Recent Advances in Supercontinuum Generation

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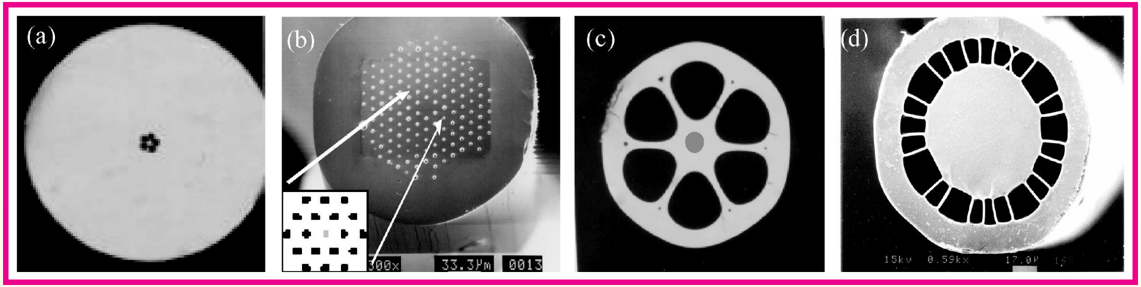
Historical Introduction

- Supercontinuum generation refers to the creation of extremely wide optical spectra produced using the nonlinear effects.
- First realized in 1969 using borosilicate glass as a nonlinear medium [Alfano and Shapiro, PRL **24**, 584 (1970)].
- In this experiment, 300-nm-wide supercontinuum covered the entire visible region, resulting in the formation of white light.
- A 20-m-long fiber was employed in 1975 to produce 180-nm wide supercontinuum [Lin and Stolen, APL **28**, 216 (1976)].
- 25-ps pulses were used in 1987 but the bandwidth was only 50 nm [Beaud et al., JQE **23**, 1938 (1987)].
- 200-nm-wide supercontinuum obtained in 1989 by launching 830-fs pulses [Islam et al., JOSA B **6**, 1149 (1989)].

Supercontinuum History

- Supercontinuum work with optical fibers continued during the 1990s with telecom applications in mind.
- A 200-nm-wide supercontinuum was used to produce a 200-channel WDM source [Morioka et al., Electron. Lett. **31**, 1064 (1995)].
- A dramatic change occurred in 2000 when new kinds of fibers were used to produce a supercontinuum extending $>$1000 nm.
- Such fibers contain air holes in their cladding and are known as the photonic crystal or microstructured fibers.
- They were developed after 1996 in an attempt to control the dispersive and nonlinear properties of silica fibers.
- Recent advances relate to improving the supercontinuum coherence and extending the wavelength range into the mid-IR region.

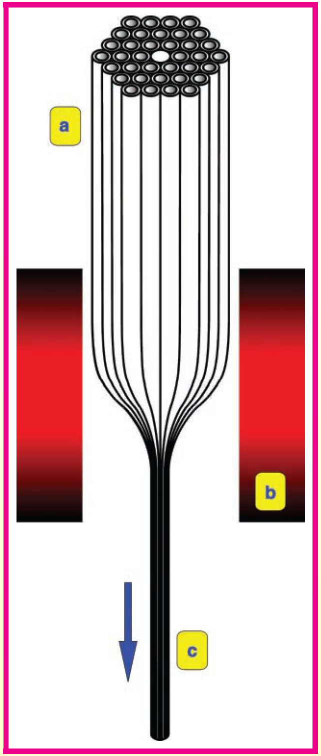
Microstructured Fibers

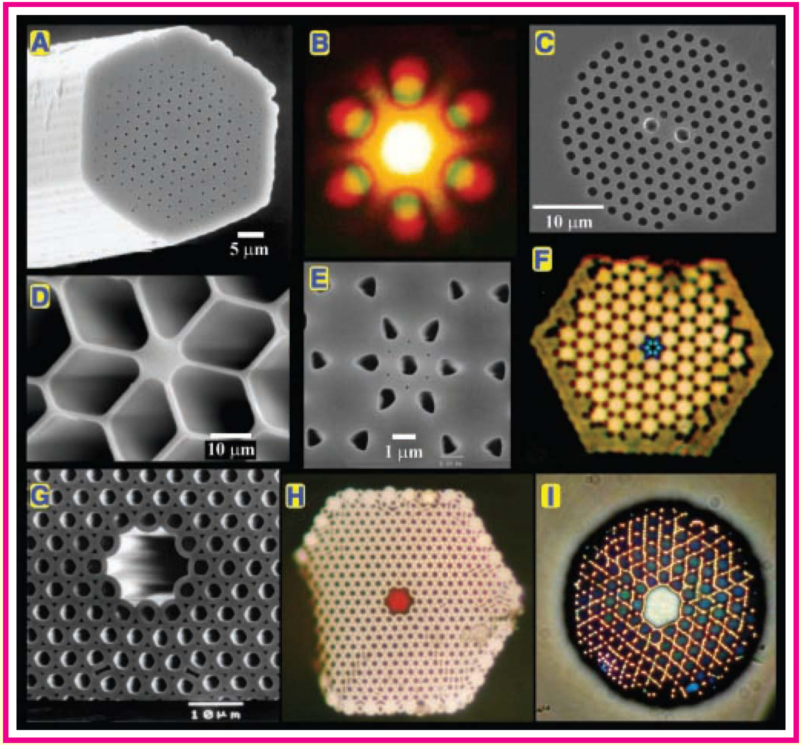


(Eggleton et al, Opt. Exp. **9**, 698, 2001)

- A narrow core is surrounded by a silica cladding with air holes.
- Photonic crystal fibers have multiple rings of holes.
- Number of air holes varies from structure to structure.
- Hole size varies from 0.5 to 5 μm depending on the design.
- Nonlinear effects are enhanced considerably (highly nonlinear fibers).
- Useful for supercontinuum generation among other things.

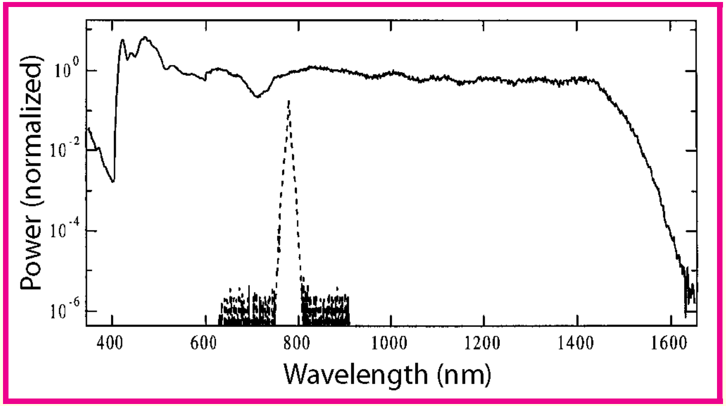
Photonic Crystal Fibers





(P. St. J. Russell, Science **299**, 358, 2003)

Supercontinuum Generation



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

- Output spectrum generated in a 75-cm section of microstructured fiber by launching 100-fs pules with only 0.8 pJ energy.
- Supercontinuum at the fiber out extended from 400 to 1600 nm.
- It was also relatively flat over a wide bandwidth (on a log scale).
- Useful in biomedical imaging as a broadband source.

