Highly Nonlinear Fibers and Their Applications

Govind P. Agrawal

Institute of Optics
University of Rochester
Rochester, NY 14627

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Introduction

- Many nonlinear effects inside optical fibers depend on the parameter $\gamma = 2\pi n_2/(\lambda A_{\text{eff}})$.
- $n_2 \approx 2.6 \times 10^{-20}$ m^2/W for silica fibers.
- For telecommunication fibers $\gamma \sim 1$ W^{-1}/km.
- This value is too small for most applications, forcing one to employ high peak powers and long fiber lengths.
- Highly nonlinear fibers solve this problem ($\gamma > 10$ W^{-1}/km).

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Highly Nonlinear Fibers

Four different approaches employed in practice:

- Narrow-core fibers with Silica Cladding: A narrow core and high doping levels reduce A_{eff} and enhance γ.
- Tapered Fibers with Air Cladding: Standard fibers stretched by a factor of 50 or more; surrounding air acts as the cladding.
- Microstructured Fibers: Air holes introduced within the cladding; photonic crystal fibers, holey fibers, etc.
- Non-silica Fibers: Use a different material with large values of n_2: lead silicates, chalcogenides, tellurite oxide, bismuth oxide.

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Tapered Fibers

(a) D = 125 µm (b) Transition Region (c) D = 2.7 µm

(Lu and Knox, Opt. Exp.**12**, 347, 2004)

- Fiber stretched to reduce its cladding diameter to ∼2 μm.
- Air acts as the cladding material for the new narrow core.
- A large index step $(\Delta n = 0.45)$ keeps the mode confined to the new core even when core diameter is 1 μm or less.
- Tapered fibers often support multiple modes $(V > 2.405)$.

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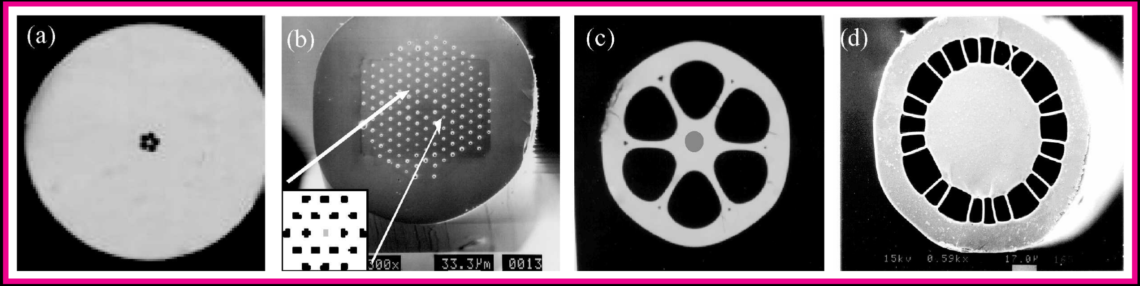
Microstructured Fibers



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

- A narrow core is surrounded by a silica cladding with embedded air holes.
- Such fibers are also known as “holey” fibers or *photonic crystal fibers* (PCF).
- Number of air holes varies from structure to structure.
- Hole size can vary from < 1 μm to > 5 μm depending on the fiber design.

Photonic Crystal Fibers

- PCFs were first made in 1996 (Russell's group); cladding contained a 2D periodic array of air holes.
- It was realized later that the periodic nature of air holes was not critical as long as the cladding has multiple air holes that reduce its refractive index below that of the silica core.
- Periodic nature becomes important in photonic bandgap fibers.
- The core of such fibers often contains air to which light is confined by the photonic bandgap.
- Such truly PCFs can act as a highly nonlinear medium if air is replaced with a suitable gas or liquid.
- When air was replaced with hydrogen, stimulated Raman scattering was observed at 100 times lower pulse energies.

