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Maximizing the Bandwidth While Minimizing the Spectral Fluctuations Using Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers

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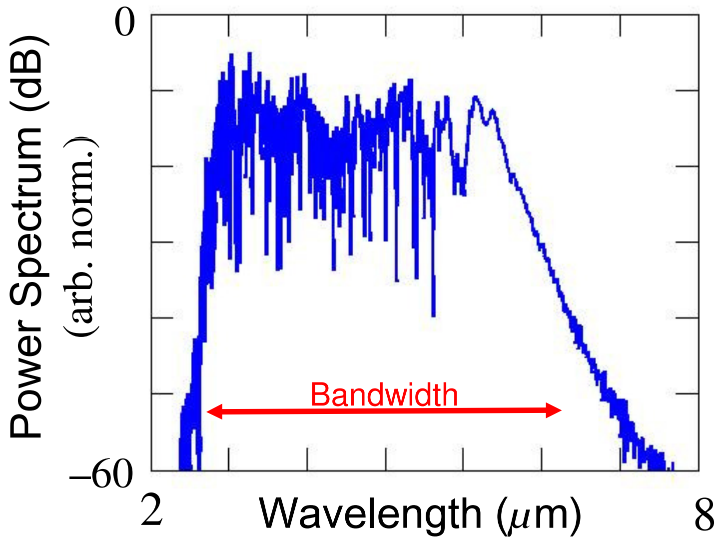
Project Goal

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



A mid-IR Light bulb

…while smoothing the spectral profile

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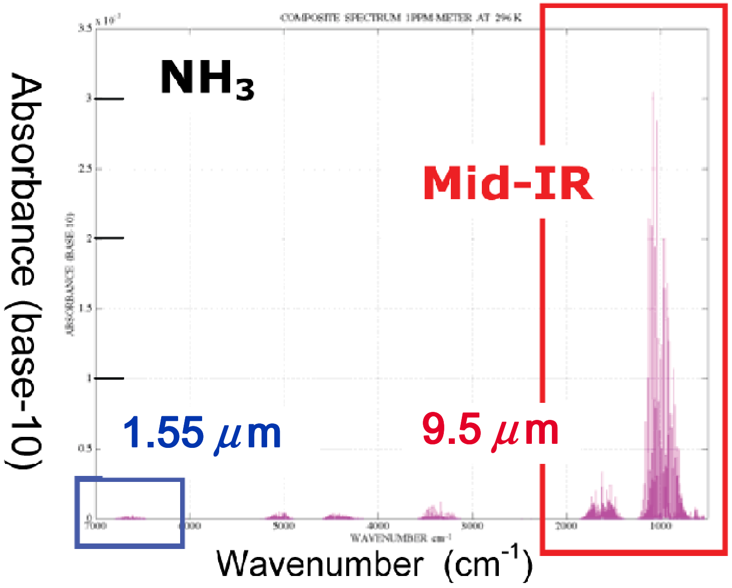
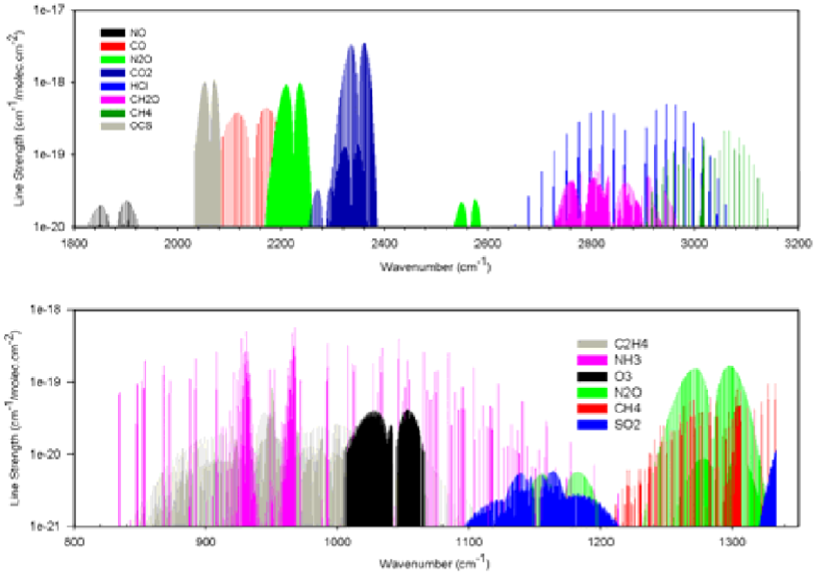
Why mid-IR sources?

Many important materials radiate or absorb in this range

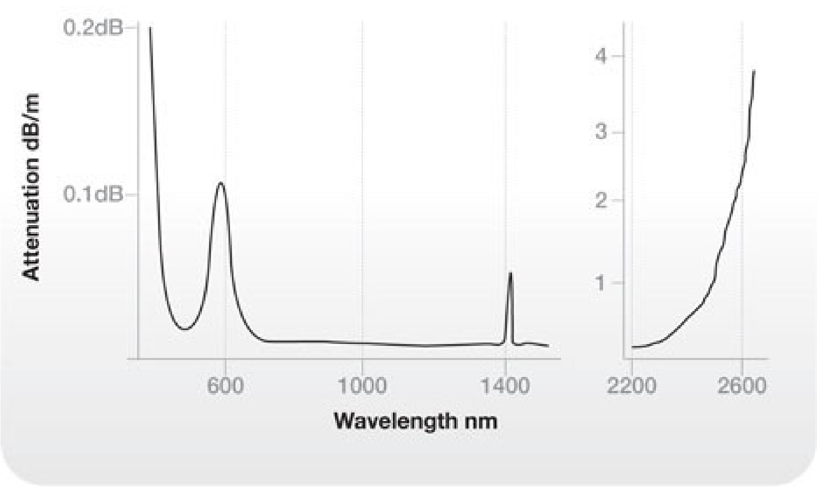




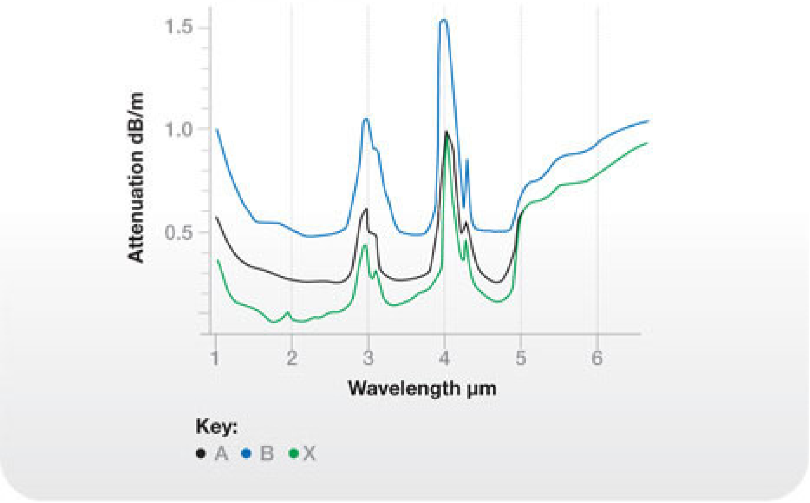
Spectral response of ammonia

…And it is not alone!

