Supercontinuum Generation in Optical Fibers and its Biomedical Applications

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Introduction

- Optical Fibers were developed during the 1960s with medical applications in mind (endoscopes).
- During 1980–2000 optical fibers were exploited for telecommunications and now form the backbone for the Internet.
- Biomedical applications of fibers increased after 2000 with the advent of photonic crystal and other microstructured fibers.
- Supercontinuum (ultrabroad coherent spectrum) is critical for many biomedical applications.
- Nonlinear effects inside fibers play an important role in generating a supercontinuum.
- This talk focuses on Supercontinuum generation with emphasis on their biomedical applications.

Supercontinuum History

- Discovered 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.
- A 20-m-long fiber was employed in 1975 to produce 180-nm wide supercontinuum using Q-switched pulses from a dye laser [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 into 1-km-long single-mode fiber [Islam et al., JOSA B **6**, 1149 (1989)].

Supercontinuum History

- Supercontinuum work with optical fibers continued during 1990s with telecom applications in mind.
- By 1995, 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 are known as the photonic-crystal or microstructured fibers.
- These were developed after 1996 in an attempt to control the dispersive and nonlinear properties of silica fibers.

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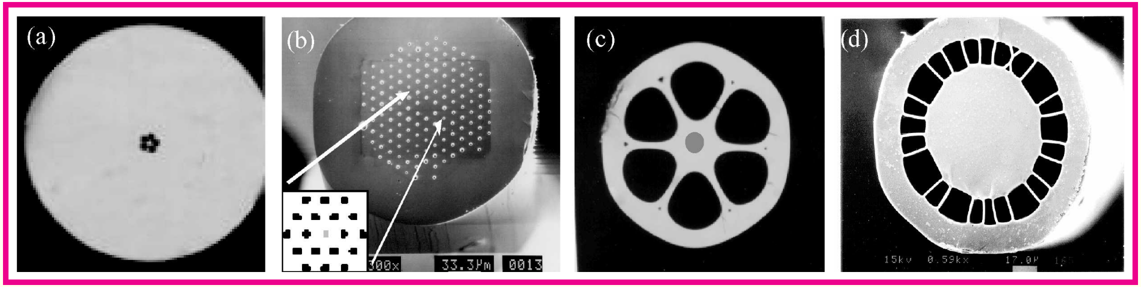
Microstructured Fibers



(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.