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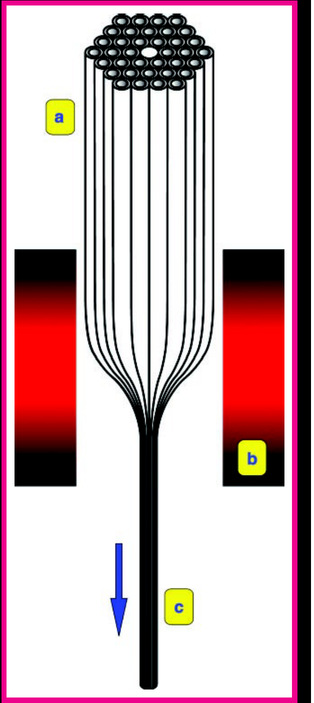
Fabrication Technique

- A perform is first made by stacking capillary tubes of pure silica (Ruselll, Science, **299**, 358, 2003).
- Preform is then drawn into a fiber.
- A polymer coating added to protect the fiber.
- Air channel created by removing the central silica rod.
- This channel can later be filled with a gas or liquid that acts as the nonlinear medium.
- Such fibers can be made relatively long.
- They are as easy to handle as conventional fibers.



Applications of HNLFs

- Highly nonlinear fibers have lead to novel nonlinear effects.
- Supercontinuum generation has attracted most attention because of its applications for WDM sources, metrology, tomography, etc.
- Large Raman-induced frequency shifts allow tuning of mode-locked lasers on the long-wavelength side.
- Harmonic generation can be used to shift laser wavelength toward the blue side.
- Main advantage of using fibers as a nonlinear medium is that their nonlinear response is ultrafast.
- Instantaneous nature of the nonlinear effects can be used for high-speed switching and ultrafast signal processing.

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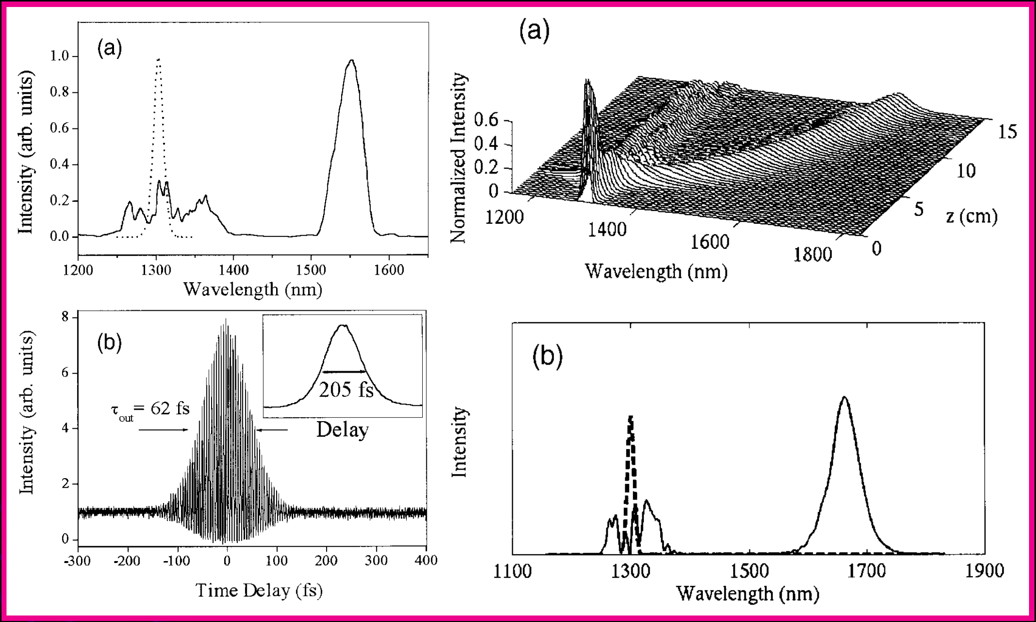
Raman-Induced Frequency Shift (RIFS)

- The spectrum of ultrashort pulses shifts toward the red side in anomalous-dispersion regime.
- This effect was first observed in 1986; also known as the soliton self-frequency shift.
- RIFS scales with pulse width as T_0^{-4} and becomes quite large for short pulses.
- It can also occur in the normal-dispersion regime but its magnitude is relatively small because of rapid pulse broadening;
  Santhanam and Agrawal, Opt. Commun. **222**, 413 (2003).
- Very large RIFS can occur in highly nonlinear fibers.
- RIFS can be used for tuning wavelength of a mode-locked laser.

Experimental Evidence



(Liu et al, Opt. Lett. **26**, 358, 2001)

Left: Measured (a) spectrum and (b) autocorrelation trace at the end of a tapered fiber. Right: Numerically simulated (a) evolution of pulse spectrum and (b) output spectrum.

