AMO Seminar, Department of Physics, National Tsing Hua University

Large-scale laser spectral compression and its applications

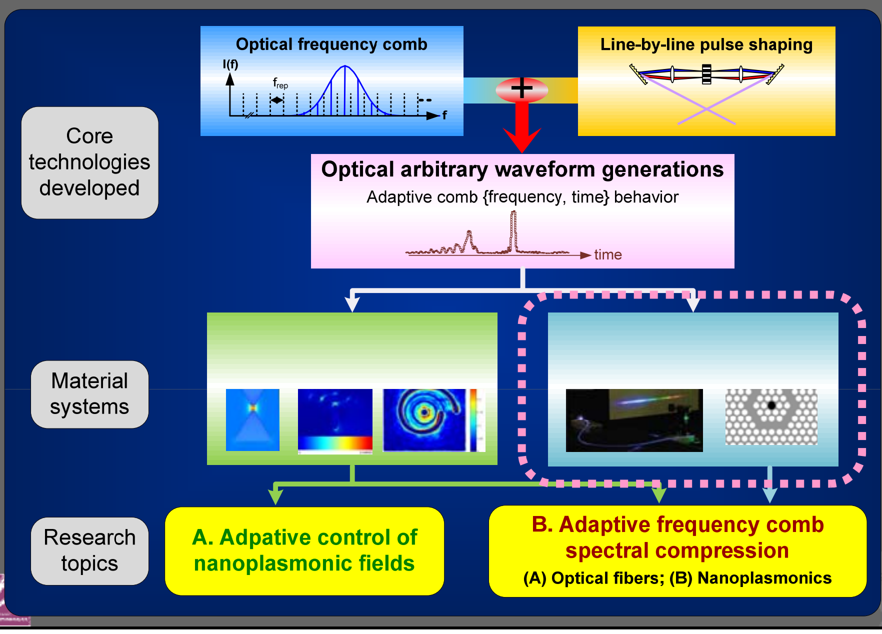
Chen-Bin Huang (黃承彬)

Institute of Photonics Technologies

National Tsing Hua University, Taiwan

March 26, 2012

Ultrafast Photonics Lab

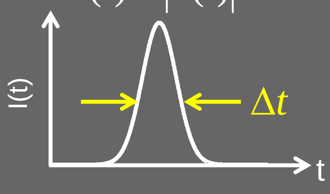


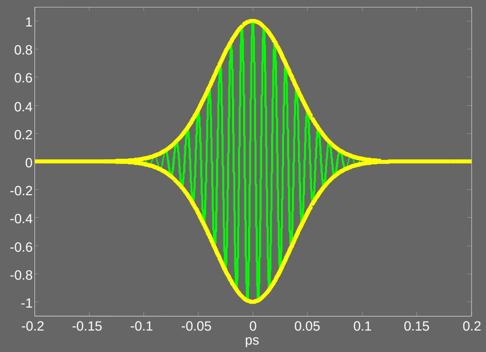
Ultrashort optical pulse

- Electric field
  - Carrier
  - Envelope function *a(t)*

$$E(t) = \mathrm{Re}\{a(t)\exp^{j\omega_o t}\}$$

$$I(t) = |a(t)|^2$$





- Ultrafast optics
  - Full-width half-maximum pulse duration Δt < 1ps

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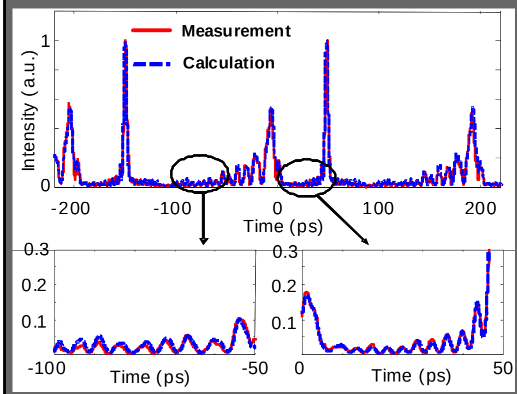
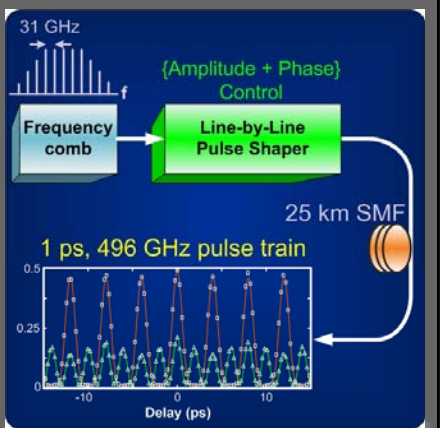
Optical pulse shaping

- We can shape the optical waveform however you like



Jiang*, Huang*, Leaird, Weiner, Nat. Photon. **1**, 463 (2007)



Chuang and Huang*, Opt. Express **18**, 24003 (2010)

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Outline

- Ultrafast 3rd-order nonlinear optics
  - Self-phase modulation
  - Optical solitons
  - Raman scattering
  - Self-steepening
- Supercontinuum generation
- Spectral compression
- Summary

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Nonlinear wave propagation equation

- The inclusion of nonlinear polarization

$$\nabla\times\nabla\times\vec{E}=\nabla(\nabla\bullet\vec{E})-\nabla^2\vec{E}=-\mu_0\frac{\partial^2\vec{D}}{\partial t^2}$$

$$\vec{D}=\varepsilon_0\vec{E}+\vec{P}_{(1)}+\vec{P}_{NL}=\vec{D}_{(1)}+\vec{P}_{NL}$$

$$\nabla_T^2\vec{E}+\frac{\partial^2\vec{E}}{\partial z^2}-\mu_0\varepsilon_{(1)}\frac{\partial^2\vec{E}}{\partial t^2}=\mu_0\frac{\partial^2\vec{P}_{NL}}{\partial t^2}$$

- Scalar treatment

$$D\approx\varepsilon_0(n_0^2+2n_0\delta n_{(1)}+2n_0\delta n_{NL})E\approx(\varepsilon_{(1)}+2\varepsilon_0 n_0\delta n_{NL})E$$

$$P_{NL}\approx 2\varepsilon_0 n_0\delta n_{NL}E$$

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Nonlinear propagation equation in waveguide

