Maximizing the Bandwidth from Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers

Curtis R. Menyuk

based on the PhD dissertation of:

Dr. Jonathan Hu

now at Princeton University

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Maximizing the Bandwidth from Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers

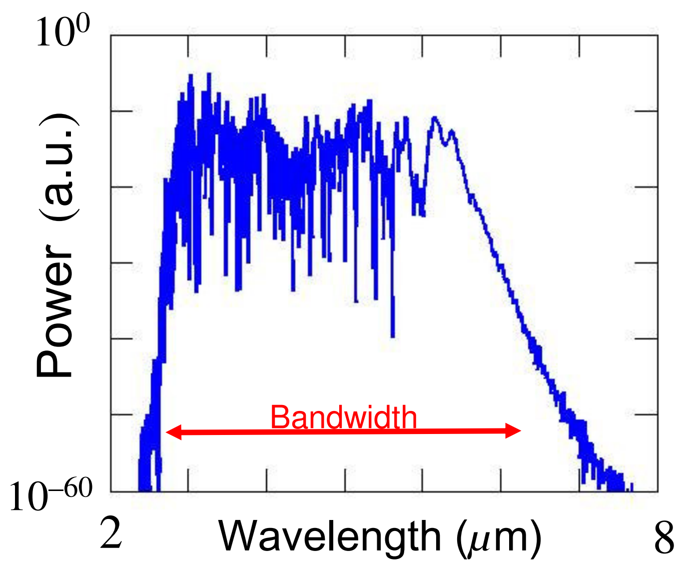
With:

Dr. L. Brandon Shaw, J. S. Sanghera,
and I. D. Aggarwal

at the Naval Research Laboratory

Project Goal

GOAL: *To make a broadband (2 – 10 μm) mid-IR source*



A mid-IR Light bulb

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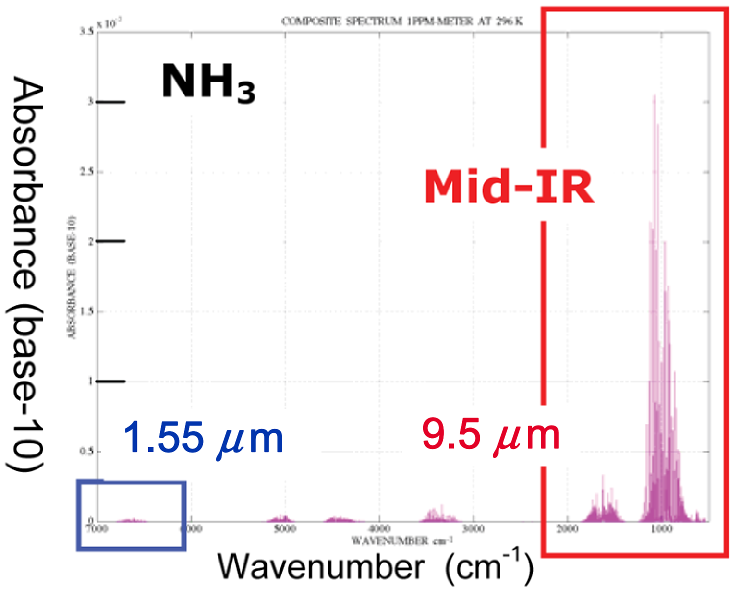
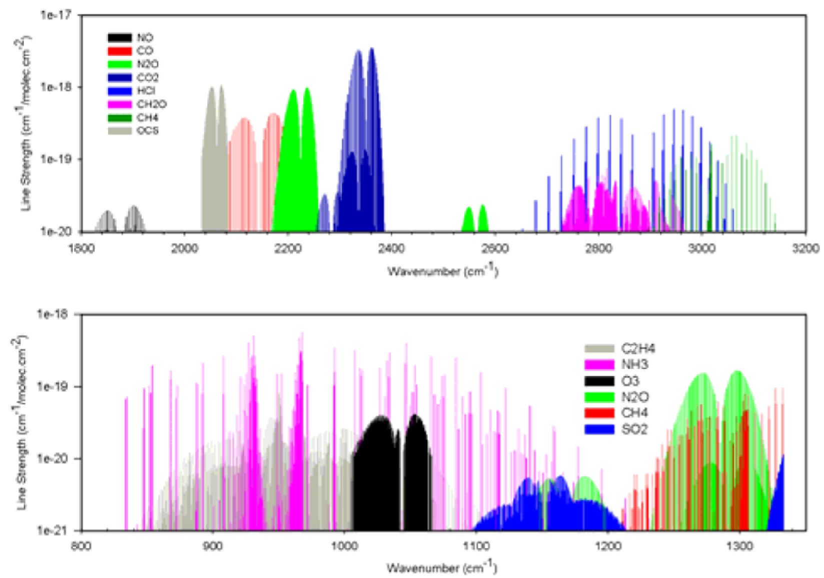
Why mid-IR sources?

Many important materials radiate or absorb in this range



Spectral response of ammonia



…And it is not alone!

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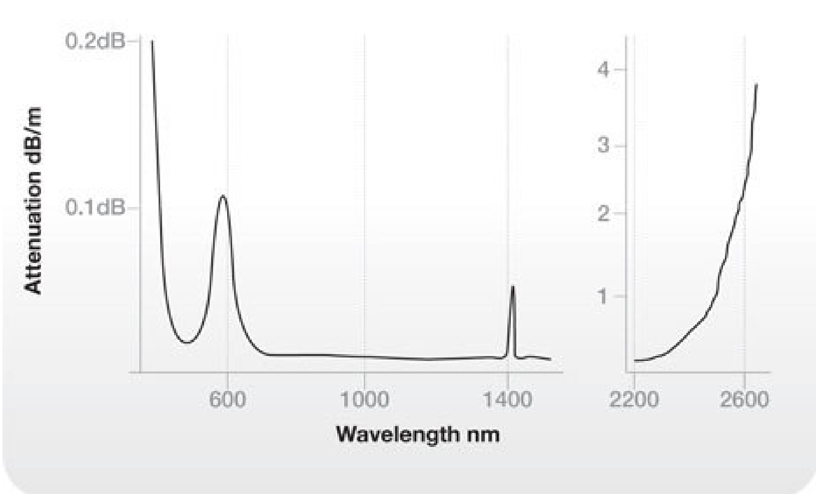
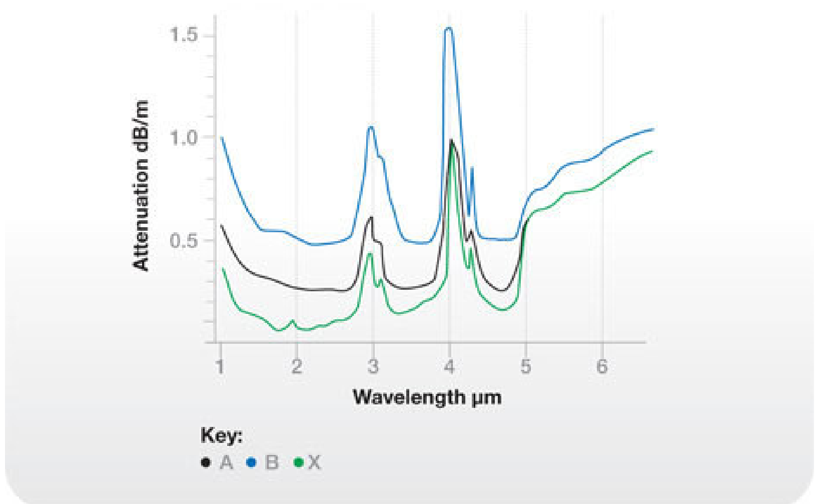
Why chalcogenide?





Attenuation in silica grows rapidly beyond 2.5 μm

Attenuation in the chalcogenides remains small beyond 10 μm

Source: Oxford Electronics
www.oxford-electronics.com

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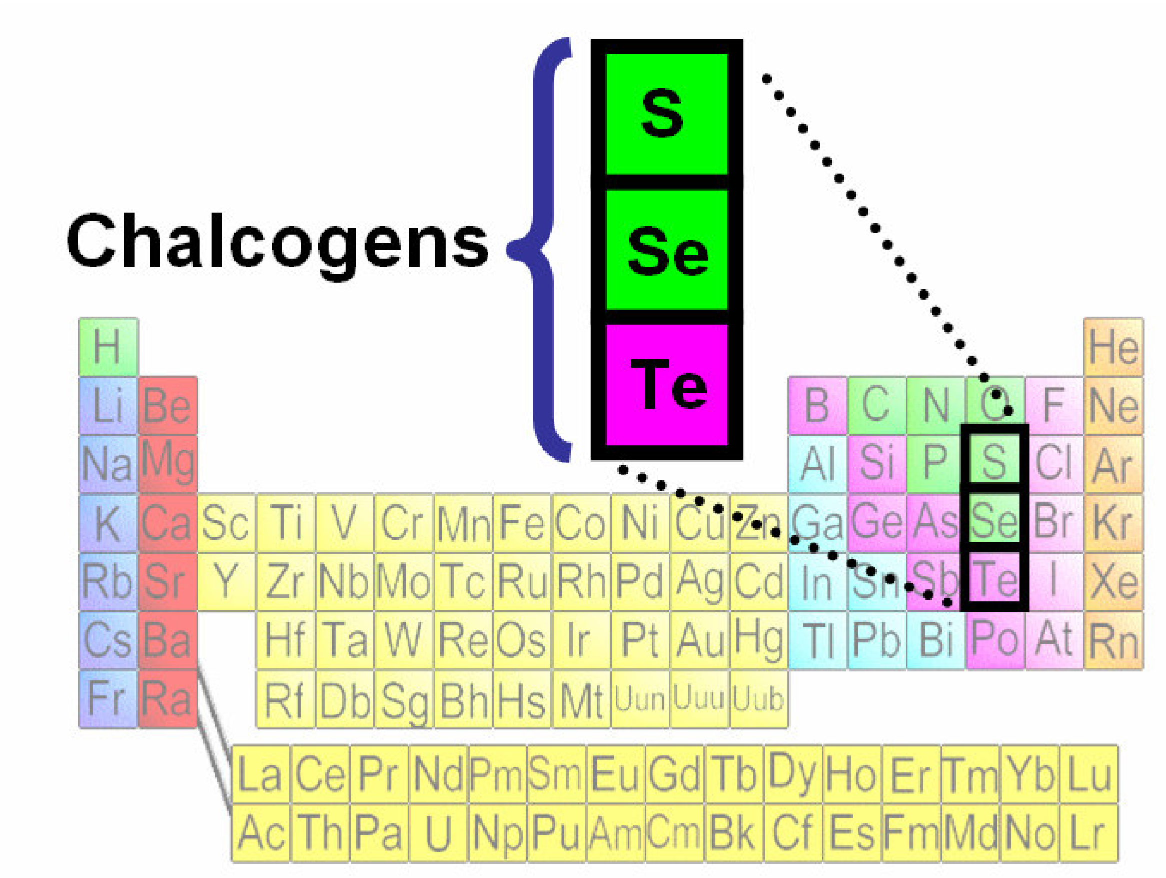
What is chalcogenide?