Why chalcogenide?



Attenuation in silica grows rapidly beyond 2.5 μm

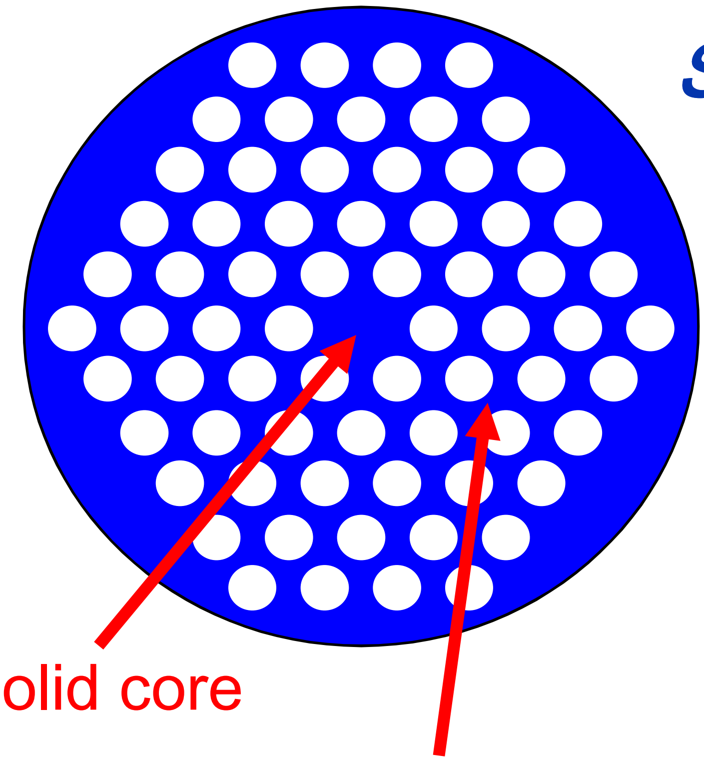


Attenuation in the chalcogenides remains small beyond 10 μm

Source: Oxford Electronics
www.oxford-electronics.com

Photonic crystal fibers (PCF)

Solid-core PCF



solid core

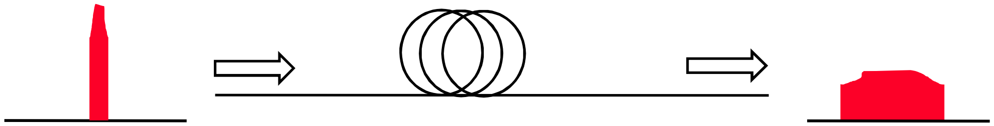
holey cladding forms
effective low-index material

Solid core PCFs allow us to:

- *design "endlessly single-mode" fibers*
- *make use of the nonlinearity*

Supercontinuum generation

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

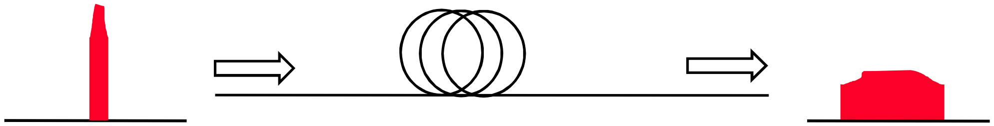


It is a complicated process!

…that produces a noise-like spectrum!!

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

We must move the energy from short to long wavelengths!

[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!

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!

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

Design criteria

Supercontinuum generation is a complicated process

BUT

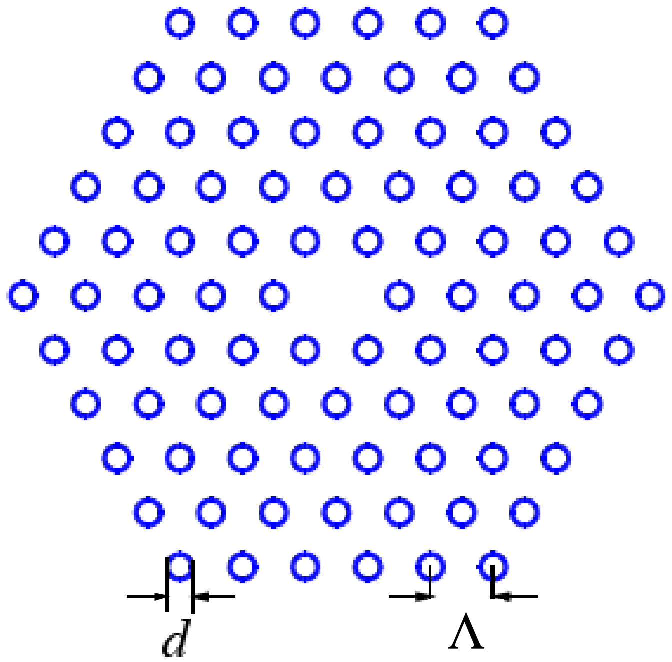
there are general design criteria that work well

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

Three Example Designs

Fixed fiber and pulse features

- (1) As_2Se_3 fiber; 2.5 μm pump
  (2) As_2S_3 fiber; 2.0 μm pump
  (3) As_2S_3 fiber; 2.8 μm pump
- Five-ring hexagonal structure



Fiber parameters to vary:

- Air-hole diameter (d)
- Pitch (Λ)

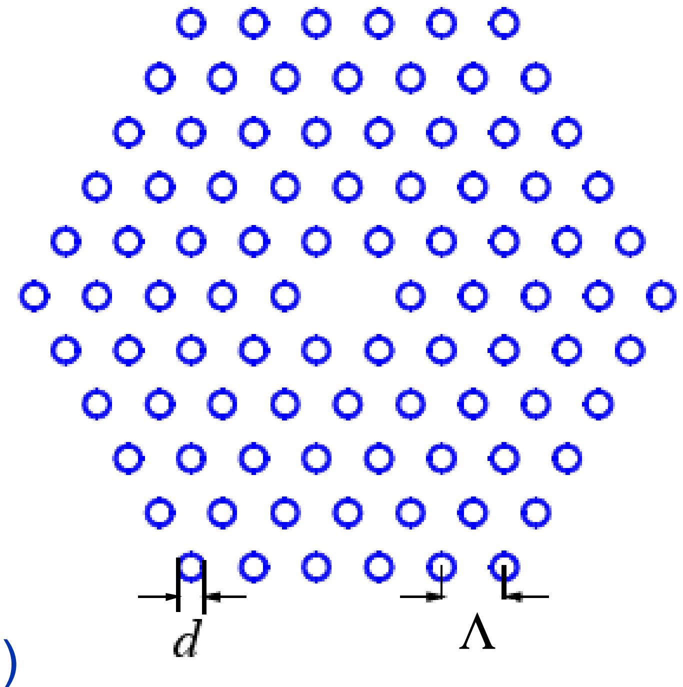
Pulse parameters to vary:

- Peak power
- Pulse duration

Three Example Designs

Needed fiber quantities (experimentally determined)

- Kerr coefficient
- Raman gain
- Material dispersion



Needed fiber quantities (calculated)

- Total Raman response
  - — calculated once
- Total dispersion (we use COMSOL)
  - — calculated for each set of fiber parameters

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 (we use COMSOL)

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

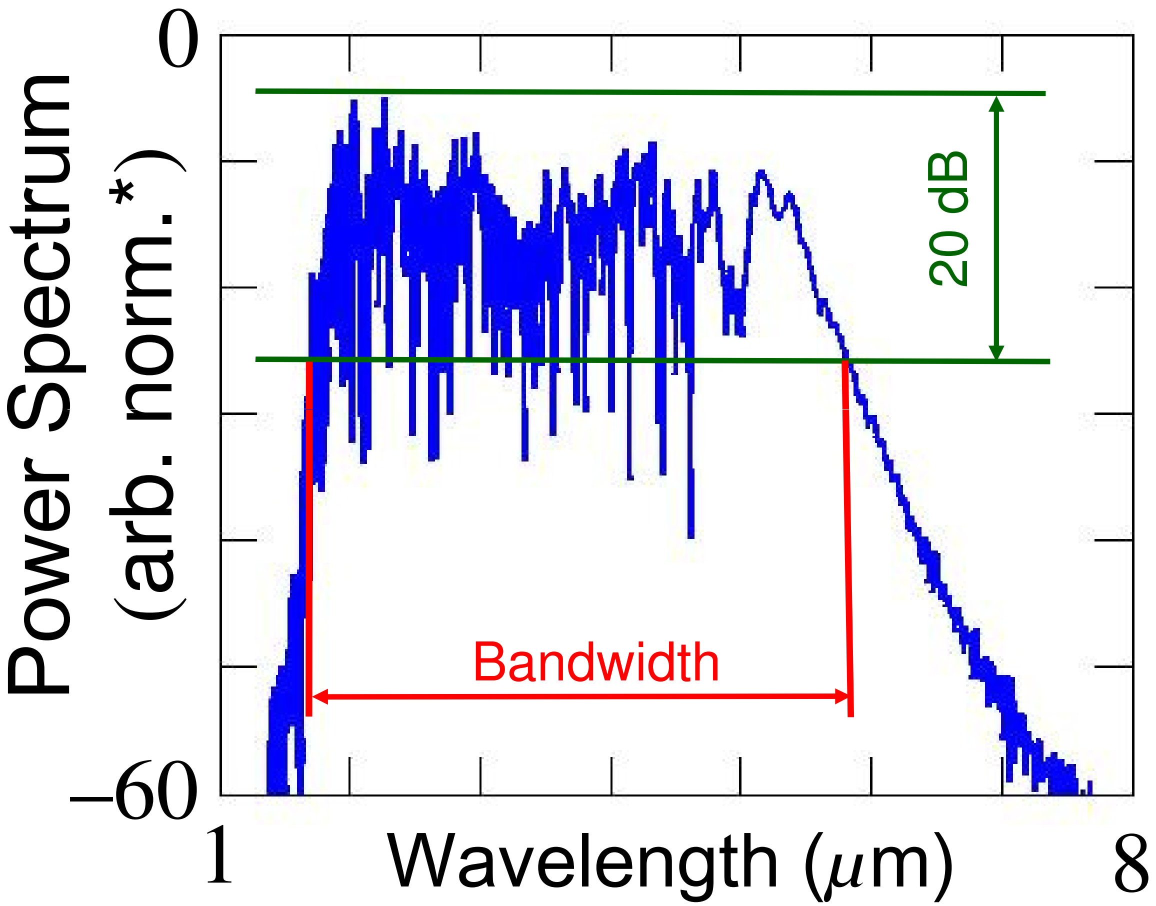
$$R(t) = \underbrace{(1-f_R)\delta(t)}_{\text{Kerr effect}} + \underbrace{f_R h_R(t)}_{\text{Raman effect}}$$

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

Output spectrum (example 1)



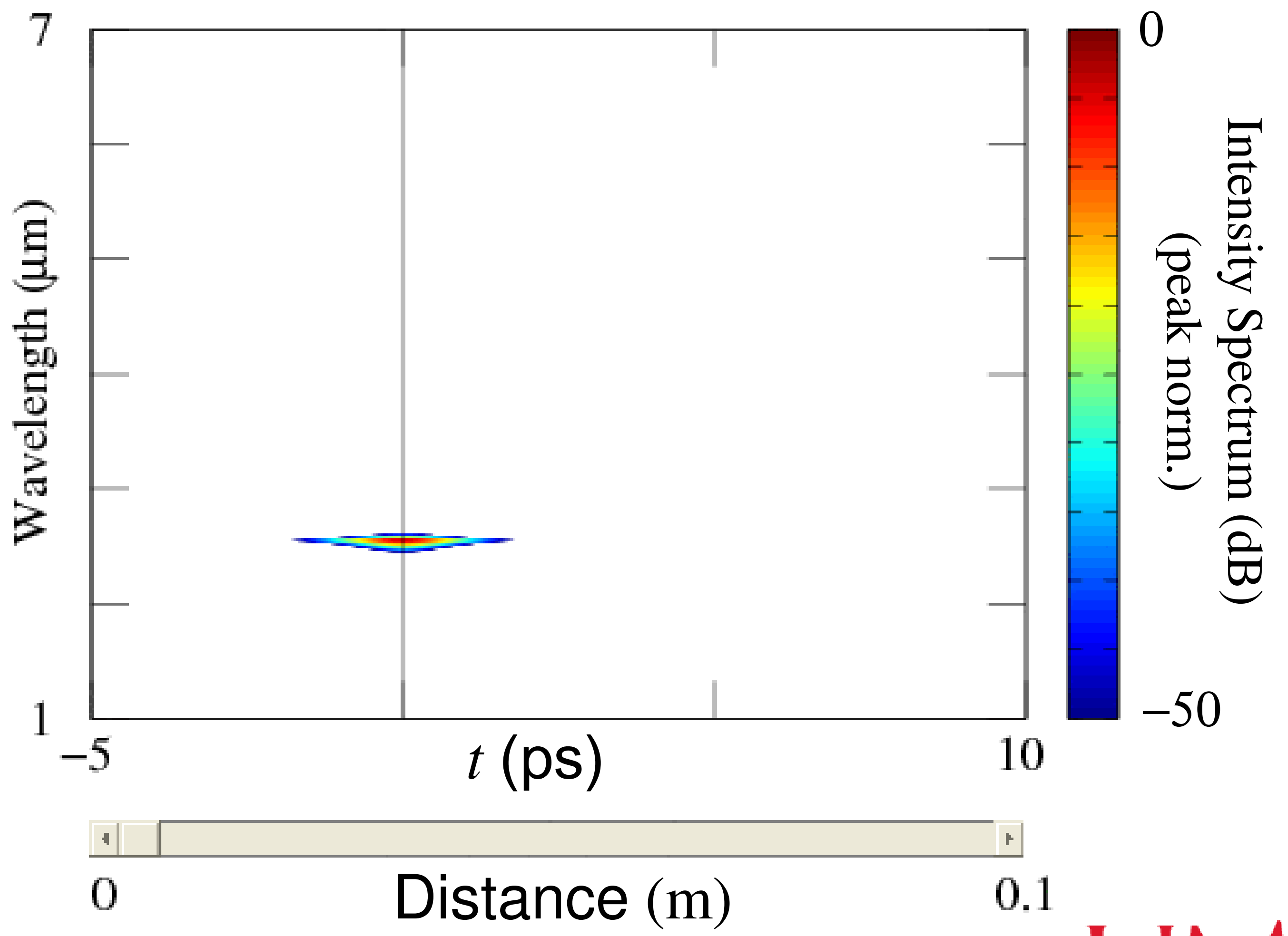
As_2Se_3 fiber
pump = 2.5 μm
peak = 1 kW
L = 0.1 m
FWHM = 500 fs
d/Λ= 0.4
Λ = 3 μm

