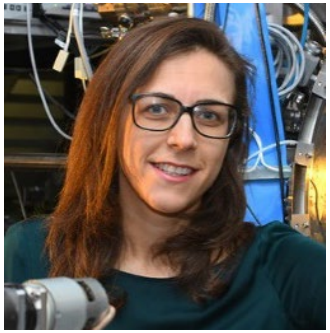
The OSA Fiber Modeling and Fabrication Technical Group Welcomes You

Current sample from another group

Technical Group Leadership 2019

Giulio Vampa
Chair
Stanford PULSE Institute

Eric Cunningham
SLAC National Accelerator Laboratory



Hanieh Fattahi
Max-Planck-Institute of Quantumoptics

Benjamin Webb
Laboratory for Laser Energetics, University Of Rochester

Zhiyi Wei
Institute of Physics, Chinese Academy of Sciences

Current sample from another group

Technical Group at a Glance

- ## Focus
  - Development and application of high intensity lasers as well as novel XUV and x-ray sources
  - The physics of high intensity light interactions with matter
  - Short wavelength sources including insertion devices for storage rings (undulators and wigglers), plasma X-ray lasers, electron beam based sources and X-ray free electron lasers.
- ## Mission
  - To benefit *YOU* and to strengthen *OUR* community
  - Webinars, podcasts, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.
- ## Find us here
  - Website: www.osa.org/OH
  - Facebook: www.facebook.com/OSAShortWavelengthTG
  - LinkedIn: www.linkedin.com/groups/8356401

Current sample from another group

Today's Webinar

Reaching for the brightest light at SLAC's FACET-II

Dr. Sebastian Meuren

Postdoctoral Researcher and PI of a strong-field QED experimental campaign at SLAC's FACET-II
Princeton University, USA
smeuren@pppl.gov

Speaker's Short Bio:
Ph.D. degree from Heidelberg University/Max Planck Institute for Nuclear Physics in 2015. Otto Hahn Medal from the Max Planck Society. Currently a postdoctoral researcher in the department of Astrophysical Sciences at Princeton University.

PRINCETON UNIVERSITY

Everything you always wanted to know about supercontinuum modelling in optical fibers

Alexander Heidt

Institute of Applied Physics
University of Bern
Switzerland

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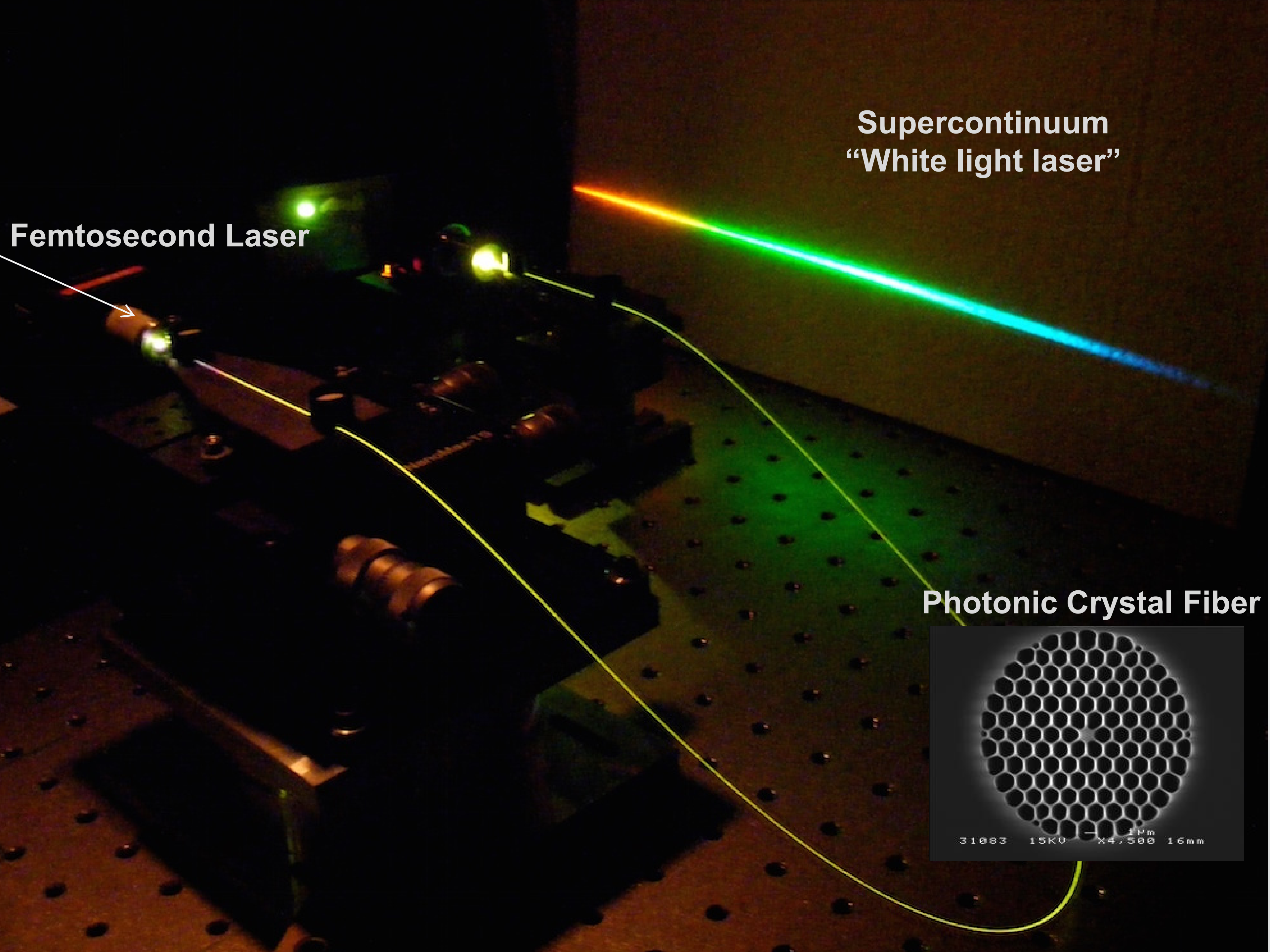
26.08.2019, OSA Webinar Series


Supercontinuum
“White light laser”
Femtosecond Laser
Photonic Crystal Fiber
1µm
31083 15KV X4,500 16mm

What you will learn

- **Concepts of Nonlinear fiber optics**
  - the power of dispersion engineering

- A short overview of the most important **nonlinear effects** occurring during supercontinuum generation in optical fibers

- Describing the physical effects mathematically in the **Generalized Nonlinear Schrödinger equation (GNLSE)**

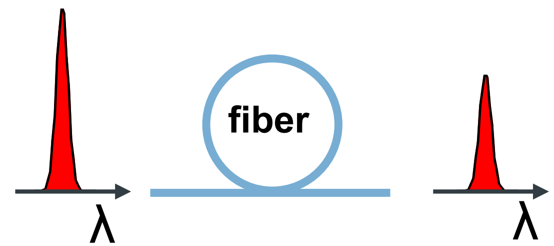
- **Solving the GNLSE** in an efficient way

- **Noise effects in supercontinuum generation** and how to include them into your simulation

Nonlinear optics – the tailor shop for light

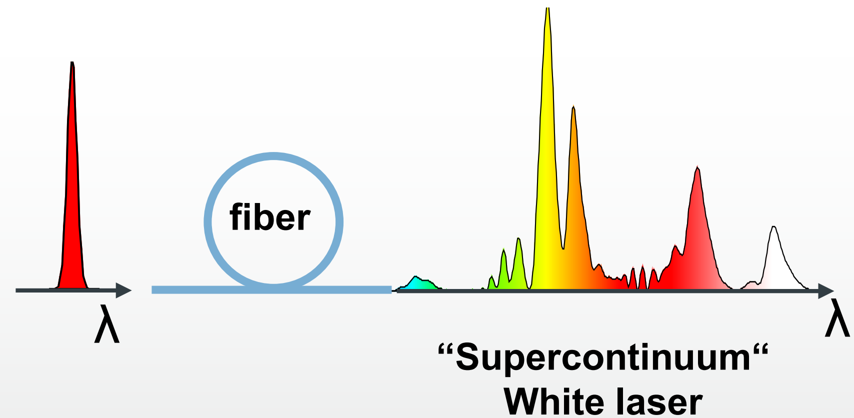
Propagation of electromagnetic fields through fibers

linear
- Dispersion
- Absorption



nonlinear
- Four wave mixing
- Self phase modulation (SPM)
- Cross phase modulation (XPM)
- Modulation instability
- Raman scattering
- Brillouin scattering
- …

intensity dependent!



Understand & Control Nonlinearity → Transform laser light to application demands

What intensities are we talking about?

"Everyday life intensities"

Intensity of sunlight on earth:
1000 W/m^2 = 0.1 W/cm^2

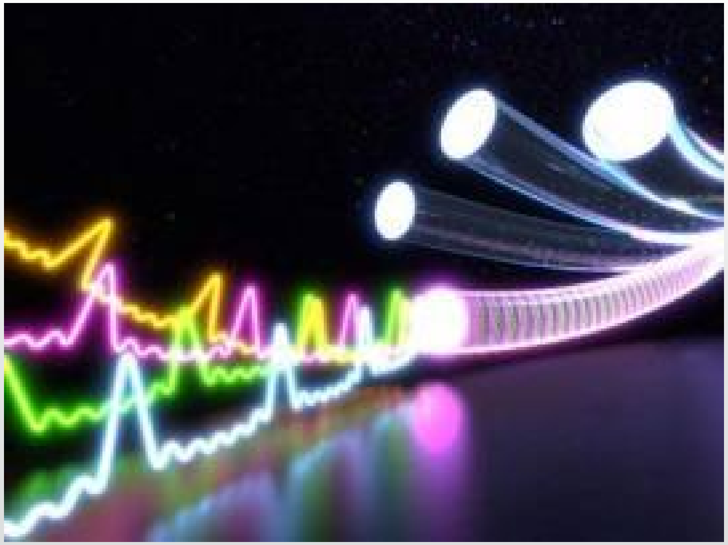
When focused with a magnifying glass:
~ 100 W/cm^2 (max)

Intensities in nonlinear fiber optics:

Femtosecond laser pulse (100 fs, 10 nJ) focused into 2 µm core diam. fiber:

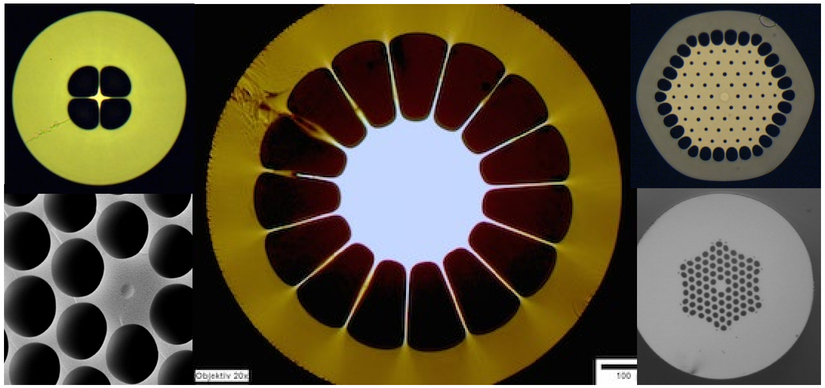
~ 1 000 000 000 000 W/cm^2
= 1 TW/cm^2

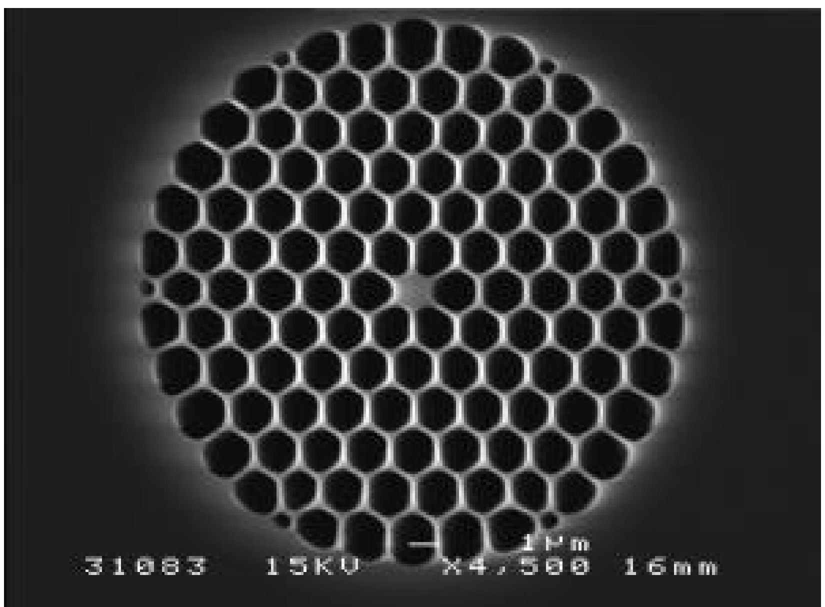
10 orders of magnitude higher than everyday life intensities!