Physics Behind SC Generation

- 100-fs input pulses propagated as high-order solitons ($N > 10$).
- Third-order dispersion (TOD) leads to their fission into multiple narrower fundamental solitons: $T_k = T_0/(2N+1-2k)$.
- Each of these solitons is affected by intrapulse Raman scattering that transfers energy from the blue side to the red side.
- Spectrum of each soliton shifts toward longer and longer wavelengths with propagation inside the fiber.
- At the same time, each soliton emits dispersive waves at different wavelengths on the blue side of the input wavelength.
- Cross-phase modulation (XPM) and four-wave mixing generate additional bandwidth to produce the observed supercontinuum.

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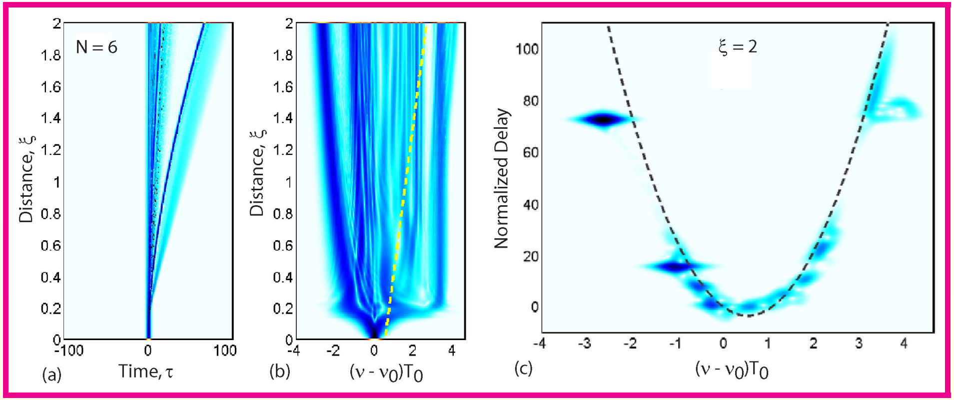
Numerical Modeling of Supercontinuum

- Soliton fission is studied by solving the generalized NLS equation:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A \; + \; i \sum_{m=2}^{M} \frac{i^m \beta_m}{m!} \frac{\partial^m A}{\partial t^m}$$
$$= \; i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t}\right) \left(A(z,t) \int_0^\infty R(t') |A(z,t-t')|^2 dt' \right).$$

- It is important to include the dispersive effects (β_m) and intrapulse Raman scattering (through $R(t)$) as accurately as possible.
- Terms up to $M = 8$ are often included in numerical simulations.
- Raman response included through the measured gain spectrum.
- Most features observed experimentally can be understood, at least qualitatively, by such a theory.

Evolution of a Sixth-Order Soliton

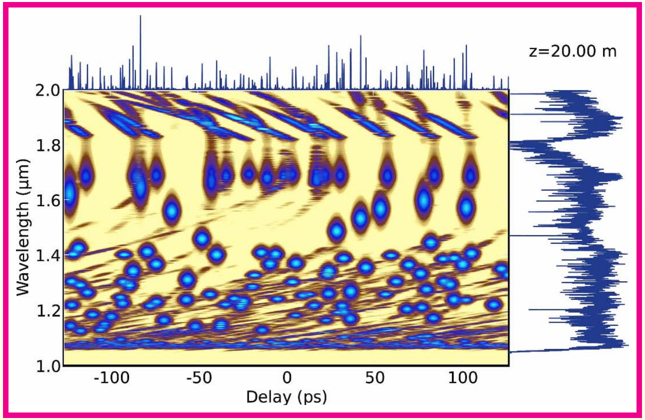


- Temporal and spectral evolution of a $N = 6$ soliton over $2L_D$.
- Corresponding spectrogram at $z = 2L_D$ shows spectra of different temporal slices (colors indicate different power levels).
- Multiple solitons and their dispersive waves are clearly visible.
- Temporal overlap between the two leads to new effects through XPM and four-wave mixing.

Supercontinuum Properties

- Supercontinuum can be generated using pulses of different widths (from fs to ns range). Even a continuous wave (CW) can be used to create a supercontinuum.
- Use of femtosecond pulses produce a wideband supercontinuum but its spectral coherence is often limited.
- Modulation instability initiates the supercontinuum process for CW light or nanosecond pulses.
- It converts CW light into a train of fundamental solitons of different widths whose spectra shift toward the red side (no soliton fission).
- Most experiments employ anomalous dispersion that is required for modulation instability and soliton formation.

CW Supercontinuum Generation



Cumberland et al., Opt. Exp. **16**, 5954 (2008)

- Formation of fundamental solitons (round objects) of different widths through modulation instability.
- Spectra of solitons shift toward red (no broadening toward blue).
- Cigar-like objects at $\lambda >$1730 nm represent dispersive waves.
- FWM generates new spectral components near 1900 nm.

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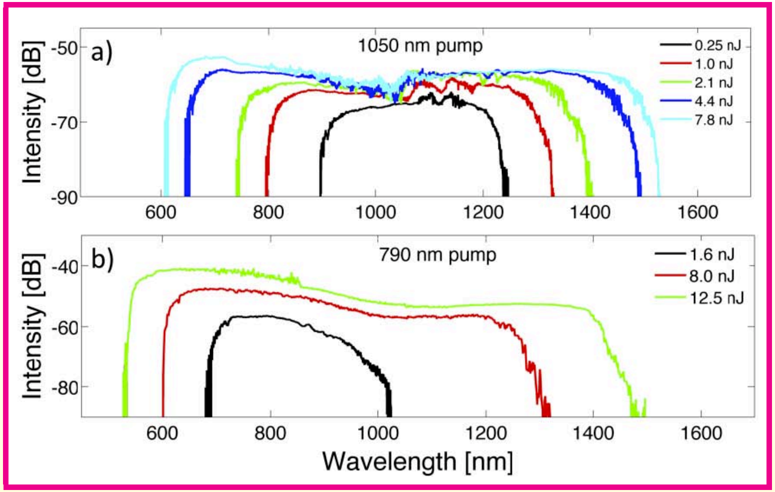
High-Quality Supercontinuum

- Good coherence and noise properties of supercontinuum are critical for biomedical and other applications.
- The use of modulation instability or soliton fission does not typically produce a high-quality supercontinuum.
- Considerable research effort has led to novel techniques for producing a high-quality supercontinuum.
- It requires launching of pedestal-free soliton-like pulses in the normal-dispersion region of a highly nonlinear fiber.
- Dispersion slope should be relatively small to ensure a nearly constant dispersion over a broad bandwidth.
- In another approach two pulses at different wavelengths are launched such that they propagate inside the fiber at nearly the same speed.

