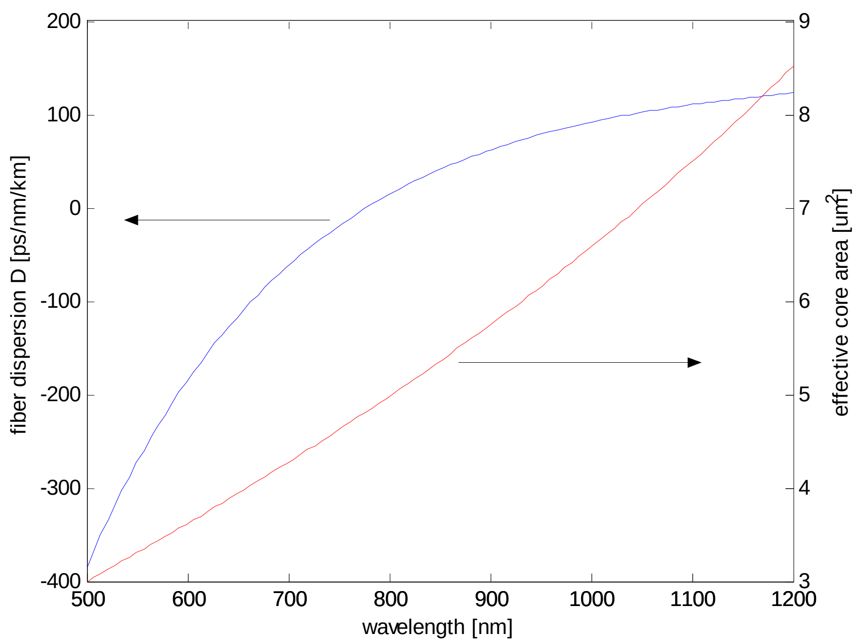
(1)Very broad spectrum

(2) Stable and smooth phase

Question:

Whether significant compression can be practically achieved from SC?

Frequency Domain Propagation Equation for Photonic Crystal Fiber (PCF)



fiber dispersion and effective core area versus wavelength for PCF

$$\frac{\partial S(\Omega,z)}{\partial z} =$$

$$-i[\beta(\omega_0+\Omega,z)-\beta(\omega_0,z)-\Omega\beta_1(\omega_0,z)-i\alpha(\omega_0+\Omega,z)]S(\Omega,z)$$

$$-i\gamma P_0\left(1+\frac{\Omega}{\omega_0}\right)F\{S(T,z)[|S(T,z)|^2+F^{-1}\{R(\Omega)F\{|S(T,z)|^2\}\}]\}$$

$R(\Omega)$ is the complex Raman susceptibility.

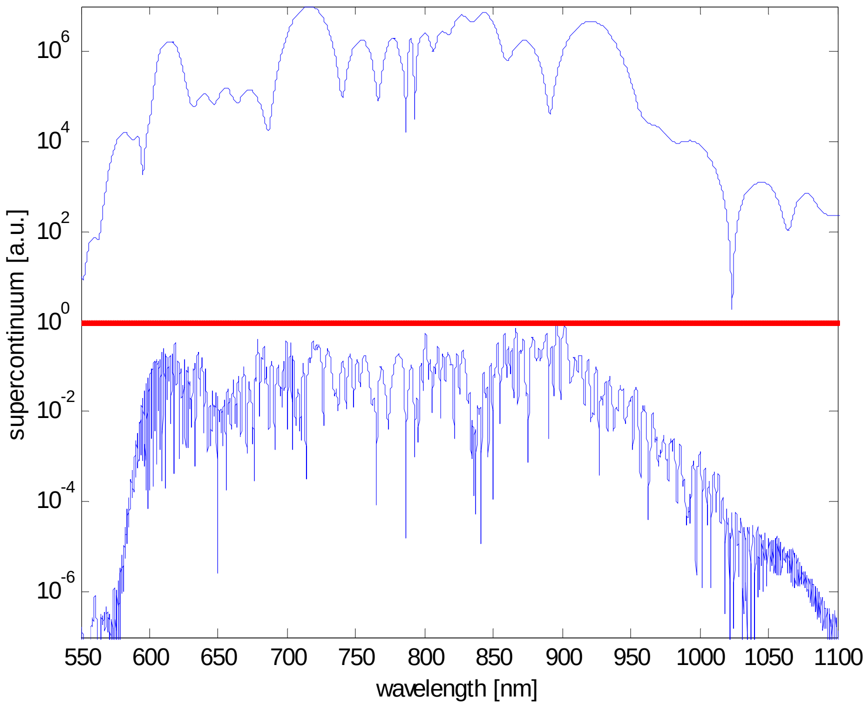
$$\gamma = \frac{\omega n_2}{cA_{eff}}$$

Advantages

(1) suitable for handling continuum over a wide spectral range and that arbitrary functions can be used to describe the chromatic dispersion and loss.

