

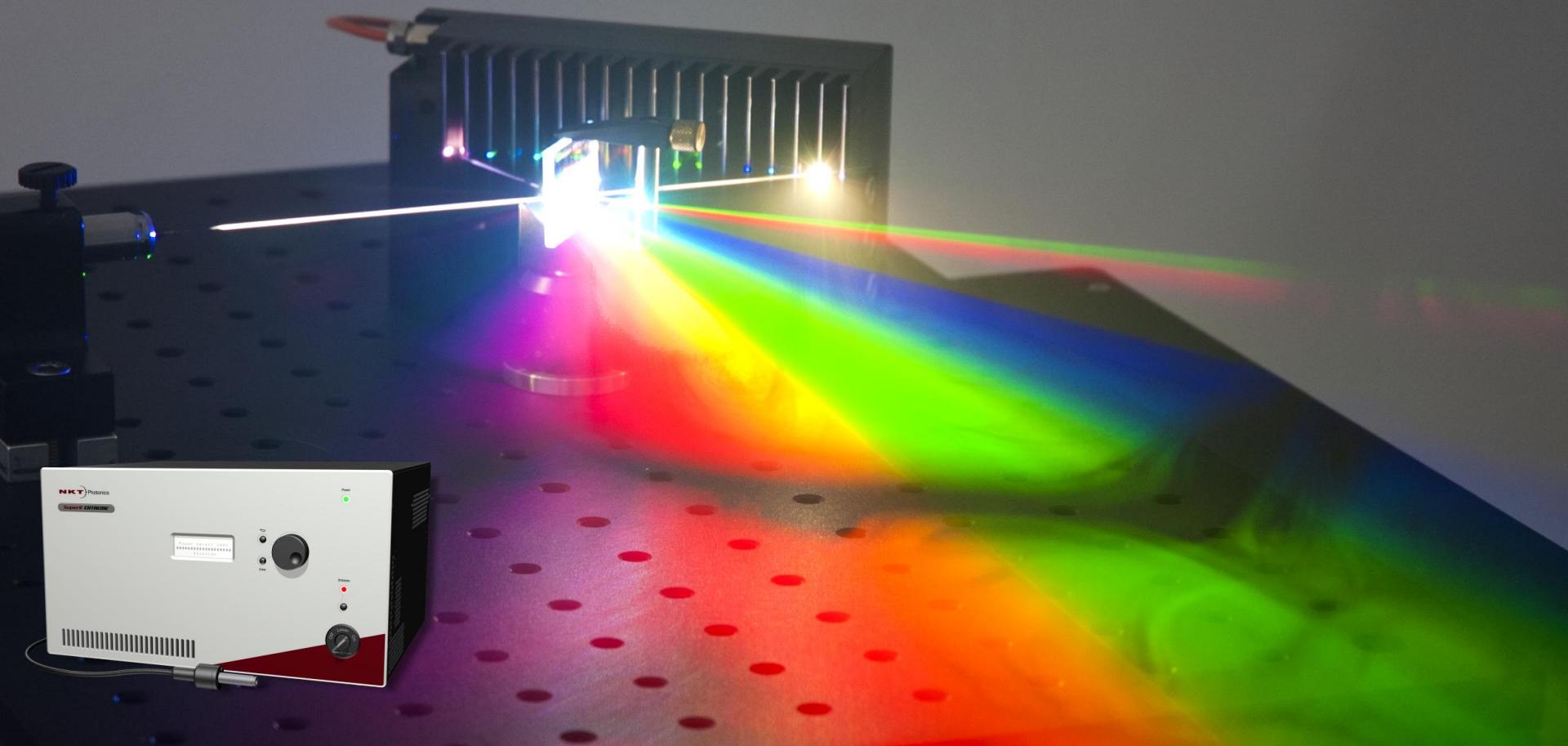
2 μm lasers as pump sources for mid-IR supercontinuum sources

June 2015

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Christian Petersen, Laurent Huot,
Chris Brooks, Carsten L Thomsen**



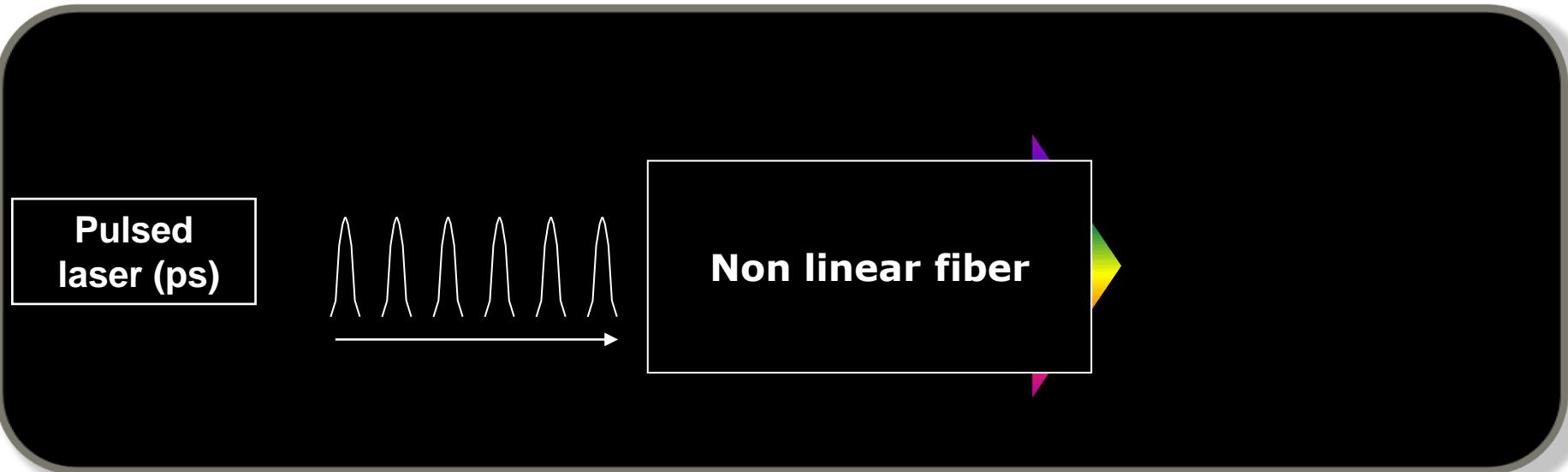
Supercontinuum light sources: A sun in a box



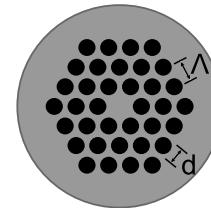
Crystal Fibre • aeroLASE • Koheras • SuperK

NKT Photonics
the power of light

Supercontinuum what is it – simplified



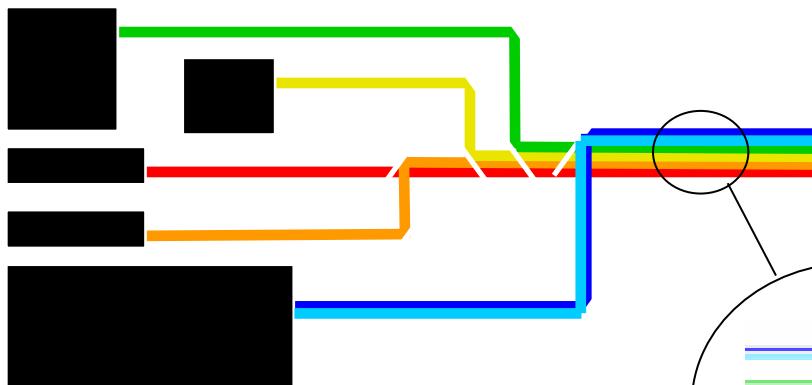
- Supercontinuum is generated when high (peak) power light enters a nonlinear material
- The enabling technology is photonic crystal fibres (PCFs):