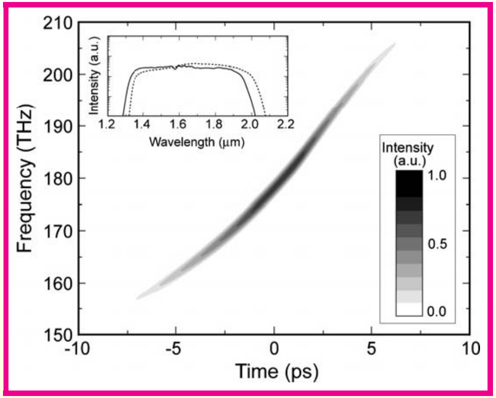
SC Generation with Normal Dispersion

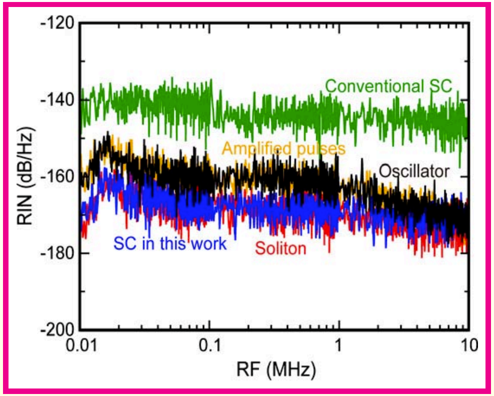


(Heidt et al., Opt. Exp. **19**, 3775, 2011)

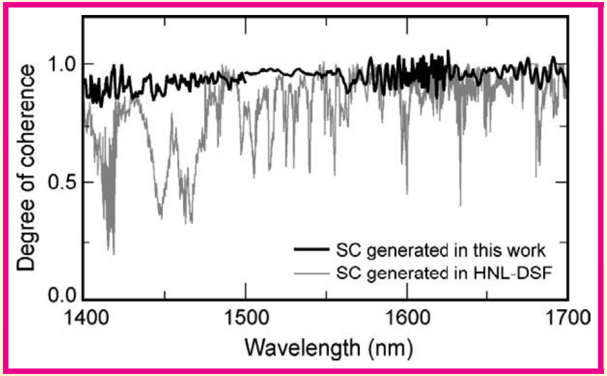
- 50-fs pulses were launched into a 50-cm-long PCF.
- Relatively coherent supercontinua formed in both cases.
- Such a source is suitable for many biomedical applications.

SC with Low Noise and High Coherence





(N. Nishizawa., Opt. Fiber. Technol. **18**, 394, 2012)

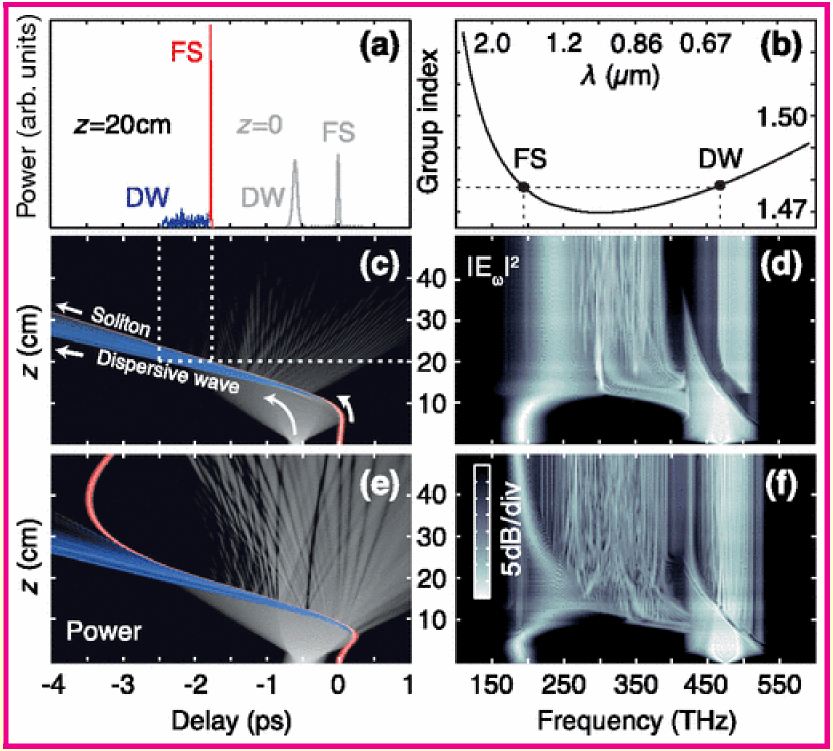


5-m-long fiber with:
$\gamma = 23$ W^{-1}/km
$\beta_2 \approx 5$ ps^2/km
$\beta_3 \approx 0.005$ ps^3/km
Dispersion relatively flat.

SC Generation by Two-Pulse Collision

- A new mechanism was proposed for SC generation in 2013: Demircan et al., PRL **110**, 233901, (2013).
- It makes use of collision of a soliton with a weak pulse at another wavelength.
- Soliton propagates in the anomalous dispersion region of fiber.
- The weaker pulse propagates in the normal dispersion region such that its speed nearly coincides with that of the soliton.
- The two pulses are separated initially, but weaker pulse spreads and collides with the soliton.
- Cross-phase modulation creates an index barrier and generates many dispersive waves that broaden the spectrum while maintaining its coherence.

Spectral and Temporal Evolution



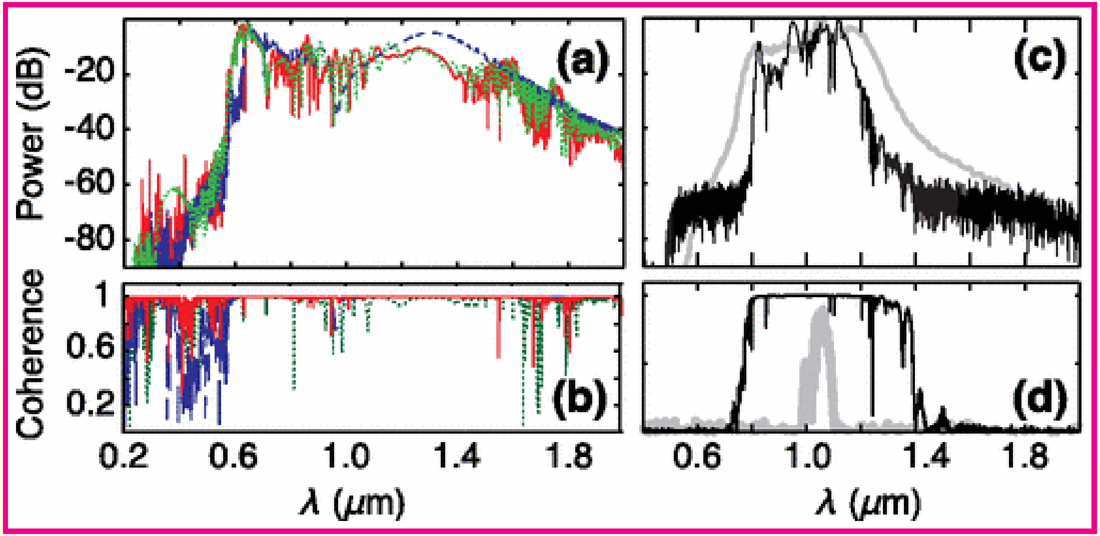
Demircan et al., PRL **110**, 233901 (2013)