- glass is based on chalcogens mixed with As
- losses ~ 0.1 – 1 dB/m
- Kerr nonlinearity = 1000X silica fiber
- CW peak power = 50 – 125 kW/cm^2
- pulse peak power = 1 – 2 GW/cm^2

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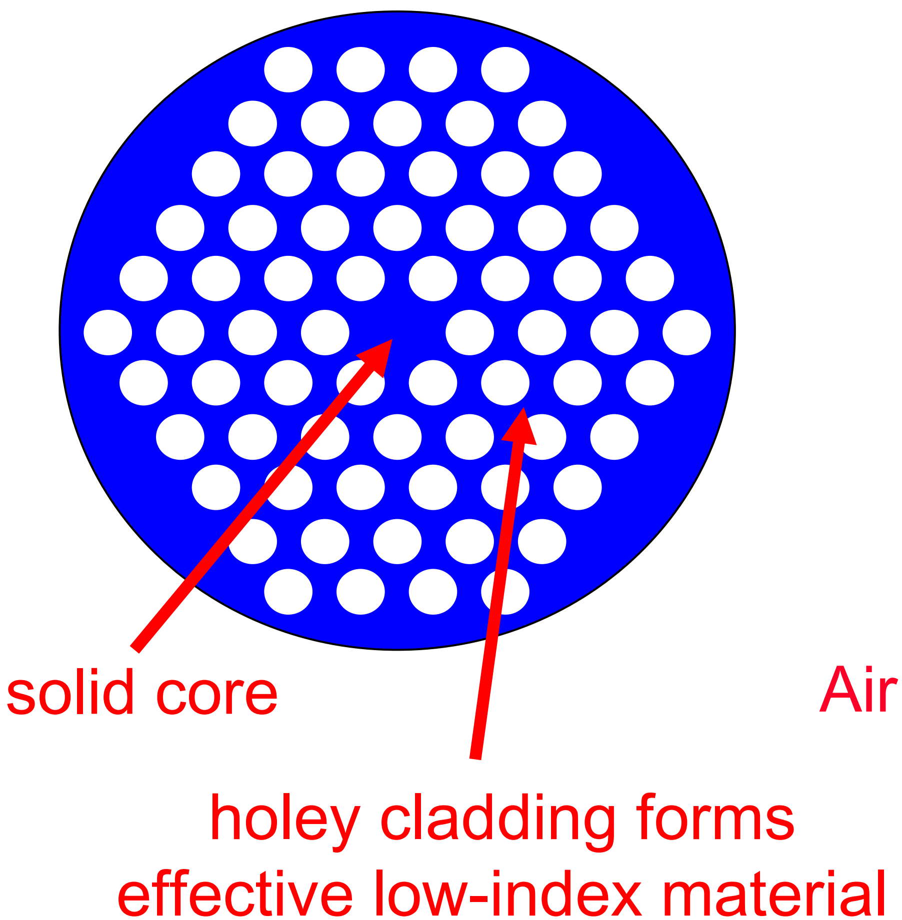
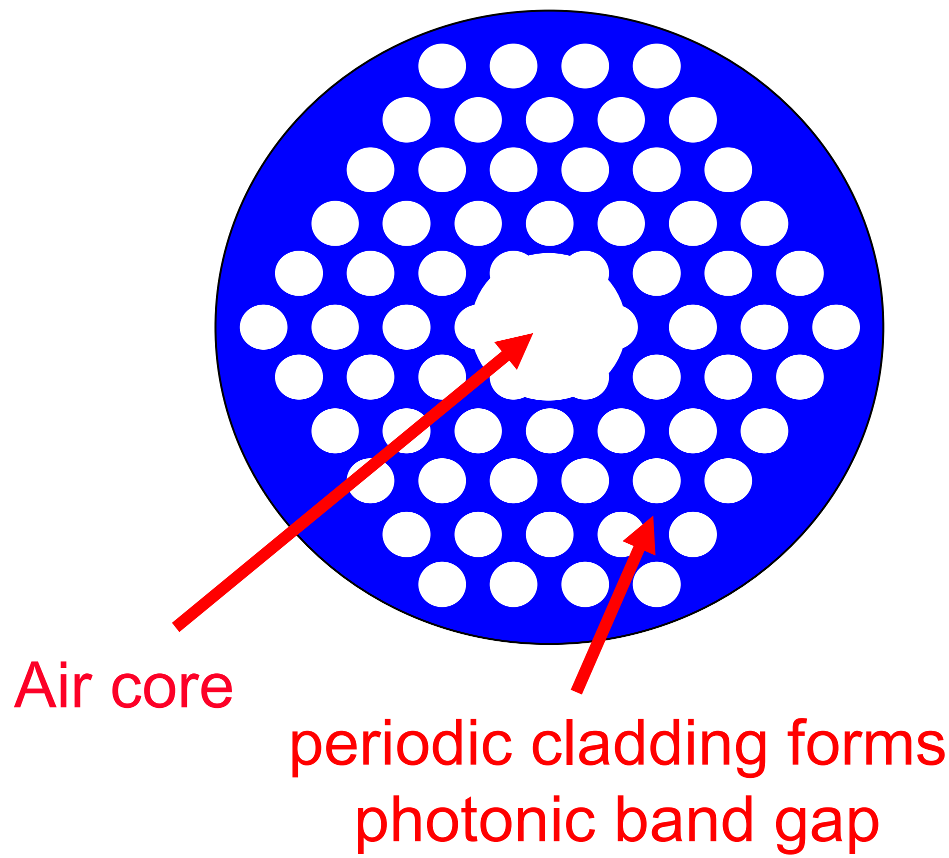
Photonic crystal fiber (PCF)

Solid-core PCF



Photonic bandgap fiber (PBGF)



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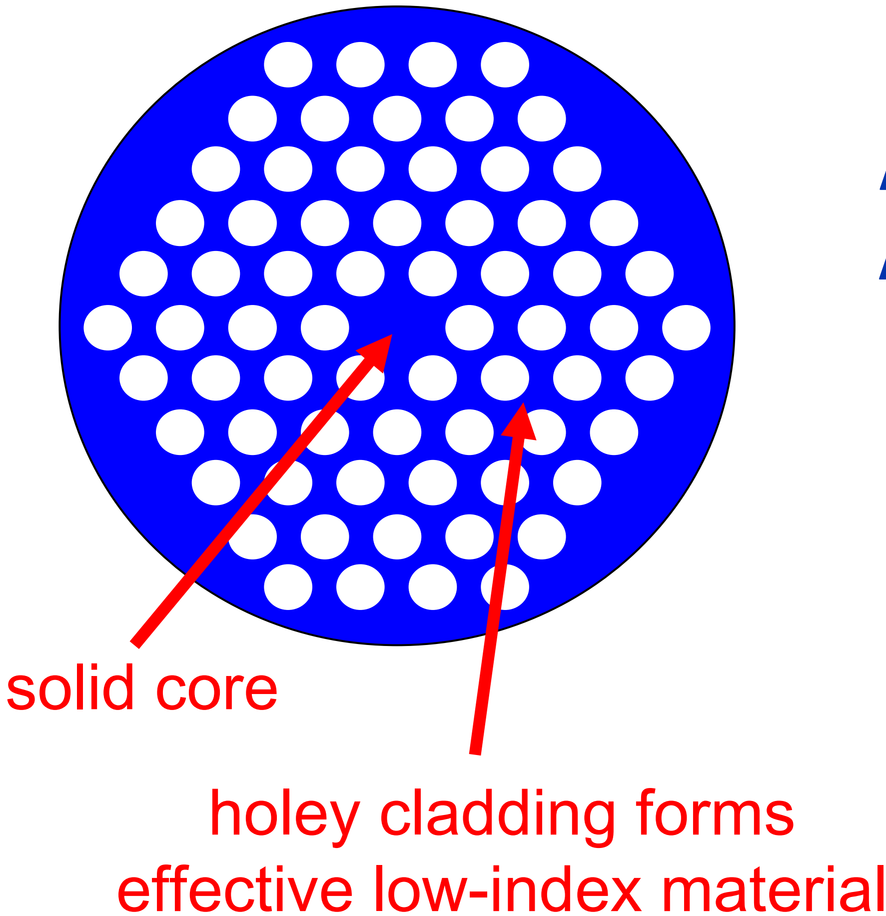
Photonic crystal fiber (PCF)

Solid-core PCF



We focus on solid-core PCFs to make use of the nonlinearity

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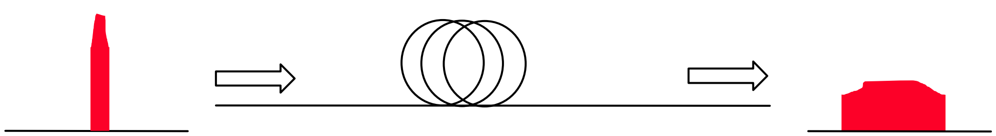
Supercontinuum generation

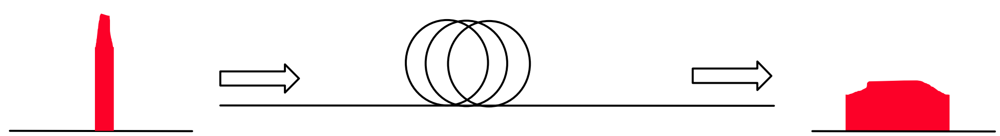
- Supercontinuum generation
  - ✓Kerr nonlinearity
  - ✓Raman effect
  - ✓Dispersion



It is a complicated, incoherent process!

Supercontinuum generation

- Supercontinuum generation
  - ✓Kerr nonlinearity
  - ✓Raman effect
  - ✓Dispersion



- Supercontinuum generation using photonic crystal fiber (PCF)[1]
  - ✓Wide single-mode region
  - ✓Enhanced nonlinearity
  - ✓Tailored dispersion

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[1]Dudley, *et al.,* Rev. Mod. Phys. **78,** 1135 (2006).

Supercontinuum generation

Supercontinuum generation in chalcogenide fibers is not the same as in silica fibers!

WHY?

- Different material properties
- There are no good sources beyond 2.5 – 3.0 μm

Our design goal is to increase the maximum wavelength of the spectrum as rapidly as possible!

