Supercontinuum Generation

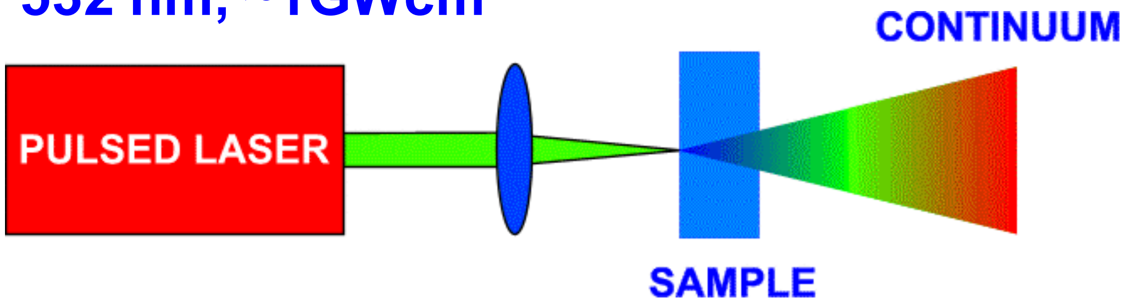
Alfano and Shapiro 1970, Phys. Rev. Lett. 24, 584

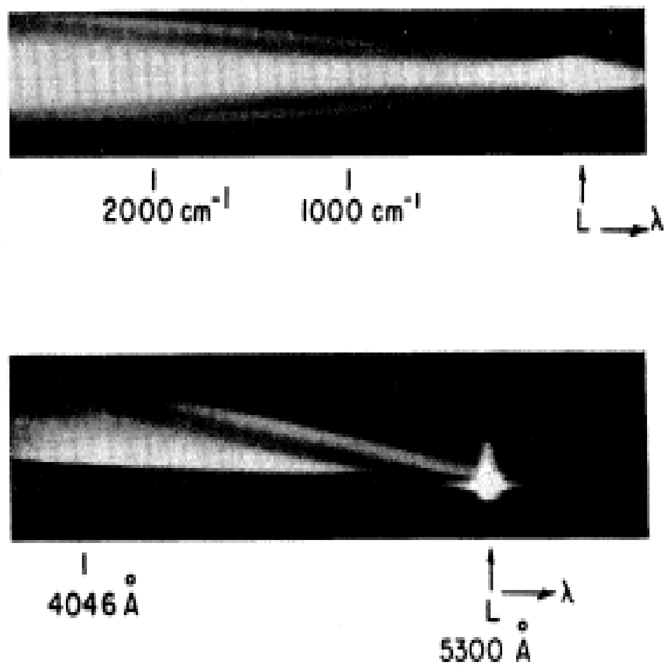
EMISSION IN THE REGION 4000 TO 7000 Å VIA FOUR-PHOTON COUPLING IN GLASS

R. R. Alfano and S. L. Shapiro
Bayside Research Center of General Telephone & Electronics Laboratories Incorporated,
Bayside, New York 11360
(Received 9 January 1970)

Four-photon stimulated scattering has been observed in borosilicate glass under high-power 5300-Å picosecond-pulse excitation. Parametric emission is generated from 4000 to 7000 Å from filaments formed in the glass, the wavelength depending on the emission angle.

532 nm, ~$1 GWcm^{-2}$





Filaments ~20mm, ~ 10^4 $GWcm^{-2}$!

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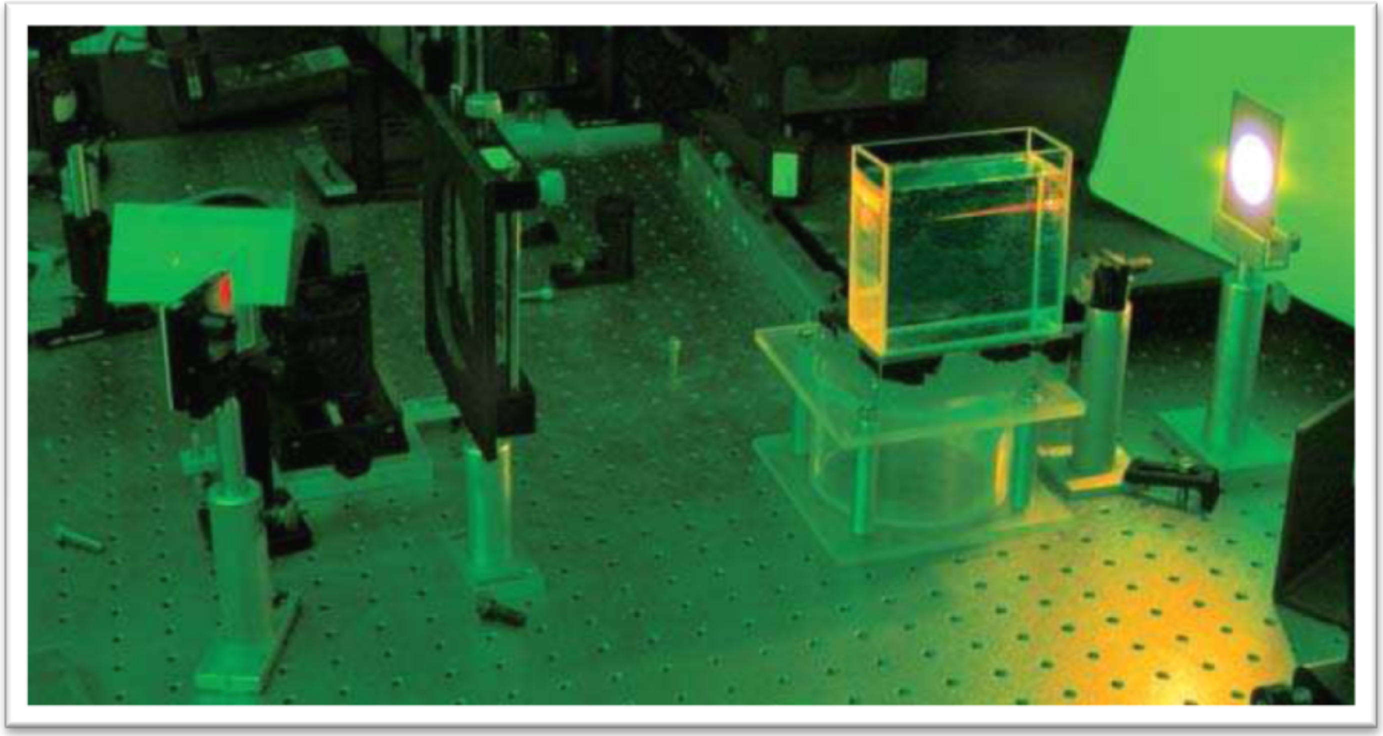
Supercontinuum generation in bulk



Numerous nonlinear processes contributing:-

- Self phase modulation
- Parametric generation
- Raman
- Spatio-temporal coupling

First use of word “supercontinuum”

Gersten et al. 1980, Phys. Rev. A 21, 1222

PHYSICAL REVIEW A VOLUME 21, NUMBER 4 APRIL 1980

Combined stimulated Raman scattering and continuum self-phase modulations

Joel I. Gersten*
Institute for Advanced Studies, Hebrew University, Mount Scopus Campus, Jerusalem, Israel

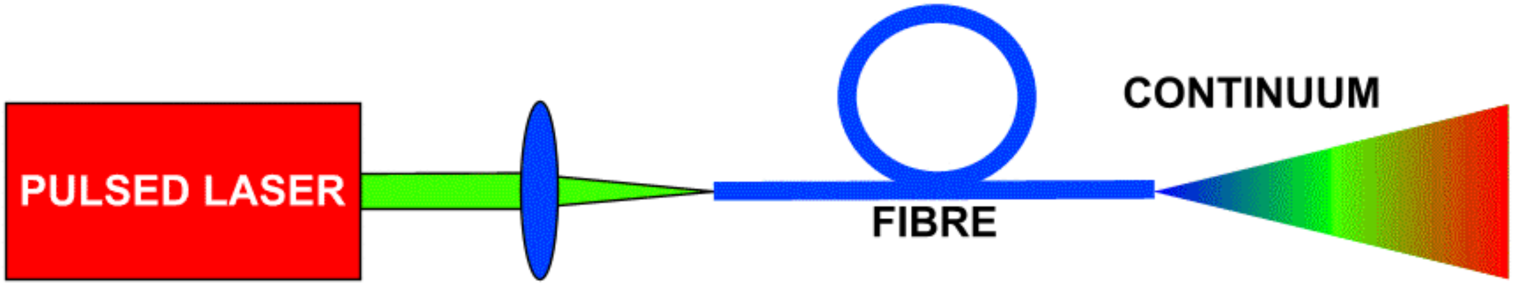
R. R. Alfano and Milivoj Belic
Department of Physics, The City College of New York, New York, N. Y. 10031
(Received 8 January 1979)

A theory describing the combined effects of stimulated Raman scattering and continuum self-phase modulation is developed. As may be expected, the effects are not simply additive. Calculations are presented which determine the interaction of these effects in various limits.

In the case of self-phase modulation (SPM), however, the repopulation of the spectral intensity takes place in a more gradual manner. Owing to the nonlinearity of the medium, the pulse heterodynes against itself and gradually increases its spectral width. There is a continuum of frequencies produced in this process. Supercontinuum generation spanning the visible and infrared region was first observed by Alfano and Shapiro when intense picosecond laser pulses were passed through liquids and solids.[3]

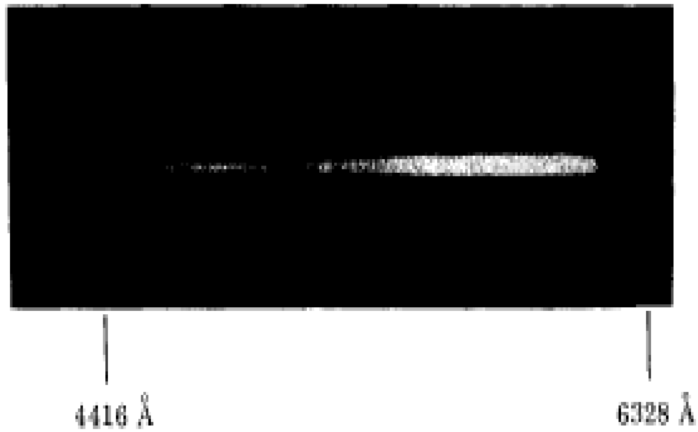
First supercontinuum in fibre

Lin and Stolen 1976, App. Phys. Lett. 28, 216



Pump:
Dye laser, ~1kW, 10nsec, 10nm

Fibre:
7μm core, ~20 m



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Fibre based supercontinuum

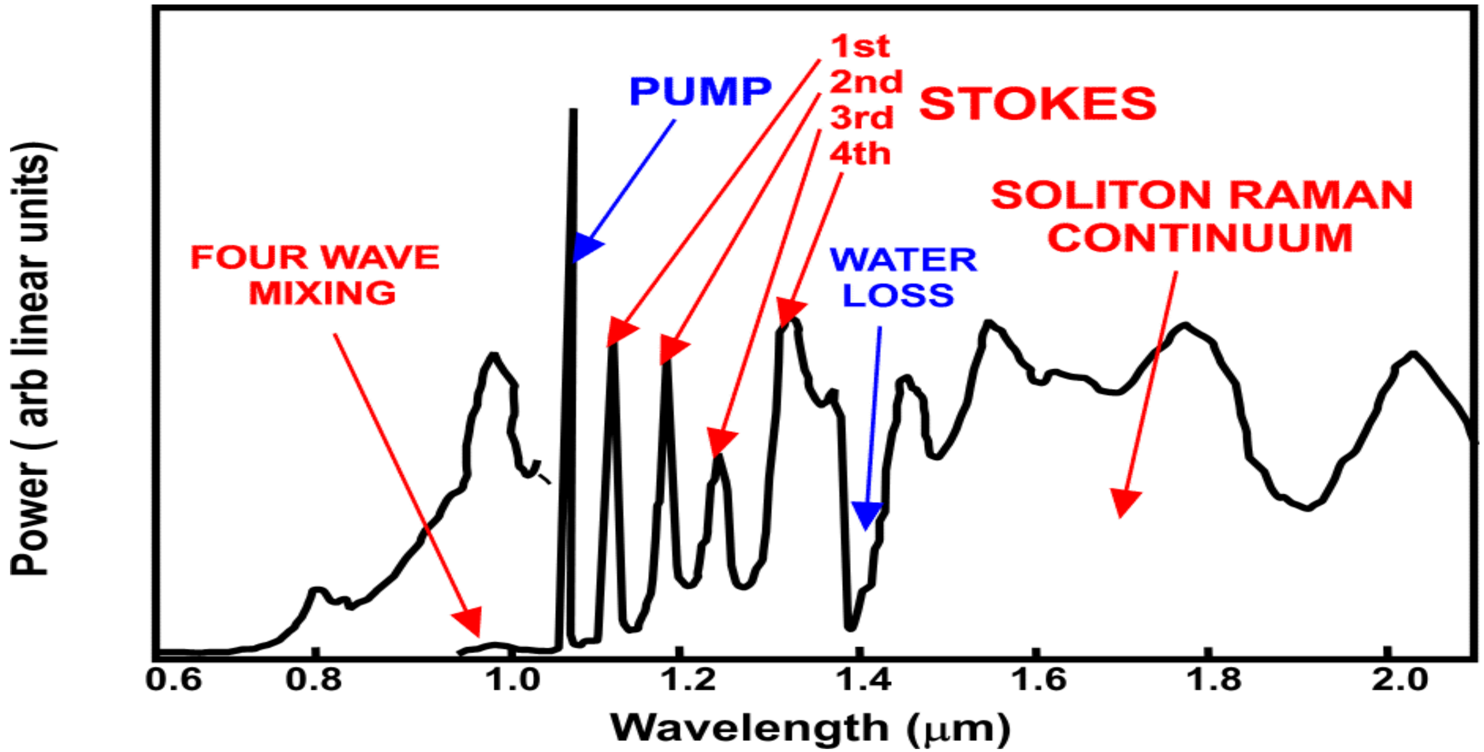
Lin et al. 1978, Elect. Lett. 14, 823

Pump:

Q-switched Nd:YAG, 1064 nm, 50kW

Fibre:

315m, GeO_2 doped, multi-mode



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The “new wave” of supercontinua

January 1, 2000 / Vol. 25, No. 1 / OPTICS LETTERS 25

Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm

Jinendra K. Ranka, Robert S. Windeler, and Andrew J. Stentz

Bell Laboratories, Lucent Technologies, 700 Mountain Avenue, Murray Hill, New Jersey 070974

Received October 13, 1999

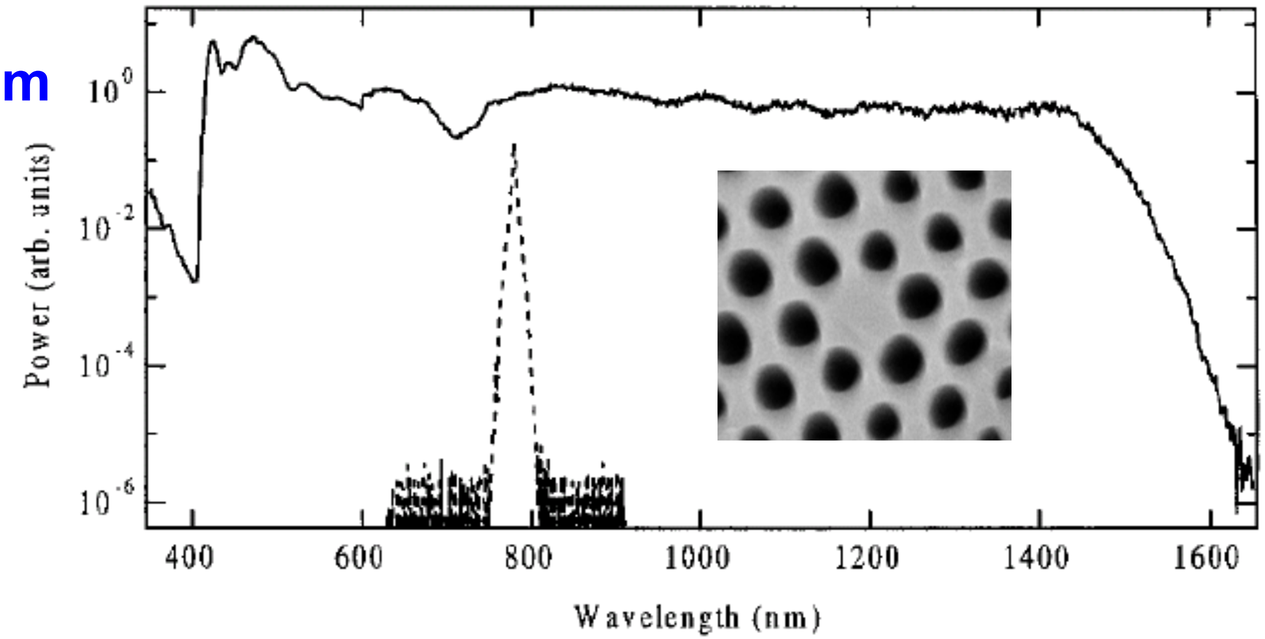
We demonstrate experimentally for what is to our knowledge the first time that air–silica microstructure optical fibers can exhibit anomalous dispersion at visible wavelengths. We exploit this feature to generate an optical continuum 550 THz in width, extending from the violet to the infrared, by propagating pulses of 100-fs duration and kilowatt peak powers through a microstructure fiber near the zero-dispersion wavelength.