Fibers for nonlinear optics

Revolution: photonic crystal fibers (PCF)





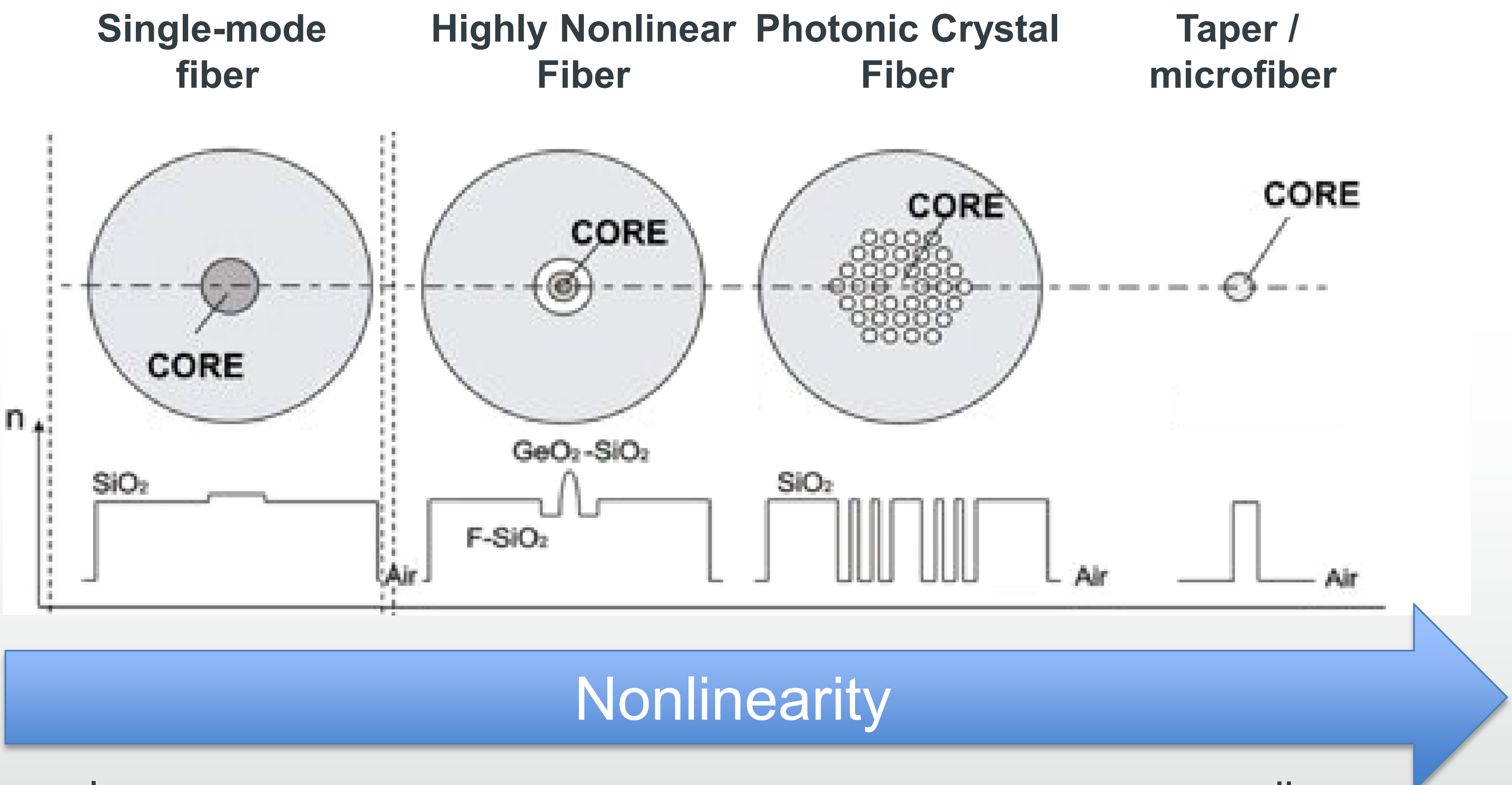
- Silica core
- Cladding of air-holes
- Design allows to "squeeze" the light into tiny cores (~ 1 μm)
  - ➔ very high intensities!
  - ➔ very high nonlinearity!
- Most important:

We can <u>control</u> nonlinear effects with the geometry of the fiber

This design flexibility only exists in fibers and waveguides!

Engineering the nonlinearity

Refractive index profile of specialty fibers

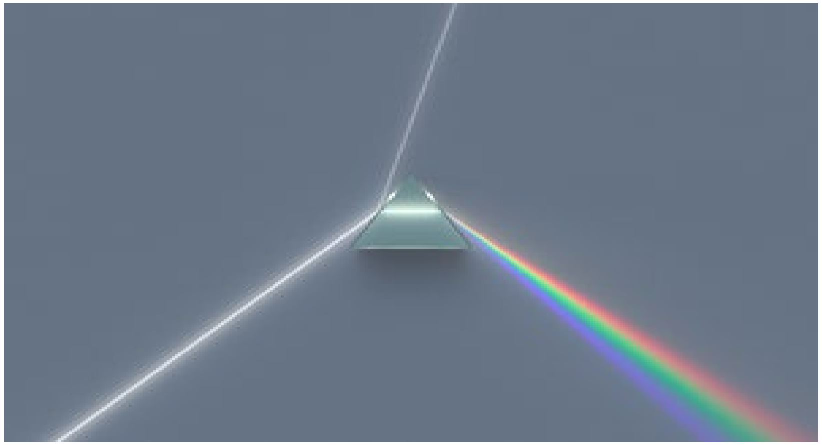


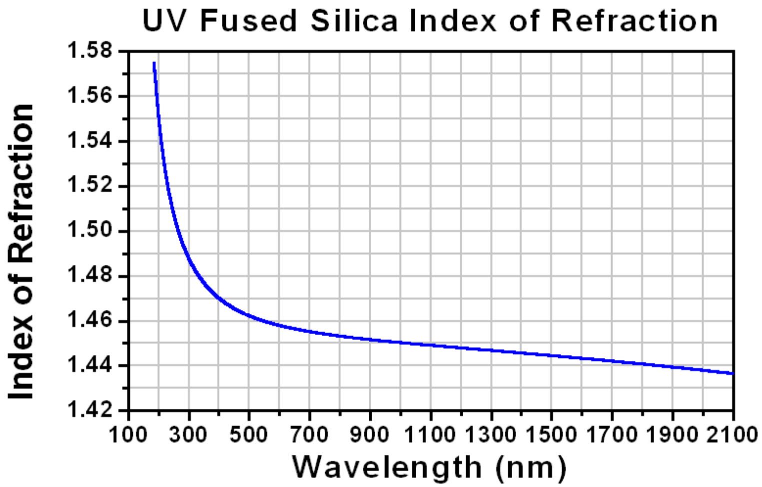
large core
small index step
low confinement
low light intensity

(material)

small core
large index step
high confinement
high light intensity

Dispersion





- Refractive index of materials depends on the wavelength
- A laser pulse propagates in a medium with the group velocity

$$v_g = c\left(n - \lambda\frac{dn}{d\lambda}\right)^{-1}$$

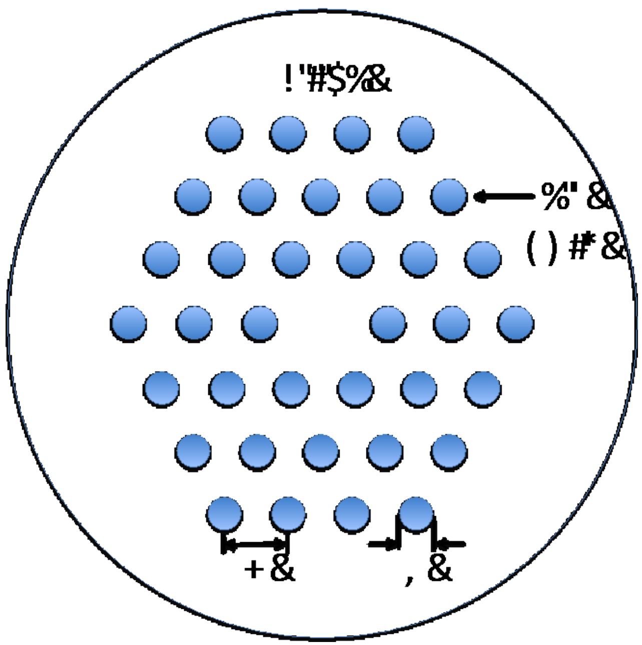
- The group velocity itself depends on the wavelength, i.e. there exists a Group Velocity Dispersion (GVD)

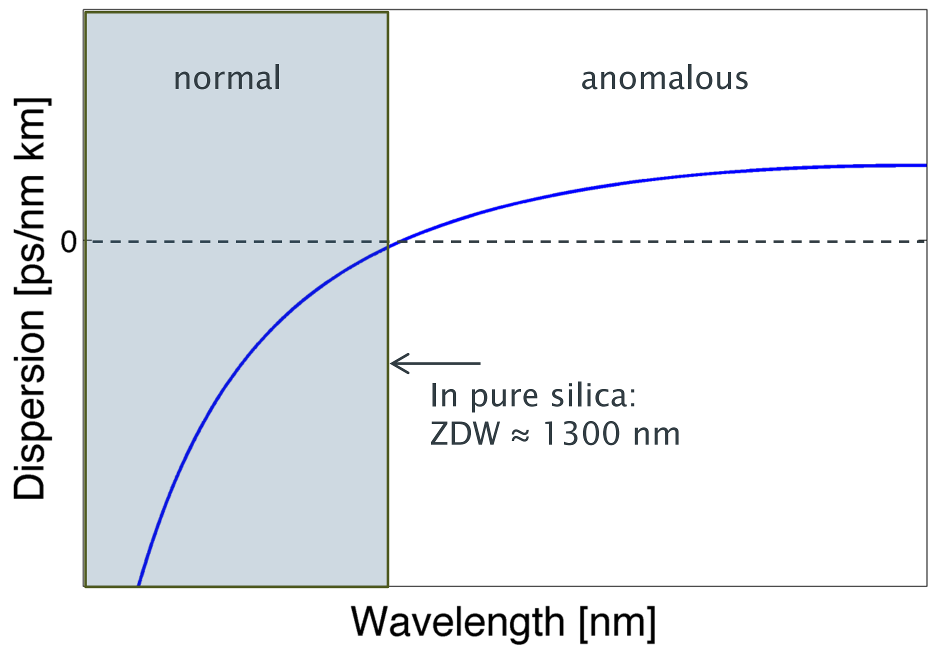
$$D = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2}.$$

D < 0: “Normal” dispersion: red faster than blue
D > 0: “Anomalous” dispersion: blue faster than red

Dispersion engineering

Most powerful tool in fiber optics

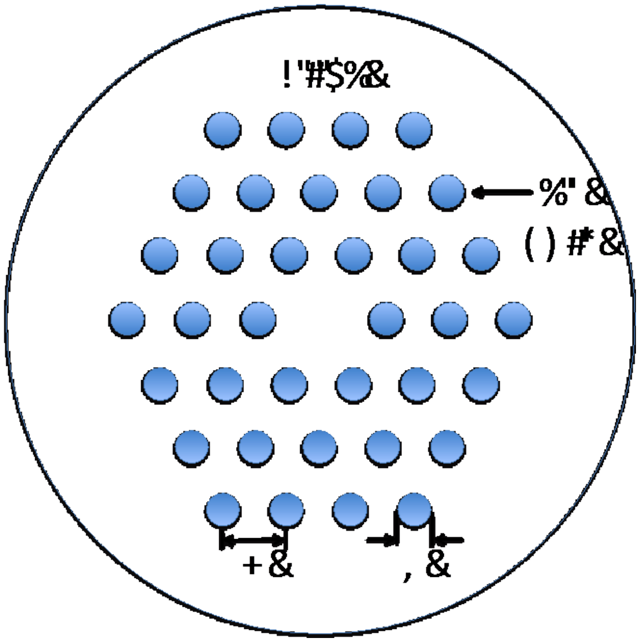


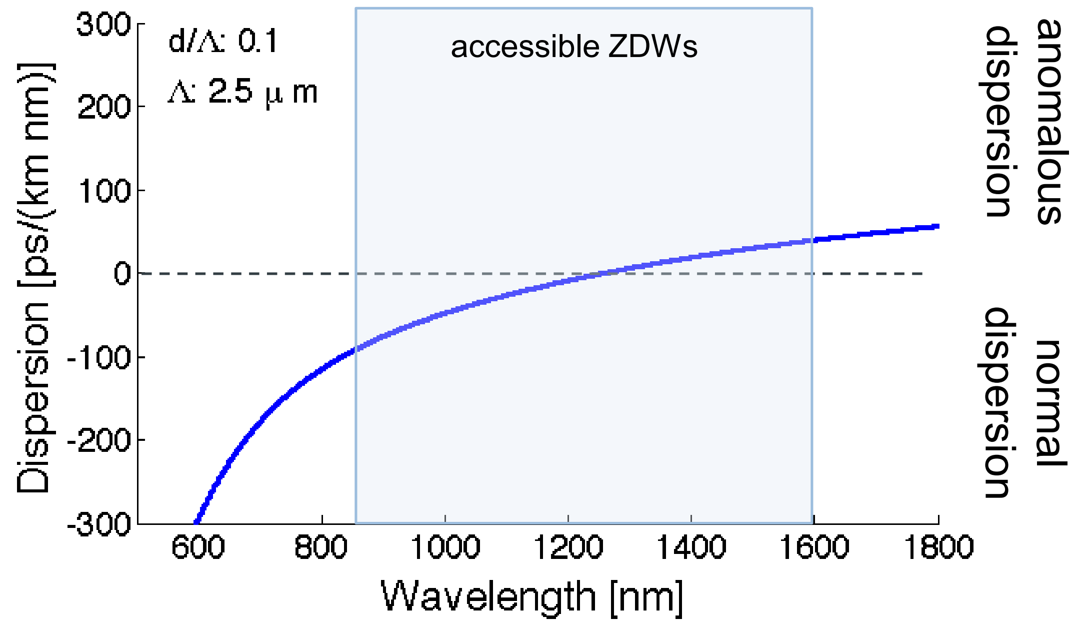


> Dispersion is highly sensitive to the geometry of the air hole cladding

Dispersion engineering

Most powerful tool in fiber optics





> Dispersion is highly sensitive to the geometry of the air hole cladding

Control nonlinear effects

by tailoring the **dispersion profile**

by designing the **geometry of the fiber**

Nonlinear effects and dispersion

Most powerful tool in fiber optics

Occurrence of nonlinear effects

	Anomalous dispersion	Normal dispersion
Self-phase modulation	✔	✔
Soliton dynamics	✔	✗
Raman effect	✔	✔
Modulation instability/ Phase-matched 4-wave-mixing	✔	✗

Control of nonlinear effects and their interaction by tailoring the dispersion!

Nonlinear effects in optical fibers

- Pulse propagation obeys

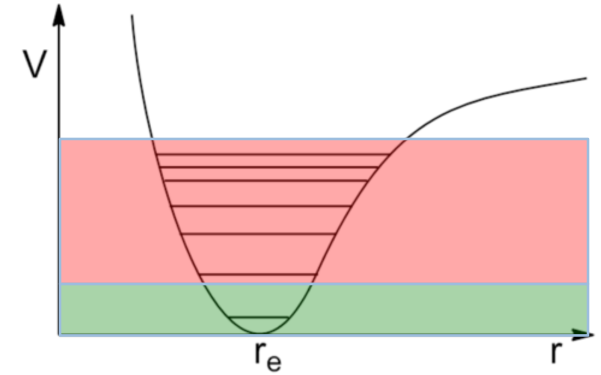
$$\nabla \times \nabla \times E(r,t) + \frac{1}{c^2}\frac{\partial^2 E(r,t)}{\partial t^2} = -\mu_0 \frac{\partial^2 P(r,t)}{\partial t^2}$$

with

$$\mathbf{P} = \varepsilon_0 \left(\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{EE} + \chi^{(3)} \vdots \mathbf{EEE} + \cdots \right)$$

Dispersion
Absorption

Nonlinearities



- $\chi^{(2)}$ = 0 in silica! (centro-symmetric material)
  (no second-harmonic generation, sum frequency generation, etc)

- Only THIRD ORDER nonlinear effects in optical fibers!