J. Hu, et al., Opt. Exp., vol. 18, p. 6722, 2010

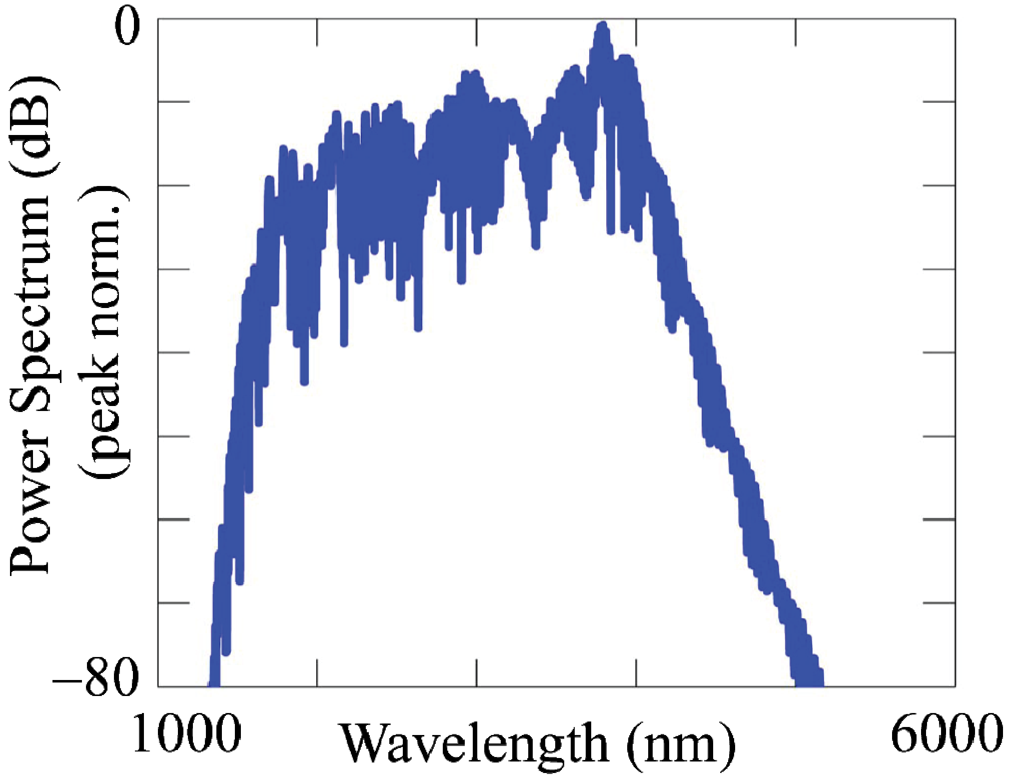
*actually the Λ = 2 μm peak

- A bandwidth > 4 μm is obtained

Spectrogram



Output spectrum (example 2)



As_2S_3 fiber

peak = 1 kW

pump = 2.0 μm

L = 0.5 m

FWHM = 500 fs

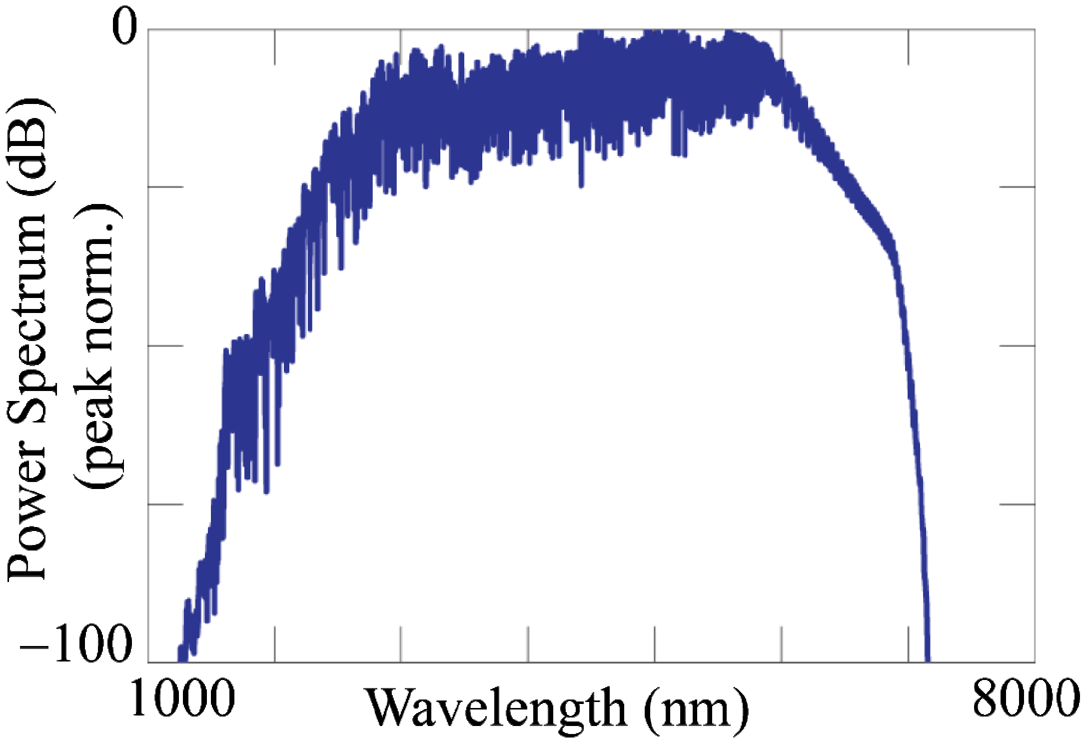
d/Λ= 0.4

Λ = 3 μm

J. Hu, et al., Opt. Lett., vol. 35, p. 2907, 2010

- The goal is to optimize the power between 3 and 5 μm
- > 25% of the power is in the desired range