(2) The Raman gain curve and hence the Raman susceptibility are obtained experimentally in frequency domain.

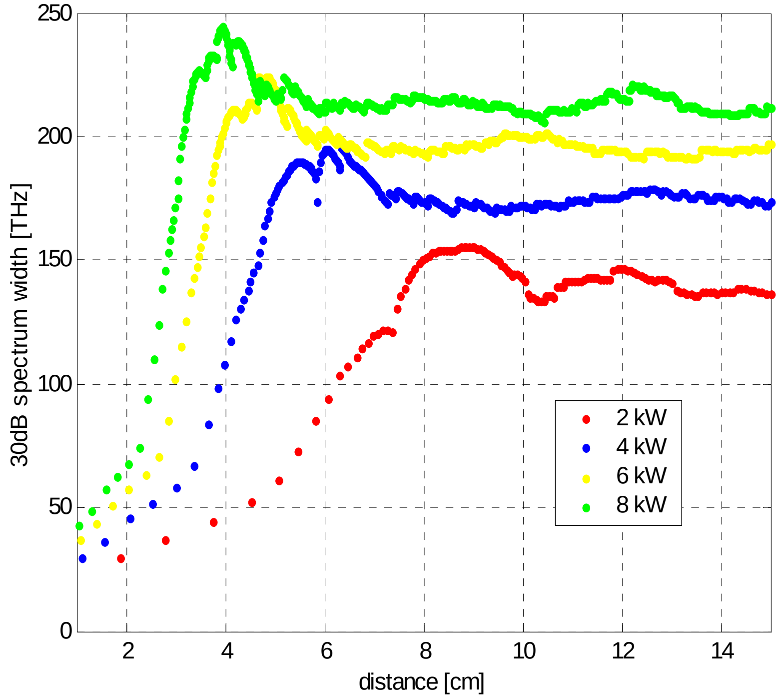
SC generated from PCF



SC generated after passage of different distances: 5 cm for the upper spectrum and 45 cm for the lower

- Parameters for the input pulse
  - Central wavelength: 790nm
  - Pulse shape: sech^2
  - Duration: 100 fs
  - Peak power: 8 kW (0.8 nJ/pulse)
- Parameters for the algorithm
  - Temporal resolution: 0.5 fs
  - Spectrum resolution: 30 GHz
  - Sample number: 2^14 (65536)

Evolution of SC along Propagation Distance



evolution of 30 dB spectrum width along propagation distance

Three stages for SC generation:

1st SPM + anomalous dispersion → pulse compressed and spectrum broadened

2nd Stronger nonlinearity + FWM in normal dispersion region → SC generation

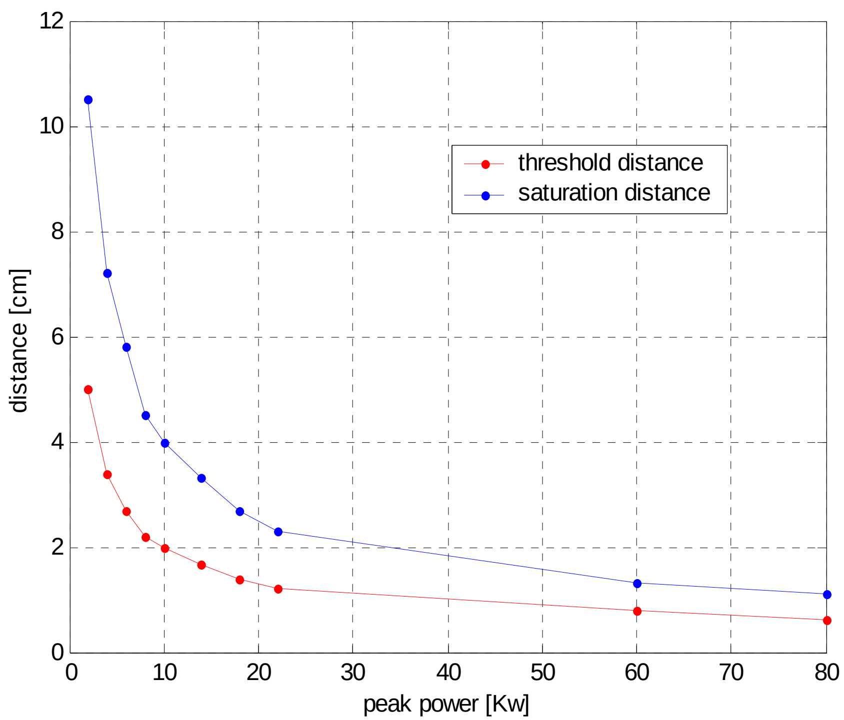
3rd pulse breakup into spikes → peak power weakened → SC saturates