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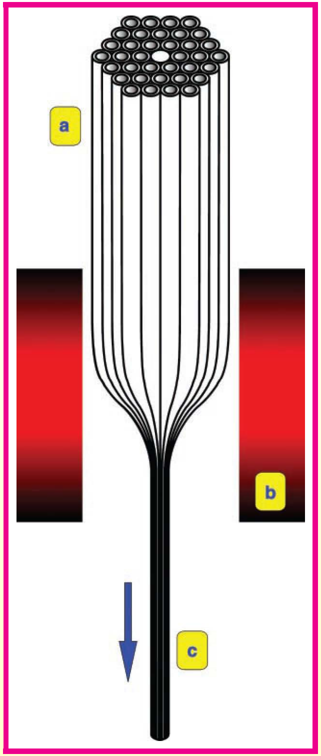
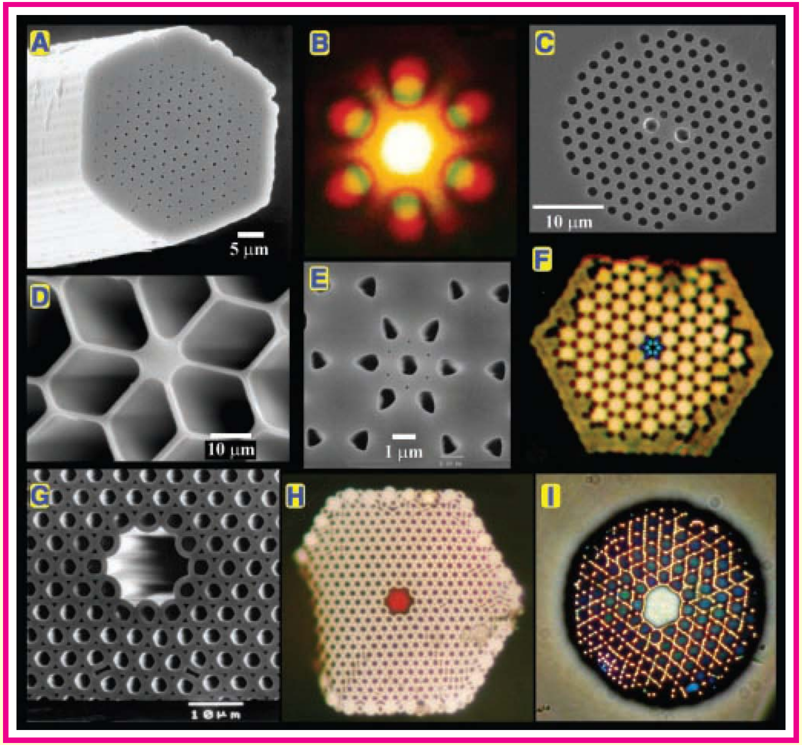
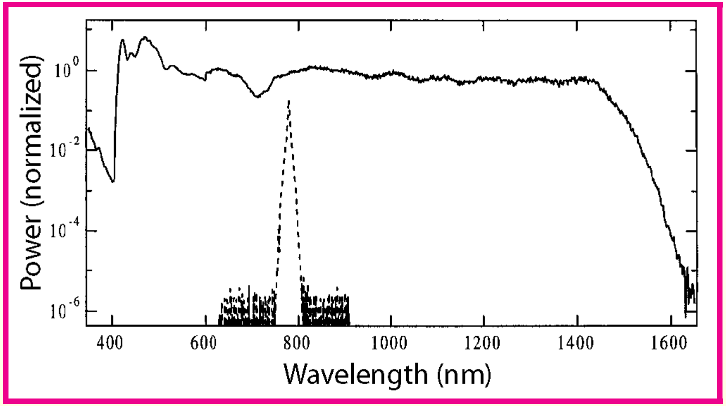
Photonic Crystal Fibers





(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 using 100-fs pules with 0.8 pJ energy.
- Supercontinuum extends from 400 to 1600 nm.
- It is also relatively flat over the entire bandwidth.
- Useful in biomedical imaging as a broadband source.

Role of Soliton Fission

- 100-fs input pulses proapgate 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 TOD and intrapulse Raman scattering.
- 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.
- XPM and FWM generate additional bandwidth and produce a broad supercontinuum.

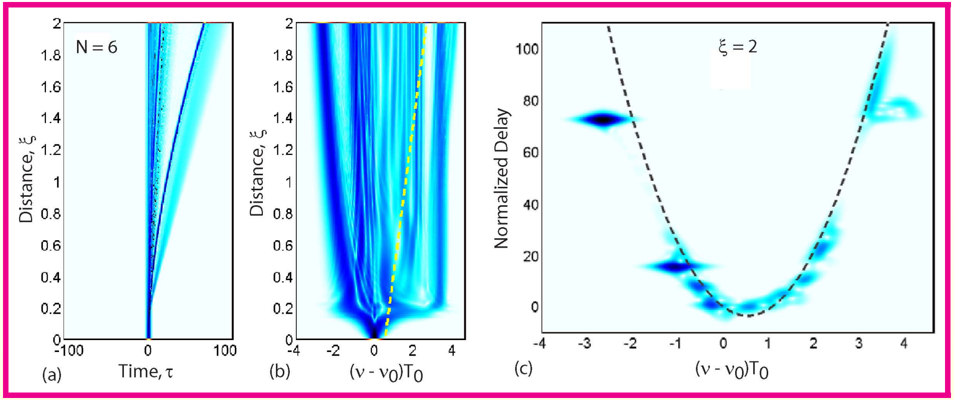
Numerical Modeling of Supercontinuum

- Soliton fission 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 and intrapulse Raman scattering 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.