[1]Dudley, *et al.,* Rev. Mod. Phys. **78,** 1135 (2006).

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Supercontinuum generation

Supercontinuum generation in chalcogenide fibers is not the same as in silica fibers!

A key finding:

supercontinuum generation proceeds in two stages

- Stage 1: four-wave mixing
- Stage 2: soliton self-frequency shift

Each stage should be as large as possible!

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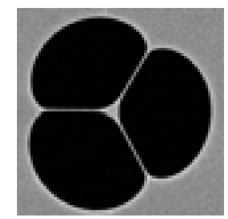
[1]Dudley, *et al.,* Rev. Mod. Phys. **78,** 1135 (2006).

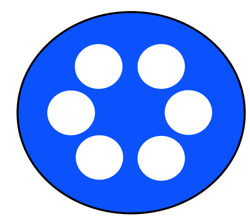
Prior work

- Delmonte, *et al.*[1] show experimental supercontinuum generation from 0.9 to 2.5 μm using a tellurite fiber with a wagon-wheel structure.



- Price, *et al.*[2] theoretically demonstrate supercontinuum generation from 2 to 4 μm using a bismuth glass fiber with a wagon-wheel structure.

- Shaw, *et al.*[3] show experimental supercontinuum generation from 2.1 to 3.2 μm in a As_2Se_3 based chalcogenide PCF with one ring of air holes.



[1]Delmonte, *et al.,* CLEO, CTuA4 (2006)
[2]Price, *et al.,* J. Sel. Topics Quantum Electron. **13,** 738 (2007).
[3]Shaw, *et al.*, Adv. Solid State Photonics TuC5 (2005)

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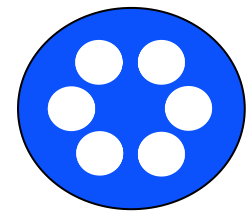
Model validation

- Shaw, *et al.*[1] show experimental supercontinuum generation from 2.1 to 3.2 μm in a As_2Se_3 based chalcogenide PCF with one ring of air holes.



We use the Shaw, et al. results to validate our model

[1]Shaw, *et al.*, Adv. Solid State Photonics, TuC5 (2005).

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Design criteria

Supercontinuum generation is a complicated process

BUT

there are general design criteria that work well

1. Design the fiber so that it is single-mode
   — increases the effective nonlinearity
2. Ensure that four-wave mixing is phase-matched with the largest possible Stokes wavelength
   — Rapidly moves energy to a large wavelength
3. Make the second zero dispersion wavelength as large as possible
   — Allows the soliton self-frequency shift to go to long wavelengths

A specific example

Fixed fiber and pulse features

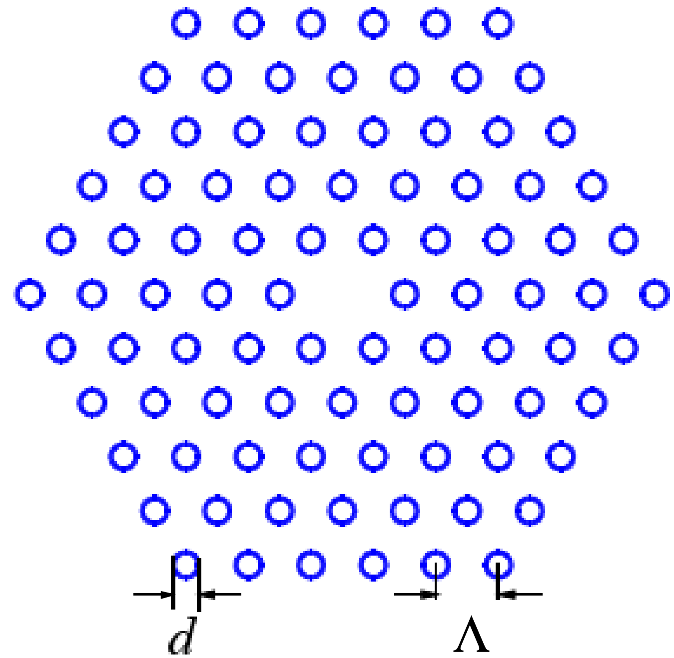
- As_2Se_3 fiber
- Five-ring hexagonal structure
- A pump wavelength of 2.5 μm

Fiber parameters to vary:

- Air-hold diameter (d)
- Pitch (Λ)

Pulse parameters to vary:

- Peak power
- Pulse duration



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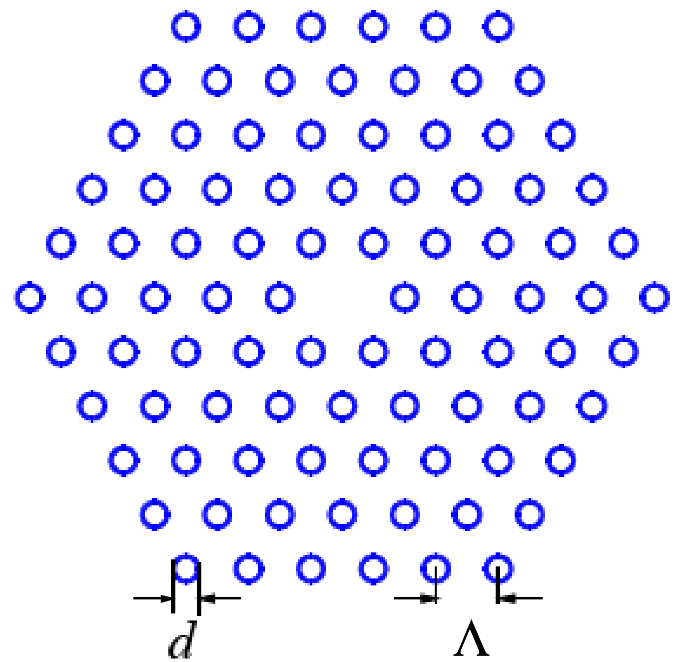
A specific example

Needed fiber quantities
(experimentally determined)

- Kerr coefficient
- Raman gain
- Material dispersion

Needed fiber quantities (calculated)

- Total Raman response
  - — calculated once
- Total dispersion
  - — calculated for each set of fiber parameters



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Generalized nonlinear Schrödinger equation (GNLS)

In principle: We can optimize by solving the GNLS for a broad set of fiber and pulse parameters

$$\frac{\partial A(z,t)}{\partial z} - i\mathrm{IFT}\left\{\left[\beta(\omega_0+\Omega)-\beta(\omega_0)-\Omega\beta'(\omega_0)\right]\tilde{A}(z,\Omega)\right\}$$
$$= i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left[A(z,t)\int_{-\infty}^{t} R(t')\left|A(z,t-t')\right|^2 dt'\right]$$

$A(z,t)$: Electric field envelope

β : Propagation constant

$\gamma = n_2\omega_0/(cA_{\mathrm{eff}})$: Kerr coefficient

$$R(t) = \underbrace{(1-f_R)\delta(t)}_{\text{Kerr effect}} + \underbrace{f_R h_R(t)}_{\text{Raman effect}}$$

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Generalized nonlinear Schrödinger equation (GNLS)

In practice: We use our design criteria to reduce the labor

In any case: We must solve the GNLS for a broad enough parameter set to verify the design criteria

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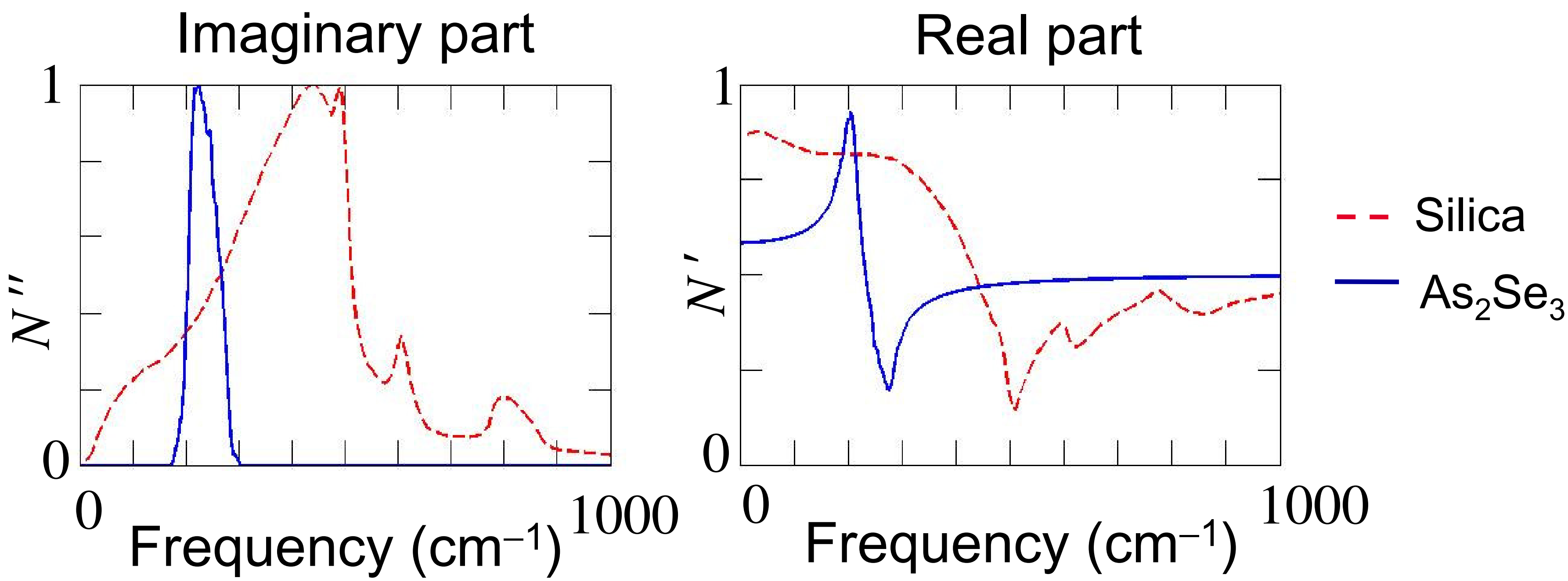
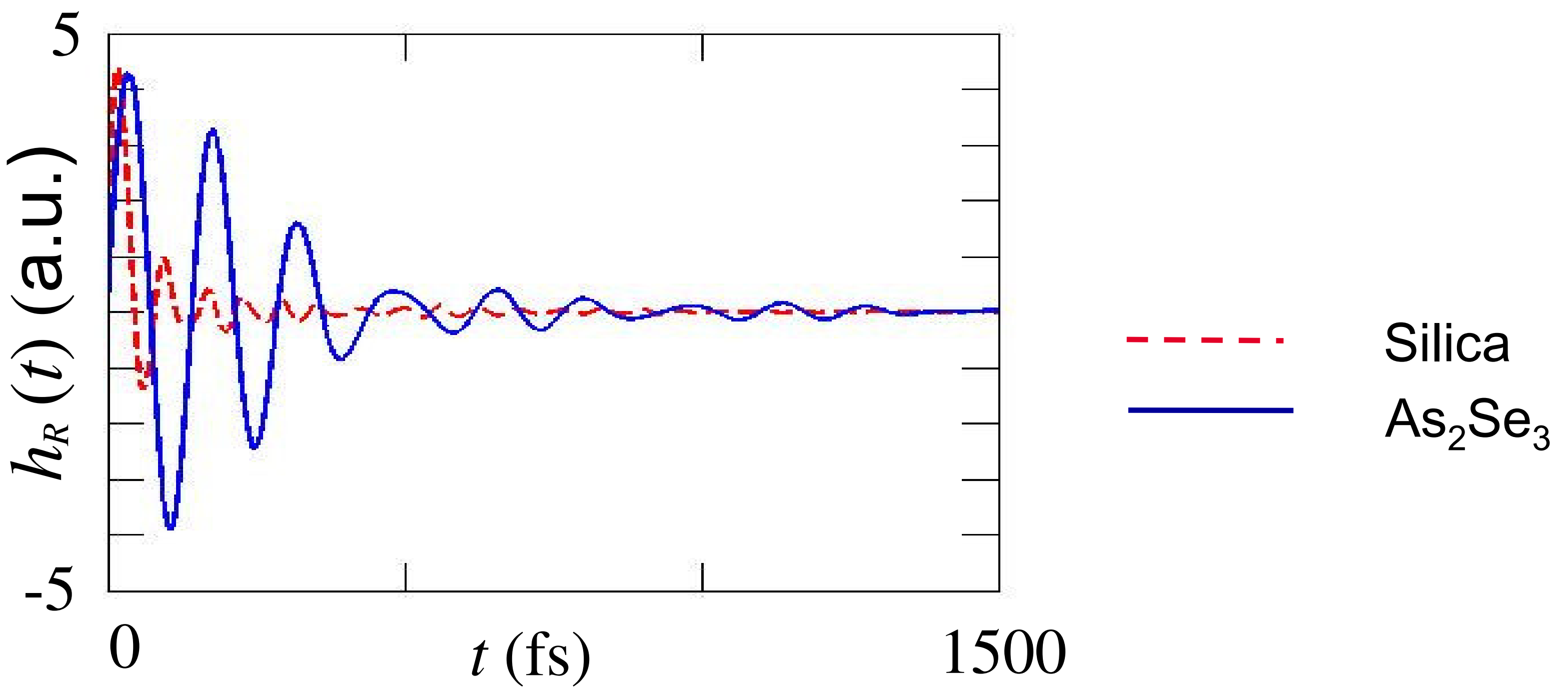
Third-order susceptibility