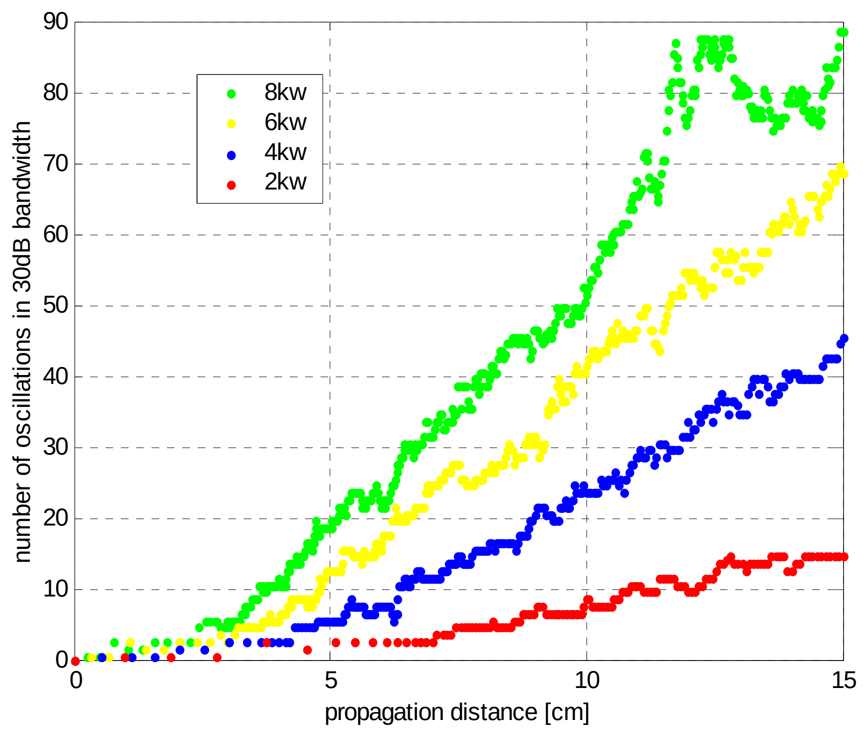
Example: given peak power=8 kW

Threshold distance: 2.2 cm

Saturation distance:4.5 cm

Parameters to Characterize SC

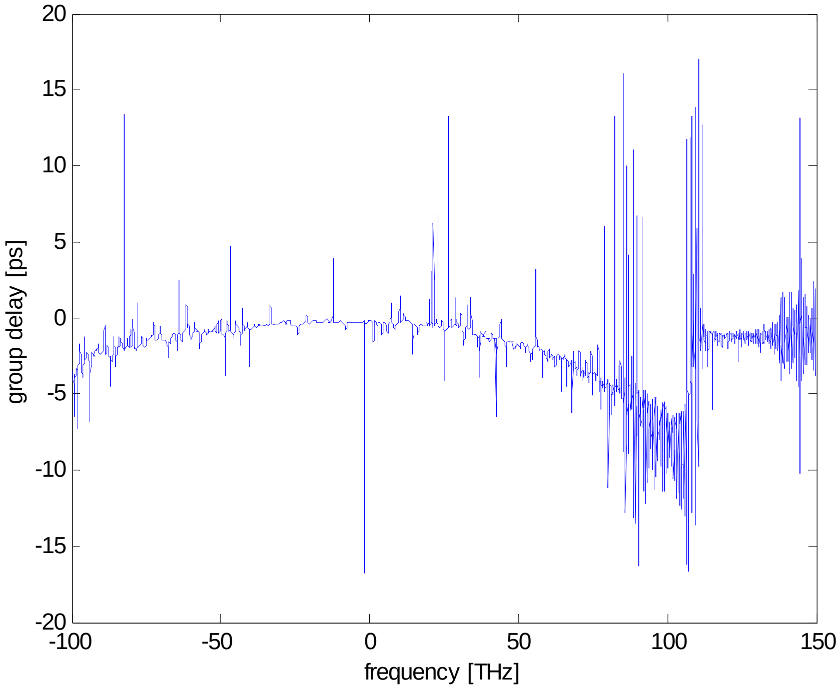




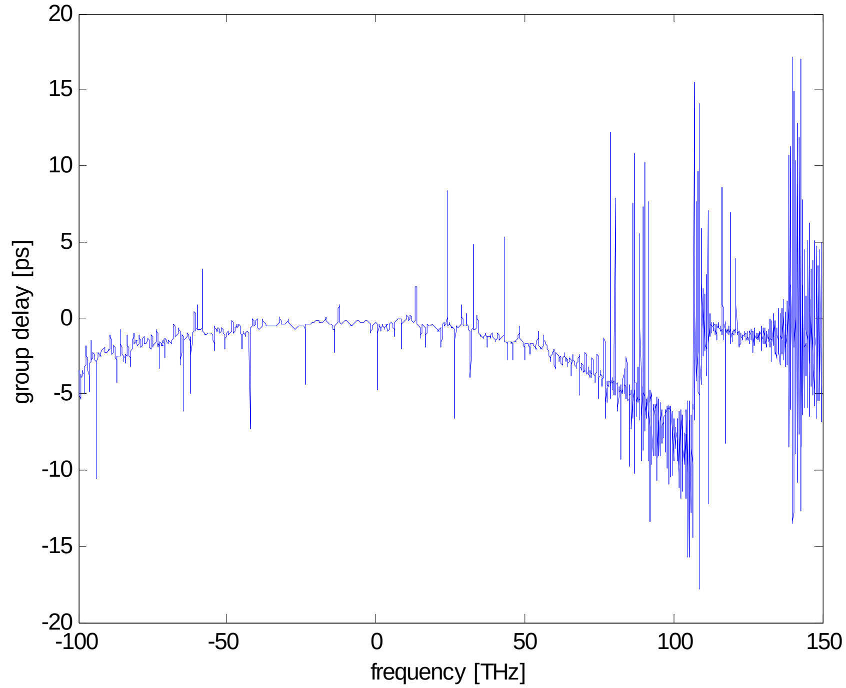