Top:
(a) Fiber Output
(b) $n_g(\omega)$

Middle:
Without Raman

Bottom:
With Raman included

Spectral Coherence of Supercontinuum



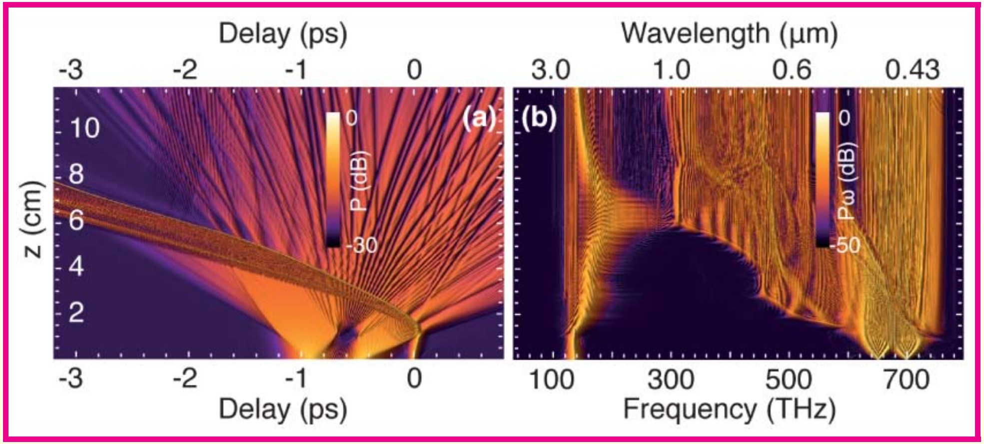
Demircan et al., PRL **110**, 233901, (2013)

- High coherence is predicted over a wide spectral range (left).
- Spectral coherence is limited when soliton fission is employed with $N = 15$ and $N = 40$ (gray).

SC Generation by Multiple Scattering

- Multiple scattering mechanism proposed for SC generation in 2014: Demircan et al., Opt. Exp. **22**, 3866 (2014).
- It makes use of XPM between a soliton and one or more weaker pulses at different wavelengths such that they travel together.
- The pulses are separated initially but weaker pulses spread and collide with the soliton.
- The XPM interaction between them creates an index barrier known as the "group velocity horizon."
- Multiple scattering from this barrier creates a supercontinuum that extends from 300 to 2300 nm.
- Spectral coherence is maintained nearly over the entire bandwidth of supercontinuum.

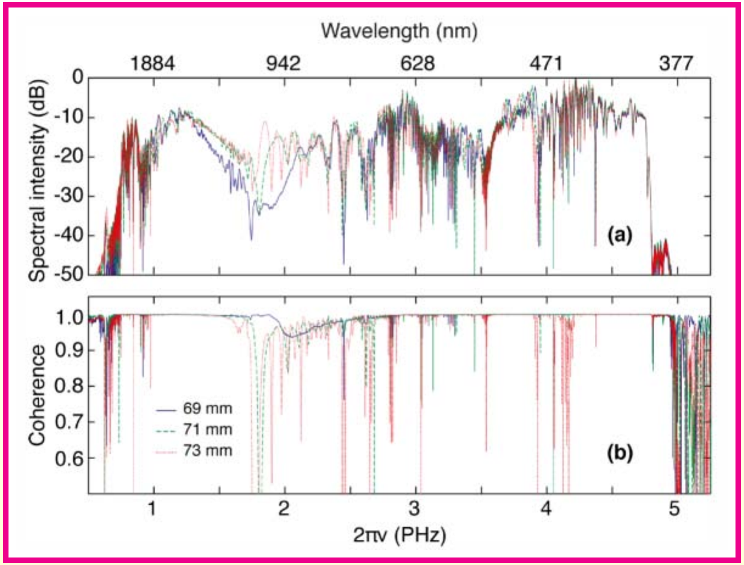
Spectral and Temporal Evolution



Demircan et al., Opt. Exp. **22**, 3866 (2014)

- Two weak pulses launched at 470 and 428 nm together with a soliton at 1800 nm.
- Multiple scatterings between dispersive waves and the soliton create a SC ranging over the whole transparency region of silica fiber.

Spectral Coherence of Supercontinuum



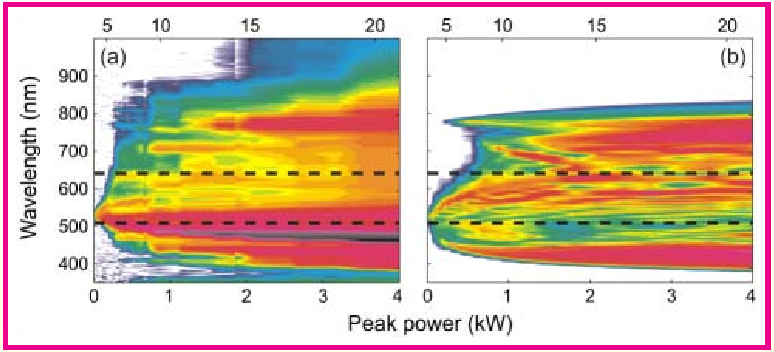
Demircan et al., Opt. Exp. **22**, 3866 (2014)

- Spectrum extends over a wide range from 380 nm to 2200 nm
- Spectral coherence remains high nearly over the entire range.

Spectral Extension into UV or IR Region

- Spectral range covered by a SC depends on the pump wavelength.
- When pumped near 800 or 1060 nm, SC extends into the visible and near-infrared (IR) regions.
- Many applications require SC sources covering the ultraviolet (UV) or/and mid-IR regions.
- Progress has been made in recent years in both directions.
- The mid-IR region requires non-silica fibers (tellurite or chalcogenide) and new pump sources operating in the 2-3 μm region.
- The UV region can use silica fibers but requires new designs such as tapering of a fiber or gas-filled hollow-core PCFs).

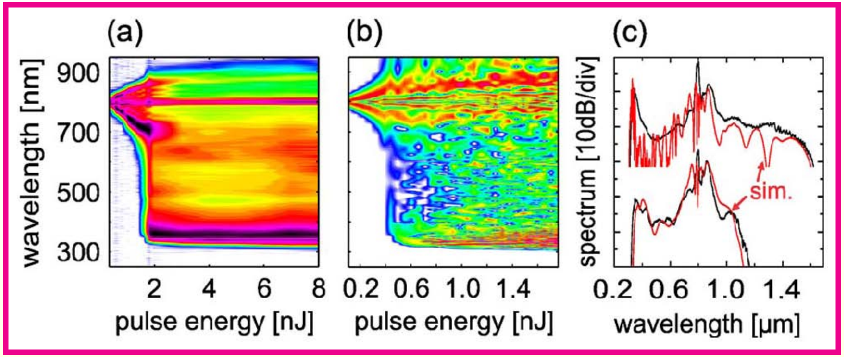
Narrow-Core Photonic Crystal Fibers



(Stark et al., JOSA B **27**, 592, 2010)

- Experimental (a) and simulated (b) SC spectra when 523-nm pulses were launched into a 5-cm-long PCF with 0.6-μm core diameter.
- PCF had anomalous dispersion between 500–630 nm.
- SC extended from 300–900 nm when soliton order was close to 20.
- Narrow core helps to extend the supercontinuum into the UV region.

