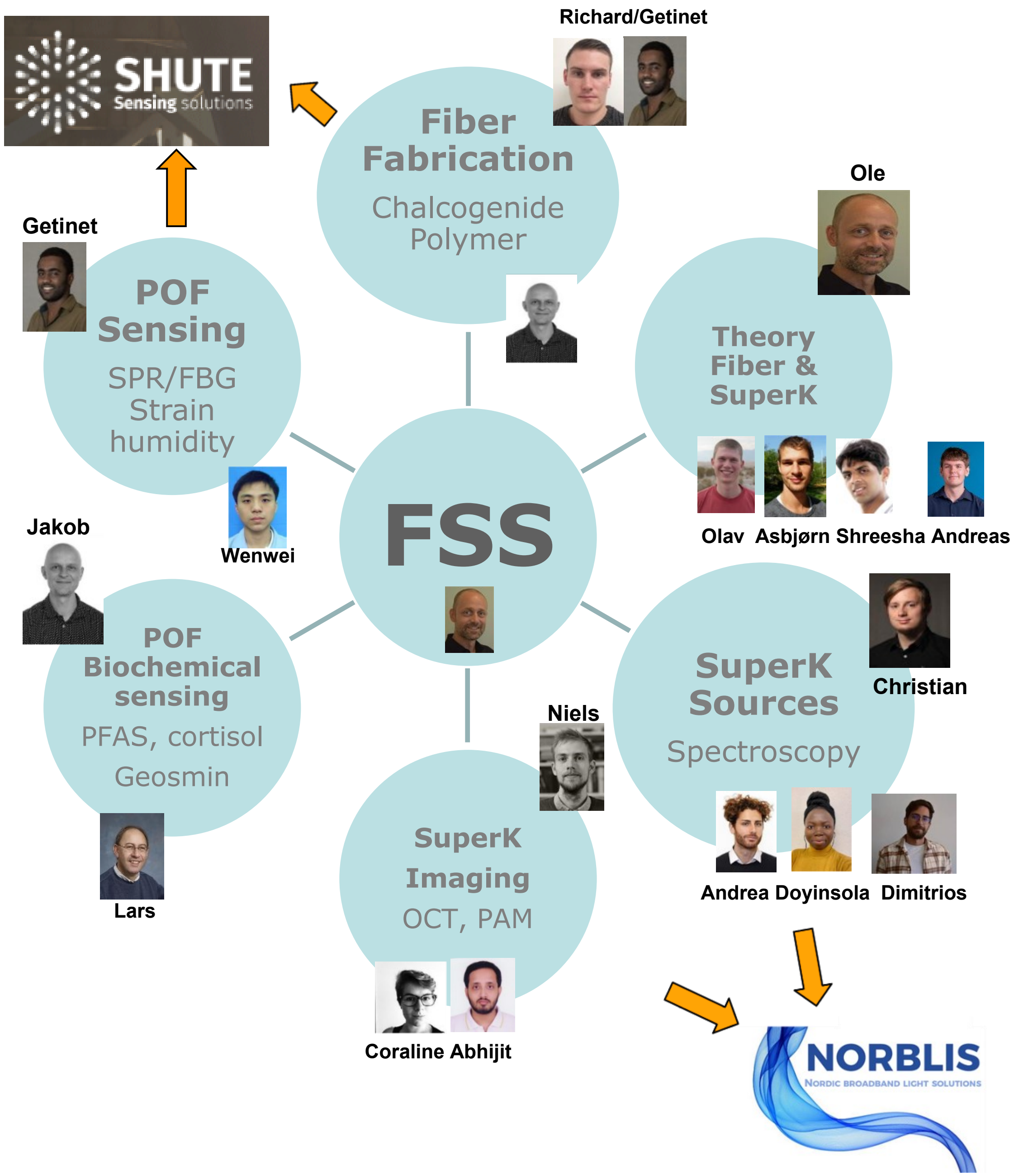
Fiber Sensors & Supercontinuum

DTU

Outline
- Group & projects
- Fiber fabrication
- Fiber sensors
- Supercontinuum sources
- Application: OCT
- (Low noise record)

Fiber Sensors & Supercontinuum group



<u>18 people:</u>
1 Professor
5 Senior Scientist
2 Tenure track
5 Postdocs
5 PhDs

<u>6 cleanroom labs</u>
- **Draw tower - glass**
- **Extruder**
- **Glass**
- **UV & grating**
- **Chemistry**
- **Supercontinuum**

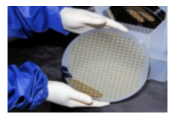
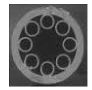
+ Polymer draw tower lab
+ Quantum OCT lab

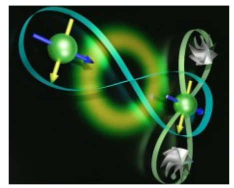
Bispebjerg Hospital

Running projects

Project	Total M€	Period	Area
H2Safe *India-Denmark Bilateral*	1.0	2026-28	Develop fiber-optical distributed and point hydrogen sensors
Counter-Drone System *National Defence Center*	0.2	2024-27	Using MIR supercontinuum laser to disable drones
GREENFRUIT *Eurostar*	0.2	2024-27	Fruit storage monitoring. We make fibers for NORBLIS
Table-top synchrotrons *Villum Investigator*	8.1	2021-27	4 superC beamlines covering 33nm to 15µm
UVSOLAR IFD Grand Solution	2.7	2023-26	UV superC for solar cell & semiconductor industry
HYPERSORT IFD Grand Solution	1.9	2023-26	*Hyper-spectral imaging for advanced textile sorting and food control*
PFAS Detect GUDP	1.6	2023-26	*Pisco, DTU Health, DTU Sustain, Zeta (Getinet/Jakob)*
SEQUOIA *EU Horizon Europe*	6.4	2022-26	Quantum OCT with AI for 0.5um resolution in eyes
ZDZW *EU Horizon Europe*	11.2	2022-25	NDT for Digitally Enhanced Zero Waste Manufacturing
TURBO *EU Horizon Europe*	9.7	2022-26	Towards tURbine Blade production with zero waste
Total	**43**		



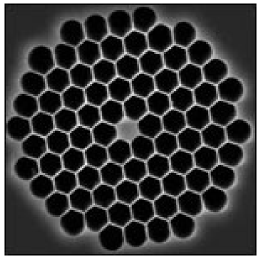



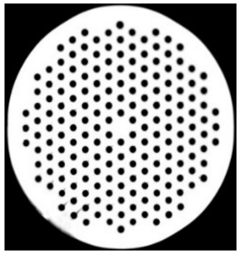



One true love – the optical fiber!