Experimental Details

- 200-fs pulses at 1.3 μm were used from a parametric oscillator pumped by a Ti:sapphire-laser.
- Pulses launched into a 15-cm-long tapered microstructured fiber (core diameter 2–3 μm).
- Most of the pulse energy appeared in a red-shifted soliton that was considerably narrower than the input pulse (62 fs).
- RIFS of up to 350 nm (50 THz) observed experimentally.
- RIFS could be tuned as it depends on pulse's peak power.
- Numerical simulations predict the observed behavior well.
- Physical Mechanism behind large RIFS: Fission of Higher-Order Solitons.

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Fission of Higher-Order Solitons

- Input pulses correspond to a higher-order soliton: $N = (\gamma P_0 T_0^2/|\beta_2|)^{1/2}$.
- Higher-order effects leads to its fission into much narrower fundamental solitons.

$$T_k = \frac{T_0}{2N+1-2k}, \qquad P_k = \frac{(2N+1-2k)^2}{N^2}P_0.$$

- Spectrum of narrowest soliton shifts most: $\Delta\nu_R = -\frac{4T_R|\beta_2|z}{15\pi T_k^4}$.
- When $N = 2.1$, two solitons have widths $T_0/3.2$ and $T_0/1.2$.
- RIFS enhanced for narrower soliton by a factor of $(3.2)^{-4} \equiv 105$.
- The predicted behavior agrees with the experimental data.

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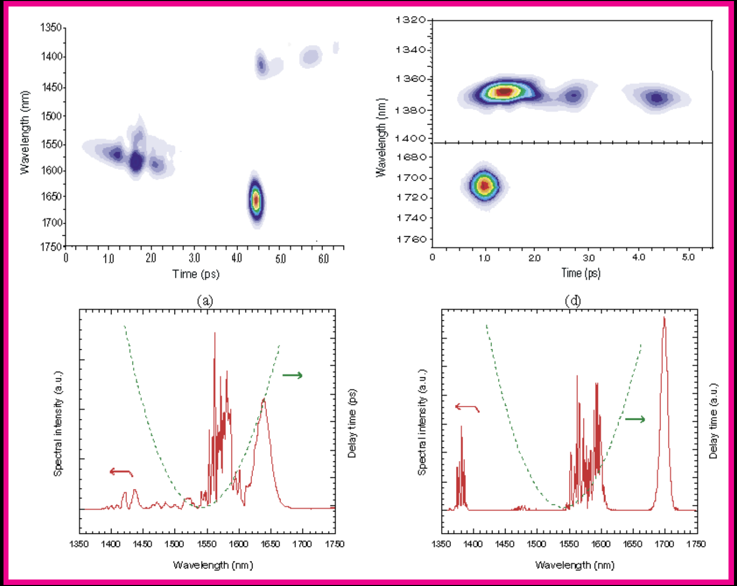
X-FROG Measurements



Nishizawa and Goto, Opt. Exp. **8**, 328 (2001)

- X-FROG traces and spectra of 110-fs input pulses at the output of 10 m and 180 m long fibers.
- Note the appearance of radiation near 1400 nm.

Nonsolitonic Radiation

- Ultrashort solitons perturbed by the third-order dispersion emit dispersive waves (an example of Cherenkov radiation).
- Energy is transferred at a wavelength for which phase velocity of radiation matches that of the soliton:

$$\sum_{m=2}^{\infty} \frac{\beta_m(\omega_s)}{m!} \Omega_d^m = \frac{1}{2}\gamma P_s \quad (\Omega_d = \omega_d - \omega_s).$$

- Solution when dispersion up to third-order is included:

$$\Omega_d \approx -\frac{3\beta_2}{\beta_3} + \frac{\gamma P_s \beta_3}{3\beta_2^2}.$$

- Frequency shift $\Omega_d > 0$ when $\beta_2 < 0$ and $\beta_3 > 0$.
- Radiation emitted at shorter wavelengths and propagates in the normal-GVD regime (Karlsson, Phys. Rev. A **51**, 2602, 1995).