Constructing a pulse propagation equation

- General Maxwell's equations are 4-dimensional
  - → computationally expensive to solve
  - → How can we adapt them to nonlinear fiber optics?

Assumptions:

Input pulse

- **linearly polarized** along x-axis,
- carrier frequency w_0

Fiber

- **single mode**
- **polarization maintaining**
- propagation along z-axis

Ansatz:

$$\mathbf{E}(\boldsymbol{r}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \underbrace{\widehat{x} F(x, y, \omega)}_{\text{fiber mode profile}} \underbrace{\tilde{A}(0, \omega)}_{\text{spectral envelope}} \underbrace{e^{i[\beta(\omega) z - \omega t]}}_{\text{phase shift}} \, d\omega$$

Constructing a pulse propagation equation

$$\mathbf{E}(\boldsymbol{r},t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \underbrace{\hat{x}F(x,y,\omega)}_{\text{fiber mode profile}}\underbrace{\tilde{A}(0,\omega)}_{\text{spectral envelope}}\underbrace{e^{i[\beta(\omega)z-\omega t]}}_{\text{phase shift}}\,d\omega$$

Some simplifications:

- **mode profile / effective mode area independent of frequency:**

$$F(x,y,\omega) \to F(x,y,\omega_0) \qquad A_{\text{eff}}(\omega_0) = \frac{\left(\iint_{-\infty}^{\infty}|F(x,y,\omega_0)|^2 \mathrm{d}x\mathrm{d}y\right)^2}{\iint_{-\infty}^{\infty}|F(x,y,\omega_0)|^4 \mathrm{d}x\mathrm{d}y}$$

- **Taylor expansion** of propagation constant:

$$\beta(\omega) = \beta_0 + \underbrace{(\omega-\omega_0)\beta_1}_{\beta_1 = v_g^{-1}} + \frac{1}{2}\underbrace{(\omega-\omega_0)^2\beta_2}_{\substack{\beta_2>0\ :\ \text{normal GVD}\\ \beta_2<0\ :\ \text{anomalous GVD}}} + \cdots \qquad \beta_m = (d^m\beta/d\omega^m)_{\omega=\omega_0}$$

- **Transform to reference frame** co-moving with the input pulse

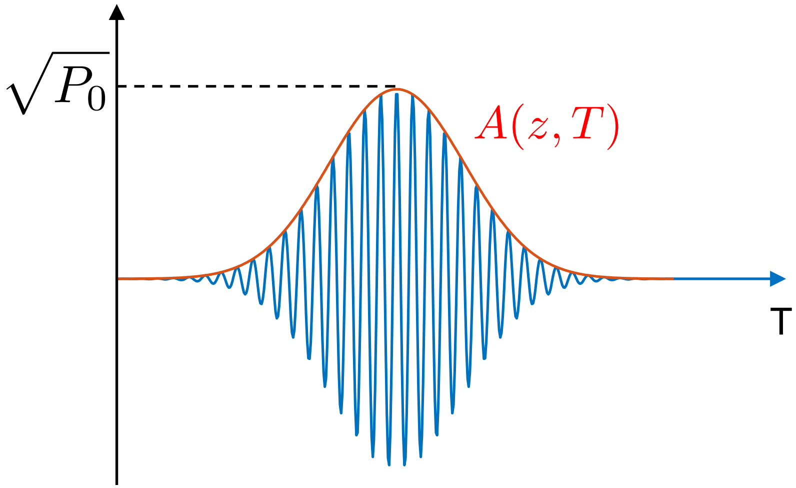
$$T = t - \beta_1 z$$

➔ in practice we set $\beta_0 = \beta_1 = 0$

Constructing a pulse propagation equation

$$\mathbf{E}(\mathbf{r},T) = \hat{x}F(x,y,\omega_0)A(z,T)e^{i\omega_0 T}$$

slowly varying envelope — rapid oscillations



A is normalized such that $|A(z,T)|^2$ yields instantaneous power in Watts.

Example for Gaussian input pulse:

$$A(z=0,T) = \sqrt{P_0}e^{-(T^2/T_0^2)}$$

Now: plug ansatz into Maxwell's equations to derive equation for A(z,T)

➔ details: e.g. Agrawal, Nonlinear Fiber Optics (Academic Press, 2013)

Generalized Nonlinear Schrödinger Equation

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$$\frac{\partial A(z,T)}{\partial z} = \left(\hat{D} + \hat{N}\right) A(z,T)$$

Remarkably simple 1+1-dimensional partial differential equation

Dispersive operator:

$$\hat{D} \;=\; \underbrace{-\frac{\alpha}{2}}_{\text{absorption}} - \underbrace{\sum_{n\geq 2} \beta_n \frac{i^{n-1}}{n!} \frac{\partial^n}{\partial T^n}}_{\text{dispersion}}$$

Nonlinear operator:

$$\hat{N} A(z,T) \;=\; i\gamma \left(1 + \underbrace{i\tau_{\mathrm{shock}} \frac{\partial}{\partial T}}_{\text{dispersion of nonlinearity}}\right) \times \underbrace{\left[A(z,T) \int_{-\infty}^{\infty} R(t') |A(z,T-t')|^2 dt'\right]}_{\text{SPM, FWM, Raman}}$$

Material response function: $R(t) = \underbrace{(1 - f_R)\delta(t)}_{\text{instantaneous (SPM, FWM)}} + \underbrace{f_R h_R(t)}_{\text{delayed (Raman)}}$

$f_R \sim 0.2 \,(\mathrm{silica})$

fractional contribution of delayed response

Nonlinear parameter: $\gamma = \dfrac{n_2 \omega_0}{c A_{\mathrm{eff}}(\omega_0)}$

$n_2 \sim 3 \times 10^{-20}\ \mathrm{m^2/W}\ \ (\mathrm{silica})$

nonlinear refractive index

Self-phase modulation (SPM)

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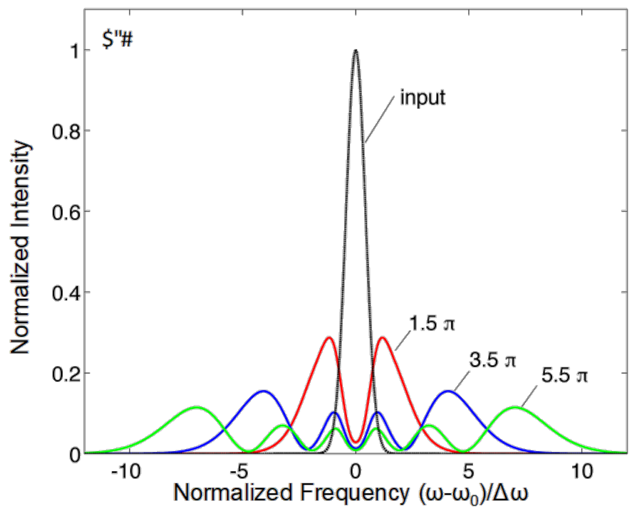
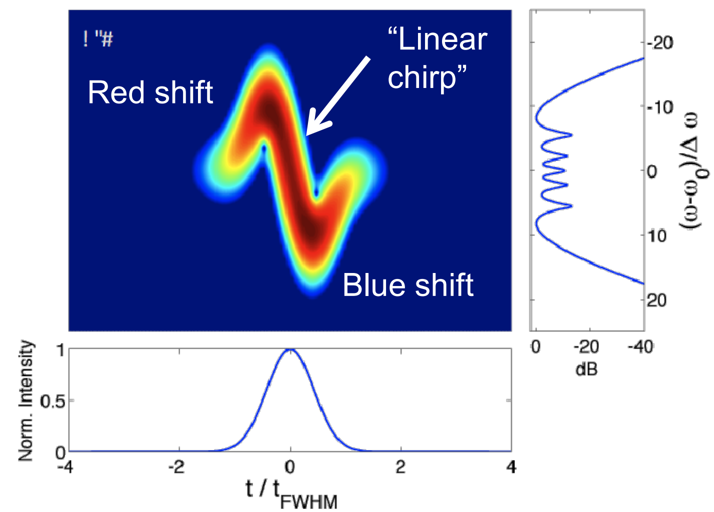




$\hat{D} = 0$
$\hat{N} = i\gamma|A|^2$
$(f_R = 0)$

- Pulse itself changes the refractive index of the medium (Kerr effect):

$$n = n_0 + n_2 I(t) = n_0 + n_2 (P(t)/A_{eff})$$

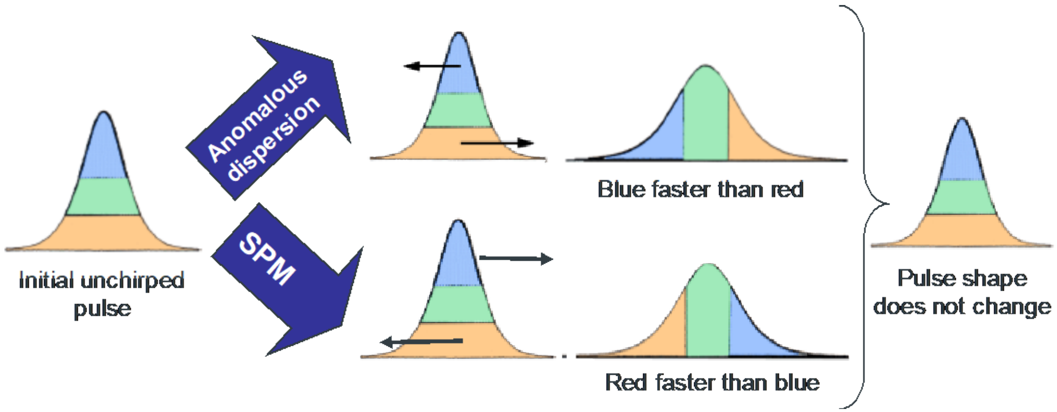
- New frequency components are created with a time correlation:

$$\omega(z,t) = \omega_0 - \gamma z \, \partial P(t)/\partial t$$

Spectral broadening
Multi-peak structure in the spectrum
"Chirped" pulse

Soliton dynamics

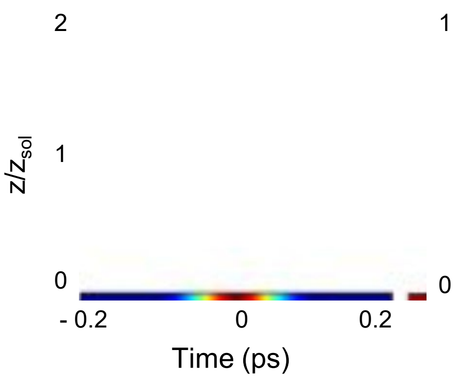
Balance of SPM and anomalous dispersion



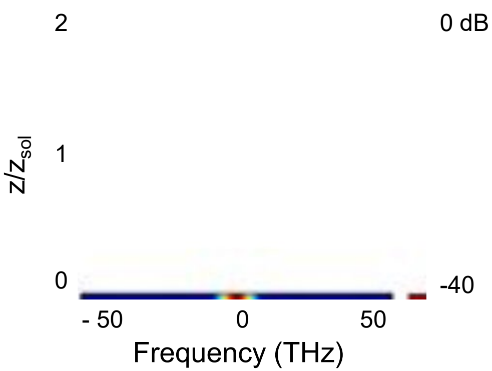
$$\hat{D} = -i\frac{\beta_2}{2}\frac{d^2}{dT^2}$$
$$\beta_2 < 0$$
$$\hat{N} = i\gamma|A|^2$$

- Fundamental soliton: invariant upon propagation (except constant nonlinear phase shift)

Temporal Evolution



Spectral Evolution



Requirements:

$$A(0,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0); \quad N = \sqrt{\frac{\gamma P_0 T_0^2}{|\beta_2|}} = 1$$

soliton number

Solution:

$$A(z,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0)e^{ik_{\mathrm{sol}}z}; \quad k_{\mathrm{sol}} = \gamma P_0/2;$$

Soliton dynamics

Higher order solitons

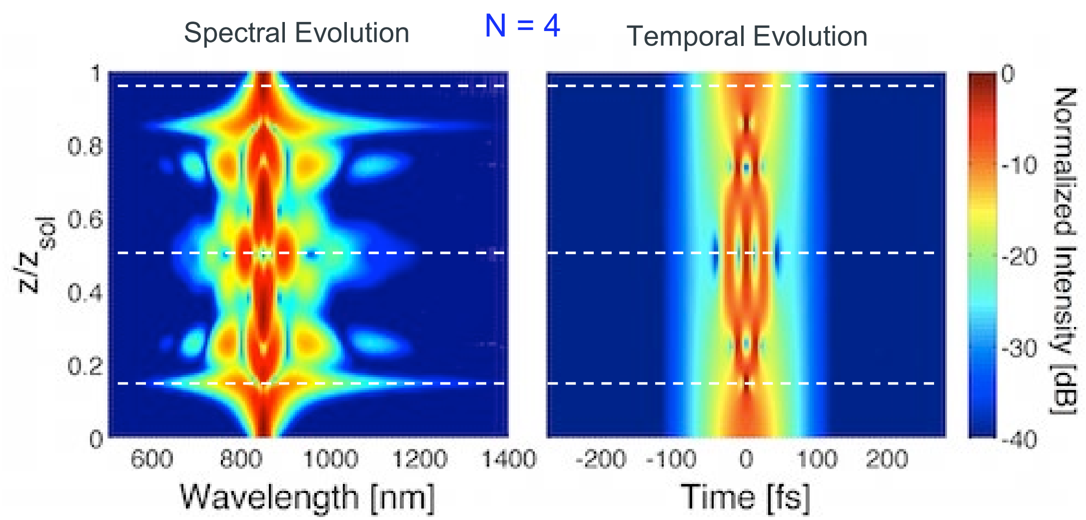
$$\hat{D} = -i\frac{\beta_2}{2}\frac{d^2}{dT^2}$$
$$\beta_2 < 0$$
$$\hat{N} = i\gamma|A|^2$$

- Higher order solitons are periodic upon propagation:

$$A(z + z_{\mathrm{sol}}, T) = A(z, T)$$

Requirements:

$$A(0,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0); \quad N = \sqrt{\frac{\gamma P_0 T_0^2}{|\beta_2|}} = 2, 3, 4\ldots \text{ quantized!} \quad z_{\mathrm{sol}} = \frac{\pi}{2}\frac{T_0^2}{\beta_2}$$