Numerical Simulations

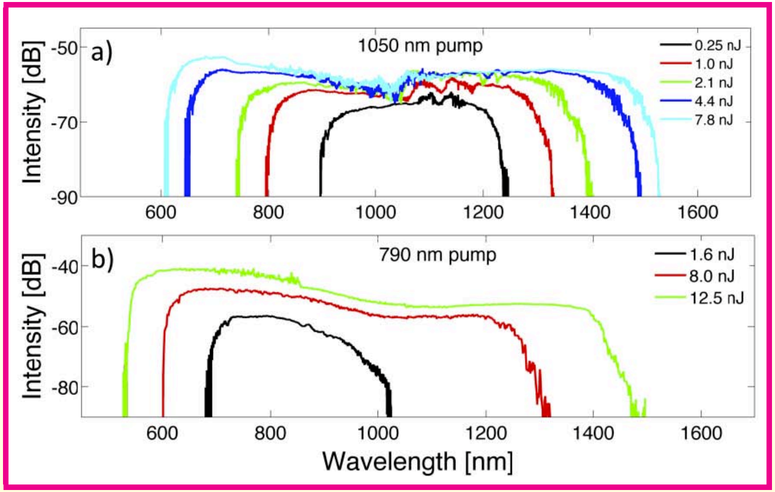


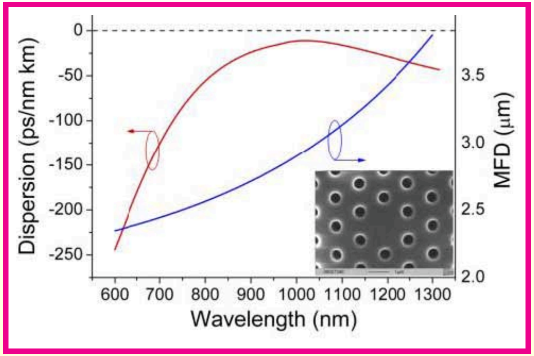
- Temporal and spectral evolution of a $N = 6$ soliton over $2L_D$.
- Corresponding spectrogram at $z = 2L_D$. Dashed curve shows changes in $d\beta/d\omega$ with frequency.
- Spectrogram shows multiple solitons and their dispersive waves.
- Temporal overlap between the two leads to new effects through XPM and FWM.

High-Quality Supercontinuum

- Good coherence and noise properties of supercontinuum are critical for biomedical applications
- Fission of femtosecond solitons 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.

PCFs with Normal Dispersion

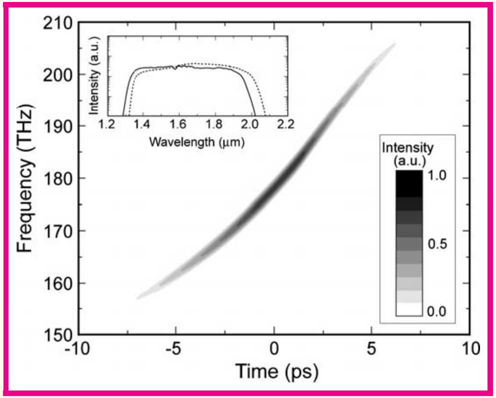


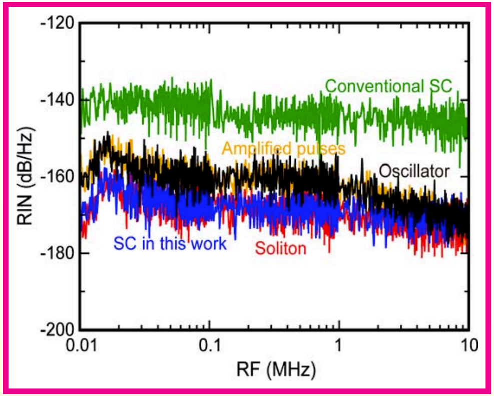


(Heidt et al., Opt. Exp. **19**, 3775, 2011)

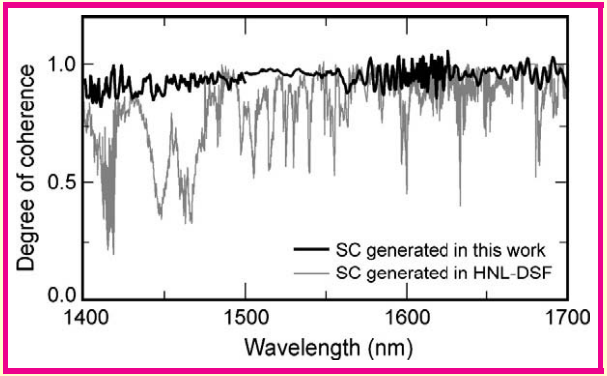
- 50-fs pulses were launched into a 50-cm-long PCF.
- Relatively coherent supercontinua for pulse energies 1-8 nJ.
- Broad bandwidth suitable for various biomedical applications.

