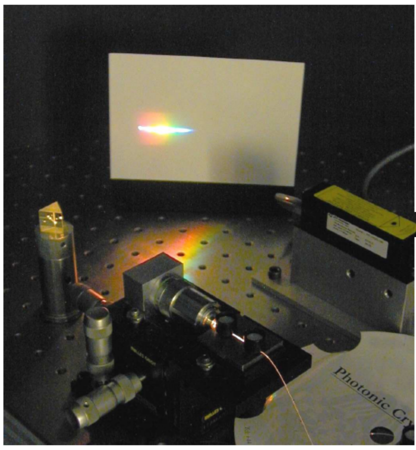

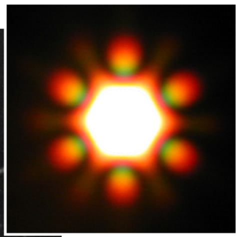

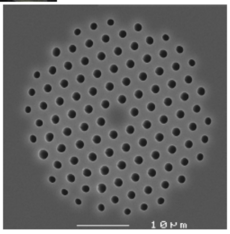

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Supercontinuum generation by Photonic Crystal Fibers

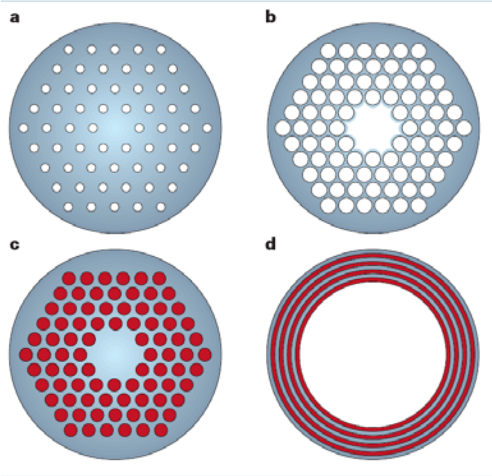
Roland Michaely

Laboratoire d'Optique Biomédicale, Ecole Polytechnique Fédérale de Lausanne
lob.epfl.ch

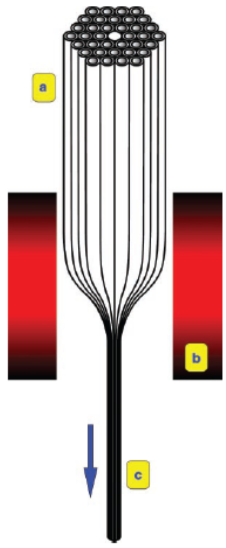
Outline

1. Photonic Crystal Fibres
2. Supercontinuum
3. Physics of supercontinuum generation
4. Broadband light sources
5. Experimental setups
6. Applications
    - FDOCT

1.PHOTONIC CRYSTAL FIBRES

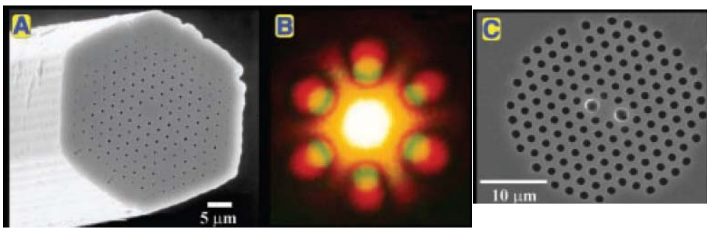


Different designs of PCF waveguide. **a** shows a single-mode fibre with a pure silica core surrounded by a reduced-index photonic crystal cladding material. The guidance is by modified total internal reflection.
b is an air-guiding fibre in which light is confined to a **hollow core** by the bandgap of the 2D air–glass photonic crystal cladding.
In **c**, the light is confined to a low-index region by a photonic bandgap, but the core is made of pure silica (**solid core**) while the holes in the cladding are filled with a highindex liquid.
d shows a hollow cylindrical multilayer fibre with an all-solid cladding. In these pictures, white represents air, blue represents a low-index solid such as silica and red represents a high-index material.

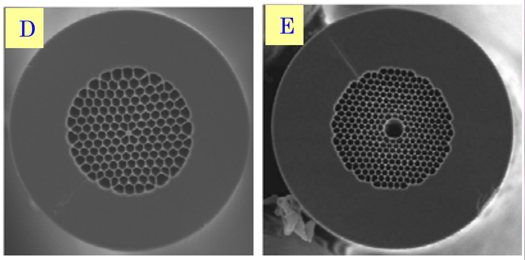


• Birks TA, Knight JC, Russell PS, *Endlessly single-mode photonic crystal fiber*, OPTICS LETTERS 22 (13): 961-963 JUL 1 1997, Times Cited: 596.
• Russell P, *Photonic crystal fibers*, SCIENCE 299 (5605): 358-362 JAN 17 2003, Times Cited: 415.
• Knight JC, Broeng J, Birks TA, et al., Photonic band cap guidance in optical fibers, SCIENCE 282 (5393): 1476-1478 NOV 20 1998 Times Cited: 378

1.PHOTONIC CRYSTAL FIBRES



(**A**) SEM of an endlessly single-mode solid core PCF. (**B**) Far-field optical pattern produced by (A) when excited by red and green laser light. (**C**) SEM of a recent birefringent PCF.



(D) Solid core PCF. This example shows a fiber designed to provide high nonlinearity by strongly confining the light in the small central core. Such fibers can be used to create supercontinuum radiation from the femtosecond output of a Ti:Sapphire laser at 800 nm wavelength

(E) Hollow core PCF. An empty core is embedded in a photonic crystal cladding, formed by large air holes in silica (fraction of hole area to total cladding area >91%). Up to 95% of the light is travelling in the hollow core and the holes in the cladding, and not in the glass

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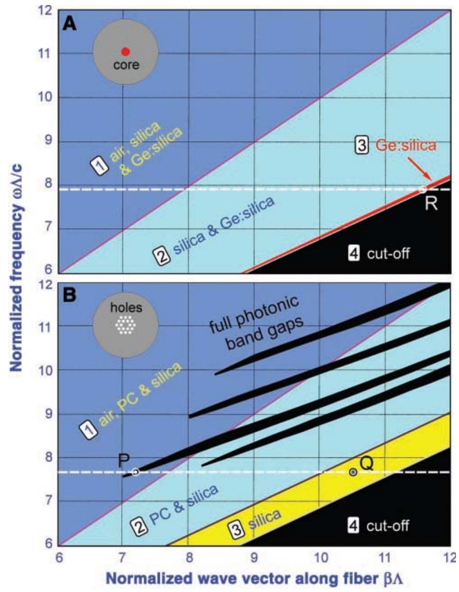
Russell P, *Photonic crystal fibers*, SCIENCE 299 (5605): 358-362 JAN 17 2003, Times Cited: 415.

1.PHOTONIC CRYSTAL FIBRES

(**A**) Propagation diagram for a conventional single-mode fiber (see schematic in the top left-hand corner) with a Ge-doped silica core and a pure silica cladding. Guided modes form at points like R, where light is free to travel in the core but unable to penetrate the cladding (because total internal reflection operates there). The narrow red strip is where the whole of optical telecommunications operates.