Ti:S 30-100 fsec, 790 nm

P_P ~8kW, P_{av} ~50 mW

75cm PCF

λ_0 ~775 nm



Controlled dispersion and nonlinearity

Group velocity dispersion $$D = -\frac{2\pi c}{\lambda^2}\beta_2$$

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

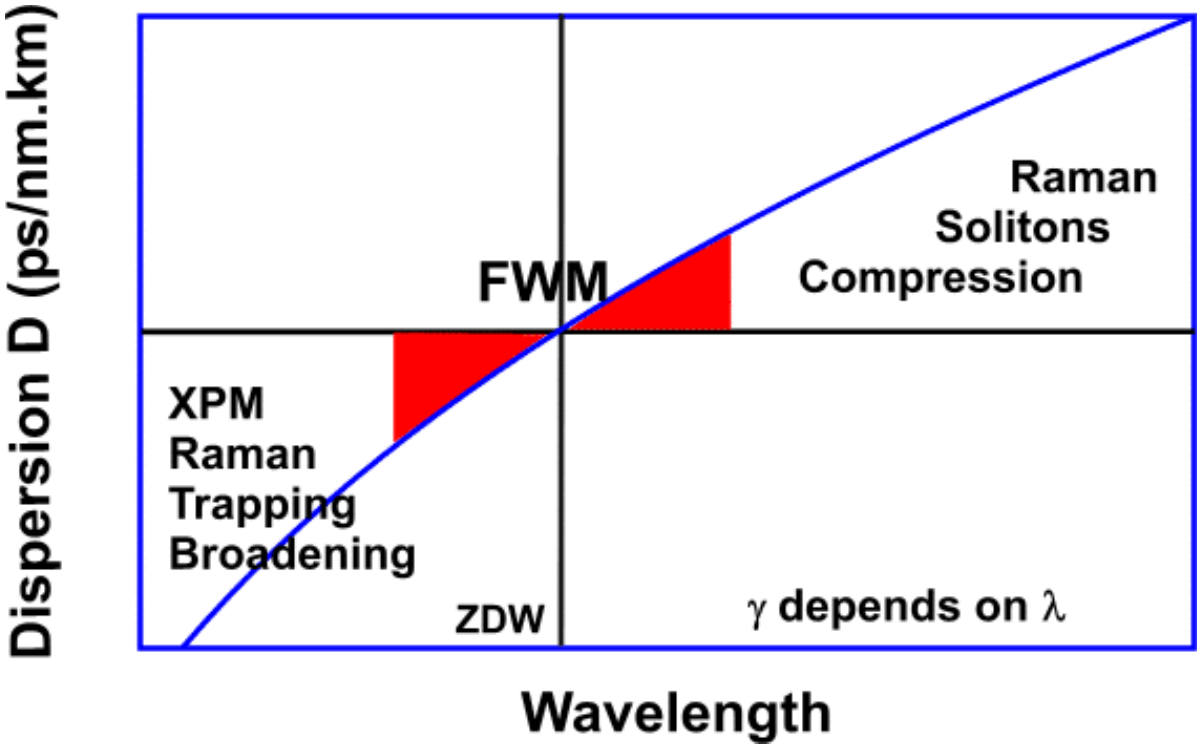
"NEW" FIBRES	PARAMETER CONTROL
Small core, doping	Dispersion
Photonic Crystal Fibre	Nonlinearity
Tapered Fibre	Confinement
Non silica fibre	

Leading to new applications – supercontinua, pulse compression

Engineered dispersion and nonlinearity

Ultrashort pulse propagation and supercontinuum generation in optical fibres can involve a number of cooperative or competing effects

Dispersion control is vital as propagation dynamics depend on pump wavelength relative to the fibre zero dispersion wavelength (ZDW)



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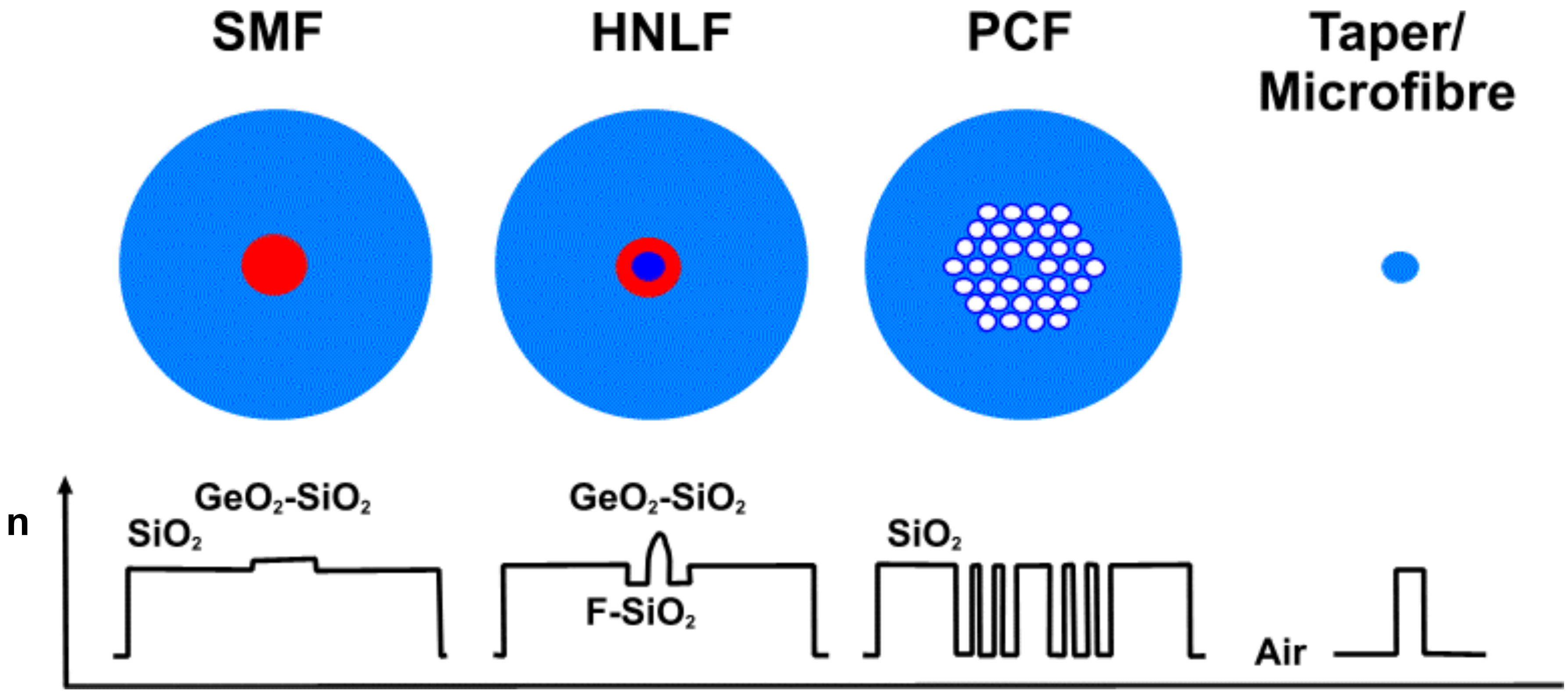
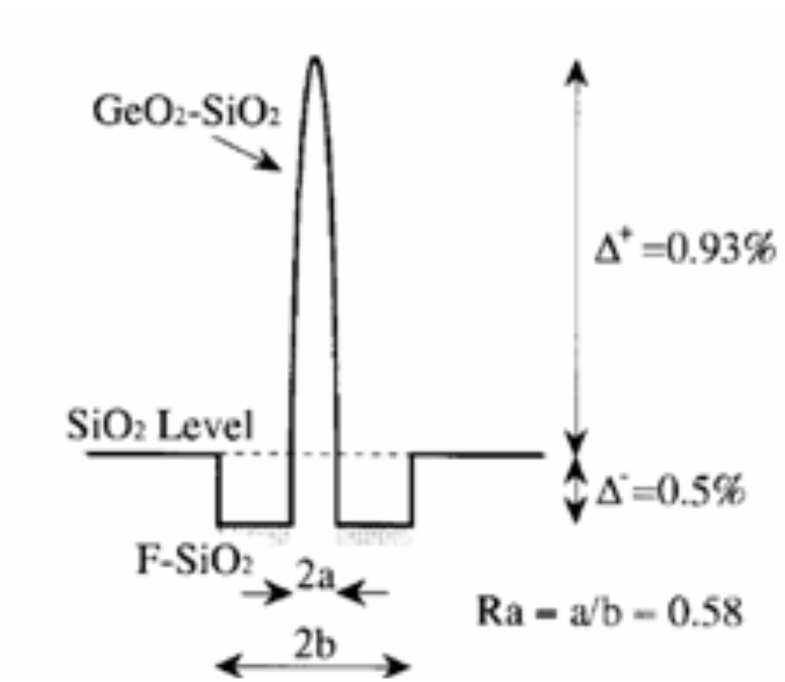
Effect of fibre structure

Chemistry and geometry both contribute to the refractive index profile and determine the modal confinement and dispersion characteristics

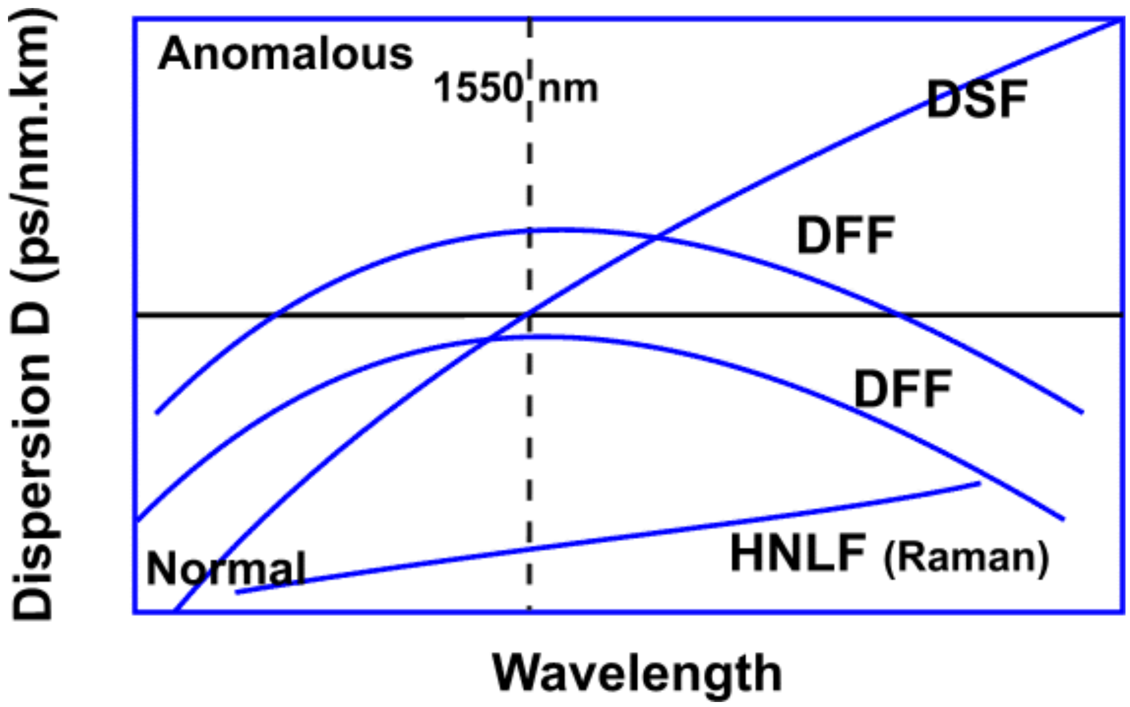


Conventional silica HNLF

Controlled refractive index profiling and doping (GeO_2 and F) Produces dispersion shifted (DSF) and flattened (DFF) highly nonlinear fiber (HNLF)



Dispersion flattened fibre



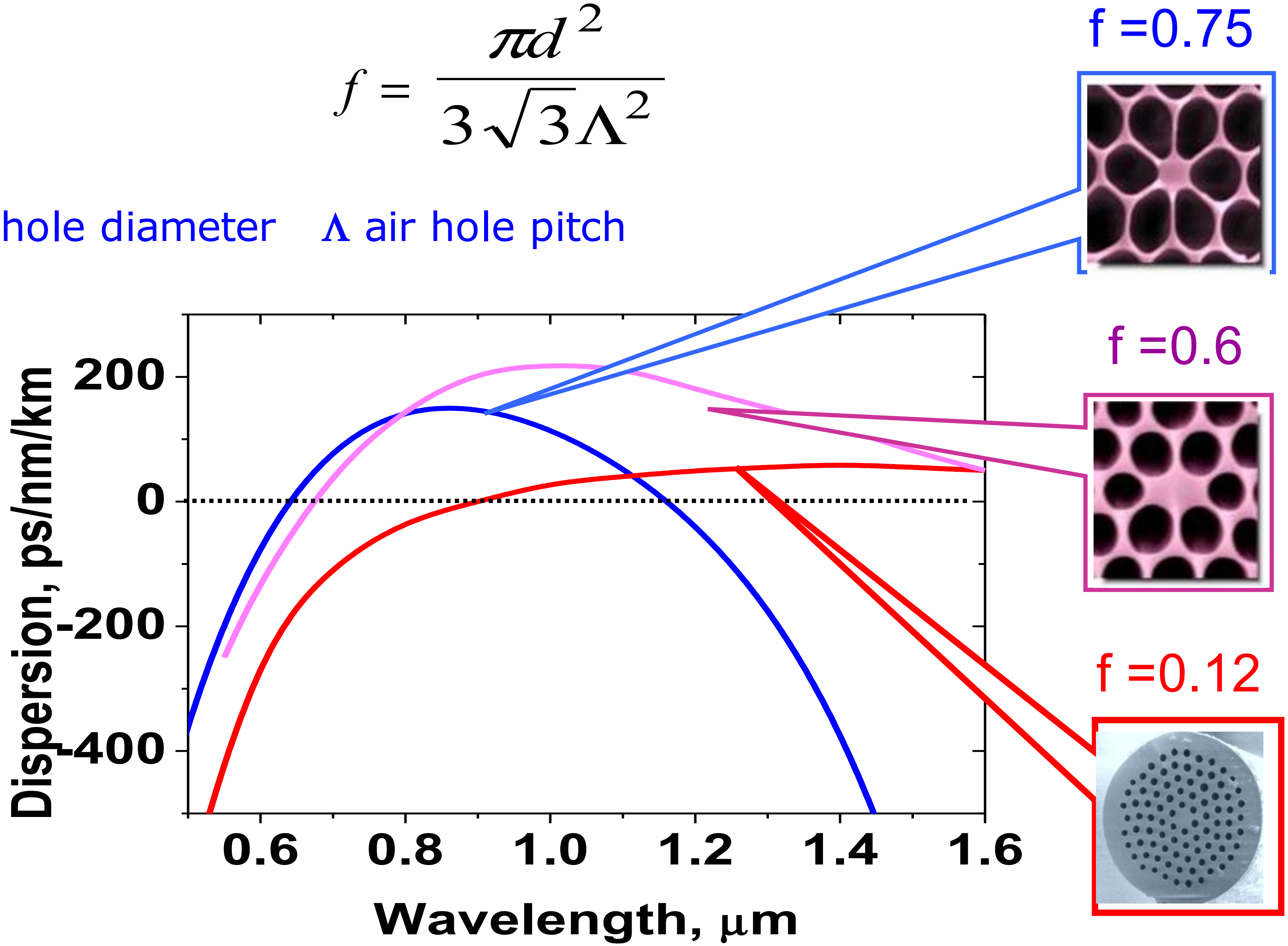
Attenuation ~ 0.5 dB/km, A_{eff} ~ 10 -20 μm^2, γ_{1550} ~ 10 -30 W^{-1} km^{-1}