Supercontinuum - The difference

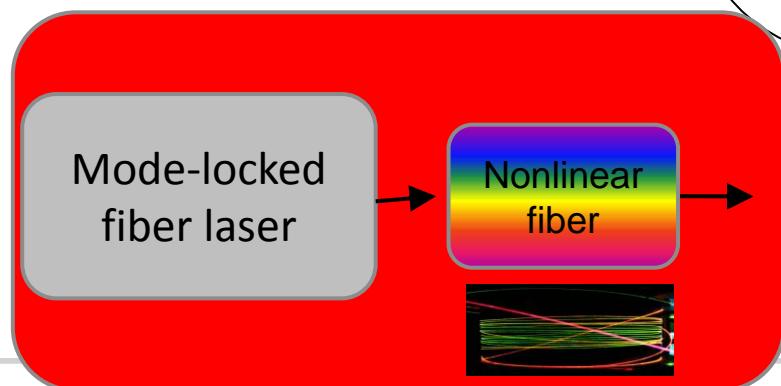
Conventional Lasers

Merged set of conventional lasers

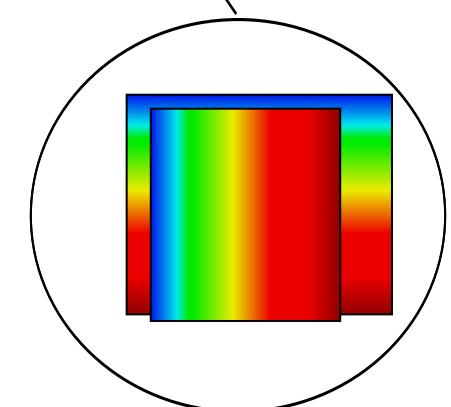


SuperContinuum

One Single Supercontinuum Source

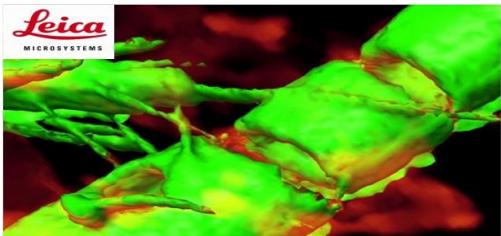


- ✓ Continues in spectrum
- ✓ High power density
- ✓ Short Pulsed in time

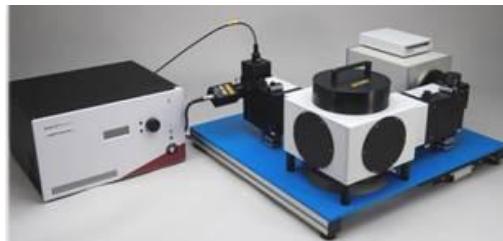


Applications of supercontinuum

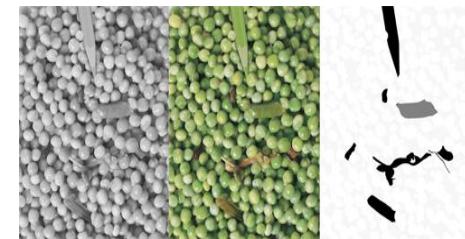
Microscopy



Diagnostics



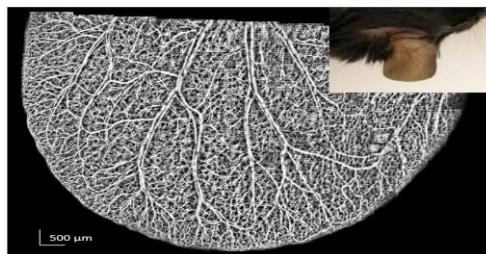
Food sorting



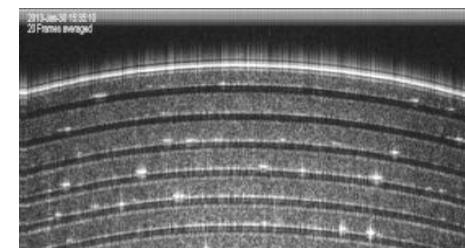
Life Science



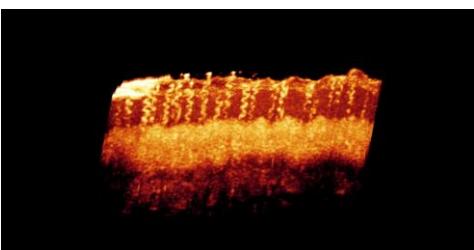
BioTech



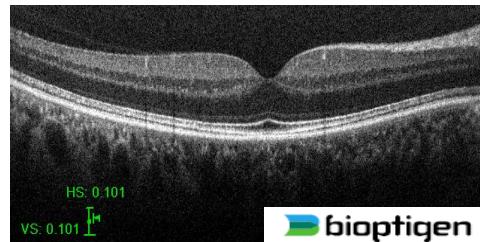
Industrial NDT



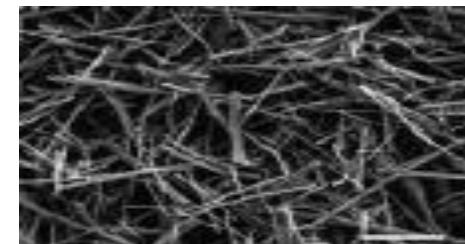
OCT



Ophthalmology



Nanotechnology

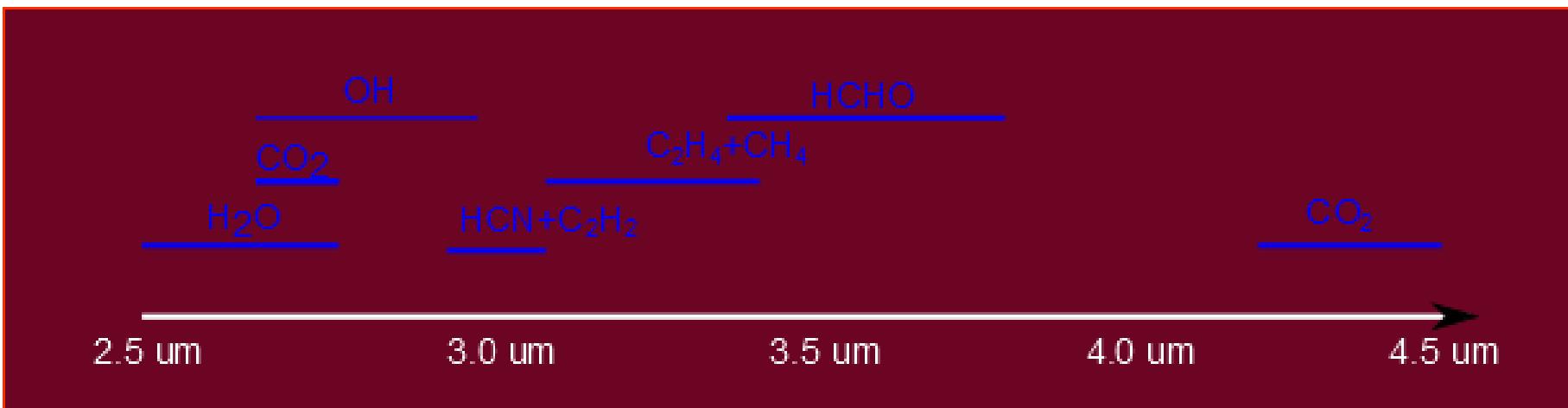


Extending the spectrum to the Mid-IR

Chasing MID IR – Why?

Chemical finger printing:

- Detecting explosives (3.2-3.5 um)
- Food analysis
- Combustion analysis
- Medical – Spectral Imaging



Chasing MID IR – Why?



Lasing in thulium-doped polarizing photonic crystal fiber

Norbert Modsching,^{1,2} Pankaj Kadwani,¹ R. Andrew Sims,¹ Lasse Leick,³
Jes Broeng,³ Lawrence Shah,^{1,*} and Martin Richardson¹

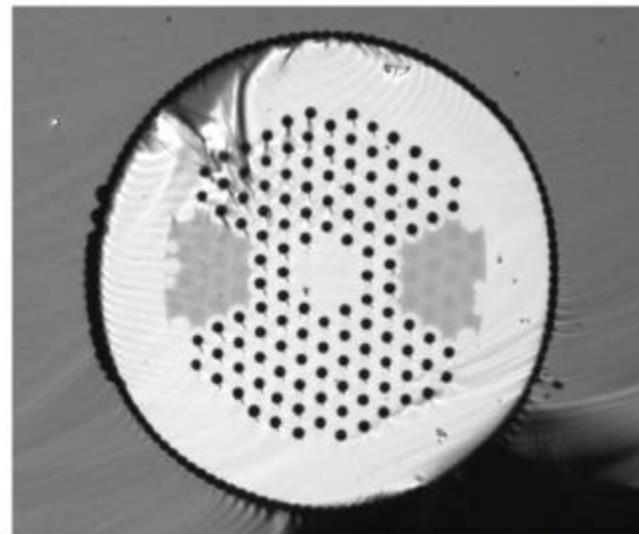
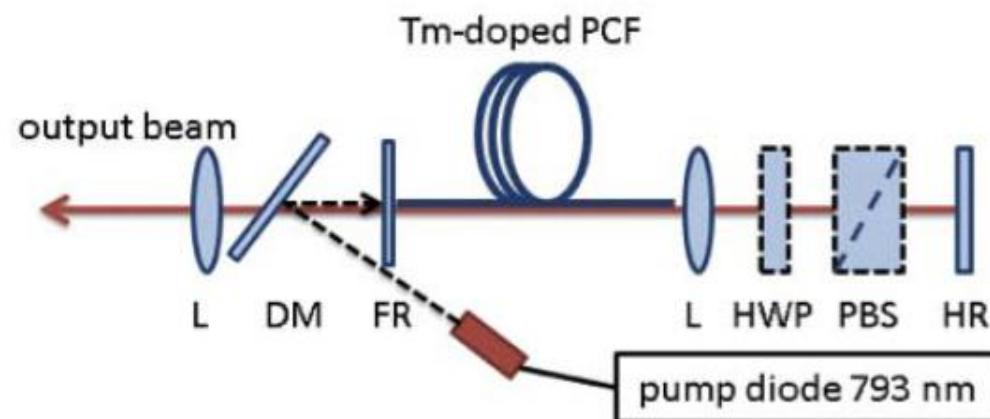


Fig. 1. Image of the fiber facet, showing the 50 μ m core, 250 μ m diameter cladding, and the stress-applying parts.