- Basic formulation

optical Kerr term

$$\frac{\partial a}{\partial z}+\beta_1\frac{\partial a}{\partial t}-\frac{j\beta_2}{2}\frac{\partial^2 a}{\partial t^2}+j\gamma|a|^2 a+\frac{\alpha}{2}a=0 \qquad \gamma=\frac{\omega_0^2 n_0 n_2}{\beta_0 c^2 A_{eff}}$$

- NonLinear Schrödinger Equation
  - Lossless

$$\frac{\partial a}{\partial z'}-\frac{j\beta_2}{2T_0^2}\frac{\partial^2 a}{\partial \tau^2}+j\gamma|a|^2 a=0$$

- Generalized NLSE

$$\frac{\partial A}{\partial z}+\frac{\alpha}{2}A-\frac{j}{2}\beta_2\frac{\partial^2 a}{\partial T^2}-\frac{1}{6}\beta_3\frac{\partial^3 a}{\partial T^3}=-j\gamma\left[|a|^2 a-T_R a\frac{\partial(|a|^2)}{\partial T}-\frac{j}{\omega_0}\frac{\partial(|a|^2 a)}{\partial T}\right]$$

SPM, Raman, dispersion, Self-steepening

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Self-phase modulation (SPM)

- No dispersion

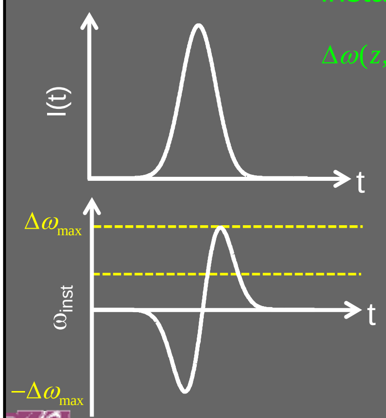
$$\frac{\partial a}{\partial z}=-j\gamma|a|^2 a$$

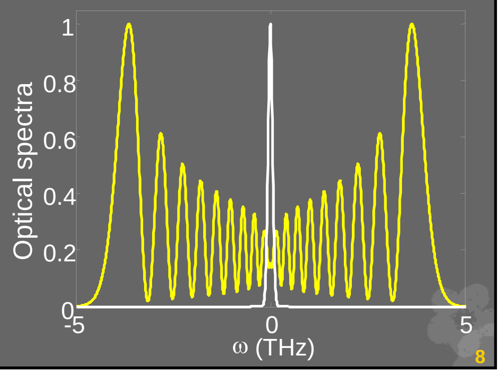
Gives broadened spectrum

$$a(z,t)=a(0,t)\exp[-j\gamma|a(0,t)|^2 z]$$

instantaneous frequency:

$$\Delta\omega(z,t)=\frac{\partial(\Delta\varphi)}{\partial t}=-\frac{\partial}{\partial t}(\gamma|a|^2 z)$$





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Optical solitons

- For anomalous dispersive materials: $\beta_2 < 0$
- Dimensionless NLSE

$$j\frac{\partial a}{\partial \zeta} = \frac{1}{2}\frac{\partial^2 a}{\partial \tau^2} + |a|^2 a$$

- Solution: solitons

$$a(z,t) = \sqrt{P_c}\,\mathrm{sech}\left(\frac{t}{T_0}\right)\exp\left[\frac{-j|\beta_2|z}{2T_0^2}\right]$$

- Complete balance between dispersion and SPM
- Pulse energy

$$U = \frac{2|\beta_2|}{\gamma T_0}$$

- Soliton order

$$N^2 = \frac{\gamma T_0 P_{peak}}{|\beta_2|}$$

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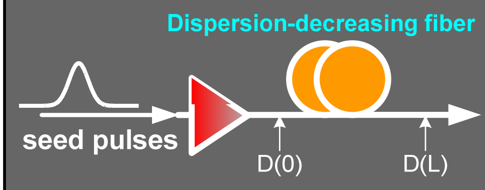
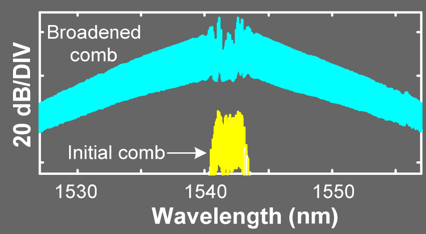
Adiabatic soliton temporal compression

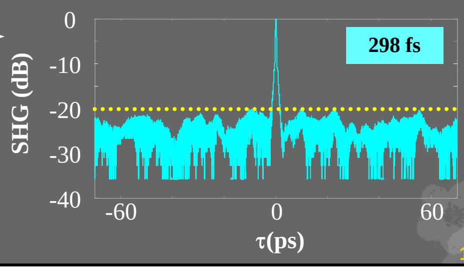
- Dispersion control
  - Energy conservation

$$U = \frac{2|\beta_2|}{\gamma T_0} \Rightarrow \frac{T_0(0)}{T_0(z)} = \frac{\beta_2(0)}{\beta_2(z)}$$

Gives broadened spectrum







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Higher-order solitons

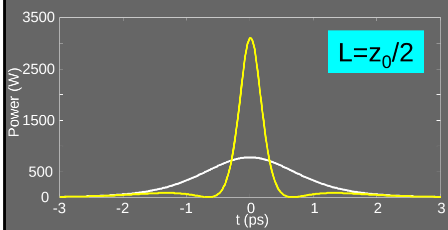
- N=2

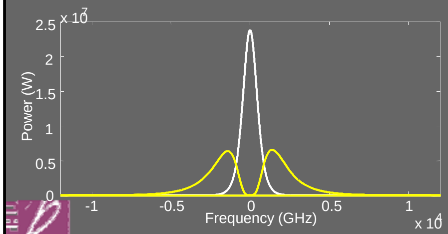
Gives broadened spectrum

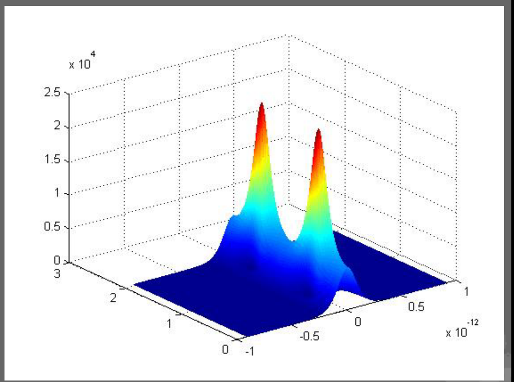
$$P_j = \frac{(2N-2j+1)^2}{N^2} P_{peak}$$