Output spectrum (example 3)



As_2S_3 fiber
pump = 2.8 μm
peak = 3.0 GW/cm^2
L = 0.5 m
FWHM = 500 fs
d/Λ= 0.4
Λ = 4 μm

- A bandwidth ~4 μm is obtained

R. J. Weiblen, et al., CLEO 2010, paper CTuX7.

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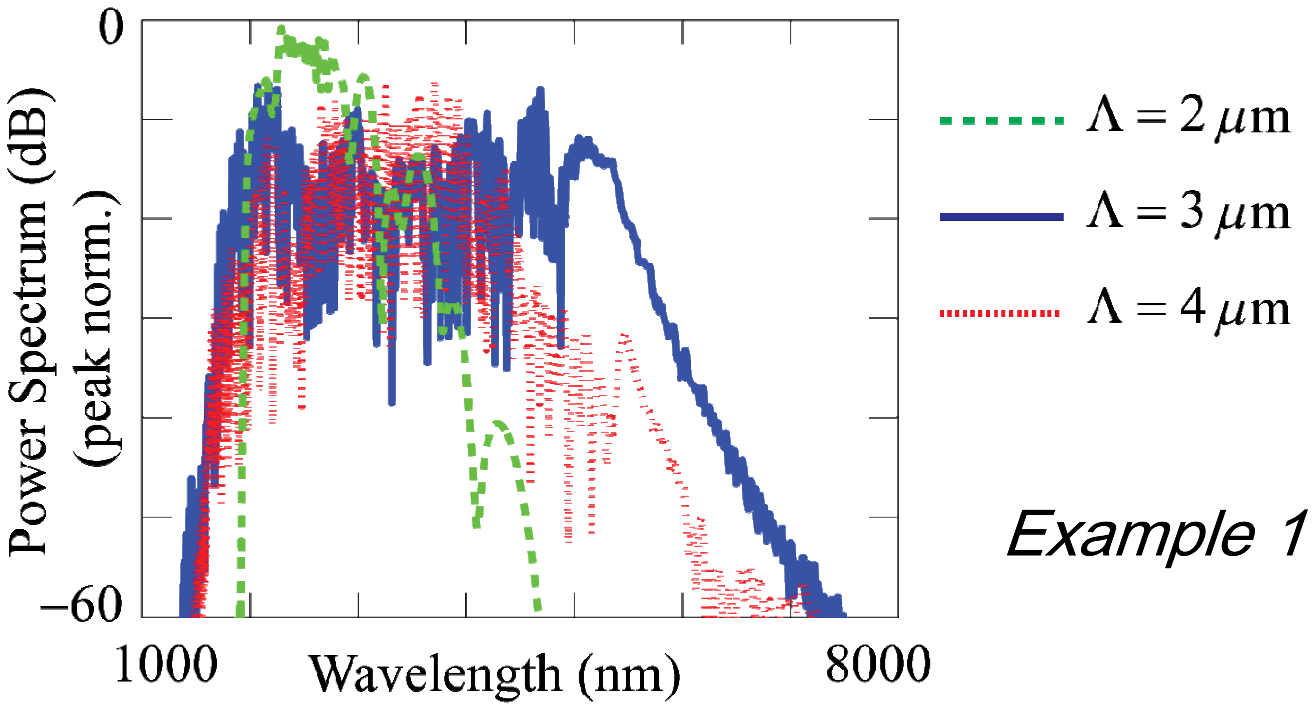
Key Issues

- ***Large fluctuations in the output spectrum***

  > 20 dB in some cases

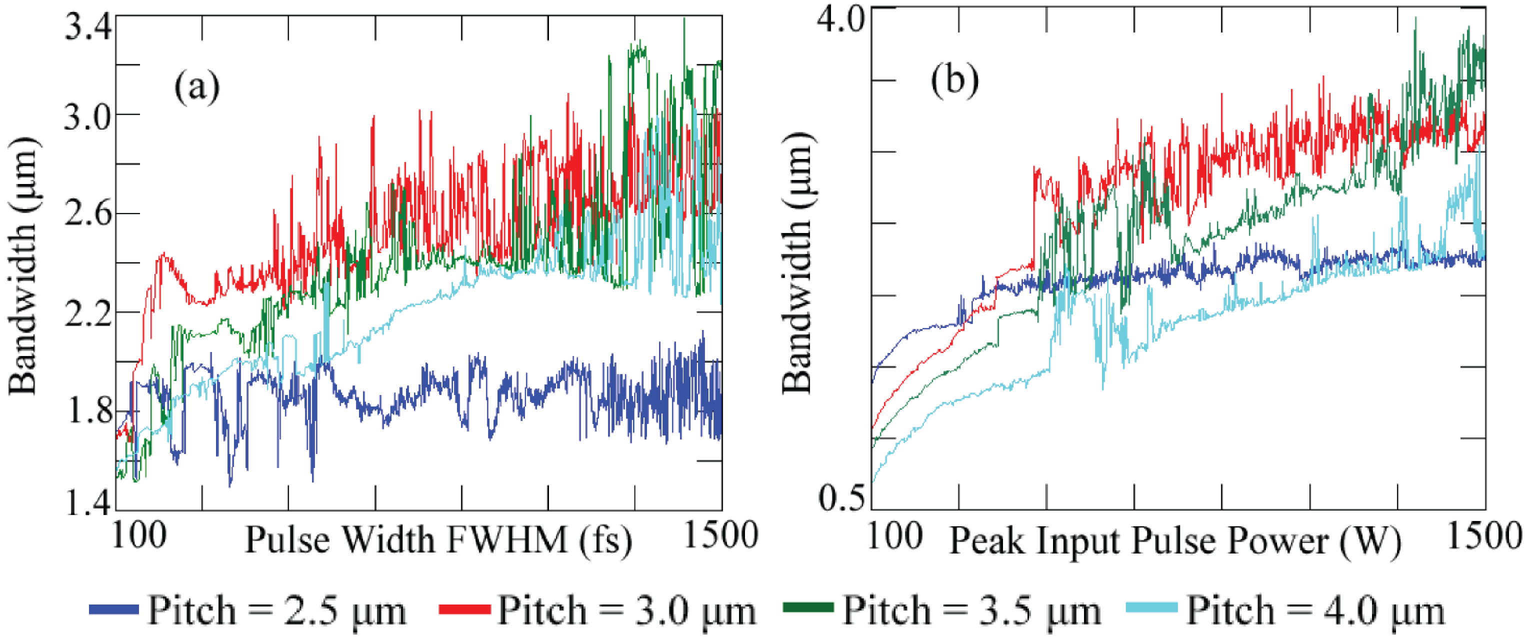


Example 1

Key Issues

- ***Extreme Sensitivity of the bandwidth***

  < 0.1% change in pulse duration or peak power changes the power spectrum significantly