PCF Dispersion control

Waveguide dispersion strongly depends on the air fill ratio *f*

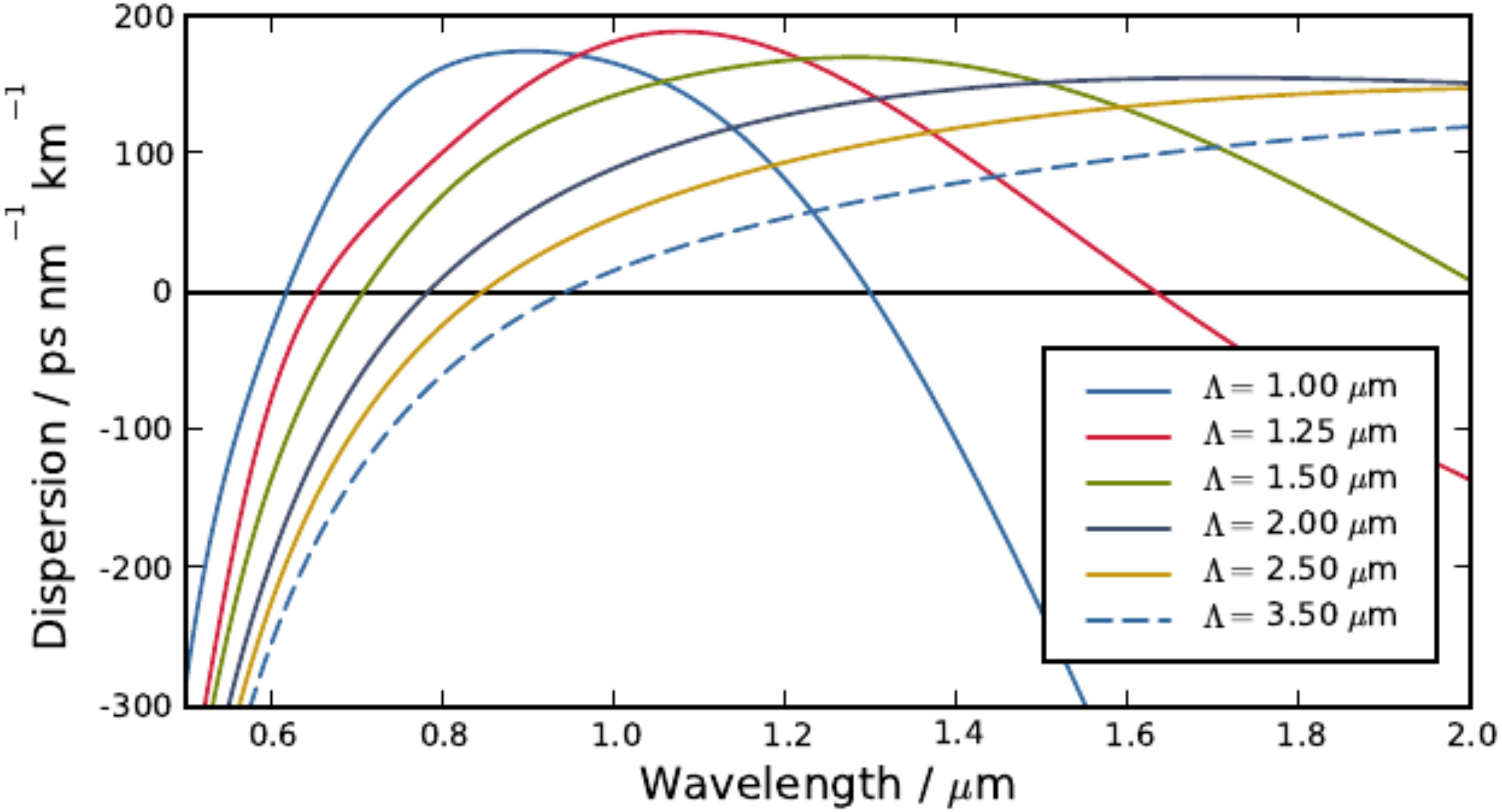
$$f = \frac{\pi d^2}{3\sqrt{3}\Lambda^2}$$

d air hole diameter   Λ air hole pitch



Engineering dispersion and nonlinearity in PCF

Fixed air fill fraction



Zero dispersion to shorter wavelengths

Loss ~ 1-10 dB/km Increased nonlinearity γ_{ZDW} ~ 100-200 W^{-1} km^{-1}

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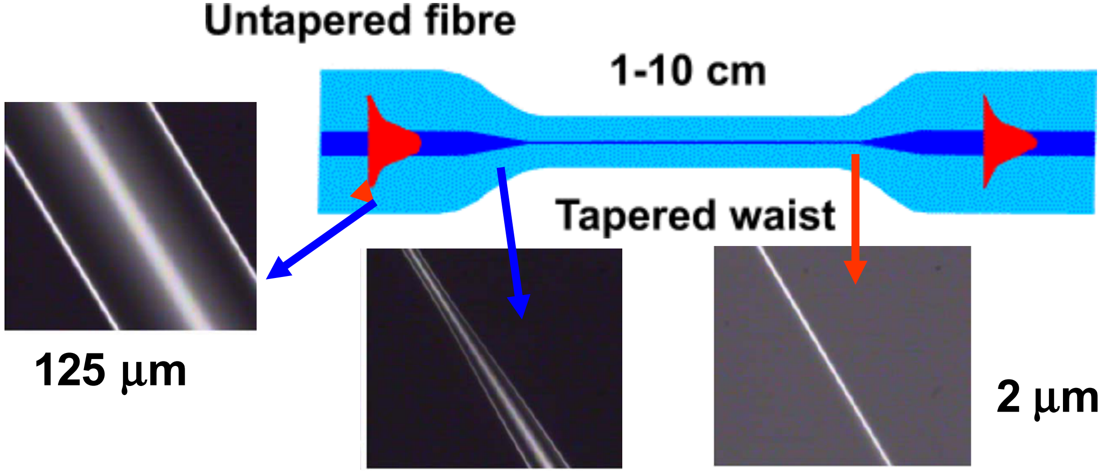
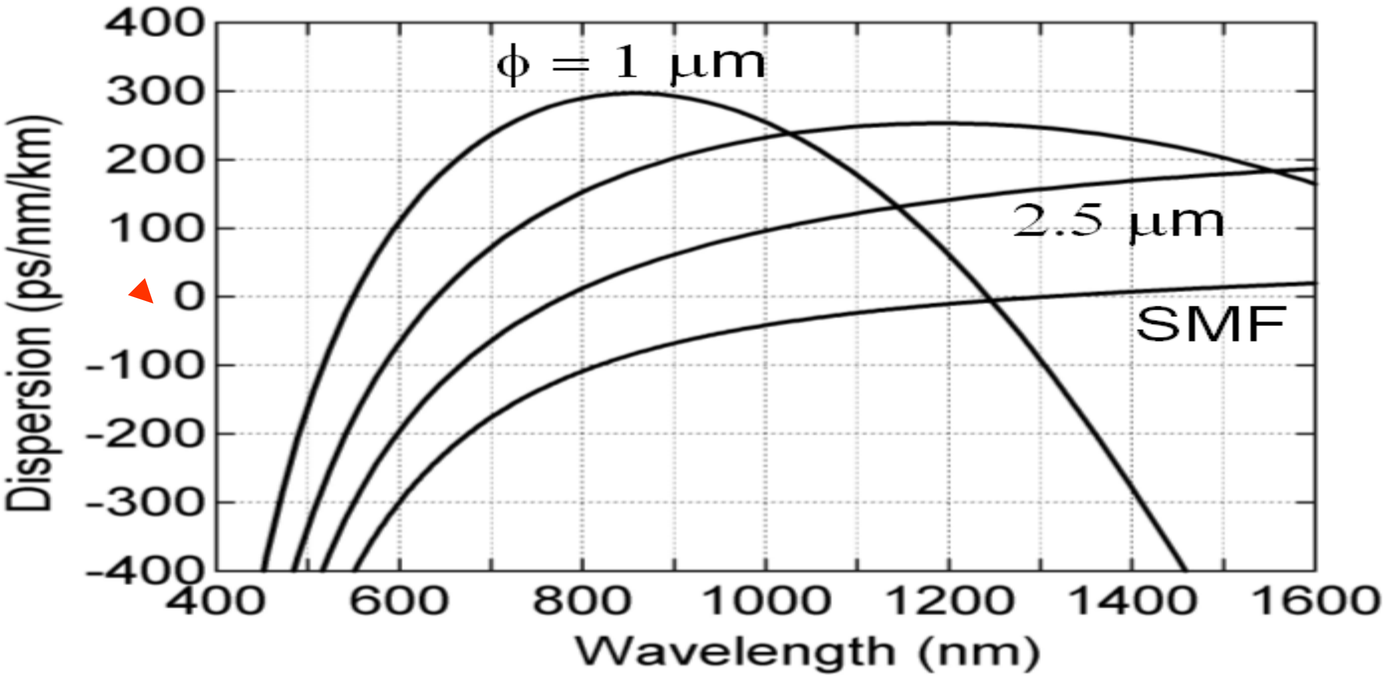
Tapers

Provides similar performance to PCF but with limited interaction length





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Tapering PCF

Provides more degrees of freedom

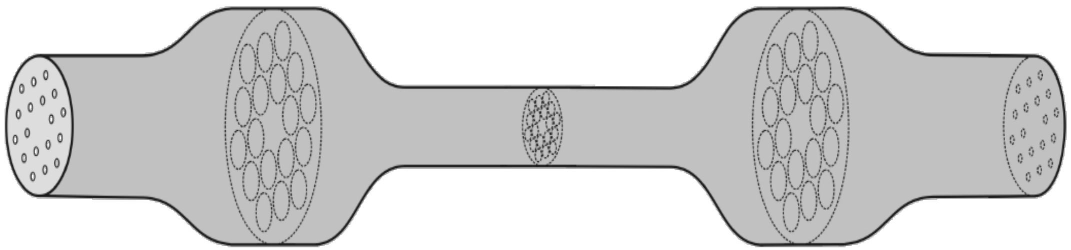
Greater care to maintain structure – hole collapse

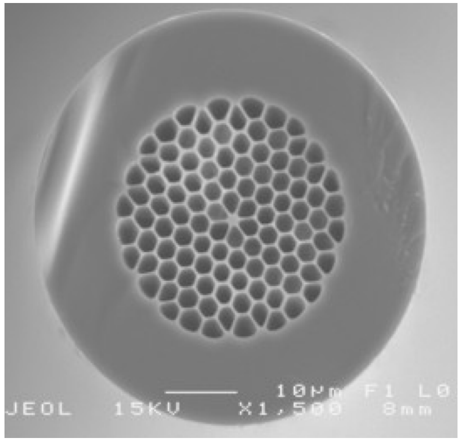
Wadsworth et al. 2005 Opt. Exp. 13, 6541

Short lengths

Kudlinski et al. 2006 Opt. Exp. 13, 5715

Long lengths at pulling tower





Modeling of supercontinuum generation

Generalized nonlinear Schrodinger Equation

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

Dispersion — *Self-steepening* — *SPM, FWM, Raman*

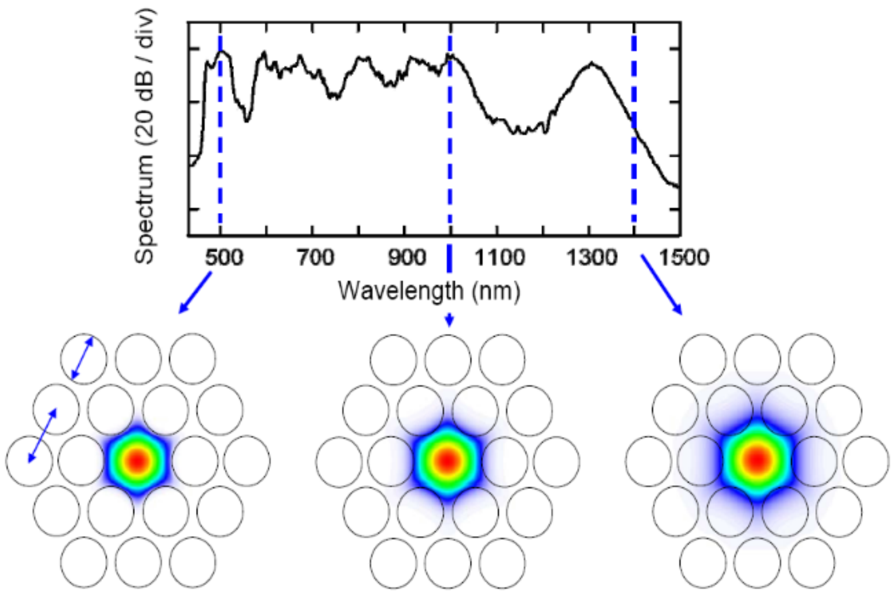
$$R(T) = (1 - f_R)\delta(T) + f_R h_R(T)$$

Kerr — *Raman*

Nonlinear response varies considerably across supercontinuum

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

$$\tau_{\mathrm{shock}} = \frac{1}{\omega_0} + \frac{\mathrm{d}}{\mathrm{d}\omega}\left[\ln\left(\frac{1}{n_{\mathrm{eff}}(\omega)A_{\mathrm{eff}}(\omega)}\right)\right]_{\omega_0}$$