The real part is obtained by a Hilbert transform of the imaginary part (Kramers-Kronig relation)

Raman response function



Chalcogenide fiber has a longer response time than silica fiber

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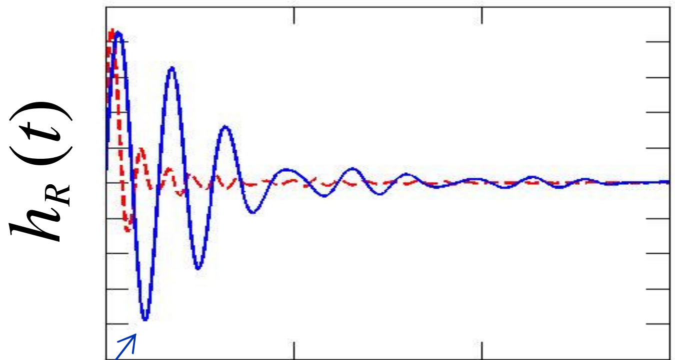
Raman gain and Raman response function

$$R(t) = \underbrace{(1 - f_R)\delta(t)}_{\text{Kerr effect}} + \underbrace{f_R h_R(t)}_{\text{Raman effect}}$$

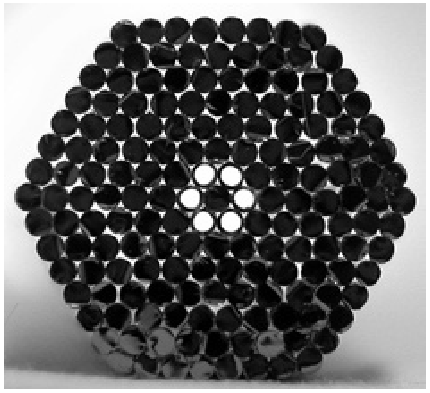


$$\underbrace{g(\Omega)}_{\text{Raman gain}} = (2\underbrace{\omega_p}_{\text{Pump frequency}} / c) n_2 \underbrace{f_R}_{\text{Raman fraction of the nonlinearity}} \mathrm{Im}\left[\mathrm{FFT}(h_R(t))\right] \Longrightarrow f_R \approx 0.1$$

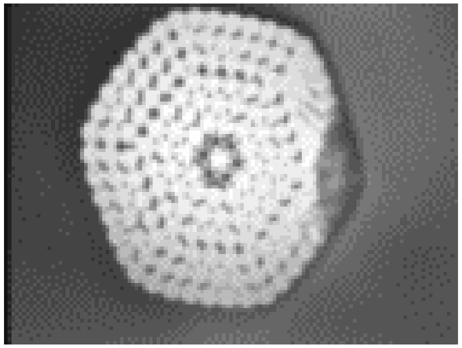
[1]Stolen, *et al.*, J. Opt. Soc. Am. B **6**, 1159 (1989).
[2]Slusher, *et al.*, J. Opt. Soc. Am. B **21**, 1146 (2004).

Fiber geometry

Experiment[1]

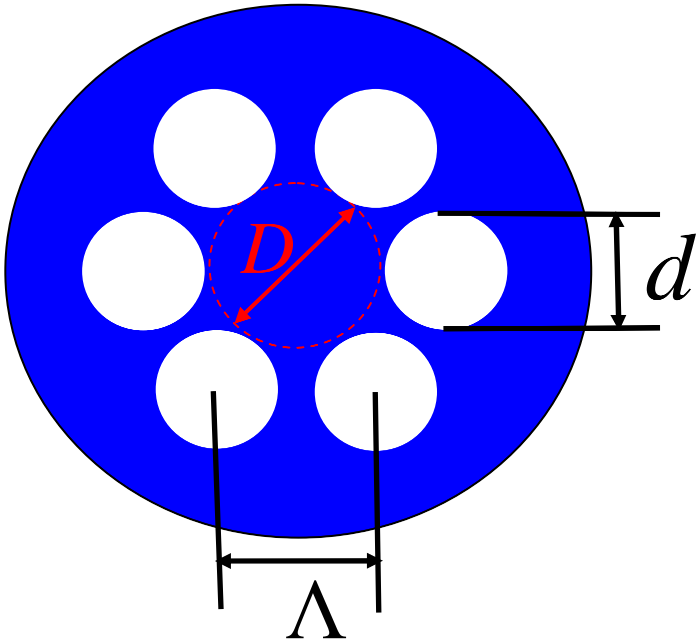


Preform



PCF

Simulation



$D = 10\ \mu$m

$d/\Lambda = 0.8$

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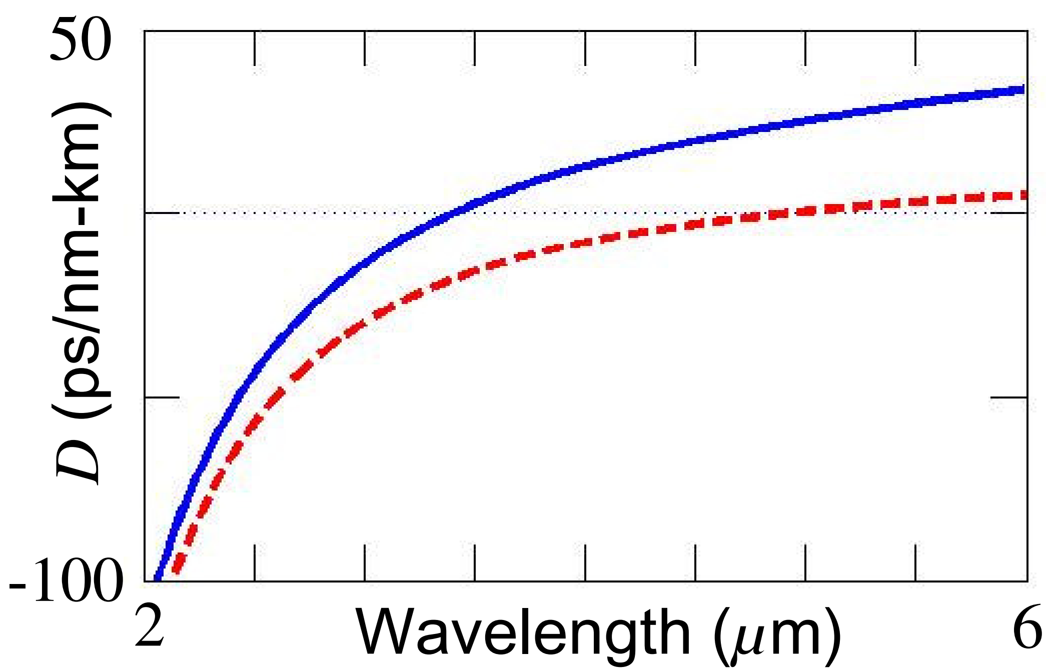
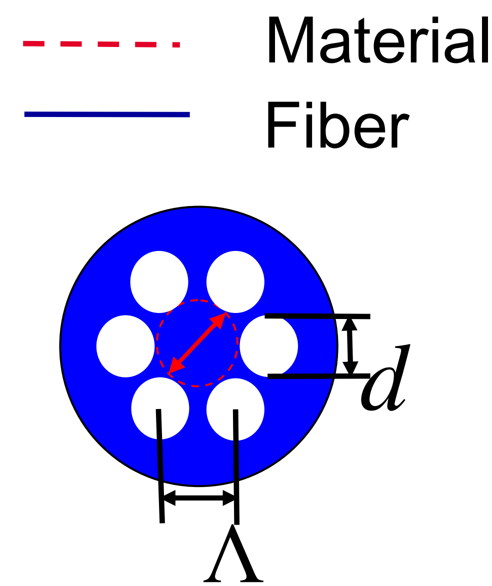
[1]Shaw, *et al.*, Adv. Solid State Photonics, TuC5 (2005)