Four-Wave Mixing in HNLFs

- Higher-order dispersive effects are important for some fibers;
  Yu, McKinistrie, and Agrawal, Phys. Rev. E **52**, 1072 (1995).
- Energy conservation requires idler frequency $\omega_i = 2\omega_p - \omega_s$.
- Momentum conservation leads to the phase-matching condition

$$\Delta\beta = \Delta\beta_L + \Delta\beta_{NL} = \sum_{m=2,4,\ldots}^{\infty} \frac{\beta_m(\omega_p)}{m!}\Omega_s^m + 2\gamma P_0 = 0.$$

- $\Omega_s = \omega_s - \omega_p$ is the shift from pump frequency.
- In the anomalous-GVD regime ($\beta_2 < 0$), $m = 2$ term dominates, and frequency shift is given by $\Omega_s = (2\gamma P_0/|\beta_2|)^{1/2}$.
- In the normal-GVD regime, the signal and idler frequencies are set by higher-order dispersive terms.

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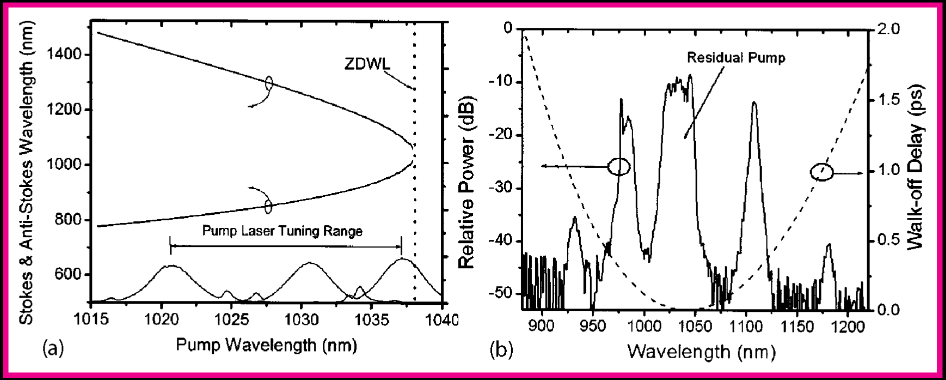
Broadly Tunable Parametric Oscillators



(Deng et al., Opt. Lett. **30**, 1234, 2005)

- FWM in the normal-GVD regime of a highly nonlinear fiber can be used to enhance the tuning range of parametric oscillators.
- In a 2005 experiment, pulses shorter than 0.5 ps were tunable over a 200-nm range when pumped synchronously using 1.3-ps pulses.
- Ring cavity contained only a 65-cm-long PCF to minimize the walk-off effects.

Supercontinuum Generation

- Ultrashort pulses are affected by a multitude of nonlinear effects, such as SPM, XPM, FWM, and SRS, together with dispersion.
- All of these nonlinear processes are capable of generating new frequencies outside the input pulse spectrum.
- For sufficiently intense pulses, the pulse spectrum can become so broad that it extends over a frequency range exceeding 100 THz.
- Such extreme spectral broadening is referred to as *supercontinuum generation*.
- This phenomenon was first observed in solid and gases more than 35 years ago (late 1960s.)
- Book: R. R. Alfano, Ed. *Supercontinuum Laser Source*, 2nd ed. (Springer, New York, 2006).

Use of Femtosecond Pulses

- Use of femtosecond pulses became practical with the advent of highly nonlinear fibers.
- Zero-dispersion wavelength of such fibers lies near 800 nm.
- Tunable Ti:sapphire lasers operate in this wavelength.
- Starting in 2000, mode-locked pulses from such pulses were used for supercontinuum generation.
- In the first 2000 experiment, 100-fs pulses at 790 nm were launched into 75-cm section of a microstructured fiber.
- Pulses formed a higher-order soliton in the presence of anomalous dispersion.

