EAGLES
International Conference on
Rare-Earth Doped Glass Materials and Fibre Lasers
MPNS COST Action MP1401

COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
COST is supported by the EU Framework Programme Horizon 2020

October 18th – 19th, 2016 | Trento, Italy

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Mid-Infrared Photonics Group
George Green Institute for Electromagnetics Research
Faculty of Engineering

Mid-infrared (MIR) fibre lasers: progress and challenges.

AB Seddon, L Sojka, Z Tang, D Furniss, H Sakr, J Nunes,
TM Benson, S Taccheo and S Sujecki

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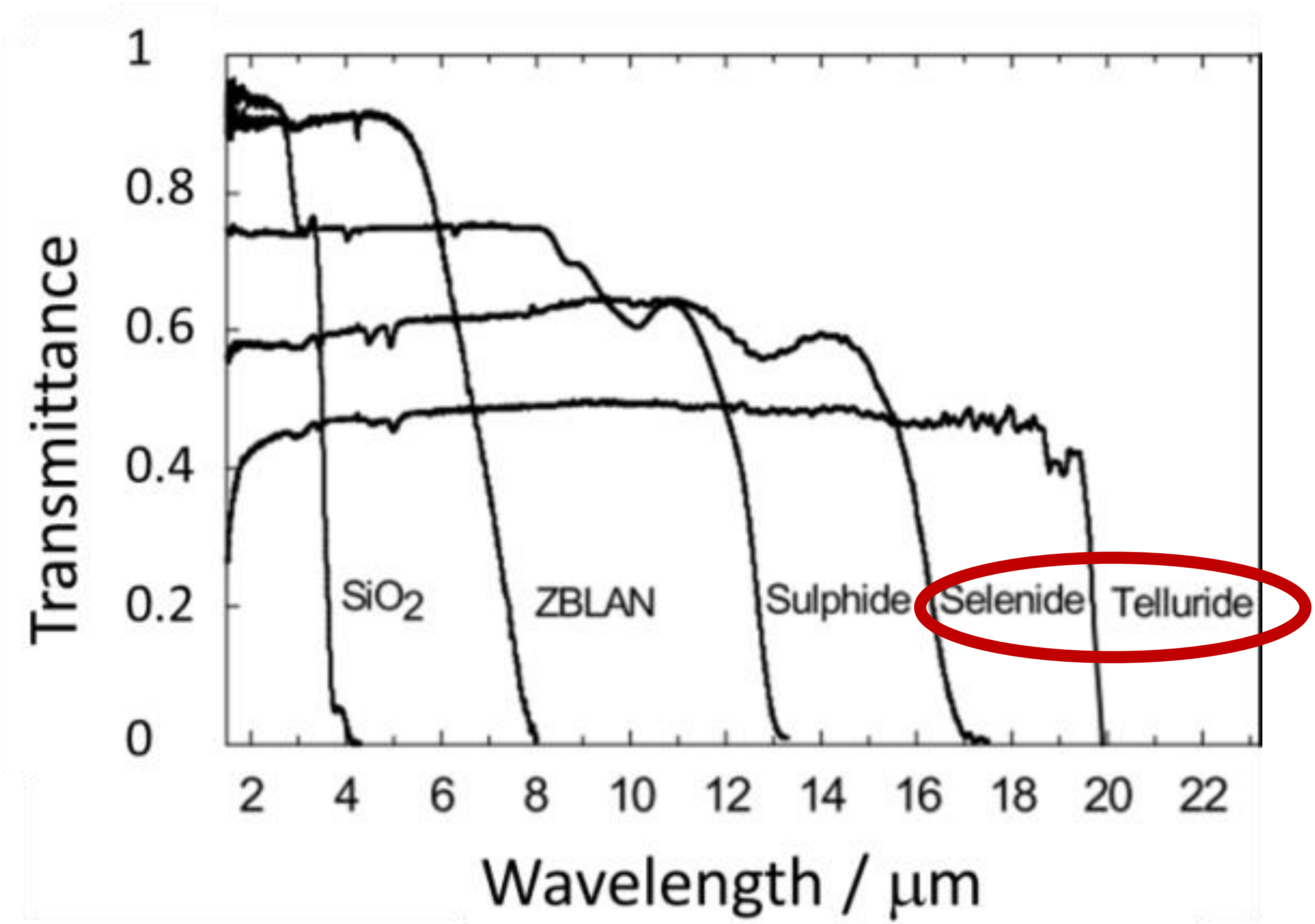
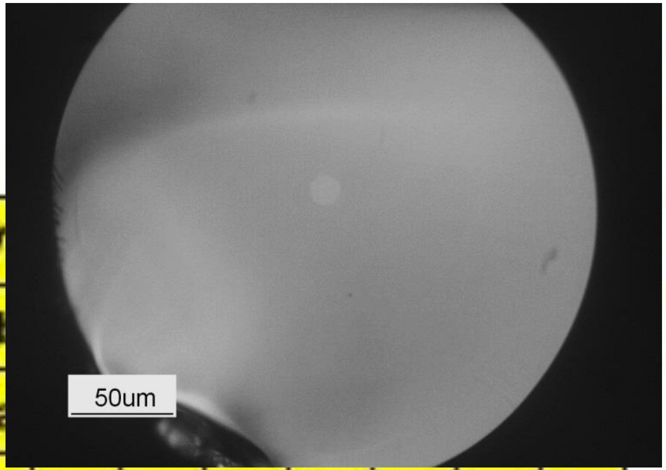
City of
NOTTINGHAM

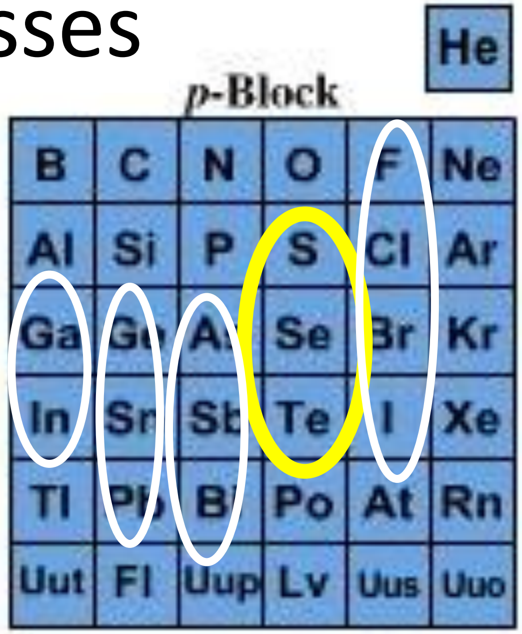
England, UK

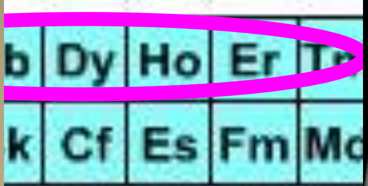
Long-wavelength glasses for the mid-infrared:

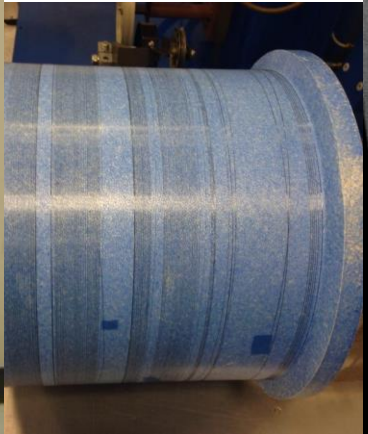


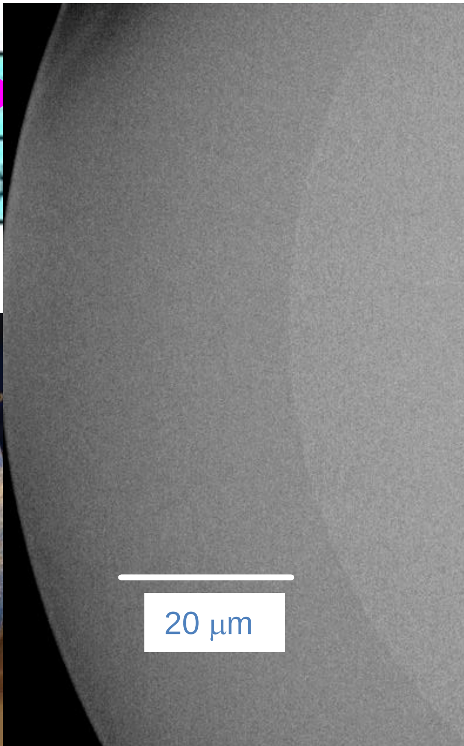
Selenide/telluride glasses











Mid-infrared (MIR) photonics:

1. Introduction
   - *I. Definitions & introduction*
   - *II. Portable, real-time MIR sensing*

2. **Wideband MIR fibre** supercontinuum **lasers** – progress and challenges

3. **Narrow-line MIR** rare earth **fibre lasers** – progress and challenges

4. Summary and future prospects

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4. Summary and future prospects

(I) Definitions & introduction

BS-ISO standard: the three spectral regions are defined as:

- near-infrared (0.78-3 μm)
- **mid-infrared (3-50 μm)**
- far-infrared (50-1000 μm)

British Standards Institution, *BS ISO 20473:2007 Optics and photonics. Spectral bands*. 2007, checked 2015, BSI. p. 10.

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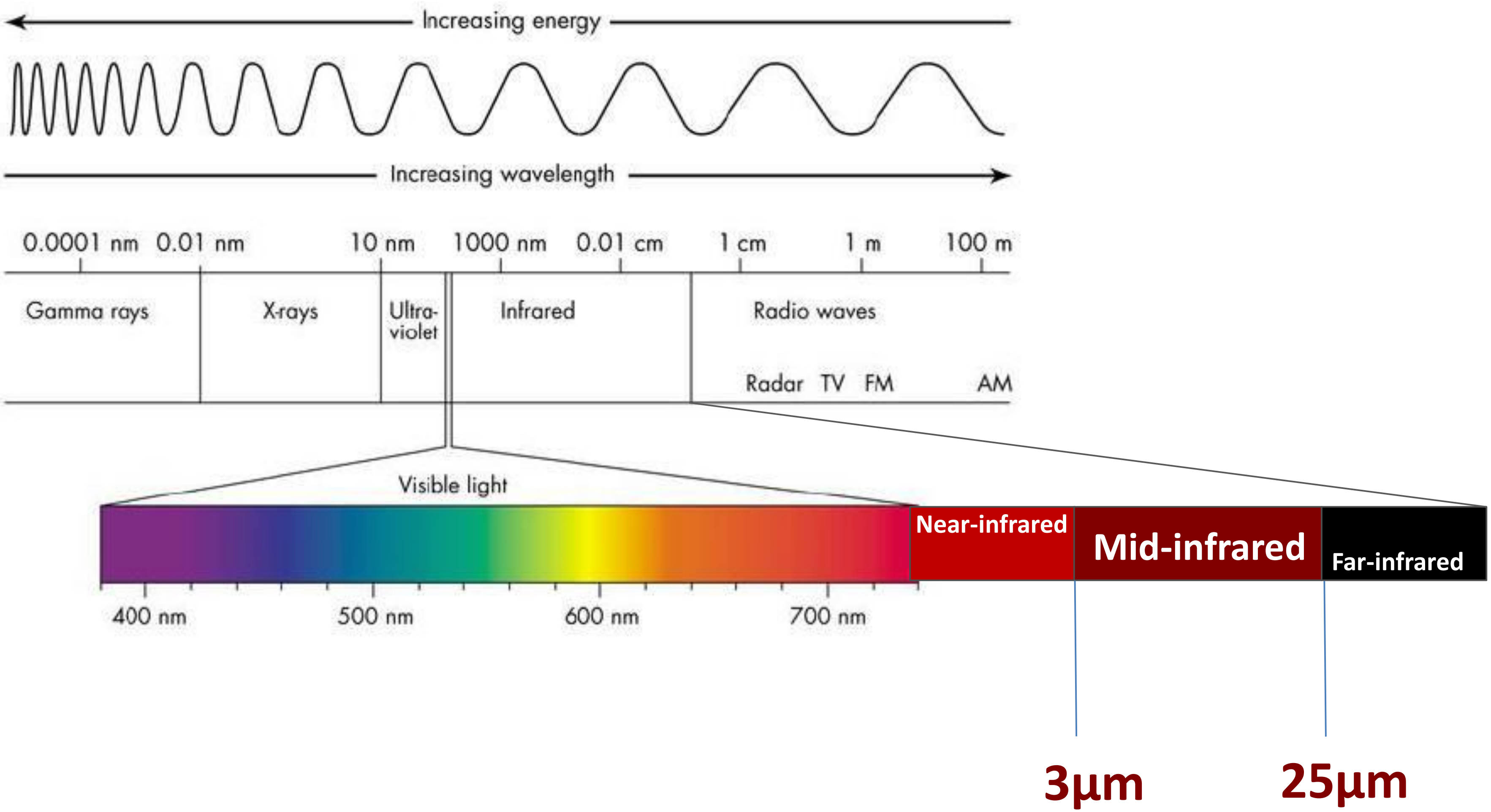
- near-infrared (0.78-3 μm)
- **mid-infrared (3-50 μm)**
- far-infrare

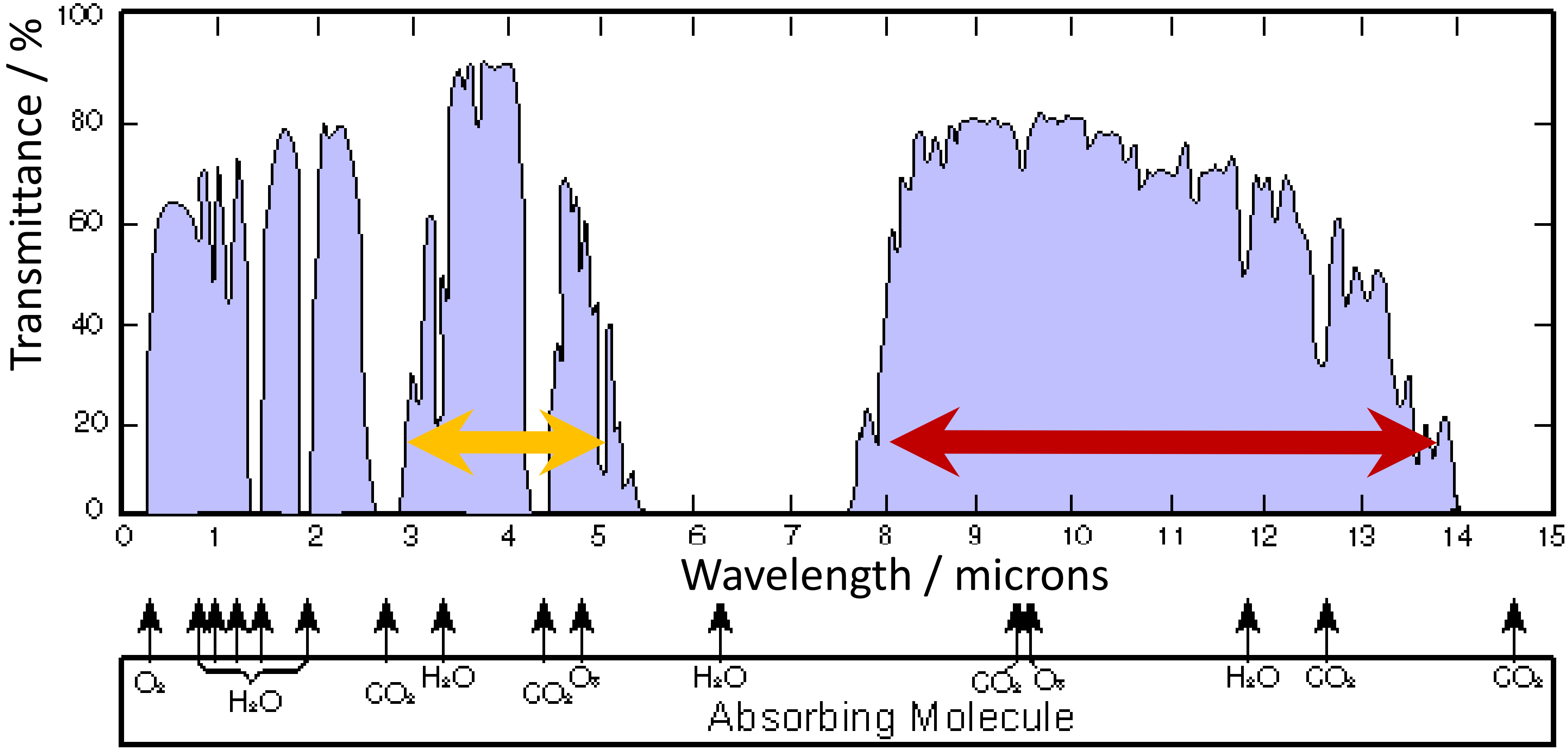
USEFUL MID-INFRARED RANGE
3-25 μm
--LIMITED BY DTGS RT DETECTOR

British Standards Institution, *BS ISO 20473:2007 Optics and photonics. Spectral bands*. 2007, checked 2015, BSI. p. 10.