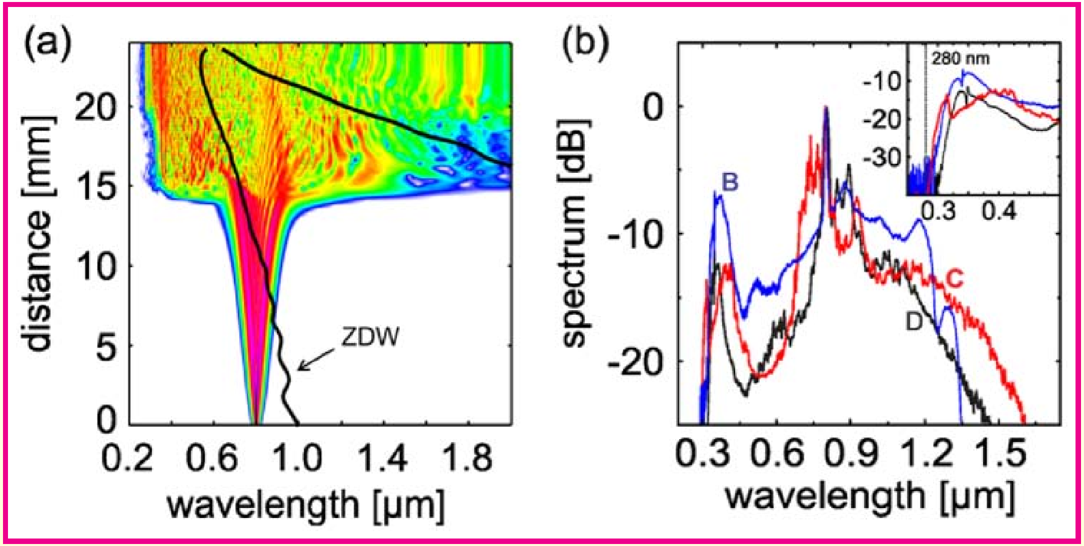
Tapered Photonic Crystal Fibers



(Stark et al., Opt. Lett. **37**, 770, 2012)

- Experimental (a) and simulated (b) SC spectra when 110-fs pulses were launched into a tapered PCF.
- (c) SC spectra at input pulse energies of 2 and 5 nJ.
- Core diameter tapered form 2.7 μm to 400 nm over 1.5 cm.
- Tapering helps to extend the supercontinuum into the UV region.

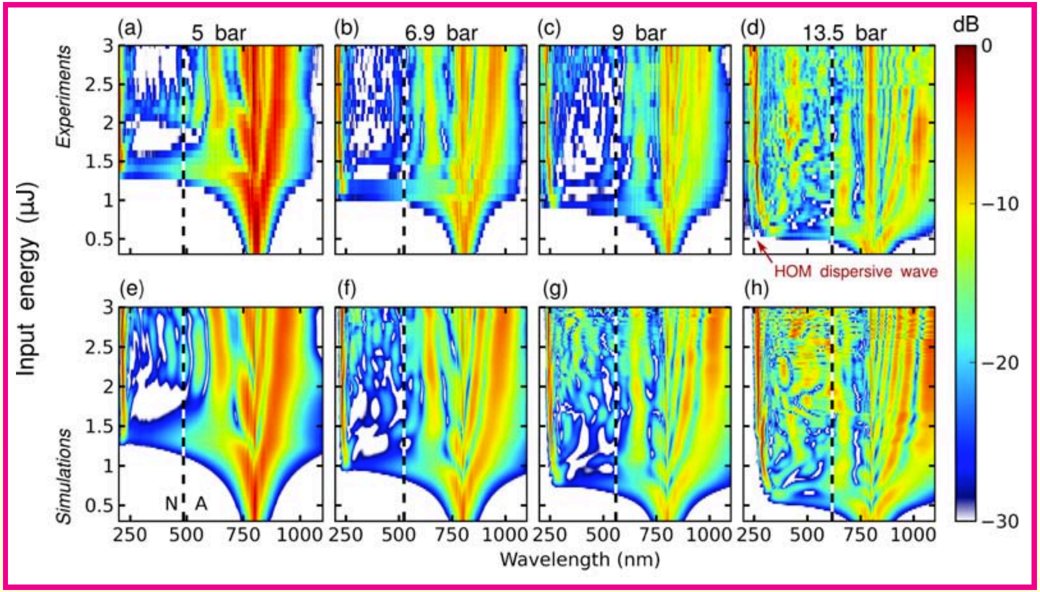
Tapered PCFs (cont.)



(Stark et al., Opt. Lett. **37**, 770, 2012)

- (a) SC evolution inside PCF when ZDW varies with z (black).
- (b) SC spectra generated in several tapered fibers.
- Shortest wavelength was 280 nm well into the UV region.

Argon-Filled Hollow-Core PCFs



(Mak et al., Opt. Exp. **21**, 10492, 2013)

- Experimental (top) and simulated spectra at different argon pressures and energies of 40-fs pulses at 800 nm.
- Shortest wavelength was as low as 200 nm in the UV region.

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SC Generation in the Mid-Infrared Region

- SC sources in the mid-IR region are needed for diverse applications including food quality control, gas sensing, and medical diagnostics.
- Several different glasses (tellurite, fluoride, ZBLAN, chalcogenide) have been used because of their low losses in the mid-IR region.
- Both planar waveguides and fibers have been used for SC generation in recent years.
- Early experiments used 1.55-μm lasers for pumping the fiber.
- Pump wavelength was moved to near 3–4 μm in later experiments.
- Recent experiments have produced a SC extending beyond 10 μm.
- I have collaborated on this topic with Prof. Rahman of City University London.