(a) threshold distance and saturation distance versus the peak power of the input pulse

(b) Number of oscillations in 30 dB spectrum width versus distance

Group Delay Extremely Sensitive to Input Power



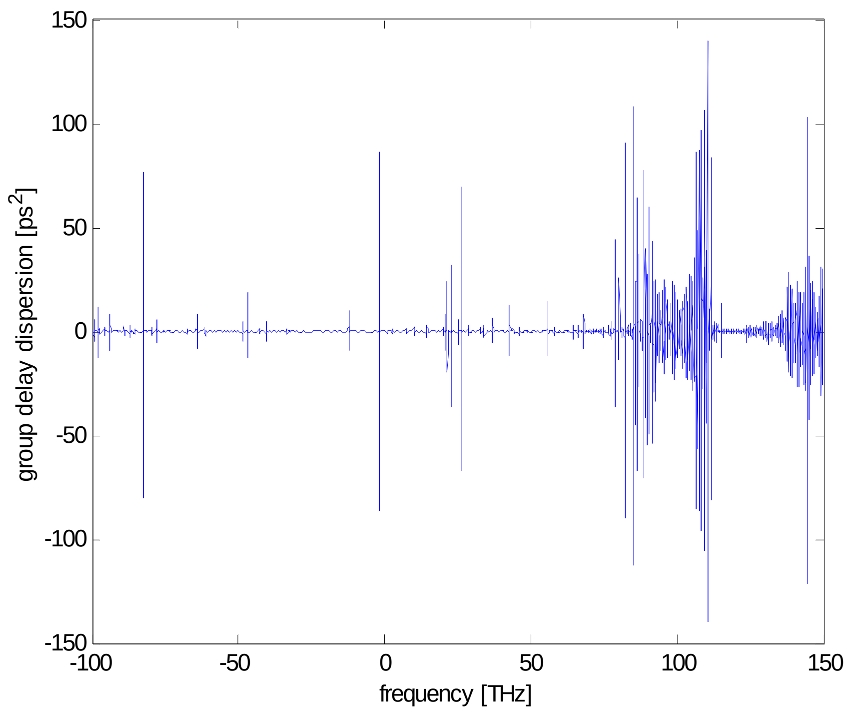
(a)