Example 3

Key Issues

- ***The extreme sensitivity will not appear in real systems!***

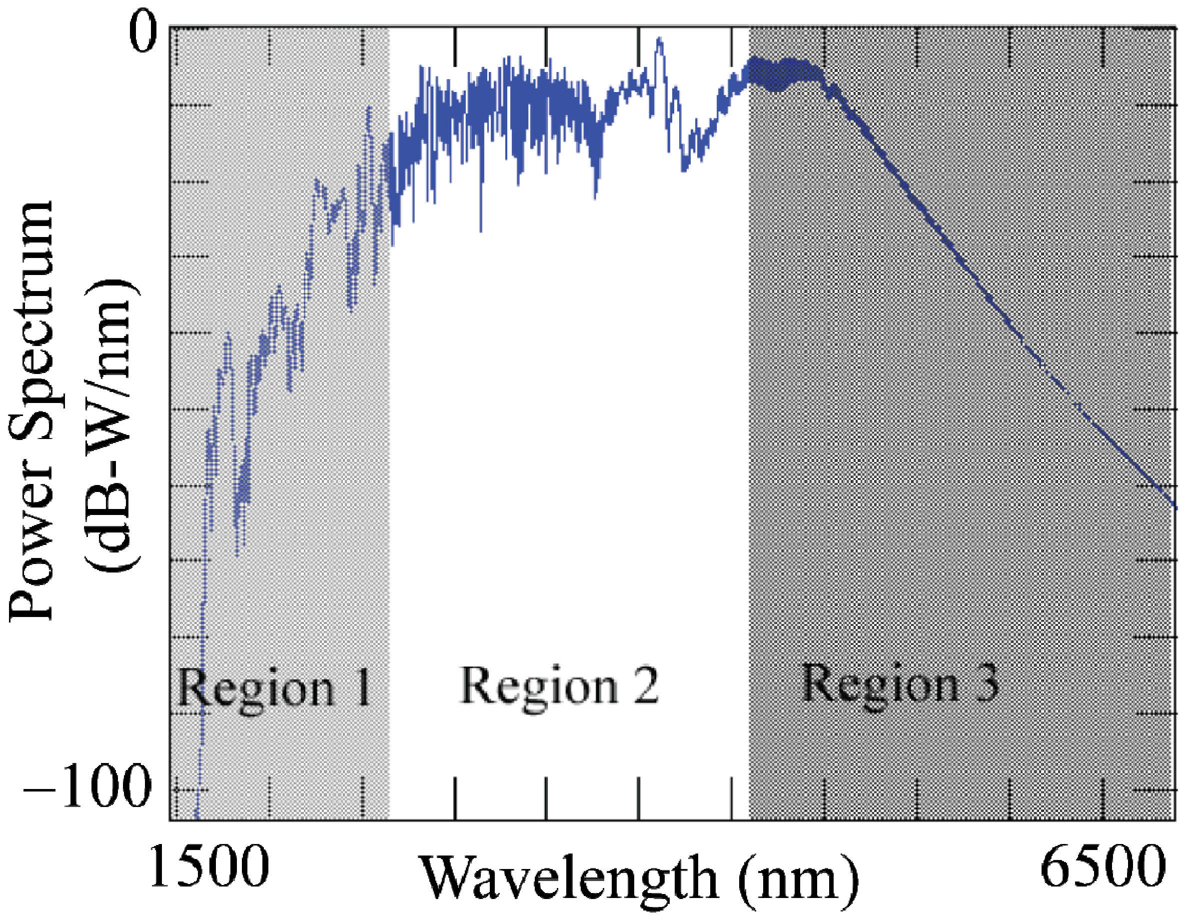
  Real systems have a 10% variation of the pulse durations and peak intensities

- ***So what are the "real" bandwidths and fluctuation levels?***

  An ensemble average is needed

- ***How big does the ensemble need to be?***

Spectral Characterization



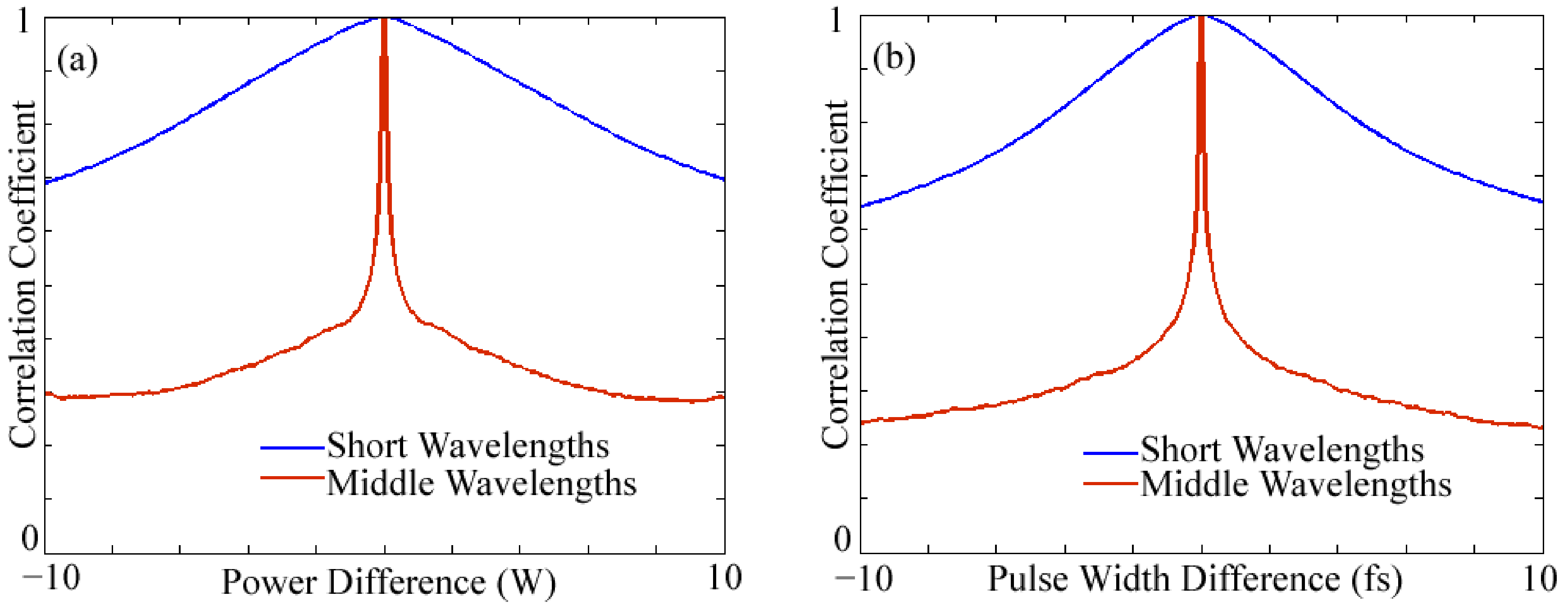
Three spectral regions are visible

Spectral Characterization

- ***Region 1***
  - ❑ Due to initial four-wave mixing; shaped by material loss
  - ❑ Does not change significantly with small changes in the pulse parameters
- ***Region 2***
  - ❑ Contains many interacting solitons
  - ❑ Flattest and most variable
- ***Region 3***
  - ❑ Due to the longest wavelength soliton
  - ❑ Has the largest effect on the bandwidth