(**B**) Propagation diagram for a triangular lattice of air channels in silica glass with 45% air-filling fraction. In region (1), light is free to propagate in every region of the fiber [air, photonic crystal (PC), and silica]. In region (2), propagation is turned off in the air, and, in (3), it is turned off in the air and the PC. In (4), light is evanescent in every region. The black fingers represent the regions where full two-dimensional photonic band gaps exist. Guided modes of a solidcore PCF (see schematic in the top left-hand corner) form at points such as Q, where light is free to travel in the core but unable to penetrate the PC. At point P, light is free to propagate in air but blocked from penetrating the cladding by the PBG; these are the conditions required for a hollow-core mode.



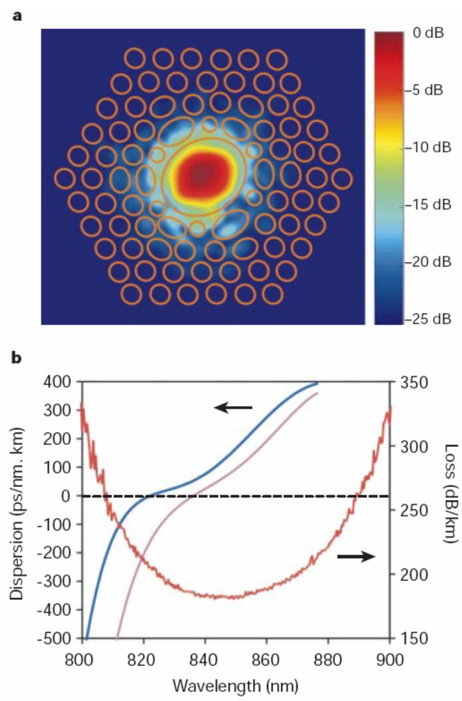
Russell P, *Photonic crystal fibers*, SCIENCE 299 (5605): 358-362 JAN 17 2003, Times Cited: 415.

1.PHOTONIC CRYSTAL FIBRES

Measured properties of a hollow-core bandgap fibre around 850 nm wavelength

a, Logarithmic plot of the near-field pattern at 848 nm after propagation through 60 m of fibre. The locations and shapes of the first few rings of air holes are shown schematically. The light is strongly confined to the core, and the light overlapping with silica is only a tiny fraction of the total.

b, Measured loss and dispersion characteristics of the fibre. The loss minimum is 180 dB/km at 850 nm wavelength and is probably limited by leakage. The dispersion is low and anomalous over much of the guiding band, which enables soliton propagation. The two lines correspond to the two fundamental polarization modes, which are split because of deformation of the structure



• Knight JC, *Photonic crystal fibres,* NATURE 424 (6950): 847-851 AUG 14 2003, Times Cited: 167

2. SUPERCONTINUUM, solitons

- Chromatic dispersion (CD) causes different frequencies to travel at different speeds, producing pulse broadening. Solitary waves form when the effects of CD are balanced by nonlinearity—a phenomenon that changes the properties of systems at high power densities.

- CD broadening gives rise to a frequency chirp because the different spectral components travel at different 'group' velocities v_G

$$D(\lambda) = \frac{\partial}{\partial \lambda}\frac{1}{v_G} = -\frac{2\pi c}{\lambda^2}\frac{\partial}{\partial \omega}\frac{1}{v_G} = -\frac{2\pi c}{\lambda^2}\beta_2(\omega) \neq 0$$

,where $D(\lambda)$ and $\beta_2(\omega)$ represent CD as funct. of wavelength and frequency, λ is the wavelength, ω the angular frequency and c the speed of light in vacuum.

In the anomalous CD region ($D(\lambda) > 0$), 'red'-shifted freq. travel more slowly than 'blue'-shifted ones, producing a negative freq. chirp that can exactly balance the positive chirp of self-phase modulation. When this happens, a soliton forms.

Reeves WH, et al., *Transformation and control of ultra-short pulses in dispersion-engineered photonic crystal fibres,* NATURE 424 (6948): 511-515 JUL 31 2003 Times Cited: 110

2. SUPERCONTINUUM

- Def.: In a single-mode optical fiber, the **zero-dispersion wavelength** is the wavelength at which material dispersion and waveguide dispersion
- Supercontinuum source:
  - Pulsed laser:
  - Non-linear element:
  - narrow-band ⇒ continuous spectrum (conserves spatial coherence)

- Photonic Crystal Fibers (PCF) are suited as non-linear medium as they provide
  - ☑ High non-linearity
  - ☑ Suitable dispersion characteristics
  - ☑ Ease of use

3. PHYSICS OF SUPERCONTINUUM GENERATION

- Q-switched pulses considered as quasi continuous wave
- Non linear phase-matched four wave mixing FWM

Conditions for phase matching and conservation of energy give :

$$2k_{pump} = k_{signal} + k_{idler} + 2\gamma P \quad (1)$$

$$2\omega_{pump} = \omega_{signal} + \omega_{idler} \quad (2)$$

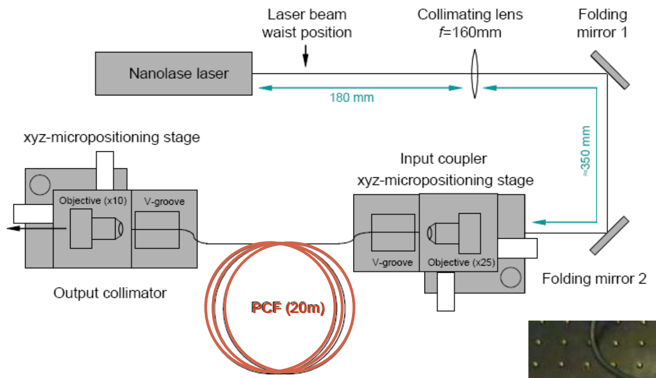
$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (3)$$

k_j wavevectors
ω_j frequencies
γ non linear coefficient of the fiber
A_{eff} effective mode area of the fiber
λ pump wavelength

Design single mode fibers with zero dispersion wavelength shorter than the pump wavelength of 1064nm

Wadsworth WJ, Joly N, Knight JC, et al., *Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibres,* OPTICS EXPRESS 12 (2): 299-309 JAN 26 2004, Times Cited: 60

4. EXPERIMENTAL SETUPS



Average power >10mW
Spectral width 500-1750 nm
Pulse repetition frequency 6kHz
Pulse duration 1ns