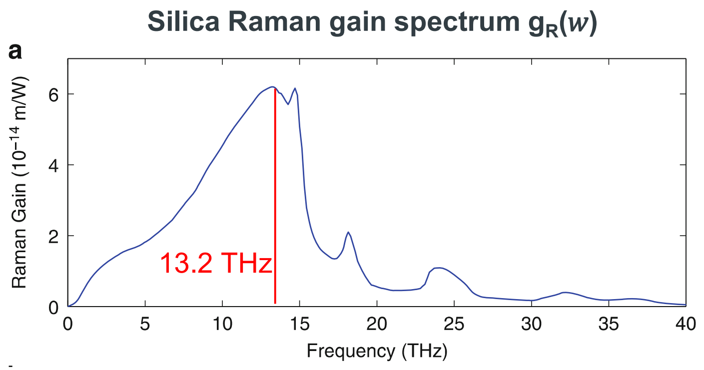


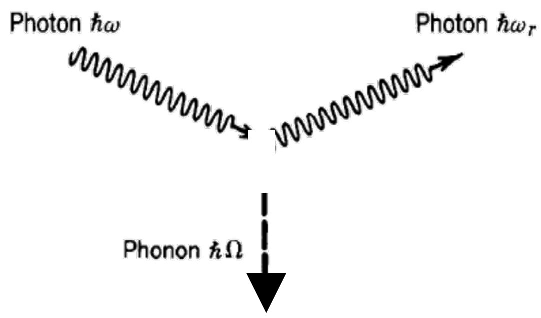
Back to original state

Multiple pulses

Extreme compression and spectral broadening

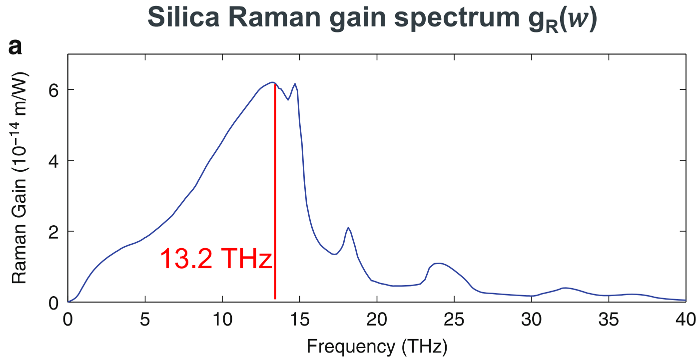
Stimulated Raman scattering

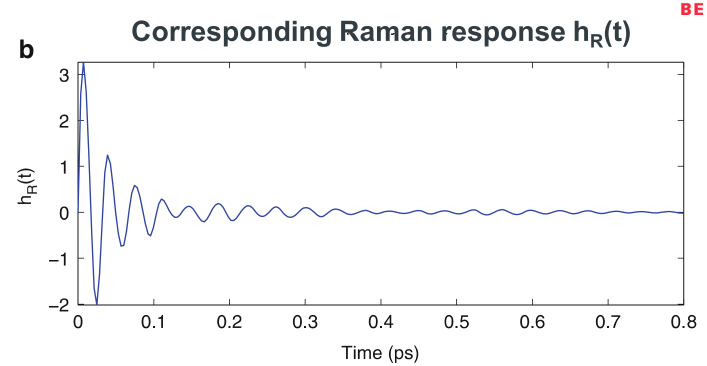




- Quantum mechanical picture: photon loses energy to phonons excited in the material
- Classical picture: amplification of "Stokes" wave red-shifted from the pump

Stimulated Raman scattering





- Quantum mechanical picture: photon loses energy to phonons excited in the material
- Classical picture: amplification of “Stokes” wave red-shifted from the pump

- GNLSE includes material response:

$$R(t) = (1 - f_R)\delta(t) + \underline{f_R h_R(t)}\,?$$

- use analytical approximation for $h_R(t)$ developed in literature
  - ➔ e.g. Lin & Agrawal, Opt. Lett. 31, 3086 (2006)

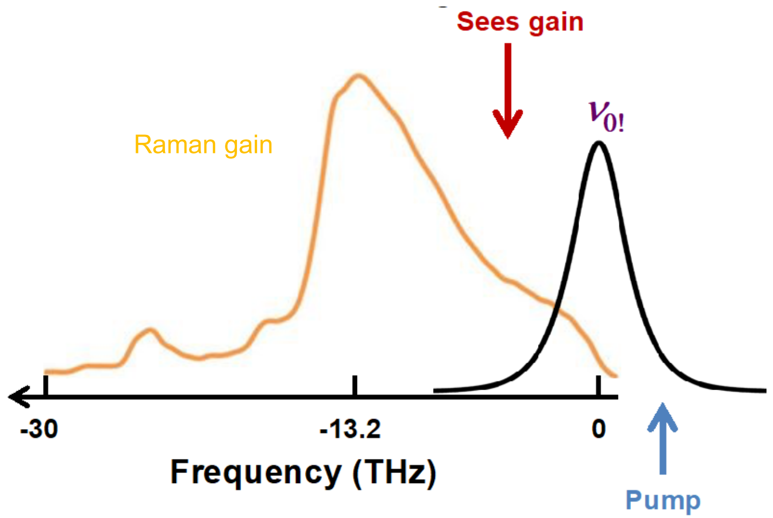
- alternative: use measured Raman spectrum $g_R(\omega) \propto \mathrm{Im}\left(\tilde{h}_R(\omega)\right)$ and Kramers-Kronig to determine real part

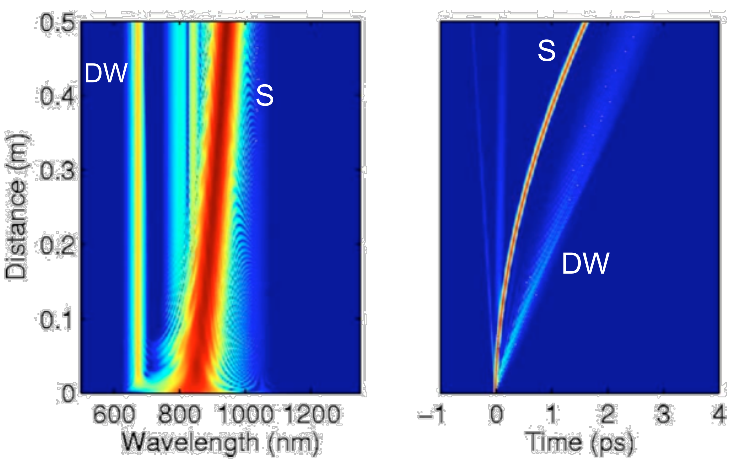
Soliton self-frequency shift and dispersive waves

Perturbations of N = 1 solitons

Ideal soliton propagation is disturbed by presence of Raman scattering and higher order dispersion:

Full GNLSE





Soliton self-frequency shift:

- ➔ continuous **spectral red-shift**
- ➔ **Soliton slows down** due to lower group velocity at longer wavelengths

Higher order dispersion:

- ➔ soliton sheds energy to a **dispersive wave** in the normal dispersion regime
- ➔ position determined by phase matching condition

Soliton fission

Perturbations of higher order solitons

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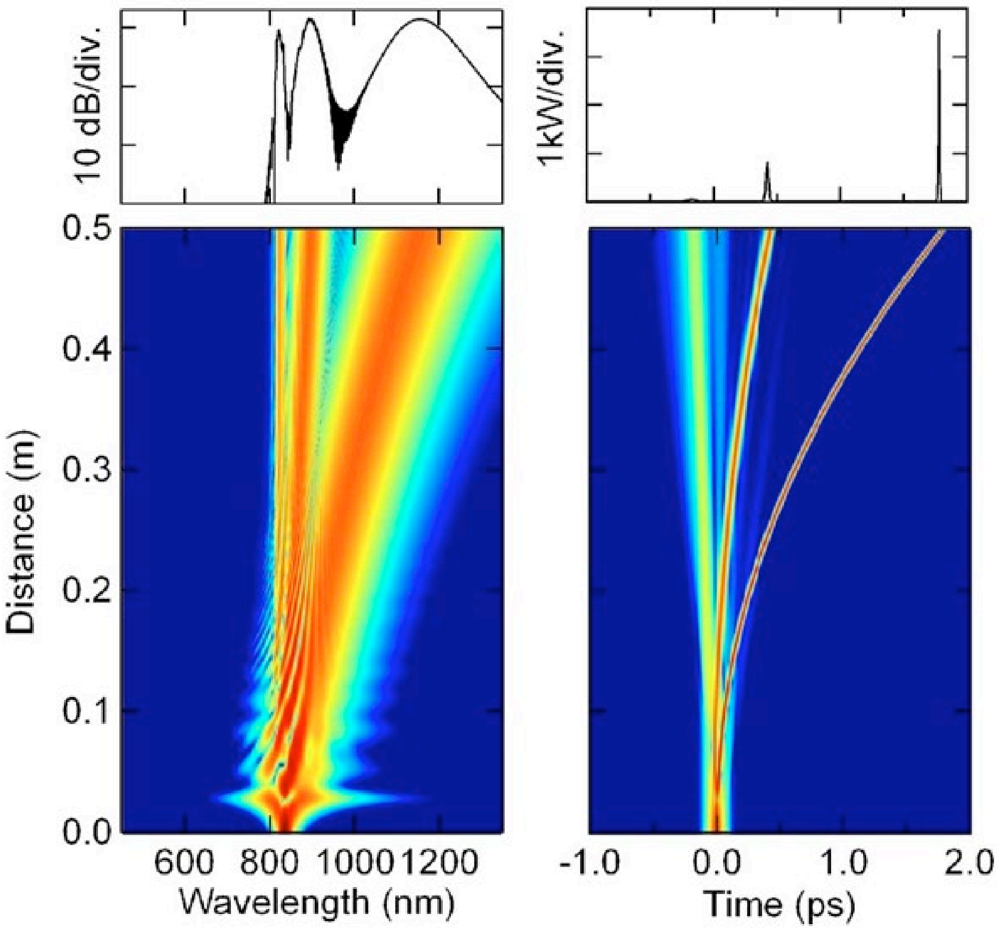
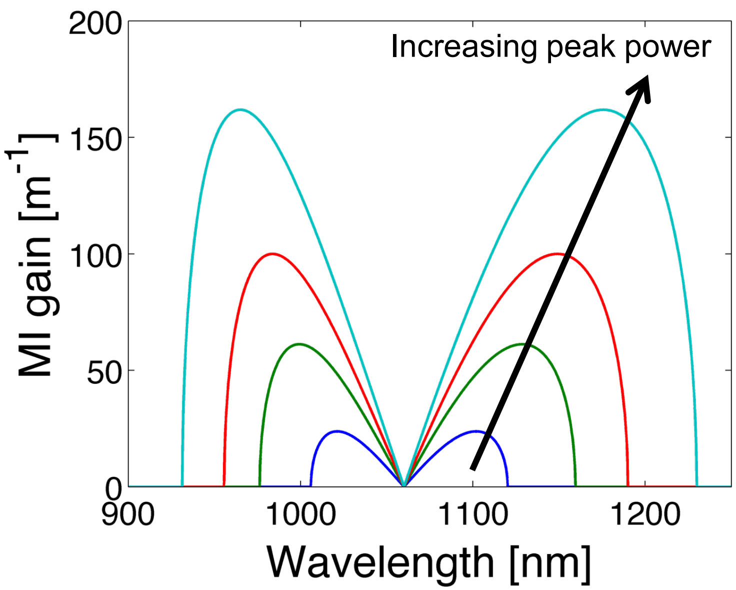
Full GNLSE

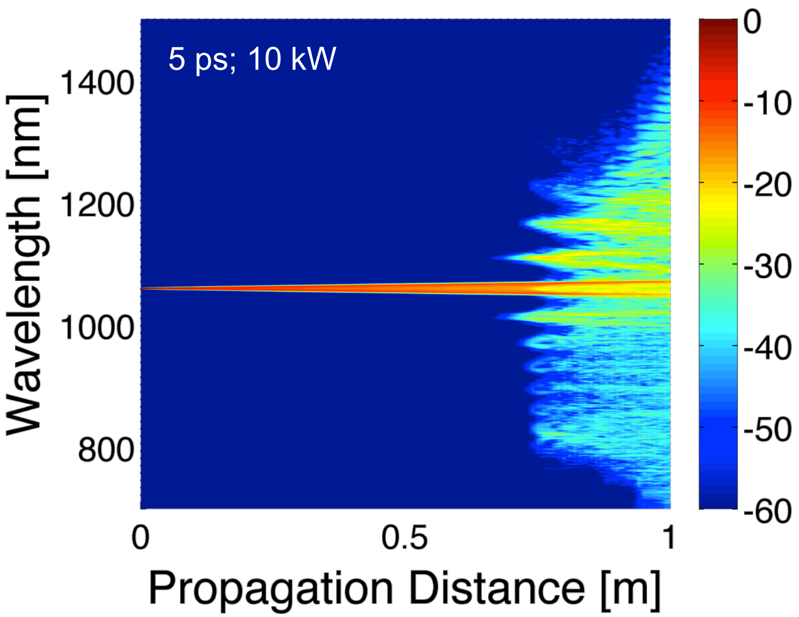


- Higher order soliton propagation disturbed by Raman scattering and higher order dispersion
- Break up into fundamental solitons (here: N = 3)
- Break up at the point of strongest temporal compression
- Pulses separate in time and spectrum due to Raman scattering