Current mid-IR light sources

○ Thermal light source

⊕ Broad spectral coverage and low cost

⊖ Power spectral density in a single mode fiber <50 dBm/nm

○ OPOs

⊕ Up to 10 W in a ultra-narrow line tunable over up to 70 nm

⊖ High cost system for lab use only

○ Mid-IR diodes

⊕ Compact, energy efficient, >100 mW output power

⊖ One fixed line w <10 nm tuning range

○ External cavity QCLs

⊕ Compact, energy efficient, >100 mW output power tunable over e.g. 600 nm @ 4.3 μm

⊖ Poor operation <4 μm, high cost >50 k\$

○ Syncrotron

⊕ High intensity and covers the full spectrum

⊖ Very large and very expensive facility

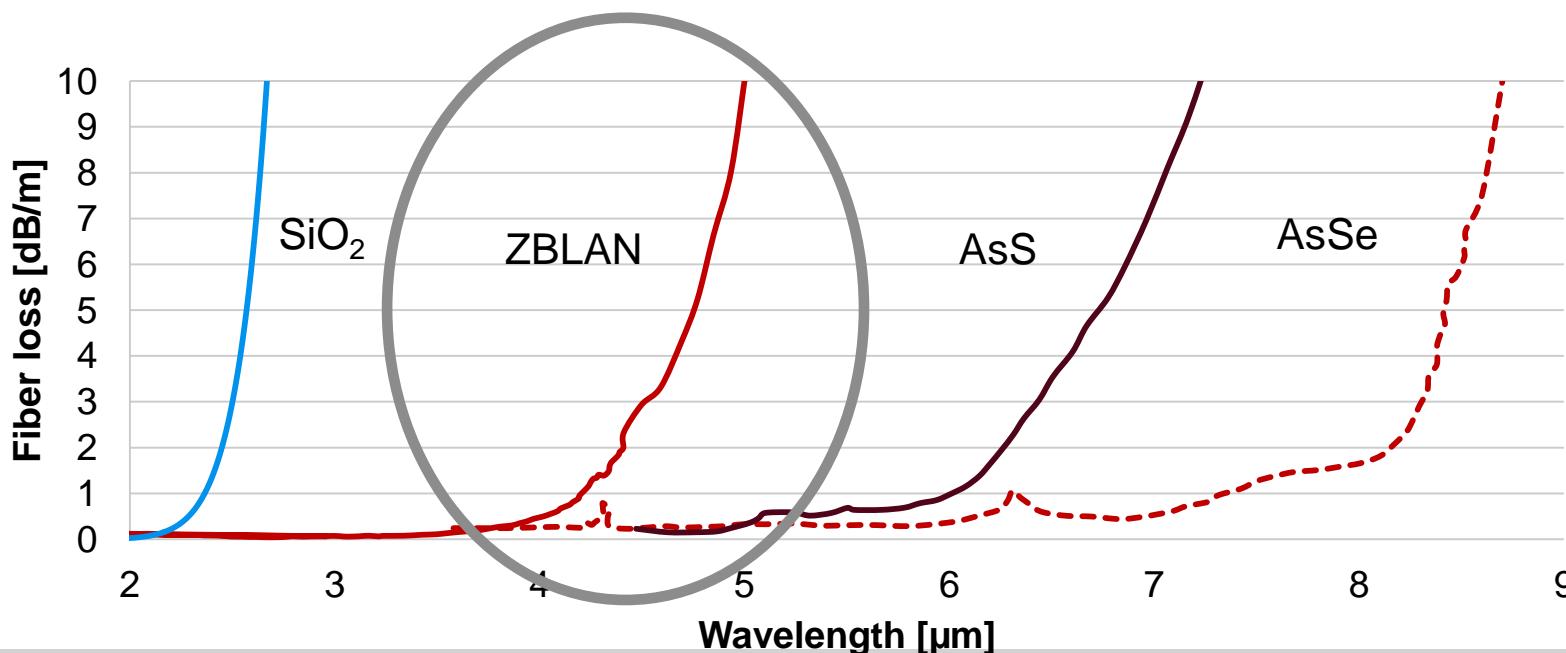
It seems that there is room for a commercial mid-IR supercontinuum source on the market

Requirements for mid-IR supercontinuum sources

1. New fiber material to generate mid-IR light
2. Pulsed laser sources (preferable with wavelengths above 1700 nm)
3. Single and multimode components to amplify the pulsed laser to high ~10 kW power
4. Components to collimate and shape mid-IR light
5. Proving reliability and mass reducibility
6. Building up the market for mid-IR SuperK sources

Fiber Material choice

- Silica is opaque above $2.4\text{ }\mu\text{m}$
- Soft glasses necessary
- Glass choice dependent on several parameters
- Dispersion, loss and nonlinearity is most important



Pump laser for the mid-IR supercontinuum

Possible options:

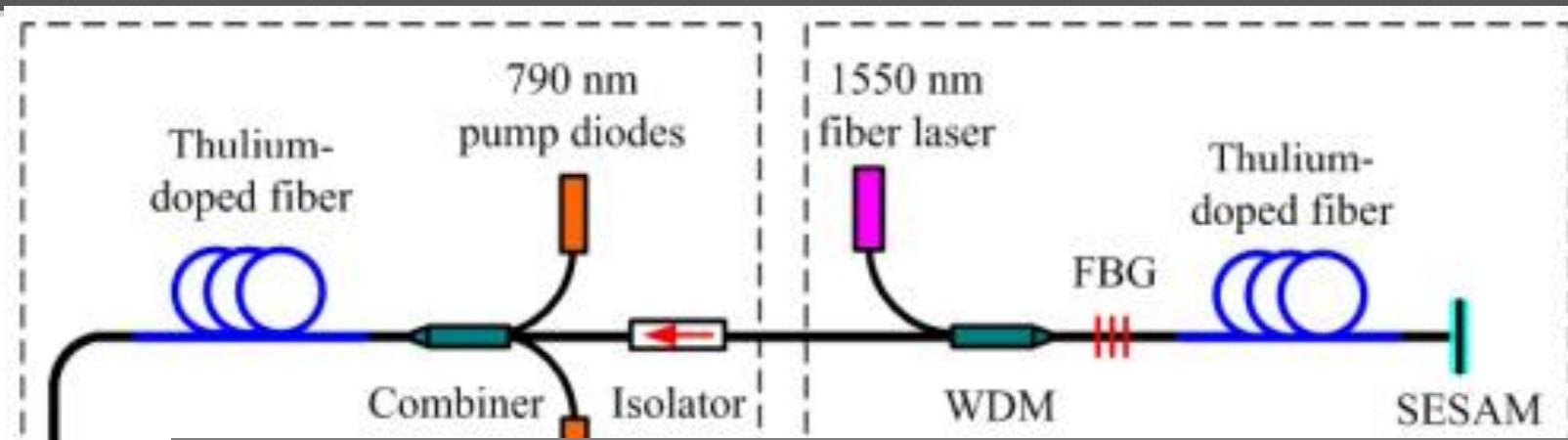
- 1.0 μm lasers (Yb)
- 1.55 μm lasers (Er)
- 2.0 μm laser (Tm)
- 2.1 μm laser (Tm:Ho)
- 2.9 μm laser