Dispersion





$D = 10\ \mu\text{m}$

$d/\Lambda = 0.8$

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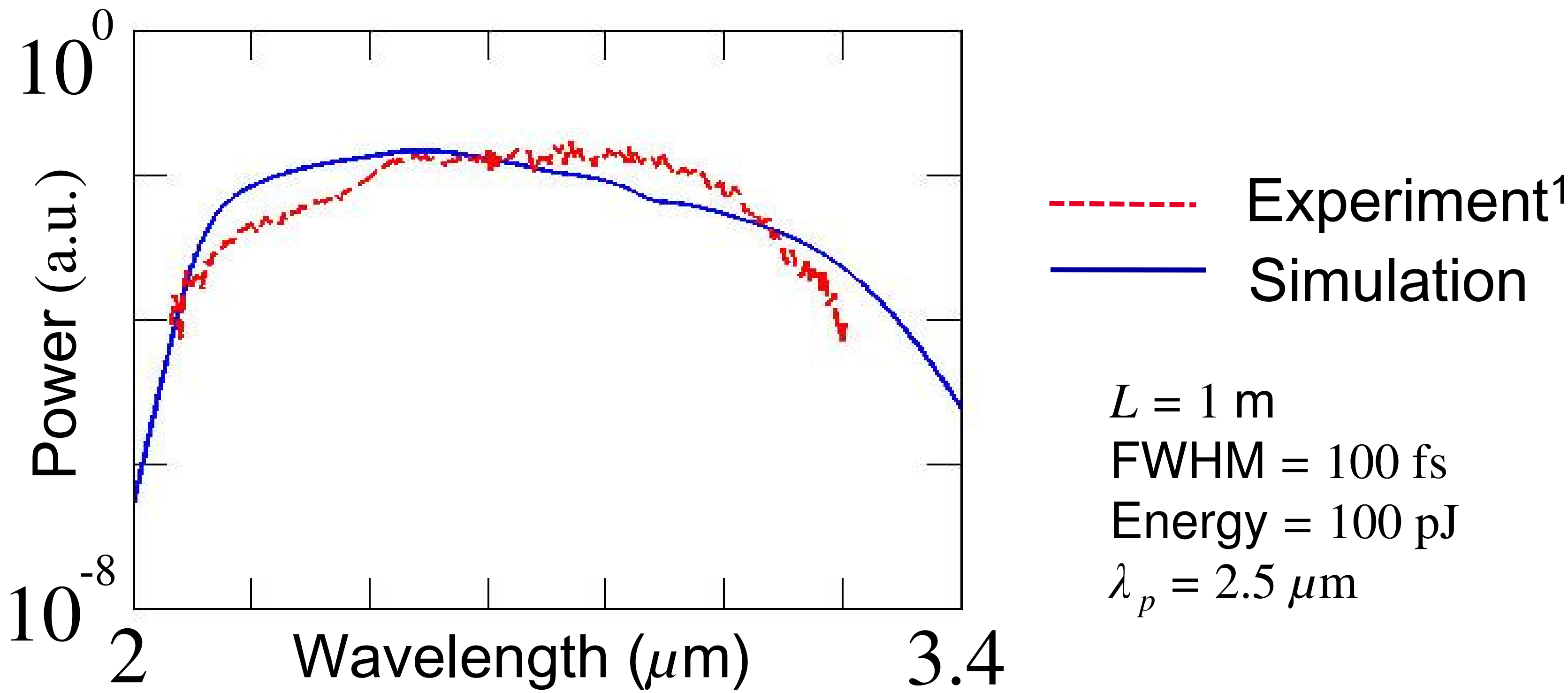
Supercontinuum generation



L = 1 m
FWHM = 100 fs
Energy = 100 pJ
λ_p = 2.5 μm

Measured nonlinear response can completely account for the supercontinuum generation

[1]Shaw, *et al.*, Adv. Solid State Photonics, TuC5 (2005)

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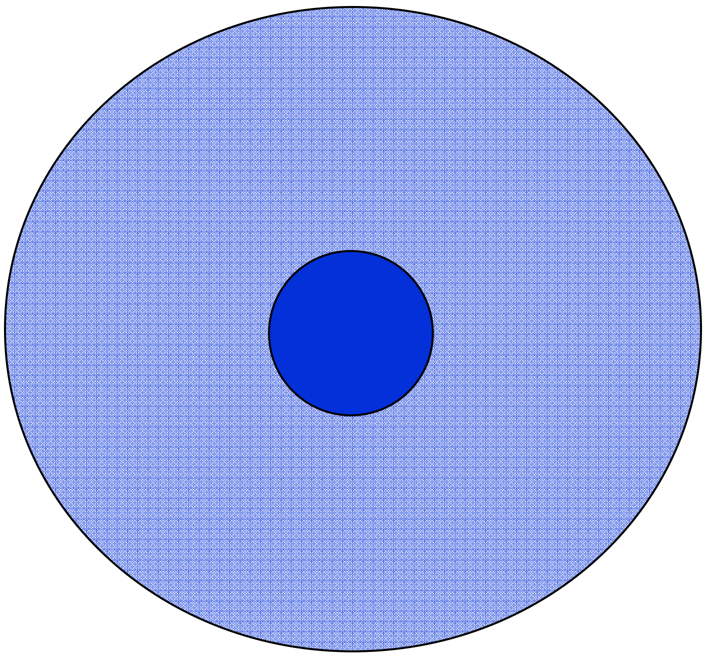
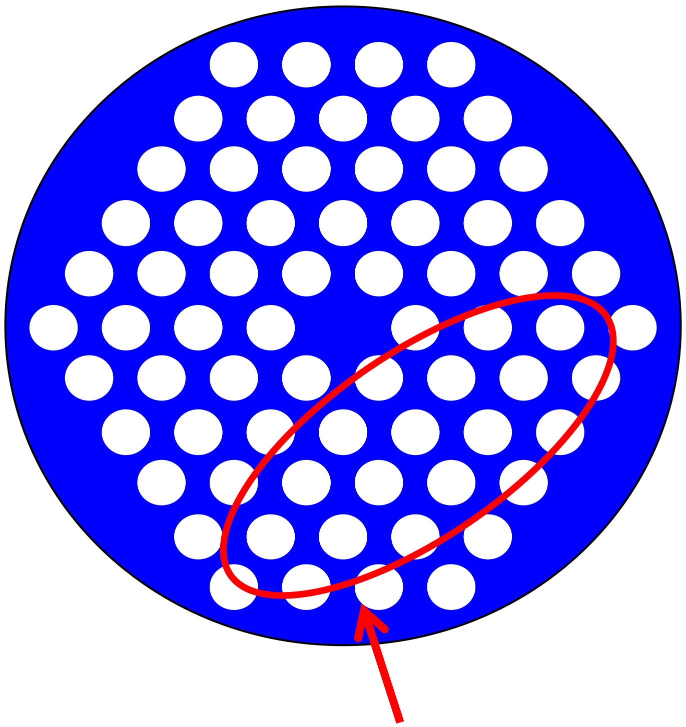
Single-mode analysis

Step-index fiber



$$V = \frac{2\pi}{\lambda} a \sqrt{n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2}$$