Modulational instability

Full GNLSE

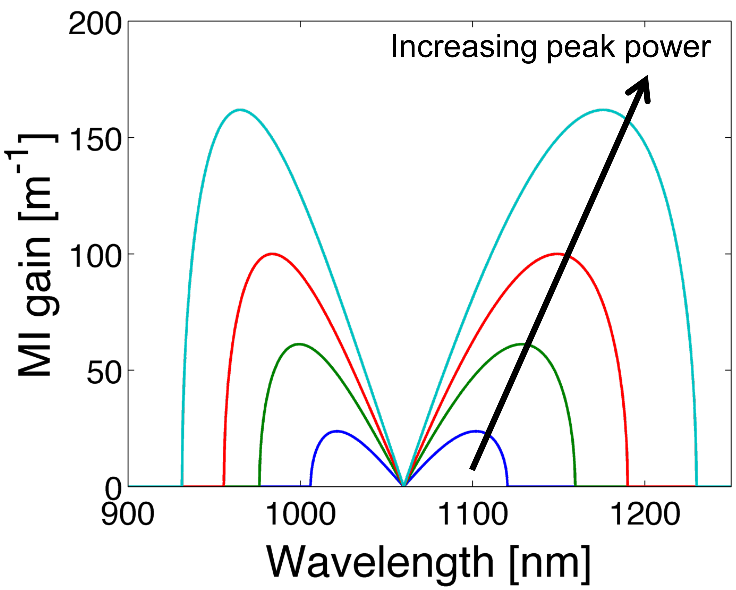


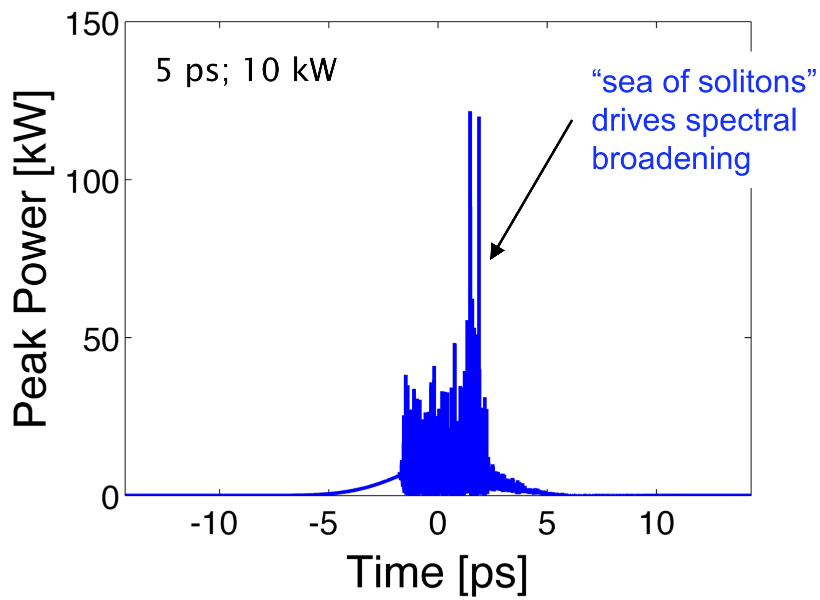


- Occurs mainly in anomalous dispersion regime
- 2 pump photons annihilated, create 1 photon in each side band
- Side band position: energy / momentum conservation ➔ dispersion!
- If unseeded: shot noise amplification!

Modulational instability

Full GNLSE





- Occurs mainly in anomalous dispersion regime
- 2 pump photons annihilated, create 1 photon in each side band
- Side band position: energy / momentum conservation ➔ dispersion!
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Dispersion engineering for SC generation

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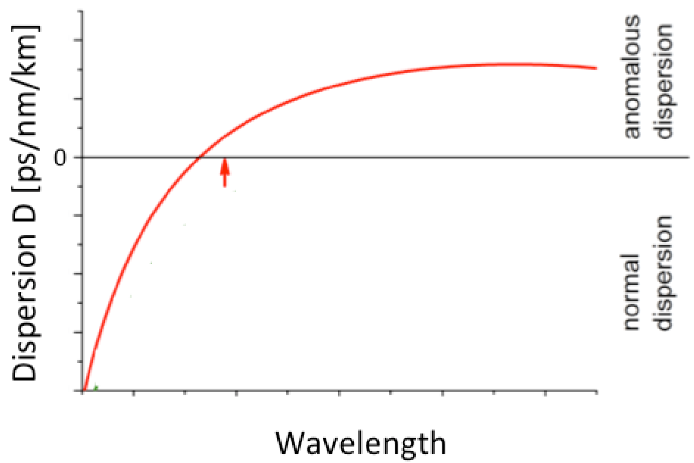
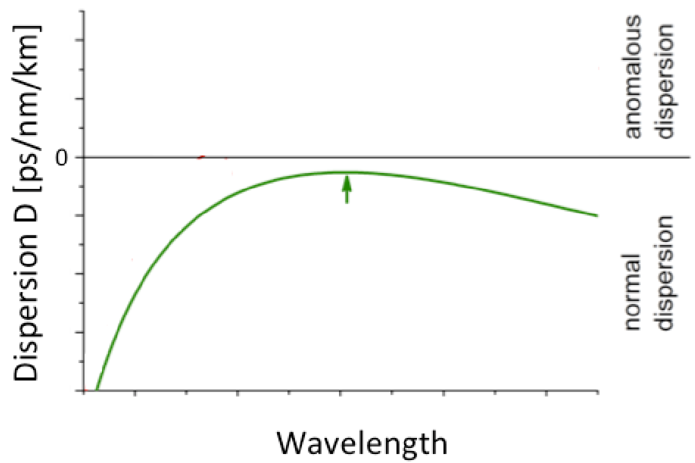
Conventional vs. ANDi design

Conventional design



- both normal and anomalous dispersion regions
- pumping in **anomalous dispersion** close to zero dispersion wavelength (ZDW)
- designed to maximize spectral bandwidth
- soliton dynamics and phase-matched 4-wave mixing play dominant role

All-normal dispersion (ANDi) design

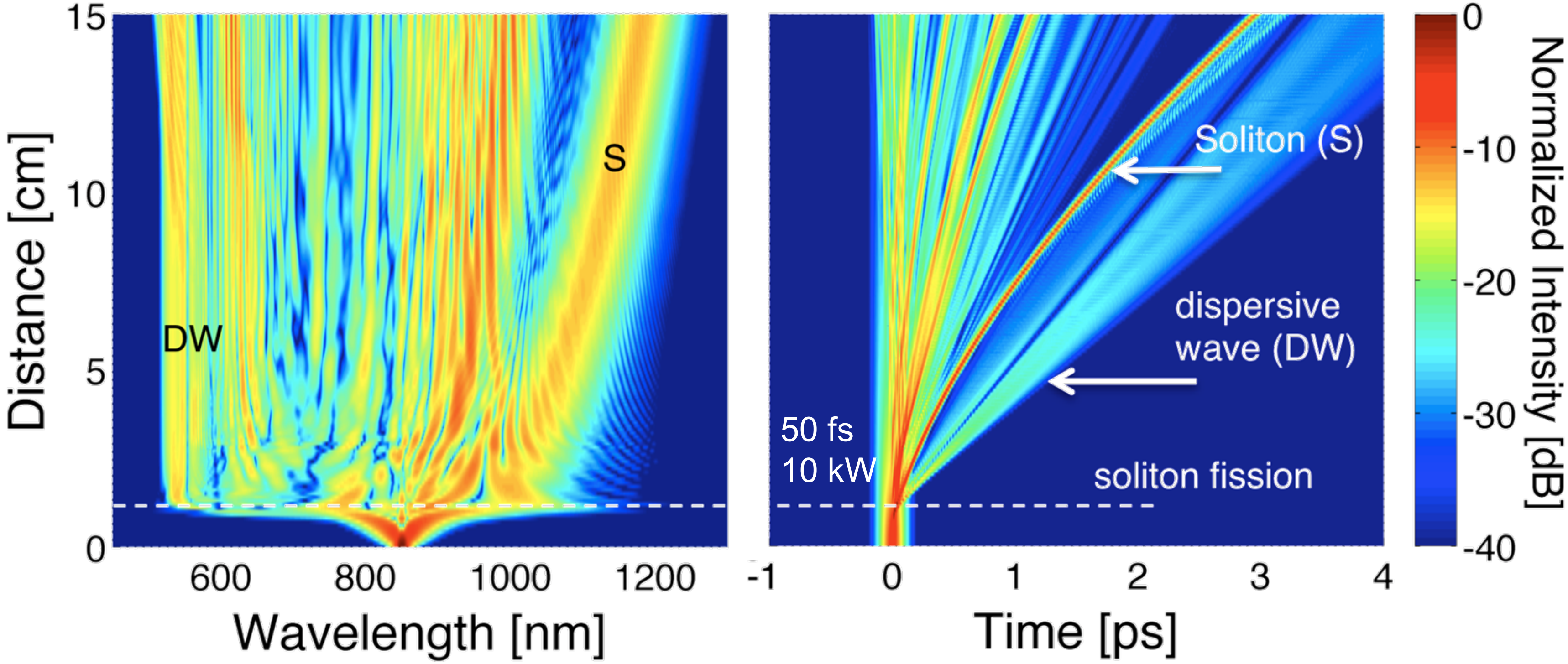


- **normal dispersion** at all wavelengths
- pumping close to the minimum dispersion wavelength (MDW)
- designed for low-noise performance
- soliton dynamics and phase-matched 4-wave mixing completely suppressed
- SPM and “optical wave-breaking” play dominant role

“Conventional” supercontinuum generation

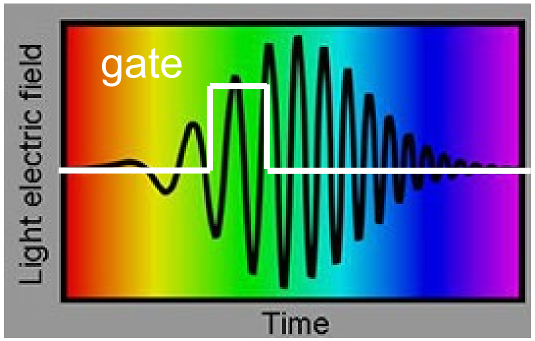
Nonlinear dynamics

Pump pulse: soliton number N ≈ 6



Analysis of simulation results

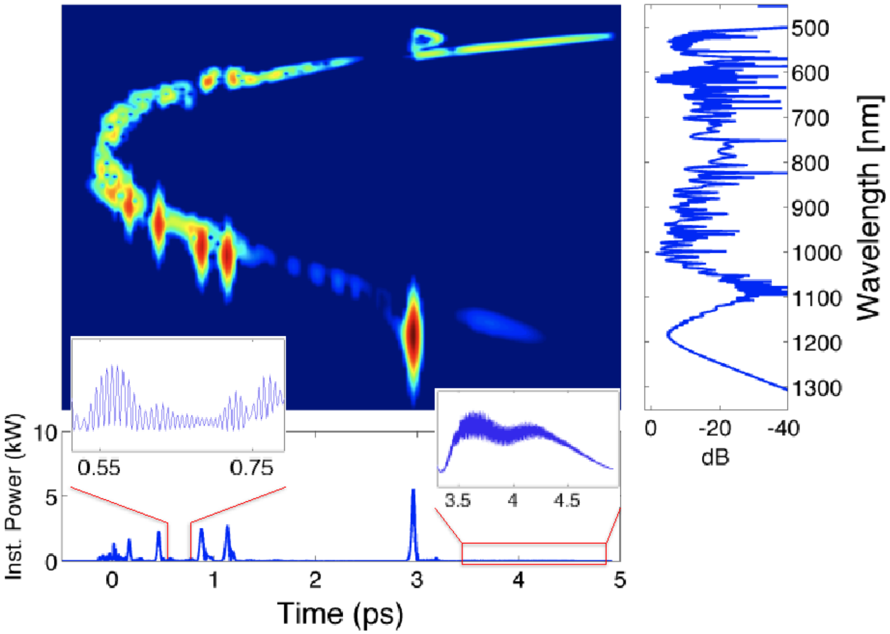
Time-frequency analysis



$$\Sigma_g^A(\omega,\tau) = \left| \int_{-\infty}^{\infty} A(t)\, g(t-\tau) \exp(i\omega t)\, dt \right|^2$$

simulated field

gate pulse
(e.g. input pulse for your simulation)



Full dynamics of continuum generation

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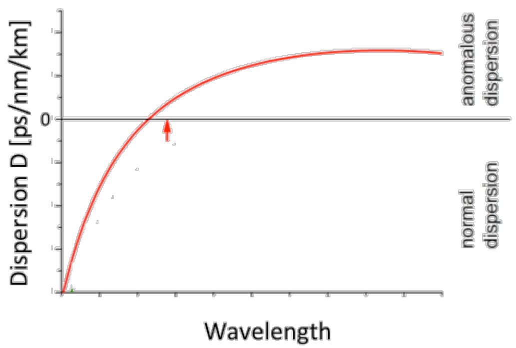
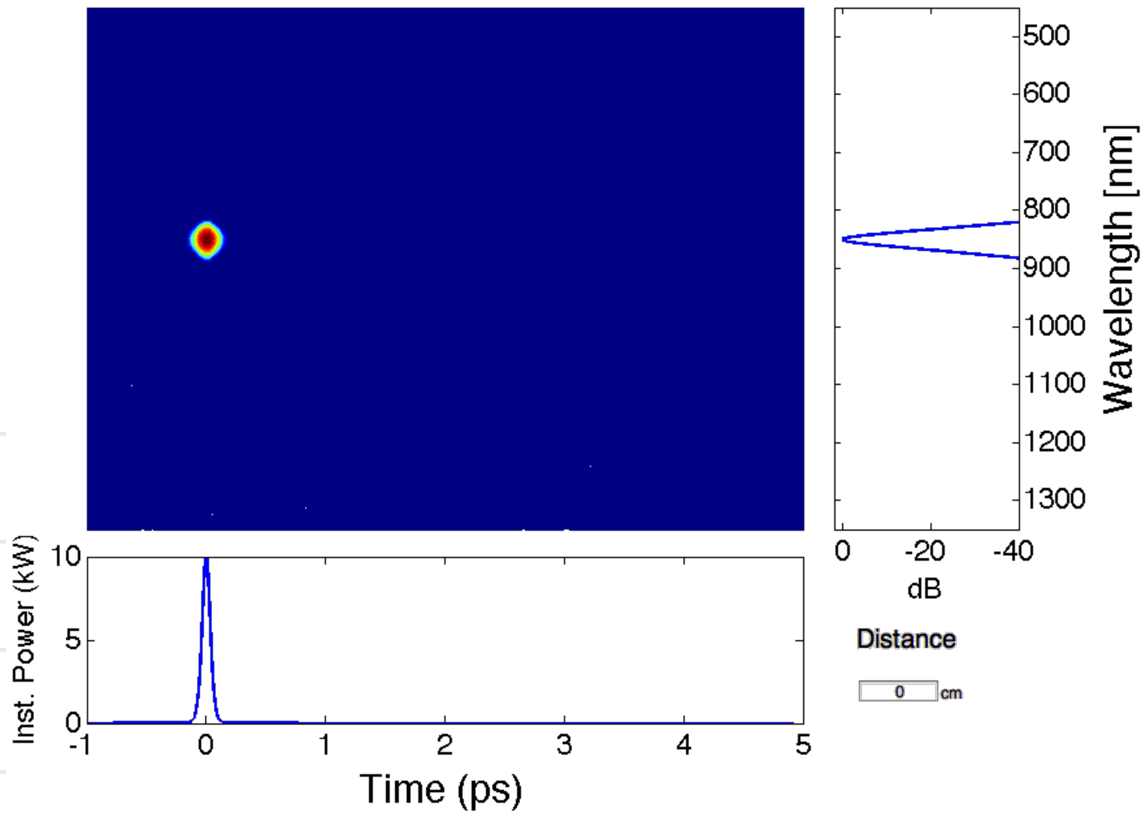
Anomalous dispersion pumping