Dispersion-Flattened Fibers





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



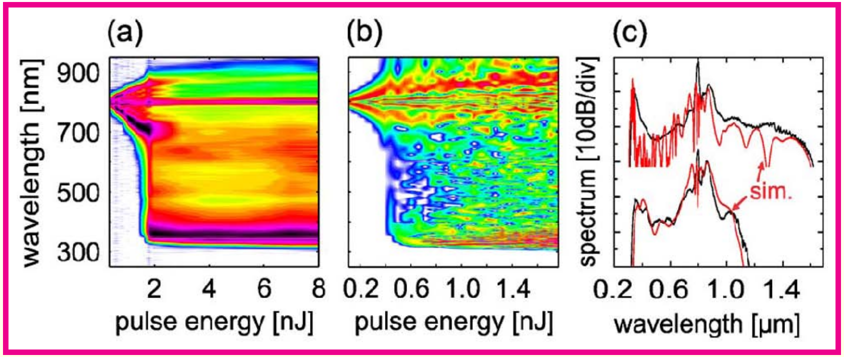
5-m-long fiber with:

$\gamma = 23$ W^{-1}/km

$\beta_2 \approx 5$ ps^2/km

$\beta_3 \approx 0.005$ ps^3/km

Tapered Photonic Crystal Fibers



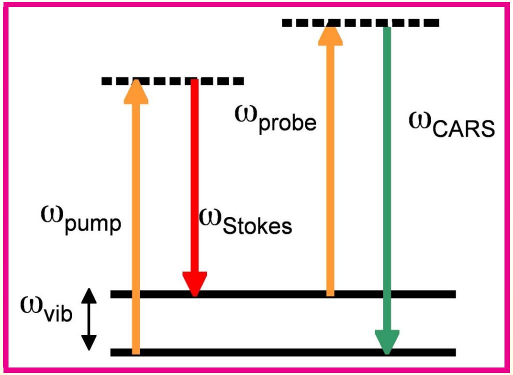
(Stark et al., Opt. Lett. **37**, 770, 2012)

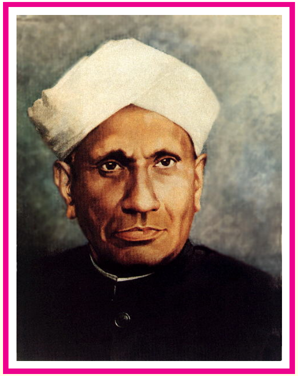
- Experimental (a) and simulated (b) SC spectra when 110-fs pulses launched into a tapered PCF.
- (c) SC spectra at input pulse energies of 2 and 5 nJ.
- Core diameter tapered form 4.5 μm to 0.6 μm over 1 cm.
- Tapering helps to extend the supercontinuum into the UV region.

Supercontinuum-Based Biomedical Imaging

- Several companies sell fiber-based supercontinuum sources (NKT Photonics, Fianium, Koheras, Leukos, etc.].
- This has led to their use in biomedical imaging.
- Imaging techniques are known by a variety of names.
- I focus on 3 techniques: CARS microscopy; STED microscopy; optical coherence tomography (OCT).