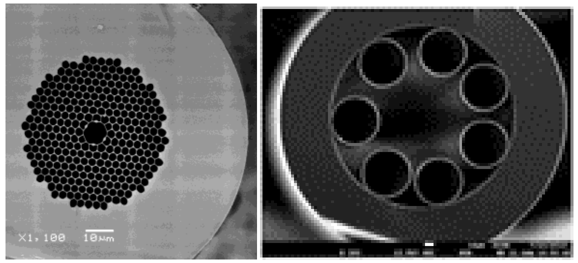
DTU

Endlessly single-mode: d/Λ<0.45

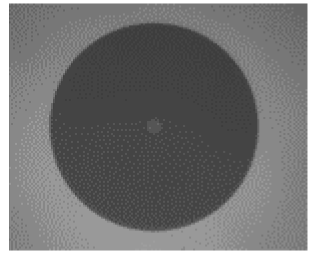




Photonic Crystal fiber



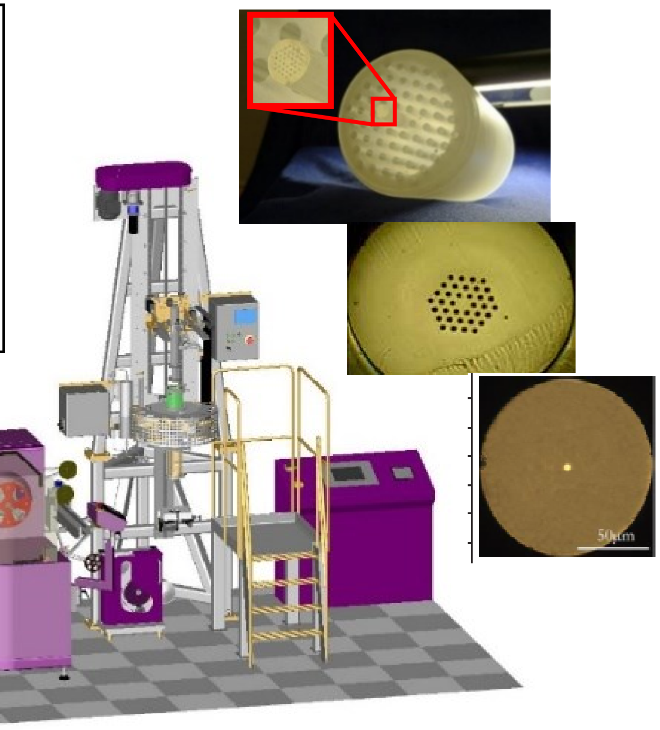
Hollow-core fiber



Step-index fiber

SHUTE Sensing solutions

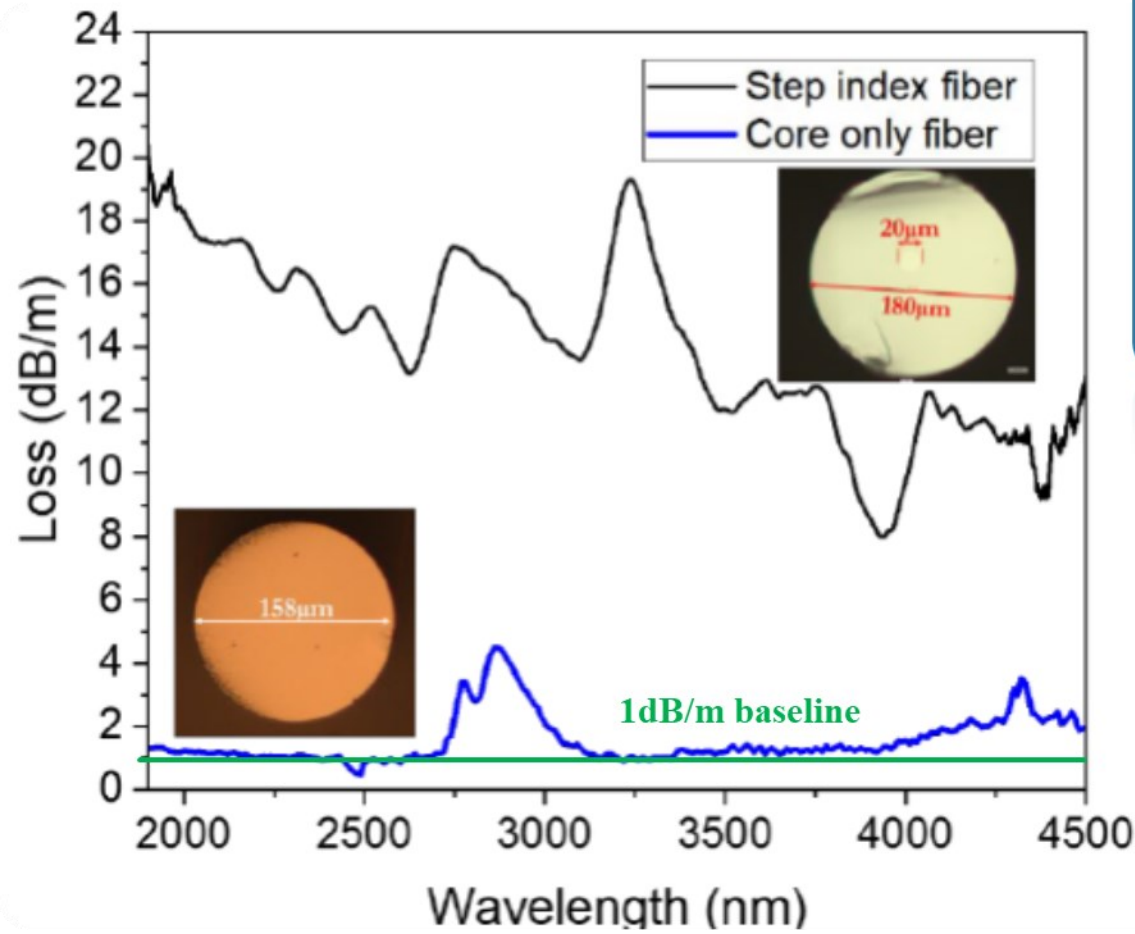
Polymer

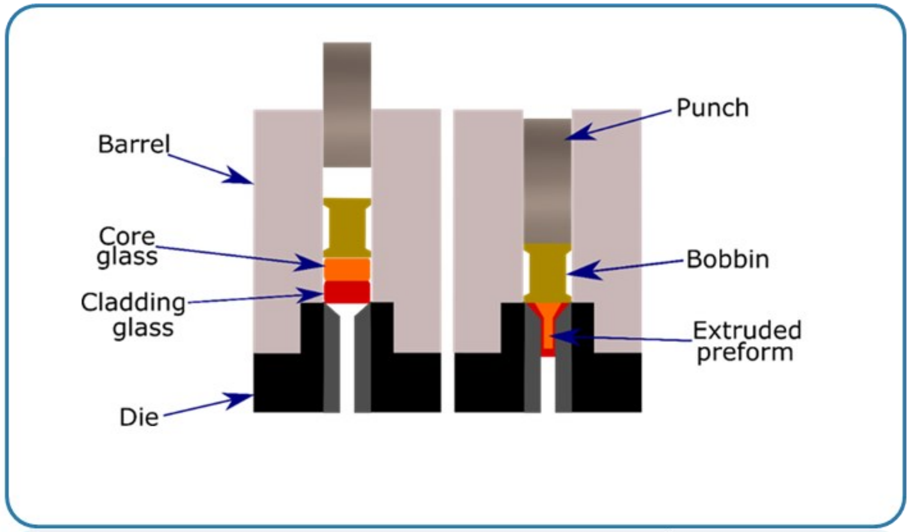


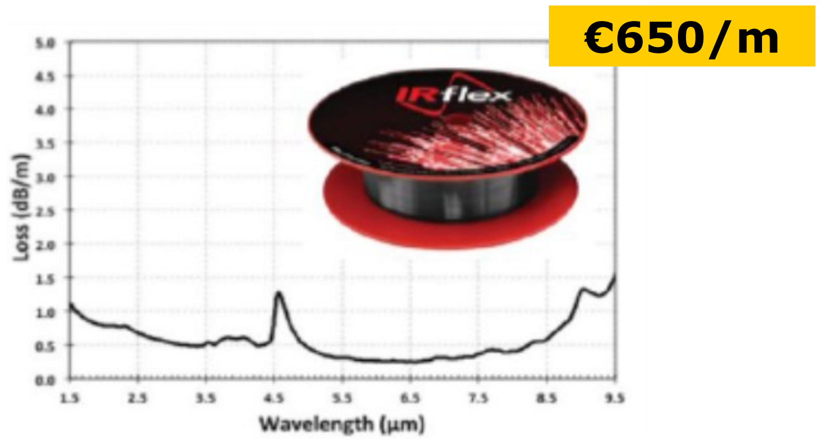
NORBLIS

Chalcogenide NA~1

Chalcogenide step-index fiber fabrication

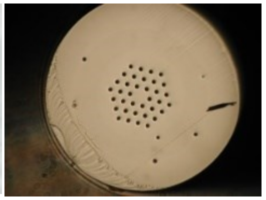






Polymer Optical Fiber (POF)

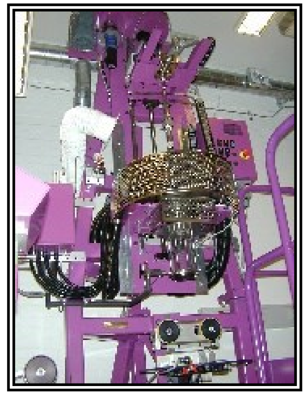
Drilled 6cm preform



Drawn 125µm fiber

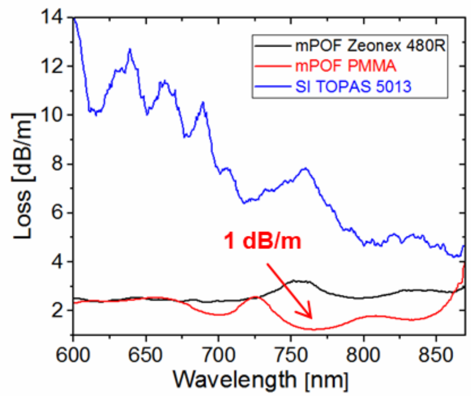
Two-stage process: Cane ➡ Sleeving ➡ Fiber

- Drill as sharp as possible
- Cooling liquid matters
- Annealing very important



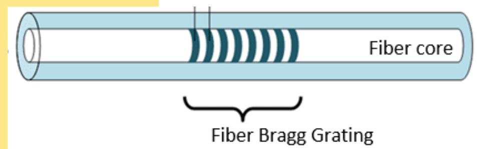
Why polymers :

- Low drawing temperature
- 30x lower Young's modulus
  - 30x more strain sensitive
- Much higher breaking strain
- No sharp edges when breaking
- Biocompatible
- Many different polymers

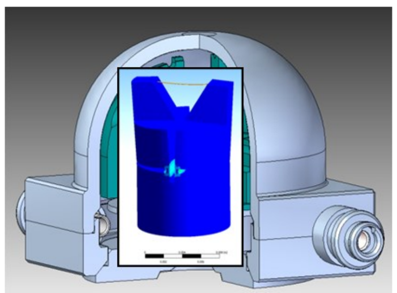


World first / records:

- Lowest loss mPOF – 1 dB/m
  - Endlessly single-mode
- First TOPAS mPOF
  - Humidity insensitive
- First Polycarbonate mPOF
  - High temperature
- First Zeonex mPOF
- First single-mode step-index POF
- Fastest FBG writing with CW
- Highest humidity sensitivity
- Highest pressure sensitivity
- First mPOF accelerometer



SHUTE Sensing solutions

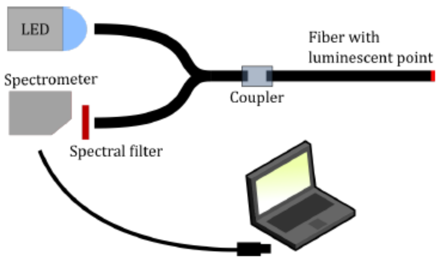


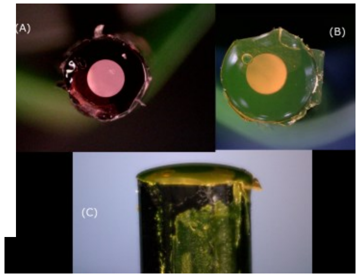
POF biosensors

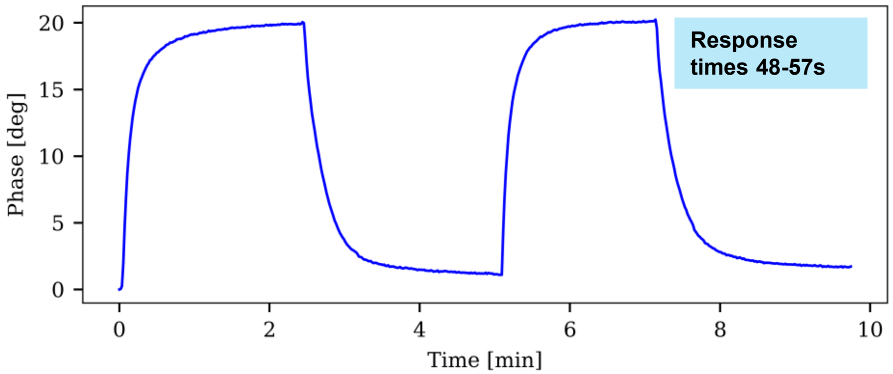
Fish farm oxygen sensor – phase-fluorometry

- with Pisco Group in 3 years development

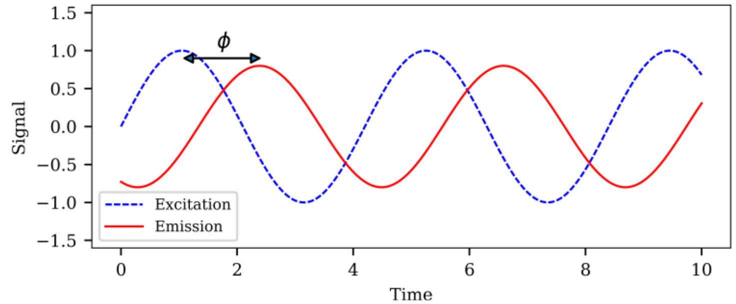
PMMA multi-mode POF & blue LED 470nm
- ***PtOeP fluorescence at 650 nm***
- ***C545T (cumarin) makes LED-PtOeP more efficient***
- ***PtOeP fluorescence quenched by Oxygen***
- ***Solvents for PMMA + PtOeP + C545T***