$$T_j = \frac{T_0}{2N-2j+1}$$

L=z_0/2





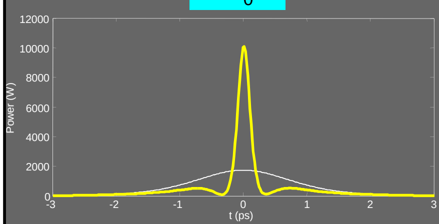


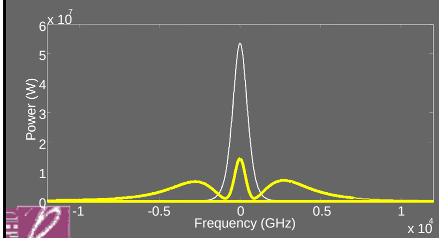
Higher-order solitons

- N=3

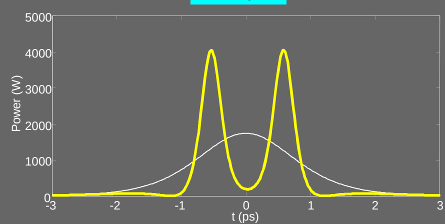
Gives broadened spectrum

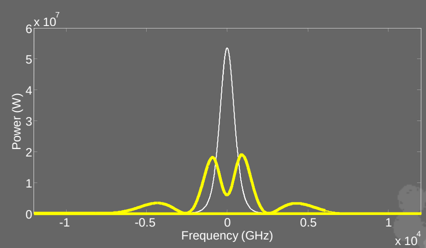
L=z_0/4





L=z_0/2



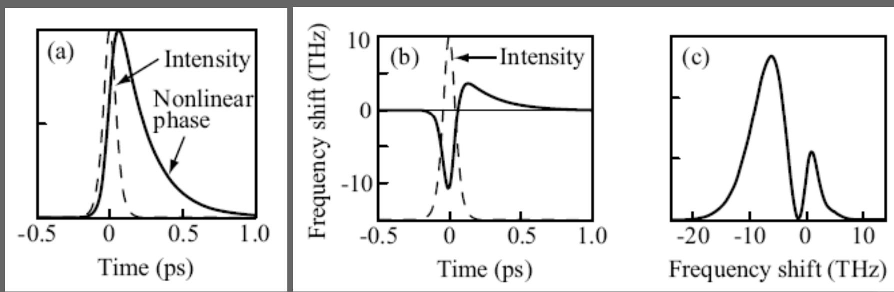


Raman response

- Delayed nonlinear phase ➔ delayed instantaneous frequency
- Red-shift of the pulse power spectrum

Gives broadened spectrum

Time-domain view



A. M. Weiner, *Ultrafast Optics* (Wiley, 2009)

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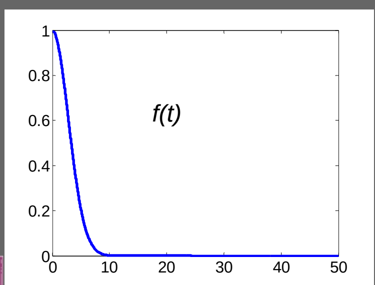
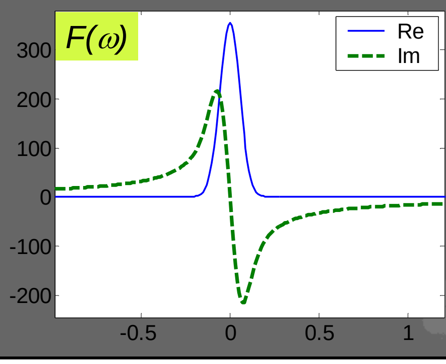
Fourier-transform properties

- Raman response real ⇔ F(-ω)=F*(ω)
- A single-sided function
  - Im{F(ω)} < 0 for ω > 0
  - Im{F(ω)} > 0 for ω < 0

Frequency-domain view

$$\mathrm{Im}\{F(\tilde{\omega}_s - \tilde{\omega}_p)\}$$





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Self-steepening

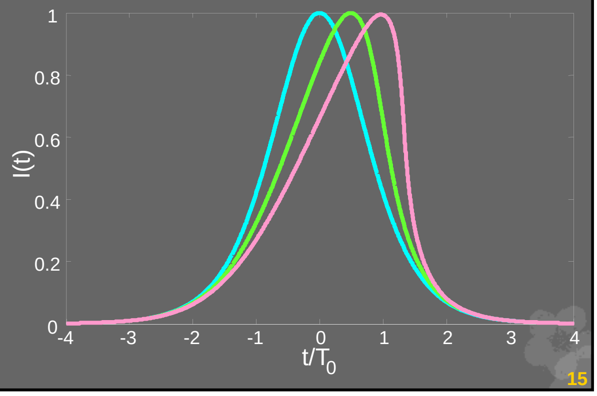
- Gives rise to intensity-dependent group velocity
  - Dispersionless, only electronic response

$$\frac{\partial a}{\partial z} + j\gamma\left(1 - \frac{j}{\omega_0}\frac{\partial}{\partial t'}\right)|a|^2 a = 0$$

$$\frac{\partial |a|}{\partial z} + \frac{3\gamma}{\omega_0}|a|^2\frac{\partial |a|}{\partial t'} = 0$$