Wavelength too low?
Cheap

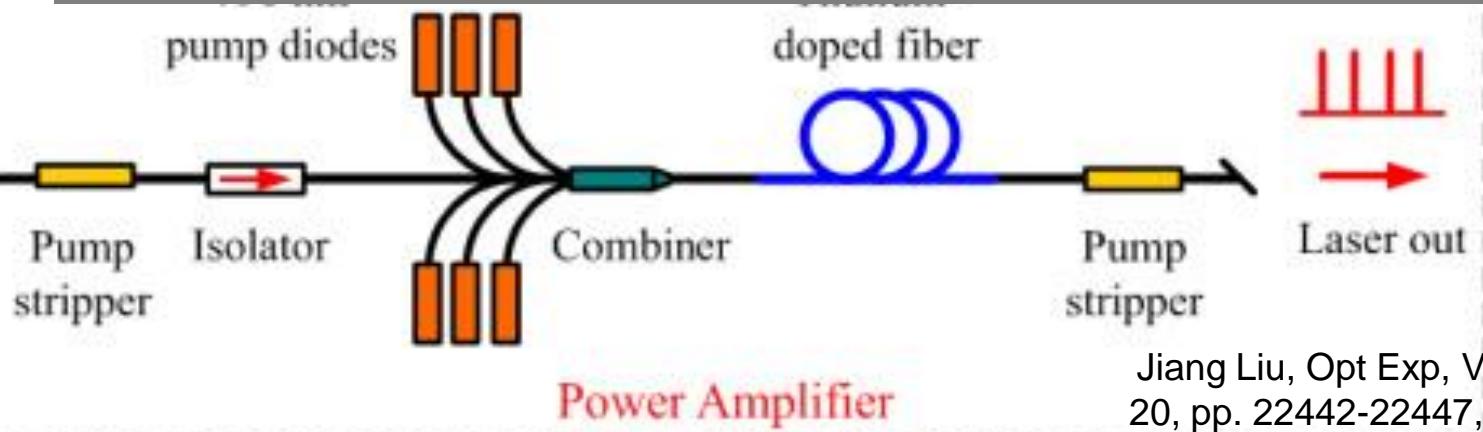
Good wavelength
Expensive

Good wavelength
Very expensive

2 μm lasers: mode-locked and MOPA



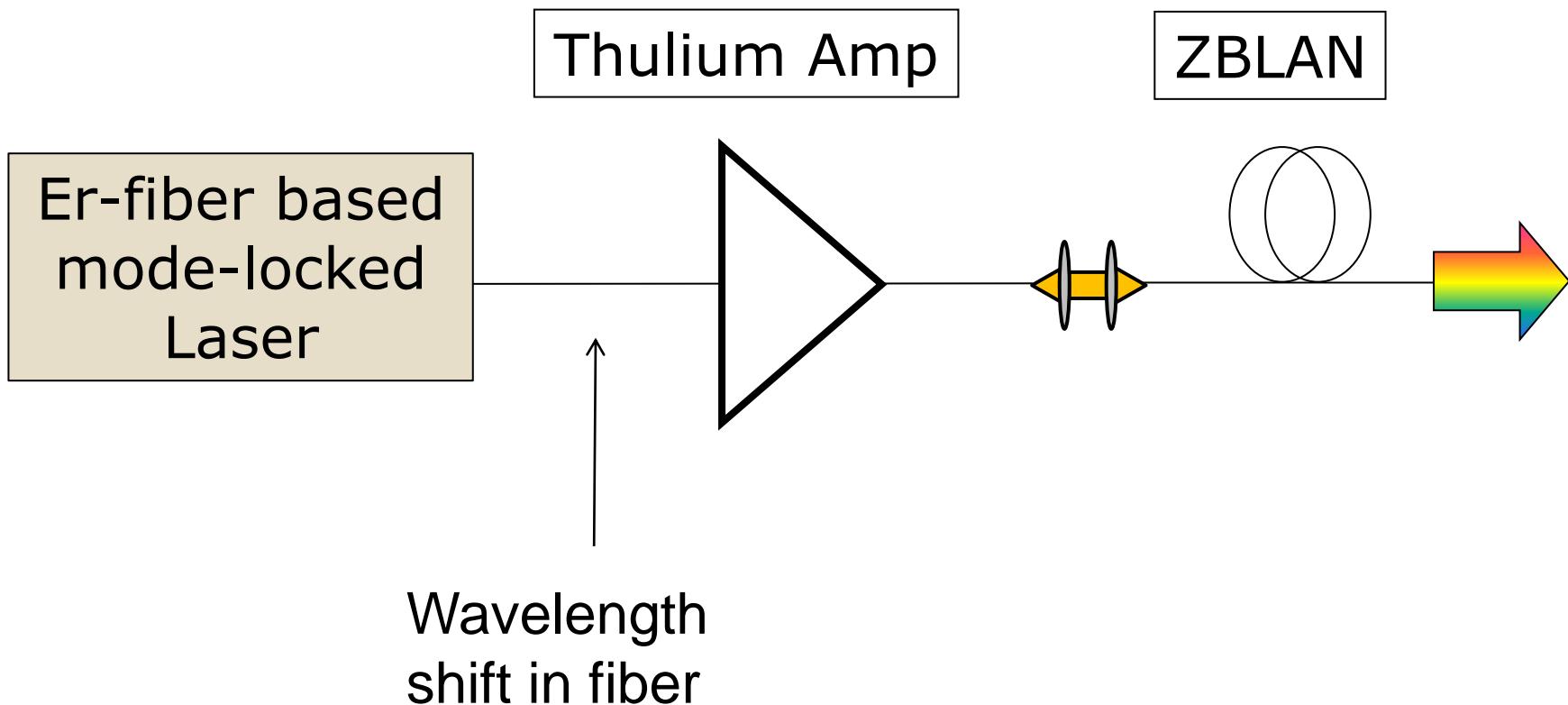
Single mode components at 2 μm are 5 - 10 times more expensive than at 1.5 μm