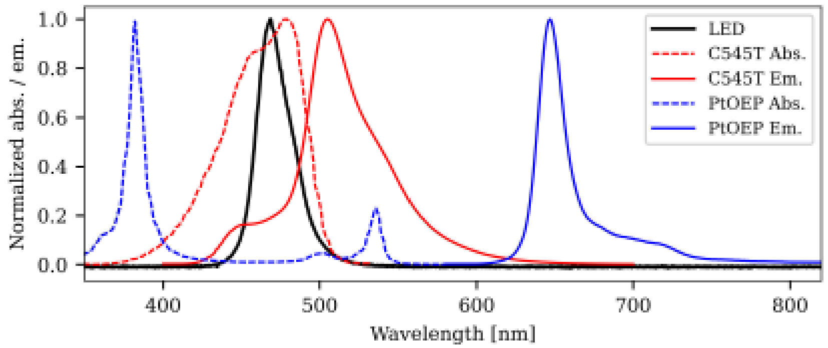






Response times 48-57s

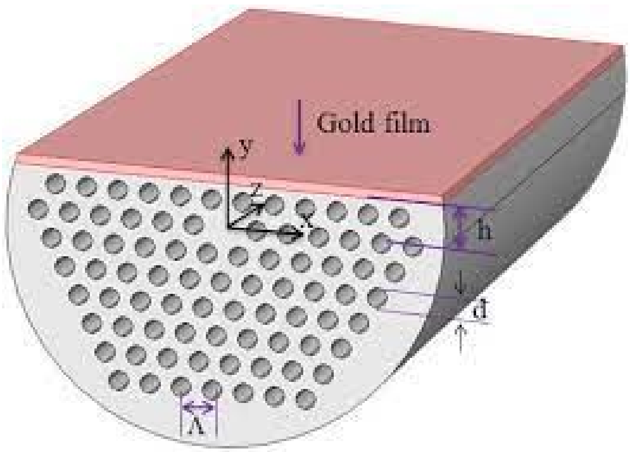


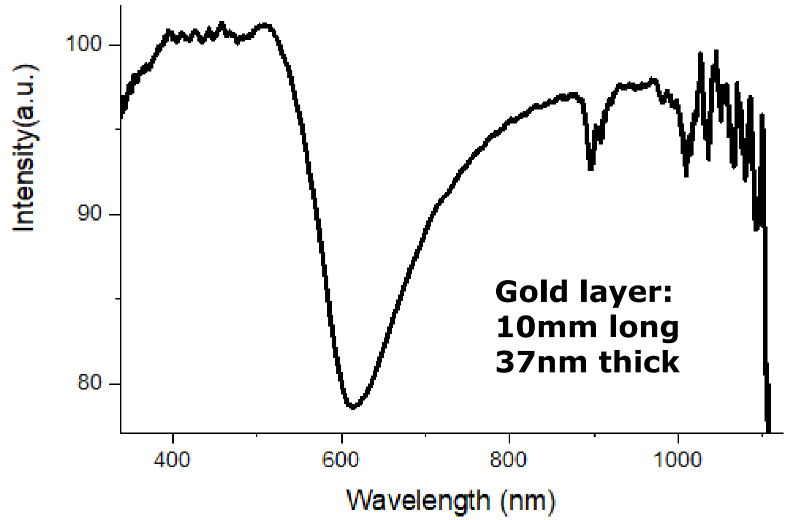


[R. Inglev, E. Møller, J. Højgaard, O. Bang, J. Janting,
Optimization of All-Polymer Optical Fiber Oxygen Sensors With Antenna Dyes and Improved Solvent Selection Using Hansen Solubility Parameters, Sensors 2021]

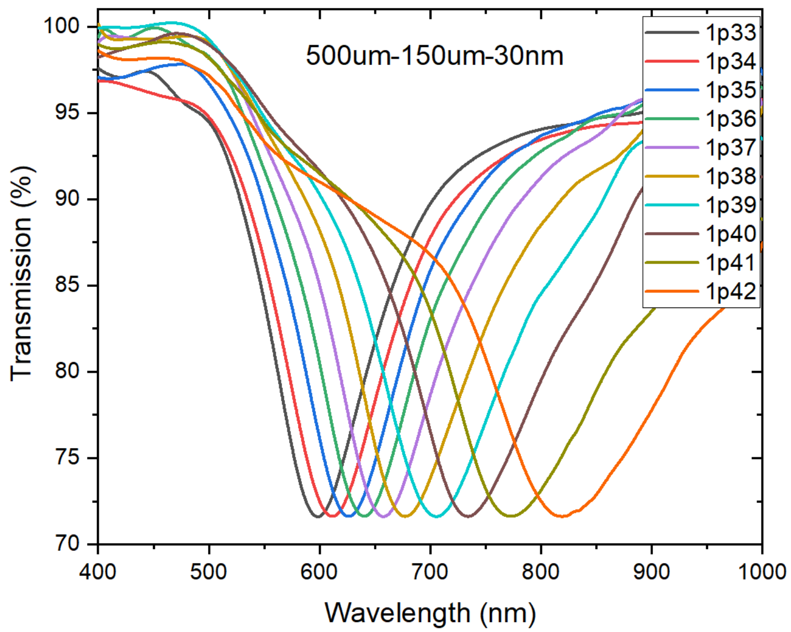
Biosensing:
- **pH**
- **Cortisol**
- **Geosmin**
- **PFAS**
- **Borelia**

POF gold SPR sensors ~ 6-700 nm





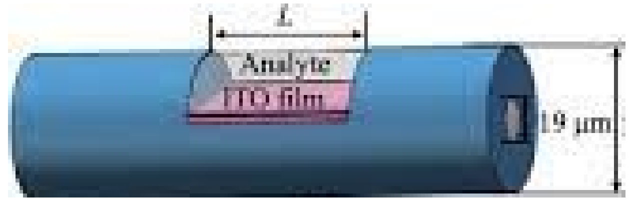
PMMA mPOF:
5 rings
500µm core

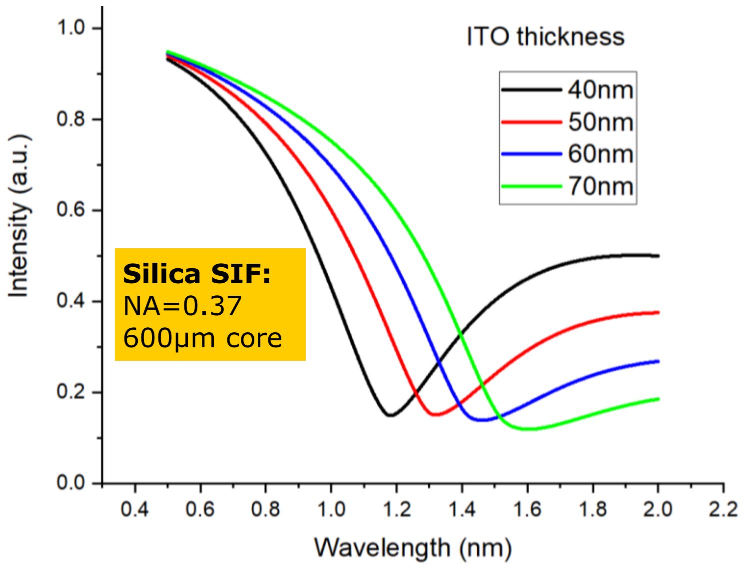


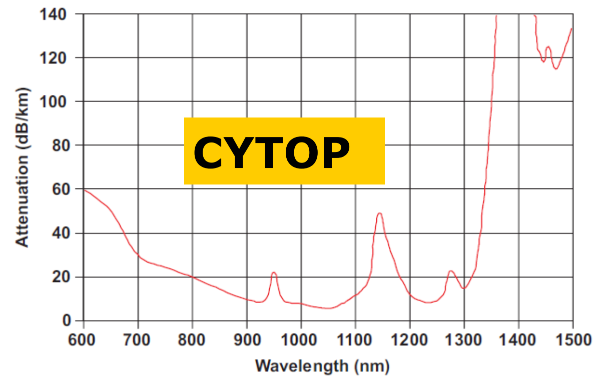
PMMA SI POF:
500µm core
commercial

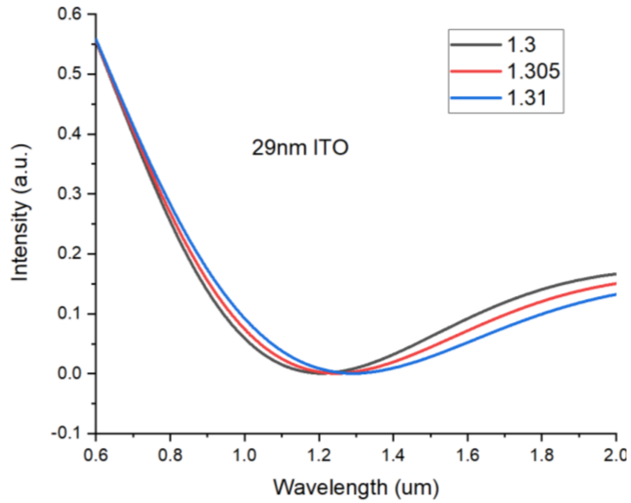
POF/Silica ITO SPR sensors ~ 1300-1500 nm

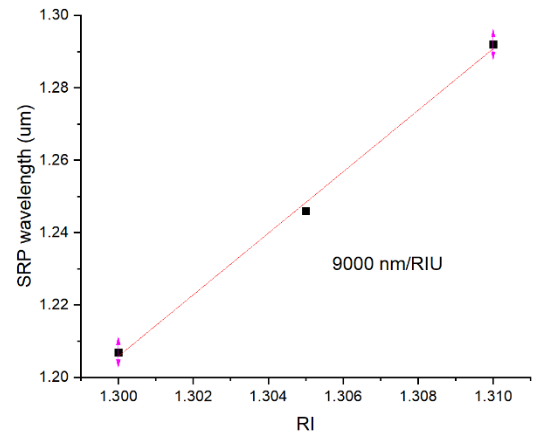
Gold replaced by
Indium Tin Oxide (ITO)