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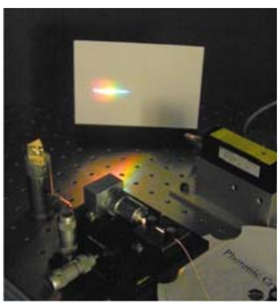
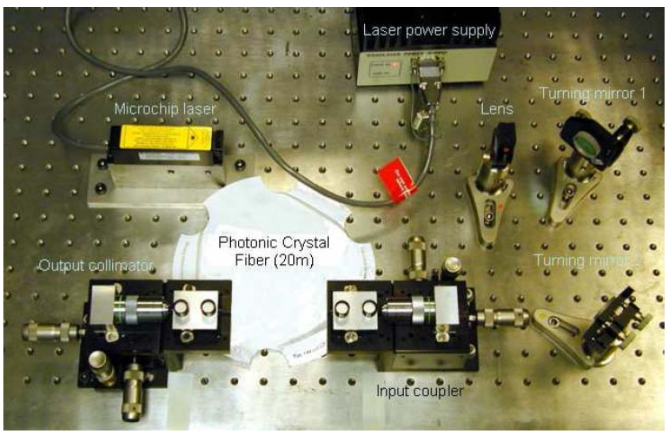
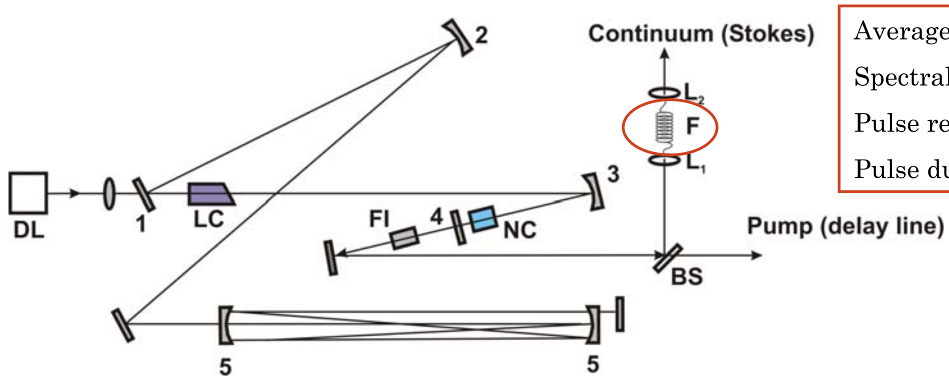




4. EXPERIMENTAL SETUPS 2

High-energy diode-pumped picosecond multi-pass Nd:GdVO4 laser source

V. Shcheslavskiy[1], W.A. Clarkson[2] ,T.Lasser[1] and R. Leitgeb[1]
1 Laboratoire d'Optique Biomédicale, École Polytechnique Fédérale de Lausannne lob.epfl.ch
2 Optoelectronics Reaserch Centre, Southampton, United Kingdom, www.orc.soton.ac.uk



Average power 4.5W
Spectral width 1150 -1350nm
Pulse repetition frequency 14.6MHz
Pulse duration 3.5 ps

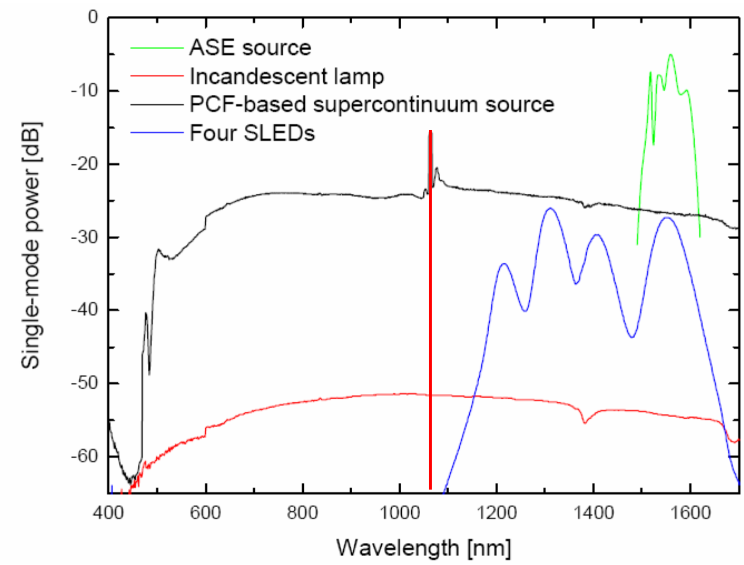
DL - LIMO diode laser (808.5nm, 30W); LC – water cooled Nd:GdVO4 laser crystal (5mm, .6% Nd doping); NC - BBO crystal (4mm, cut for I-type phase matching), FI - Faraday Isolator; **F- fiber (GeO2 or photonic crystal);** L1 - aspheric lens; L2 - achromatic lens; 1- flat mirror (HR@1064nm, HT@808nm); 2 - concave mirror (R = 700mm; HR@1064nm); 3 - concave mirror (R = 200mm, HR@1064nm); 4 - flat output mirror (HR@532nm, T=15%@1064nm); 5 - concave mirror (R = 2000mm, HR@1064nm); BS - beam splitter.

5. BROADBAND LIGHT SOURCES

Supercontinuum

- ✓ High brightness
- ✓ High spectral flatness
  Pulsed Output (0.5-1ns)

- ✗ Pulses are free-running, no synchronisation
- ✗ polarization difficult to control
- ✗ Intensity fluctuations



6. APPLICATIONS

- Low-coherence “white light” interferometry
  - Axial resolution depends on bandwidth
- Optical coherence tomography
  - Axial resolution depends on bandwidth
- Spectroscopy

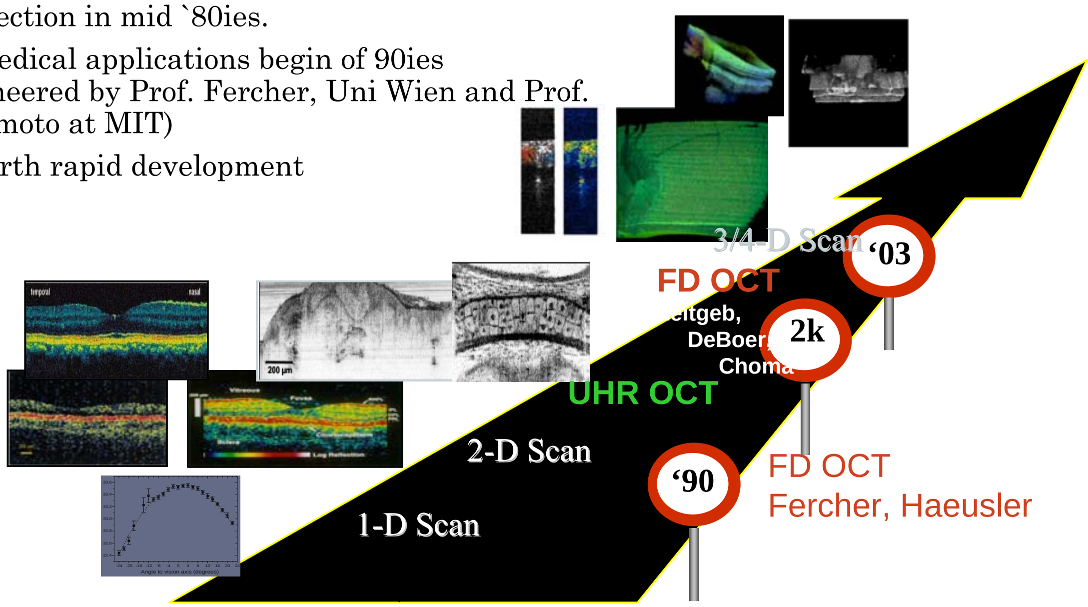
6. APPLICATIONS

Short coherence interferometry already known for more than hundred years

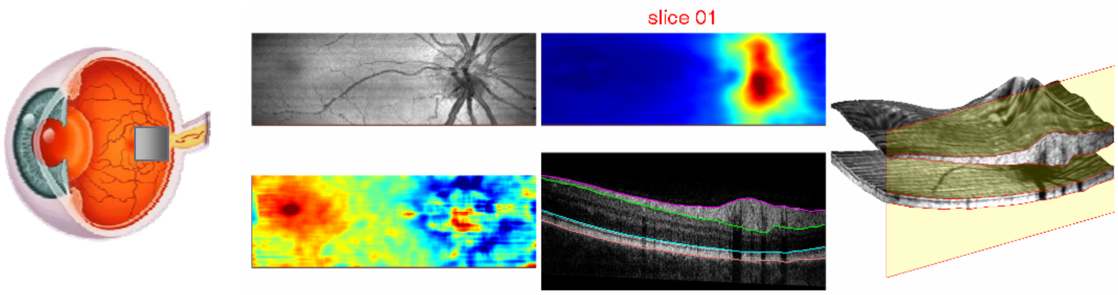
Optical Short Coherence Reflectometry for material inspection in mid `80ies.