Spectral Characterization

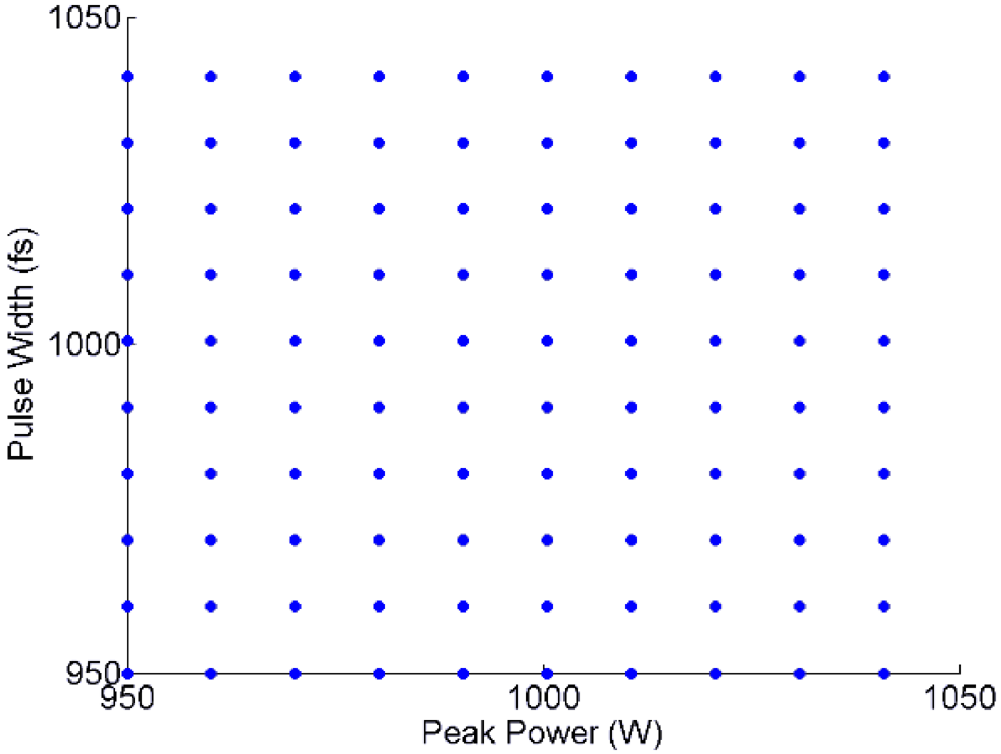
Pearson (spectral) autocorrelation traces



The results suggest that there are up to 10^6 independent realizations

Computational Approach

- 10^6 realizations
- We tile the parameter space in groups of 100



Correlations are minimized!

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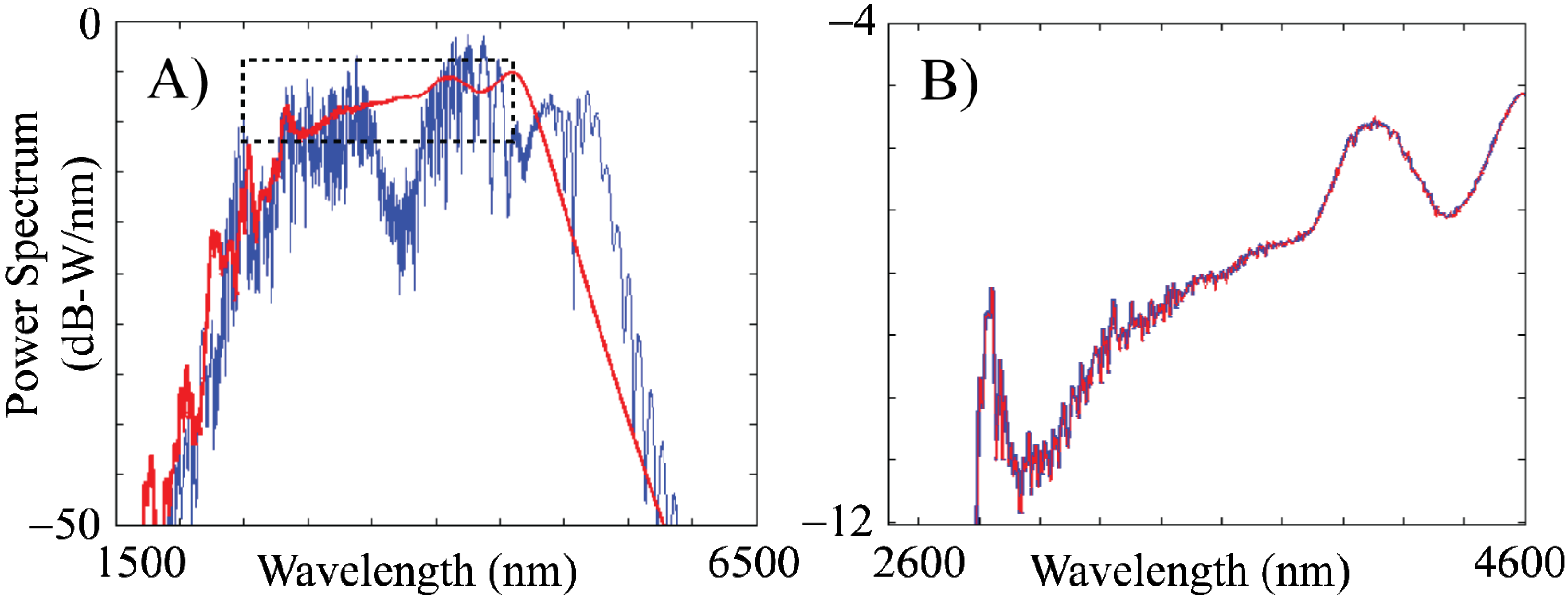
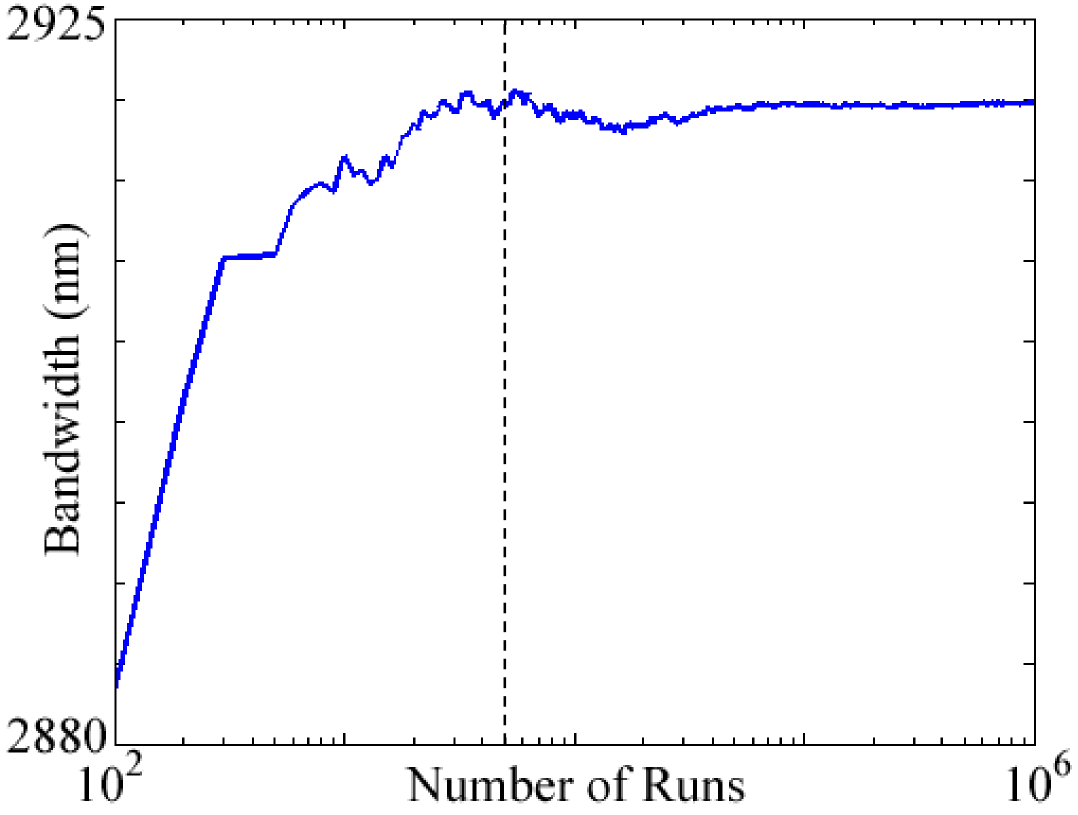
Key Results