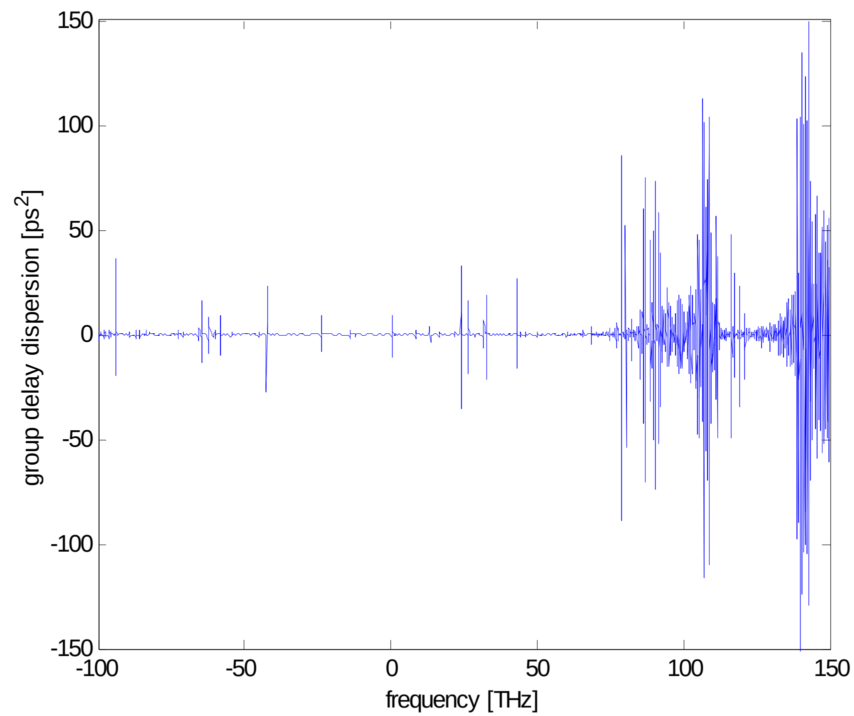
(b)

group delay for 45 cm propagation distance with different input peak power:
(a) peak power=8 kW and (b) peak power=8.016 kW *(0.2% different)*

Group Delay Dispersion VS Input Power



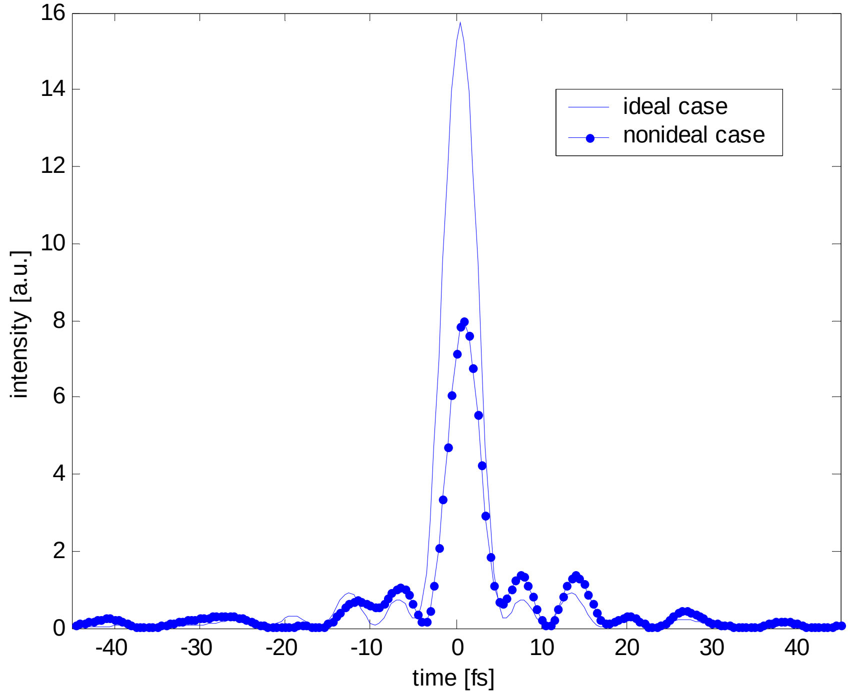
(a)



(b)

group delay dispersion for 45 cm propagation distance with different input peak power: (a) peak power=8 kW and (b) peak power=8.016 kW *(0.2% different)*

Pulse Compression by Ideal Compressor



Pulse compression with ideal compressor to compensate SC phase generated under conditions:pulse duration = 100 fs, propagation distance=45 cm,Peak power=8 kW (ideal case) and 8.016 kW (nonideal case)

Phase for SC:

$\phi_{SC1}(\omega)$ (ideal case)

$\phi_{SC2}(\omega)$ (nonideal case)