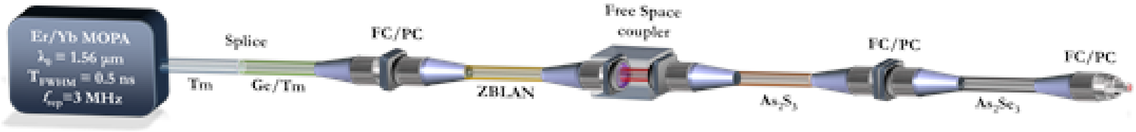


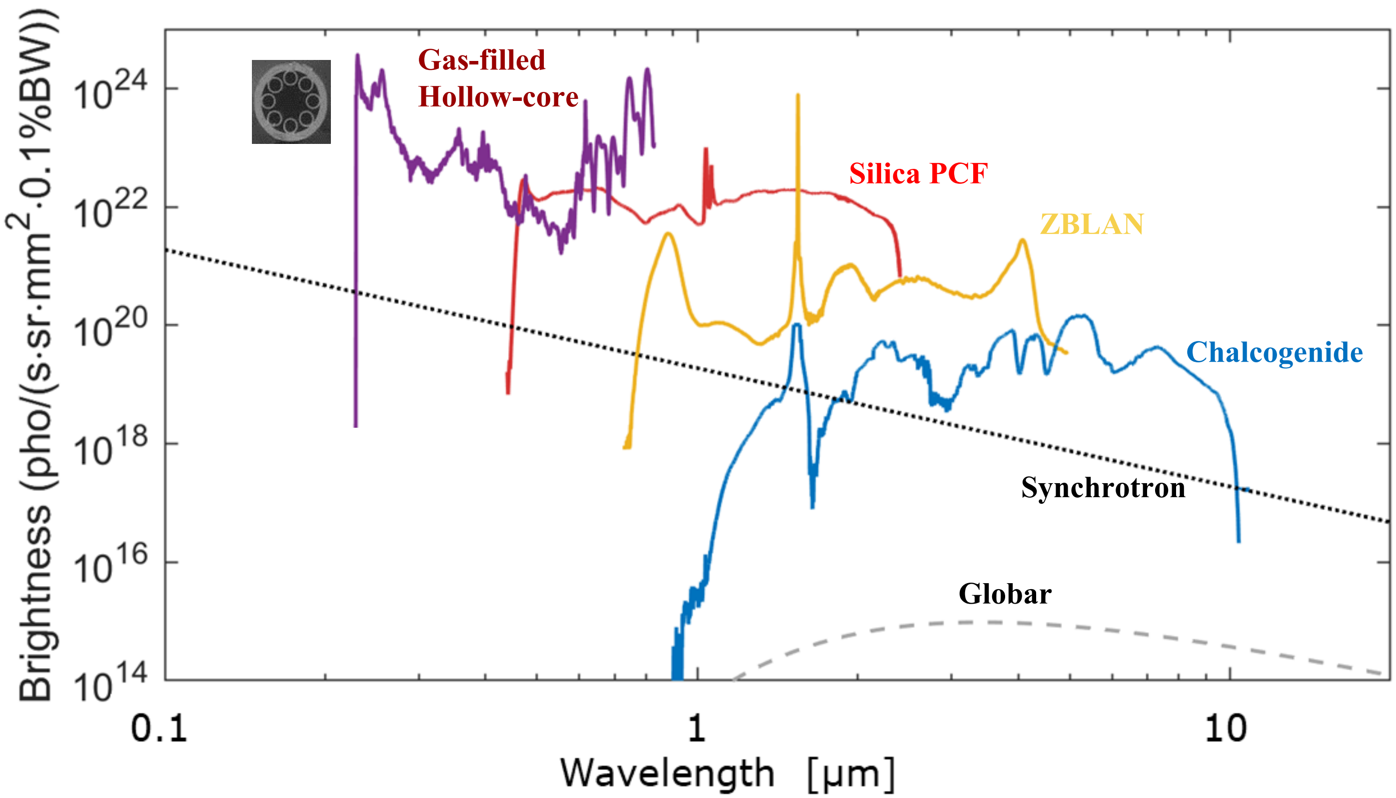


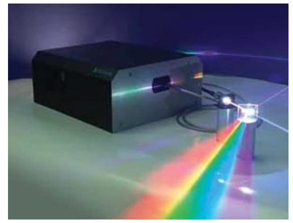




The supercontinuum source / laser





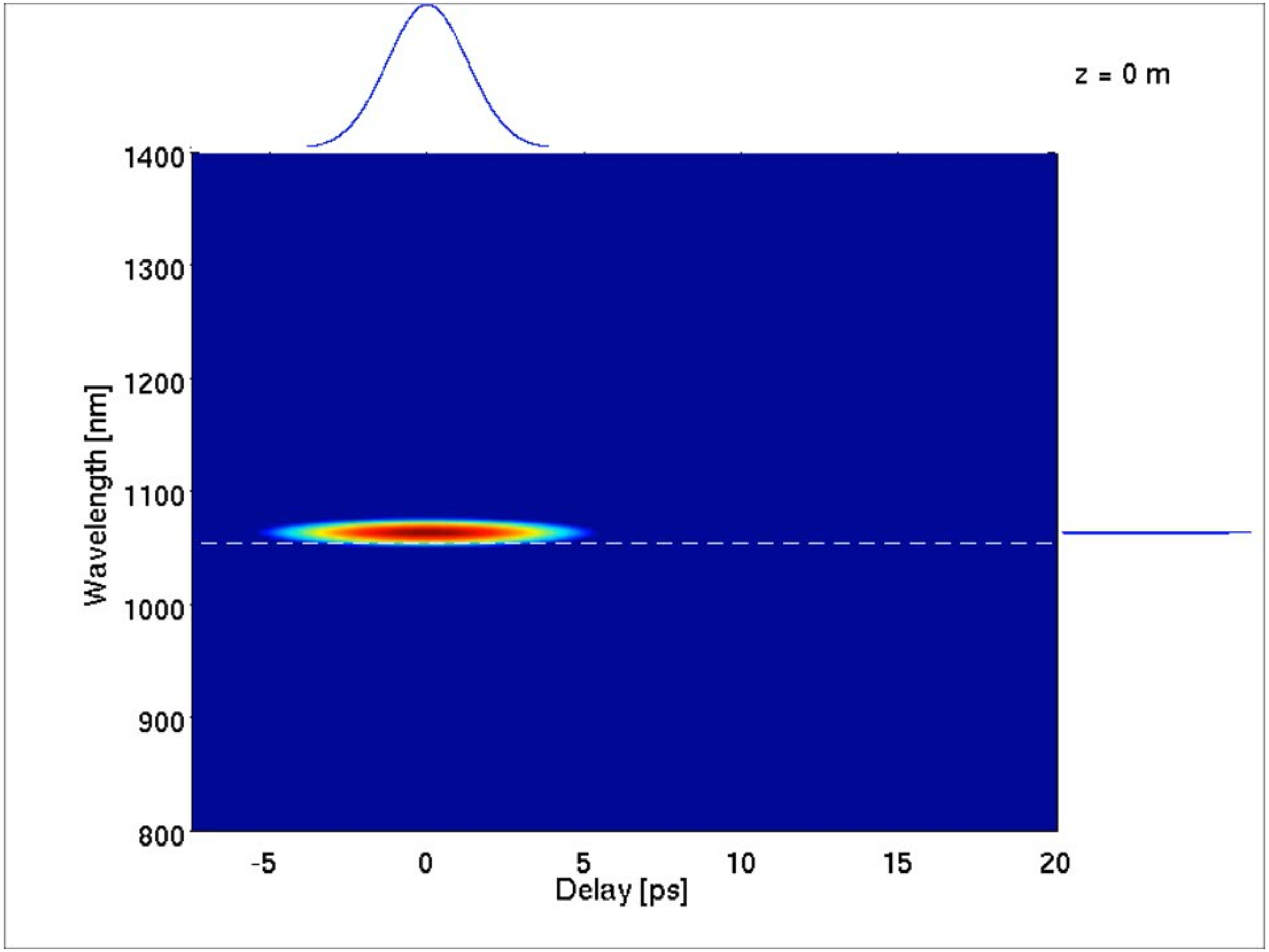


- Spatially coherent
- Fiber delivered
- Shoe-box sized
- Brightness 100x
- Ideal for:
  - *Imaging (OCT)*
  - *Spectroscopy*

- Huge !

- Spatially incoherent
- Omni-directional
- Low brightness

Supercontinuum physics (MI induced)



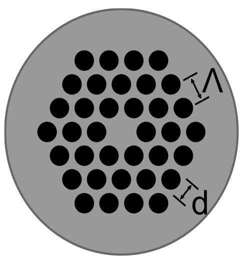
1) Modulation instability (MI)

2) Soliton spectrum and DW generation

3) Soliton redshift, collision, DW trapping

Fiber-optical Rogue waves

Self-regulated

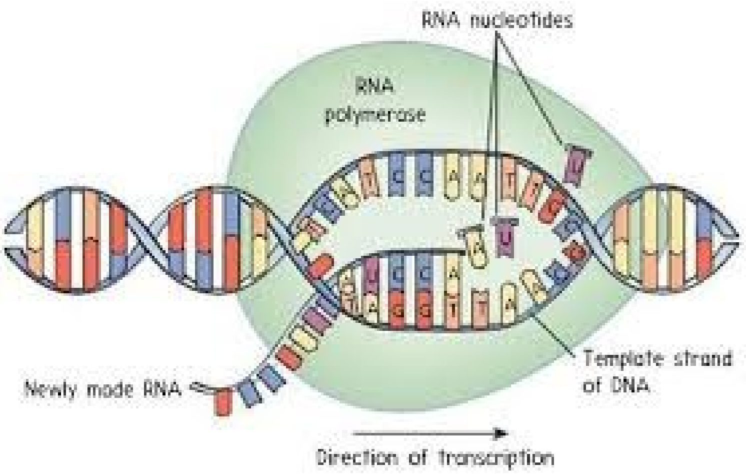


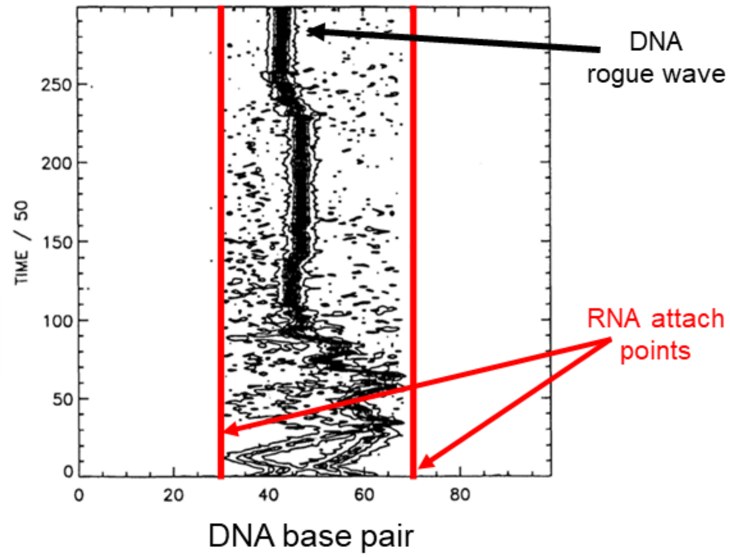
N=112 solitons
3 ps (FWHM)
0.5 kW peak power
d/Λ=0.52, Λ=3.6 um

Oceanic rogue waves

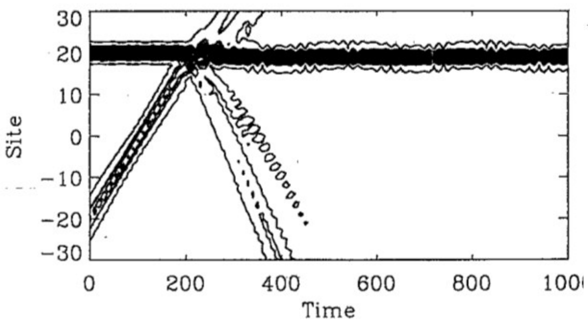
Observations 2004-2005

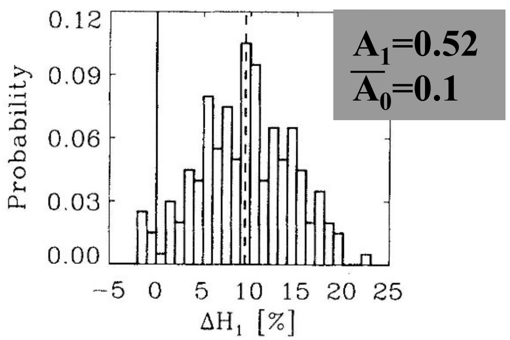
DNA dynamics – Biological Rogue wave leads to denaturation!