$|a| \propto f(t' - \frac{z}{v})$ $v = \frac{\omega_0}{3\gamma |a|^2}$

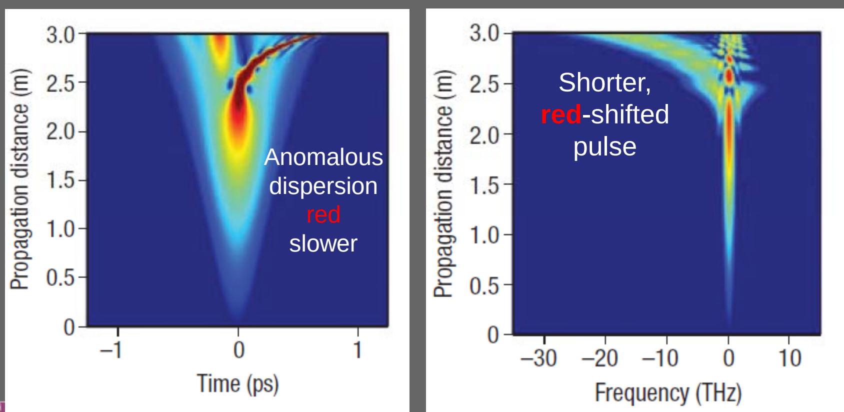
Gives broadened spectrum



Soliton fission

- Nth-order solitons will break into N fundamental solitons
  - Raman: soliton self-frequency shift (SSFS)
  - Self-steepening

Gives broadened spectrum



Dudley et.al, Nat. Phys. **3**, 597 (2007)

- Ultrafast 3rd-order nonlinear optics
- Supercontinuum generation
- Spectral compression
- Summary

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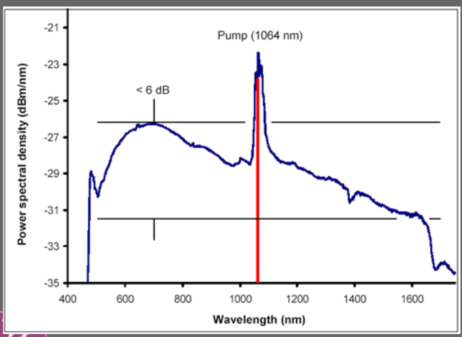
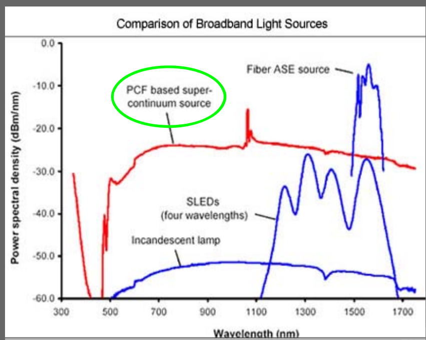
SC: Definition

- What is SC?
  - Coherent light source having large bandwidth
  - Broadened input spectrum by nonlinear optical processes
- Applications
  - Metrology, spectroscopy, sensing, ultrashort pulse……





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SC: History

- Historical evolution

Year	*Nonlinear medium*	*Laser type*	*Pulse width*	*Pulse intensity/ Peak power*	*SC -20 dB bandwidth*
1970	Borosilicate	Nd:Glass	5 ps	1 GW/cm^2	300 nm
1977	Water	YAlG:Nd	30 ps	45 MW	600 nm
1983	Ethylene glycol	Rh6G	80 fs	3 GW	130 nm
1987	MMF	Nd:YAG	25 ps	1.5 GW/cm^2	60 nm
1995	DSF	Er^{3+} fiber laser	1 ps	1.2 kW	300 nm
1999	MF	Ti:Sapphire	100 fs	8 kW	1200 nm

birth of
optical frequency comb
tightly linked

www.bath.ac.uk/physics/groups/ppmg/research_pcf_scg.html

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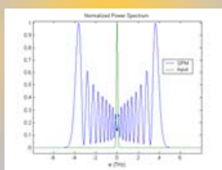
SC: Major Nonlinear Processes

SPM

$$\Delta\omega_{inst} = -\gamma L \frac{\partial |A|^2}{\partial t}$$



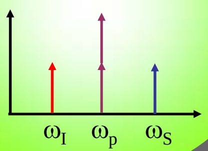
Elastic processes

FWM

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

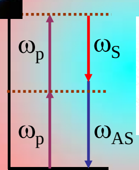
$$2\omega_p = \omega_S + \omega_I$$

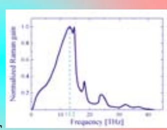
$$\Delta k_M + \Delta k_{WG} + \Delta k_{NL} = 0$$



SRS

$$2\omega_p = \omega_S + \omega_{AS}$$





Inelastic Process Along with SSFS + SS

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Microstructured Fibers

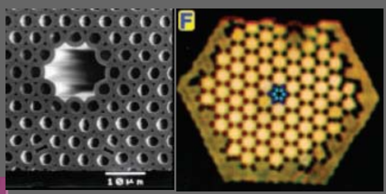
Photonic Crystal Fibers (PCF)

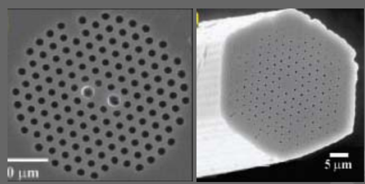
Photonic Band-gap Fibers (PBF)

Guided by photonic band-gap
Confined within air

Microstructured Fibers (MF)

Effective index
Confined within material





Russel, Science **299**, 358 (2003)

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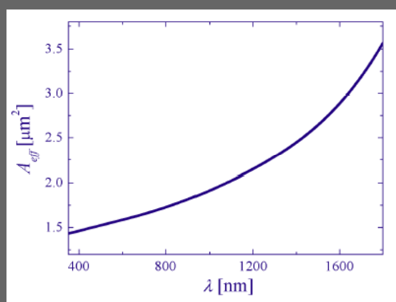
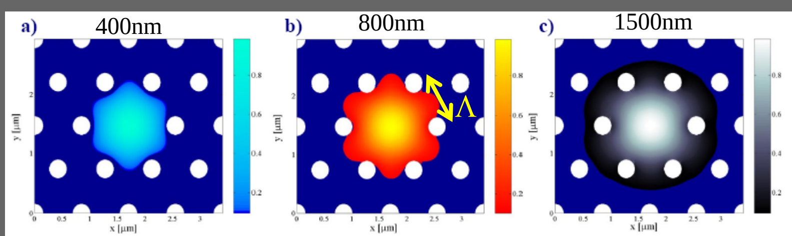
Variable MF Properties