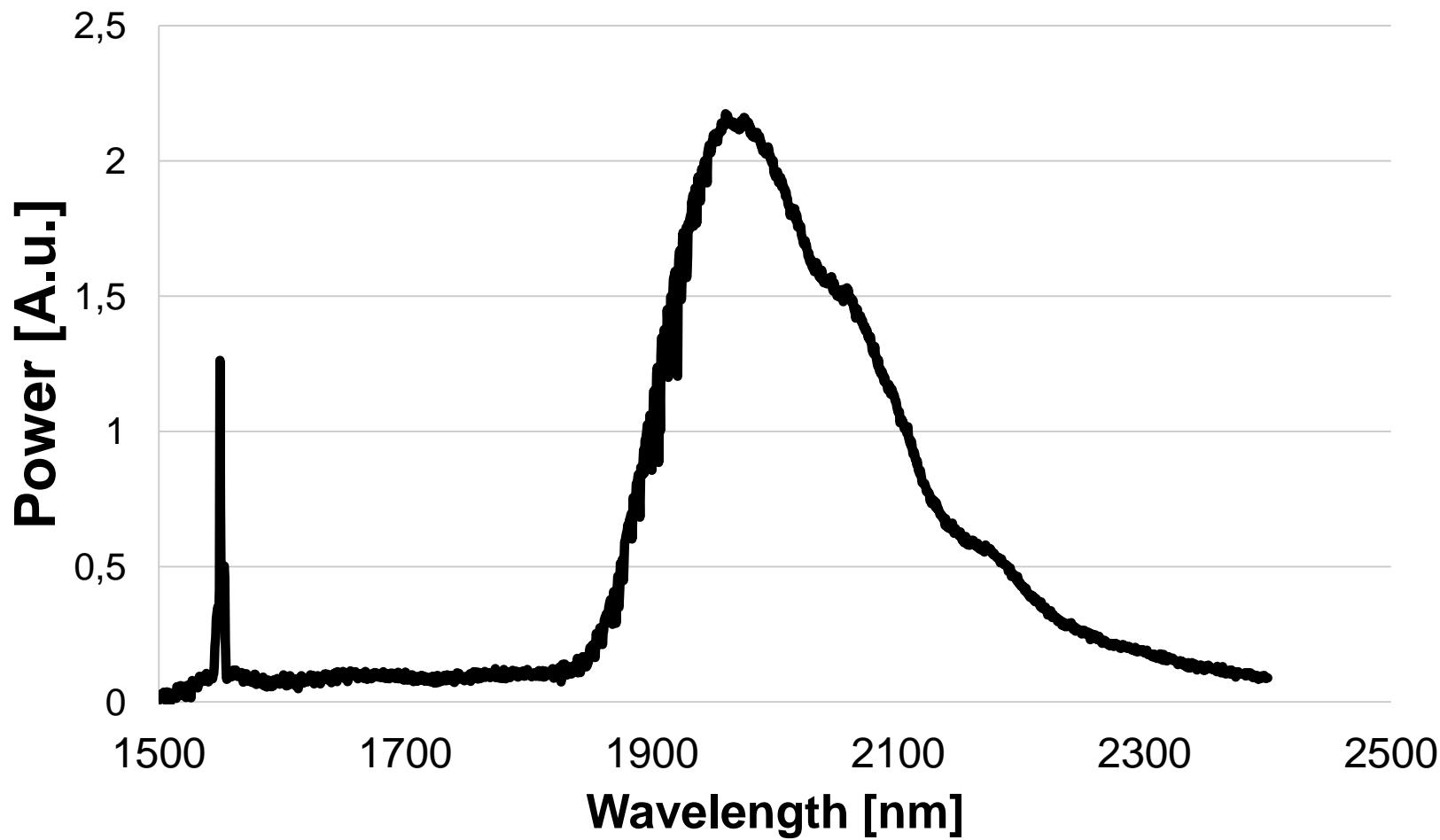
Power Amplifier

Jiang Liu, Opt Exp, Vol.
20, pp. 22442-22447, 2012

Wavelength shifted lasers



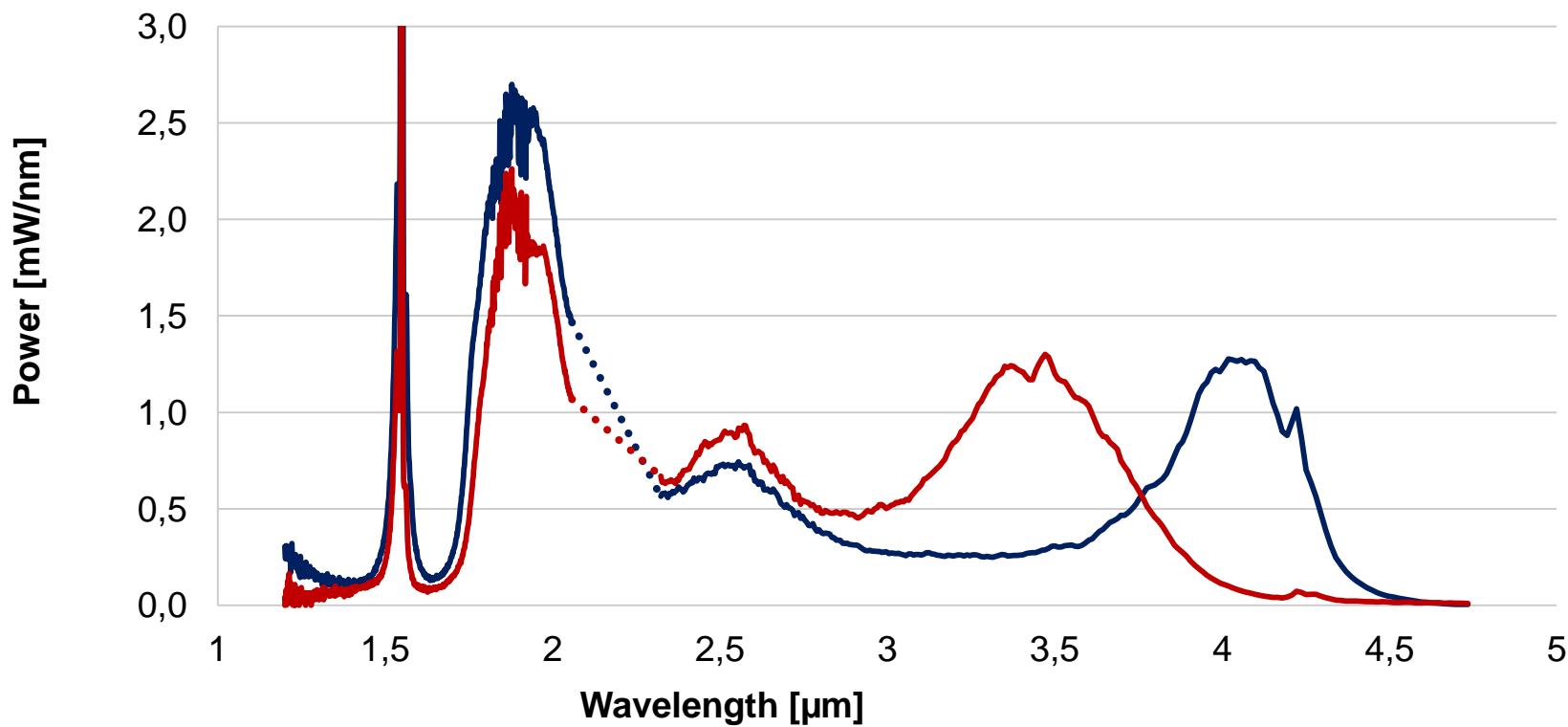
Spectrum before the ZBLAN fiber



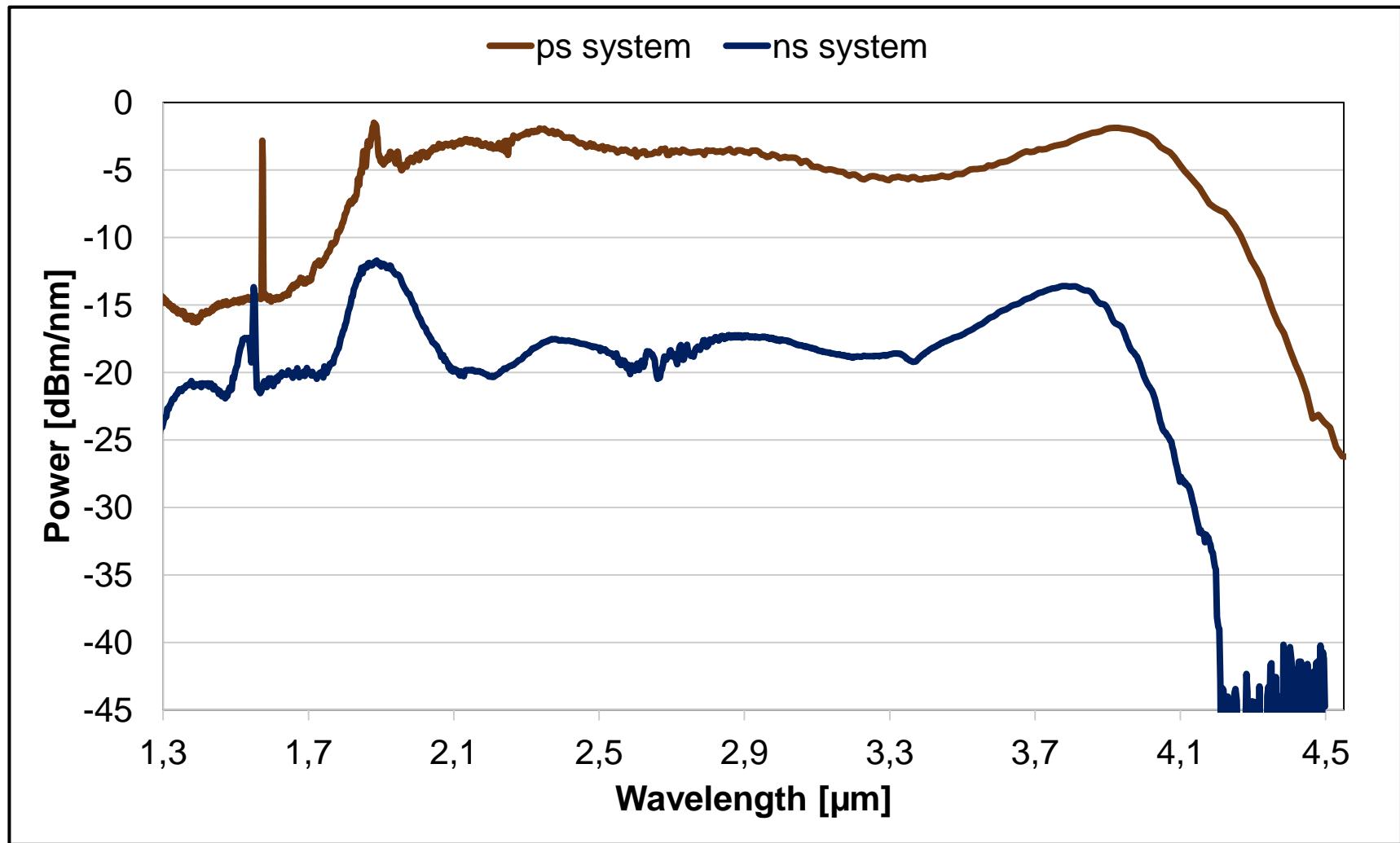
Spectrum consists of many short solitons with high peak power
Bandwidth not so important for pumping supercontinuum