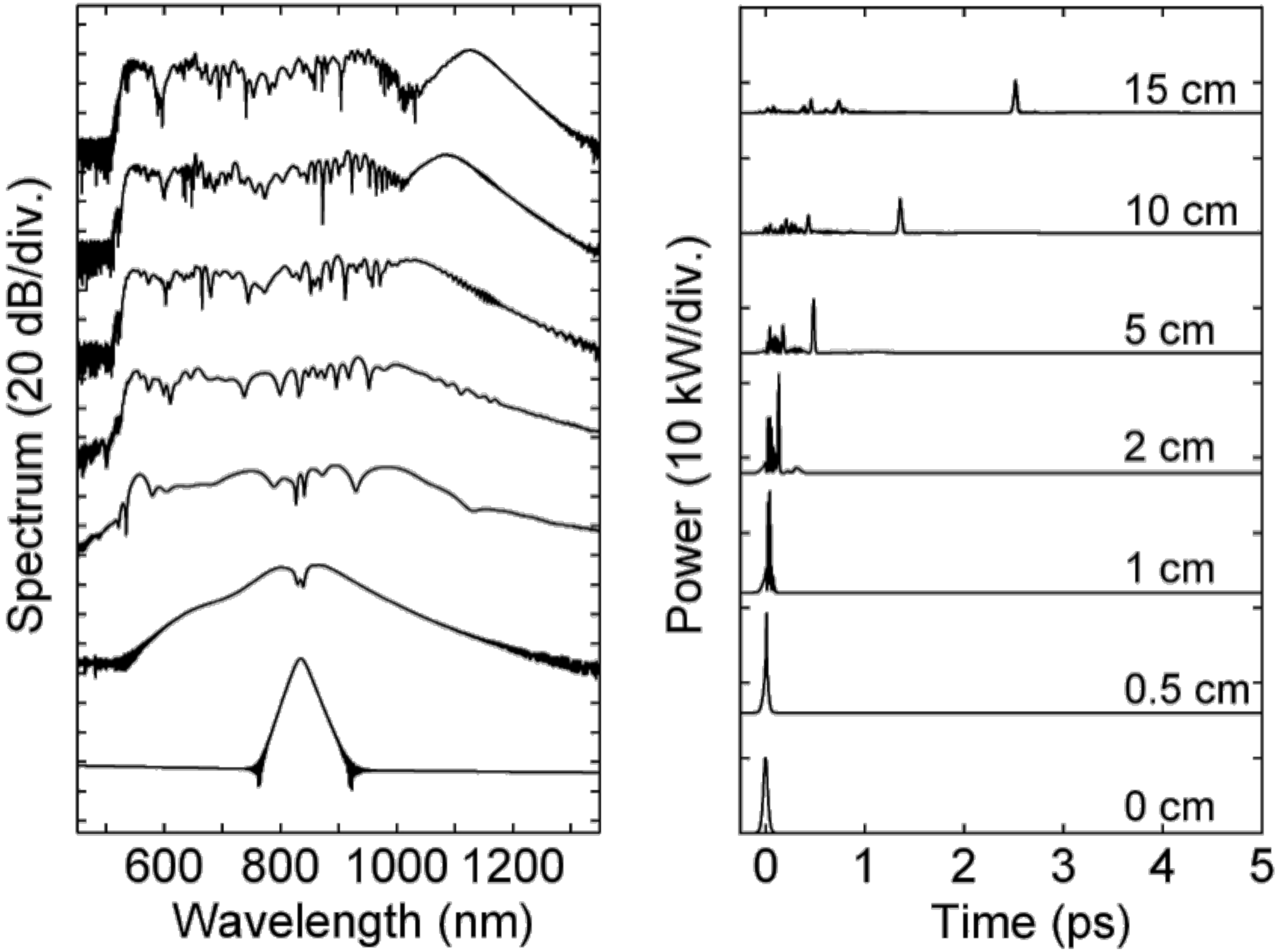


Supercontinuum simulation

Femtosecond laser pumping **Dudley**

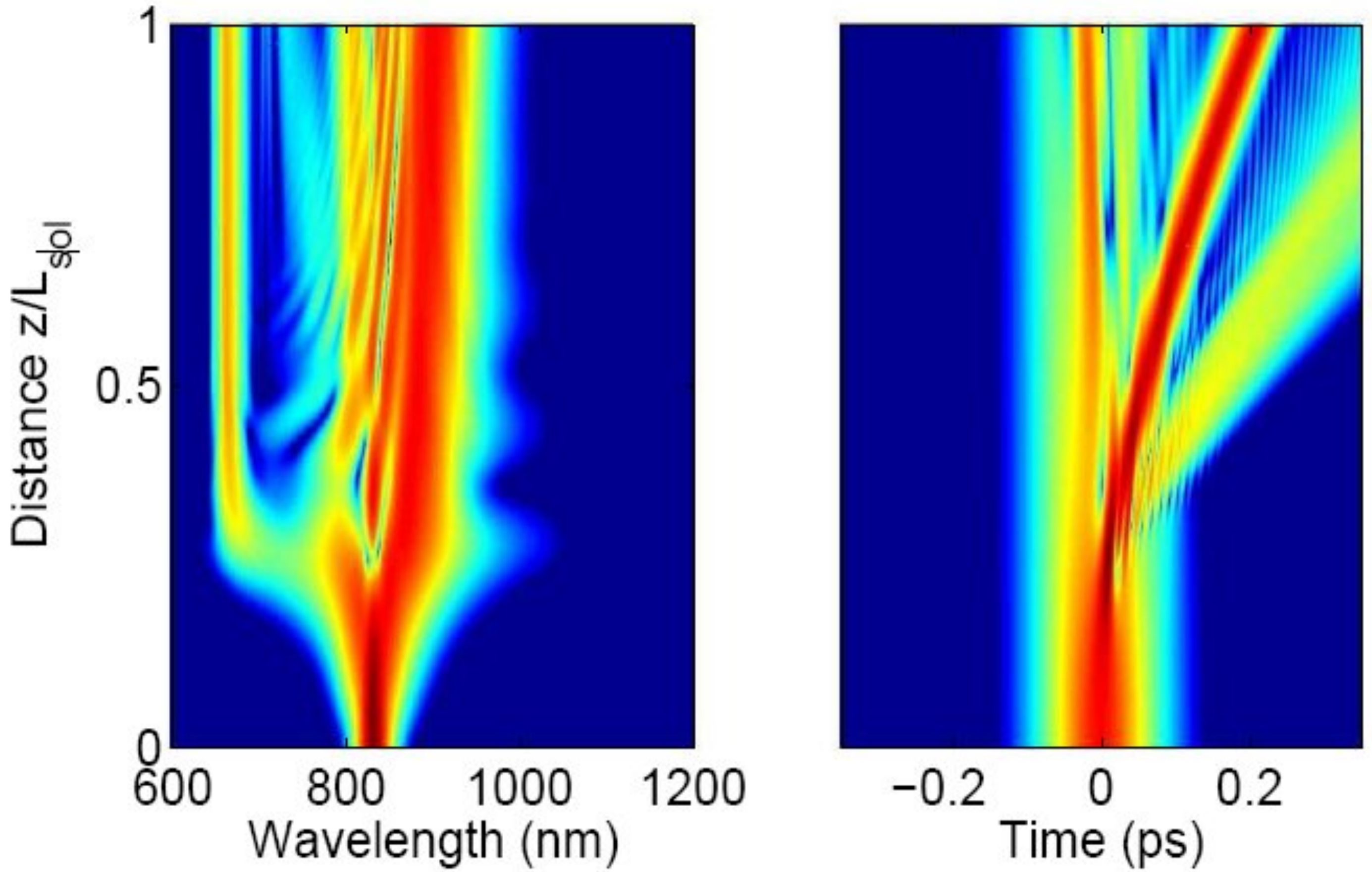
50 fsec, 835 nm, 0.5nJ, 10kW

15 cm PCF, N=9



Higher order soliton instability

$$L_{sol} = \frac{\pi}{2}\frac{\tau^2}{|\beta_2|}$$



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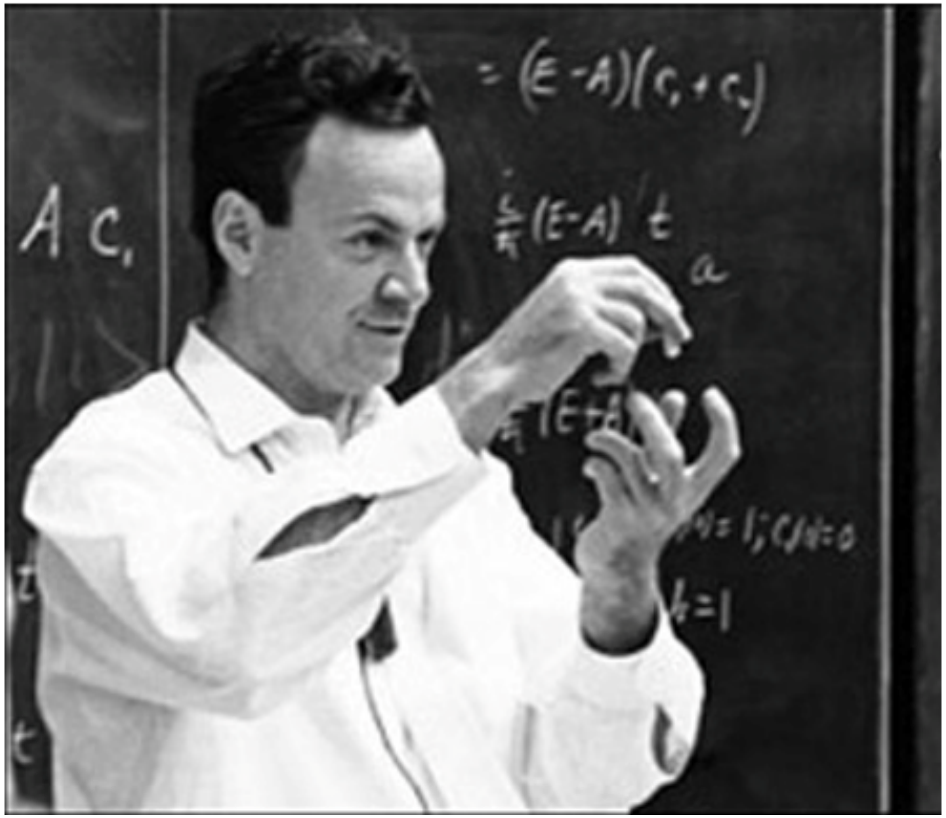
but........according to Feynman

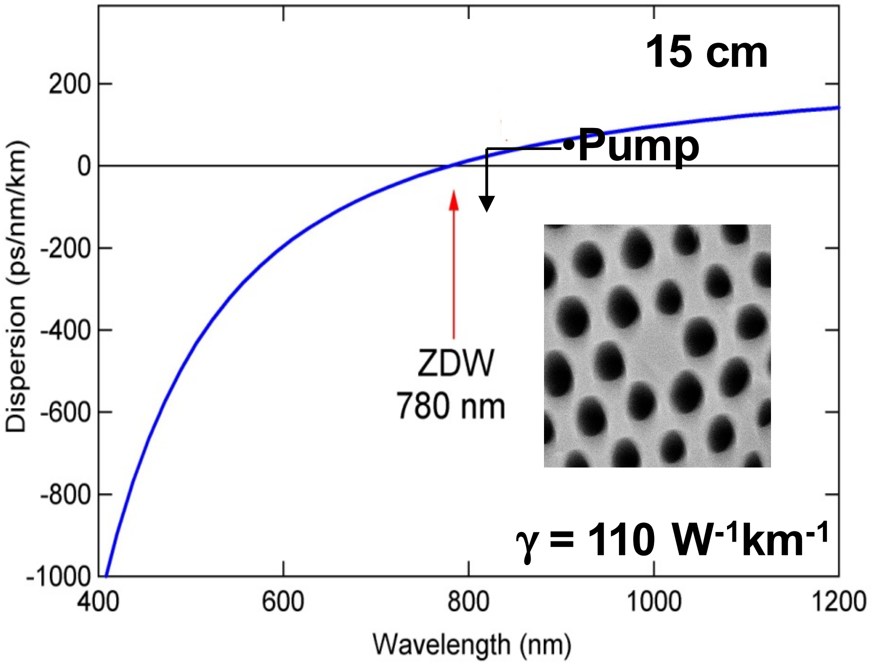
It doesn't matter how beautiful your theory is.
It doesn't matter how smart you are.
If it doesn't agree with experiment, it's wrong

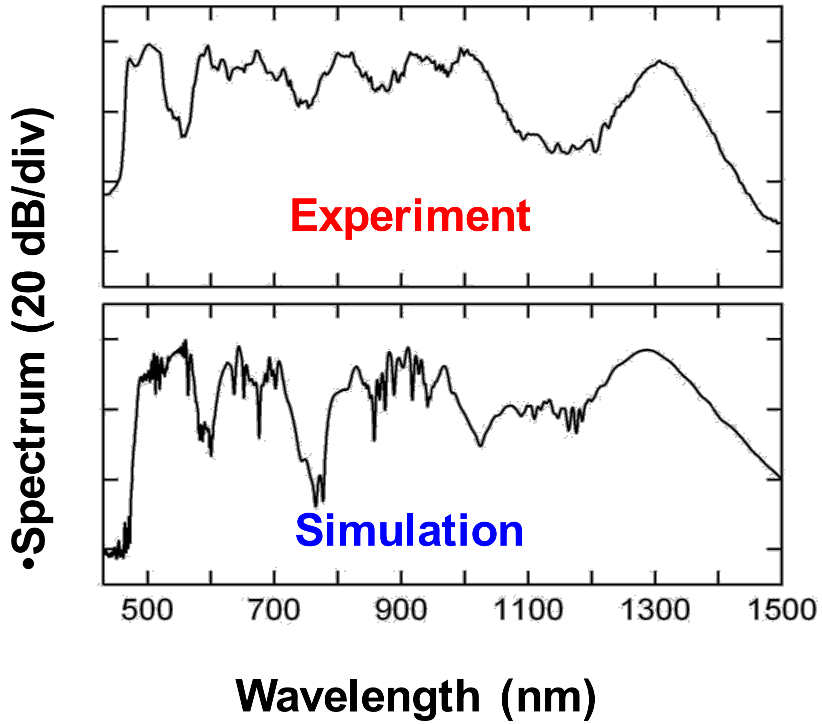


Supercontinuum generation Theory and experiment

Corwin et al. 2003 Phys. Rev. Lett. 90, 113904

Pump: 22fsec, 810 nm, 0.9 nJ, 40kW





Coloured solitons

In the presence of a perturbation, a high order N-soliton is unstable and breaks up into N constituent N=1 solitons.