- Small effective modal area
  - Large nonlinearities!
- Endlessly single-mode
  - Cladding index engineering



Lattice pitch, not core diameter!

$$V_{eff} = \frac{2\pi\Lambda}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2} < 2.405$$



G. Genty, Ph.D. Dissertation, (Helsinki University of Technology,2004).

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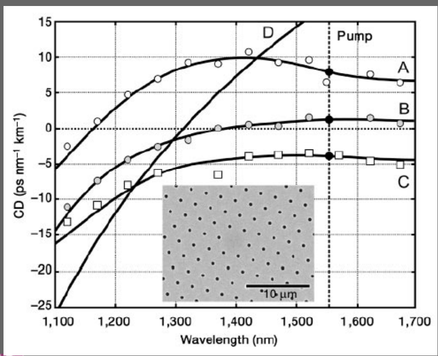
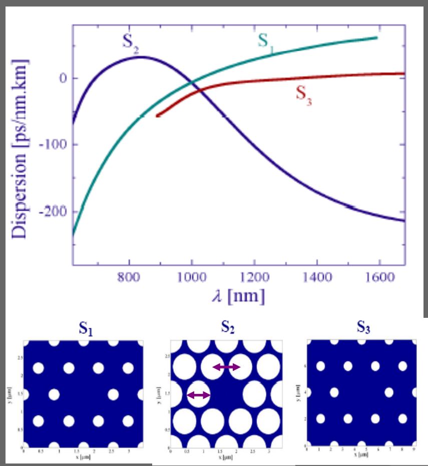
Variable MF Properties

- Zero-dispersion wavelength (λ_{ZD})
  - Core size
- Dispersion relation
  - Air-hole diameter
  - Lattice



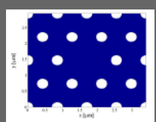


Reeves et. al., Nature **424**, 511 (2003)

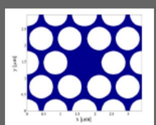
G. Genty, Ph.D. Dissertation

Comparison of MF Properties

Fiber\Properties	SMF	DSF	DCF	HNLF	MF
Attenuation (dB/km)	0.2	0.2	0.45	0.7	80-240
Modal area (um²)	85	50	19	12	3
γ (1/W/km)	1.8	2.7	5	15	50



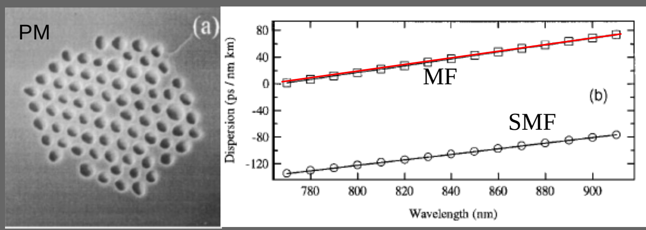
Ability to tune L and NL properties

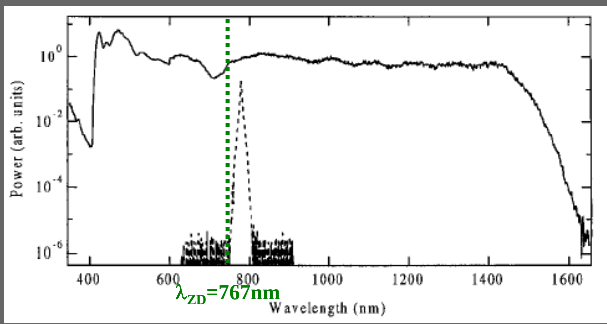


Much lower power is required to generate SC

First SC Generated using MF

- Ranka, Windeler and Stentz (2000)





λ_p = 790 nm
λ_{ZD} = 767 nm
Δt = 100 fs
P_p = 8 kW
P_{av} = 64 mW
L = 75 cm

Ranka et. al., Opt. Lett. **25**, 25 (2000)

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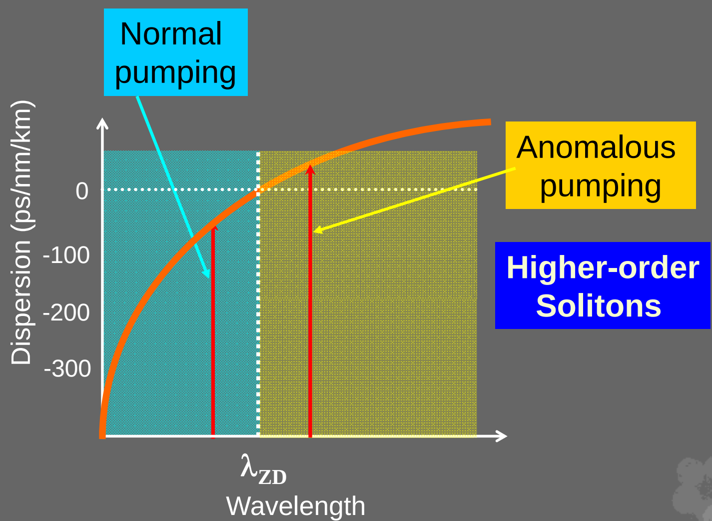
SC Generation in MF

- Defining pumping modes
  - Anomalous
  - Normal



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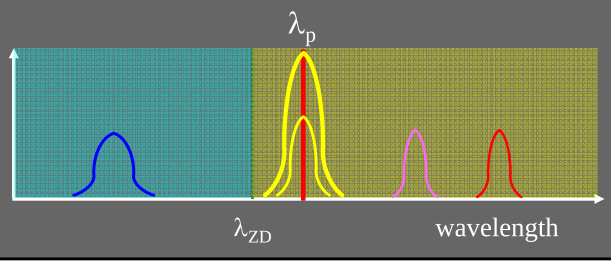
Anomalous pumping flow chart

- Higher-order soliton formation
  - Soliton fission
  - Linear radiation wave (RW)
  - Stimulated Raman scattering (SSFS)
  - Later broadening
    - FWM + SRS for anomalous dispersion regime
    - SPM for normal dispersion regime