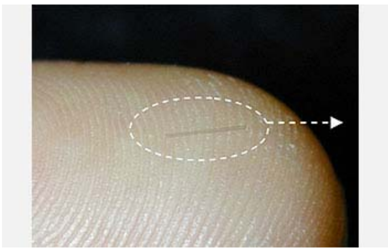
First medical applications begin of 90ies (pioneered by Prof. Fercher, Uni Wien and Prof. Fujimoto at MIT)

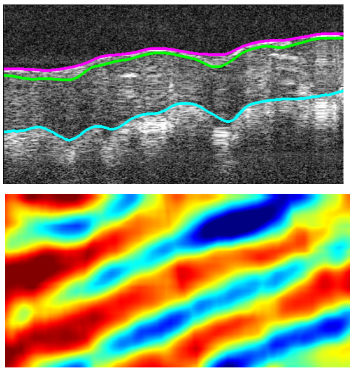
henceforth rapid development

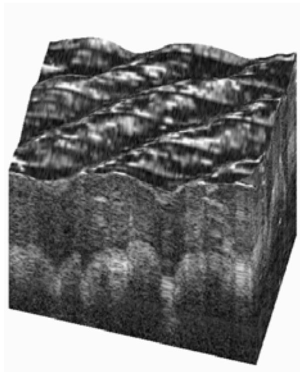


6. APPLICATIONS: FDOCT

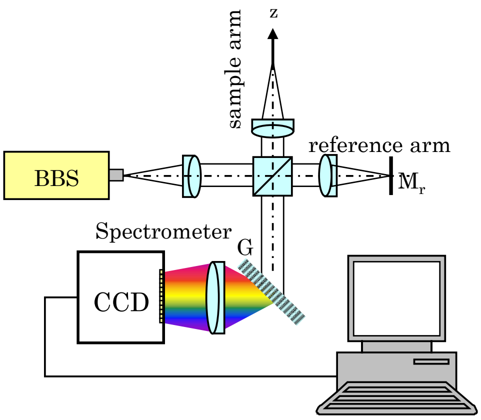








6. APPLICATIONS : FDOCT



$$I(k) = I_0(k) + I_M(k)\int_0^{\infty} h(z)\cdot\cos(2k\Delta z)\,dz$$

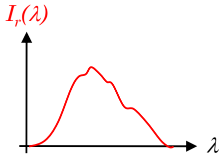
local reflectivity $h(z)$

optical path difference Δz

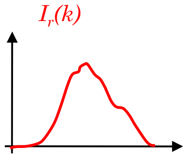
$$I_0(k) = I_r(k) + I_s(k)$$

$$I_M(k) = 2\sqrt{I_r(k)\,I_s(k)}$$

$$\text{depth resolution } \delta z = \frac{2\ln(2)\lambda_0^2}{\pi\Delta\lambda}$$