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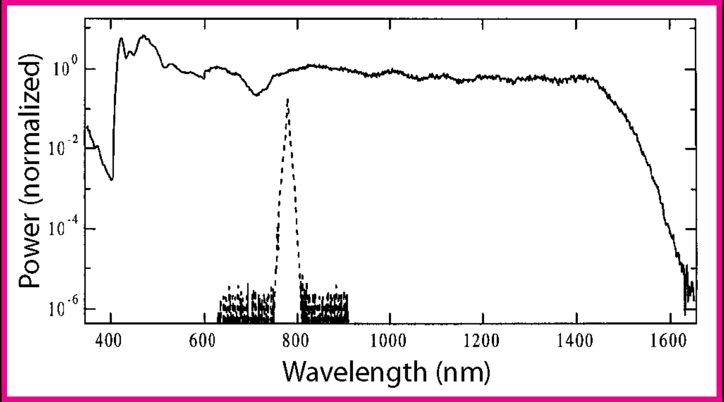
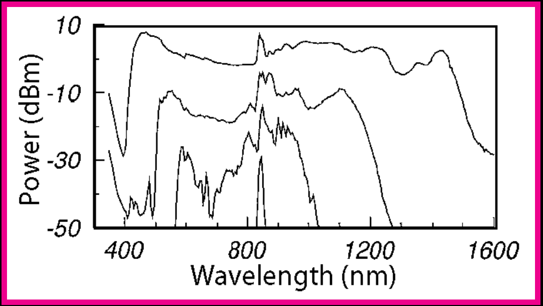
SC Generation in a microstructured fiber



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

- Output spectrum generated in a 75-cm section of microstructured fiber using 100-fs pules with 0.8 pJ energy.
- Even for such a short fiber, supercontinuum extends from 400 to 1600 nm.
- Supercontinuum is also relatively flat over the entire bandwidth.

SC Generation in a Tapered fiber



(Birk et al., Opt. Lett. **25**, 1415, 2000)

- Output spectra for a 9-cm tapered fiber with 2-μm waist.
- 100-fs pulses with average power of 380, 210, and 60 mW (from top to bottom).
- Relatively flat supercontinuum extends from 400 to 1600 nm.
- Nearly symmetric nature of supercontinuum indicates a different physical mechanism for femtosecond pulses.

SC Generation through Soliton Fission

- Input pulses correspond to a higher-order soliton of large order; typically $N = (\gamma P_0 T_0^2/|\beta_2|)^{1/2}$ exceeds 10.
- Higher-order effects leads to their fission into much narrower fundamental solitons: $T_k = T_0/(2N+1-2k)$
- Each of these solitons is affected by intrapulse Raman scattering.
- Spectrum of each soliton is shifted toward longer and longer wavelengths with propagation inside the fiber.
- At the same time, each soliton emits nonsolitonic radiation at a different wavelength on the blue side.
- XPM and FWM generate additional bandwidth and lead to a broad supercontinuum.

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Numerical Modeling of Supercontinuum

- Soliton fission studied by solving the generalized NLS equation:

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

- It is important to include the dispersive effects and intrapulse Raman scattering as accurately as possible.
- Terms up to $M = 15$ are included for numerical simulations.
- Raman response included through the measured gain spectrum.
- Most features observed experimentally can be explained, at least qualitatively.

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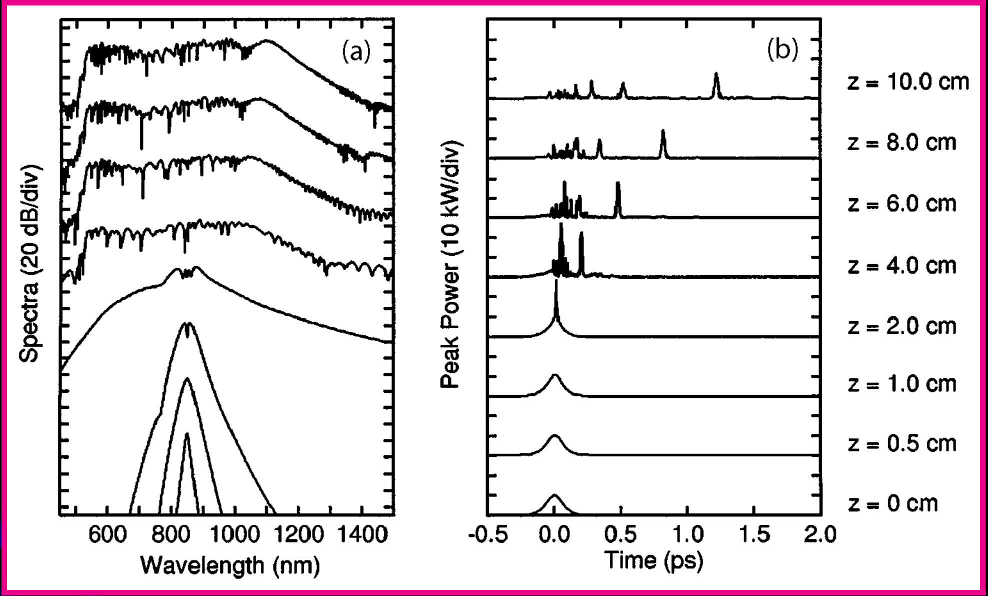
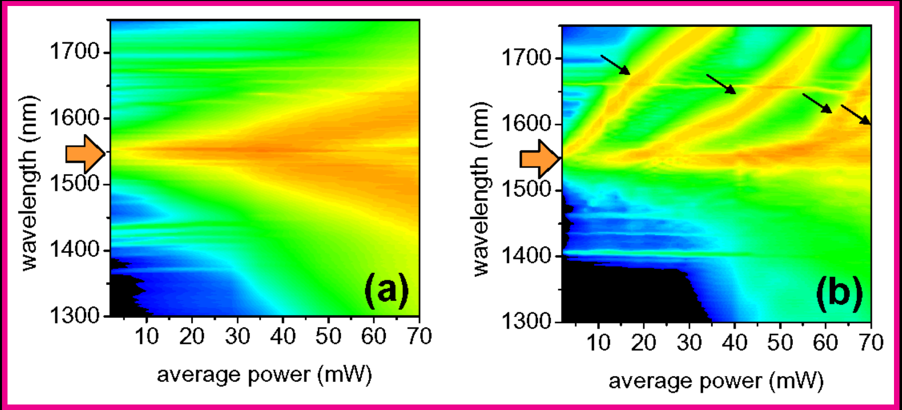
Numerical Simulations