Spectral Tailoring

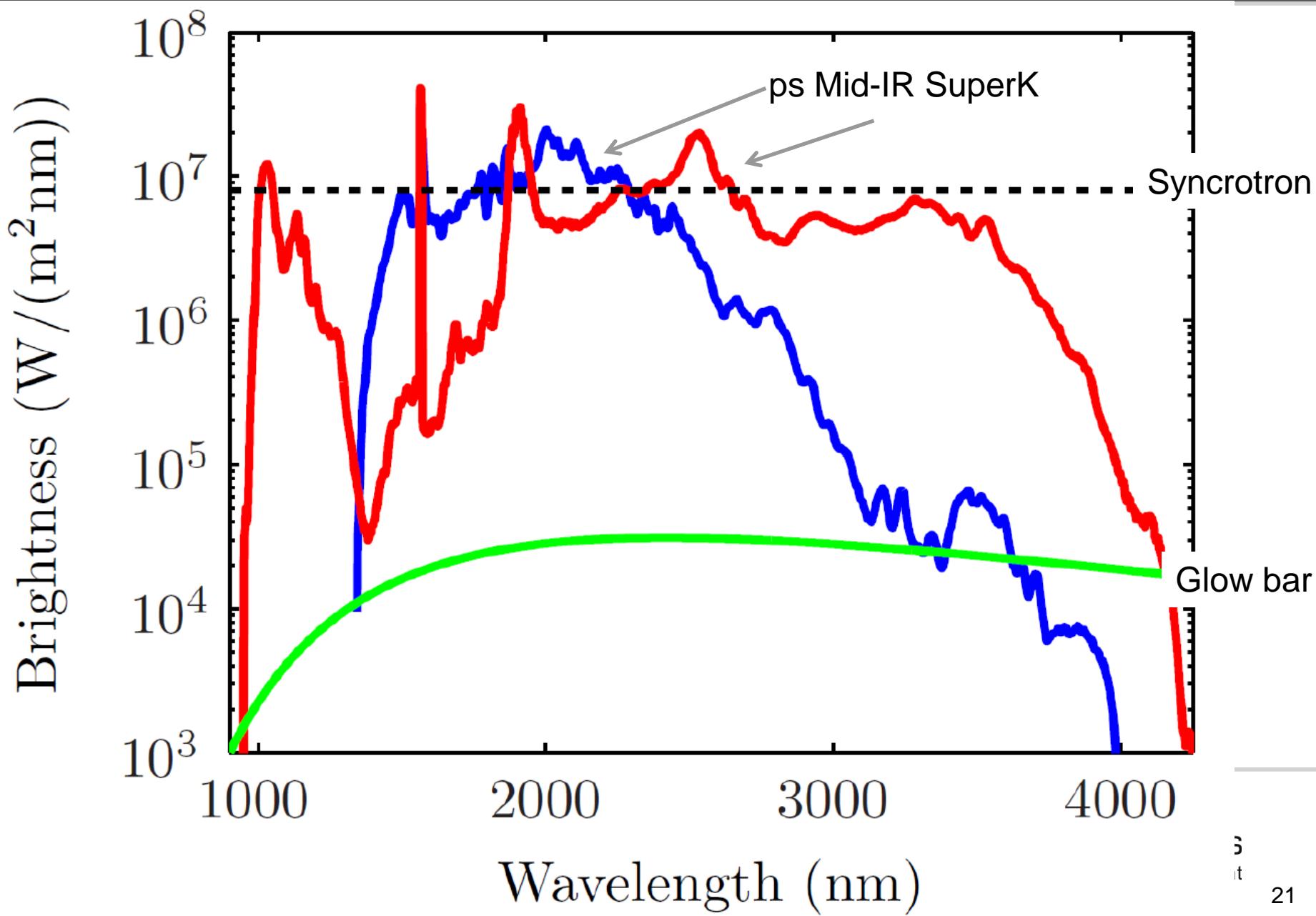
➤ By tailoring the design of the nonlinear fiber one can control the output spectrum