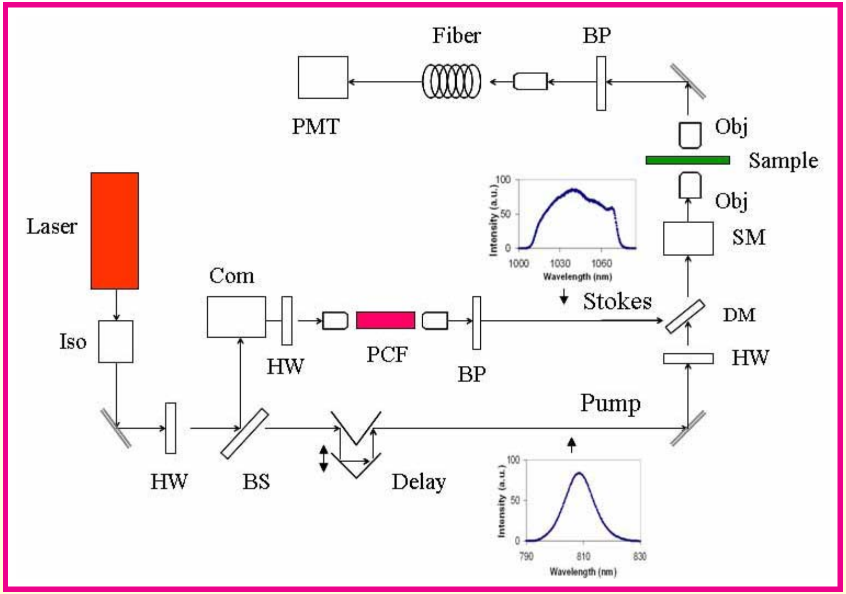
CARS Nonlinear Process





- Coherent anti-Stokes Raman scattering (CARS) is a well-known nonlinear process (Maker and Terhune, Phys. Rev., 1965).
- Pump and Stokes beam at ω_p and ω_s drive coherently a vibrational resonance at the frequency $\omega_{\rm vib} = \omega_p - \omega_s$ (optical phonons).
- CARS signal generated at $\omega_{\rm CARS} = 2\omega_p - \omega_s$.
- CARS is a kind of Raman-enhanced four-wave mixing process.

CARS Microscopy



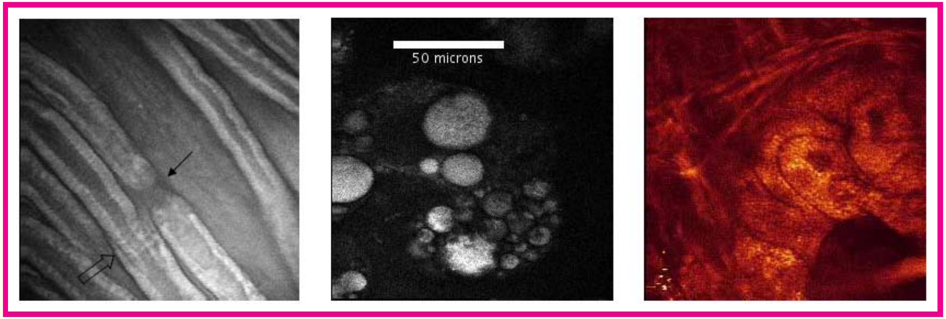
(Murugkar et al., Opt. Exp. **15**, 14028, 2007)

Laser pulses (65-fs) split to produce pump and Stokes beams.

Bandpass filter after the PCF selects the Stokes bandwidth.

Different Stokes frequencies excite different molecules in sample.

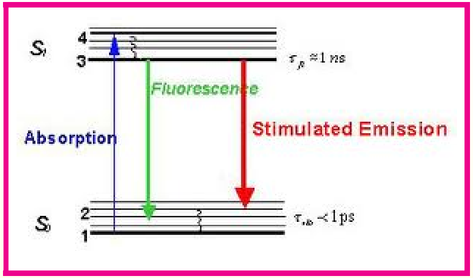
CARS Microscopy

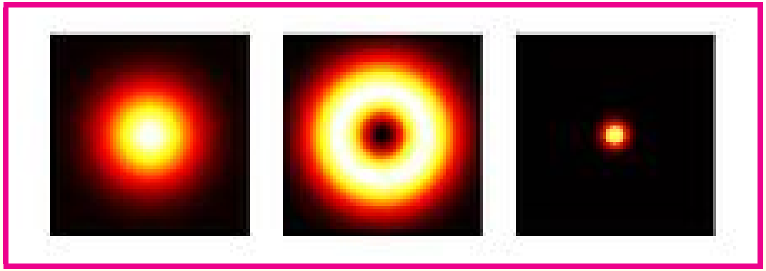


(Murugkar et al., Opt. Exp. **15**, 14028, 2007)