ELECTROMAGNETIC SPECTRUM

Atmospheric transmittance over a 6000 feet sea-level path



Two important atmospheric windows:

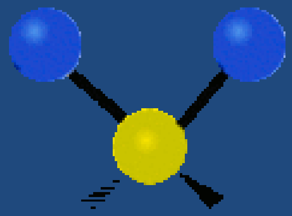
- 3-5 μm **MWIR** Mid-wave infrared window;
- 8-14 μm **LWIR** Long wave infrared window.

Savage, "Infrared Optical Materials and their Antireflection Coatings," Adam Hilger, Bristol, 1985.

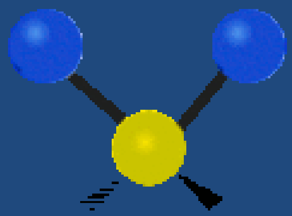
Mid-infrared energy is emitted or **absorbed** by molecular species when their vibrational (-rotational) state changes.

Three types of fundamental vibrations of molecules and molecular units:

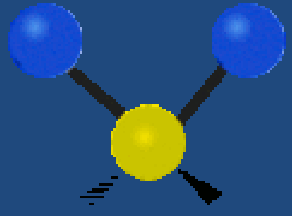
Symmetric stretching



Bending



Asymmetric stretching



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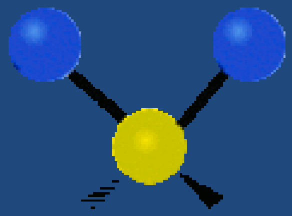

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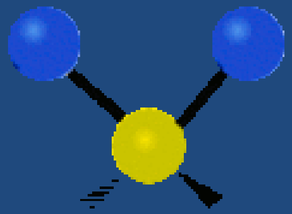

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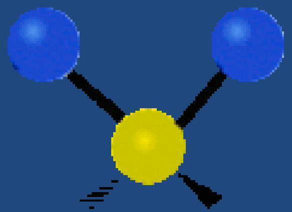
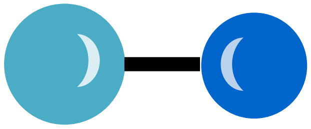


Szigeti:



$$\nu \propto (f/m)^{1/2}$$

ν = frequency of simple oscillator.

f is (chemical) bond force constant.

$m = (m_1 m_2/(m_1+m_2))$.

Planck:

$$E = h\nu$$

E = photon energy.

h = Planck's constant.

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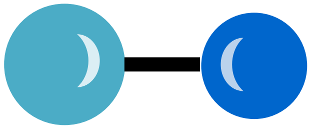

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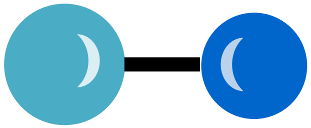

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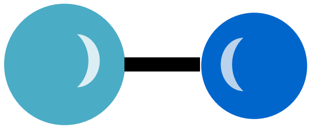

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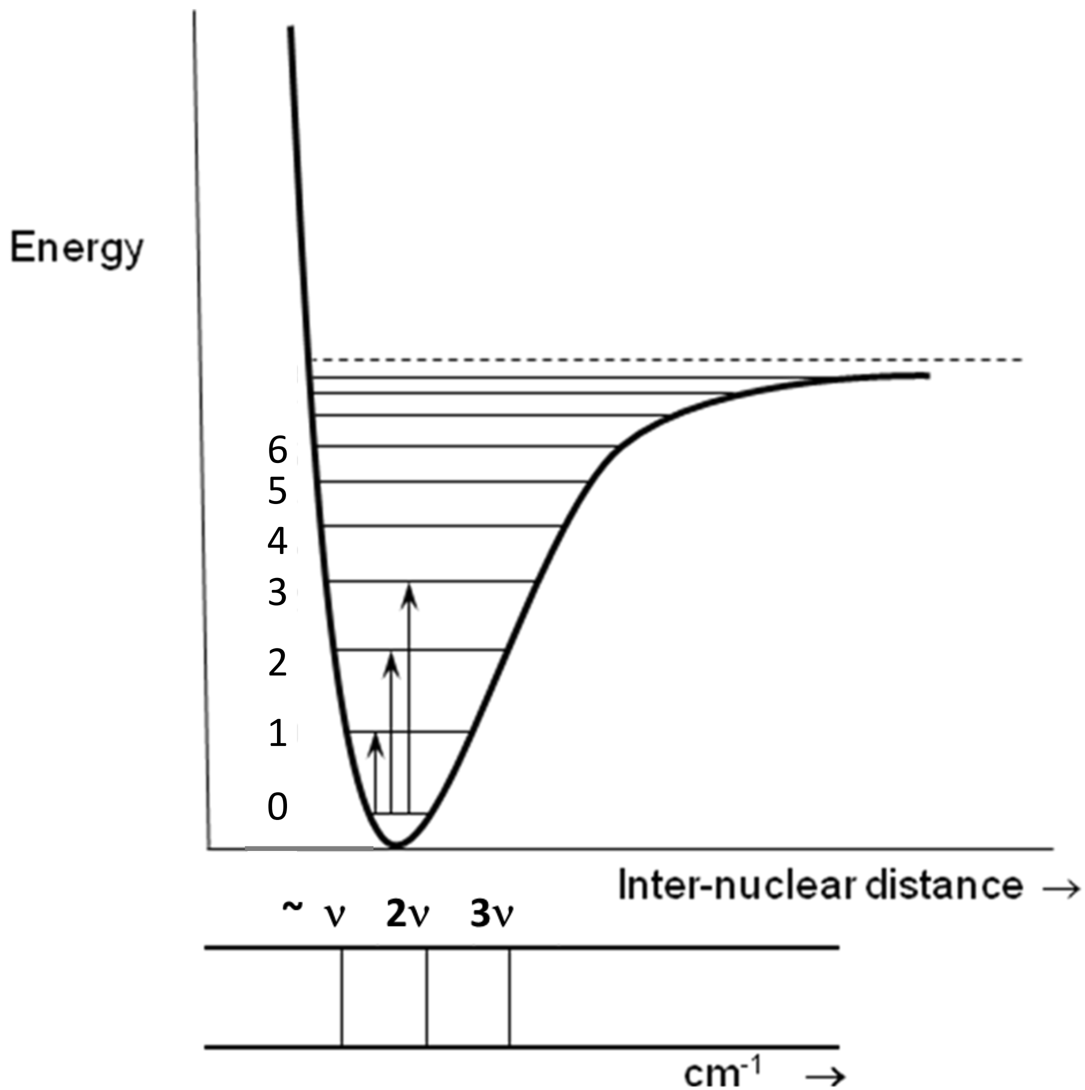
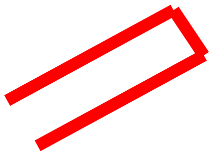
Morse potential