- ***Fluctuations persist*** **BUT** ***are less than 5 dB***



Key Results

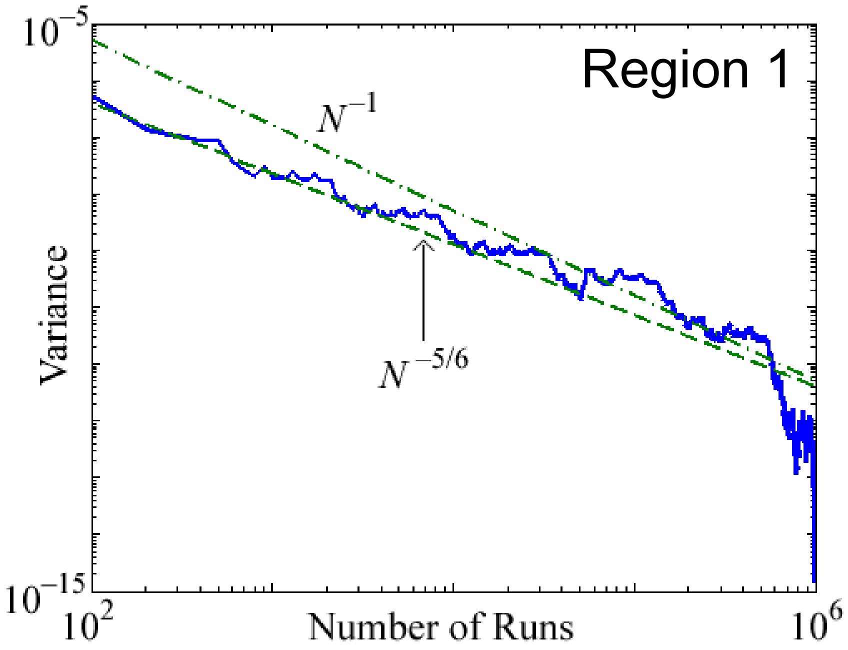
- ***5000 realizations determine the bandwidth***

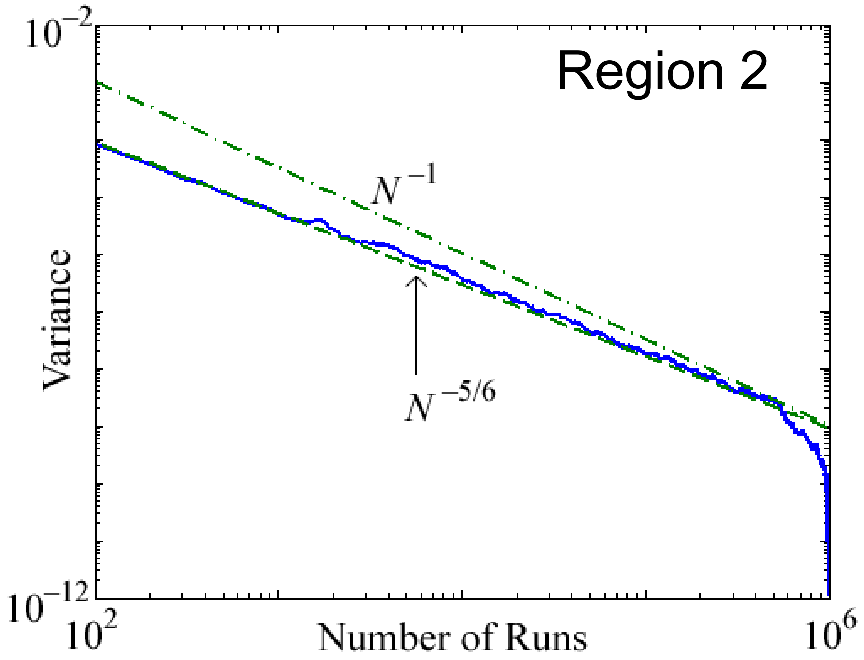


Maximum excursion from the final value after 5000 runs is about 0.1%

Key Results

- ***Tiling is efficient and needed***





Conclusions

- We have elucidated the physical process of super-continuum generation in chalcogenide fibers.
- We have shown (in one case) that an average over 5000 realizations is sufficient to accurately determine the bandwidth and fluctuation levels.
- Our average result shows (in this case: As_2S_3 fiber with a 2.8 μm pump):
  - ☐ a bandwidth of 3 μm
  - ☐ A fluctuation level of 5 dB in the mid-range

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