Ideal compressor:

$$\phi_c(\omega) = -\phi_{SC1}(\omega)$$

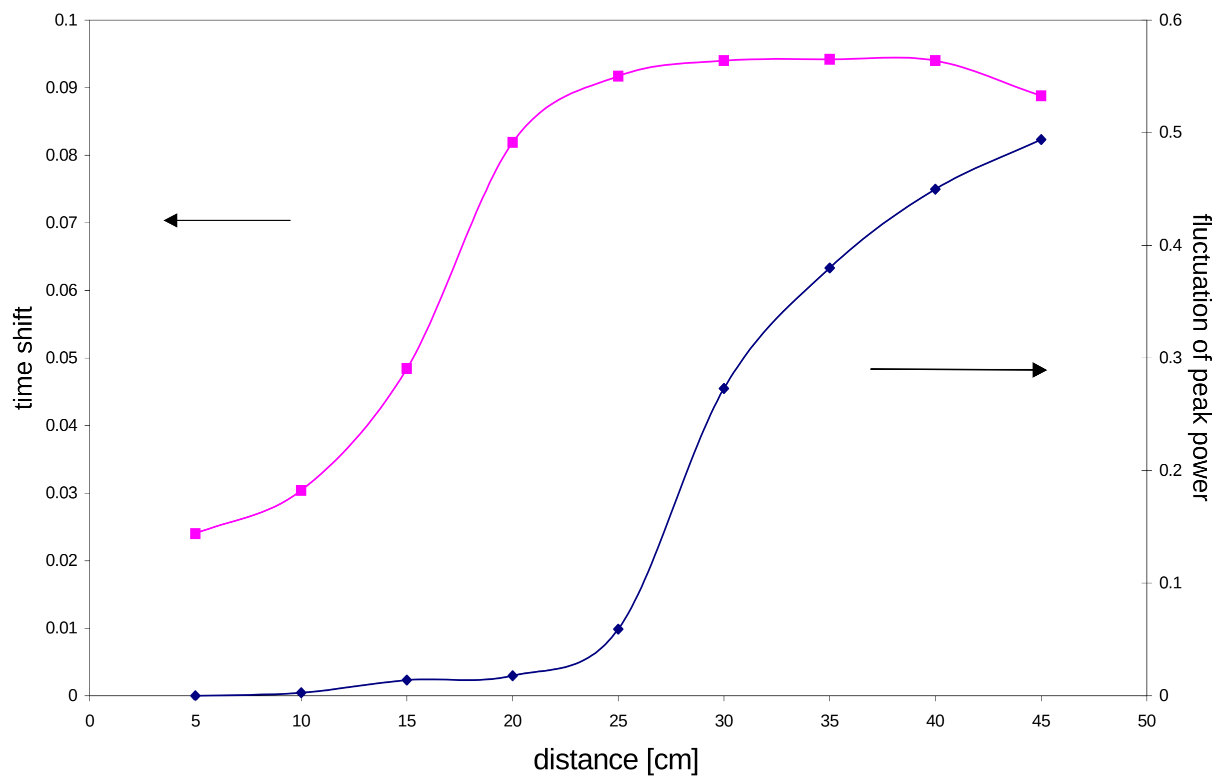
Average compressor:

$$\phi_c(\omega) = -(\phi_{SC1}(\omega) + \phi_{SC2}(\omega))/2$$

Result:

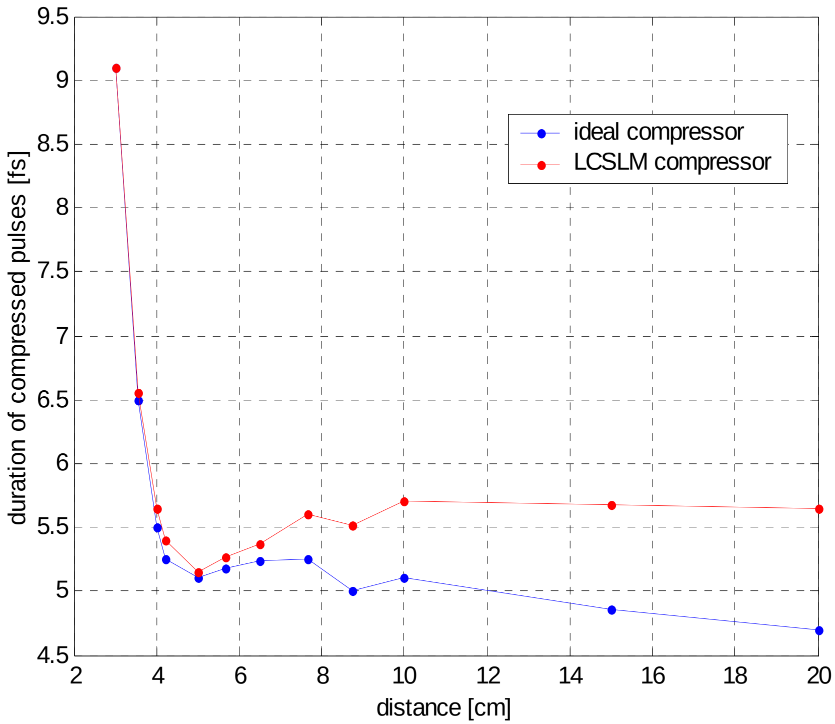
slightly fluctuation of input peak power ⟶ different substructure for Phase, GD, GDD ⟶ amplified power fluctuation and time shift for compressed pulses