Globar

Mid-infrared
wideband
light source



Globar

Mid-infrared
wideband
light source

Mid-infrared light beam

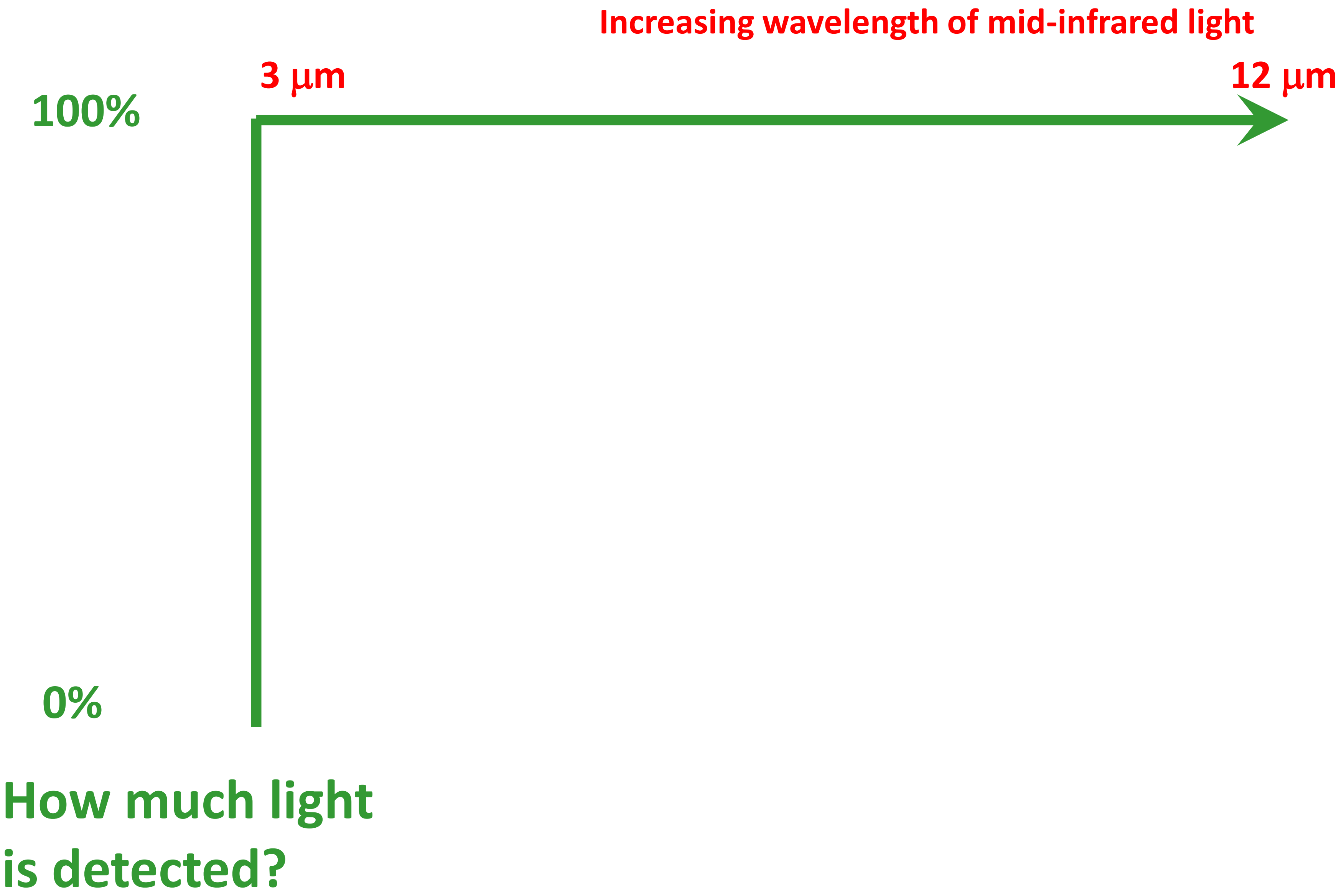
Globar

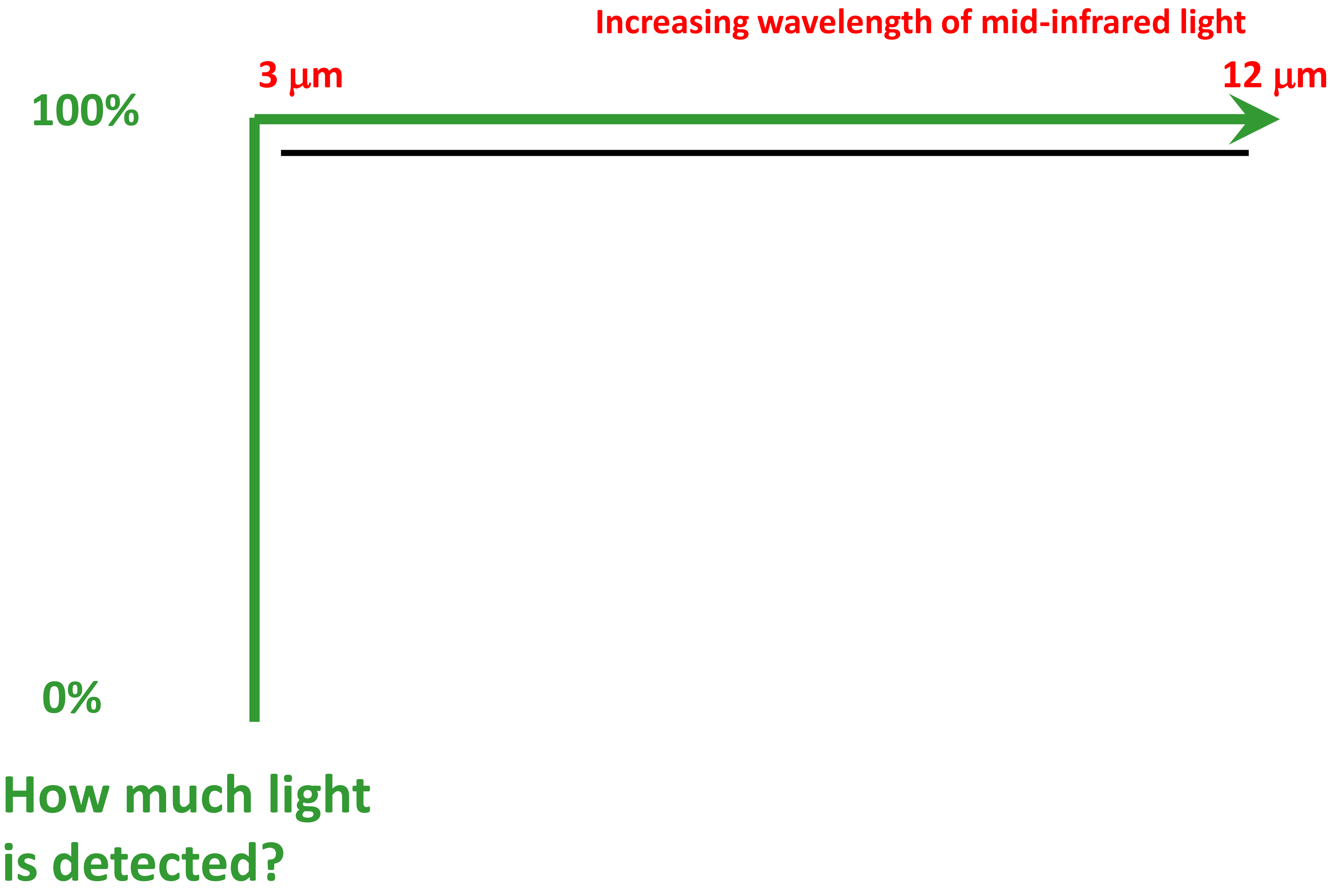
Mid-infrared
wideband
light source

Globar

Detector

Mid-infrared
wideband
light source


Increasing wavelength of mid-infrared light
3 μm
12 μm
100%
0%
How much light
is detected?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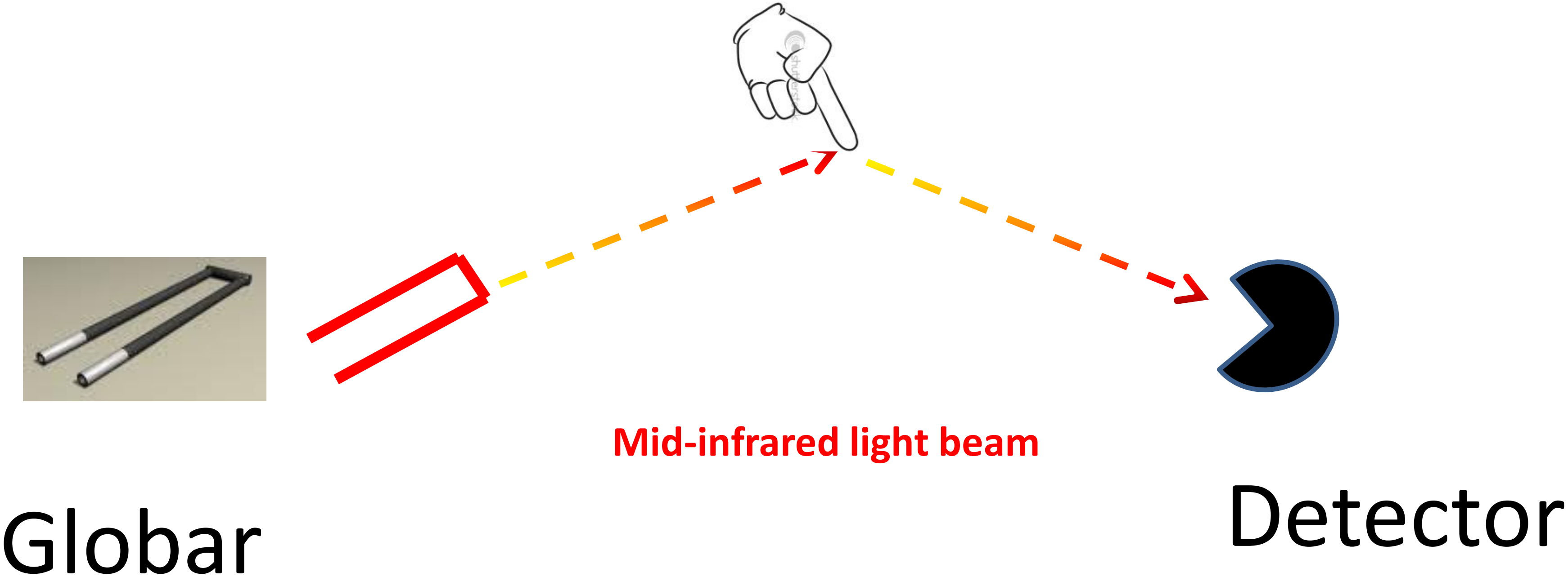

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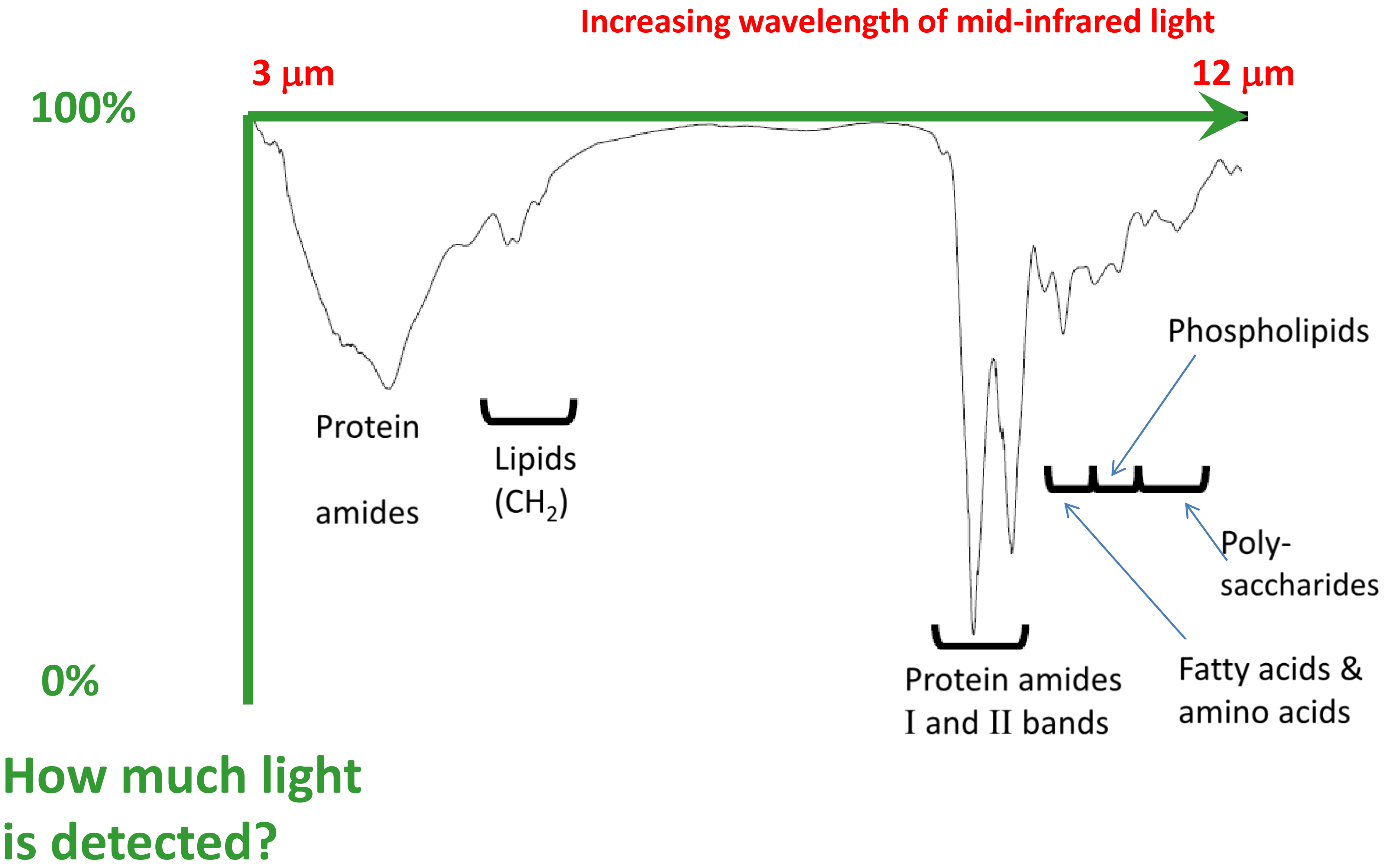

Increasing wavelength of mid-infrared light
3 μm
12 μm
100%
0%
Protein
amides
Lipids
(CH2)
Phospholipids
Poly-
saccharides
Protein amides
I and II bands
Fatty acids &
amino acids
How much light
is detected?

MINERVA European Consortium 2012-2017:

MINERVA
improved medical diagnostics

MId- to NEaR infrared spectroscopy for improVed medical diAgnostics

The 12 Project Partners are a mix of academics, medical scientists & industrialists:

Gooch & Housego

LSA

NKT Photonics the power of light

Xenics Infrared Solutions

University of Exeter

BBT

IRnova

Gloucestershire Hospitals NHS
NHS Foundation Trust

DTU

Westfälische Wilhelms-Universität Münster

Global Top 100 University
The University of Nottingham
United Kingdom · China · Malaysia

Mid-Infrared Photonics Group
George Green Institute for Electromagnetics Research
Faculty of Engineering

VIVID Components

MINERVA European Consortium 2012-2017:

MINERVA
improved medical diagnostics

MId- to **NE**a**R** infrared spectroscopy for impro**V**ed medical di**A**gnostics.

Two specific high impact mid-infrared applications being addressed:

1) high volume pathology mid-infrared screening;

(*i.e.* automated microscope-based examination of samples)

2) *in vivo*, remote, real-time skin surface examination.

(*i.e.* non-invasive investigation of suspected skin cancer)

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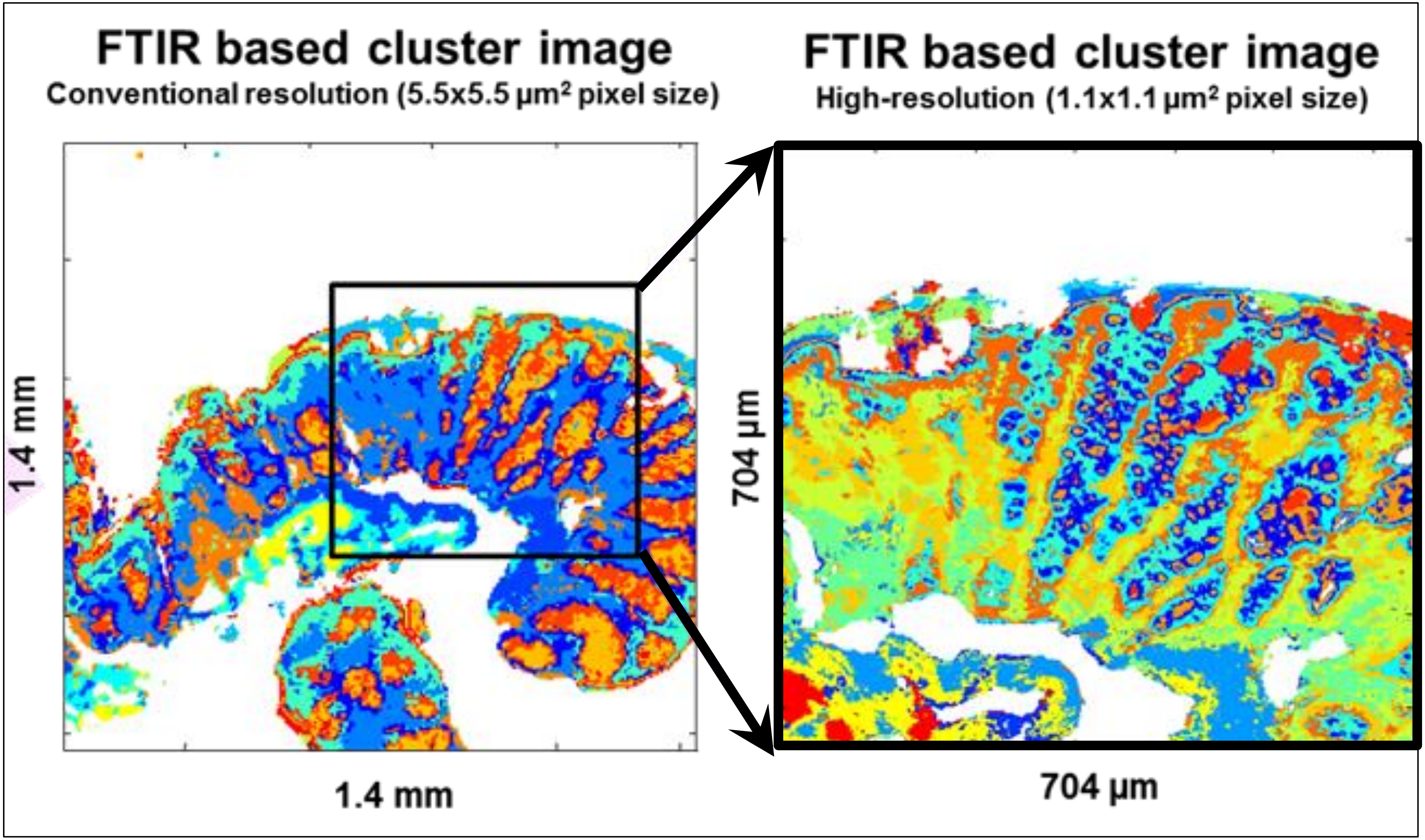
New high resolution MIR imaging in 2016 -

MIR imaging:
based on MIR absorption of tissue



*Nick Stone et al. Analyst (**2016**) .*

(MIR is mid-infrared)

Comparison with conventional imaging of excised tissue:

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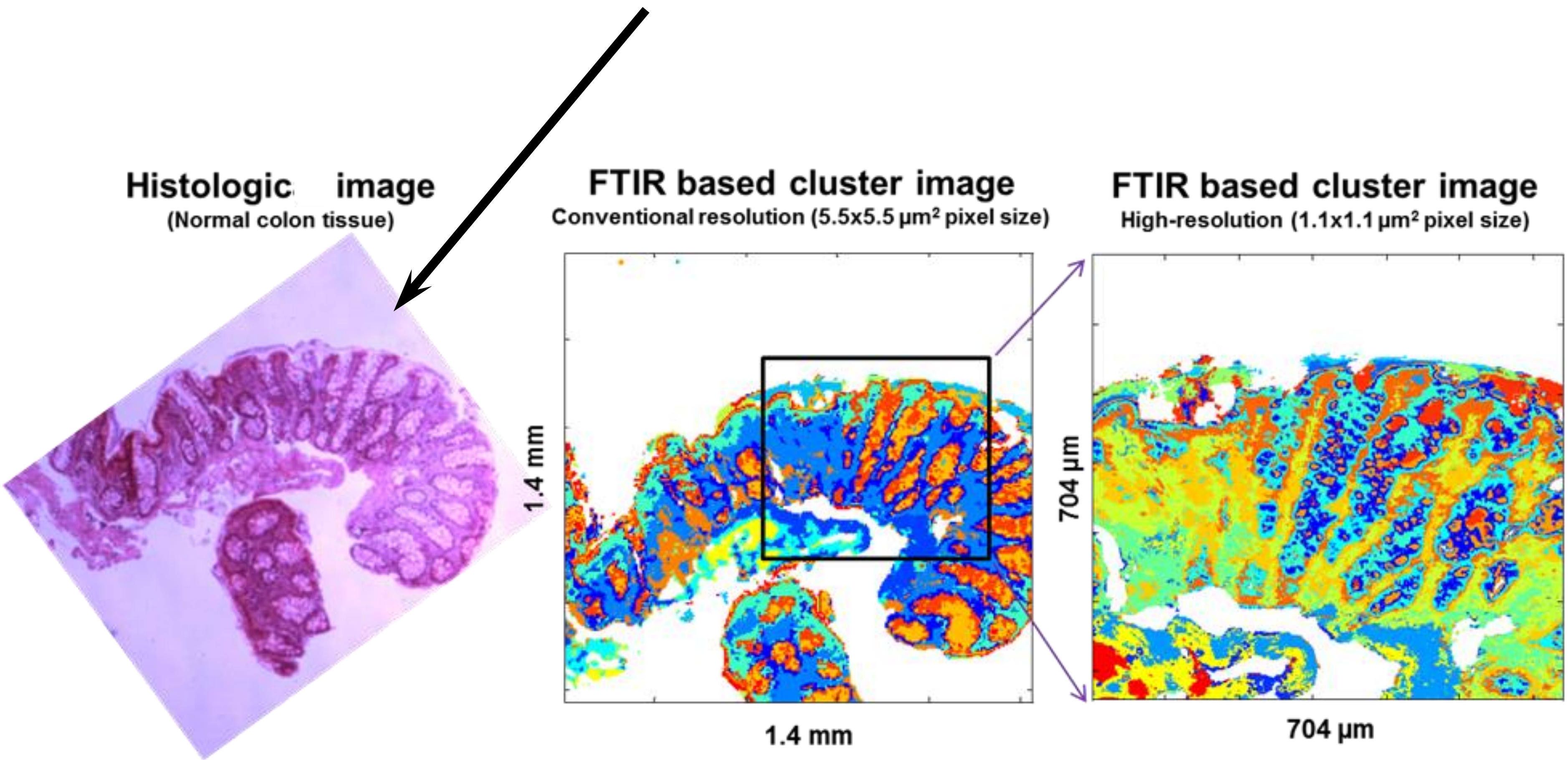
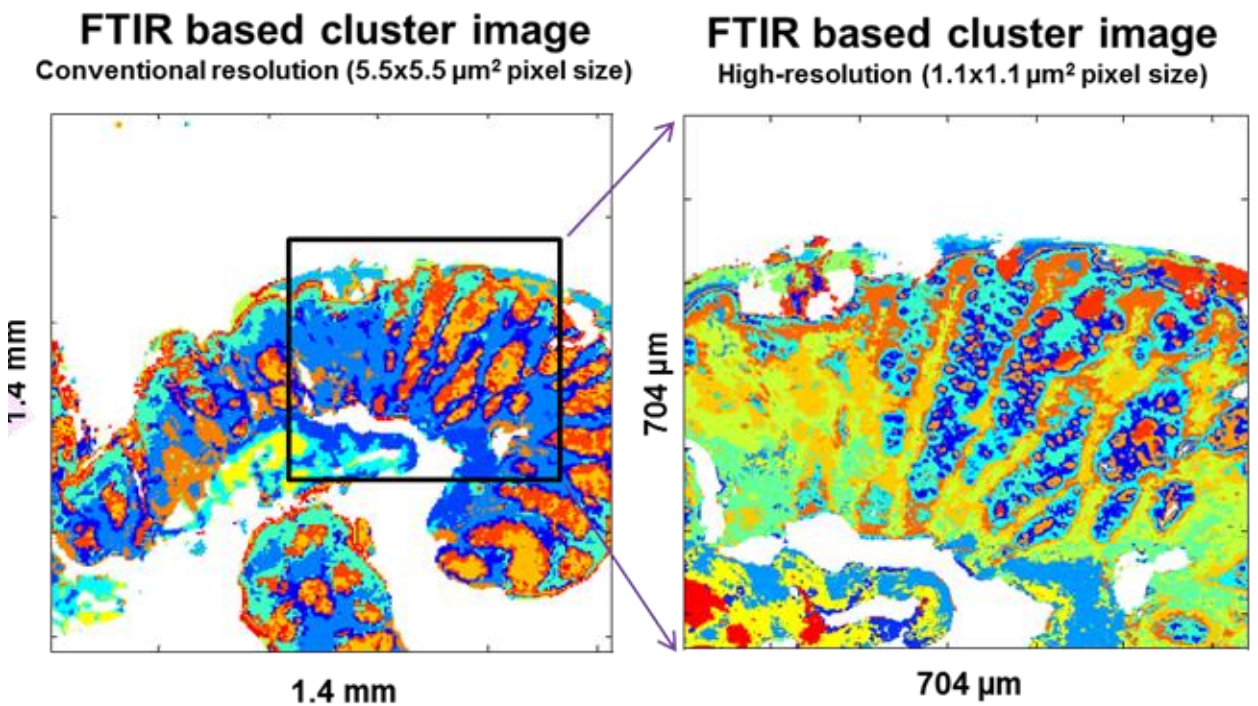