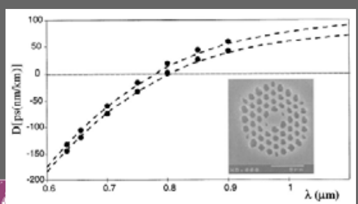


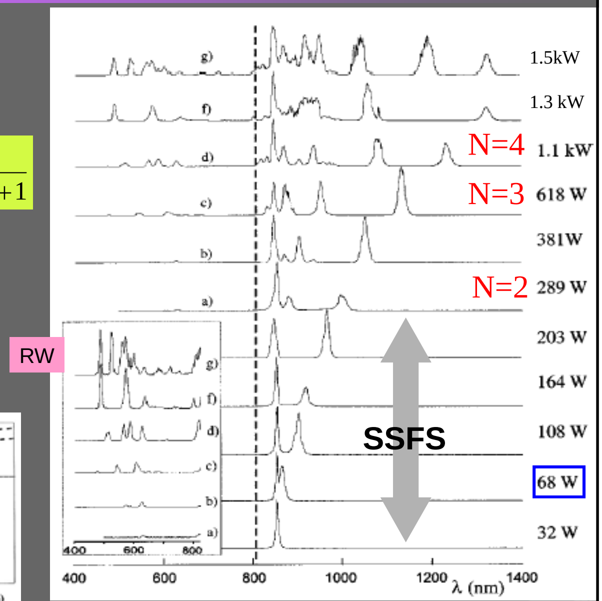
Higher-order soliton: anomalous pumping

- Effect of pump power
  - Wider, flatter

$$N = \sqrt{\frac{\gamma P_{peak}}{|\beta_2|}}\,\frac{\Delta t}{1.665} \qquad T_j = \frac{T_0}{2N-2j+1}$$

λ_p = 850 nm
λ_{ZD} = 806 nm
Δt = 200 fs
L = 6 m





Ortigosa-Blanch et. al., JOSA-B **19**, 2567 (2002)

- Ultrafast 3rd-order nonlinear optics
- Supercontinuum generation
- Spectral compression
  - Brief history
  - Our approach
  - Numerical and experimental results
- Summary

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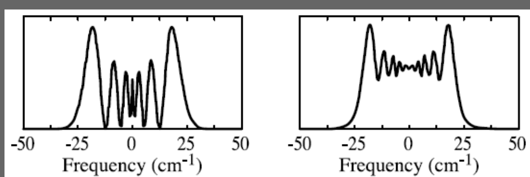
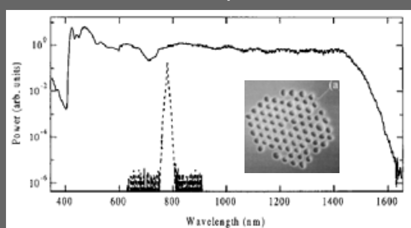
Nonlinear processes → spectral broadening

- Self-phase modulation



A. M. Weiner, *Ultrafast Optics* (Wiley, 2009)

- Supercontinuum generation
  - Higher-order solitons: SPM, dispersion, FWM, SSFS, soliton fission



J. K. Ranka et.al., Opt. Lett. **25**, 25 (2000)

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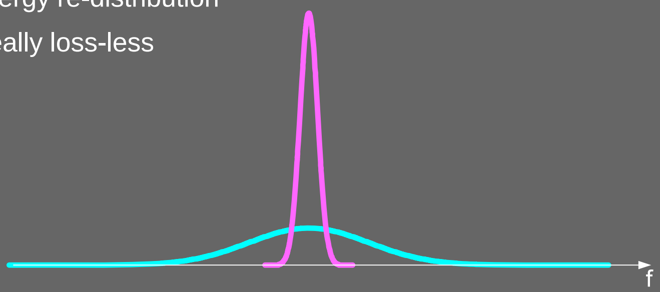
Applications

- Highly spectrally bright coherent sources
  - Optical metrology, linear/nonlinear spectroscopy
- ps pulse trains
  - Narrow-band, CARS
- Different compared to spectral filtering
  - Energy re-distribution
  - Ideally loss-less



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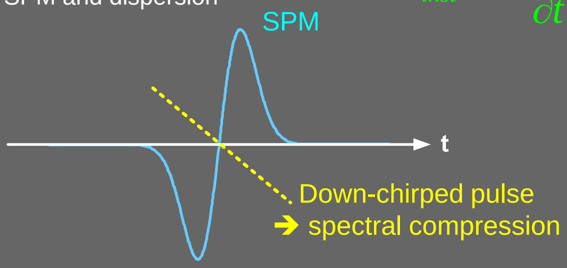
Spectral narrowing/compression

- Earliest experimental observation
  - R. H. Stolen and C. Lin, Phys. Rev. A **17**, 1448 (1978)
- Physical insight explained
  - S. A. Planas et.al, Opt. Lett. **18**, 699 (1993).
  - M. Oberthaler and R. A. Höpfel, Appl. Phys. Lett. **63**, 1017 (1993).
- Instantaneous frequency
  - Pulse chirp, SPM and dispersion

$$\omega_{inst} = \frac{\partial \phi(t)}{\partial t}$$



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Prior works

- Various fiber types and input chirp conditions
- Compression ratio

Publications	Fiber type (sign of β_2)	Input chirp	Compression ratio
Shen et.al, JLT **17**, 452 (1999)	SMF (-)	+	2
Washburn et.al, OL **25**, 445 (2000)	SMF (+)	-	3.5
Limpert et.al, APB **74**, 191 (2002)	Yb-doped (+)	-	16
Andresen et.al, OL **30**, 2025 (2005)	PCF (~0)	-	21
Sidorov-Biryukov et.al., OE **16**, 2502 (2008)	HNPCF (-)	X	7
Fedotov et.al., OL **34**, 662 (2009)	HNPCF (-)	X	6.5
Nishizawa et.al., OE **18**, 11700 (2010)	CPF (-)	X	**25.9**
Andresen et.al., OL **36**, 707 (2011)	HNPCF (+)	-	5