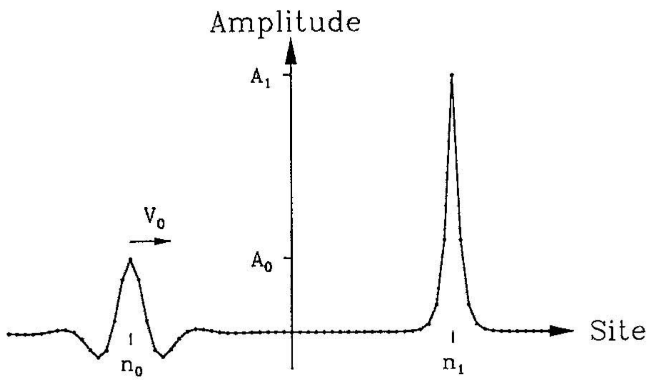


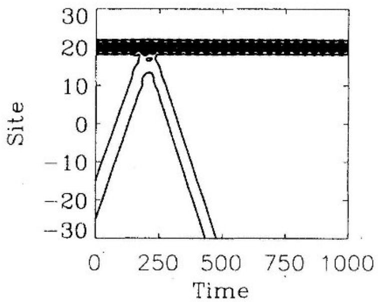


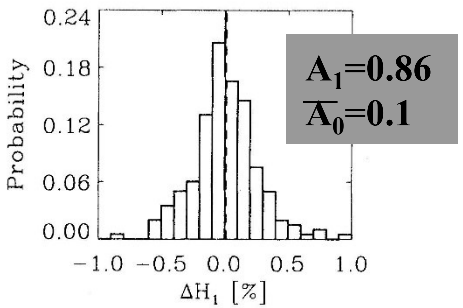
"Big boss"
Michel Peyrard
ENS Lyon, France







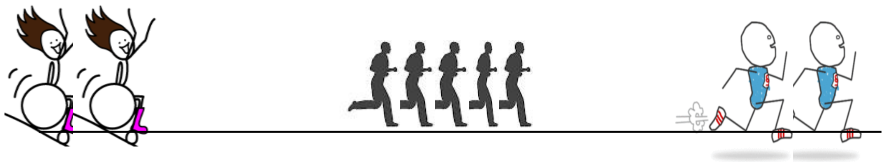




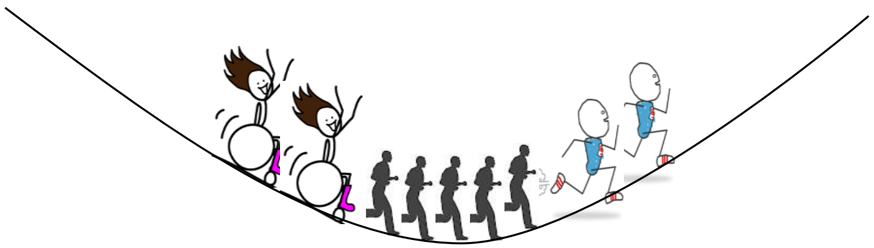
$$\ddot{U}_n - (U_{n+1} - 2U_n + U_{n-1}) + V'(U_n) = 0$$

$|U_n| \ll 1$ gives discrete NLS

The Soliton – illustrated

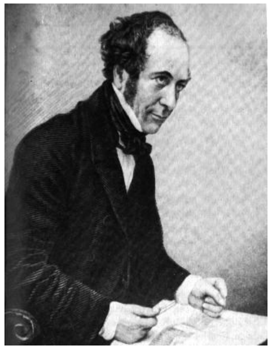


Straight road
Dispersion

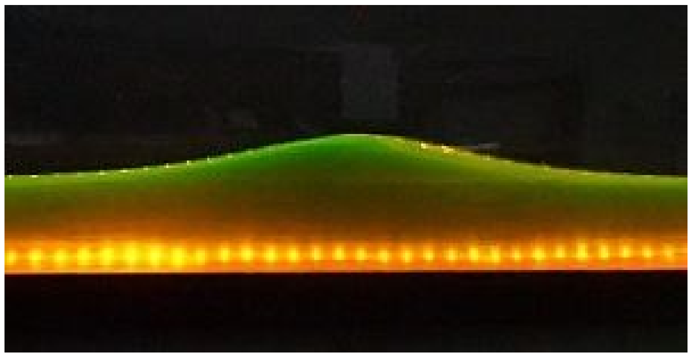


Rubber band
Dispersion +
Nonlinearity

John Scott Russell 1834 – first observation



Lab.Wave channel

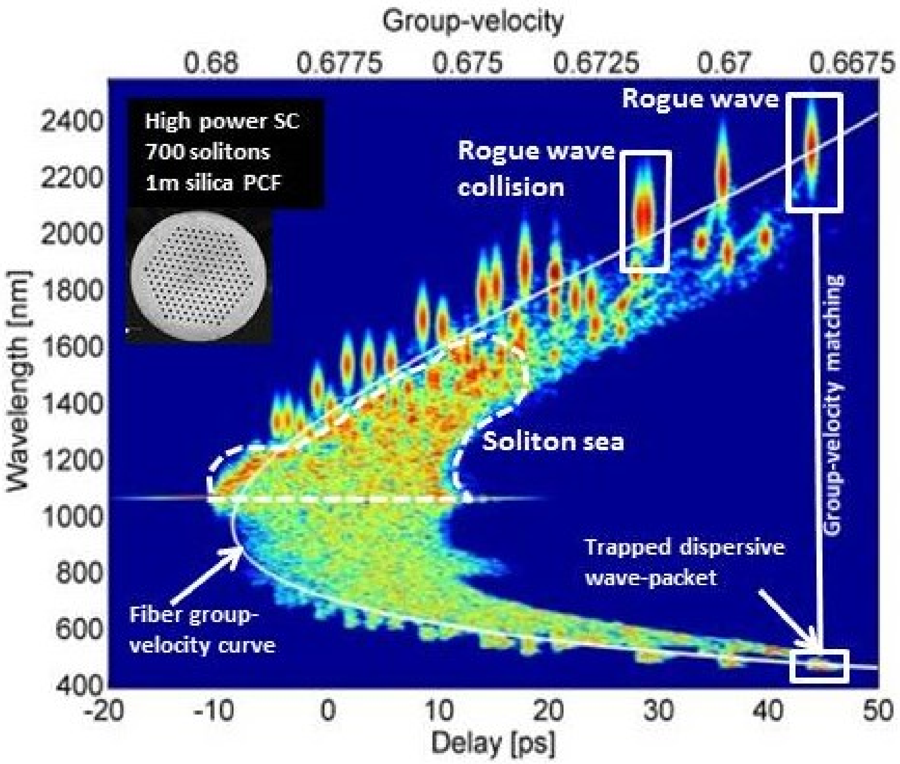


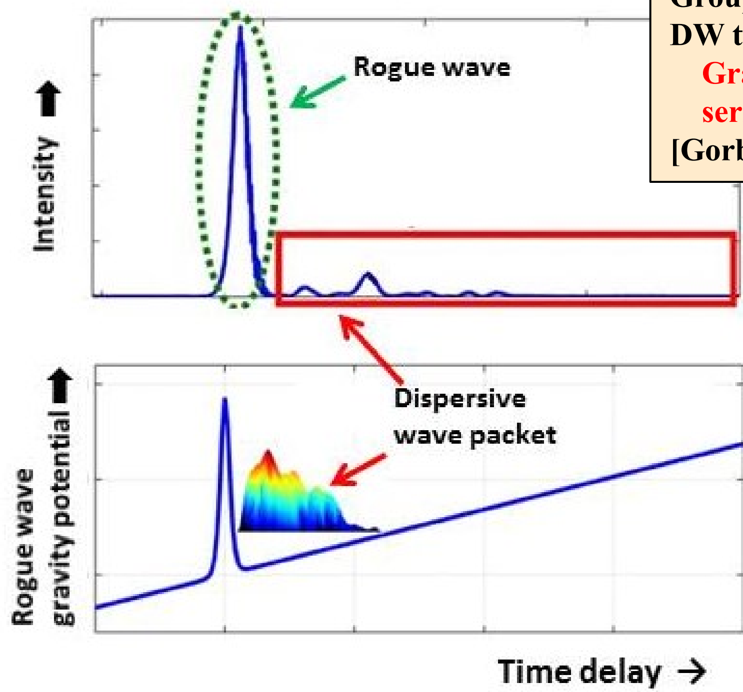
Soliton on the Scott Russell Aqueduct on the Union Canal near Heriot-Watt Univ., 12 July 1995.

Solitons are every where in nature

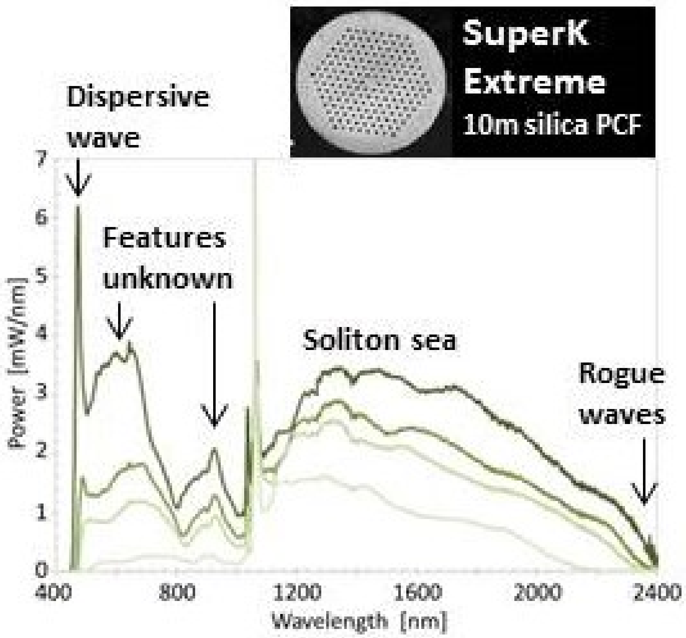
- Optics
- Telecommunication
- Water waves
- Biomolecules
- Superconductivity
- Matter waves

Summing up (anomalous ps pump close to ZDW)

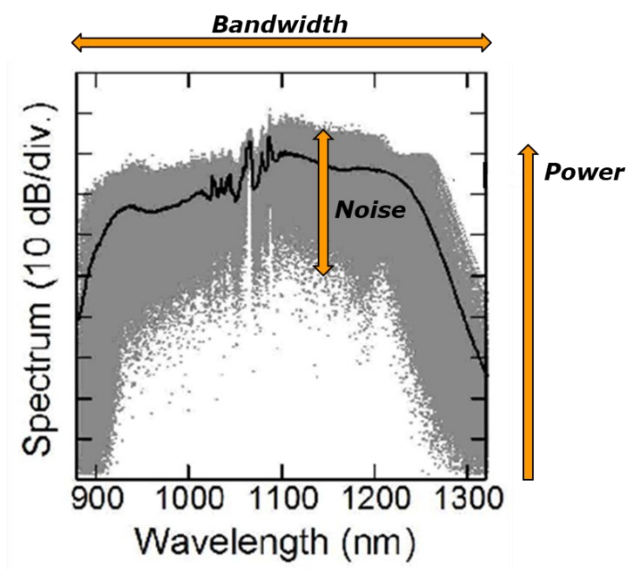




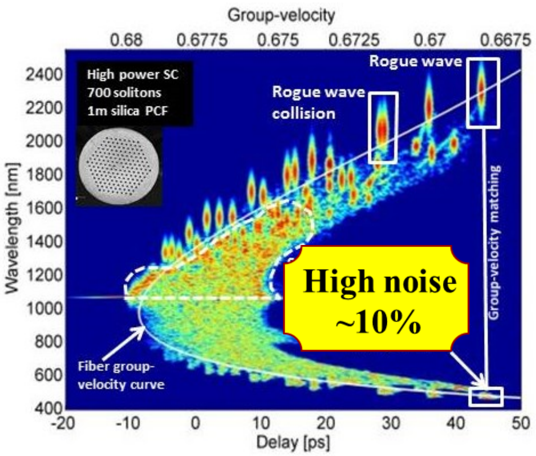
Group-velocity matched edges
DW trapping and blue shift by
Gravitational well /
series of collisions
[Gorback, Skryabin, Nat. Phot 2007]