Different mid-IR prototypes from NKT



Mid-IR SuperK has brightness as a synchrotron

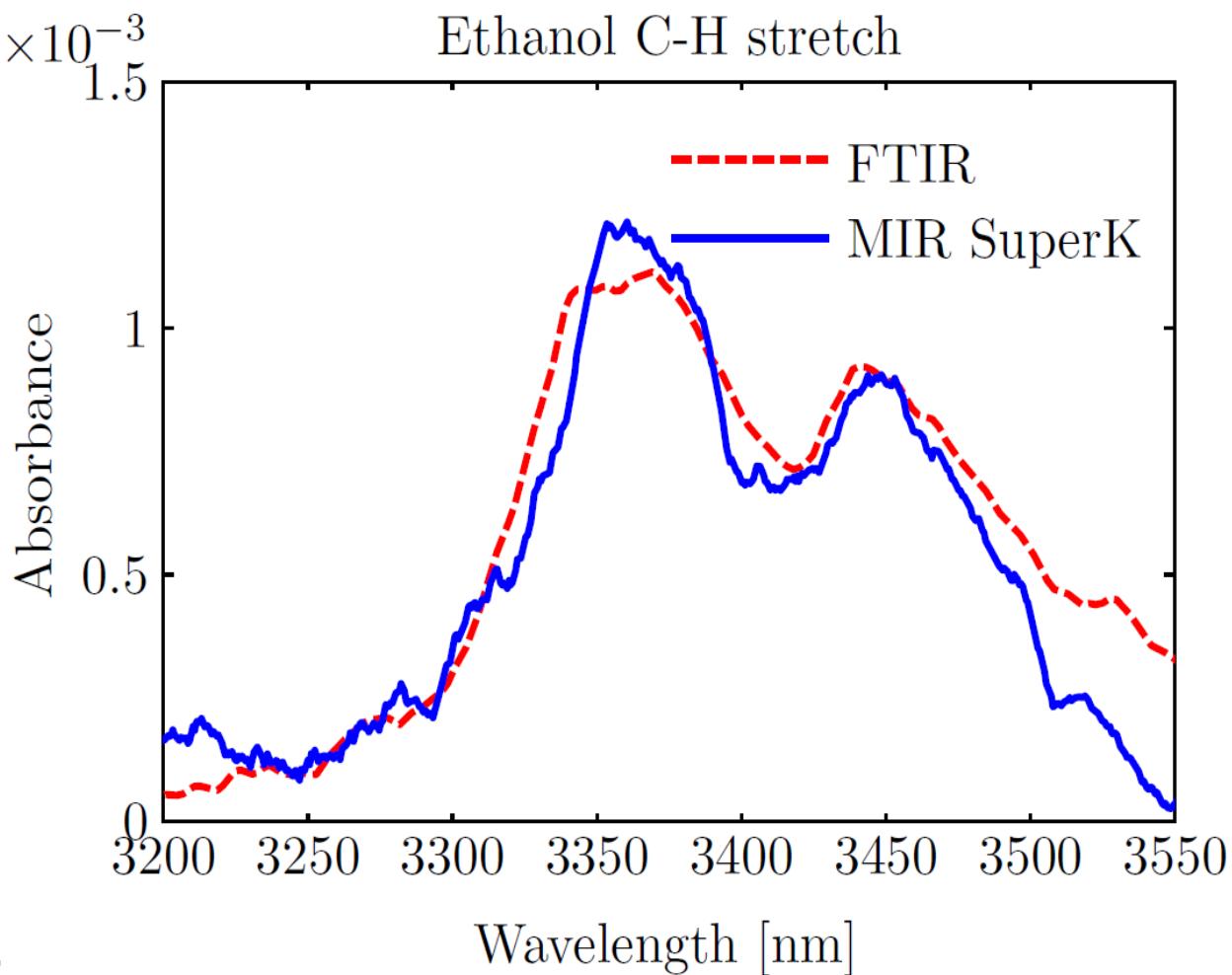


Mid-IR spectroscopy



Lab-data from June 2014

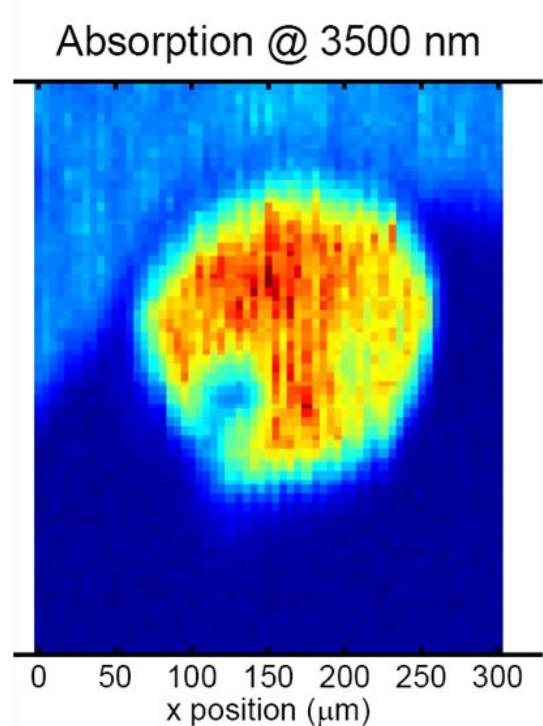
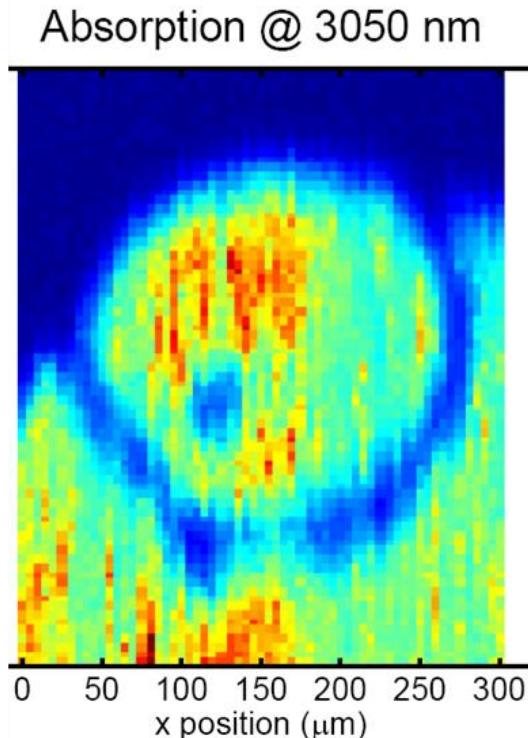
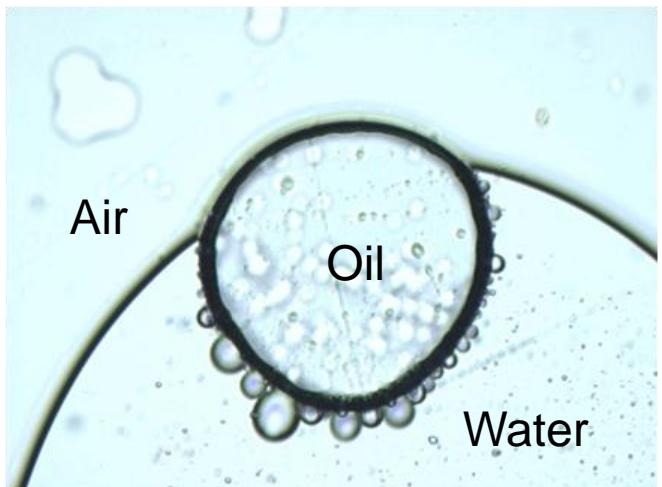
- Detection limit as FTIR but faster
- Acquisition of full spectrum
- in milliseconds
- 30 sec for FTIR



Mid-IR Microscopy



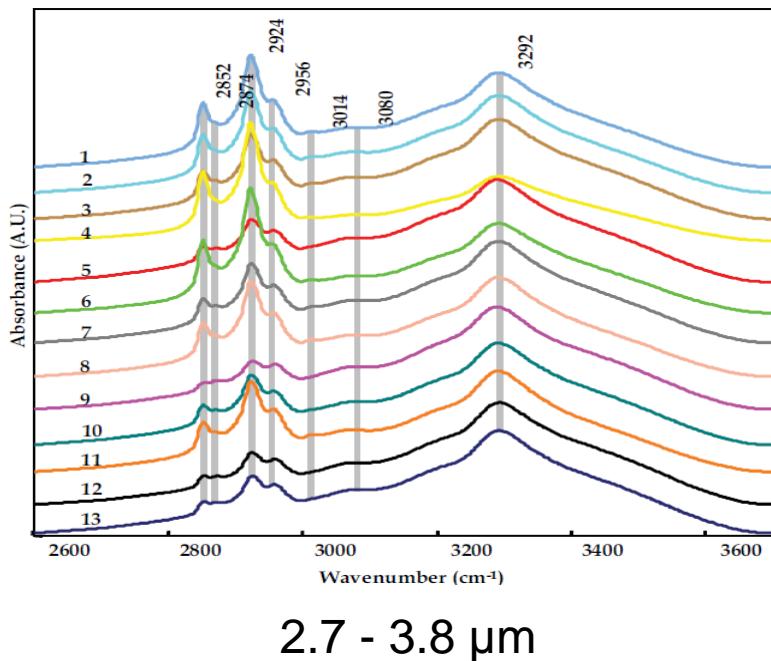
Test sample:
Water, Oil and Air



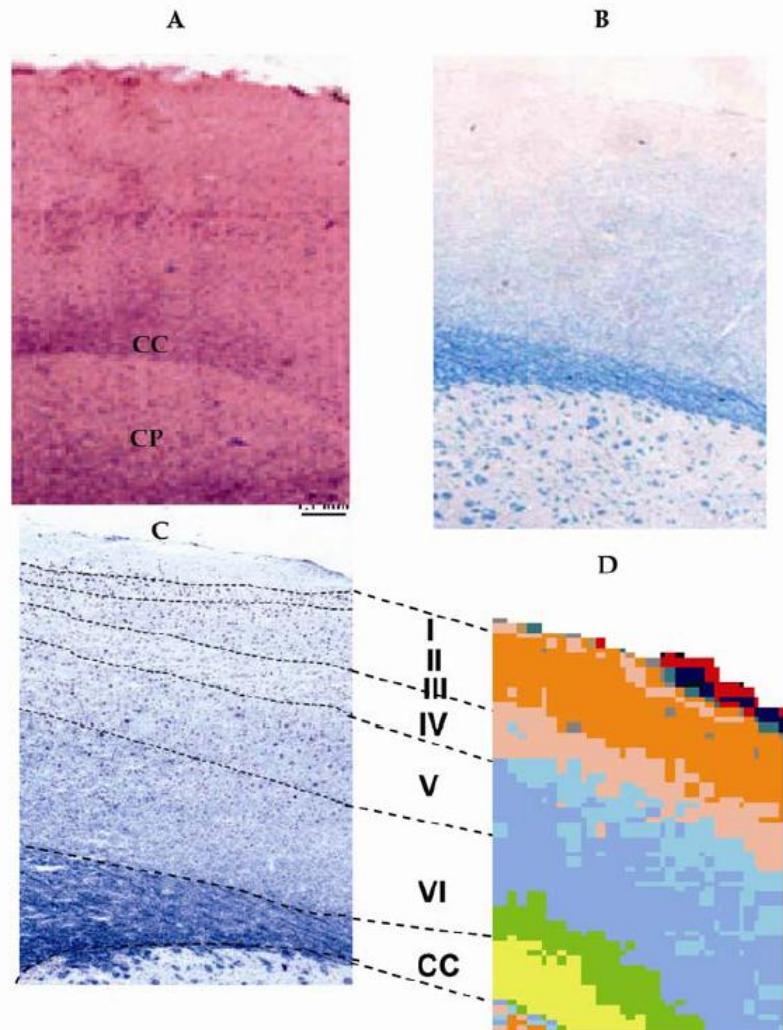
Søren Keiding et al.
Opt. Exp, Vol. **20**, p. 4887 (2012)

MIR microscopy – Cancer diagnostics

- Infrared hyperspectral imaging is simpler than traditional staining methods
- The infrared data is less ambiguous and thus requires less training to interpret



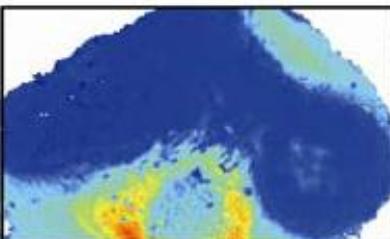
Beljebbar A. et. al. "Fourier Transform Infrared Microspectroscopy for Cancer Diagnostic of C6 Glioma on Animal Model"



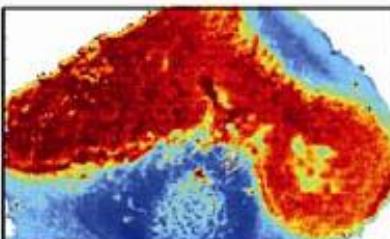
MIR microscopy – Cancer diagnostics

Brain cancer diagnostics on rats
2.7 - 3.8 μm

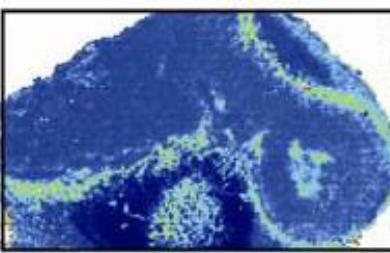
3.33-3.57 μm



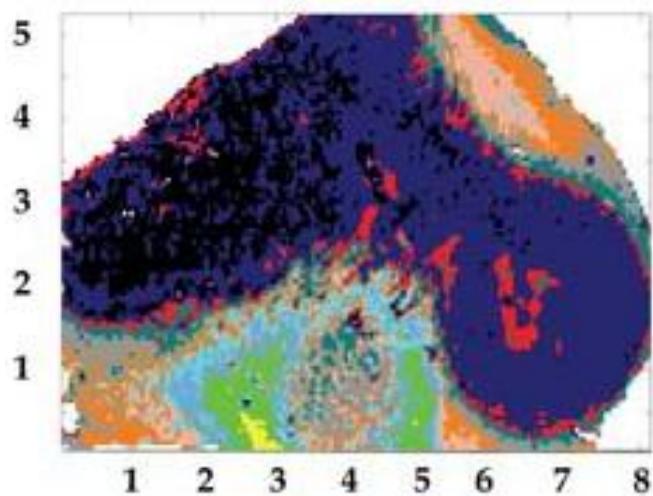
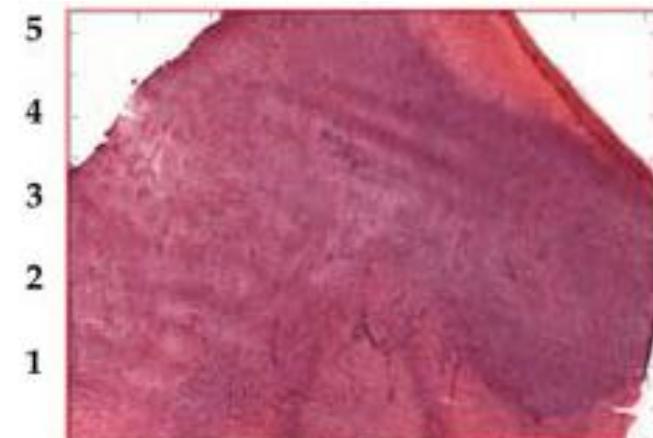
3.04 / 3.51 μm