(Dudley and Coen, JSTQE **8**, 651, 2002)

- 150-fs pulses with 10-kW peak power launched into a 10-cm tapered fiber with 2.5-μm waist.
- Evolution of pulse spectrum and shape along the fiber.

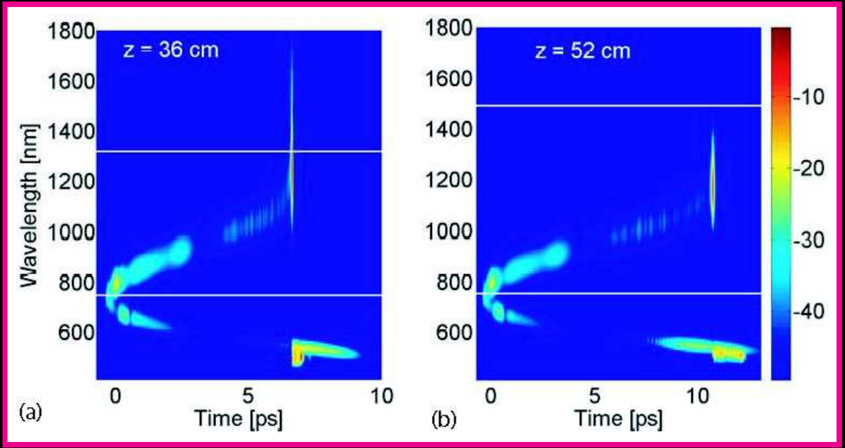
SC Genertaion in Non-silica Fibers



Omenetto et al., Opt. Exp. **14**, 4928 (2006)

- Spectra for (a) 0.57 cm and (b) 70 cm long lead-silicate PCF.
- Number of solitons with RIFS increases with P_{av} for long fiber.
- Soliton fission does not occur for the short fiber; broad supercontinuum (350 to 3000 nm) generated predominantly through SPM.
- n_2 larger by a factor of $>$10 for lead silicate glasses.

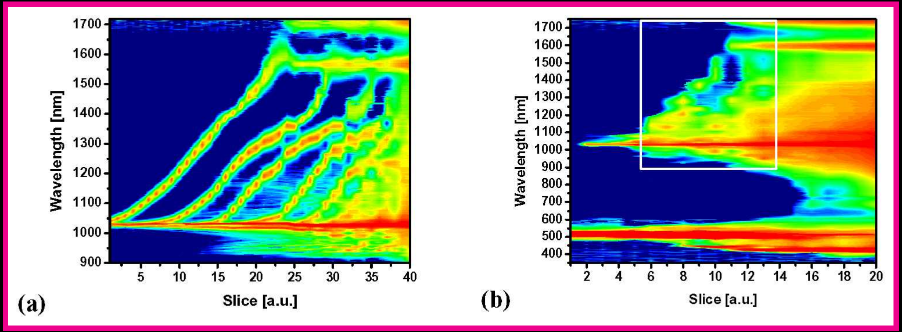
Soliton Trapping



Frosz et al., Opt. Exp. **13**, 4614 (2005)

- In a numerical study, XPM coupling led to soliton-pair formation.
- Two PCFs are identical with the only difference that spacing of 1-μm-diameter air holes changes from (a) 1.2 to (b) 1.3 μm.
- Horizontal lines indicate ZDWLs of the fiber.