Dianov et al. 1985, JETP Lett. <u>42</u>, 87

Kodama and Hasegawa 1987, IEEE JQE <u>23</u>, 510

Break up and appearance of dispersive waves

Beaud et al 1987, IEEE JQE <u>23</u>, 1938

Soliton fission

Hermann et al. 2002, Phys. Rev. Lett. <u>88</u>, 173901

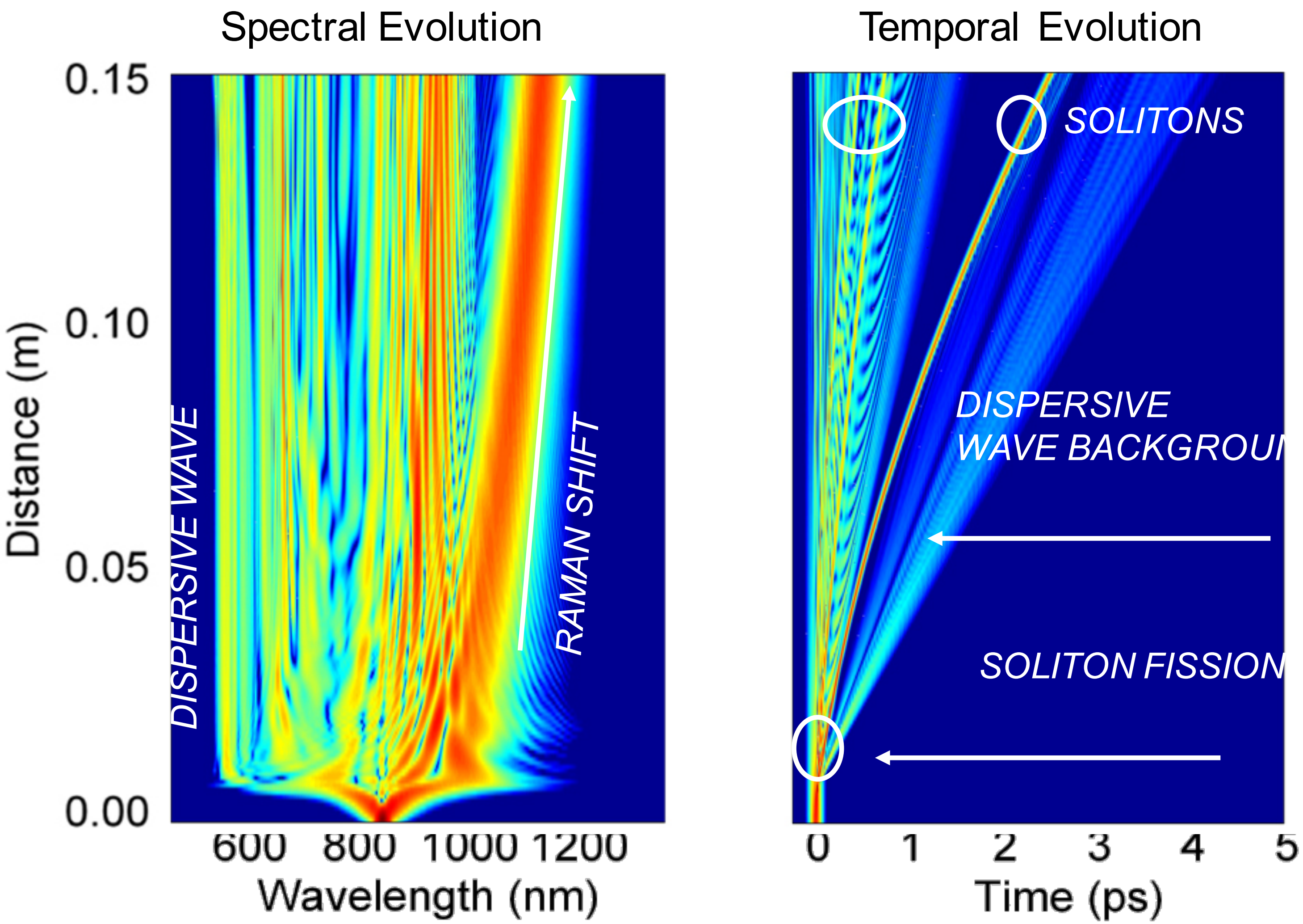
Perturbations : Raman

Higher order dispersion

Supercontinuum evolution

Femtosecond laser pumping **Dudley**

50 fsec, 835 nm, 0.5nJ, 10kW, 15 cm PCF, N=9



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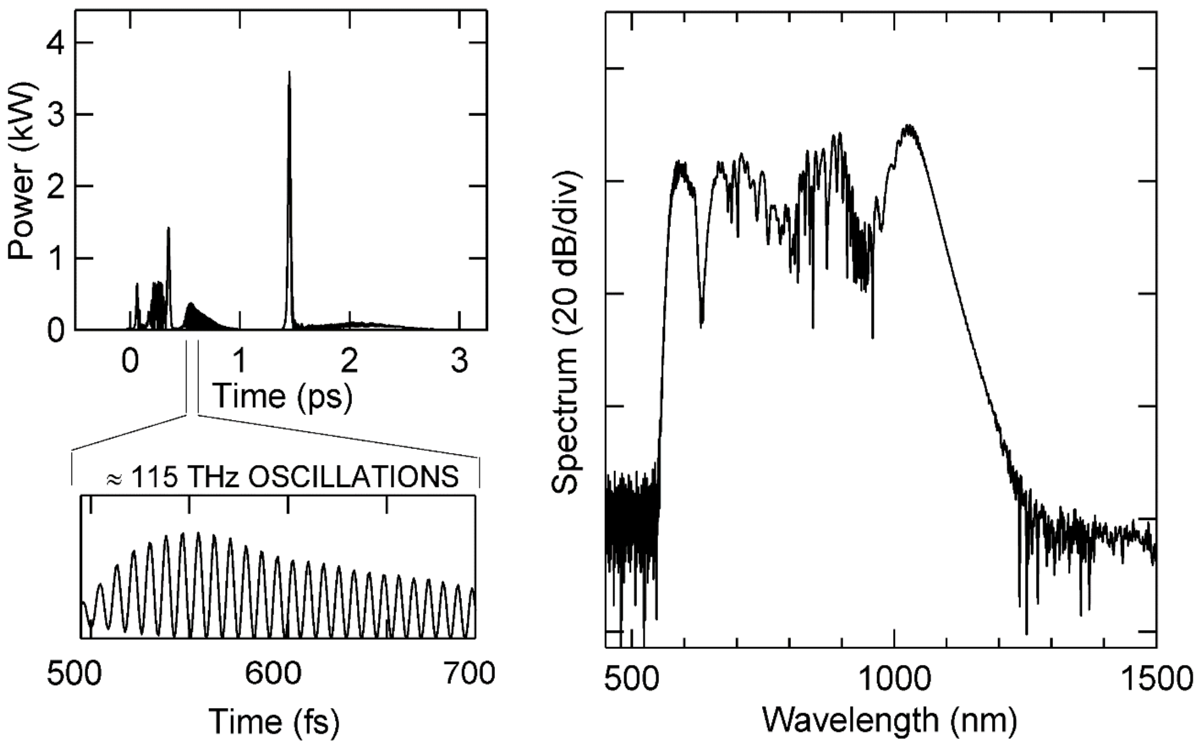
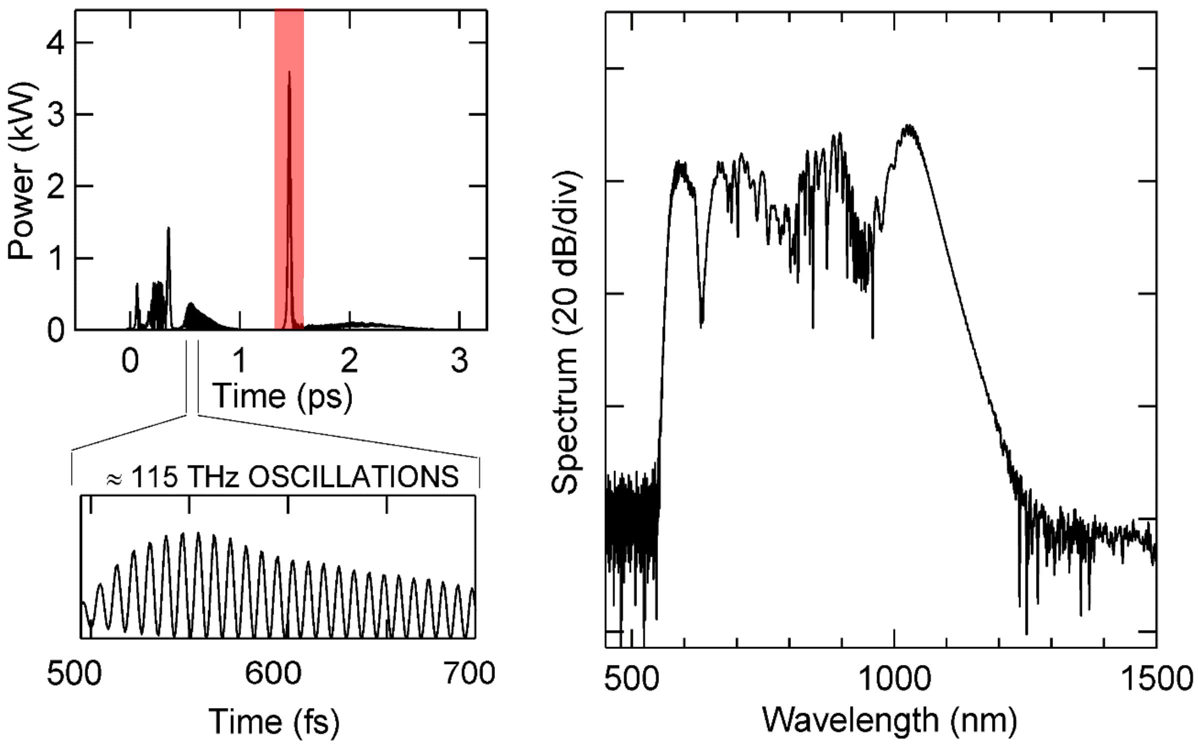
Correlating the time and frequency domains

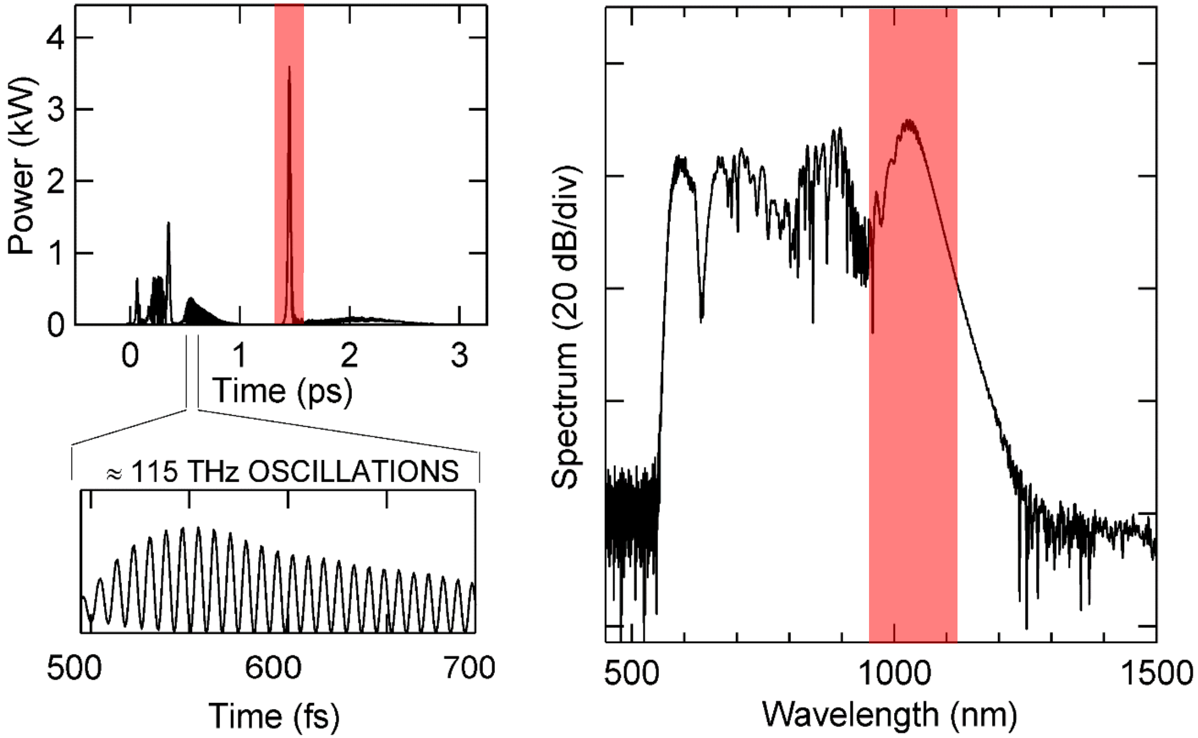
Numerical filtering allows time and frequency domain features to be correlated



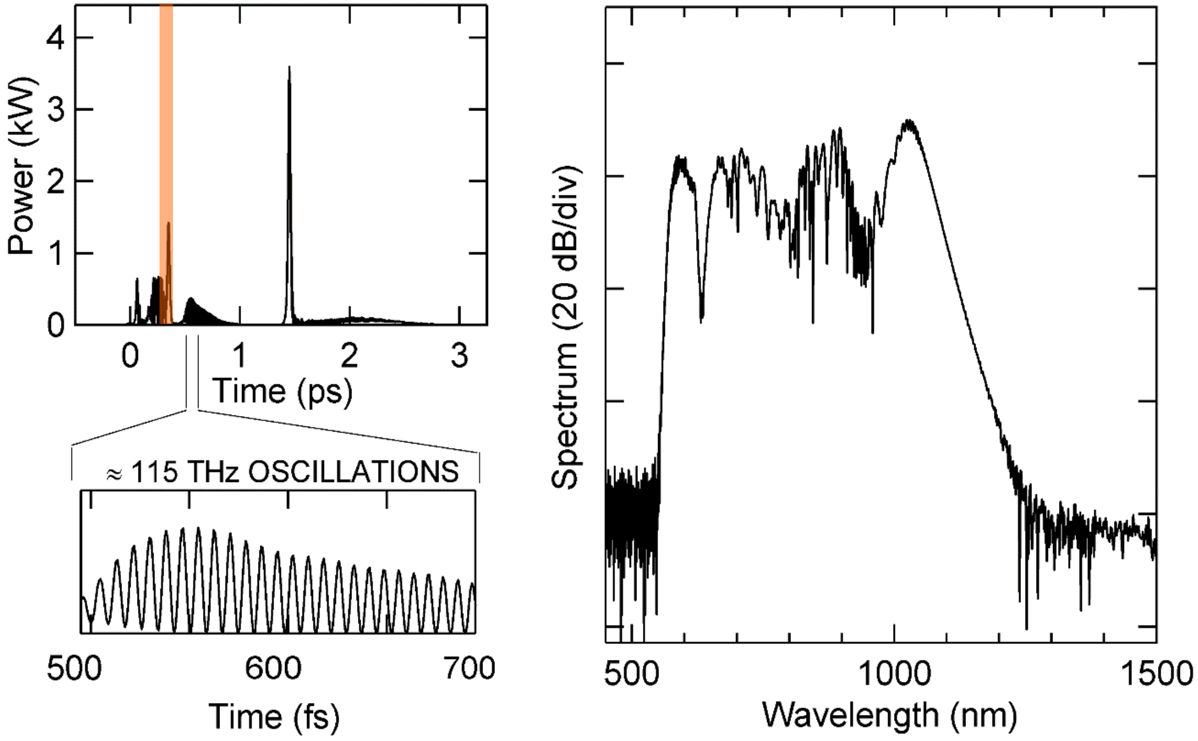
Correlating the time and frequency domains



Correlating the time and frequency domains



Correlating the time and frequency domains



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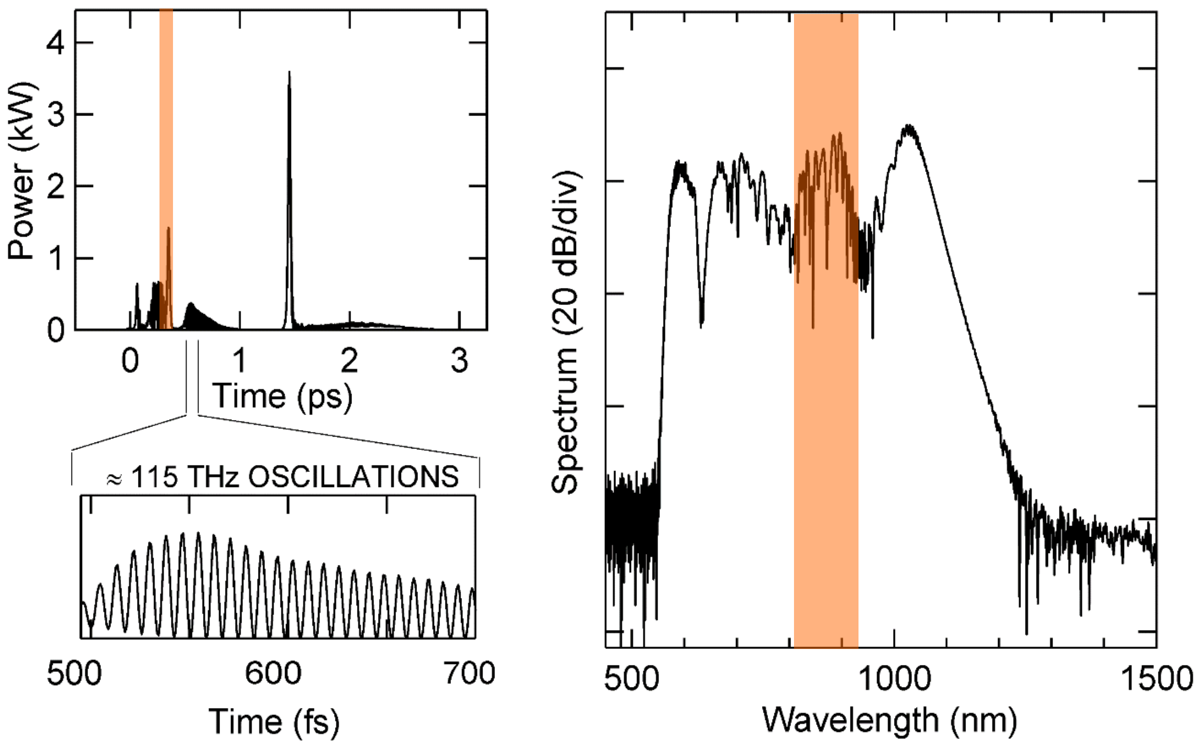
Correlating the time and frequency domains