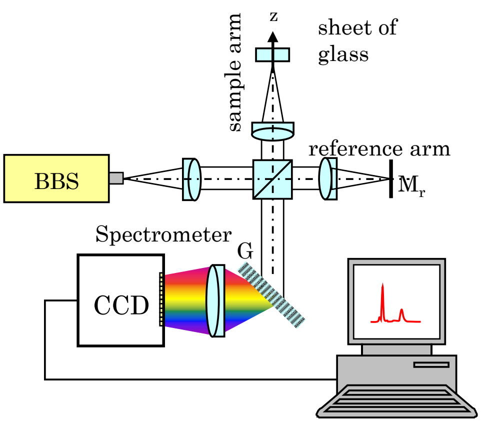
$\Rightarrow \lambda \rightarrow k$



$\Rightarrow FT$

$PSF(\Delta z) = FT\{I_r(k)\}$

6. APPLICATIONS : FDOCT



$$I(k) = I_0(k) + I_M(k)\int_0^\infty h(z)\cdot\cos(2k\Delta z)\,dz$$

local reflectivity $h(z)$

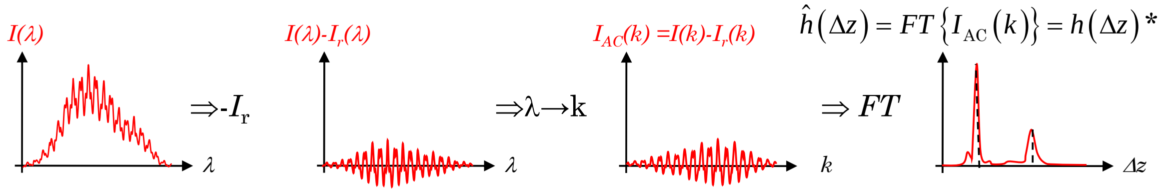
optical path difference Δz

$$I_0(k) = I_r(k) + I_s(k)$$

$$I_M(k) = 2\sqrt{I_r(k)\,I_s(k)}$$

depth resolution $\delta z = \dfrac{2\ln(2)\lambda_0^2}{\pi\Delta\lambda}$

$$\hat{h}(\Delta z) = FT\{I_{AC}(k)\} = h(\Delta z) * PSF(\Delta z)$$



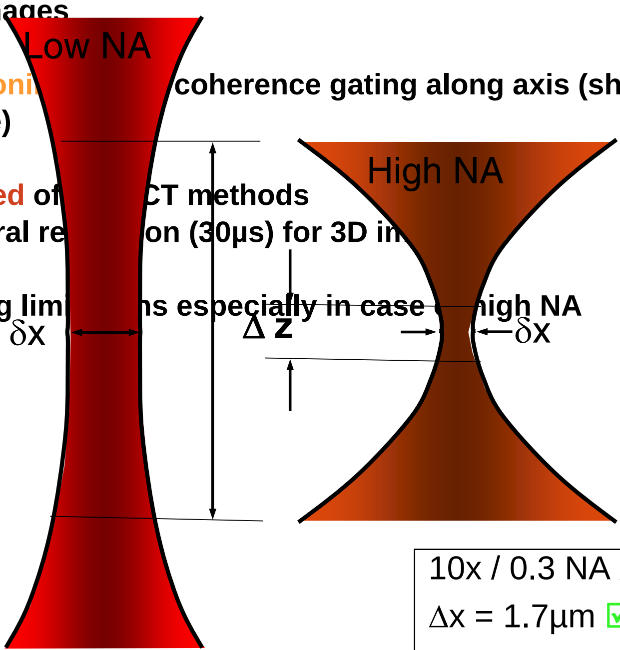
6. APPLICATIONS : FDOCT

☑ **coherent amplification of sample signal high contrast images**

☑ **optical sectioni… coherence gating along axis (short coherent source)**

☑ **imaging speed of … CT methods**
⇒ high temporal re… on (30µs) for 3D i…

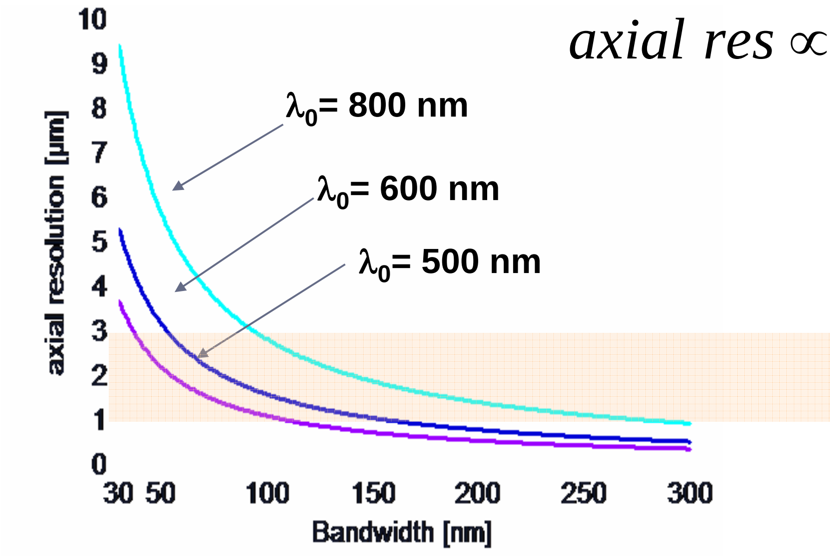
☒ **depth ranging lim… ns especially in case … high NA**



10x / 0.3 NA / 800nm
Δx = 1.7µm ☑
Δz = 18 µm ☒

towards Optical Coherence Microscopy

$$axial\ res \propto \lambda^2 / \Delta\lambda$$



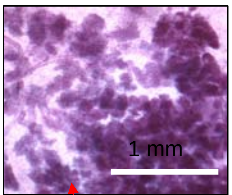
Assumptions: Gaussian Spectrum

PO14 Photonics Crystals 2007

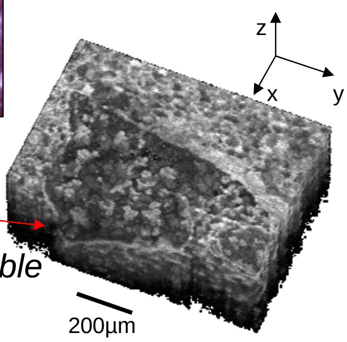
6. APPLICATIONS : FDOCM setup

1.5 x 1.5µm² x 2.7µm resolution
20kHz frame rate

Application to developmental biology (mouse mammary glands)



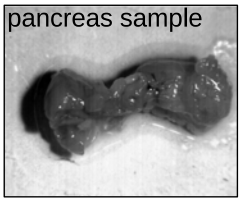
stained µ-scopy



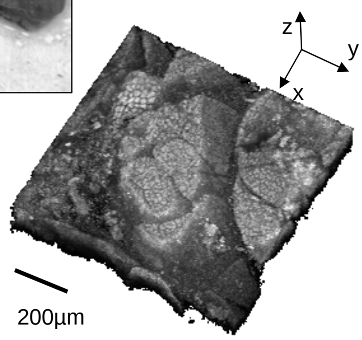
comparable contrast

xf-SOCT

Application to diabetes research (visualization of Langerhans islets within unprepared rat pancreas)



pancreas sample



xf-SOCT

6. APPLICATIONS : FDOCT Supercontinuum

- ☒ spectrum : peaks and valleys
  - problems with coherence function
- ☒ spectrum not polarized uniformly, (sample polarizing)
  - Loss of modulation depth
- ☒ ps (pumped) laser source
  - Random Intensity Noise (depending on λ)
- ☒ Detector Si: up to 900nm, InGaAs >1000nm
  - 900-1000nm?
- ☑ Broad spectrum => spectroscopy
  - ☑ 500nm, 900nm subtraction of log scale spectra, provide information on scattering and absorption in tissue
  - ☑ 1300nm, 1800nm allow water absorption measurements

6. APPLICATIONS : FDOCT Supercontinuum

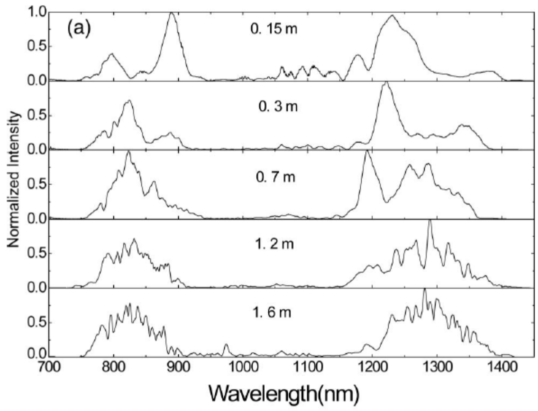
Hsu IJ, Lu CW, Deng CR, et al., *Optical coherence tomography using nonlinear optics in fiber for broadband source generation*, OPTICS COMMUNICATION, 212 (4-6): 391-396 NOV 2002. Times Cited: 2.

Unterhuber A, Povazay B, Bizheva K, et al., *Advances in broadband light sources for ultrahigh resolution optical coherence tomography*, PHYSICS IN MEDECINE AND BIOLOGY 49 (7): 1235-1246 APR 7 2004. Times Cited: 10.

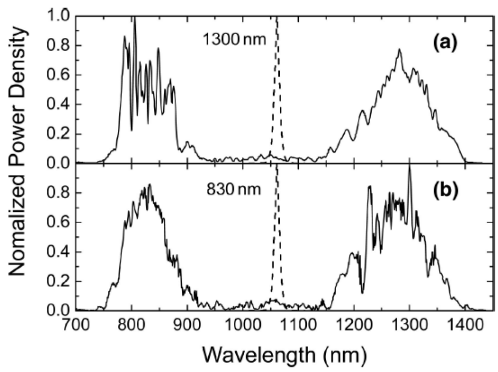
Aguirre AD, Nishizawa N, Fujimoto JG, et al., *Continuum generation in a novel photonic crystal fiber for ultrahigh resolution optical coherence tomography at 800 nm and 1300 nm*, OPTICS EXPRESS 14(3): 1145-1160 FEB 6 2006. Times Cited: 0

Wang H, Rollins AM, *Optimization of dual-band continuum light source for ultrahigh-resolution optical coherence tomography,* APPLIED OPTICS 46 (10): 1787-1794 APR 1 2007. cited 0