Pump-Probe Configuration



Schreiber et al., Opt. Exp. **13**, 9556 (2005)

- Measured spectra at the output of a 5-m-long fiber when 30-fs input pulses were propagated (a) without and (b) with weak SHG pulses.
- Fiber had two ZDWLs located at 770 and 1600 nm.
- Supercontinuum does not extends in the spectral region below 900 nm when only pump pulses are launched.
- XPM effects extend the supercontinuum in the visible region.

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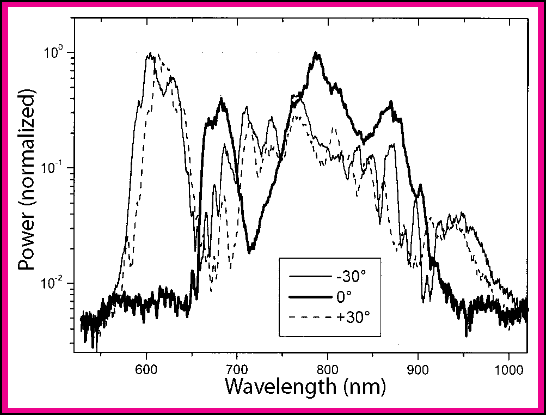
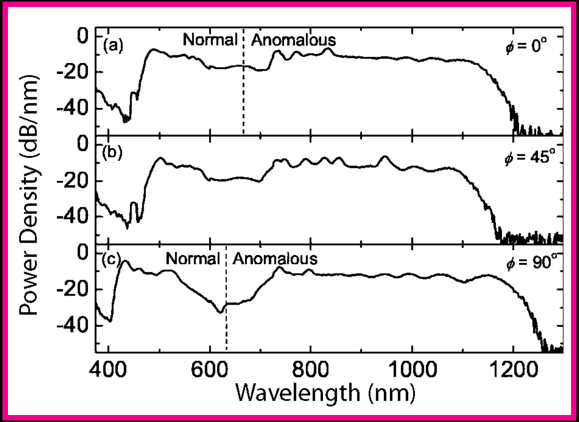
Polarization Effects





Apolonski et al., JOSA B (2002); Lehtonen et al., APL (2003)

- Typically, PCFs do not have a circular core.
- Supercontinuum spectra change with input state of polarization (SOP) because of birefringence.
- Even at a given input SOP, output may exhibit complicated polarization properties.

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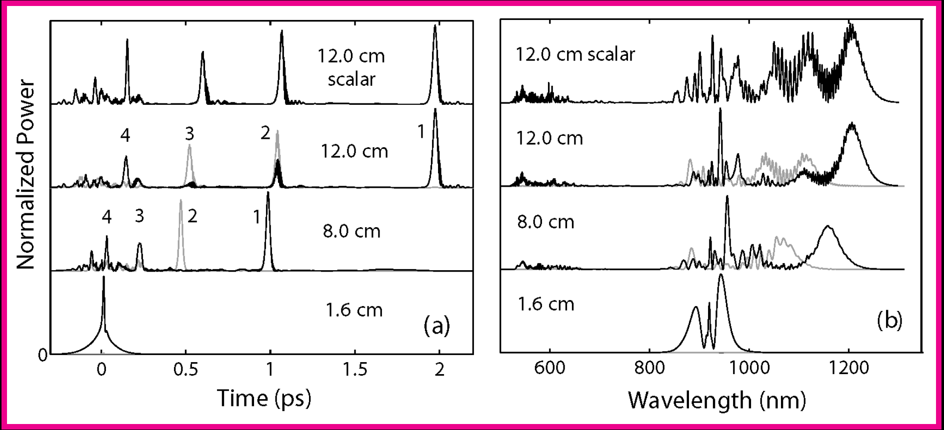
Vector NLS Equation