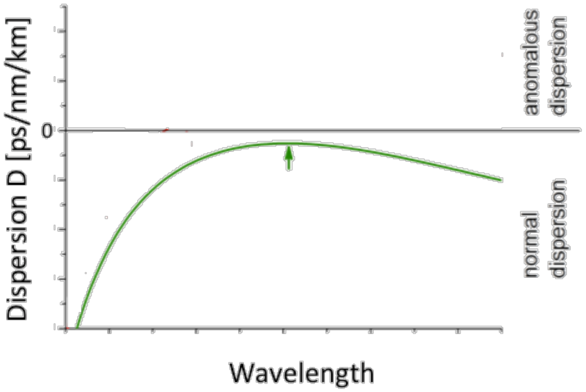


- low required peak power
- pulse break-up
- complex profiles, fine structure
- can be affected by quantum noise (modulation instability)

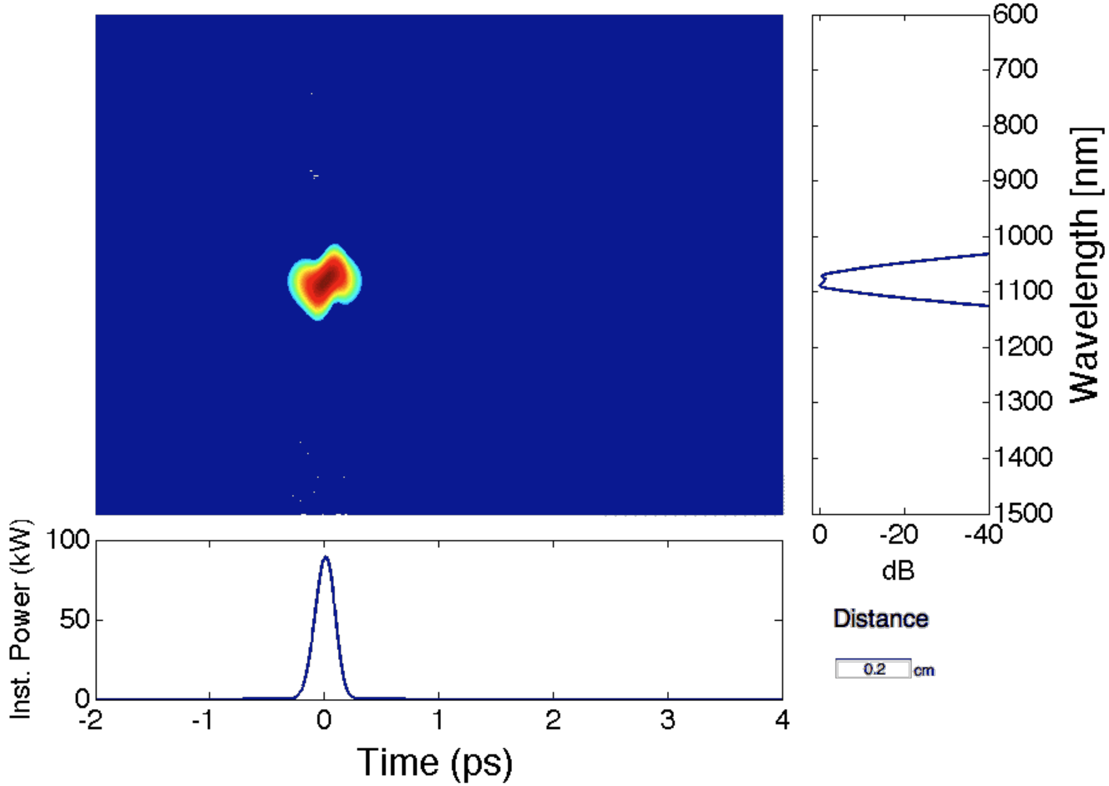


Full dynamics of continuum generation

All-normal dispersion supercontinuum



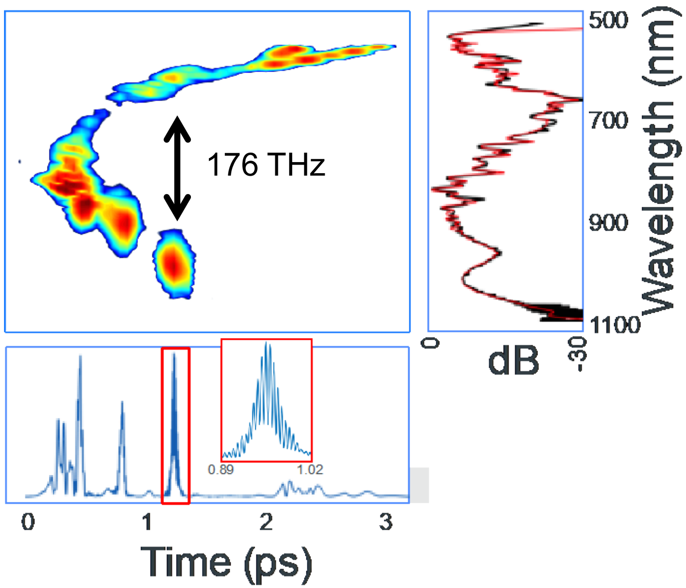
- no pulse-breakup
- minimum fine structure
- Unaffected by noise (up to ~1 ps pump pulses)



Dispersion engineering for SC generation

Conventional vs. ANDi SC (Femtosecond pumping)

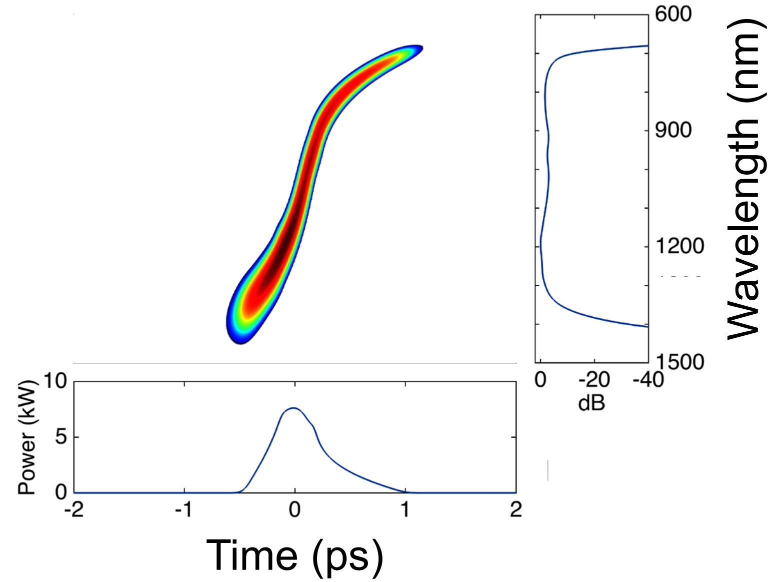
Conventional supercontinuum



Focus: spectral bandwidth

> low pump power, very broad spectra
> highly structured and complex spectral profiles
> pump pulse breaks up into multiple solitons
> temporal and spectral interference effects
> susceptible to noisy pulse-to-pulse fluctuations

ANDi supercontinuum



Focus: ultrafast and low-noise applications

> single ultrashort pulse maintained
> smooth, flat spectra, steep edges
> excellent pulse-to-pulse stability
> higher pump peak power required to obtain bandwidth comparable to conventional SC

Numerical solution of the GNLSE

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \sum_{k\geq 2} \frac{\mathrm{i}^{k+1}}{k!}\beta_k \frac{\partial^k A}{\partial T^k} = i\gamma \left(1 + i\tau_{\mathrm{shock}} \frac{\partial}{\partial T}\right) \times \left(A(z,T) \int_{-\infty}^{\infty} R(T') \left|A(z,T-T')\right|^2 \mathrm{d}T'\right)$$

- Numerics: continuous problem is solved approximately on a discrete grid of points

- Idea:
  - represent input field on a discrete temporal grid of size n_t with resolution ΔT
  - Fourier relations then define a frequency grid with resolution $\Delta\nu = 1/(n_t \Delta T)$
  - propagate stepwise through z (fiber length)

- Time-domain formulation contains a few difficulties:
  - Temporal derivatives in dispersive operator and shock term can only be approximated in discrete case → errors
  - Convolution integral difficult to compute

➔ **Solution: transfer into frequency domain!**

Advantages of frequency domain formulation

- **Time derivatives vanish:**

$$\mathcal{F}\left(\frac{\partial}{\partial T}\right) = -i(\omega - \omega_0)$$

➔ dispersive and nonlinear operators can be applied in approximation-free manner
➔ frequency domain formulation is fundamentally more accurate

- **Convolution integral vanishes:**

$$\mathcal{F}(\int_{-\infty}^{\infty} A(\tau)B(t-\tau)\mathrm{d}\tau) = \tilde{A}(\omega)\tilde{B}(\omega)$$

Explicitly:

$$\int_{-\infty}^{\infty} R(T')|A(z,T-T')|^2 \mathrm{d}T' = \int_{-\infty}^{\infty} [(1-f_\mathrm{R})\delta(T') + f_\mathrm{R} h_\mathrm{R}(T')]|A(z,T-T')|^2 \mathrm{d}T'$$

$$= \underbrace{(1-f_\mathrm{R})|A(z,T)|^2}_{\text{Kerr effect}} + \underbrace{f_\mathrm{R}\int_{-\infty}^{\infty} h_\mathrm{R}(T')|A(z,T-T')|^2 \mathrm{d}T'}_{\text{stimulated Raman scattering}}$$

$$\mathcal{F}\left(\int_{-\infty}^{\infty} h_R(T')|A(z,T-T')|^2 dT'\right) = \mathcal{F}(h_R(T))\mathcal{F}(|A(z,T)|^2)$$

Frequency domain version of the GNLSE

$$\frac{\partial \tilde{A}(z,\omega)}{\partial z} = \left(\hat{D}(\omega) + \hat{N}(z,\omega)\right)\tilde{A}(z,\omega)$$

$$\hat{D}(\omega) = -\frac{\alpha(\omega)}{2} + i(\beta(\omega) \underbrace{- \beta_1(\omega-\omega_0) - \beta(\omega_0))}_{\text{co-moving reference frame}}$$

$$\hat{N}(z,\omega)\tilde{A}(z,\omega) = i\gamma\left(1 + \frac{\omega-\omega_0}{\omega_0}\right)$$

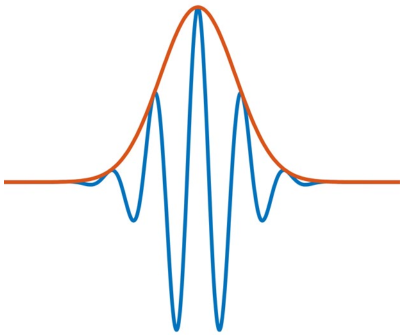
frequency dependence of the nonlinearity

$$\times\mathcal{F}\left\{\underbrace{(1-f_R)|A(z,T)|^2 A(z,T)}_{\text{Kerr effect}} + \underbrace{f_R A(z,T)\mathcal{F}^{-1}\left(\mathcal{F}(h_R(T))\mathcal{F}(|A(z,T)|^2)\right)}_{\text{Stimulated Raman scattering}}\right\}$$

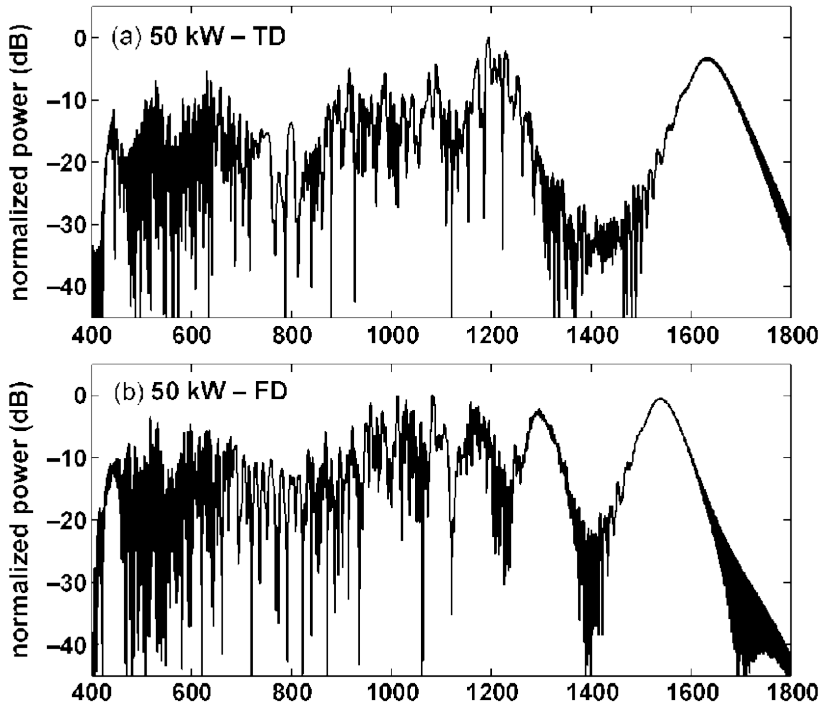
Validity: does the envelope approximation break down for very short pulses?

➔ No, still valid even for single cycle and sub-cycle pulses!