6. APPLICATIONS : FDOCT Supercontinuum



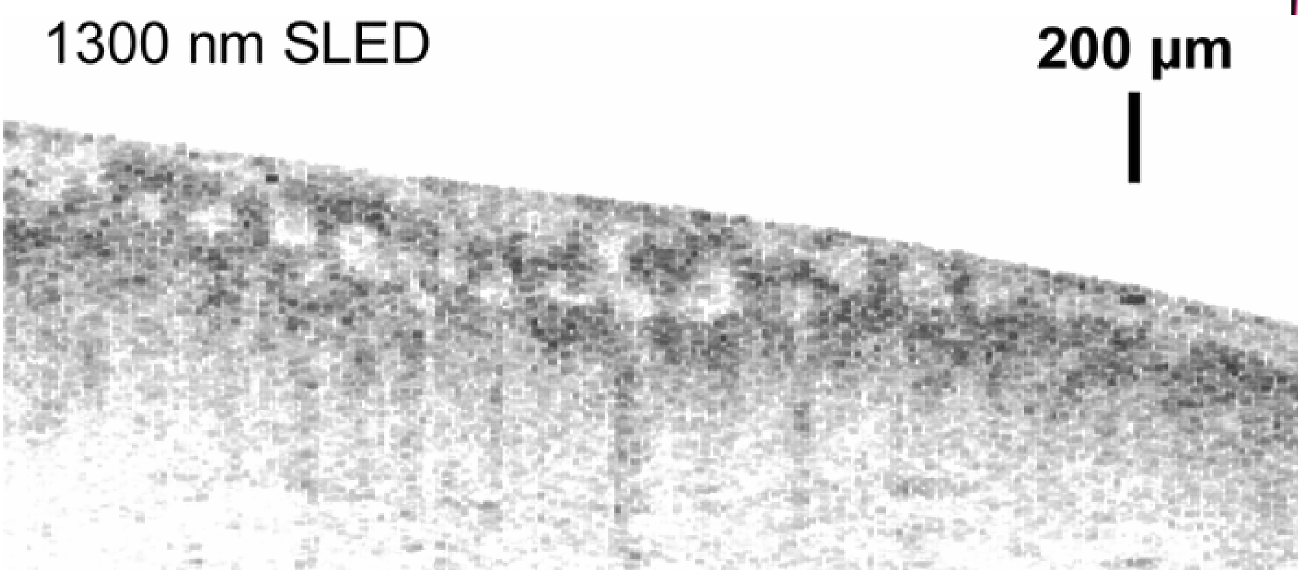
Continuum generated with different lengths of NL-1050-ZERO-2 PCF. The continuum spectrum is relatively smooth when the PCF is less than 0.7 m, but the sidebands are fully extended only after 1.2 m. Significant modulations can be observed on the two sidebands after 1.2 m of PCF.



Smoothing of the spectrum of continuum at (a) 1300 nm and (b) 830 nm with polarization control. The dashed curve is the spectrum of the pump laser.

Wang H, Rollins AM, *Optimization of dual-band continuum light source for ultrahigh-resolution optical coherence tomography*
APPLIED OPTICS 46 (10): 1787-1794 APR 1 2007. cited 0

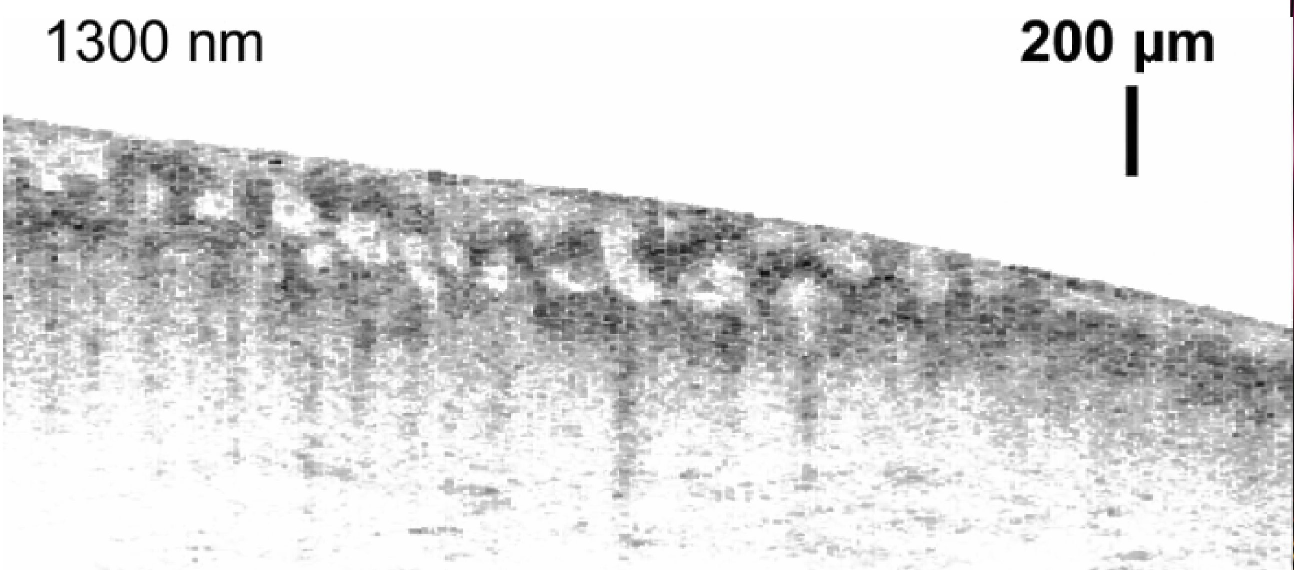
6. APPLICATIONS : FDOCT Supercontinuum



OCT image of human colon *in vitro* at using a common SLED light source at 1310 nm with axial resolution of 11 m in the tissue.

Wang H, Rollins AM, *Optimization of dual-band continuum light source for ultrahigh-resolution optical coherence tomography*
APPLIED OPTICS 46 (10): 1787-1794 APR 1 2007. cited 0

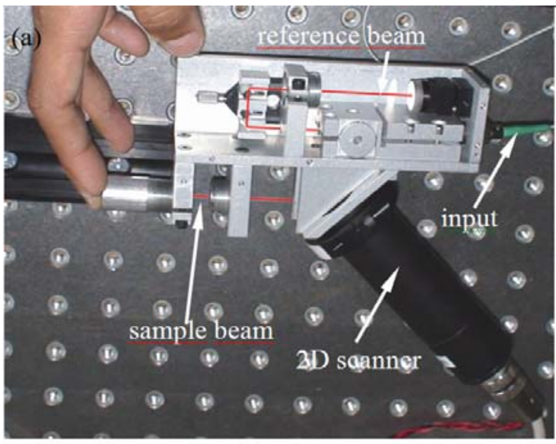
6. APPLICATIONS : FDOCT Supercontinuum

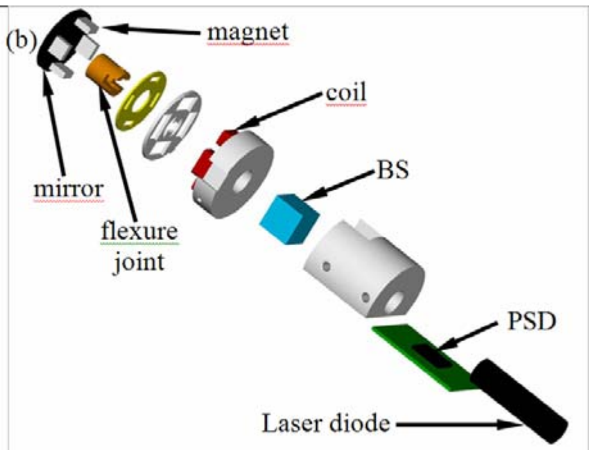


OCT image of the same tissue and using the same interferometer but 1300 nm with axial resolution of 4.5 m in the tissue