Solid-core PCF



Fundamental space-filling mode

n_{FSM}

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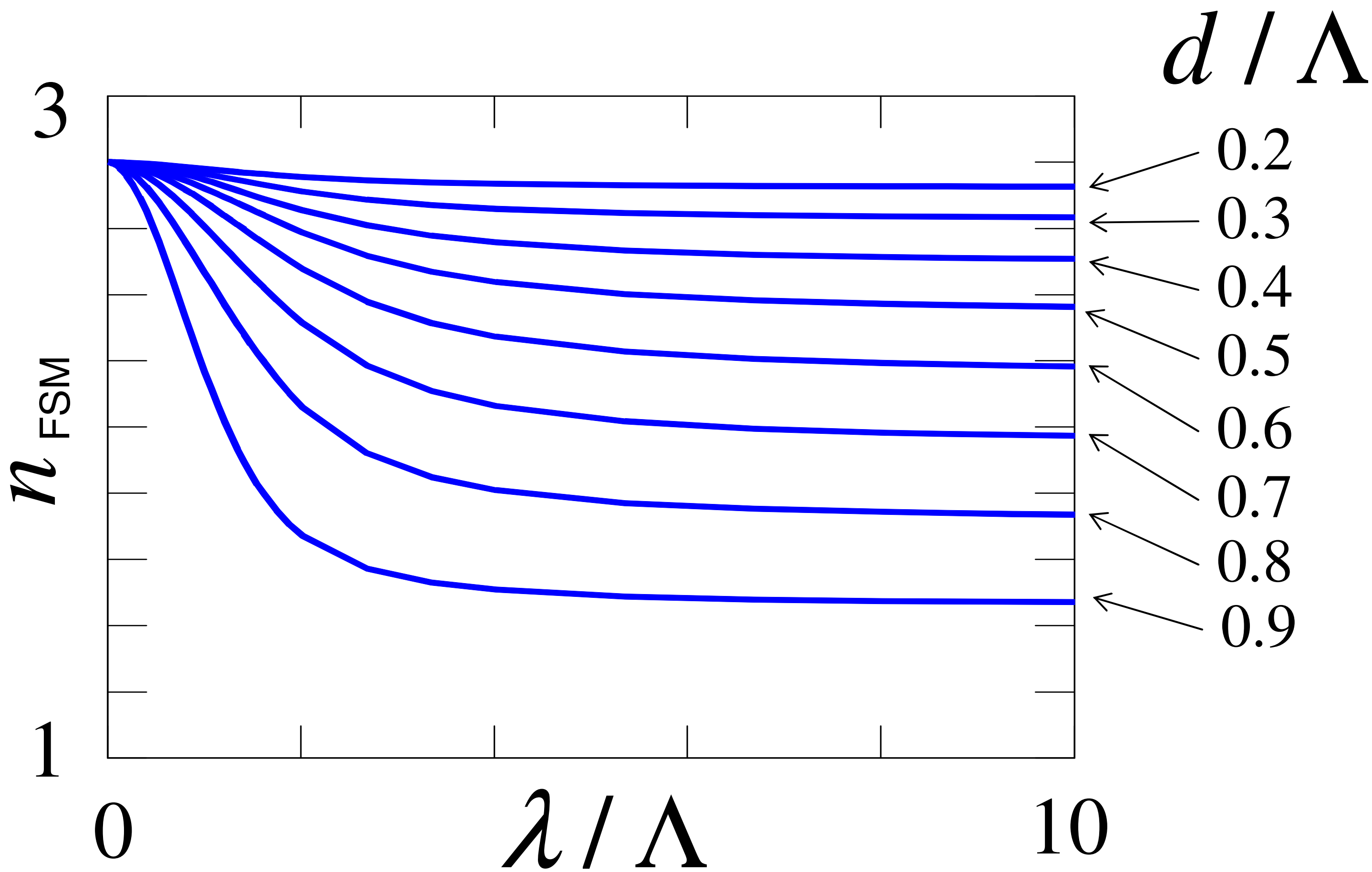
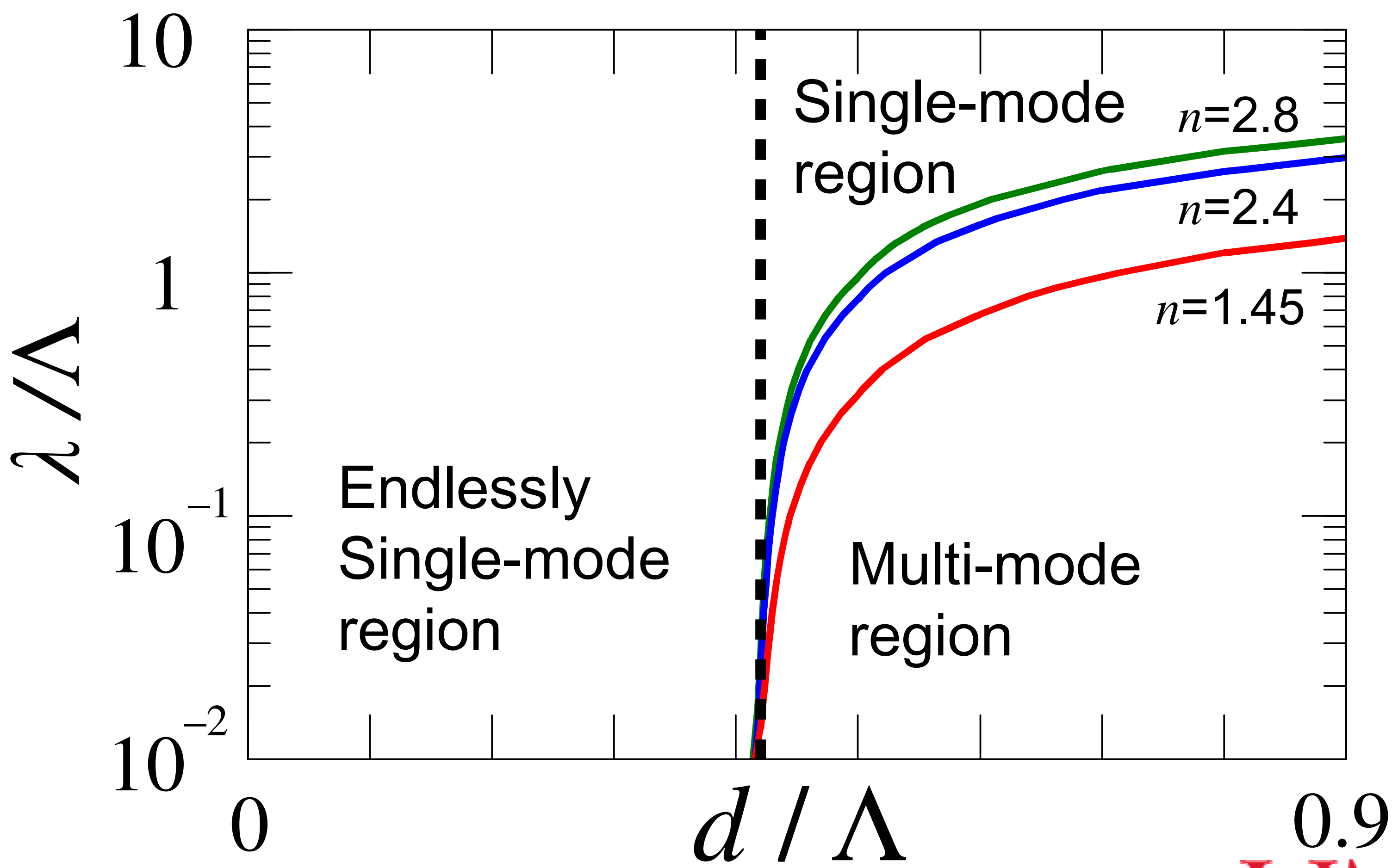
Fundamental space-filling mode



Endlessly single-mode region



Endlessly single-mode region

What we learned:

When $d / \Lambda = 0.4$, the fiber is single mode

AND

We have the best mode confinement.

We set $d / \Lambda = 0.4$ from this point on.

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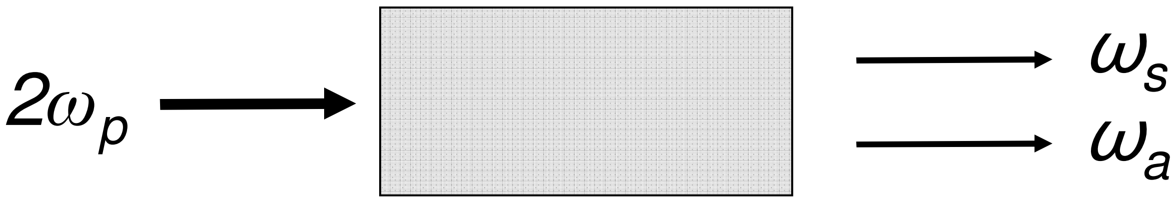
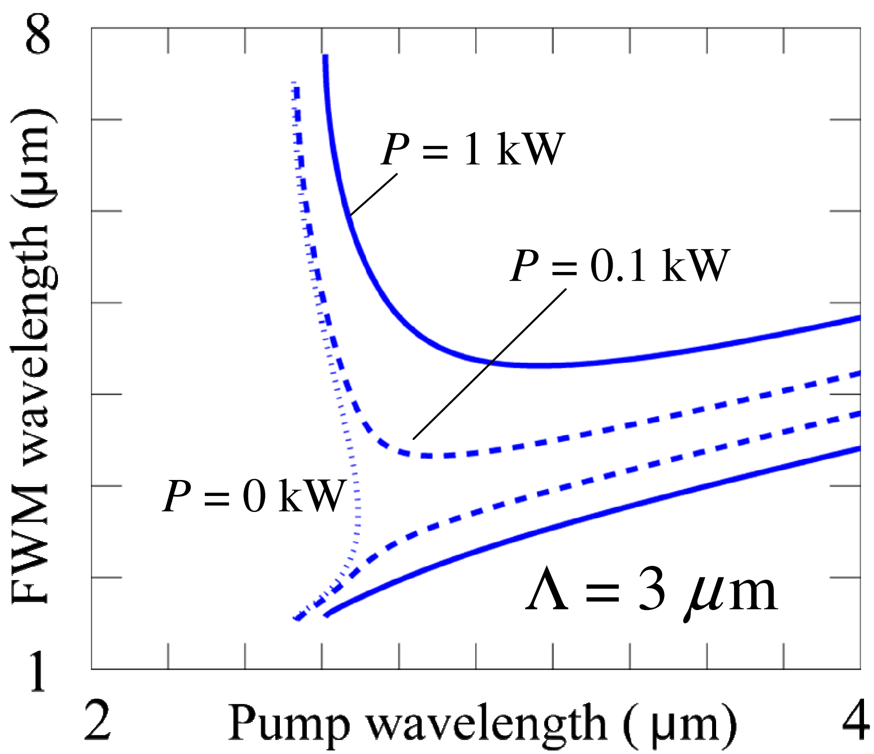
Four-wave mixing (FWM)