How was this MIR imaging of tissue captured?



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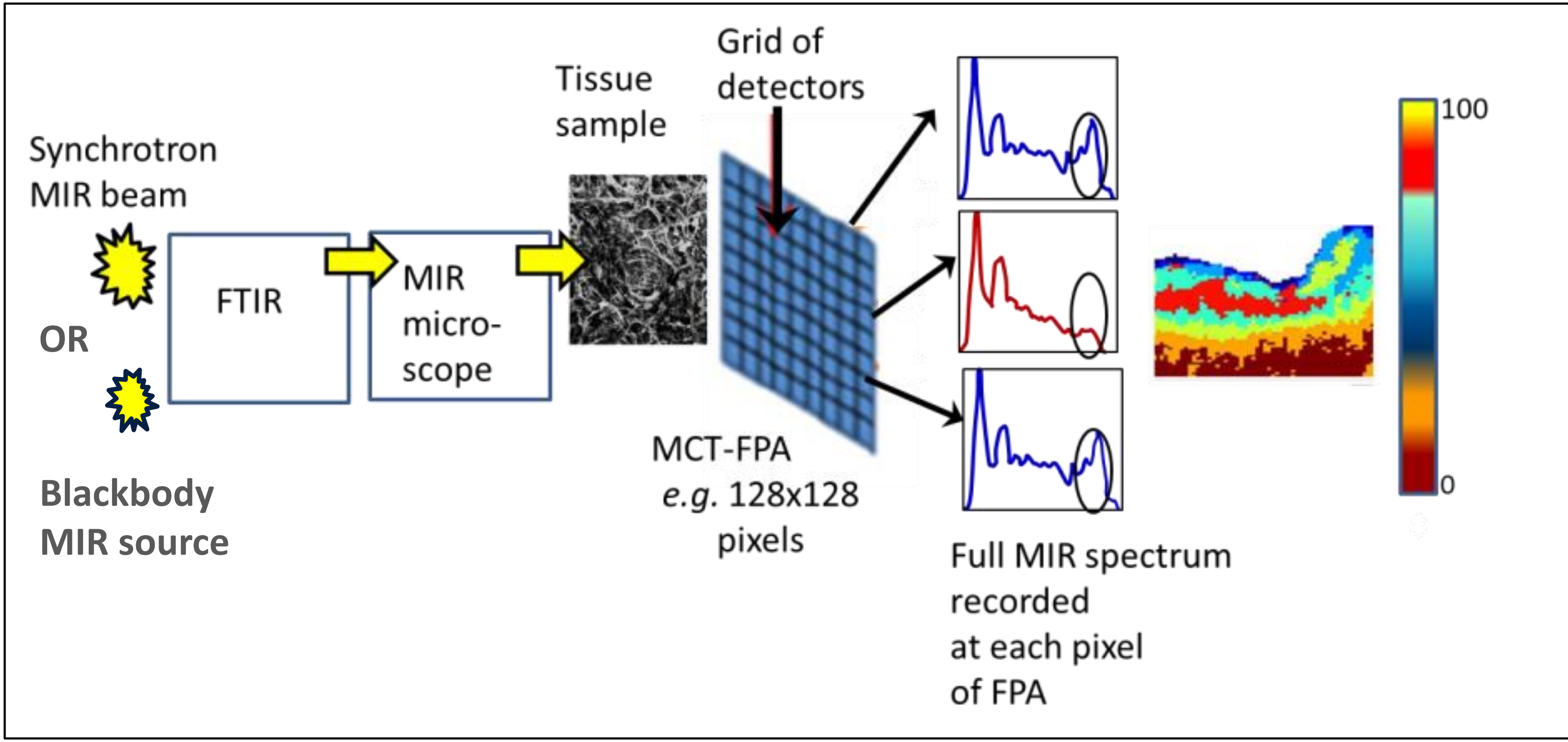


- Source light: pass through Ft-MIR spectrometer, onto tissue in MIR microscope.
- MCT-FPA (**HgCdTe- focal plane array**) detector captures full spectrum at each pixel.
- Spectra treated statistically to yield molecular discrimination across the tissue. Mathematically group similar spectra, assign color codes to form an objective map, free from subjective assignment.

Seddon *et al. BioOptics World* ***2016****.*

MINERVA European Consortium 2012-2017:

MINERVA improved medical diagnostics

MId- to **NE**a**R** infrared spectroscopy for impro**V**ed medical di**A**gnostics.

Nottingham is fabricating active and passive mid-infrared fibreoptics for this:

1) high volume pathology mid-infrared screening;

   (*i.e.* automated microscope-based examination of samples)

2) *in vivo*, remote, real-time skin surface examination.

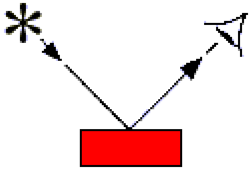
   (*i.e.* non-invasive investigation of suspected skin cancer)

(II) Portable, real-time, MIR sensing

Globar: the ubiquitous blackbody wideband MIR source –heat electrically:

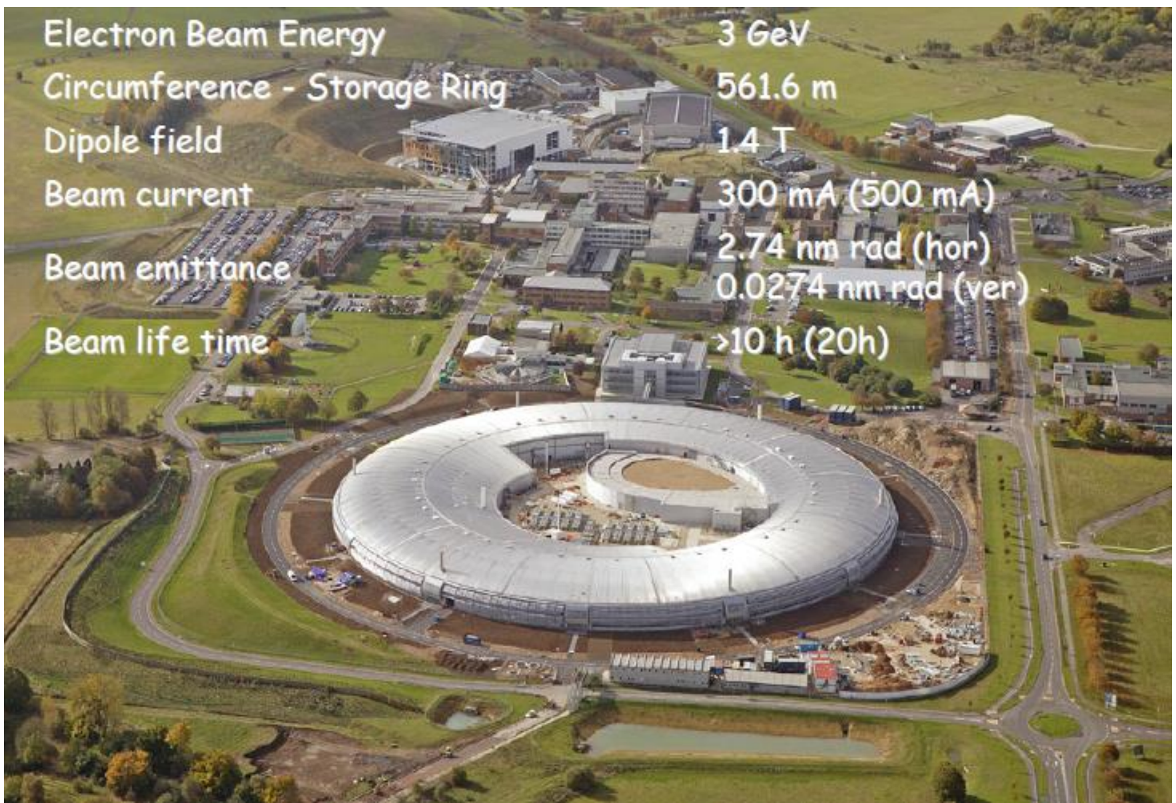
– is weak!

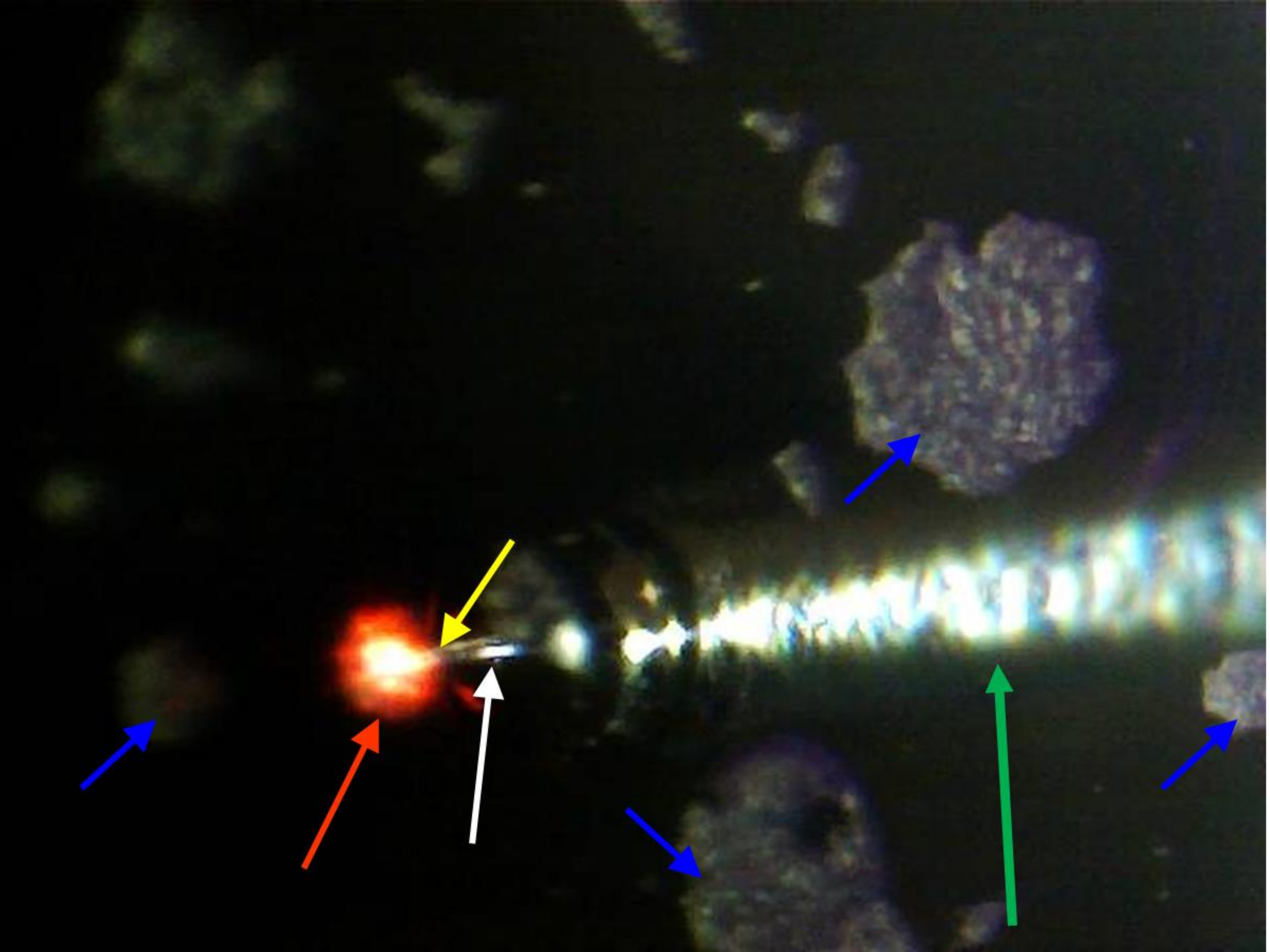
Used in Ft-MIR - based on Michelson interferometer with moving mirror. (Entire MIR spectrum collected at one go, then Fourier transformed to deconvolute the sample absorption at each wavelength.)