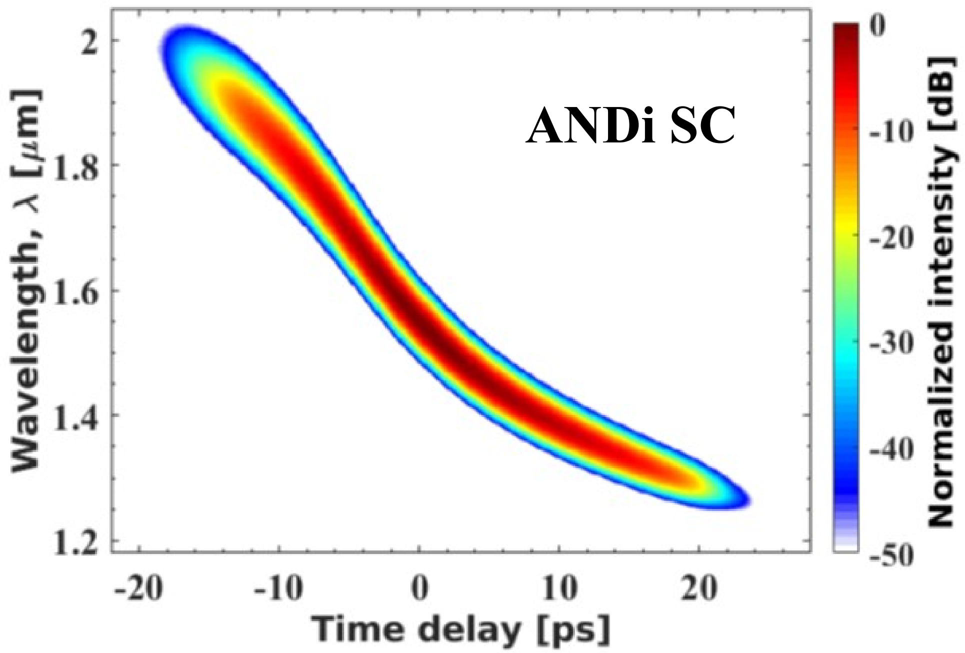
The noisy source ! (Roy Taylor)]



How to combat noise?



Go femtosecond !



High rep rate
Spectrometer averages over many pulses

SuperK Fiannium OCT 320MHz

Short pump pulses (fs)
Fundamental coherent physics:
- Normal dispersion
- Self-phase modulation
- Optical wave breaking

Low noise ~0.1%

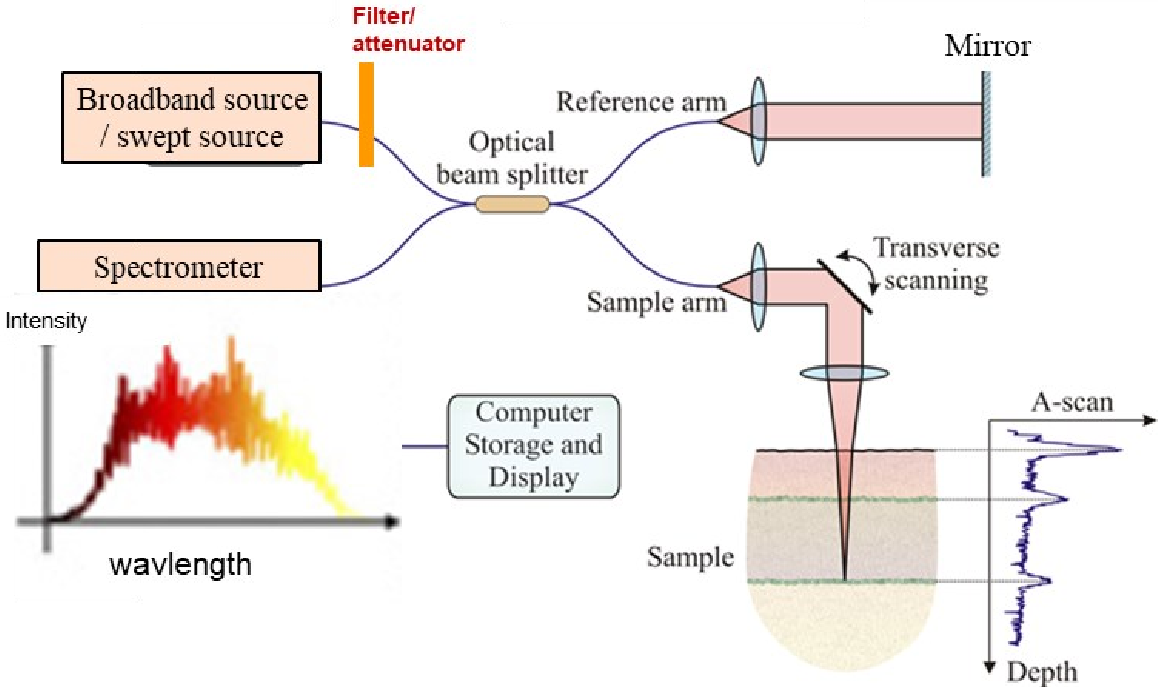
ANDi Fundamental::

[Finot, J. Opt. Soc. Am. B 25 (2008)]
[Heidt, J. Opt. Soc. Am. B 27 (2010)]
[Gonzalo, Sci. Rep. 8 (2018)]

ANDi applications:

OCT: [Rao D.S., Light: Sci. Appl. 10 (2021)]
SNOM: [Kaltenecker, APL Photon. 6 (2021)]

Mid-IR OCT – spectral domain



Depth resolution:

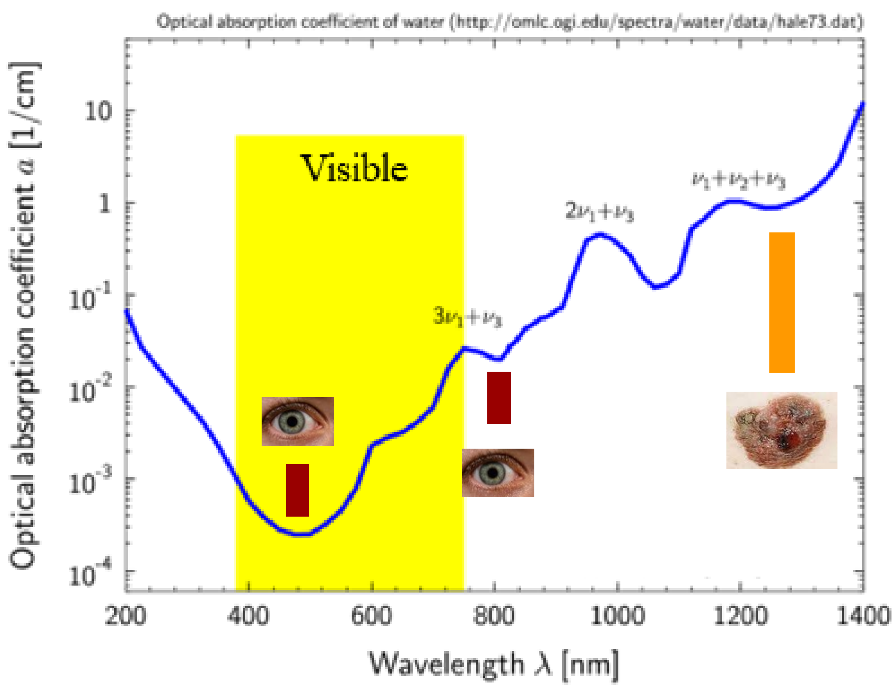
$$\Delta z = C\,\frac{\lambda_0^2}{\Delta\lambda}, \qquad C = \begin{cases} 0.44 & \text{Gaussian} \\ 0.61 & \text{square} \end{cases}$$

Scattering loss:

$$\alpha \rightarrow \frac{1}{\lambda_0^4}$$

Material loss:

$$\alpha = ?$$

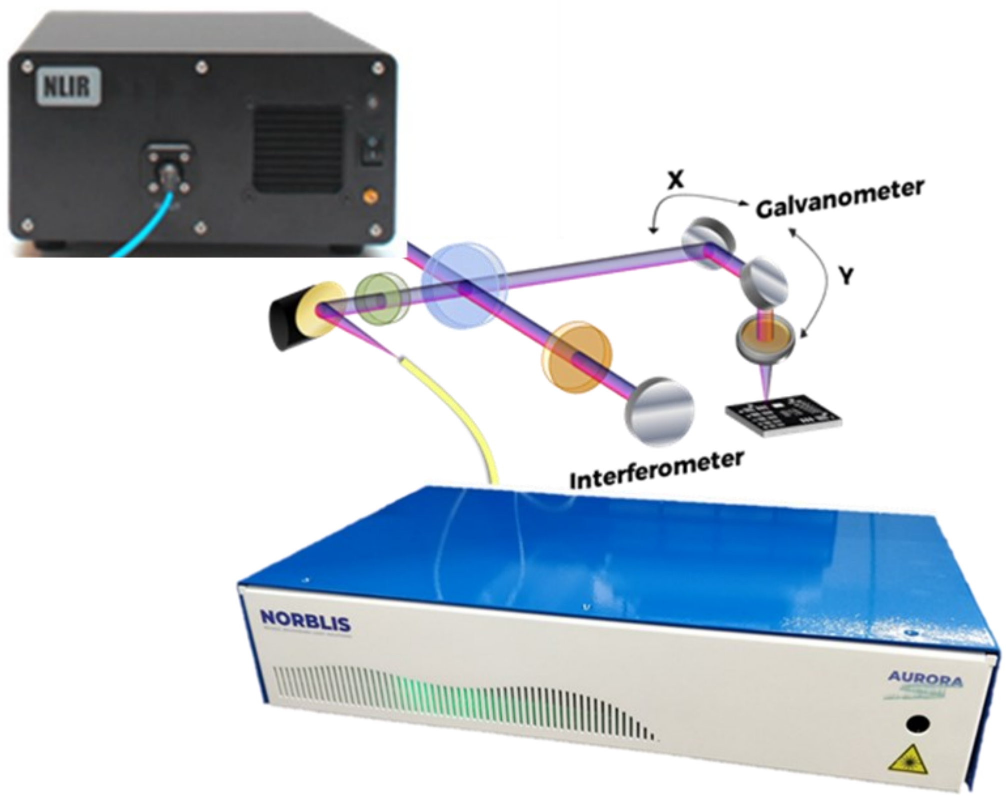


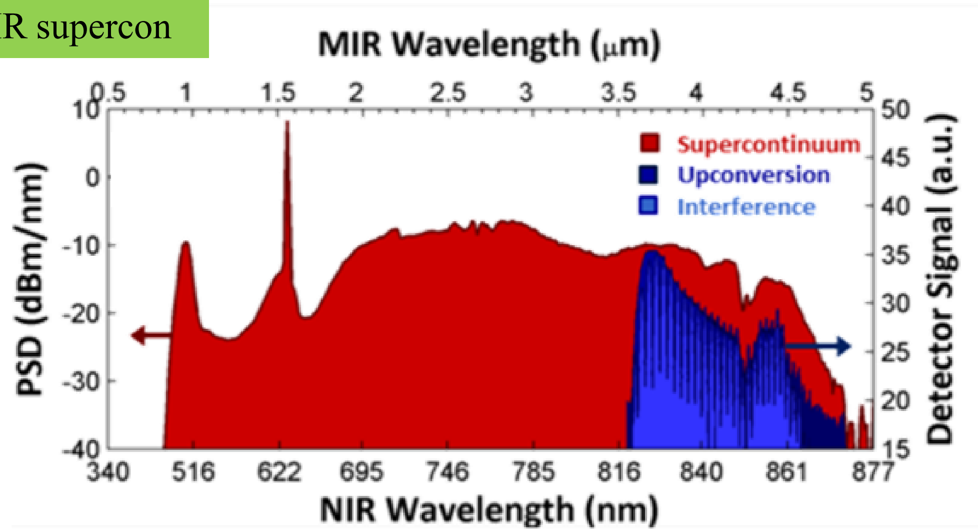
Mid-IR

No water!