- Stokes pulses, broadened spectrally using a PCF, are sent to the sample together with pump pulses.
- Anti-Stokes signal generated inside the sample is used for microscopy.
- (a) Live rat dorsal root axon; (b) lipid droplets in a cell culture; (c) sebaceous gland in a mouse ear.
- Resolution is typically limited to 2-3 μm.

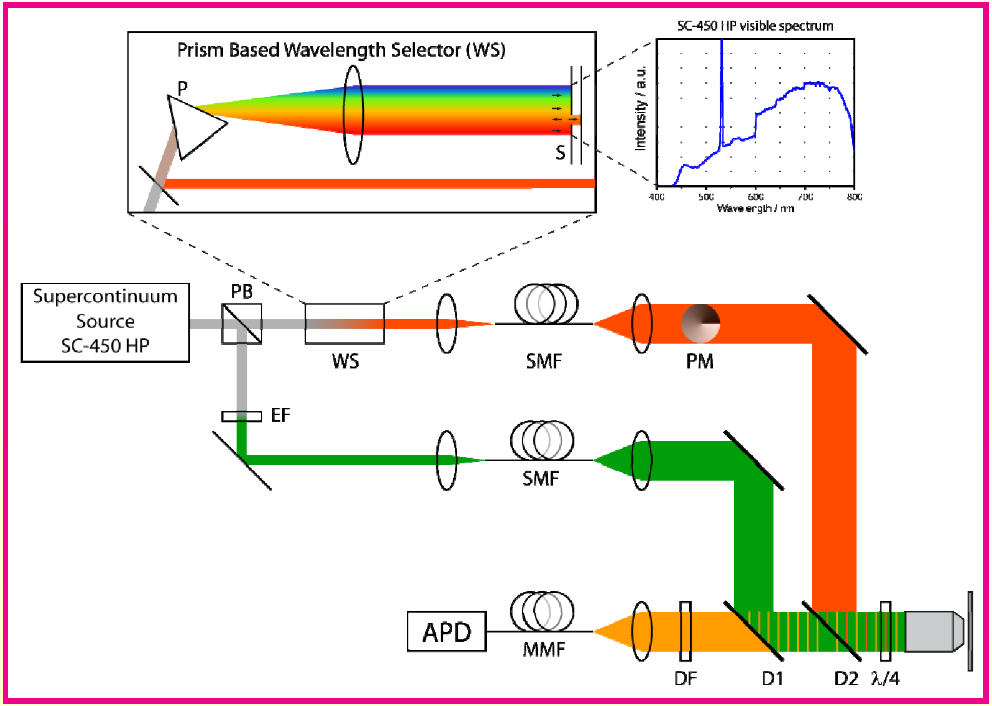
STED Microscopy





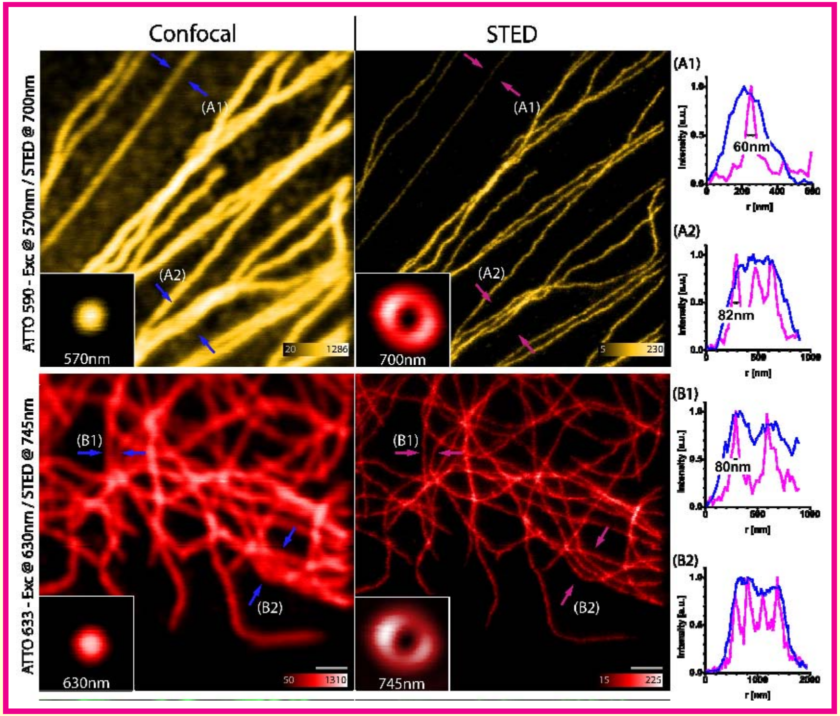
- Stimulated-emission depletion (STED) microscopy was first proposed in 1994 (Hell and Wichmann, Opt. Lett. **19**, 780, 1994).
- Fluorescence is suppressed in the off-center region using a second beam that removes excited molecules through stimulated emission.