3.22 / 3.48 μm



Traditional FTIR used
Spatial resolution 25 μm
Spectral resolution 4-6 nm



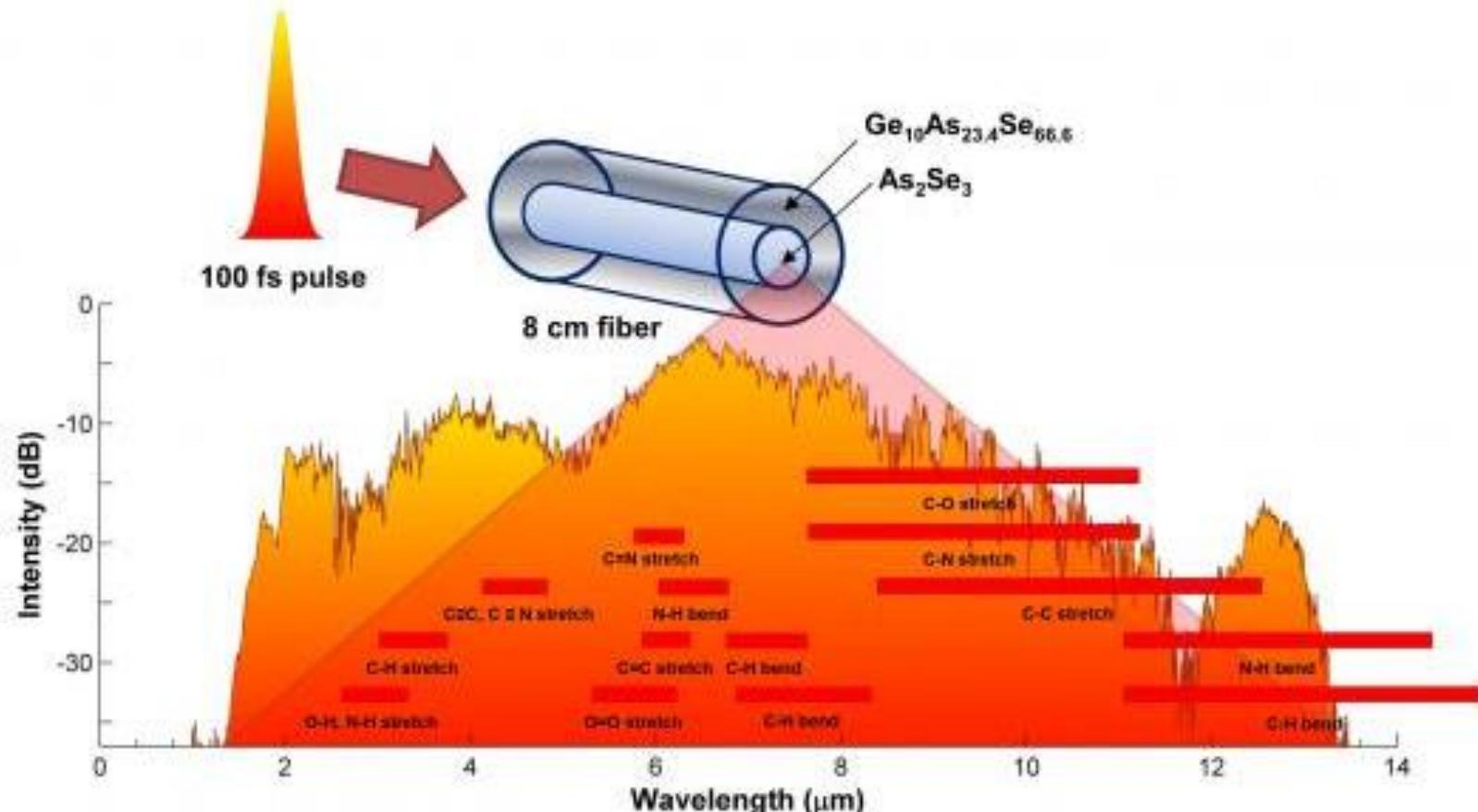
Beljebar A. et. al. "Fourier Transform Infrared Microspectroscopy for Cancer Diagnostic of C6 Glioma on Animal Model" ...

Mid-IR SuperK in Nature Photonics

Mid-infrared supercontinuum covering the 1.4–13.3 μm molecular fingerprint region using ultra-high NA chalcogenide step-index fibre

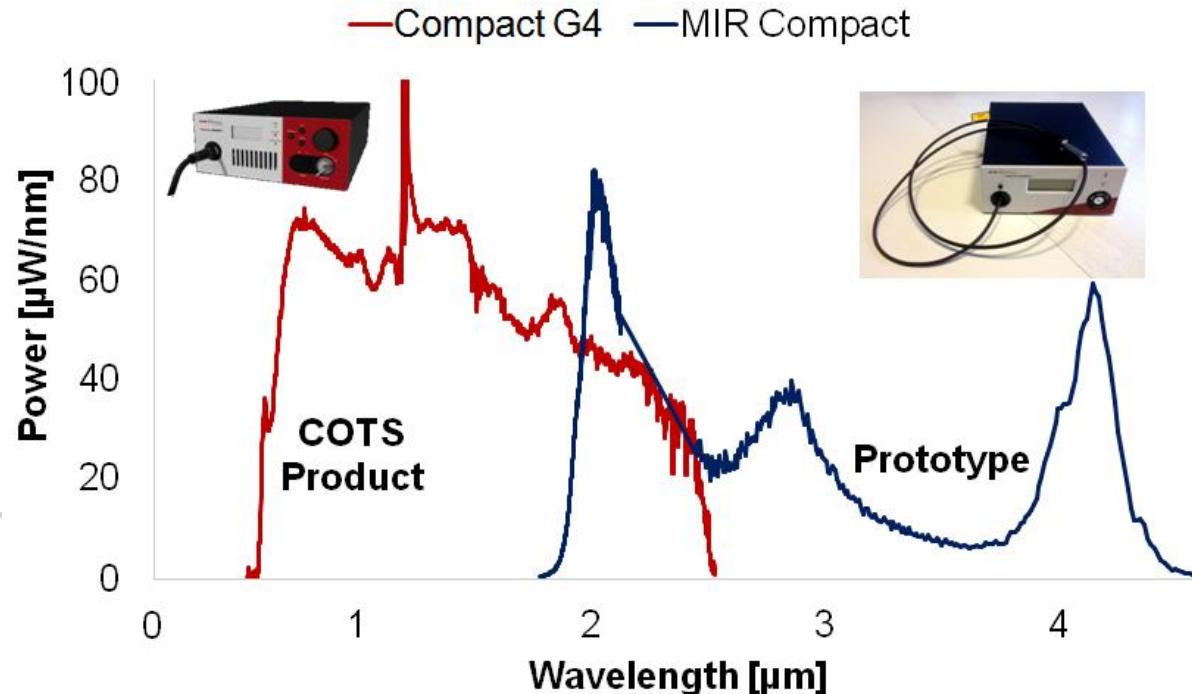
Christian Rosenberg Petersen, Uffe Møller, Iiris Kubat, Binbin Zhou, Sune Dupont, Jacob Ramsay, Trevor Benson, Slawomir Sujecki, Nabil Abdel-Moneim, Zhuoqi Tang, David Furniss, Angela Seddon & Ole Bang

Nature Photonics 8, 830–834 (2014) | doi:10.1038/nphoton.2014.213



Conclusions

- NKT wants to commercialize mid-IR supercontinuum
- Requires soft-glass fibers
- Requires pulsed lasers with wavelengths >1700 nm
- 2 μm lasers are very interesting, but expensive
- Hopefully this will change in the future





NKT Photonics