Wang H, Rollins AM, *Optimization of dual-band continuum light source for ultrahigh-resolution optical coherence tomography*, APPLIED OPTICS 46 (10): 1787-1794 APR 1 2007. cited 0

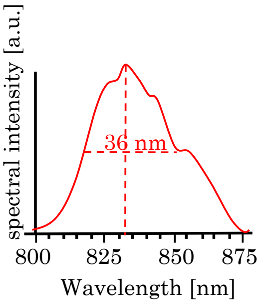
6. APPLICATIONS : FDOCT Setup1





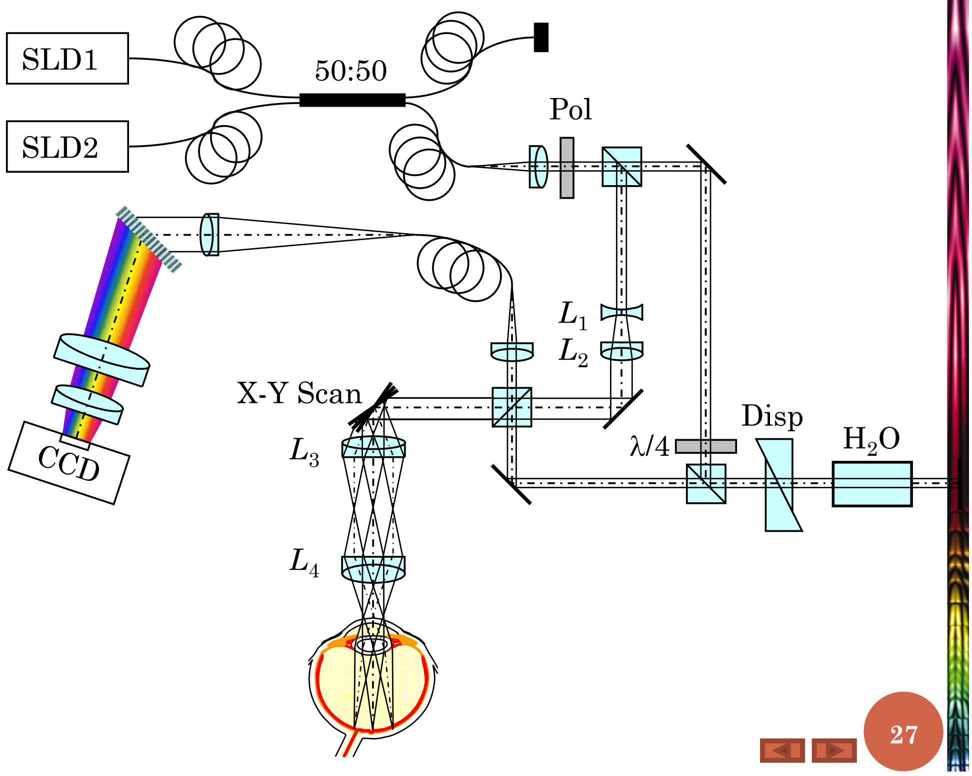
(a) Handheld scanner with integrated reference beam, (b) 2D scanner: the mirror is articulated by a 2D flexure joint and driven by a push-pull magnet-coil system. A laser diode illuminates the back of the mirror. The back reflection, deviated by a beam splitter BS on a Position Sensitive Device PSD, is used for the position regulation.

6. APPLICATIONS : FDOCT Setup2

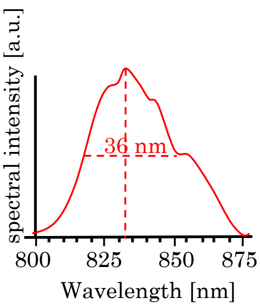


SLD, 300μ*W*
λ_0=833.5nm
axial res δz =8.5μm
pen. depth: 1.5mm

17.4kHz@12bit
sensitivity 98dB
3 x 750 depth scans

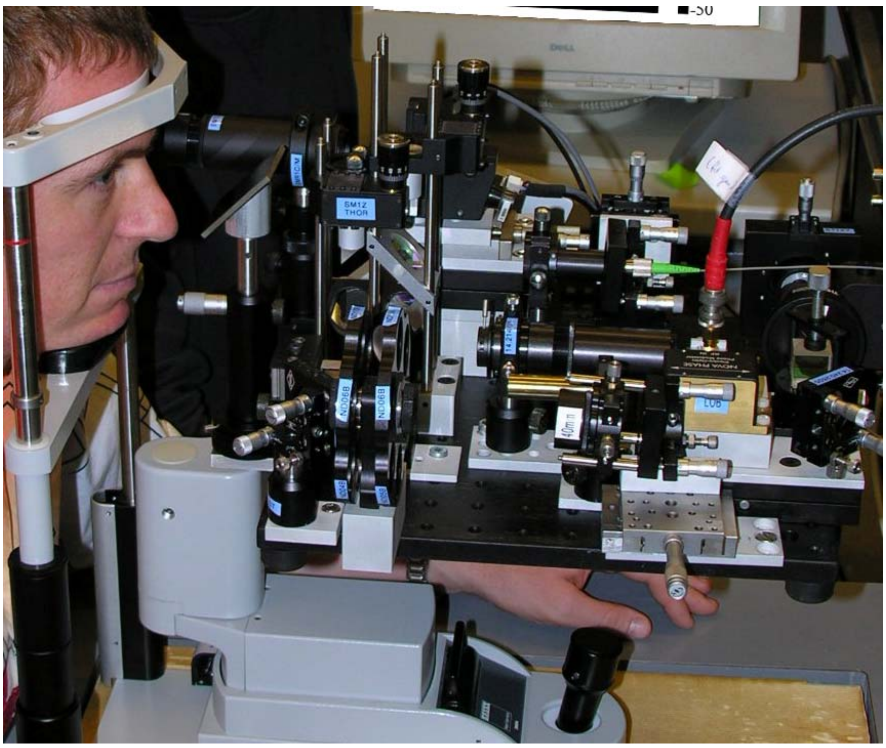


6. APPLICATIONS : FDOCT Setup2



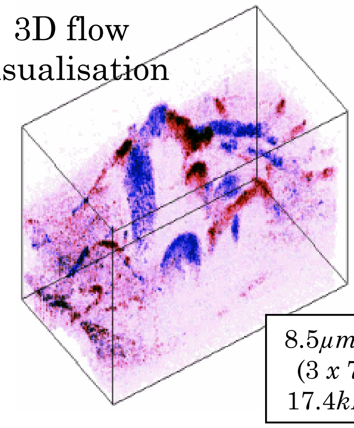
SLD, 300μ*W*
λ_0=833.5nm
axial res δz =8.5μm
pen. depth: 1.5mm