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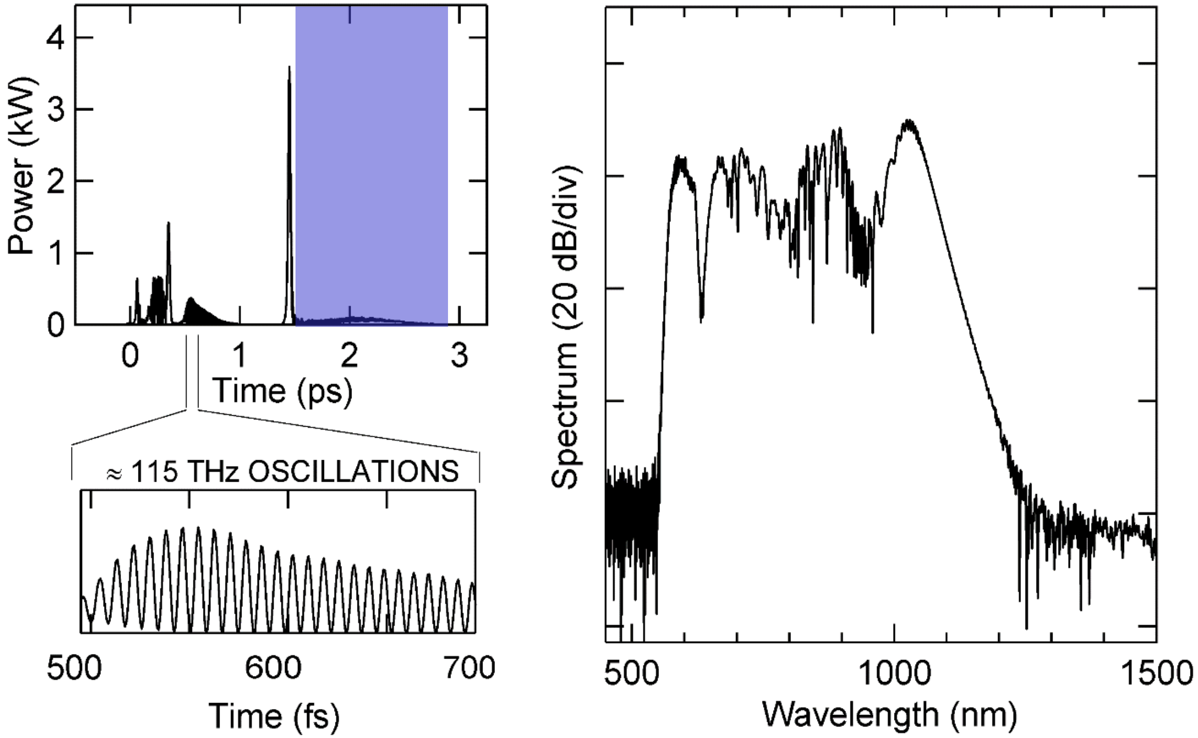
Correlating the time and frequency domains



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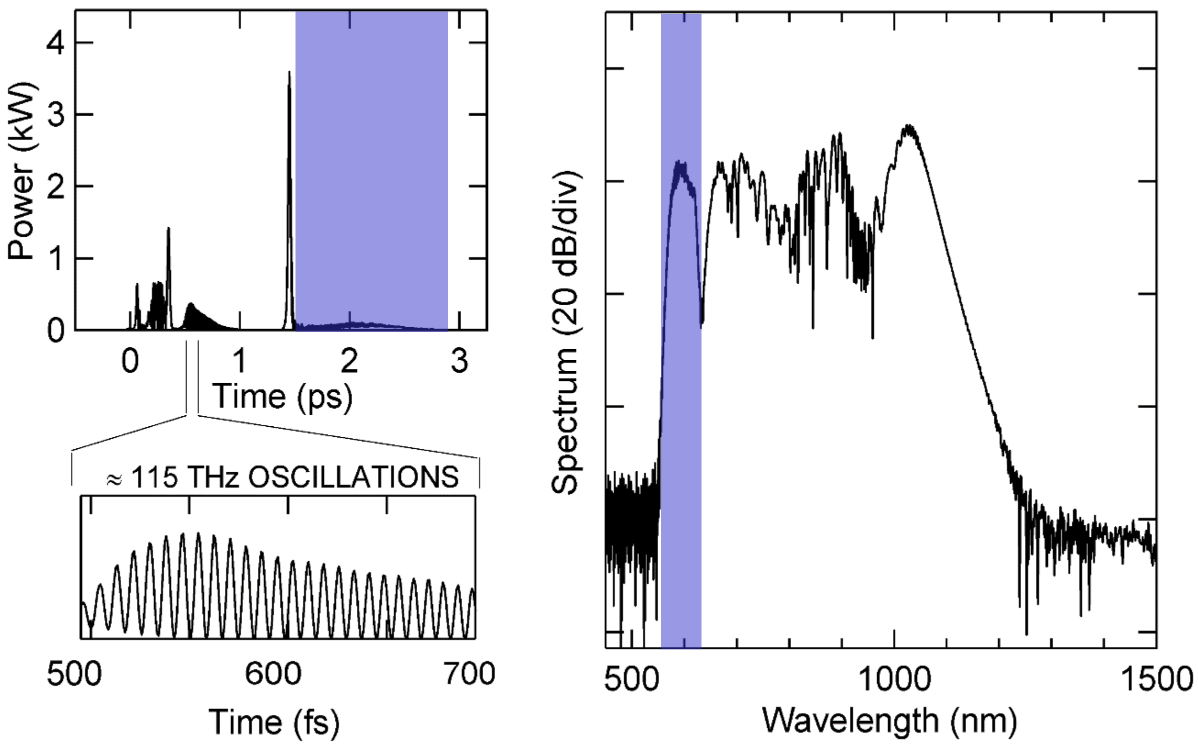
Correlating the time and frequency domains



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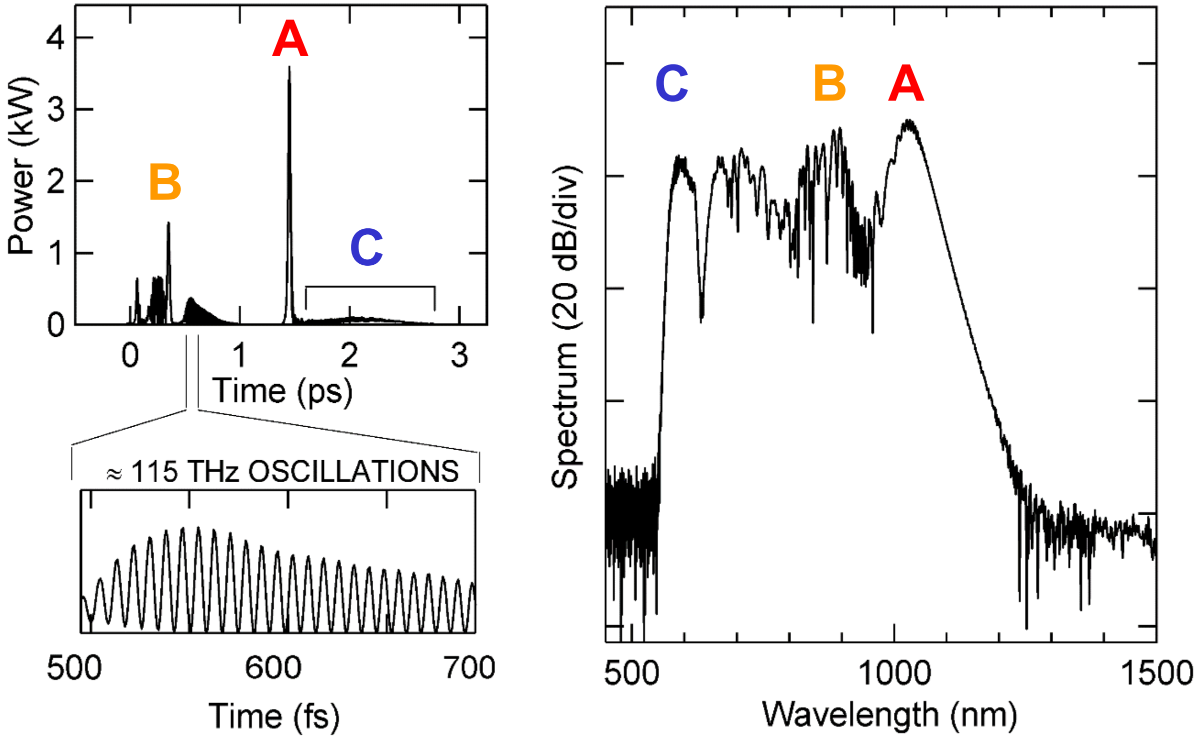
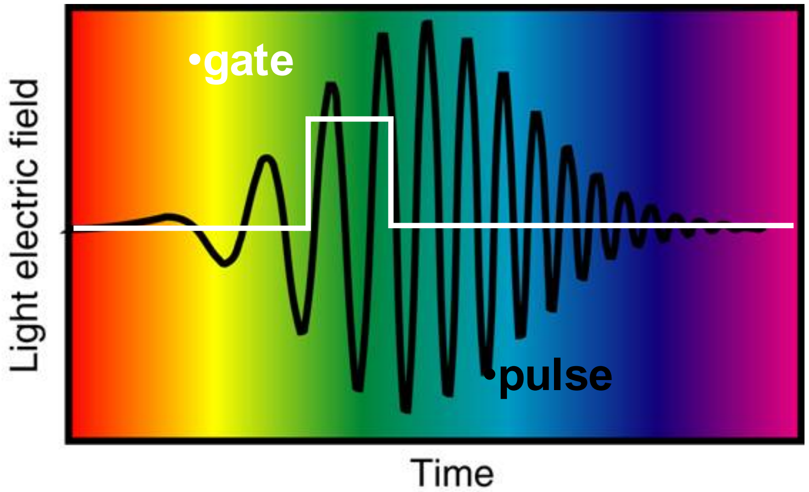
Correlating the time and frequency domains



Supercontinua in the time- frequency domain

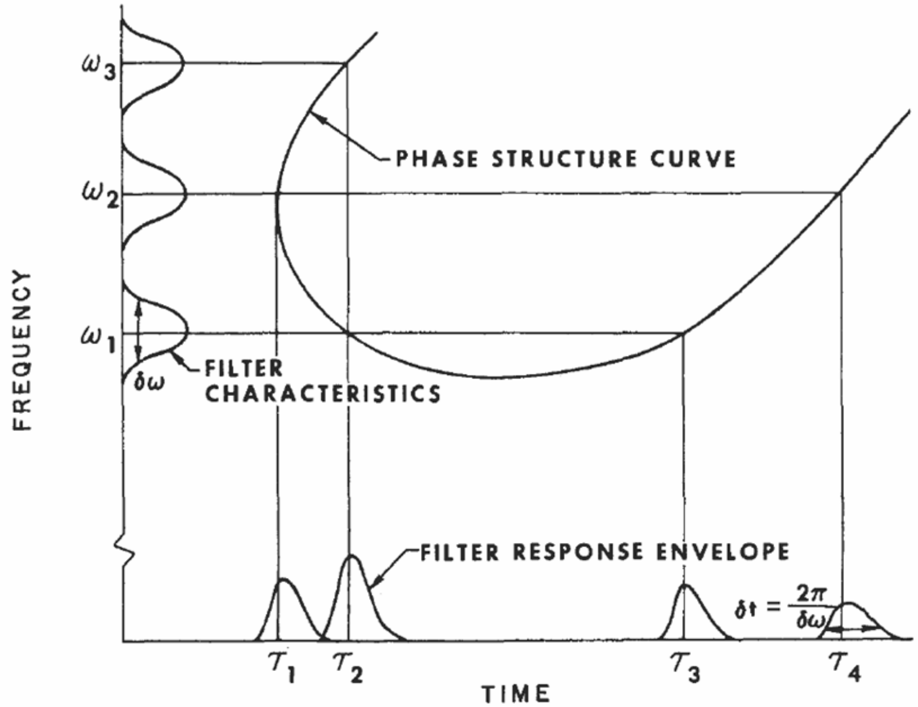
Treacy 1971, J. App. Phys. 42, 3848



Spectrogram

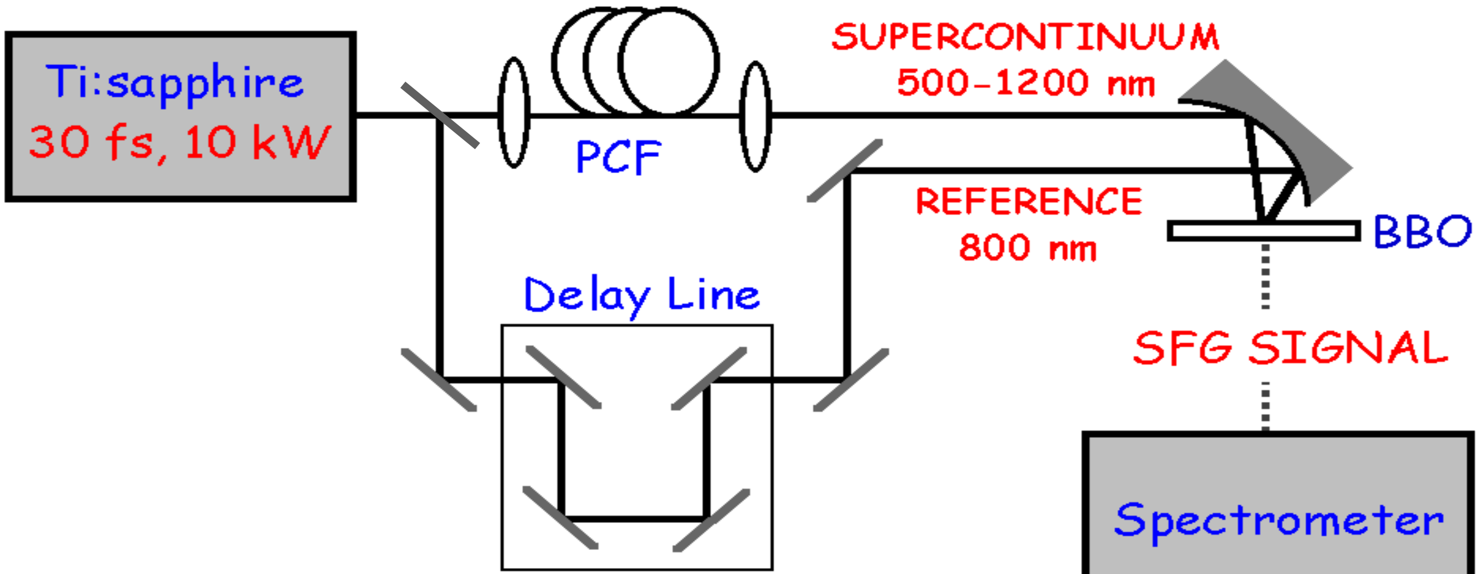
$$\Sigma_g^E(\omega,\tau) = \left| \int_{-\infty}^{\infty} E(t) g(t-\tau) \exp(i\omega t) dt \right|^2$$

pulse *variable delay gate*



Supercontinua in the time- frequency domain

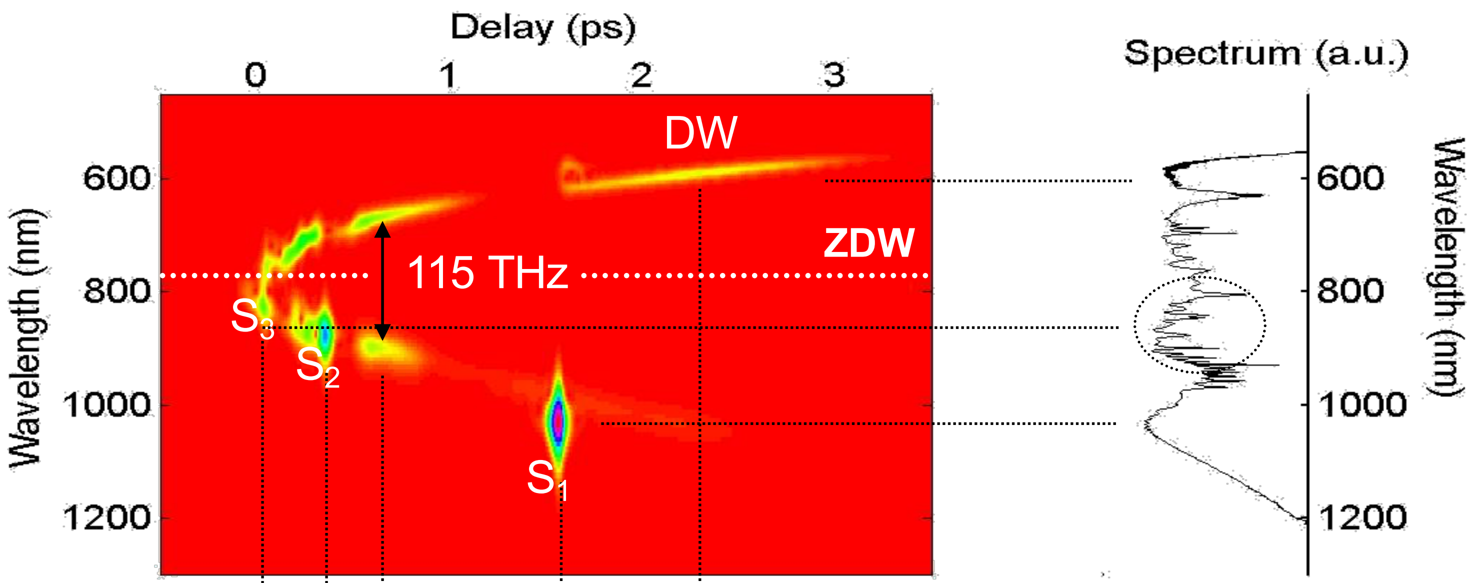
Frequency vs time
Intensity information on top