Mid-IR OCT + upconversion

Key patent:
- Up-conversion +
- Mid-IR supercon

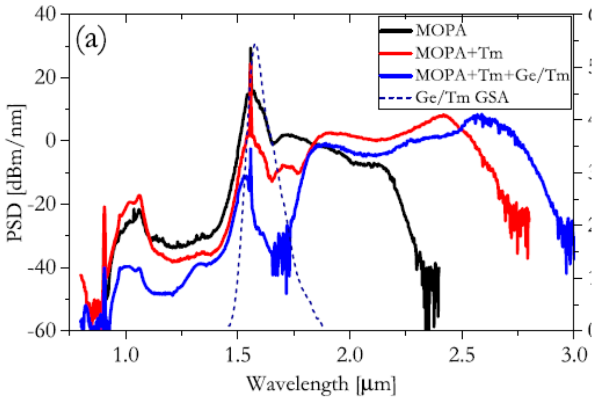


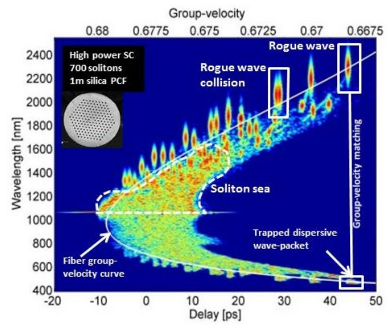


MIR OCT can provide real-time high-resolution NDT

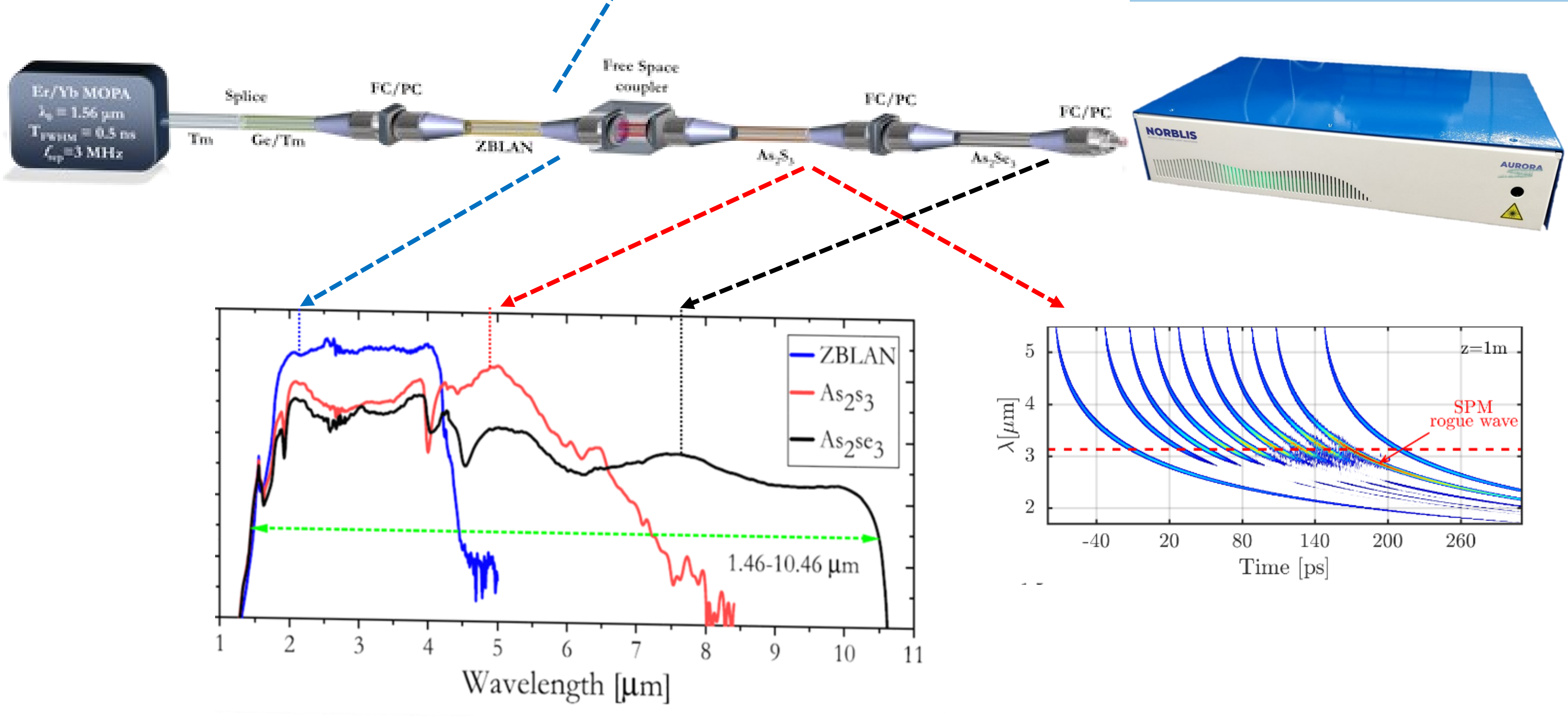
- Source rep rate 1 MHz
- Central wavelength: 4.1 μm
- Bandwidth: 1.1 μm
- Axial resolution: 5.8 μm
- Line rate: 3.33 kHz
- B-scan: 0.3 s (1000 A scans)
- Scan area (galvo): 3 x 3 mm