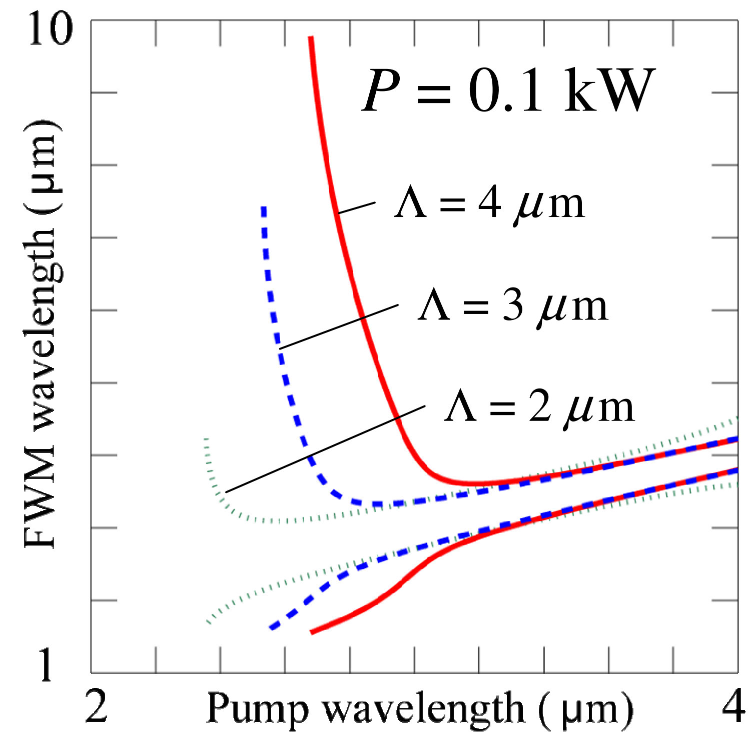


Phase-matching condition

$$(n_s\omega_s + n_a\omega_a - 2n_p\omega_p)/c + 2(1 - f_R)\gamma P_p = 0$$

FWM wavelength





At $P = 0.1$ kW, $\Lambda = 3\ \mu$m gives a large Stokes wavelength

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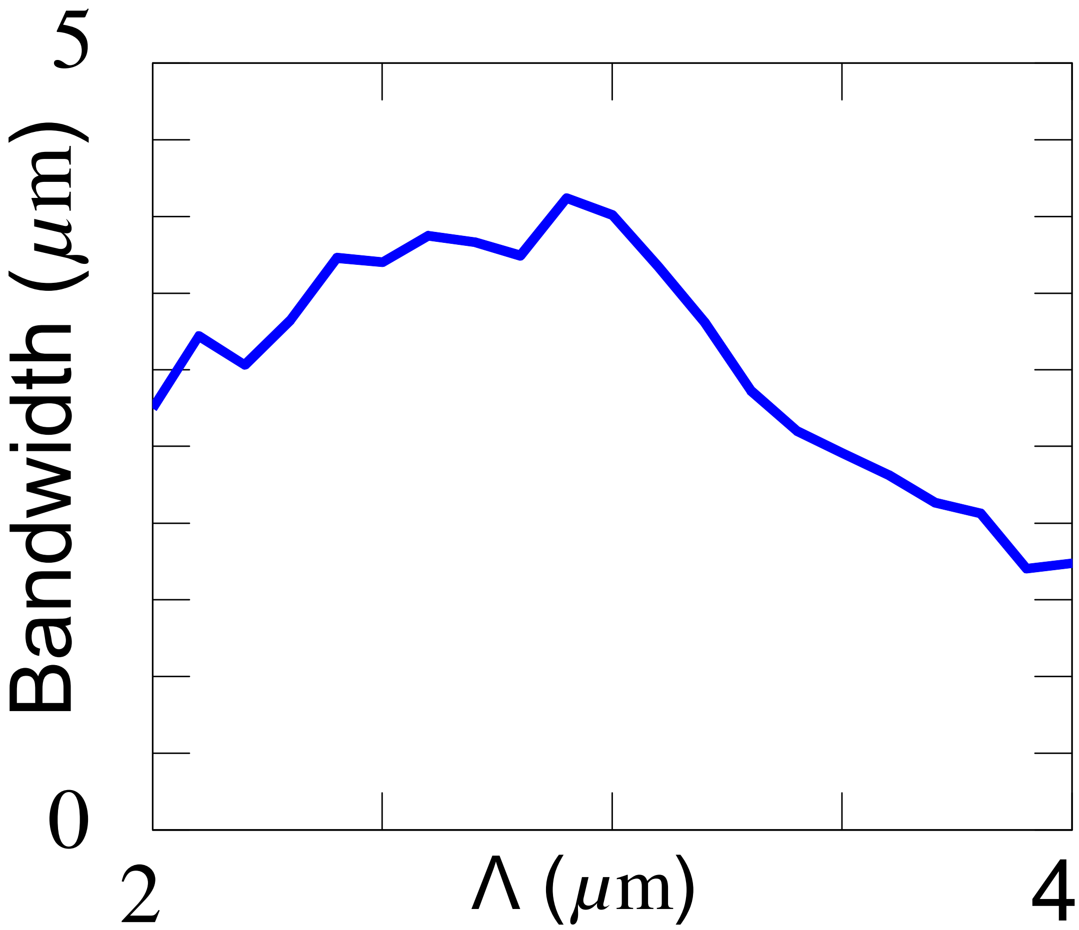
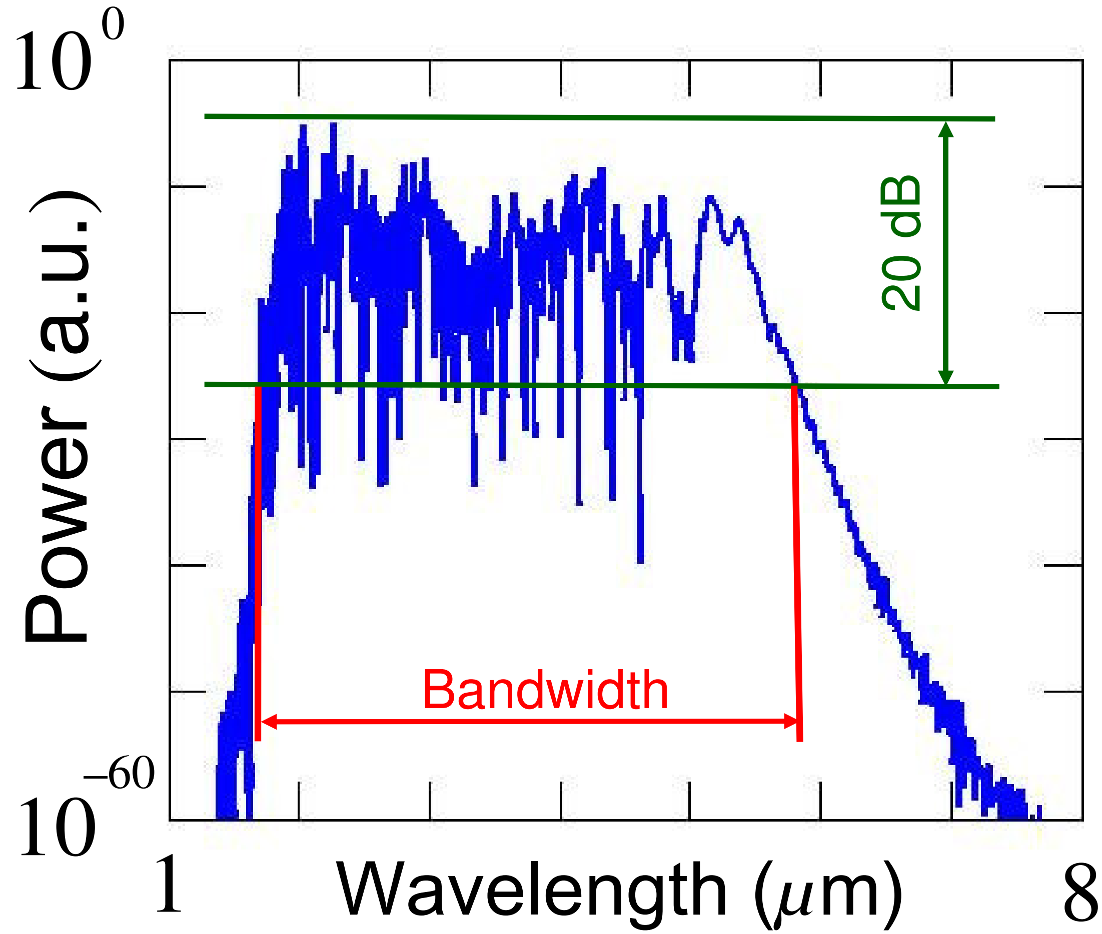
Bandwidth as a function of pitch



Output spectrum



L = 0.1 m
FWHM = 500 fs
d/Λ= 0.4
Λ = 3 μm

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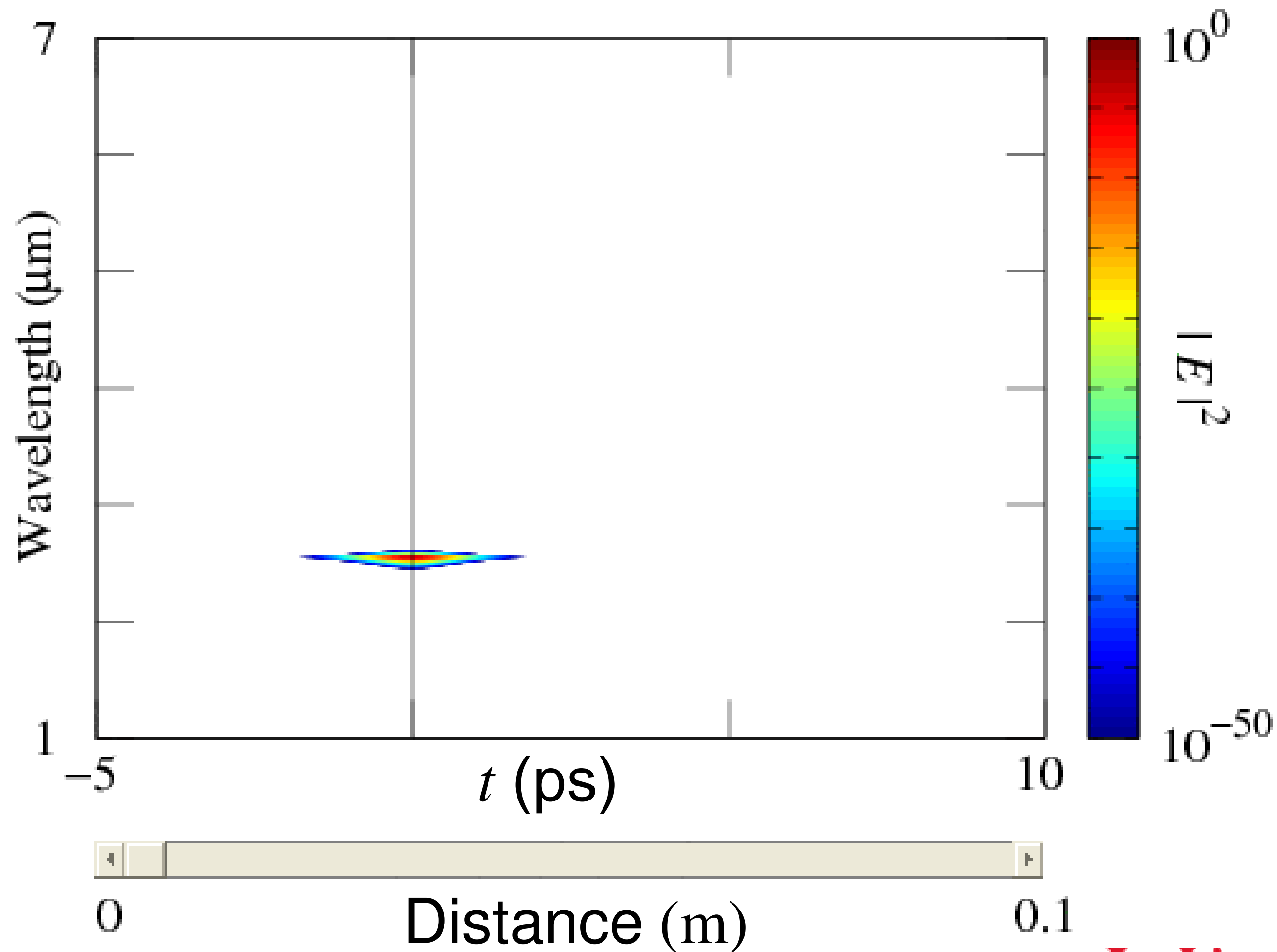
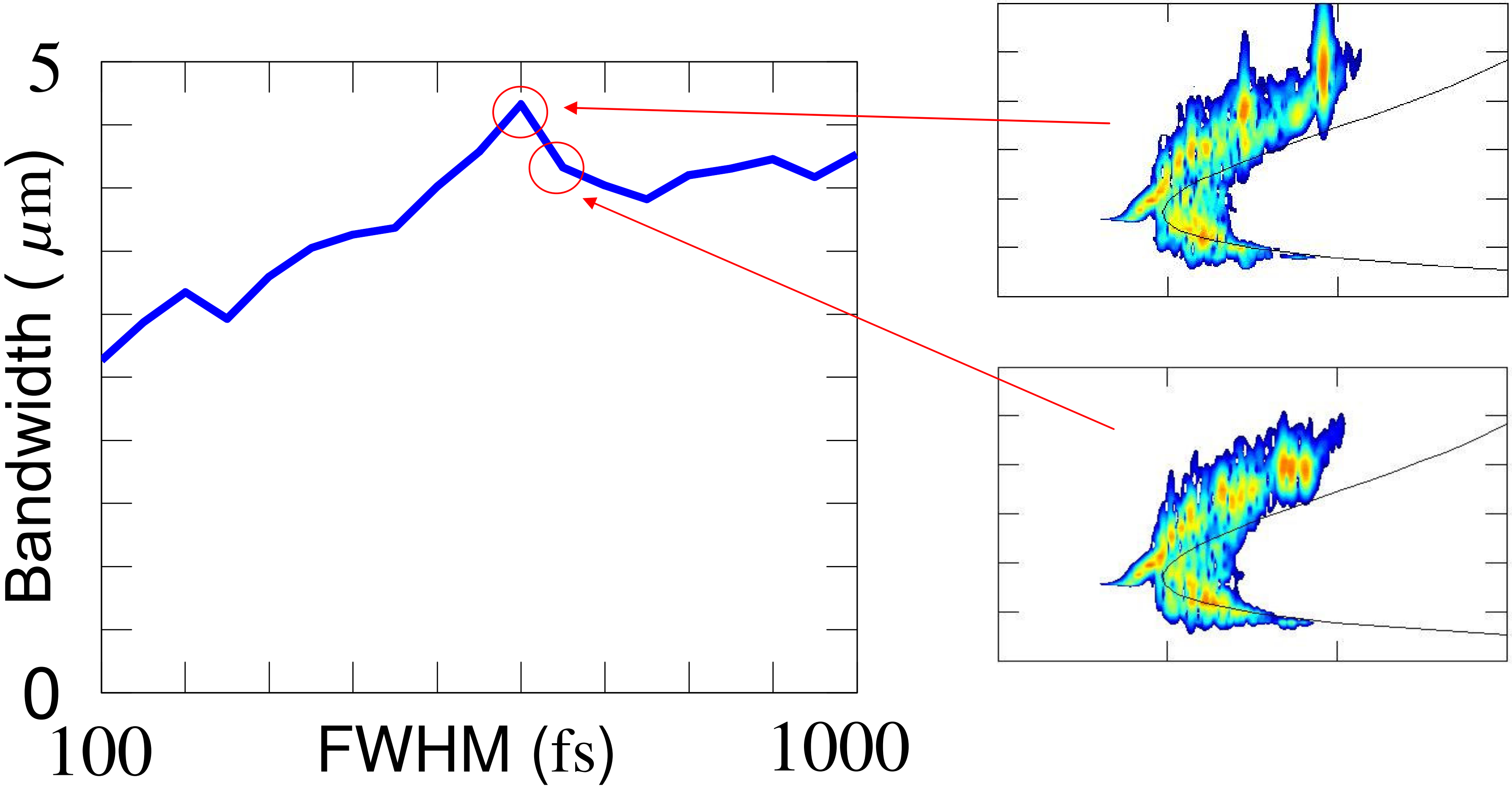
Spectrogram