➔ e.g. Genty et al., Opt. Express 15, 5382 (2007)



Time vs. frequency domain formulation



Errors caused by approximate treatment of derivatives in time-domain

”Correct” frequency domain simulation

and more accurate

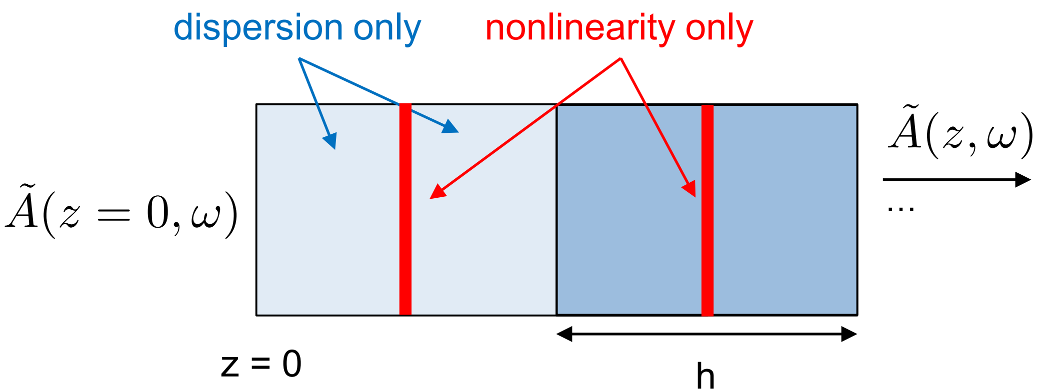
Rieznik et al., Photonics Journal 4, 556 (2012)

Numerical solution of the GNLSE

Split-step Fourier method

$$\frac{\partial \tilde{A}(z,\omega)}{\partial z} = \left(\hat{D}(\omega) + \hat{N}(z,\omega)\right) \tilde{A}(z,\omega)$$

Idea: dispersion and nonlinear operator act independently over small propagation step *h*



$$\tilde{A}(z+h,\omega) \approx \exp\left(\frac{h}{2}\hat{D}\right) \exp\left(\int_z^{z+h} \hat{N}(z')dz'\right) \exp\left(\frac{h}{2}\hat{D}\right) \tilde{A}(z,\omega)$$

Error: in reality, dispersion and nonlinearity act together

the bigger, the better!

$$\tilde{A}_{\text{calc}}(z+h,\omega) = \tilde{A}_{\text{true}}(z+h,\omega) + \mathcal{O}(h^3)$$

Numerical solution of the GNLSE

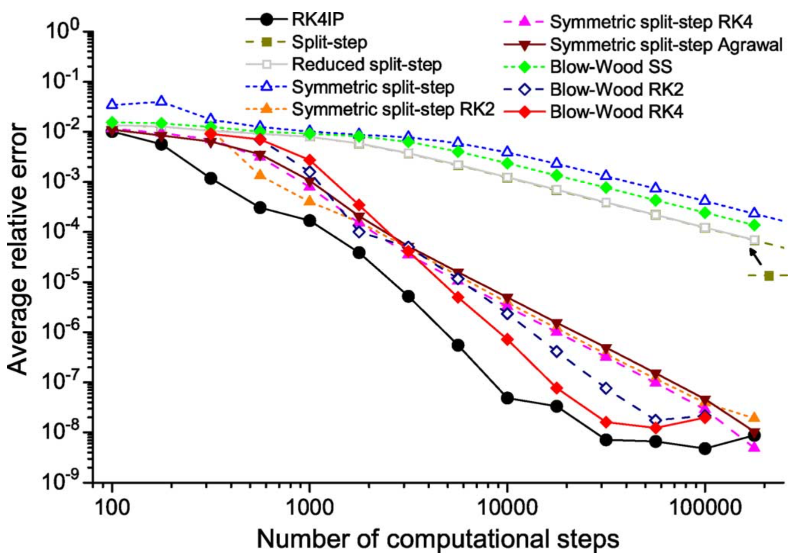
Runge-Kutta in the Interaction Picture (RK4IP)

$$\frac{\partial \tilde{A}(z,\omega)}{\partial z} = \left(\hat{D}(\omega) + \hat{N}(z,\omega)\right) \tilde{A}(z,\omega)$$

Idea: intelligent combination of the split-step Fourier method and an efficient integration of the nonlinear step using a Runge-Kutta algorithm

Explicit algorithm to propagate $\tilde{A}(z,\omega) \rightarrow \tilde{A}(z+h,\omega)$

➔ *see Hult, J. Lightwave Technol. 25, 3770 (2007)*

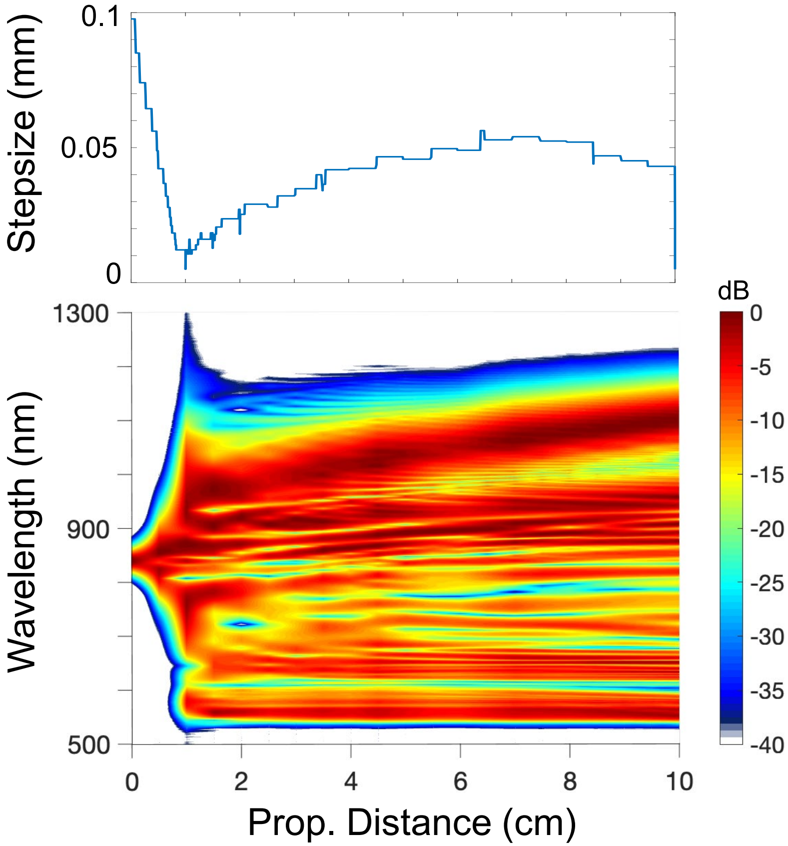


Error of RK4IP method:

$$\tilde{A}_{\mathrm{calc}}(z+h,\omega) = \tilde{A}_{\mathrm{true}}(z+h,\omega) + \mathcal{O}(h^5)$$

Adaptive step size algorithms

Efficient and fast calculations



Concept:

- Estimate current error during calculation
- Increase or decrease step size in order to maintain a given level of accuracy

➔ Makes the calculation significantly faster

➔ Avoids manual search for an appropriate constant step size

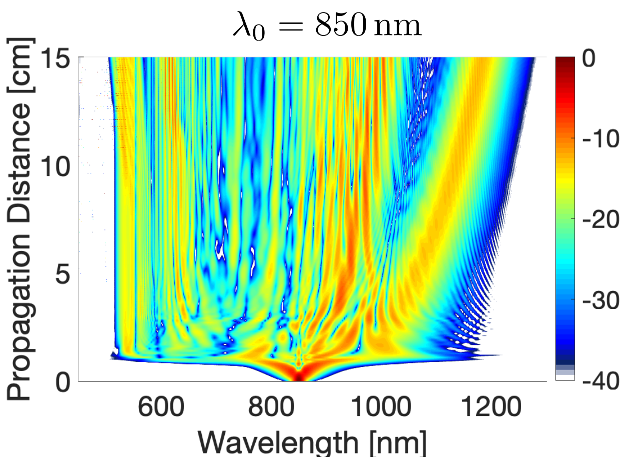
Examples of methods:

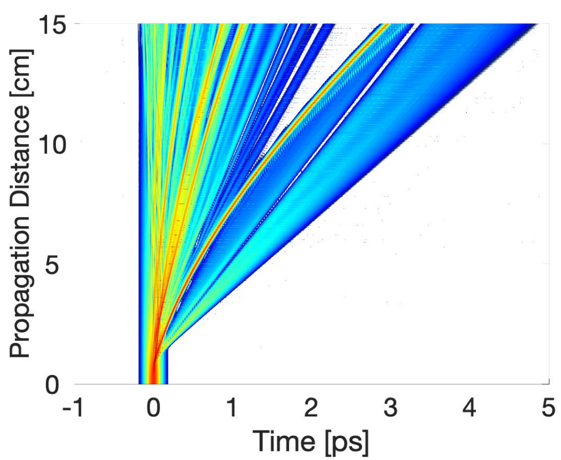
- Photon number conservation
  Heidt, J. Lightwave Technol. 27, 3984 (2009)

- Step size doubling
  Sinkin et al., J. Lightwave Technol. 21, 61 (2003)

Implementation details

Determining grid sizes





2 constraints:

- Sampling frequency > maximum frequency of the field (Nyquist)

$$\lambda_{\min} = \frac{c}{\frac{1}{2\Delta t} + \frac{\omega_0}{2\pi}} = \frac{1}{\frac{1}{2c\Delta t} + \frac{1}{\lambda_0}} \qquad \lambda_{\min} \sim 500\,\mathrm{nm} \rightarrow \Delta t < 2\mathrm{fs}$$

- Width of the grid > maximum time delay of the field

Maximum delay ~5 ps → Time window T > 10 ps

Number of grid points $n_p = T/\Delta t = 5000$ (set $n_p = 2^{13}$)

To avoid negative frequencies: $\Delta t > \lambda_0/(2c) \rightarrow \Delta t > 1.41\mathrm{fs}$

Be aware of wrap around effects if your window size is too small!

Implementation details

Extras

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- **Frequency dependent nonlinear parameter** $\gamma(\omega_0) \to \gamma(\omega)$

$$\tilde{C}(z,\omega) = \left[\frac{A_{\mathrm{eff}}(\omega)}{A_{\mathrm{eff}}(\omega_0)}\right]^{-1/4} \tilde{A}(z,\omega) \qquad \gamma(\omega) = \frac{n_2 n_0 \omega_0}{c n_{\mathrm{eff}}(\omega)\sqrt{A_{\mathrm{eff}}(\omega) A_{\mathrm{eff}}(\omega_0)}}$$

solve GNLSE as usual. Requires knowledge of $A_{\mathrm{eff}}(\omega), n_{\mathrm{eff}}(\omega)$

- **Non-polarization maintaining fiber**
  - ➔ 2 coupled GNLSEs, one for each principal polarization axis.
  - ➔ implementation / solver identical to ”simple” GNLSE
  - ➔ e.g. Bravo Gonzalo et al., Sci. Rep. 8, 6579 (2018), “Methods”

- **Multimode fiber**
  - ➔ many coupled GNLSEs
  - ➔ gets complicated
  - ➔ Poletti and Horak, J. Opt. Soc. Am. B 25, 1645 (2008).

Noise properties of SC sources

Conventional supercontinuum

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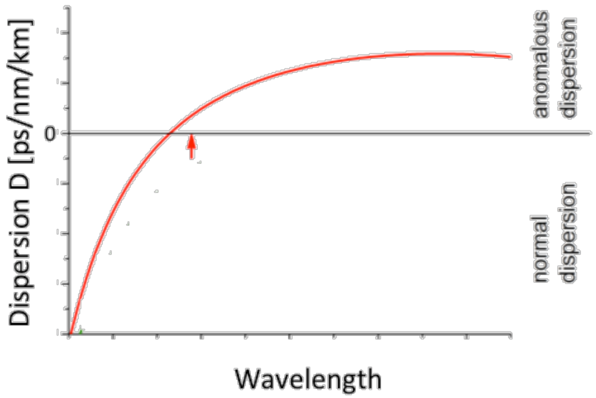
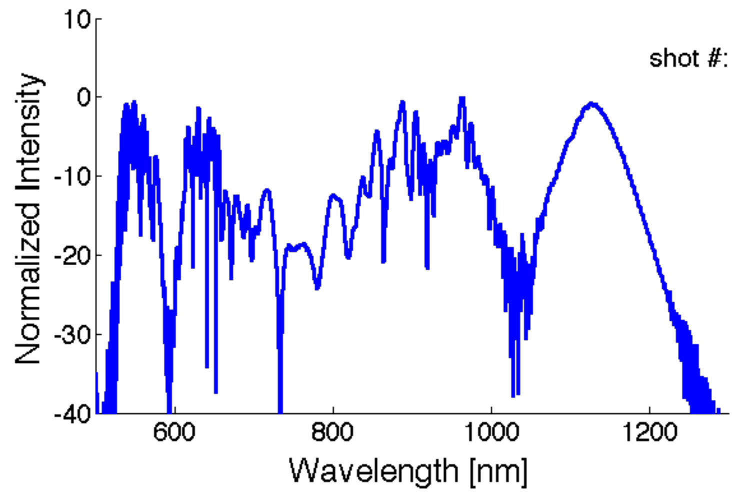
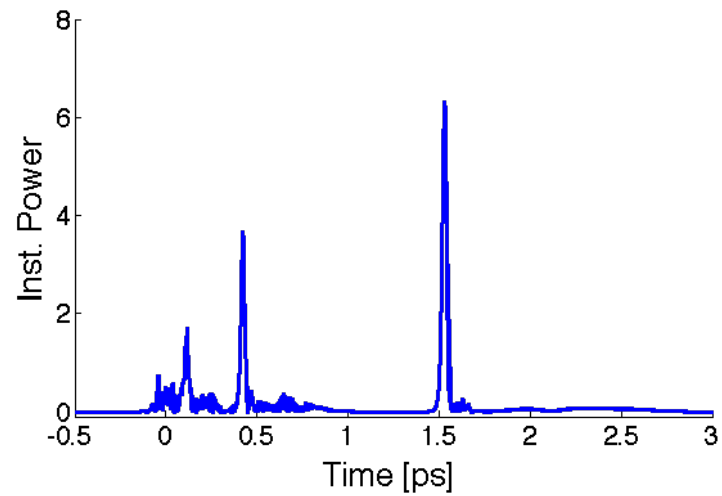


Simulations including shot noise

(best case scenario excluding any technical noise)

Shot-to-shot fluctuations: **50 fs** pump pulse (10 kW)