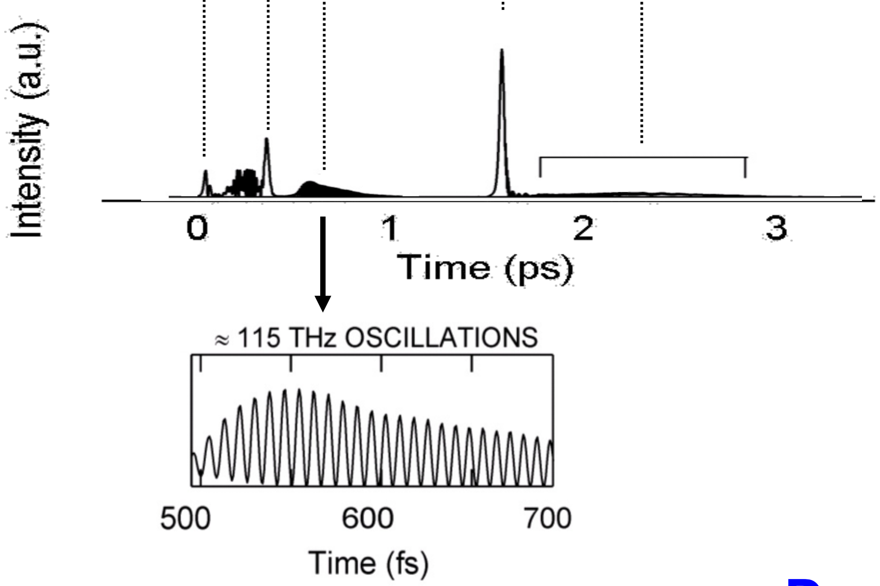


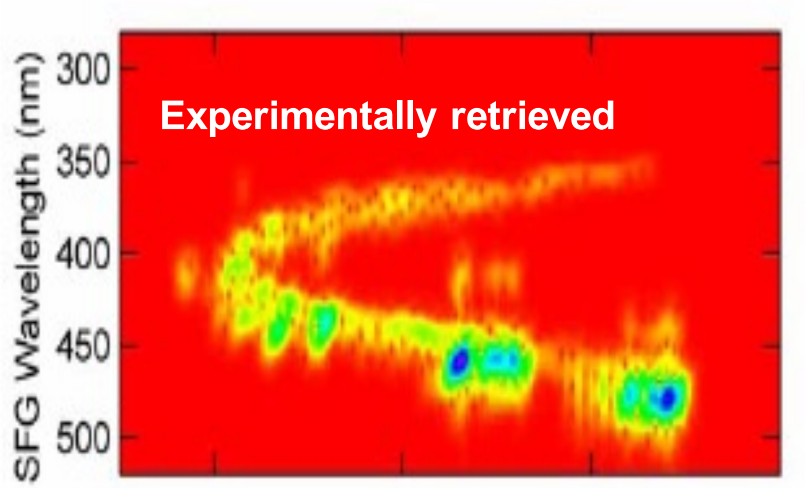
XFROG - Cross Correlation Frequency Gating

Linden at al. 1998, Phys. Status Sol. B 206, 119

Supercontinuum spectrogram





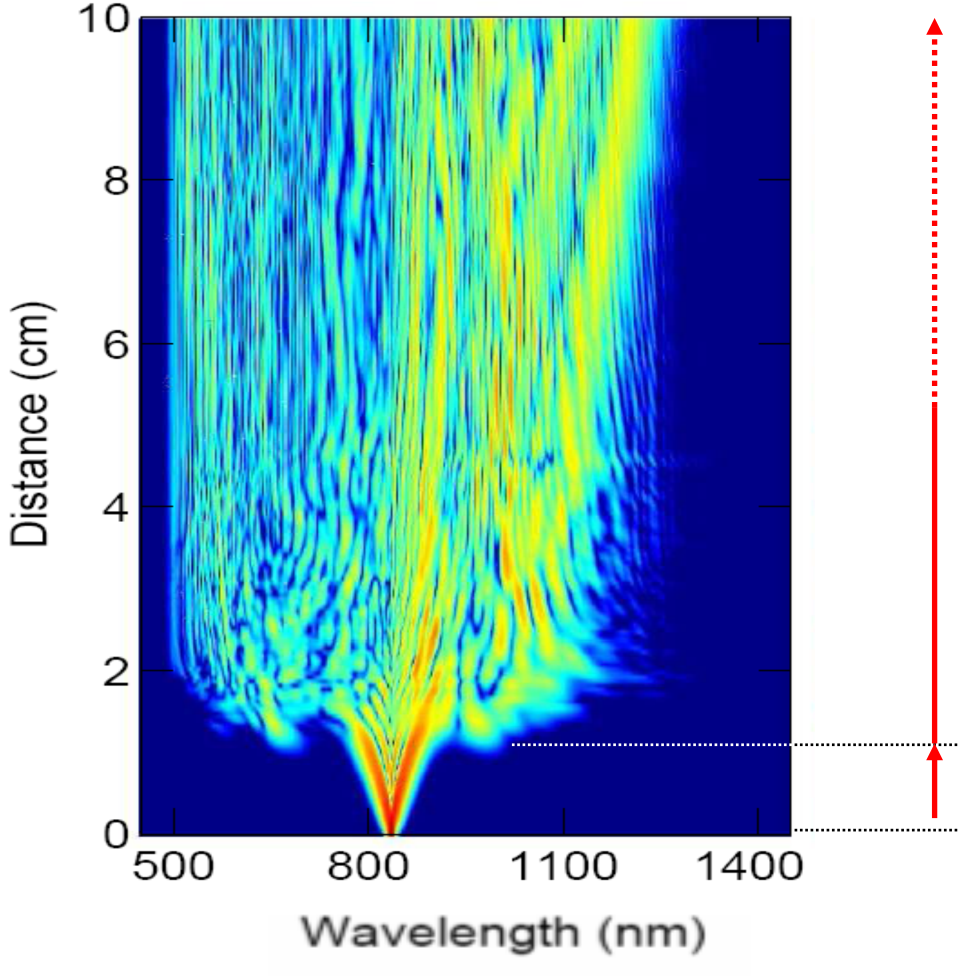


Dudley et al 2002, Opt Exp 10, 1215

Supercontinuum stability

Propagation beyond the soliton break up point leads to instability as the pulse duration increases

150 fsec, 10kW, 835 nm, 10 cm PCF **Dudley**



M I seeds spectral components outside soliton bandwidth

Initial phase, spectral broadening, rapid high order soliton compression

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Supercontinuum instability

Propagation beyond the soliton break up point leads to instability noise driven processes influence modulational instability evolution

150 fsec, 10kW, 835 nm, 10 cm PCF **Dudley**

Average spectra – measured

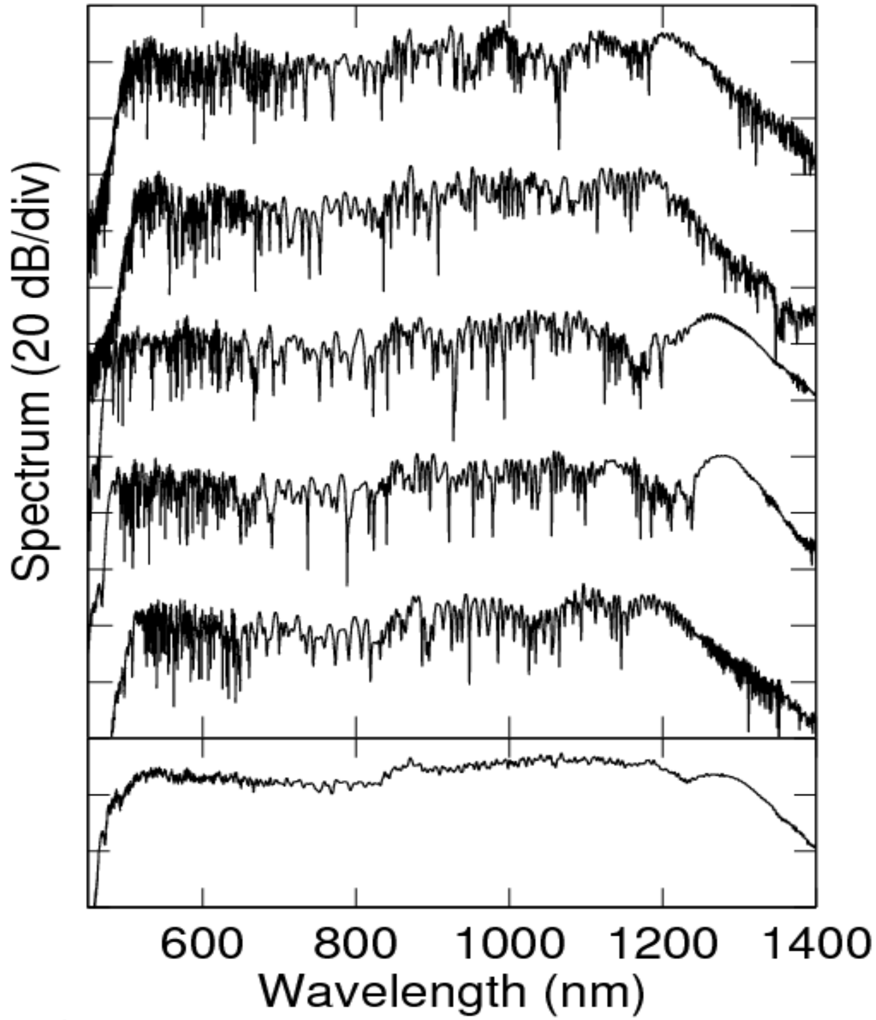
exhibit artificial smoothness

Poor shot to shot stability and coherence

Need stability, ie metrology

Use

- **high power**
- **<50 fsec**
- **short fibre lengths**



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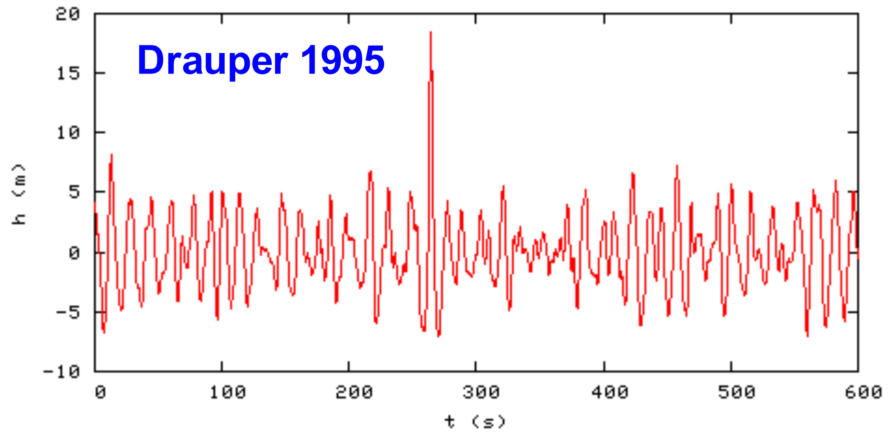
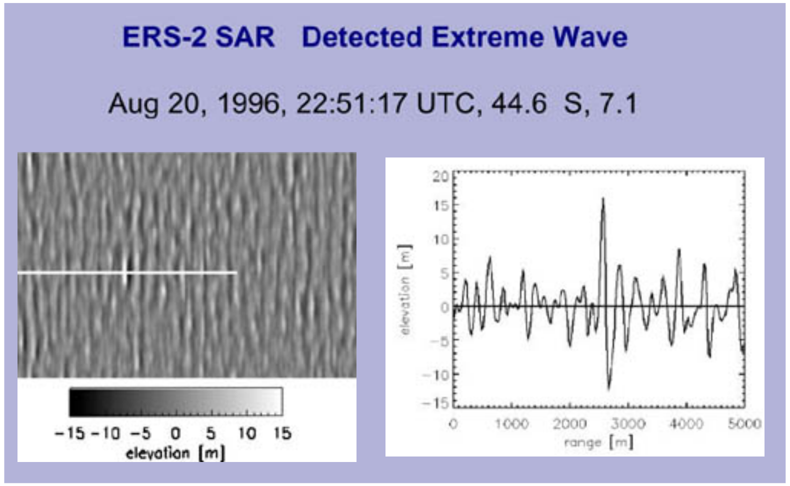
Supercontinua and Rogue Waves ?

Rogue wave are large spontaneous oceanic surface waves that represent statistically rare wave height outliers

Existence confirmed in the 1990s through oil platform measurements and satellite observation.





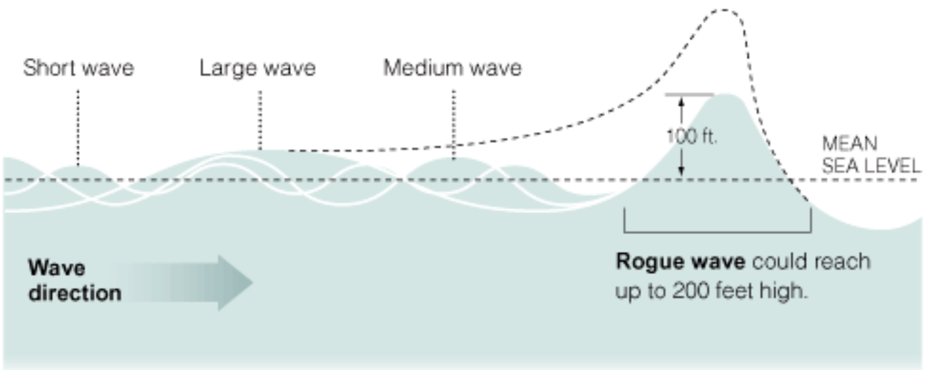
Rogue waves – Noise and MI ?