17.4kHz@12bit
sensitivity 98dB
3 x 750 depth scans

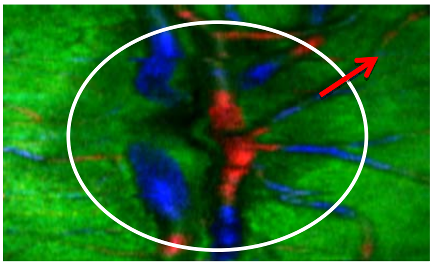


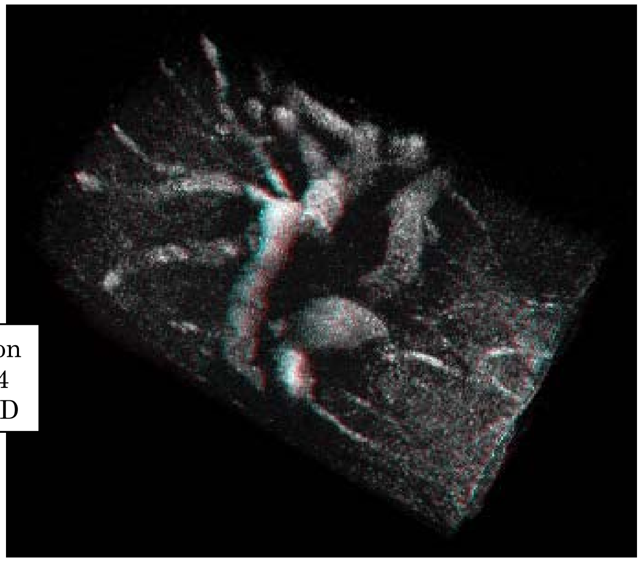
6. APPLICATIONS : FDOCT Setup2

3D flow visualisation

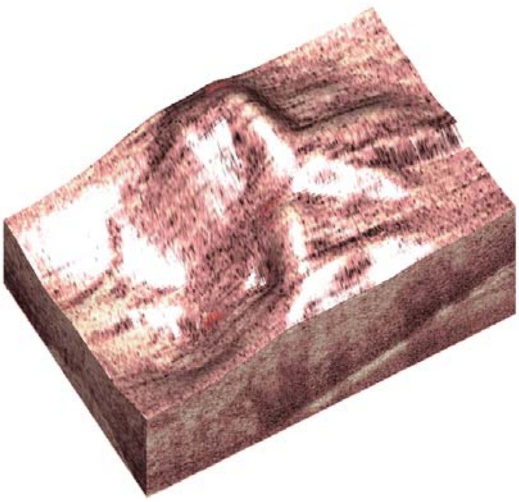


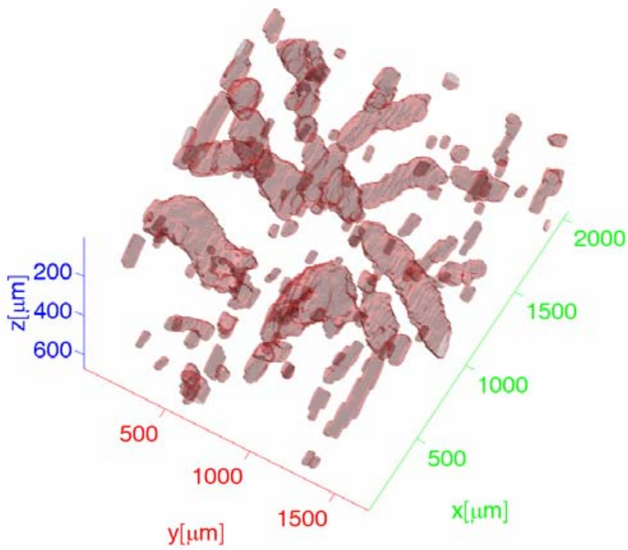
8.5μm axial resolution
(3 *x* 750) *x* 81 *x* 1024
17.4kHz, 300μW, SLD



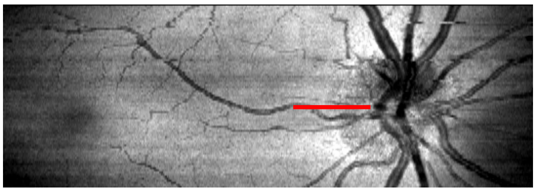


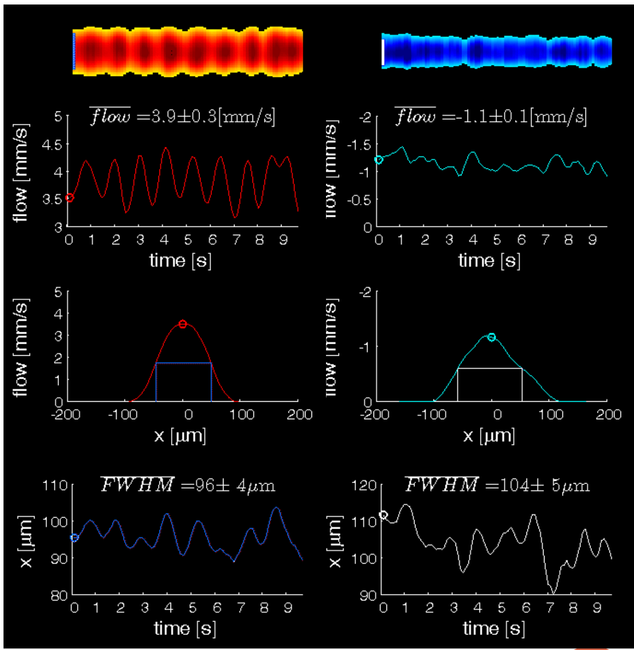
6. APPLICATIONS : FDOCT Setup2



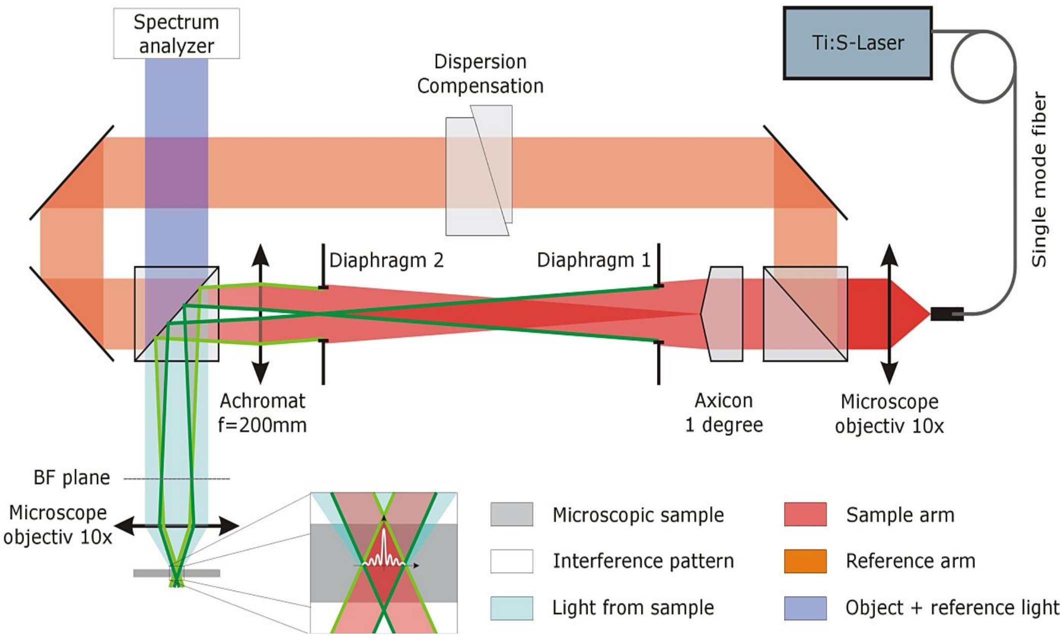


6. APPLICATIONS : FDOCT Setup2





6. APPLICATIONS : FDOCM setup



Questions?

Thank you for your attention!