- Nanoscale resolution ($\lambda/50$) realized by 2005 using a doughnut-shape STED pulsed beam.
- A fiber-based supercontinuum source was used by 2008.

STED Setup



(Wildanger et al., Opt. Exp. **16**, 9614, 2008)

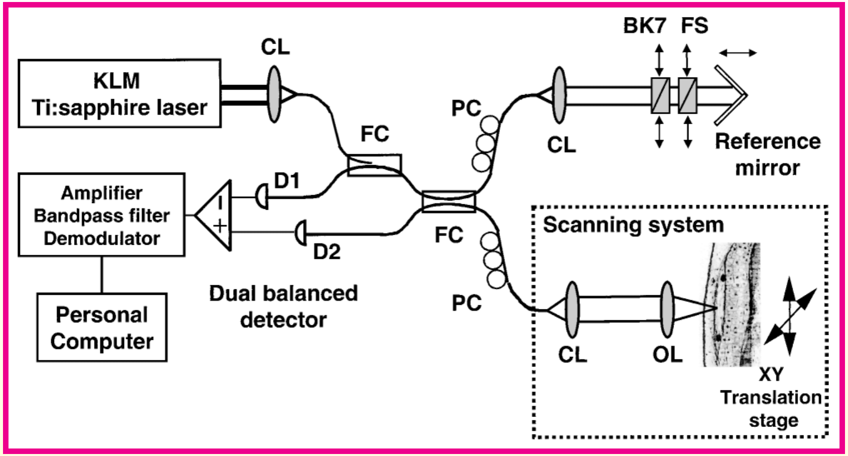
STED Results



(Wildanger et al., Opt. Exp. **16**, 9614, 2008)

Immunolabeled tubulin fibers imaged at 570 nm and 630 nm.

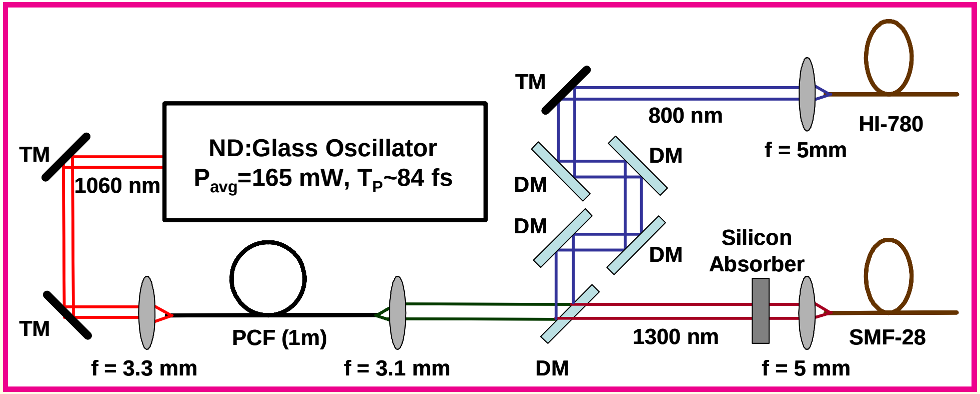
Optical Coherence Tomography (OCT)



(Drexler et al., Opt. Lett. **24**, 1221, 1999)

- A linear imaging technique based on Michelson interferometry.
- Image resolution ($\Delta z = c\tau_c$) depends on the coherence time τ_c.
- Supercontinuum sources provide a resolution of $< 1\ \mu$m.