Noise properties of SC sources

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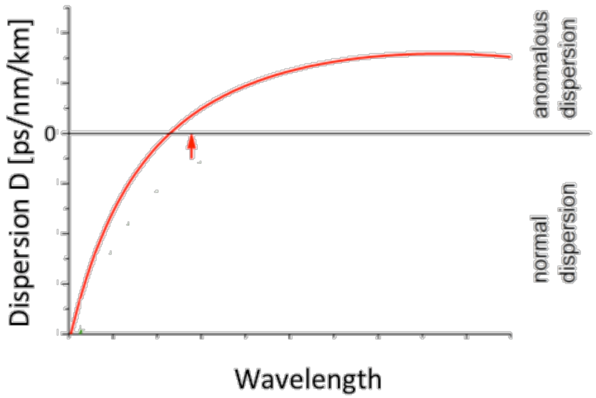
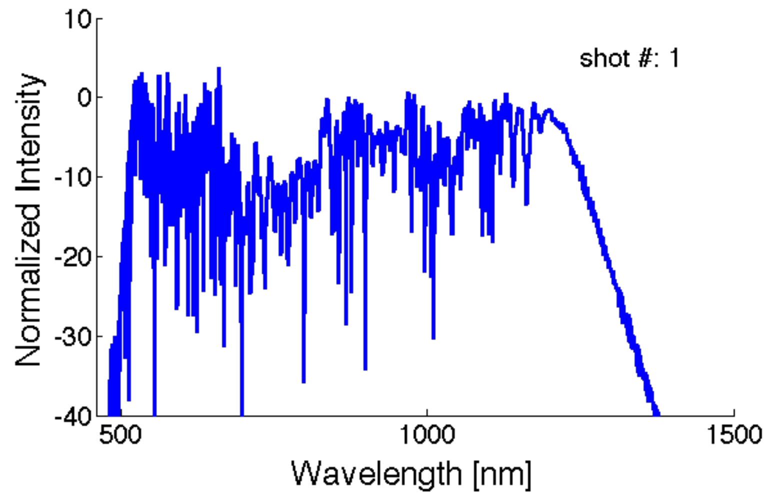
Conventional supercontinuum

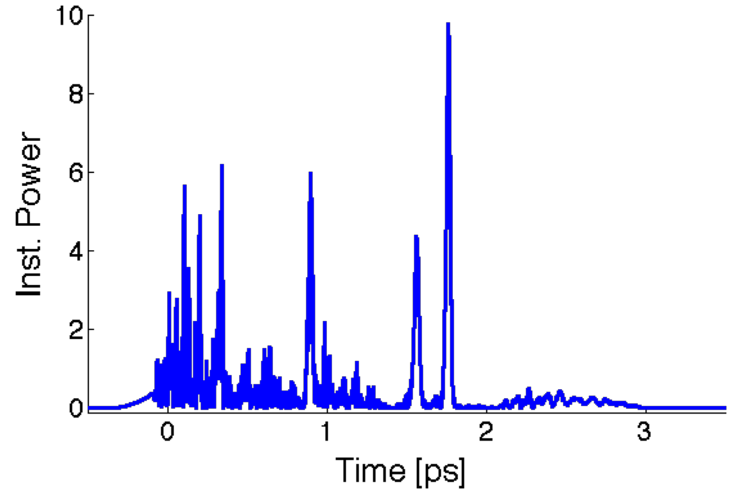
Shot-to-shot fluctuations: **150 fs** pump pulse (10 kW)





Simulations including shot noise

(best case scenario excluding any technical noise)



Noise in GNLSE simulations

One photon per mode model

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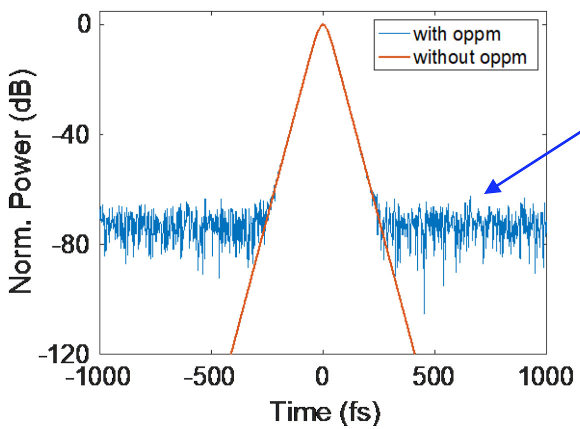
Shot noise can be included into the simulations by injecting **one photon with random phase** into each spectral simulation bin : ω_m

$$\tilde{A}_{\mathrm{oppm}}(\omega_m) = \sqrt{\hbar(n_p - 1)dT\omega_m}\exp\left(-i\Phi(\omega_m)\right)$$

$\Phi(\omega_m)$ randomly sampled in interval $[0, 2\pi]$

This oppm field is then added to the input pulse:

$$A(z=0,T) = A_{\mathrm{input\ pulse}}(T) + \mathcal{F}^{-1}\left(\tilde{A}_{\mathrm{oppm}}(\omega)\right)$$

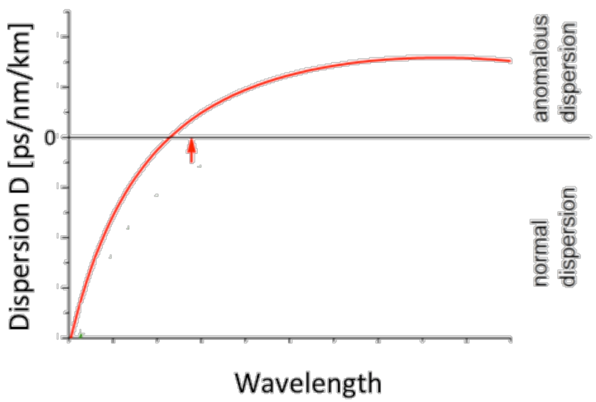


Noise floor important for correct simulation of noise-seeded nonlinearities

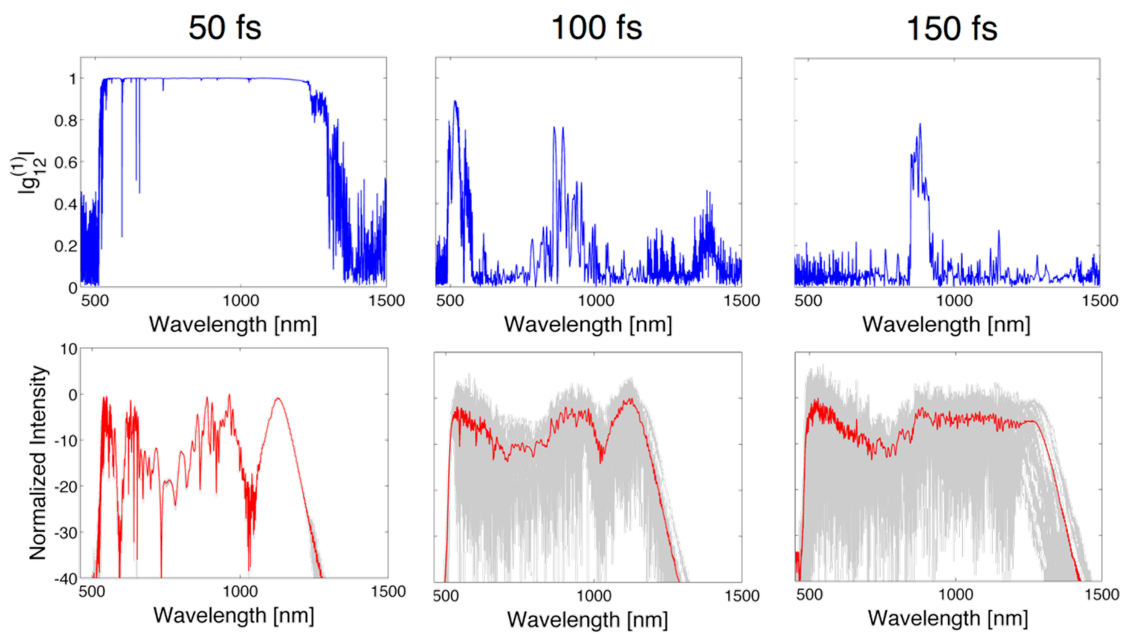
- Modulational instability
- Raman effect

Noise properties of SC sources

Conventional supercontinuum



Pump pulse duration (10 kW peak power)



Quantify shot-to-shot fluctuations by **first-order coherence function at zero path difference**

$$\left|g_{12}^{(1)}(\omega)\right| = \left| \frac{\langle \widetilde{A}_i^*(\omega)\widetilde{A}_j(\omega)\rangle_{i\neq j}}{\sqrt{\langle|\widetilde{A}_i(\omega)|^2\rangle\langle|\widetilde{A}_j(\omega)|^2\rangle}} \right|$$

g = 1: perfect amplitude / phase stability

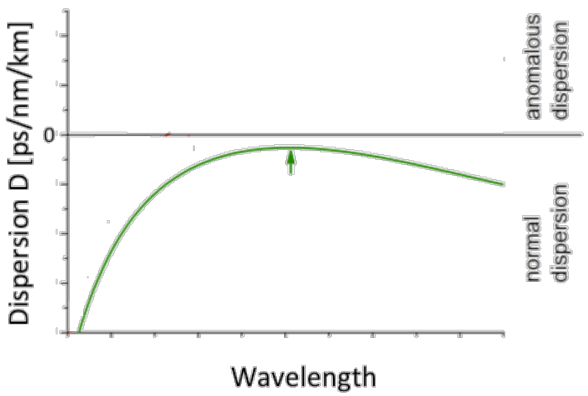
g = 0: random fluctuations

20 independent simulations ➔ 190 unique pairs

Increasing noise amplification
Increasing “apparent” flatness

Noise properties of SC sources

ANDi supercontinuum



Quantify shot-to-shot fluctuations by
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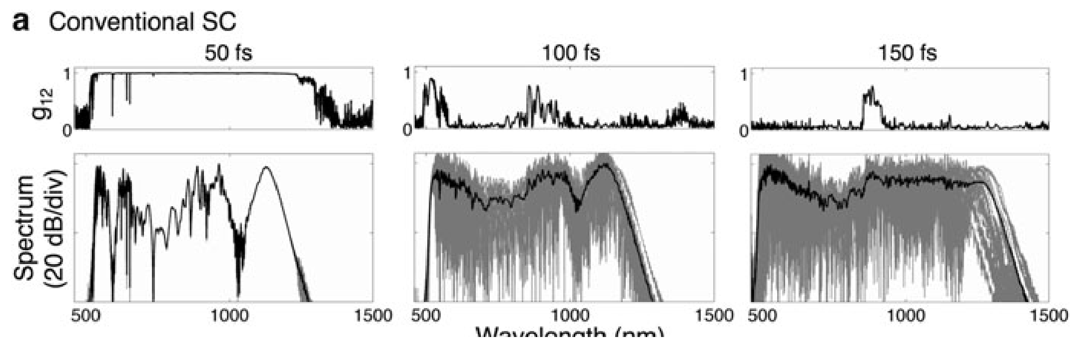
$$|g_{12}^{(1)}(\omega)| = \left| \frac{\langle \widetilde{A}_i^*(\omega) \widetilde{A}_j(\omega) \rangle_{i \neq j}}{\sqrt{\langle |\widetilde{A}_i(\omega)|^2 \rangle \langle |\widetilde{A}_j(\omega)|^2 \rangle}} \right|$$

g = 1: perfect amplitude / phase stability

g = 0: random fluctuations

20 independent simulations ➔ 190 unique pairs

Pump pulse duration (50 kW peak power)



Decoherence only becomes significant at Tp ≈ 1 ps
(vs. ~100 fs in conventional SC generation)

Noise properties
are sensitive to fiber design!

Conclusions

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- **Nonlinear fiber optics** provides powerful tools to shape laser pulses
  - in the spectral domain
  - In the temporal domain
  - in their noise and coherence properties
- **Numerical simulations** based on the GNLSE help to
  - understand nonlinear effects and their interaction
  - design new light sources with properties tailored to specific applications
- Using tips of this webinar and mentioned resources **coding your own simulation** is not difficult!

Have fun exploring nonlinear optics!

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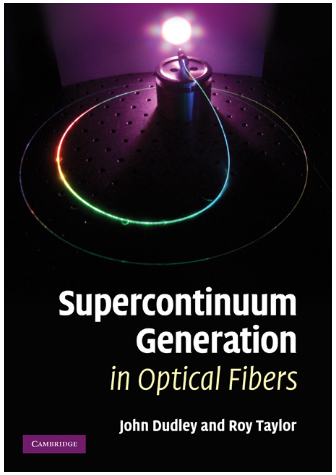
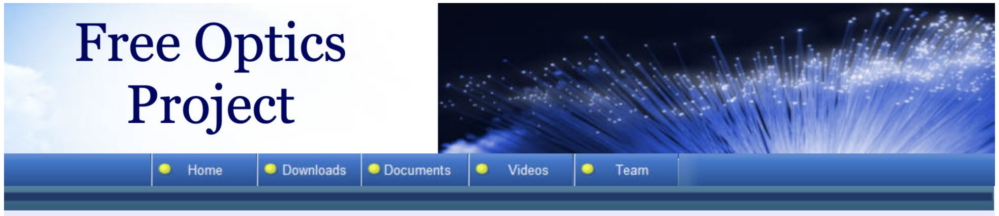
Sources of sample code



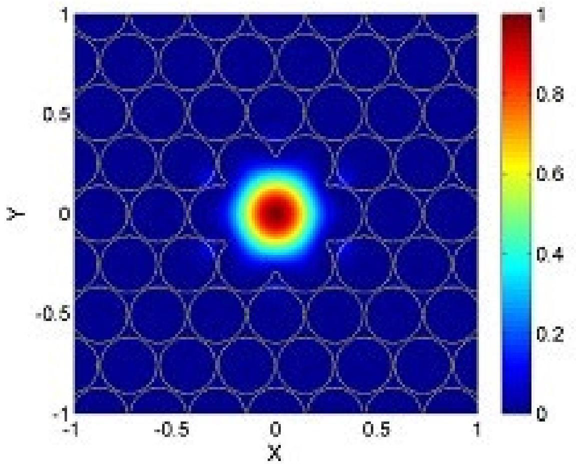
- **Book "Supercontinuum Generation in Optical Fibers"**
  - contains some simple sample code suitable for solving with Matlab's internal ODE solver
  - This code does not contain full complexity of GNLSE

- www.freeopticsproject.org



- Complete Matlab scripts to download
- GNLSE with RK4IP solver and adaptive step size control using photon number conservation
- Good starting point to customize your own code

Where to get fiber parameters?



- **Commercial mode solving software**
  - e.g. COMSOL Multiphysics
  - Solves stationary Maxwell equations with the boundary conditions of the fiber geometry
  - extracts dispersion and mode field parameters

- **Empirical models**
  - Exist for an increasing number of specialty optical fibers
  - Provide empirical fitting values to generate dispersion profiles directly from fiber design parameters
  - Excellent for quickly scanning over a large range of fiber designs
  - for hexagonal PCF structures:
    - ➔ Koshiba and Saitoh, Opt. Lett. 29, 1739 (2004).
    - ➔ Saitoh and Koshiba, Opt. Express 13, 267 (2005)