Bandwidth as a function of input pulse width



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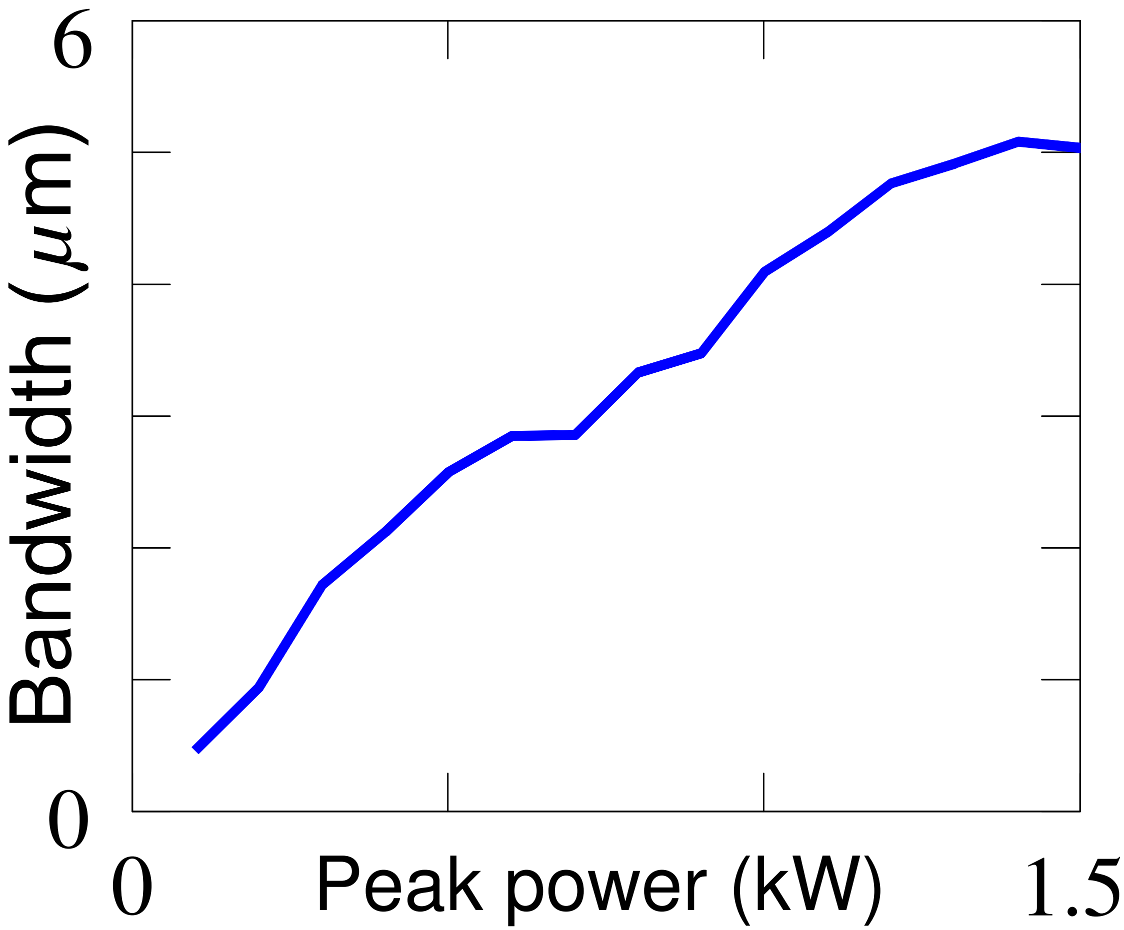
Bandwidth as a function of input peak power



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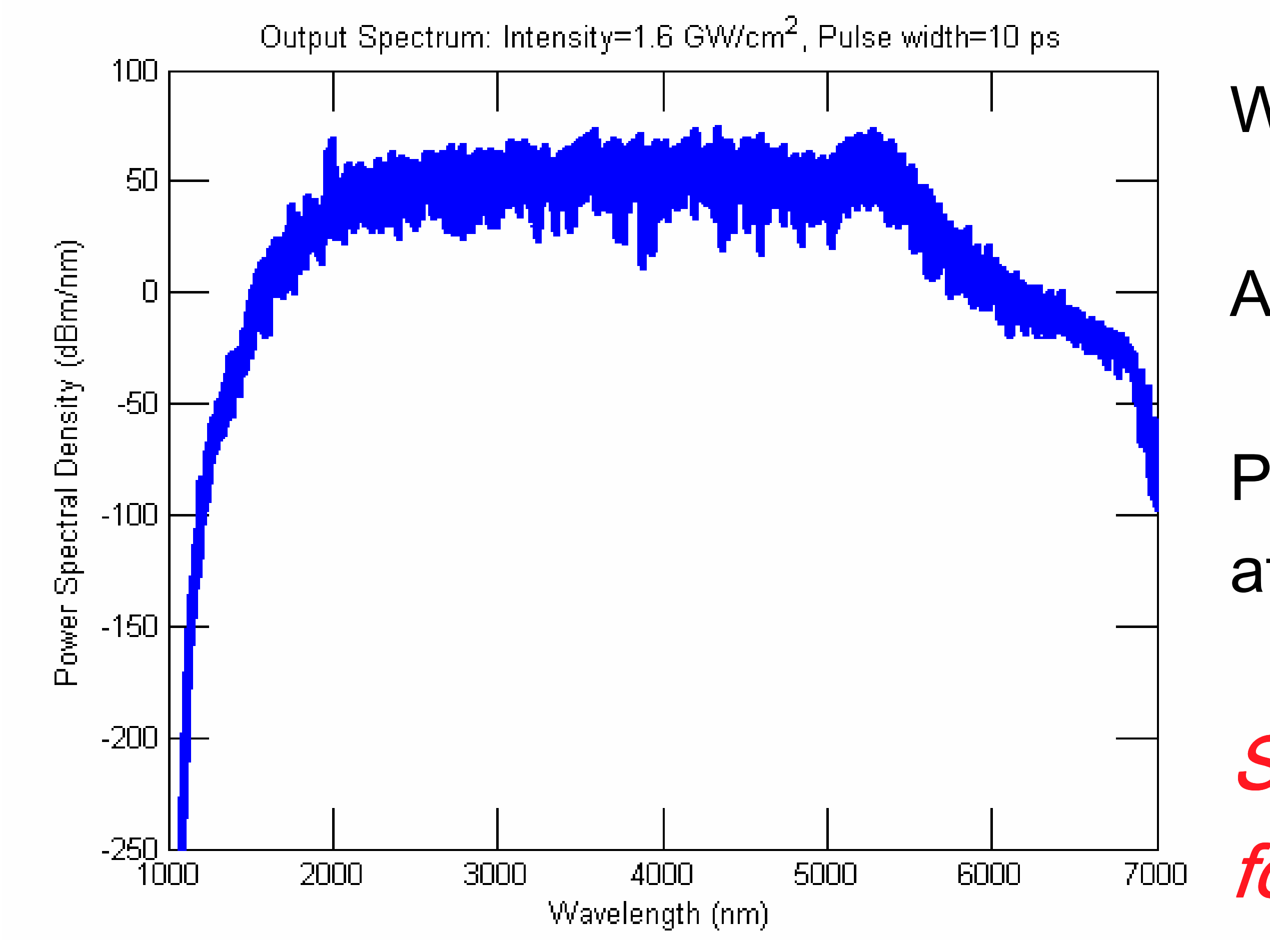
Application of this approach to other fibers



Weiblen, *et al.*

As_2S_3 fiber

Presented at CLEO 2010

Stay tuned for more!

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Conclusions

- We have developed a design approach that allows us to maximize the supercontinuum bandwidth in chalcogenide fibers

- We showed that a bandwidth of 4 μm can be generated using an As_2Se_3 PCF with d/Λ = 0.4 and Λ = 3 μm at a pump wavelength of 2.5 μm

- This same approach can be applied to a wide variety of chalcogenide fibers.

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Thank you!

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