- XPM coupling between two orthogonally polarized pulses should be included.
- Mathematically, we should solve the vector NLS equation:

$$
\begin{aligned}
\frac{\partial|A\rangle}{\partial z} &+ \frac{1}{2}\left(\alpha + i\alpha_1\frac{\partial}{\partial t}\right)|A\rangle + \sum_{m=2}^{M} i^{m-1}\frac{\beta_m}{m!}\frac{\partial^m|A\rangle}{\partial t^m} \\
&= \frac{i}{2}\left(\Delta\beta + i\Delta\beta_1\frac{\partial}{\partial t}\right)\sigma_1|A\rangle + i\left(\gamma + i\gamma_1\frac{\partial}{\partial t}\right)|Q(z,t)\rangle
\end{aligned}
$$

$$
\begin{aligned}
|Q(z,t)\rangle &= \frac{2}{3}(1-f_R)\left[\langle A|A\rangle\right]|A(z,t)\rangle + \frac{1}{3}(1-f_R)\left[\langle A^*|A\rangle\right]|A^*(z,t)\rangle \\
&+ f_R|A(z,t)\rangle \int_{-\infty}^{t} h_R(t-t')\langle A(z,t')|A(z,t')\rangle\,dt'.
\end{aligned}
$$

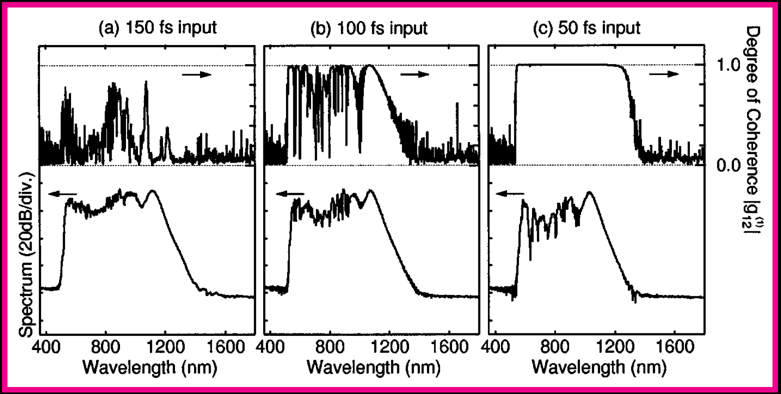
Vector Nature of Soliton Fission



Lu et al., PRL **93**, 183901 (2004)

- Propagation in ideal isotropic fiber (no birefringence).
- Input SOP slightly elliptical (32 dB extinction ratio).
- A 150-fs pulse with $N \approx 12$ is launched into a tapered fiber.
- Different solitons exhibit different SOPs.

Coherence Properties



Dudley and Coen, JSTQE **8**, 651 (2002)

- Degree of spectral coherence: $g_{12}(\omega) = \frac{\langle \tilde{A}_1^*(L,\omega)\tilde{A}_2(L,\omega)\rangle}{[\langle|\tilde{A}_1(L,\omega)|^2\rangle\langle|\tilde{A}_2(L,\omega)|^2\rangle]^{1/2}}$
- It is measured by interfering two successive pulses in a pulse train and recording the contrast of spectral fringes.
- Shorter pulses provide a more coherent supercontinuum.

Conclusions

- Recent advances in designing HNLFs have led to a number of novel applications of nonlinear fiber optics.
- Raman-induced frequency shift can be used to tune ultrashort pulses on the longer-wavelength side.
- Four-wave mixing can be used for enhancing the tuning range of parametric oscillators.
- Supercontinuum generated in such fibers is useful for metrology, coherence tomography, and other application requiring wideband sources.
- Photonic bandgap fibers whose core is filled with nonlinear gases and liquids are likely to lead to many other advances.
- This is an exciting are of research for new graduate students.

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Further Reading

- G. P. Agrawal, *Nonlinear Fiber Optics*, 4th ed. (Academic Press, 2007).
- J. M. Dudley, G. Genty, and S. Coen, “Supercontinuum generation in photonic crystal fibers,” *Rev. Modern Physics*, **78**, 1135-1184 (2006).
- R. R. Alfano, Ed., *The Supercontinuum Laser Source*, 2nd ed. (Springer, New York, 2006).

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