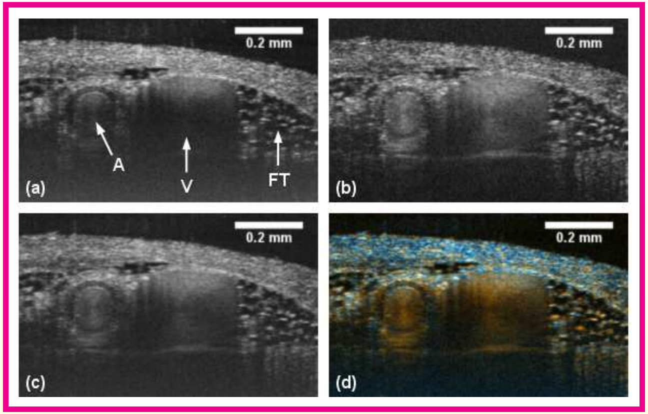
Dual-Band OCT



(Fujimoto et al., Opt. Exp. **14**, 1145, 2006)

- OCT is performed simultaneously using two spectral bands located near 800 and 1300 nm.
- Image resolution $< 3\ \mu$m at 800 and $< 5\ \mu$m at 1300 nm.
- Combined *in vivo* images of good quality possible.

Dual-Band OCT



(Cimalla et al., Opt. Exp. **17**, 19486, 2009)

- Simultaneous *in vivo* scans of murine saphenous artery (A), vein (V) and perivascular fat tissue (FT) during the diastole.
- (a) Image at 800 nm; (b) same image at 1250 nm.
- (c) Compounded image of (a) and (b).
- (d) Color-encoded differential image.

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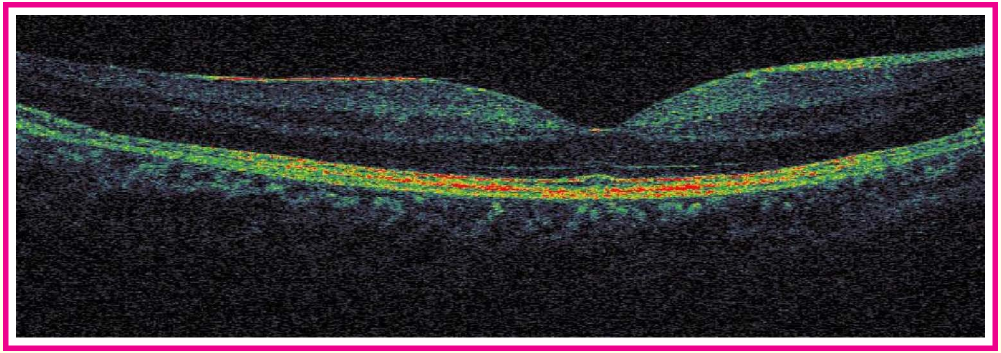
High-Resolution OCT



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

- OCT *in vivo* image of human retina around fovea.
- Observed axial resolution was 2.1 μm in tissue.
- A Gaussian-shape 150-nm-wide supercontinuum was employed for this image.
- OCT is an established medical imaging technique. It is often used to image anterior segment of the eye or the retina.

Concluding Remarks

- Optical fibers were developed during the 1950s and used for biomedical applications during the 1960s.
- They became relevant for telecommunications after 1970 with the development of low-loss fibers.
- By 2000, more than 60 million kilometers of fiber was installed worldwide (on land and in the oceans).
- Biomedical applications of optical fibers are attracting attention in recent years.
- Nonlinear effects in optical fibers make it possible to create a supercontinnum whose bandwidth exceeds 100 THz.
- Such sources are useful for tissue tomography and nonlinear microscopy (biomedical imaging).