Normalized Time Shift and Fluctuation for Compressed Pulses



Time shift and fluctuation versus propagation distance. In the figure, the time shift and fluctuation of peak power have been normalized to the duration and the peak power of the compressed pulse with ideal compensation.

Optimum Distance to Compress Pulse



duration of compressed pulses versus distance for ideal compressor and LCSLM

LCSLM: liquid-crystal spatial light modulator

Assume the 0.55-1.1 μm spectrum is divided into 256 channels. The phase of one channel is assigned to cancel exactly the mean phase within the spectral range of this channel.

Optimum compressed distance = 5cm

given

duration of input pulse = 100fs

peak power = 8 kW

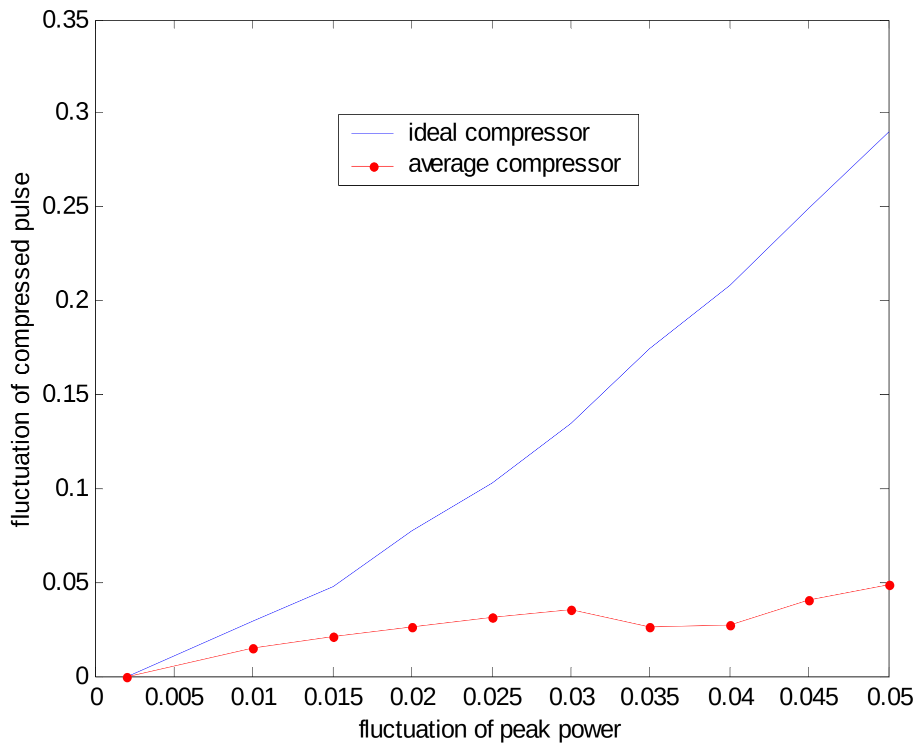
Compressed pulse

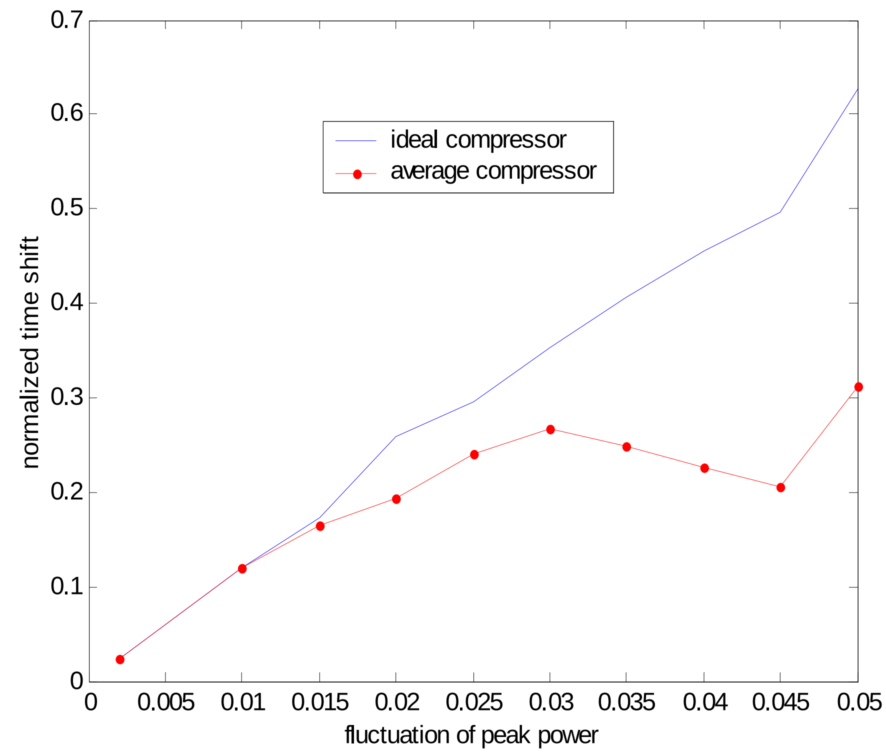
Duration : 5.15 fs

fluctuation: negligible

time shift: 0.12 fs.

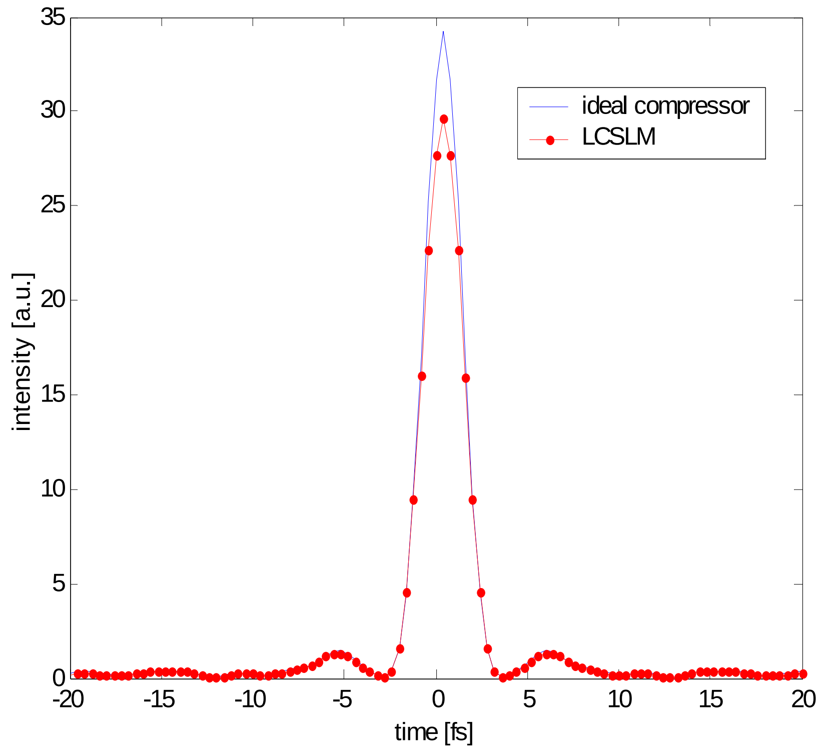
Fluctuation and Time Shift under Different Peak Power Fluctuations





Output peak power fluctuation and time shift vs input peak power fluctuation at the optimum compression distance (peak power = 8 kW, pulse duration = 100 fs, propagation distance = 5 cm)

Single-cycle Pulse Generation from SC



compressed single-cycle pulses obtained from SC with 80 kW peak power for an input pulse that propagates 1.2 cm in the PCF

SC generated under conditions:
- Duration of input pulse=100fs
- Peak power = 80 kW
- Propagation distance = 1.2 cm

Compressed pulse:
- Duration=2.4 fs (idealcompressor)
  =2.54 fs (LCSLM)
- Duration of single cycle = 2.64 fs (at 790 nm)

Conclusion

- Three stages for SC evolution: initial broadening below a certain threshold propagation distance, dramatic broadening to a SC at a threshold distance, and finally, saturation of the spectral width on propagation.

- Group delay and group delay dispersion of the SC are sensitive to the input pulse peak power after further propagation at the third stage.

- Fluctuations from the input pulse are amplified and translated into fluctuations and time shift of the compressed pulses.

- There exists an optimum compressed distance where compressed pulses with negligible fluctuation and time shift can be obtained.

For more information, please refer to

Chang GQ, Norris TB, Winful HG,OPTICS LETTERS 28 (7): 546-548 APR 1 2003