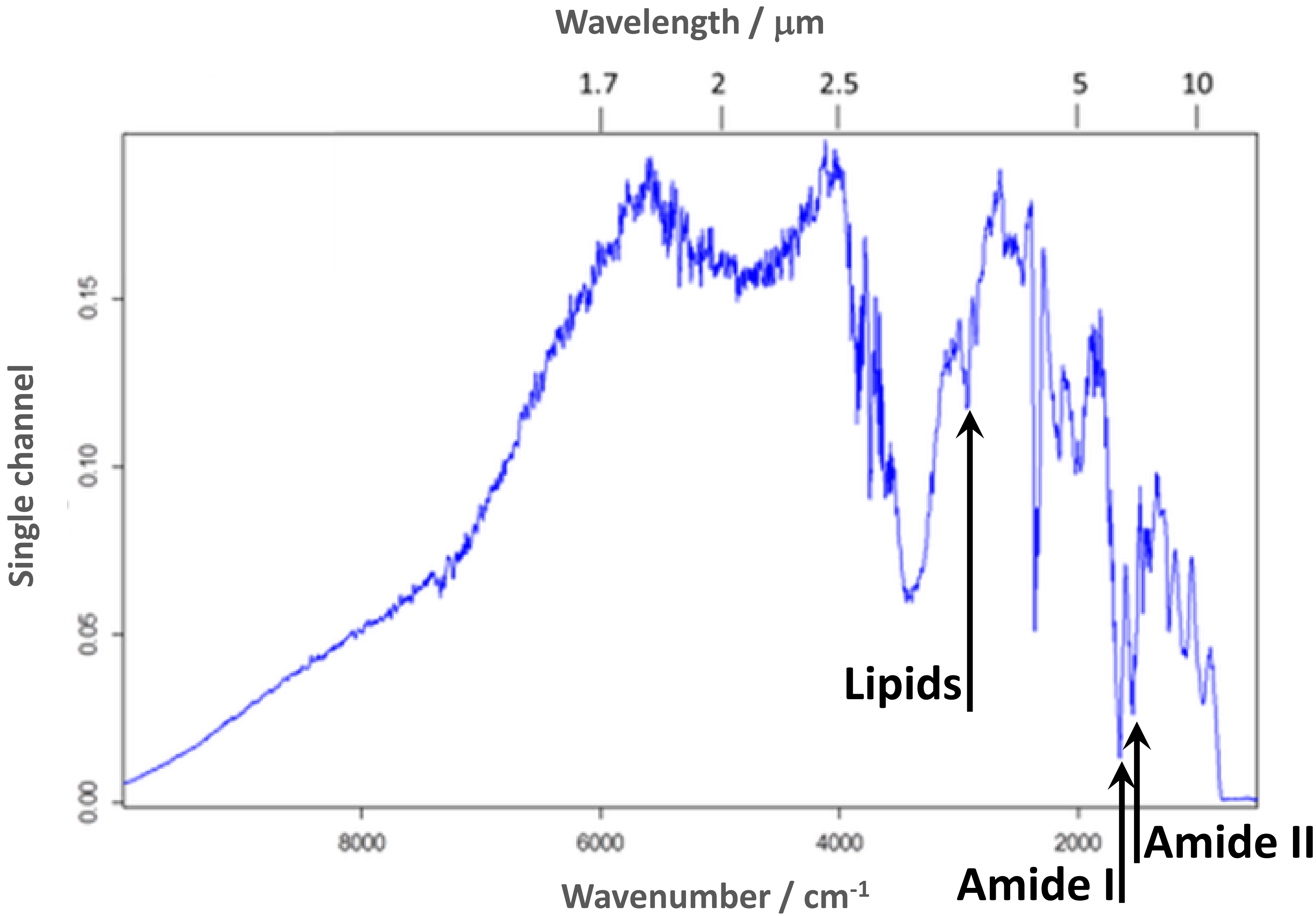
Consider the Synchrotron MIR light source:

- parallel beam of few mm diameter
- high brilliance
- wide-band
- can give unique molecular identification.

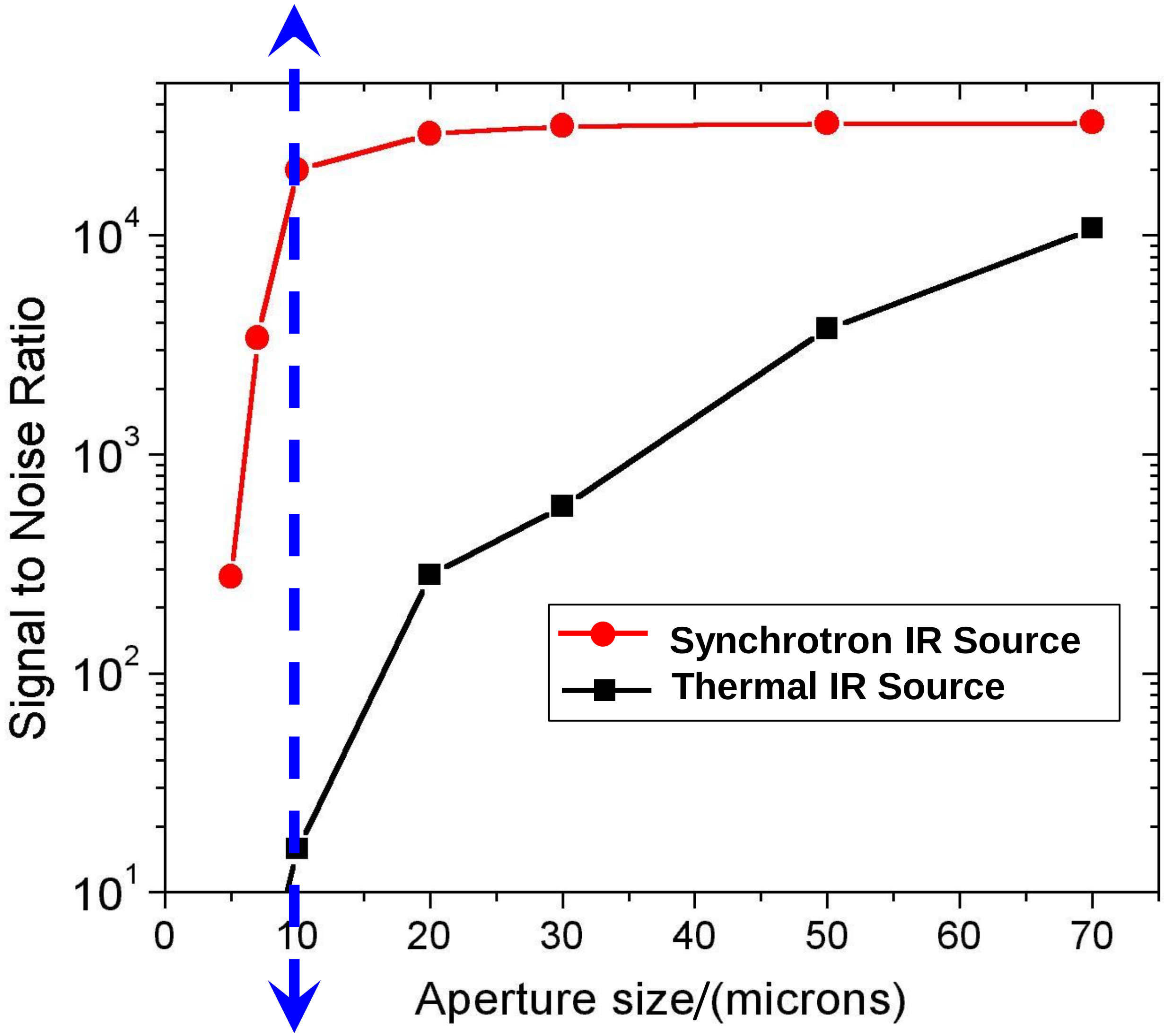




Preliminary MIR spectrum of cell collected through single MIR fibre:



High Brilliance of Synchrotron Source.



Holman *et al.*, Spectroscopy 17 [2-3] 139-159 (2003).

(IR is infrared)

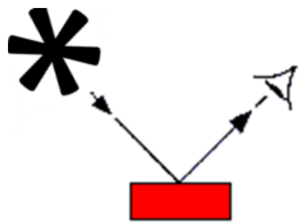
The Synchrotron MIR light source:

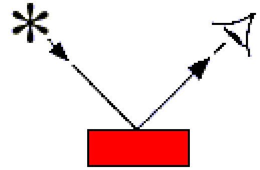
-is high brilliance,

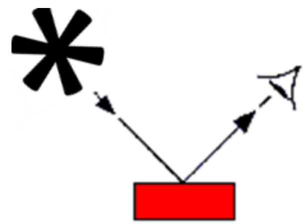
-is wide-band,

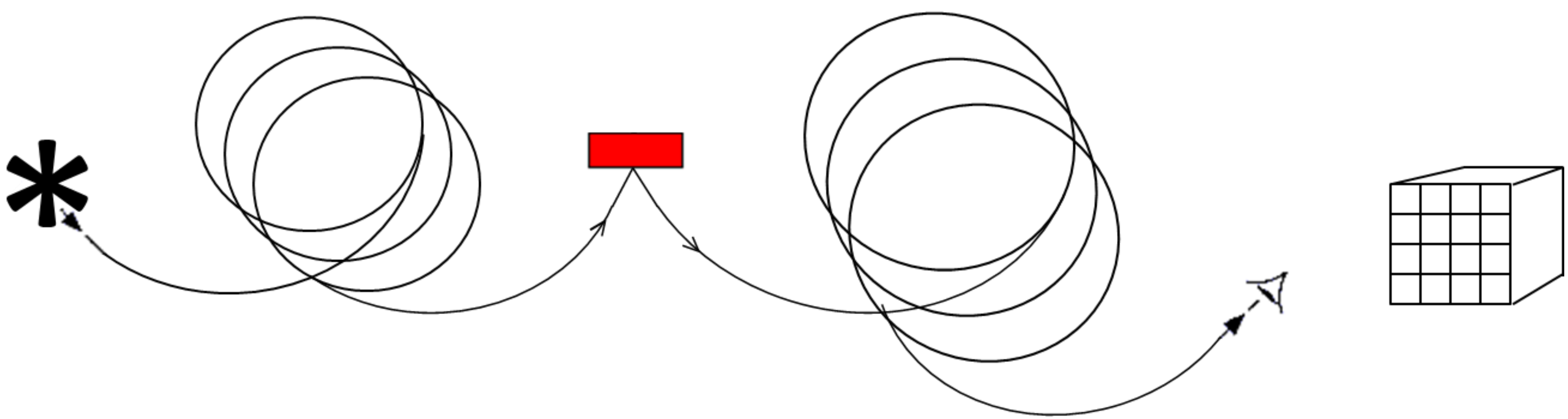
-gives unique molecular identification

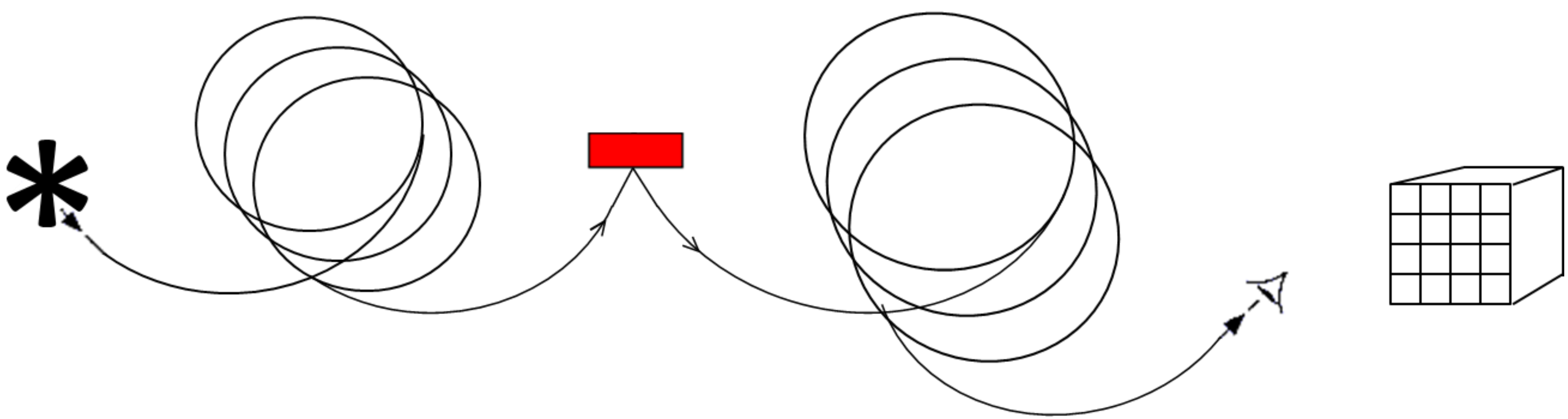
but it is not portable!











MIR photonic molecular sensing:

- direct
- non-destructive
- label-free
- no fluorescent tag
- sensitive
- high contrast
- quantitative
- fast acquisition times
- widely applicable
- use fibres and planar waveguides
- distributed fibre sensing possible

MIR PORTABLE, REAL-TIME sensing & imaging is potentially disruptive for:

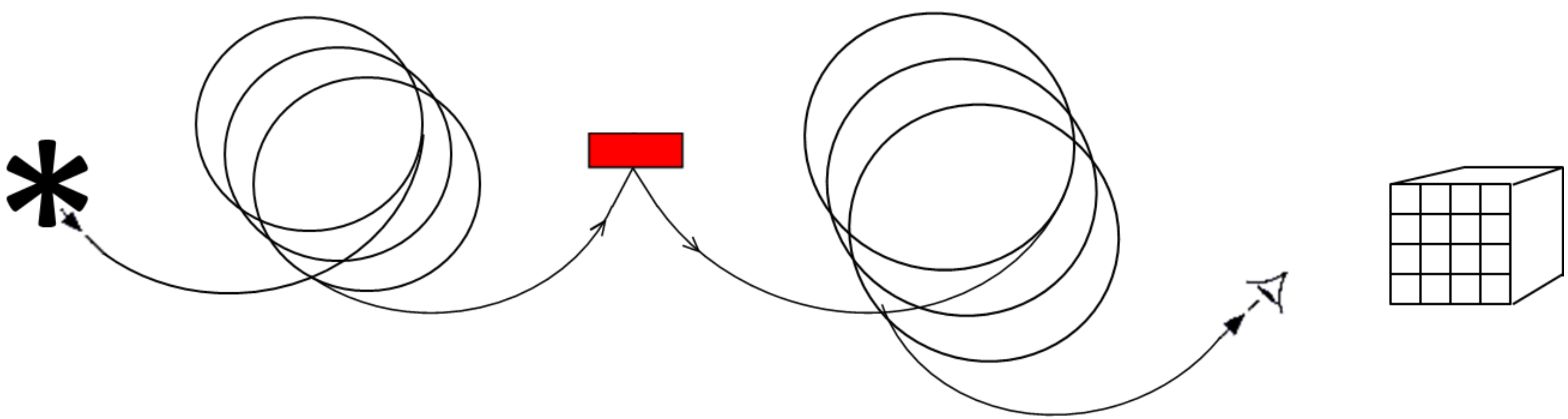
- Healthcare (early disease detection, bacterial detection, coherent imaging)
- Manufacturing (plastics)
- Chemical processing (oil fractionation)
- Energy production / use (fuel efficiency)
- Security (explosives, narcotics)
- Environmental monitoring (H_2S *CO_2 +many gases*)
- Agriculture, aquaculture (*fruit crop ripening; bacterial)*
- Food and drink (authenticity & adulteration)
- Pharmaceuticals and cosmetics (purity)

MIR fibre lasers:

- Defense: MIR ”radar” (collision avoidance , ship-to-ship comms.)
- Machining and welding of soft materials (laser surgery)

For this we need:

- MIR passive fibre for routeing
- Bright, portable, wideband, MIR source



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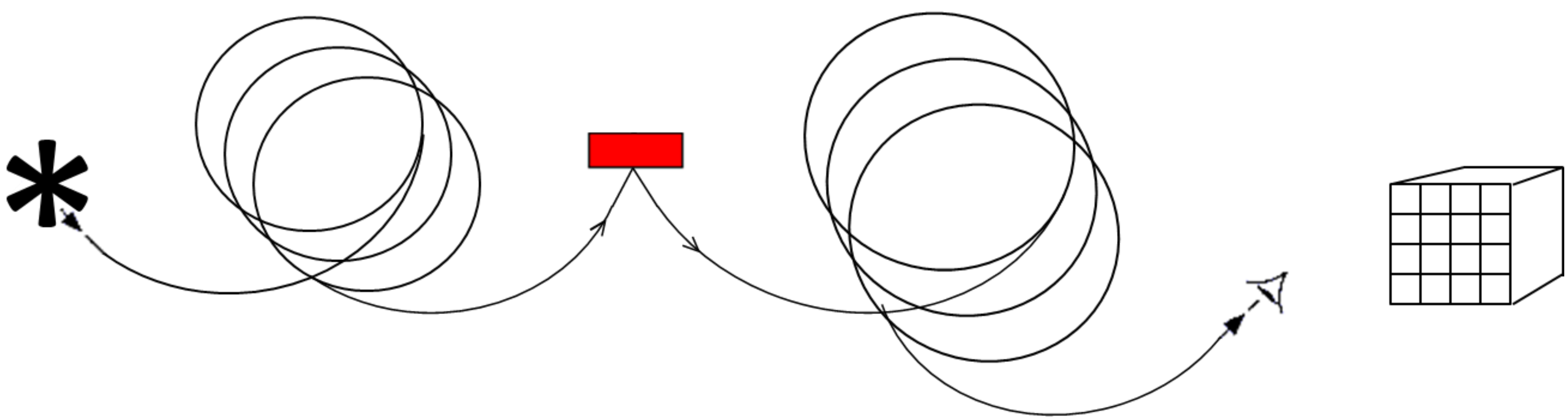


fibre routeing in mid-infrared:

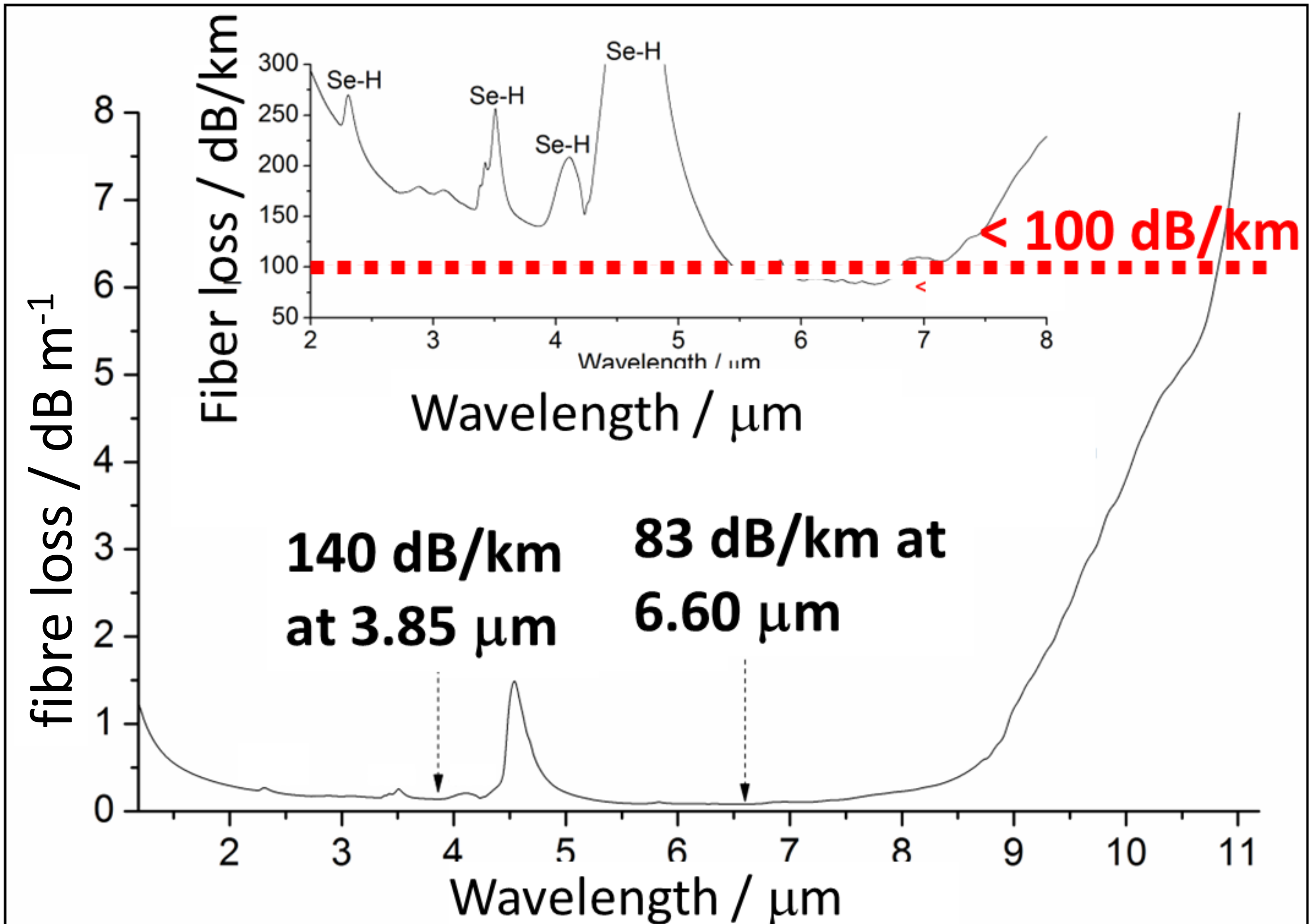
Record mid-infrared ultra-low optical loss mid-infrared fibre:

- we have achieved GeAsSe fibre with 84 dB/km loss at 6.6 μm wavelength

- **MIR transmission through 52 m fibre.**

Tang, Seddon, Shiryaev, Churbanov et al. Opt. Mat . Exp. 2015.

Record low-loss in Ge-As-Se fibre: 52 m transmission:



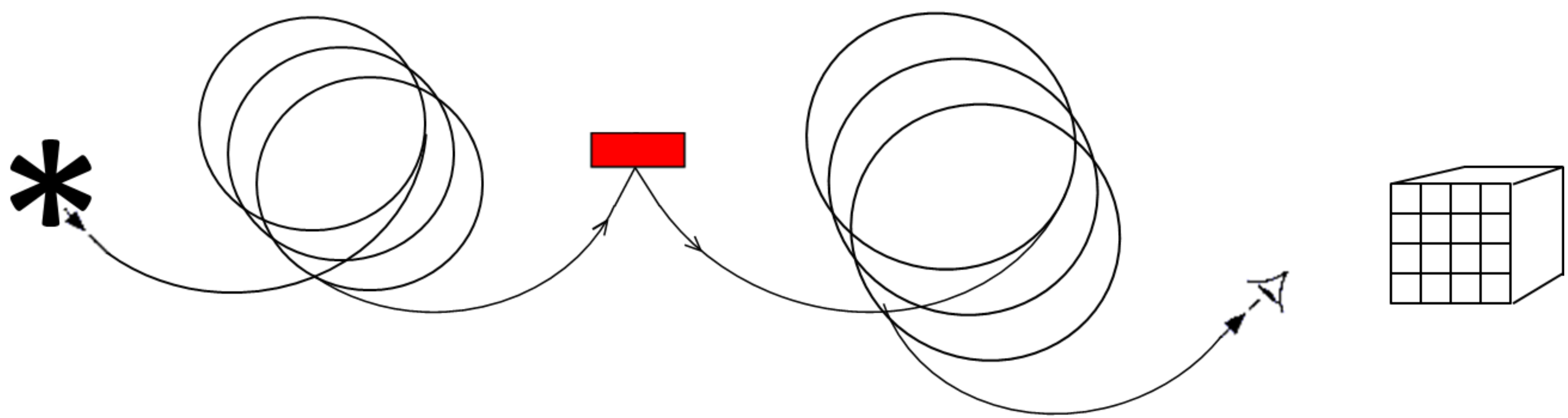
Tang et al. Opt. Mat . Exp. 2015.

Typical ultra-low loss data for chalcogenide glass MIR fibre based on different elemental systems.

Glass system	fibre structure	Minimum loss / (dB/km)	Wavelength / (µm)		Reference
		Two element systems			
As-S	core/clad.	12	3.0		Churbanov *et al.*
As-Se	unclad.	76	4.0		Churbanov *et al.*
Ge-Se	unclad.	100	6.6		Adam *et al.*
		Three element systems			
As-Se-Te	unclad.	40	6.7		Adam *et al.*
Ge-Sb-S	unclad.	50	2.3		Adam *et al.*
As-Se-S	core/clad.	60	4.8		Churbanov *et al.*
Ge-As-Se	**unclad.**	**83**	6.6	**Our work**	Tang, *et al.*
		Four element systems			
Ge-Sb-Ga-S	unclad.	100	2.8		J Troles *et al.*
Ge-As-Se-Te	unclad.	110	6.6		J Sanghera *et al.*

For this we need:

- MIR passive fibre for routeing
- Bright, portable, wideband, MIR sources



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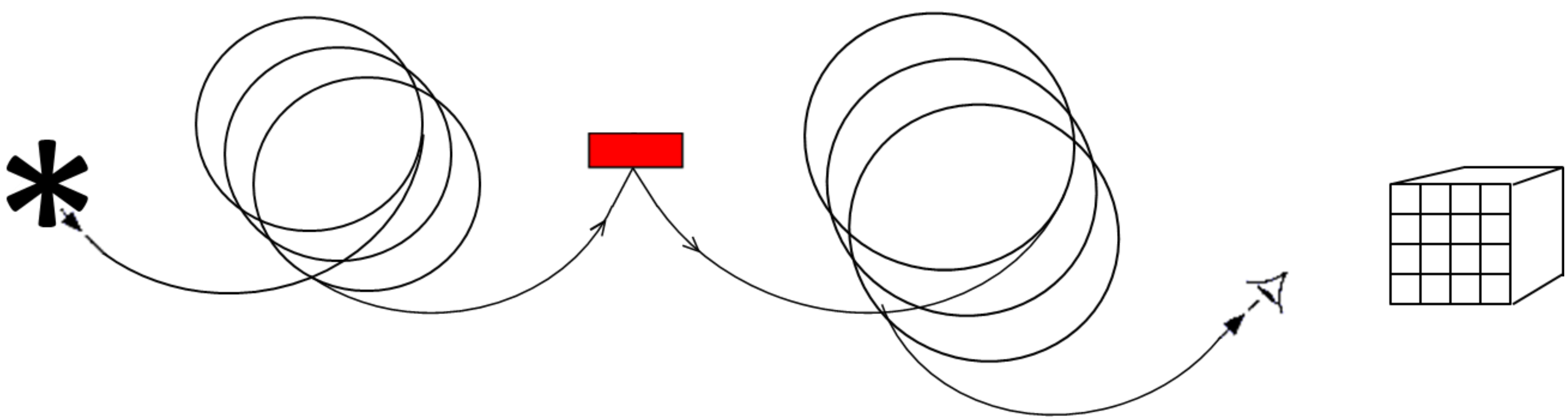
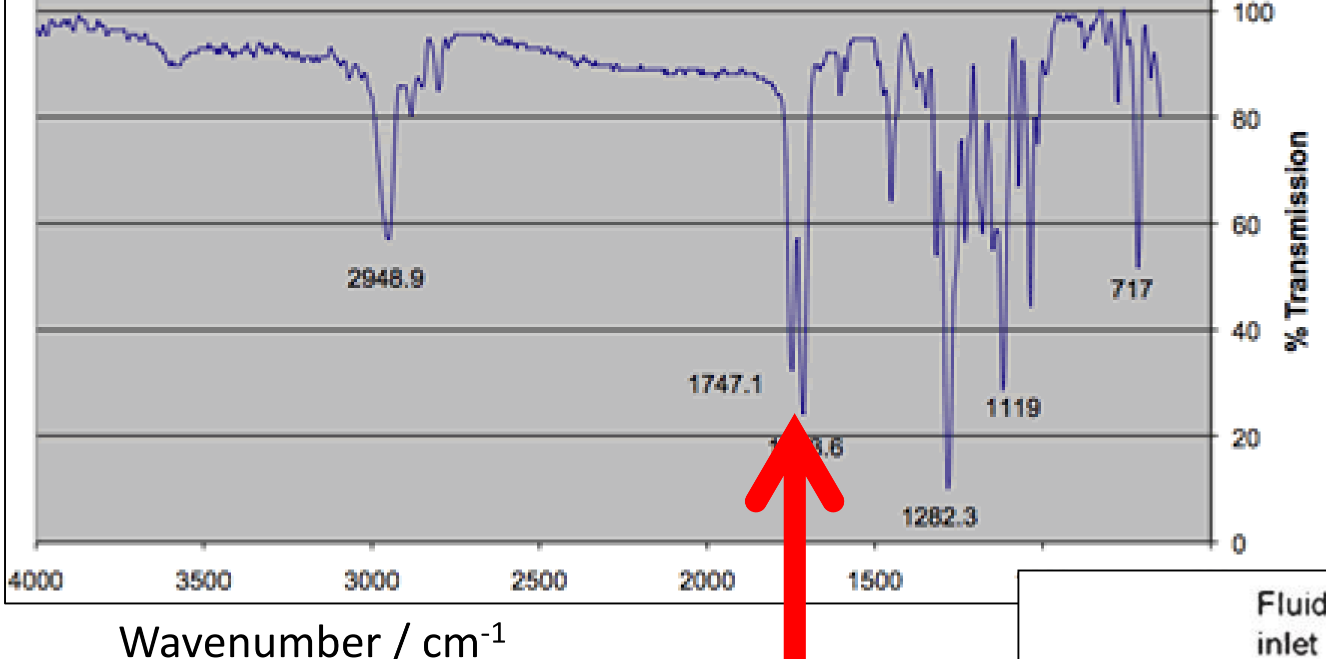
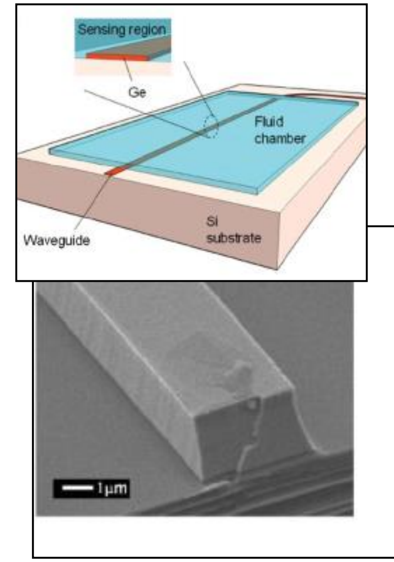


What about using MIR-QCLs?