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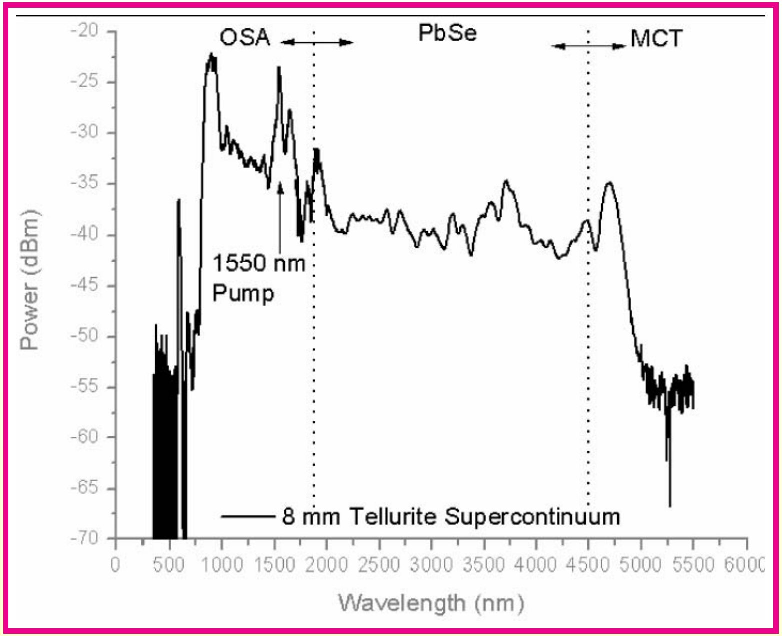
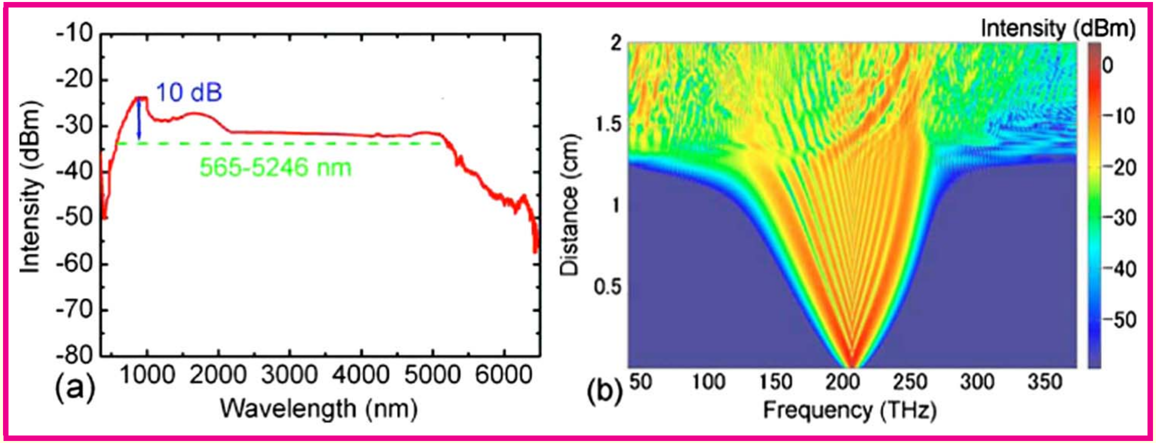
Tellurite Fiber Pumped at 1.55 μm



(Domachuk et al., Opt. Exp. **18**, 7161, 2008)

- Tellurite fiber (<1 cm) pumped at 1.55 μm using 100-fs pulses.
- The resulting SC extended into the IR region up to 5 μm.

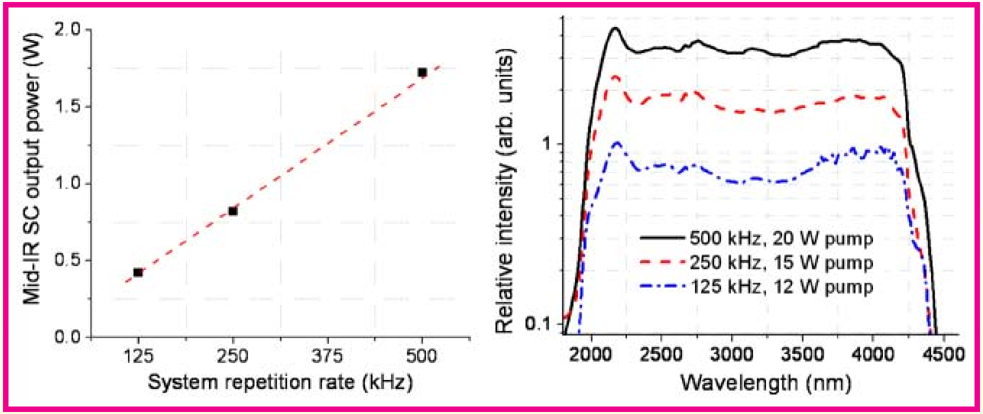
Fluoride Fiber Pumped at 1.45 μm



(Qin et al., Appl. Phys. Lett. **95**, 161103, 2009)

- Ultrabroad SC generated using a 2-cm-long fluoride fiber pumped at 1.45 μm using 180-fs pulses with 50 MW peak power.
- The SC extended from ultraviolet to the IR region up to 6.3 μm.
- Simulated evolution of the SC is shown on the right.

ZBLAN Fiber Pumped at 2 μm



(Kulkarni et al., JOSA B **28**, 2486, 2011)

- A 8.5-m-long ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) fiber pumped at 2 μm using nanosecond pulses.
- The SC extended from 2 to 4.5 μm with high output power.
- Pump power was up to 30 W at a repetition rate of 500 kHz.

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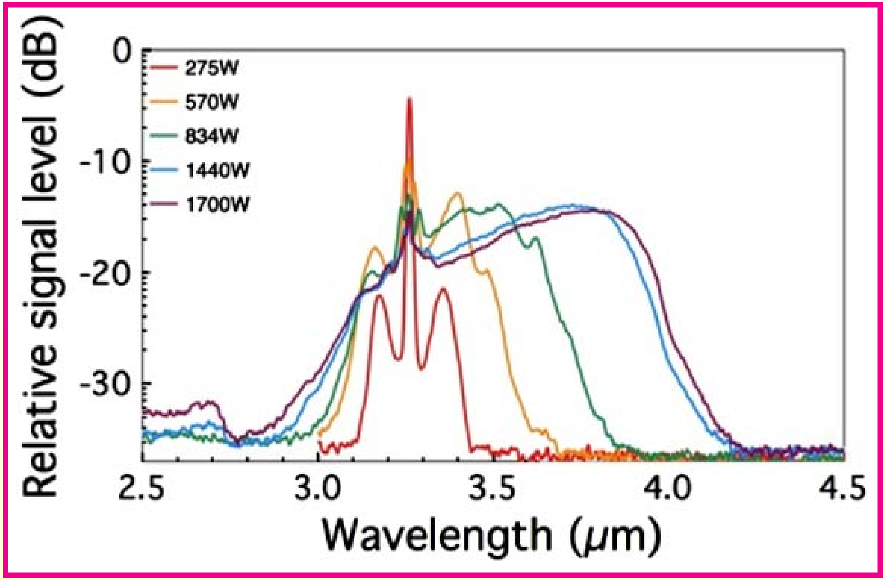
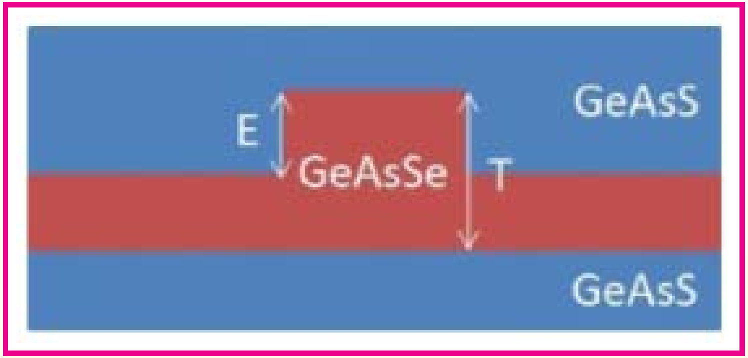
Chalcogenide waveguide Pumped at 3.26 μm



(Gai et al., Opt. Lett. **37**, 3870, 2013)

- A 6.6-cm As_2S_3 waveguide pumped at 3.26 μm using 7.5-ps pulses.
- The SC extended up to to 4.2 μm at a peak power of 1.7 kW.
- Extension beyond 4.2 μm was limited by the cladding absorption.

