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

Supercontinuum Generation

- Output spectrum generated in a 75-cm section of microstructured fiber by launching 100-fs pulses 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.
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 ($\beta_m$) 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.
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

- 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.

(Heidt et al., Opt. Exp. 19, 3775, 2011)
SC with Low Noise and High Coherence


5-m-long fiber with:

\[ \gamma = 23 \text{ W}^{-1}/\text{km} \]
\[ \beta_2 \approx 5 \text{ ps}^2/\text{km} \]
\[ \beta_3 \approx 0.005 \text{ ps}^3/\text{km} \]

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

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

Middle:
Without Raman

Bottom:
With Raman included

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).

Demircan et al., PRL 110, 233901, (2013)
SC Generation by Multiple Scattering


- 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 from 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.
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.
Tellurite Fiber Pumped at 1.55 $\mu$m

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

- Tellurite fiber ($<1$ cm) pumped at 1.55 $\mu$m using 100-fs pulses.
- The resulting SC extended into the IR region up to 5 $\mu$m.
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 (ZrF₄-BaF₂-LaF₃-AlF₃-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.
Chalcogenide waveguide Pumped at 3.26 µm

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

- A 6.6-cm As$_2$S$_3$ waveguide pumped at 3.26 µm using 7.5-ps pulses.
- The SC extended up 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 $\mu$m 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.
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.
Chalcogenide Fiber Pumped at 4 µm


- 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.
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 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 $\mu$m

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

- A 8.5-cm-long $\text{As}_{40}\text{S}_{60}$ fiber pumped at 6.3 $\mu$m using 100-fs pulses. An OPO was used to tune the pump wavelength.

- The SC extends from 2–13 $\mu$m at a peak power of 7.2 MW.
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 fingerprinting (food quality, gas sensing, medical imaging).