MIR-QCL – Mid-Infrared Quantum Cascade Laser

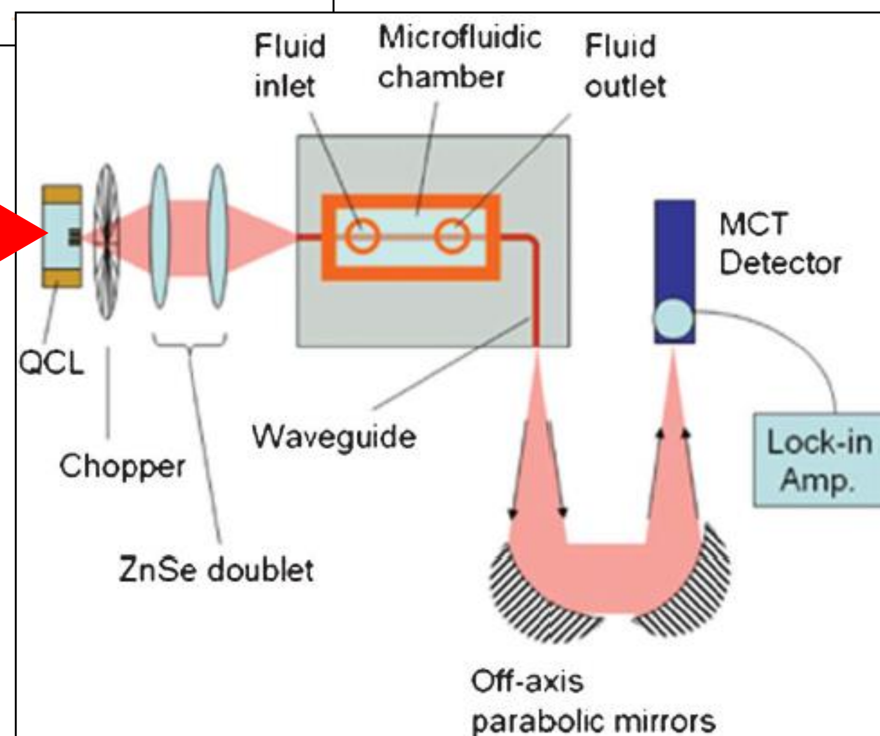
Cocaine sensor: MIR absorption





Evanescent field detection

5.8 µm QCL



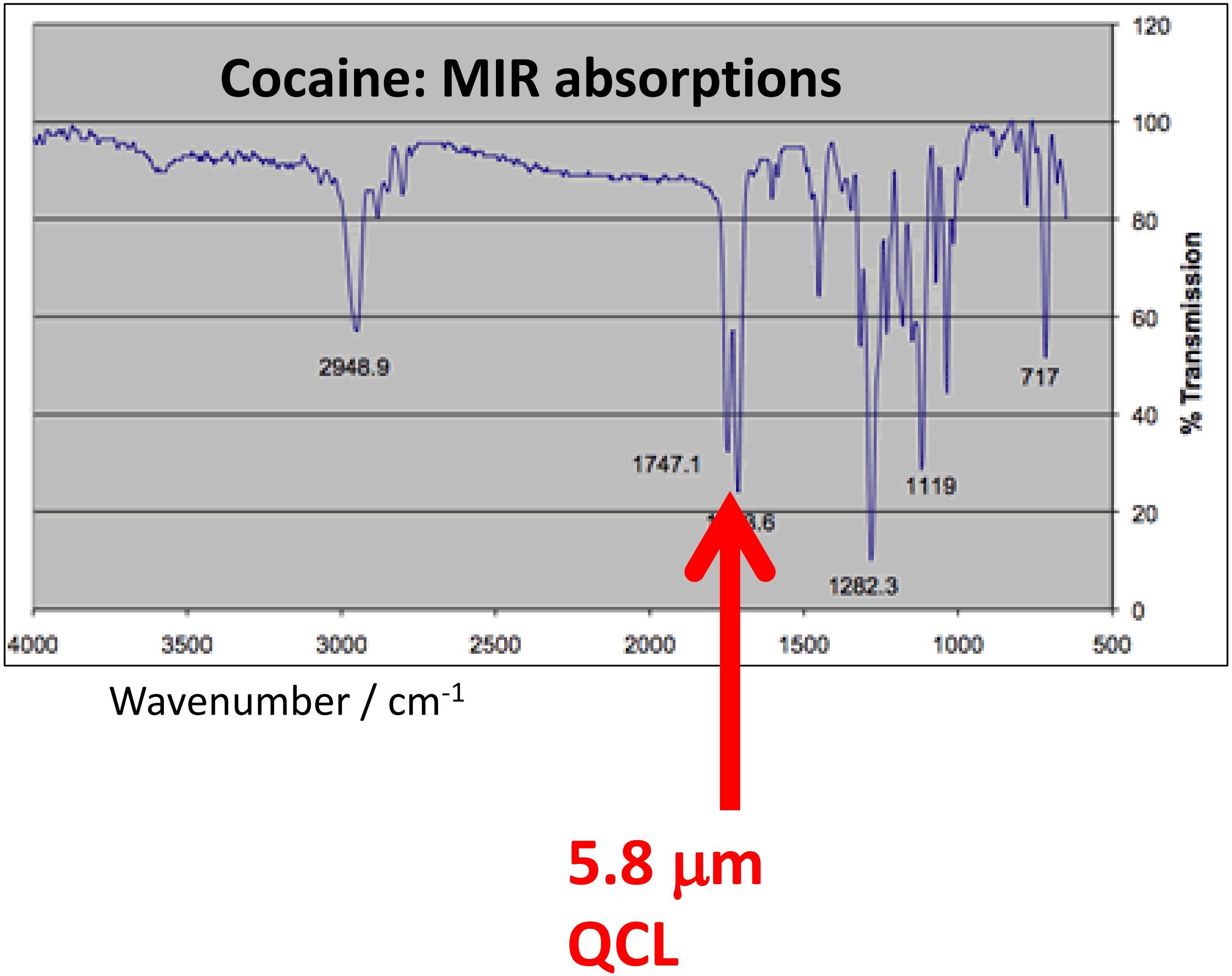
5.8 µm ≡ 1724 cm^{-1}

*Chang et al. 'Cocaine detection by mid-IR waveguide' Lab Chip **12** (2012) 3020*

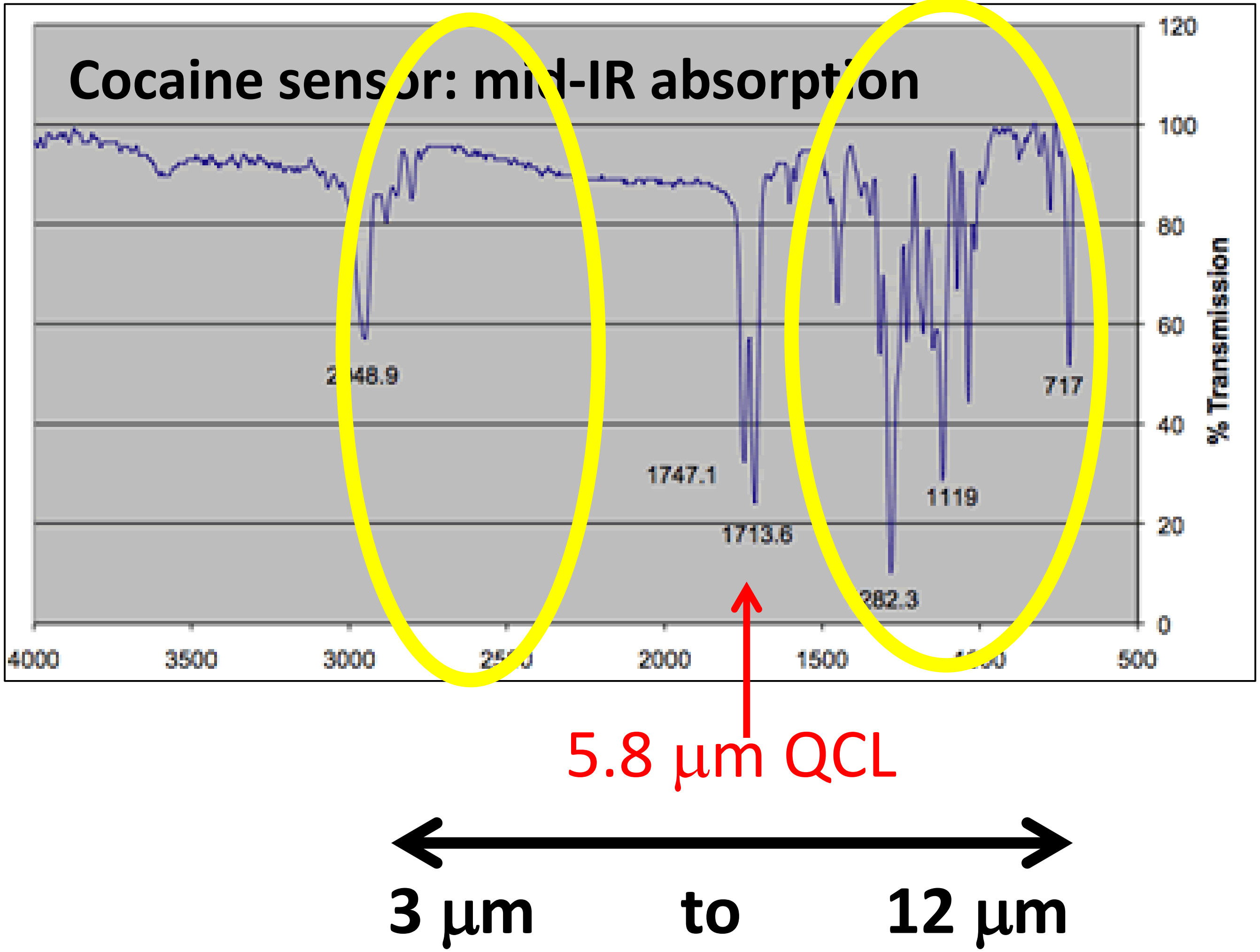
QCLs have high brilliance,

- but are narrow band,

- so give non-specific
  molecular identification



$5.8\ \mu m \equiv 1724\ cm^{-1}$



- The QCL misses the rich spectral signature.
- Need arrayed, tuneable QCLs for high specificity.

Mid-infrared (MIR) photonics:

1. Introduction
   - *I. Definitions & introduction*
   - *II. Portable, real-time MIR sensing*

2. **Wideband MIR fibre** supercontinuum **lasers** – progress and challenges

3. **Narrow-line MIR** rare earth **fibre lasers** – progress and challenges

4. Summary and future prospects

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Sunlight
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cost
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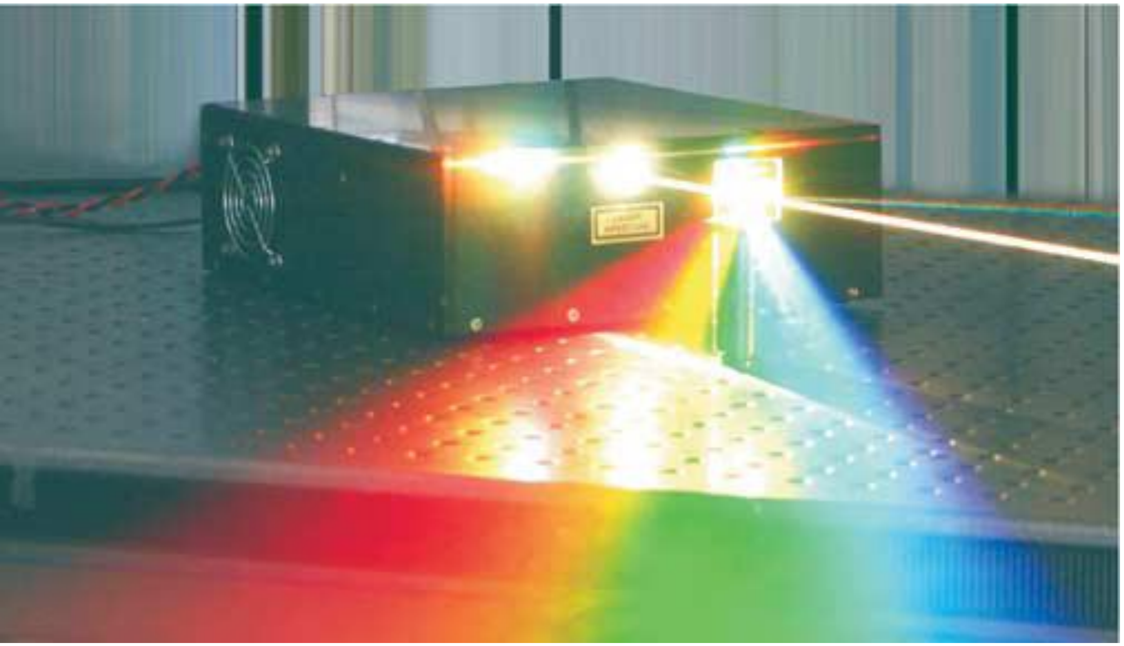
COST is supported by the EU Framework Programme Horizon 2020

Wideband MIR fibre supercontinuum lasers

- progress and challenges

Photonic crystal fibre (PCF) for super-continuum (SC) generation:



Total SC power out 6.5 W

10-W peak pump power

Repetition rate 50 MHz

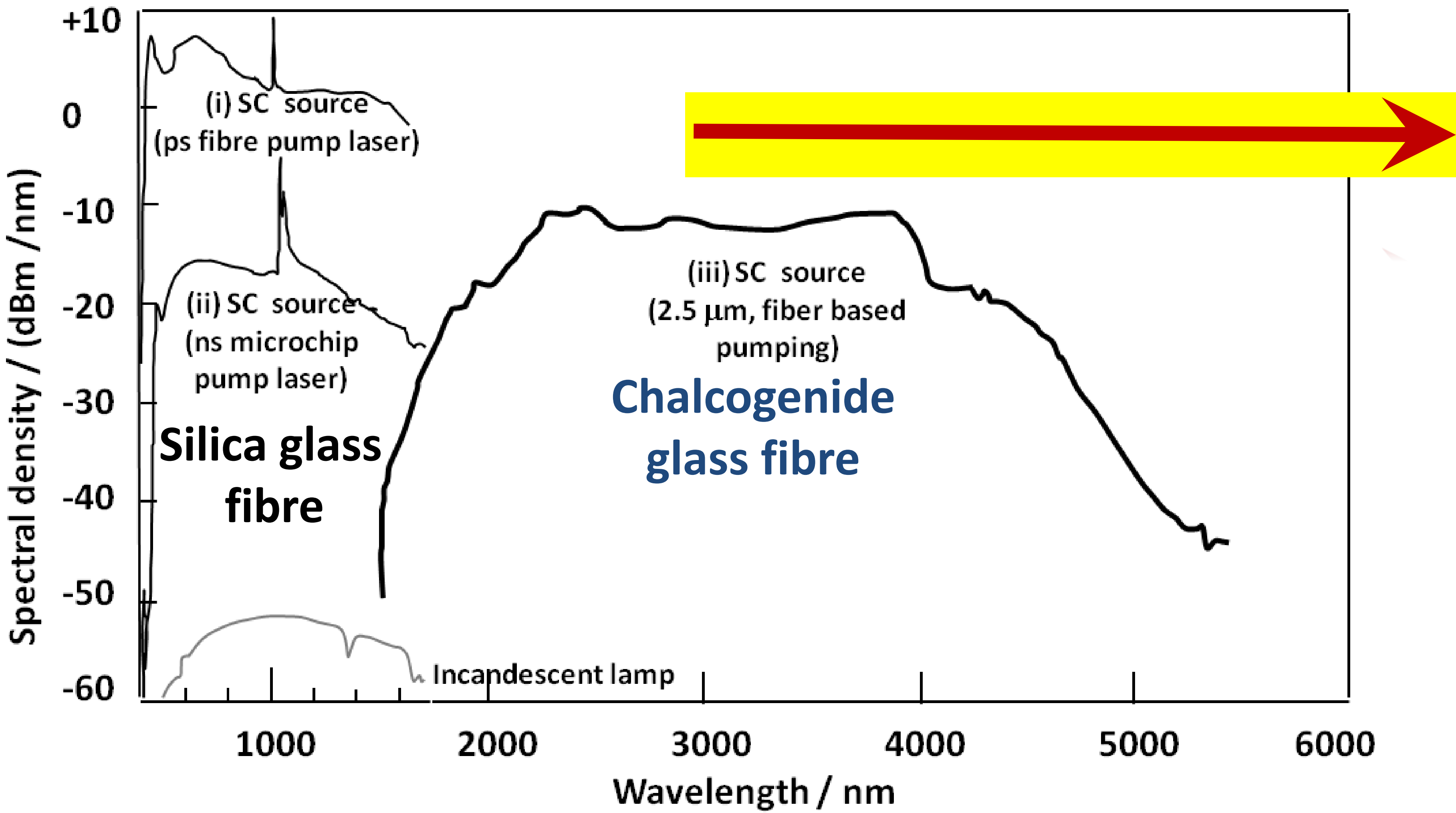
Average spectral power density 450–800 nm ***~4.5 mW/nm***

Silica glass PCF-SC

P. St.J. Russell, J. Lightwave Technol (2006).

We need ≥ 3-12 μm to capture MIR molecular signatures:

Seddon. J. Appl. Glass Sci. (2011).