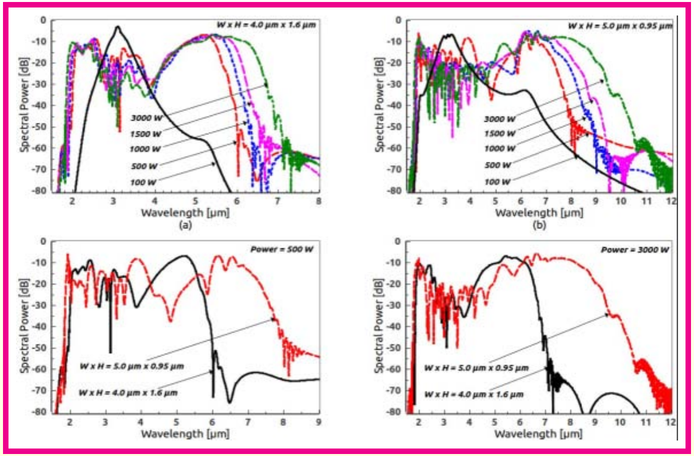
Improved Chalcogenide waveguides



(Yu et al., Opt. Mat. Exp. **3**, 1075, 2013)

- Several groups have used planar rib waveguides for SC Generation in the mid-IR region.
- These are grown on a MgF_2 substrate to reduce losses.
- In one design $Ge_{11.5}As_{24}Se_{64.5}$ and $Ge_{11.5}As_{24}S_{64.5}$ are used as the core and cladding materials, respectively.
- Simulations show that using MgF_2 for lower cladding is better.

Chalcogenide waveguides with MgF_2 Cladding



(Karim et al., Opt. Exp. **23**, 6903, 2015)

- Simulated SC spectra at a pump wavelength of 3.1 μm for a waveguide with (a) GeAsS and (b) MgF_2 as the lower cladding material.
- Comparison of two claddings at 0.5 and 3 kW pump powers.
- Work done in collaboration with Aziz Rahman of City Univ. London.

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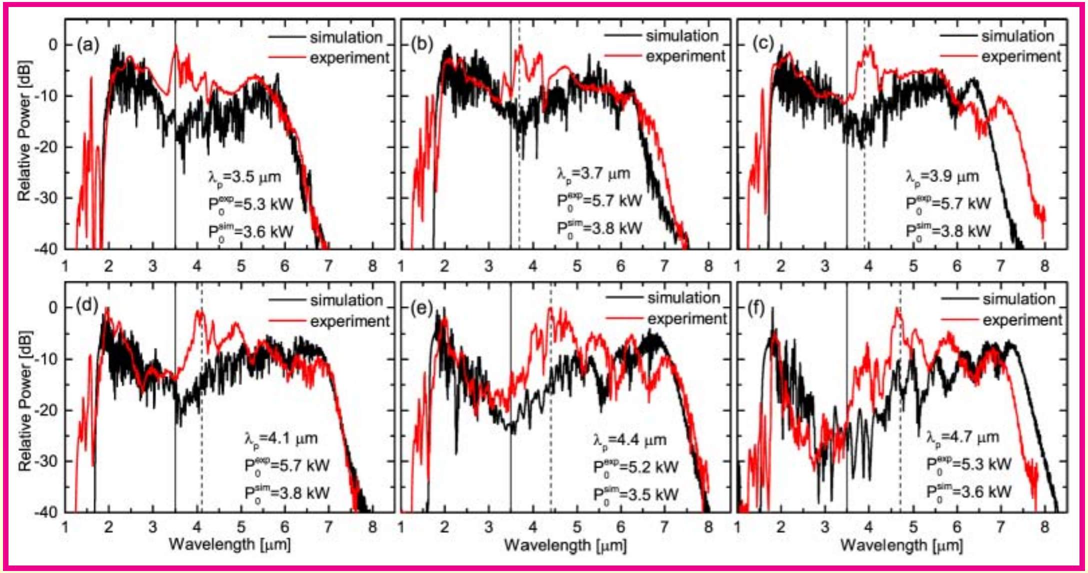
Chalcogenide Fiber Pumped near 4 μm



(Møller et al., Opt. Exp. **23**, 3282, 2015)

- A 18-cm-long $As_{38}S_{62}$ fiber pumped from 3.3–4.7 μm using 320-fs pulses. An OPO was used to tune the pump wavelength.
- The SC extended up to 7.5 μm at a peak power of 5.2 kW.

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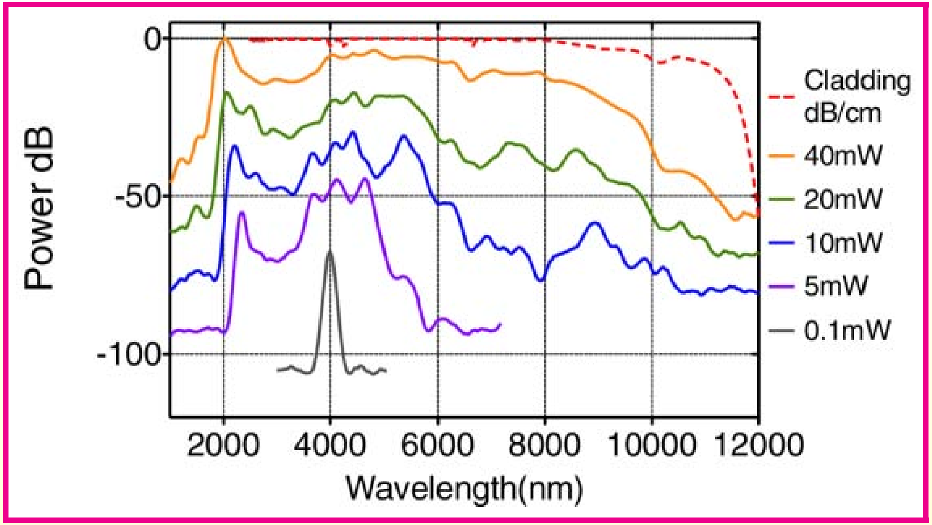
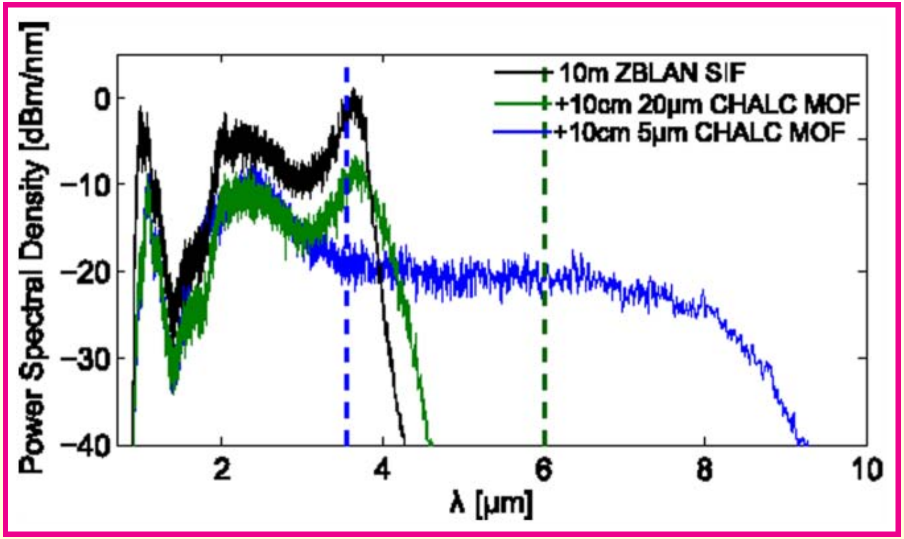
Chalcogenide Fiber Pumped at 4 μm