chirp-free, below soliton P_{peak} solitons

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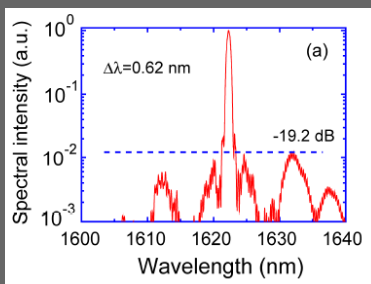
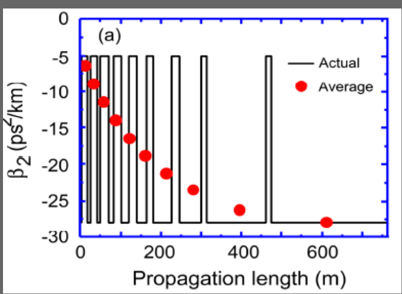
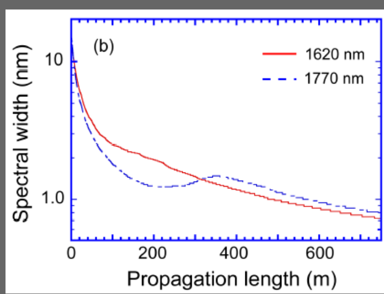
Soliton effect for spectral compression

- Comb-profile fiber
  - 19 segments of SMF and DSF
  - Large compression ratio of 25.9
  - Excellent side-lobe suppression







N. Nishizawa et.al., Opt. Express **18**, 11700 (2010)

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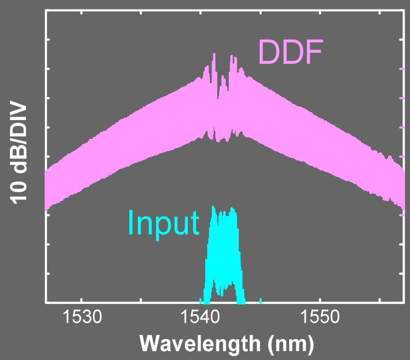
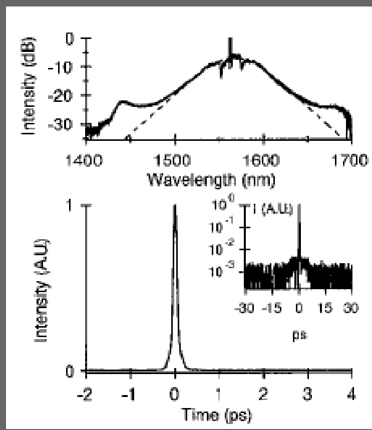
Adiabatic soliton temporal compression

- Dispersion-decreasing fiber
  - Fundamental soliton
  - 60 times pulse compression

$$\Delta\tau_{out} = \frac{D_{out}}{D_{in}}\Delta\tau_{in}$$





C.-B. Huang et.al., Opt. Express **16**, 2520 (2008)

K. R. Tamura et.al., Opt. Lett. **26**, 762 (2001)

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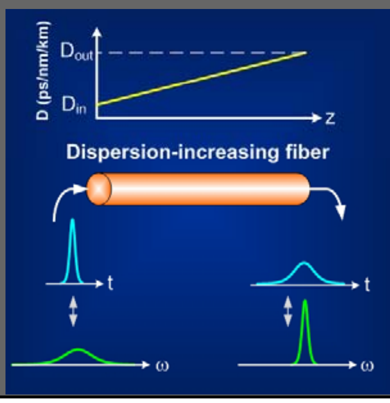
Our idea

- Simply run the adiabatic soliton temporal compression in reverse!
- Adiabatic soliton spectral compression
  - Simple idea, never realized!
  - DDF➔ dispersion-increasing fiber (DIF)
    - Short pulse (wide spectrum) in, broad pulse (narrow spectrum) out



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Split-step Fourier method

- Input pulse envelope $a(0,t)$

$$\frac{\partial a}{\partial z} = \frac{j\beta_2}{2}\frac{\partial^2 a}{\partial t^2} - j\gamma |a|^2 a$$

$\downarrow$ F.T.

- Spectral envelope $A(0,\tilde{\omega})$
- Dispersed spectral envelope $A_D(\Delta z,\tilde{\omega}) = A(0,\tilde{\omega})\exp[-j\frac{\beta_2\tilde{\omega}^2\Delta z}{2}]$

$\downarrow$ I.F.T.

- Dispersed pulse envelope $a_D(\Delta z,t)$
- Dispersed, SPM pulse envelope $a_{D,SPM}(\Delta z,t) = a_D(\Delta z,t)\exp[-j\gamma |a_D(\Delta z,t)|^2 \Delta z]$
- *Now do iterations all the way to the output*

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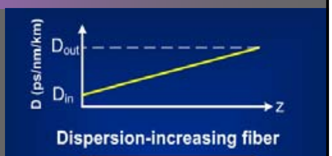
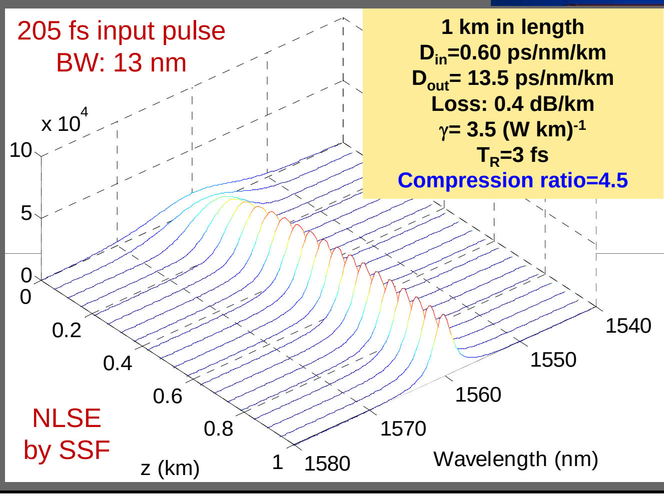
Adiabatic soliton spectral compression