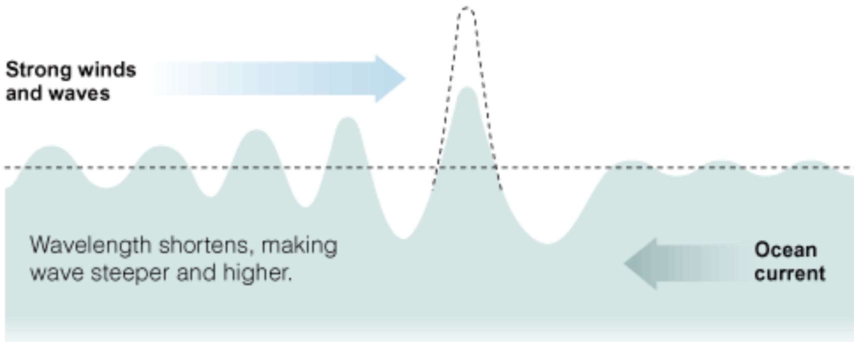
Physics of rogue wave formation of current interest
Difficulty of observation

- **Spatial focusing due to continental shelf topography**
- **Directional focusing of randomly generated wave trains**

- **Exponential amplification of surface noise**
- **Formation of quasi-localized surface states**

] **MI - Modulation instability**





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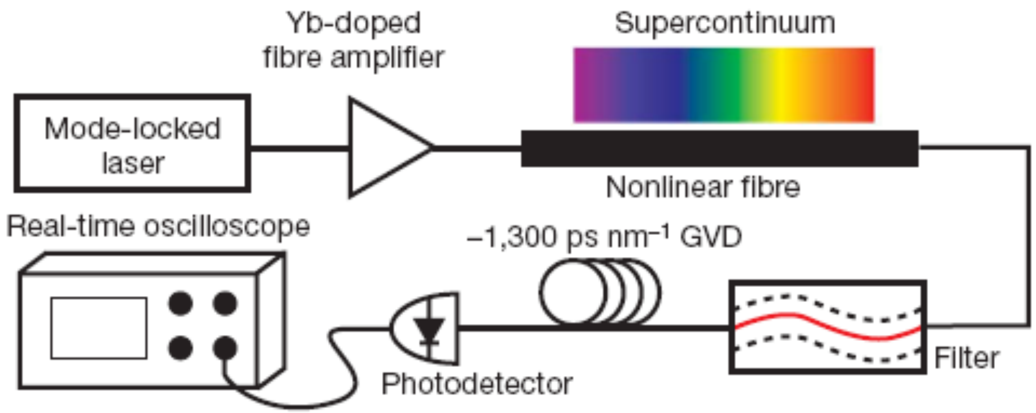
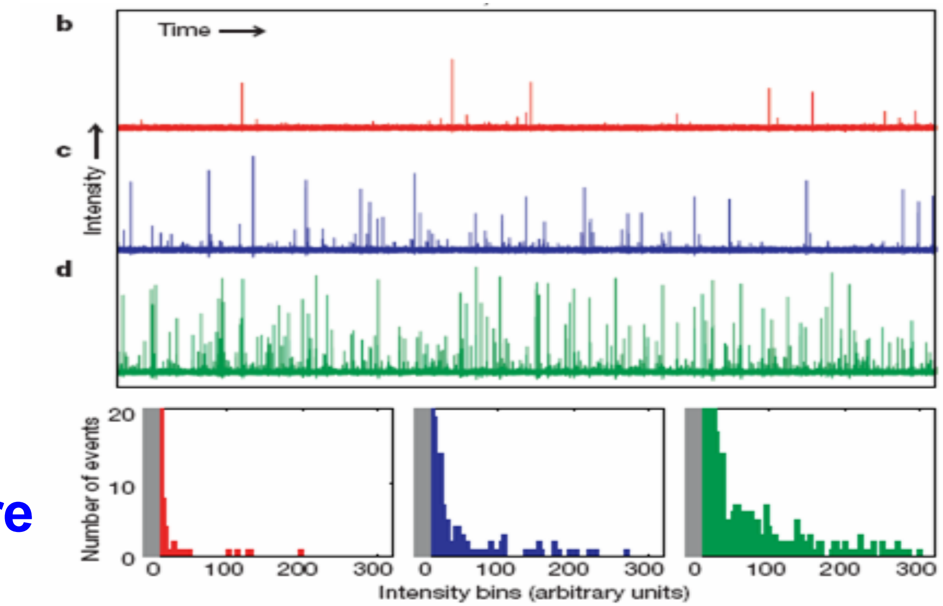
Rogue waves and supercontinua

Solli et al 2007, Nature 450, 06402



Dispersion maps wavelength to time
Filtering selects long wavelength edge – region of interest



"L –shaped" histogram
High amplitude events are rare

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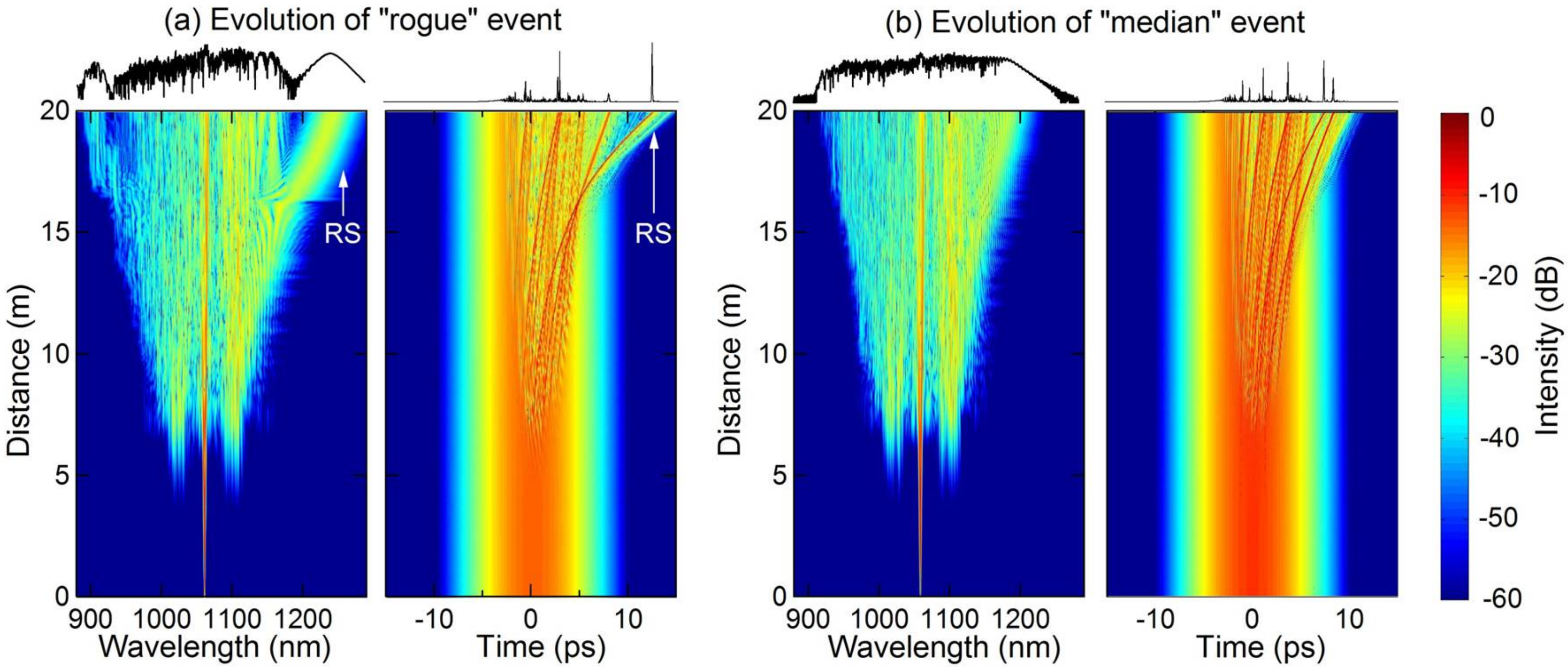
Rogue events in a supercontinuum

Influence of rogue soliton is apparent in propagation dynamics
Dudley 2009



But – it's really just the statistics of noise in new wrapping!
The old story of nonlinear optics in fibre!

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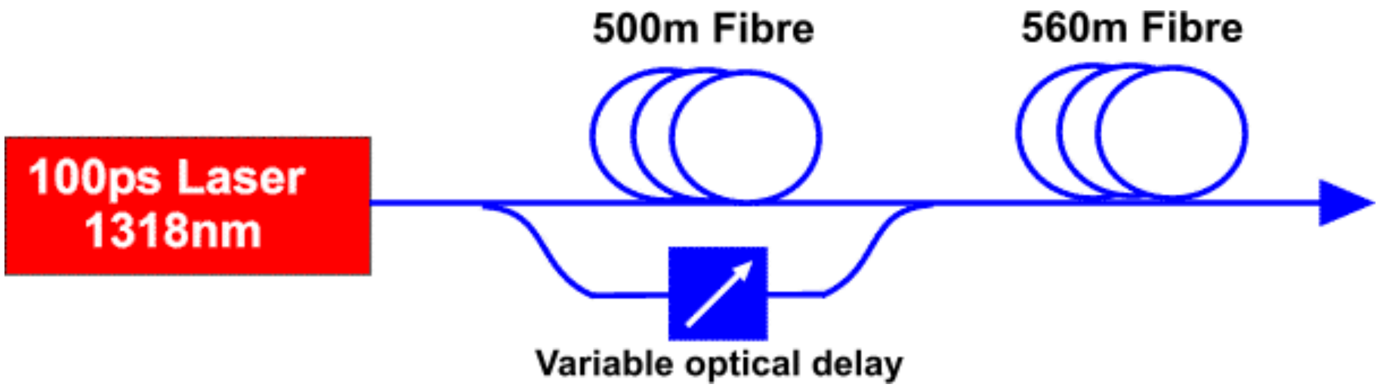
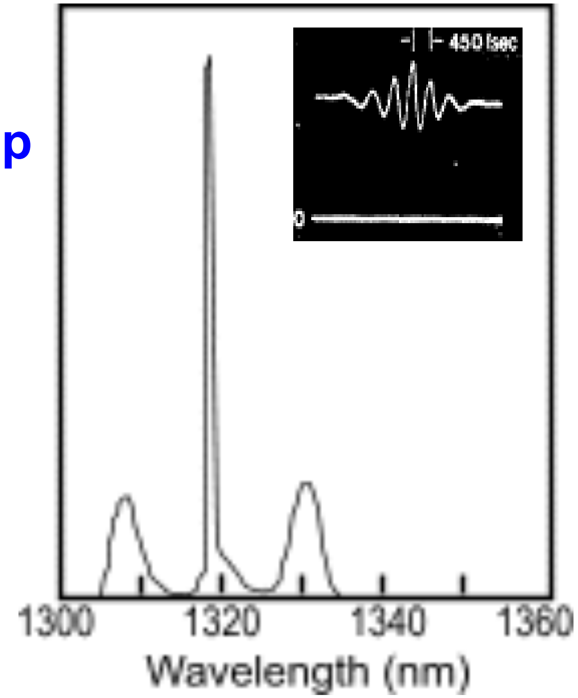
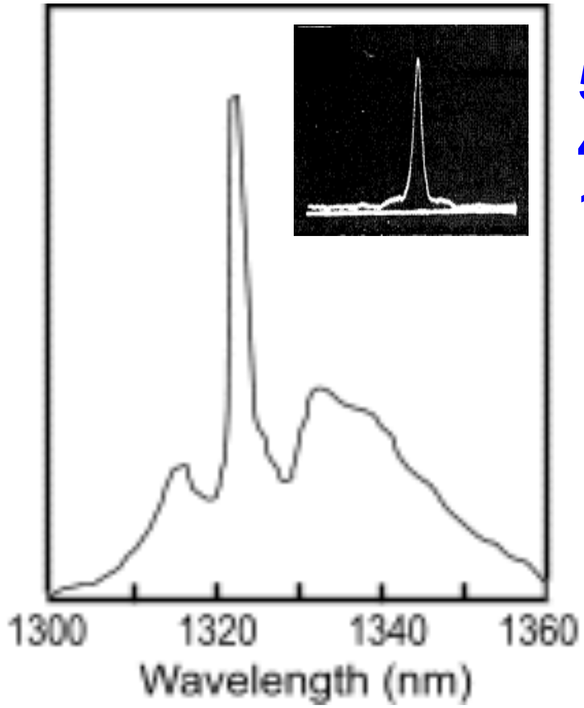
Seeded MI enhances continuum

Gouveia-Neto et al. 1988, Opt. Lett. 13, 1029



560m
60 mW pump
0 mW seed

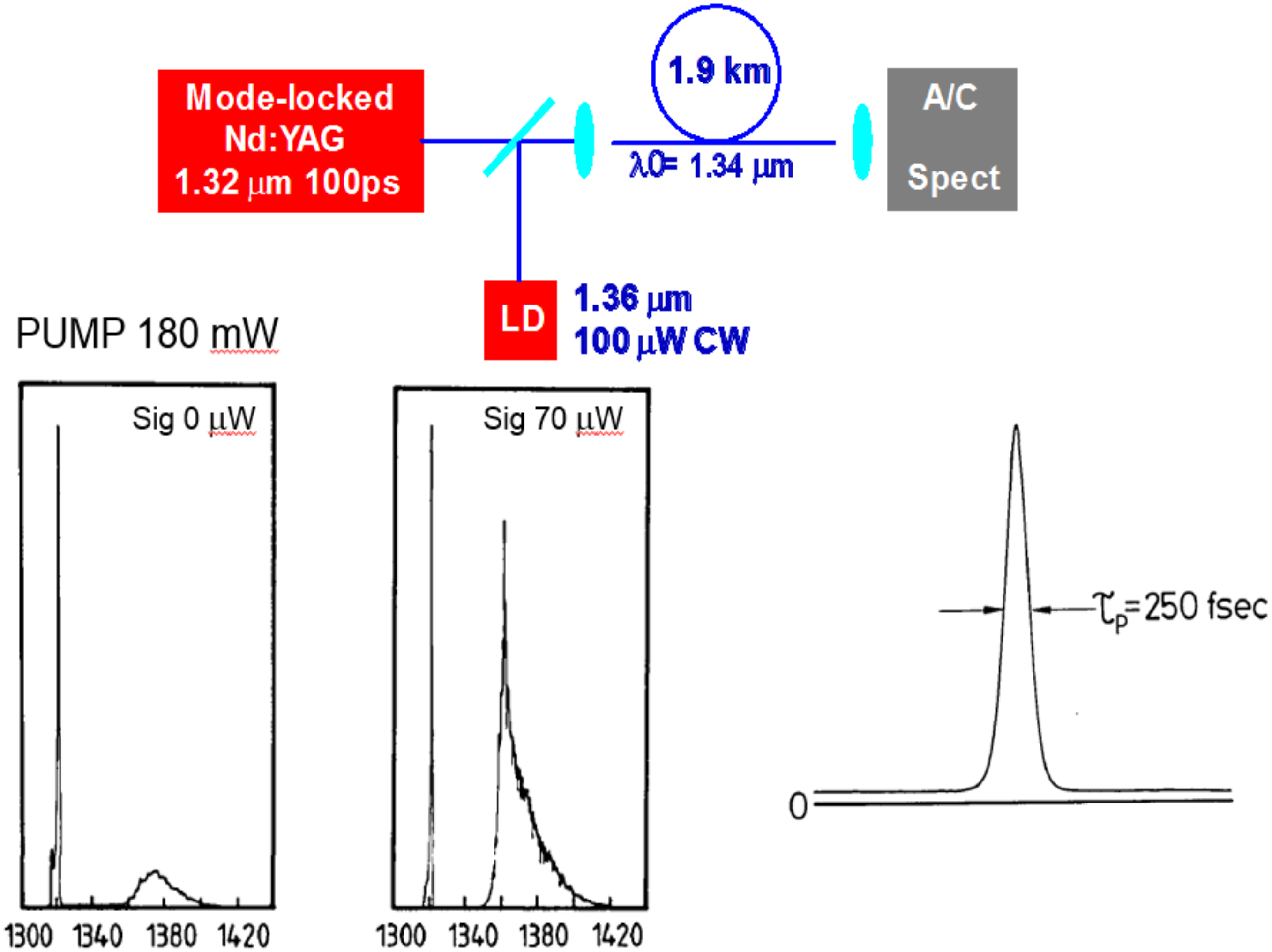




560m
45 mW pump
15 mW seed

Imperial College London

Modulational instability side band seeding



Tunable, femtosecond soliton generation from amplified cw diode laser signals

Greer, Patrick, Wigley, Vukusic & Taylor **Opt. Lett. 15, 133 1990**

200 fsec pulses tunable 1.33 -1.38 µm