(Yu et al., Opt. Lett. **40**, 1081, 2015)

- A 11-cm-long $Ge_{12}As_{24}S_{64}$ fiber pumped at 4 μm using 320-fs pulses. An OPO was used for the experiment.
- The SC extended up to 10 μm at an average power of 40 mW.
- Cladding losses limited further extension into the mid-IR region.

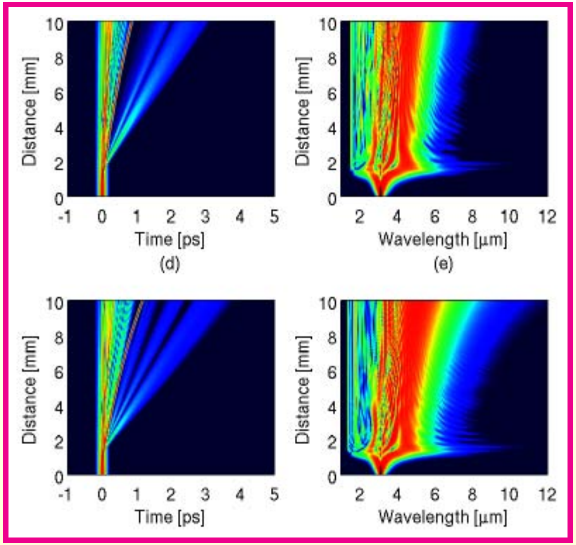
Combination of Two Fibers Pumped at 2 μm

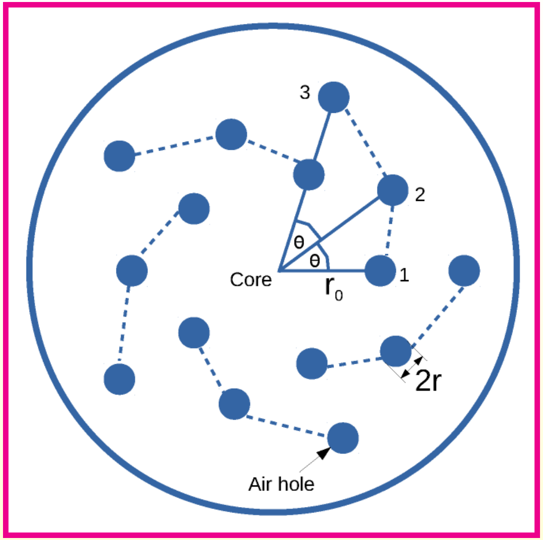


(Kubat et al., Opt. Exp. **22**, 3959, 2014)

- A combination of 10-m fluoride and 10-cm chalcogenide fibers was pumped at 2 μm using 3.5-ps pulses with 20-kW peak power.
- The SC extended up to to 8 μm for the narrow-core ChG fiber.

Chalcogenide PCF Designs

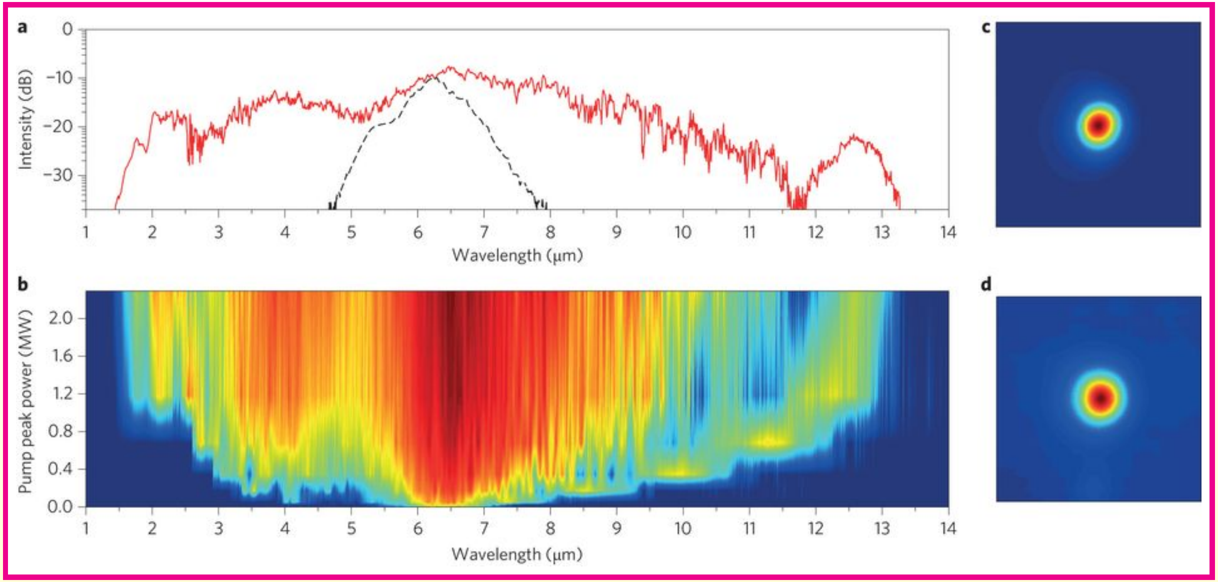




Karim et al., JOSA B (accepted Oct. 2015)

- SC simulations for hexagonal (top) and spiral (bottom) PCFs.
- Pumping is at 3.1 μm using 85-fs pulses with 3-kW peak power.
- Work done in collaboration with Aziz Rahman of City Univ. London.

Chalcogenide Fiber Pumped at 6.3 μm



(Petersen et al., Nature Photon. **8**, 830, 2014)

- A 8.5-cm-long $As_{40}S_{60}$ fiber pumped at 6.3 μm using 100-fs pulses. An OPO was used to tune the pump wavelength.
- The SC extends from 2–13 μm at a peak power of 7.2 MW.

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Concluding Remarks

- The history of supercontinuum generation using glasses goes back to 1969 when borosilicate glass was used to create the white light.
- Recent interest stems from a 2000 experiment in which a short piece of PCF (75 cm) expanded the spectrum over 400 to 1600 nm.
- Supercontinuum can be created using CW light or pulses with widths ranging from 10 fs to 100 ns.
- Use of normal dispersion reduces the bandwidth but makes the supercontinuum spectrally coherent.
- Recent research is focusing on extending the spectral range into the mid-infrared region beyond 10 μm.
- Such sources are useful for a variety of applications requiring molecular finger printing (food quality, gas sensing, medical imaging).