Mid-IR supercontinuum - cascading

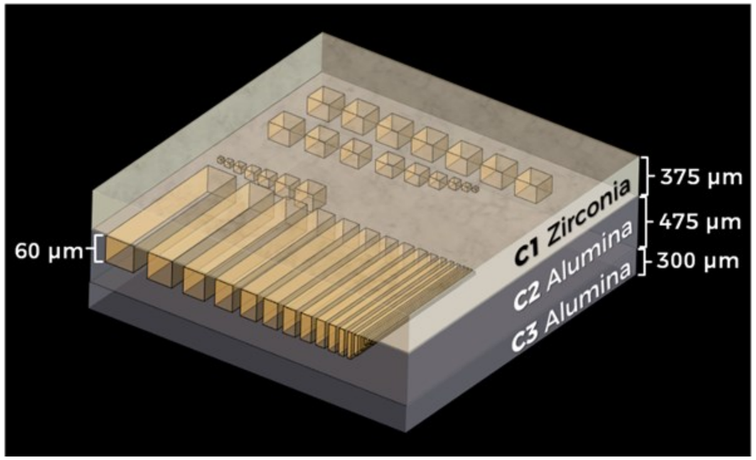


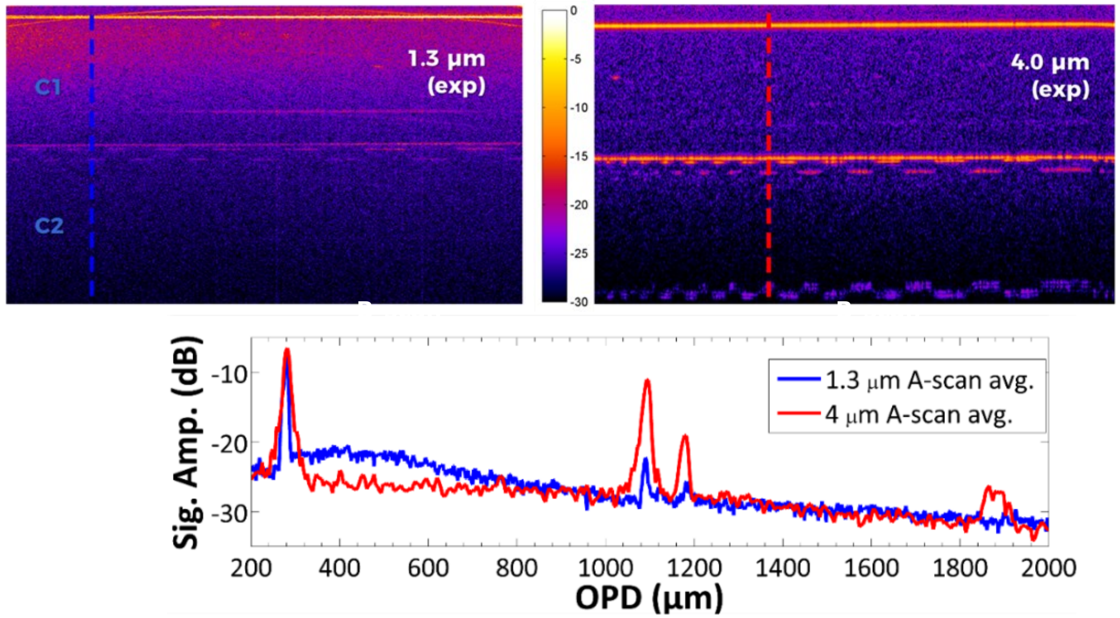


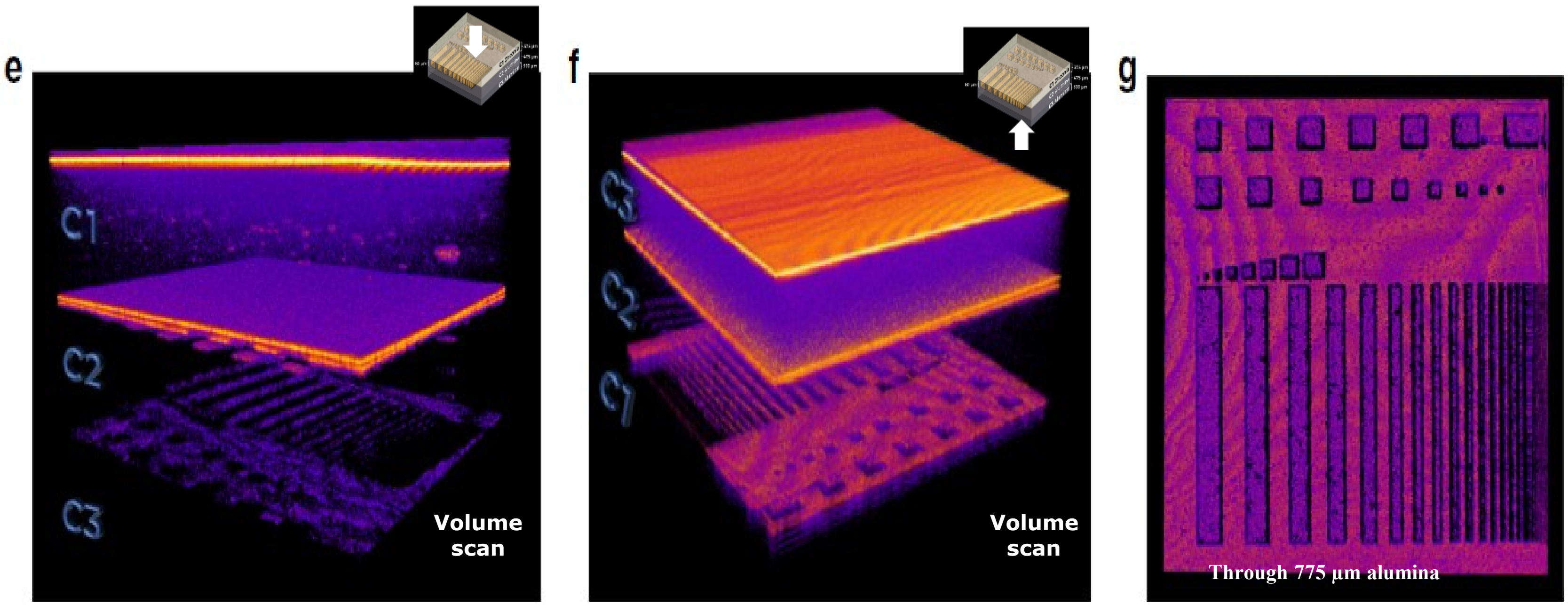
[**G. Woyessa**, Optics Letters **46,** 1129 (2021)]



Mid-IR OCT - ceramics



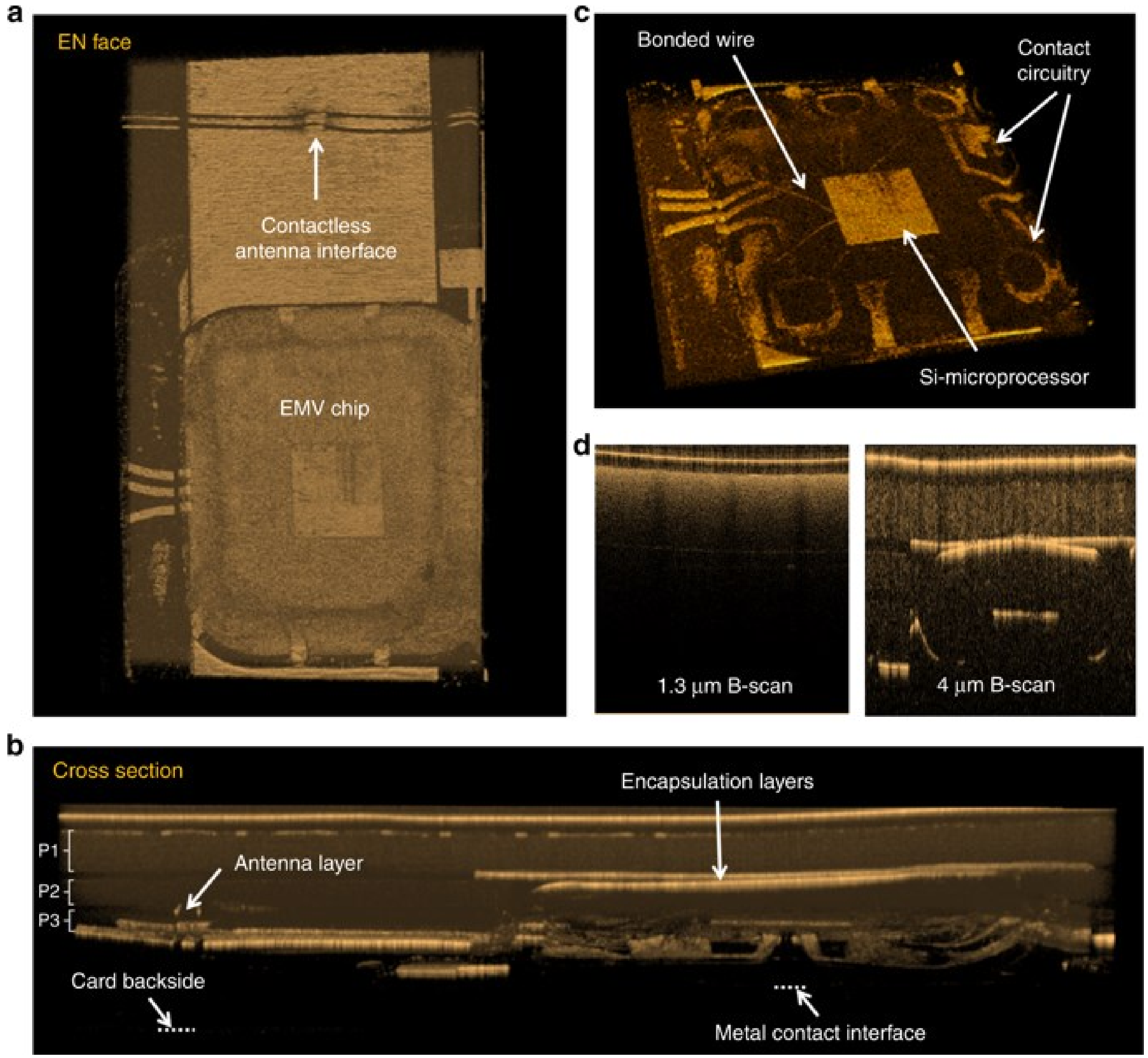




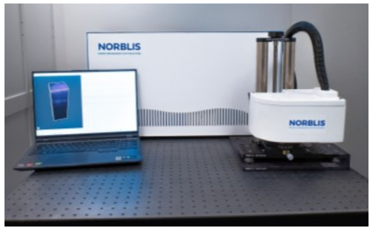
Mid-IR OCT – cedit card

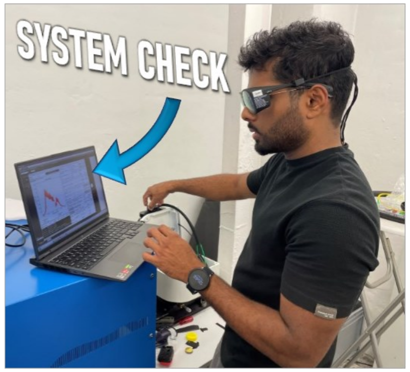
Credit Card

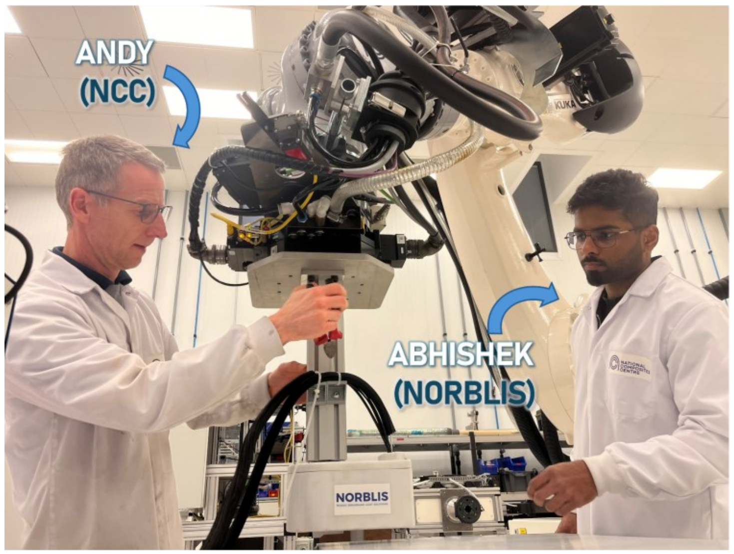
- Laminated polymers
- Resins / epoxy
- Silicon microchip
- Metal circuit

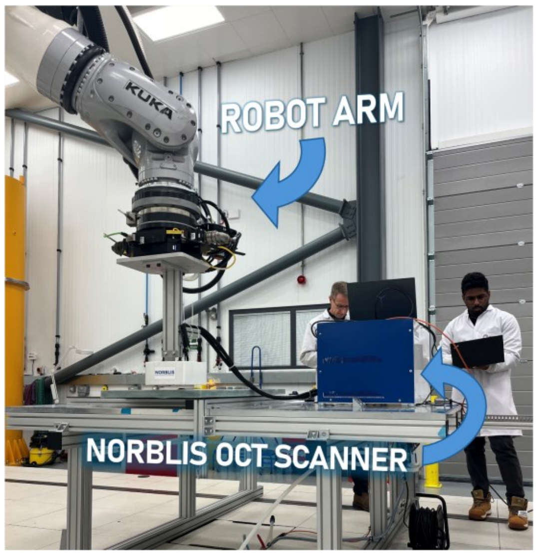


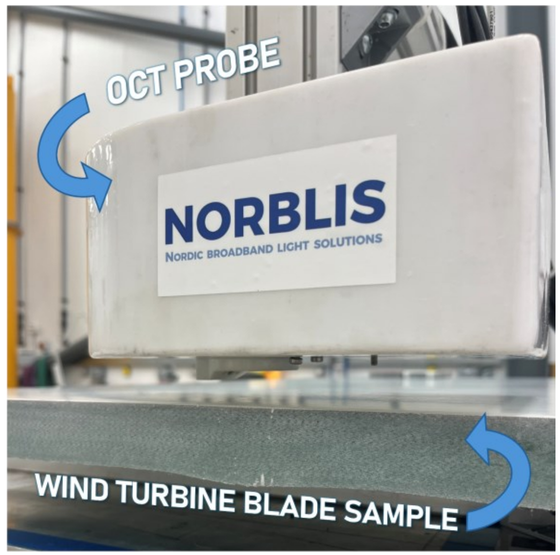
NORBLIS
NORDIC BROADBAND LIGHT SOLUTIONS











Thank you audience!

Thank you Radek and Barbora!

SMART OPTICAL FIBER SENSORS WITH FUNCTIONAL COATINGS AND DATA FUSION

#@APP-FORM-HERIAIA@#

List of participants

Participant No. *	Participant organisation name	Country
1 (Coordinator)	Université de Mons – **UMONS**	Belgium
2	Vivid Components Germany UG – **VIVID**	Germany
3	Danmarks Tekniske Universitet – **DTU**	Denmark
4	Institut National Polytechnique de Toulouse – **INP**	France
5	Universidade de Aveiro – **UAVEIRO**	Portugal
6	Technical University Ostrava – **VSB**	Czech Republic
7	Safibra – **SAF**	Czech Republic
8	Artikode Intelligence – **AKD**	Spain
9	SHUTE Sensing Solutions A/S – **SHUTE**	Denmark
10	Riasearch Lda – **RIA**	Portugal
11	Ratio et Ars srl – **Ratio@Ars**	Italy

World-record broad bandwidth low-noise ANDi supercontinuum