- Dispersion-increasing fiber
  - Ideal compression ratio = D_{out}/D_{in}=22.5





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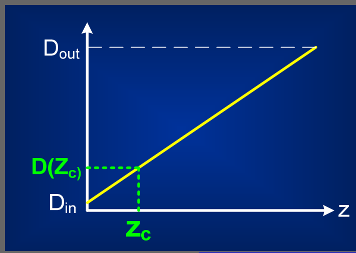
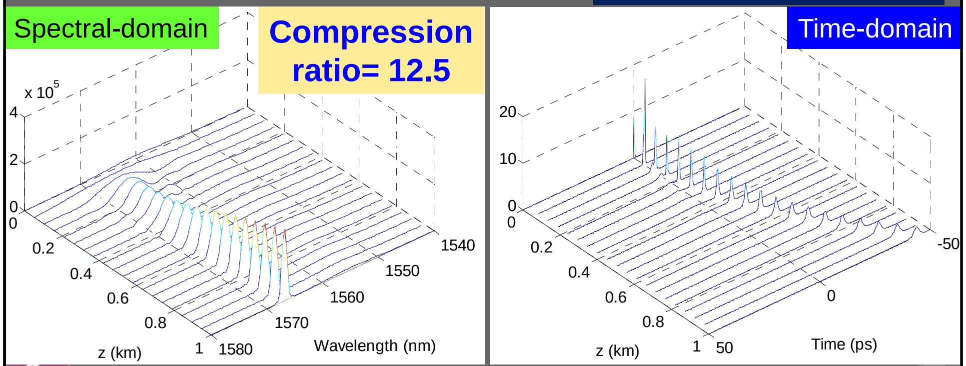
Large spectral compression ratio

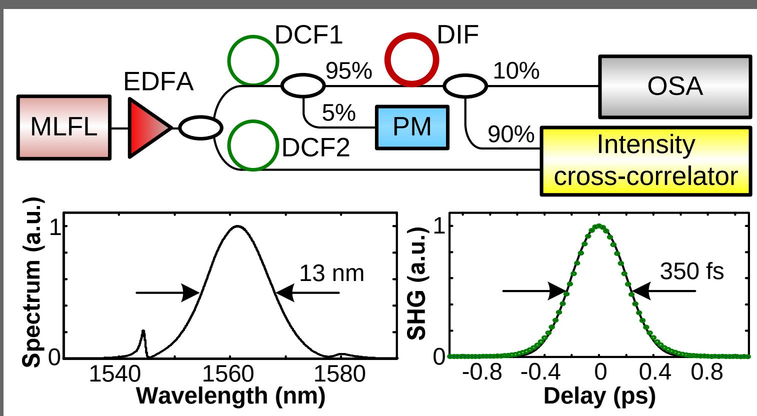
- Positively chirped 305 fs input pulse
- Explanation
  - Stability



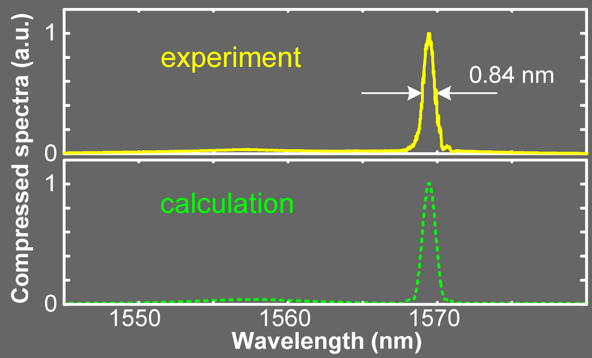


Experiment: setup

1 km in length
D_{in}=0.60 ps/nm/km
D_{out}= 13.5 ps/nm/km
Loss: 0.4 dB/km
γ= 3.5 (W km)$^{-1}$
T_R=3 fs

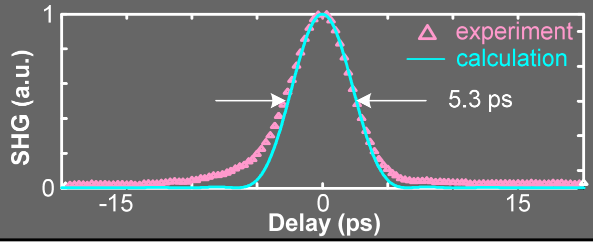


Experiment: results



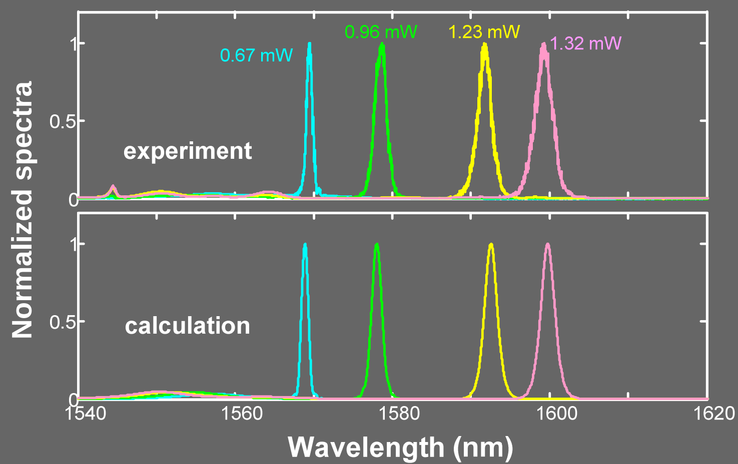
Spectral compression ratio=15.5

Intensity cross-correlation



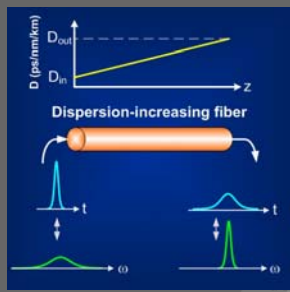
Experiment: wavelength tuning

- Control of input power
- Soliton order N: 1~1.4



Summary

- Adiabatic soliton propagation in a dispersion-increasing fiber is a simple means in achieving spectral compression
- Positively chirped pulse provides better spectral compression ratio if dispersion ramp is too large
- Experiments for the first time: 350 fs chirped pulse in a 1-km DIF
  - Spectral compression ratio of 15.5
  - Temporal broadening
  - 30 nm of wavelength tuning ability



H.-P. Chuang and C.-B. Huang, Opt. Lett. **36**, 2848 (2011)

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