(i)(ii) *P. St.J. Russell, J. Lightwave Technol* ***24*** *(12) 4729-4749 (2006).* (iii) *Sanghera et al. SPIE* ***7924****-24 (2011)*

- Supercontinuum generation (SCG) in bulk glass – 1st reported by Alfano, 1970

- 1st SCG in PCF (photonic crystal fibre) – Ranka *et al.*, 2000

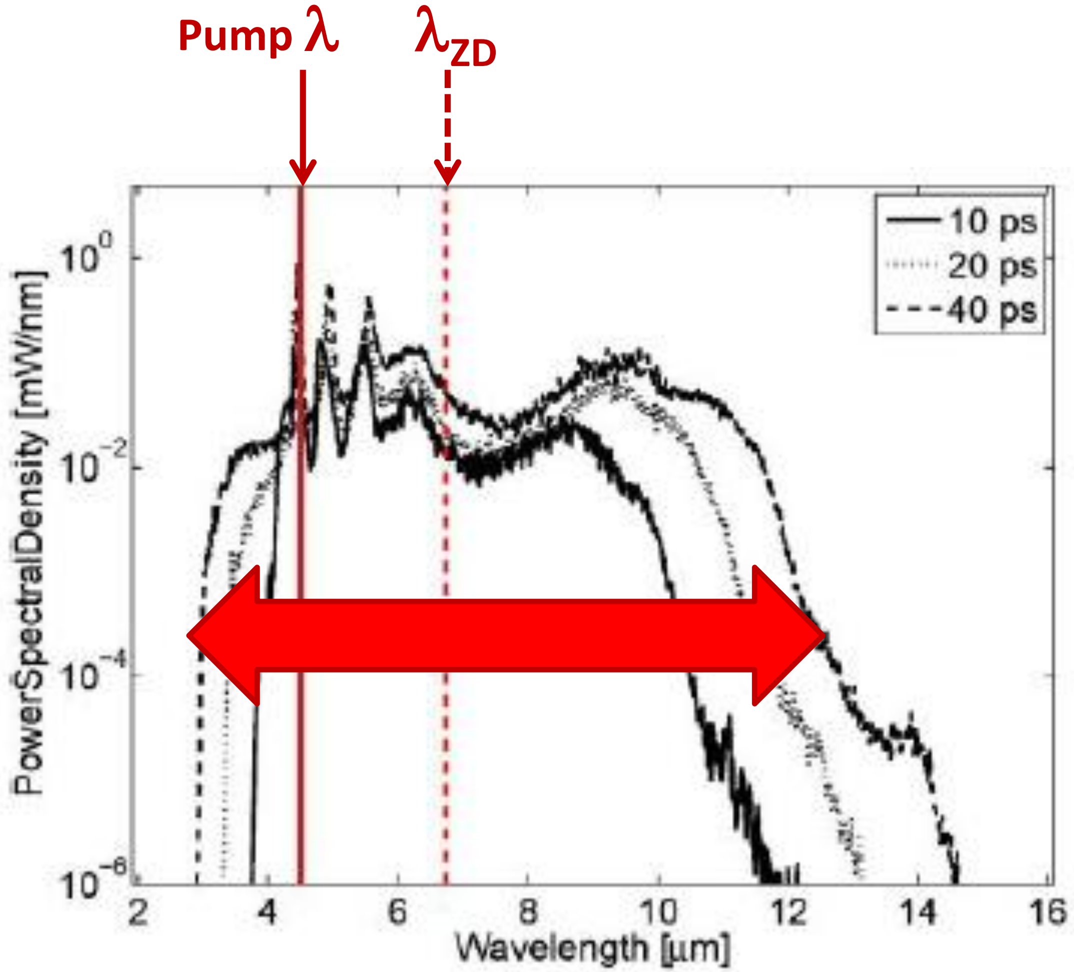
- SCG: monochromatic laser light converted to broad spectral bandwidth, of low temporal coherence and high spatial coherence – a ”laser generated rainbow”.

- Spectral broadening achieved by propagating short, high power, monochromatic optical pulses through an **optically nonlinear medium**, at zero point dispersion λ.

- **Optical nonlinearity of chalcogenide glasses is ~ 1000 x silica glass.**

Zackery & Elliott: *Optical Nonlinearities in Chalcogenide Glasses and their Applications* (Springer Series in Optical Sciences 135, New York, USA, 2007).

Numerical modelling:
mid-infrared (MIR) fibre supercontinuum (SC) generation



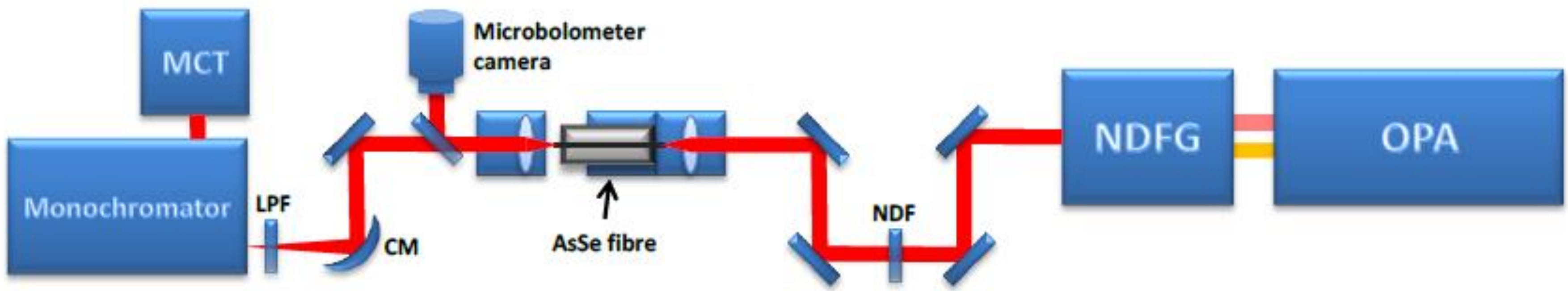
- 3 m fibre
- Core-diameter=20 µm
- Mode-locked Pr^{3+} chalcogenide-fibre-laser (does not exist yet !)
- Ps pump, 1 kW peak power

- modelled 2-12 µm fibre MIR-SC to cover absorption bands of key bio-molecules.

Led by O Bang, DTU, Denmark

1st announced: Numerical Modelling Conf. Hawaii, 2013.

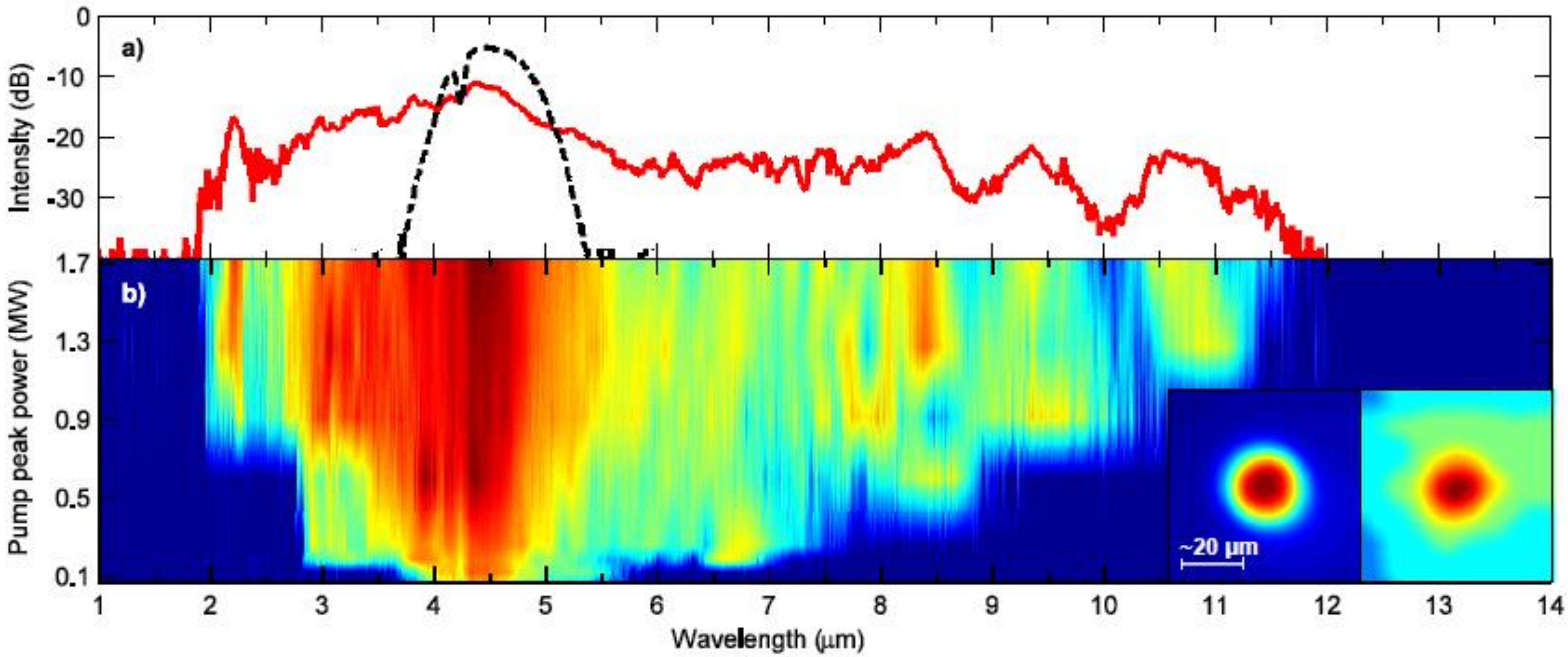
Record 1.3 to 13 μm mid-infrared fibre supercontinuum now achieved.



- Mid-infrared pump = a non-co-linear difference frequency generation (NDFG) unit pumped using an optical parametric amplifier (OPA) .
- Output was free-space coupled into the chalcogenide fibre and proper coupling verified by means of a micro-bolometer.

Bang, Seddon et al. NATURE PHOTONICS 8 830-834 2014.

Mid-infrared fibre SC - pump centred at 4.5 μm.



1.4–11.5 μm mid-infrared SC

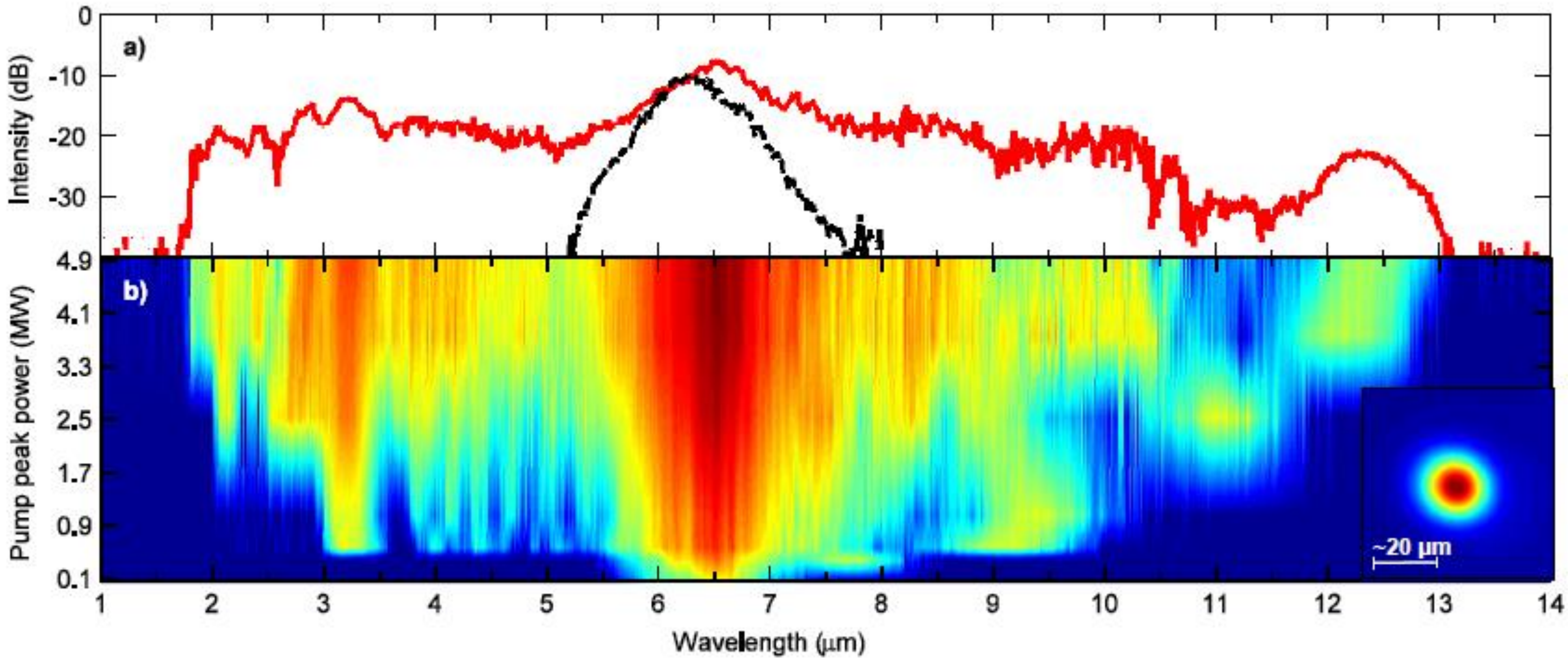
(a)Spectral profile at max. pump power - relatively flat (1.91 – 9.84 μm at – 20 dB from the signal peak) with 3 distinct peaks forming at the long-wavelength edge until ~ 11.5 μm.

(b) The spectral evolution with increasing pump power with gradual red-shift of the distinct spectral peak.

Inset shows the output beam profile corresponding to spectrum in (a) for all wavelengths (left) and wavelengths > 7.3 μm (right).

Bang, Seddon et al. NATURE PHOTONICS 8 830-834 2014.

Mid-infrared fibre SC - pump centred at 6.3 μm.



Record: 1.3–13 μm mid-infrared SC

(a) Spectral profile at max. pump power - relatively flat (1.81 – 10.73 μm at – 20 dB) followed by a strong spectral peak to 13 μm and

(b) spectral evolution with increasing pump power, with gradual red-shift of the distinct spectral peak & corresponding blue-shifted dispersive wave peaks.

Inset shows the captured beam corresponding to spectrum in (a) for all wavelengths.

Seddon, Bang et al. NATURE PHOTONICS 8 830-834 2014.

LETTERS
PUBLISHED ONLINE 14 SEPTEMBER 2014 | DOI: 10.1038/NPHOTON.2014.213
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[1,4], Uffe Møller[1], Irnis Kubat[1], Binbin Zhou[1], Sune Dupont[2], Jacob Ramsay[2], Trevor Benson[3], Slawomir Sujecki[3], Nabil Abdel-Moneim[3], Zhuoqi Tang[3], David Furniss[3], Angela Seddon[3] and Ole Bang[1,4]

The mid-infrared spectral region is of great technical and scientific interest because most molecules display fundamental vibrational absorptions in this region, leaving distinctive spectral fingerprints[1,2]. To date, the limitations of mid-infrared light sources such as thermal emitters, low-power laser diodes, quantum cascade lasers and synchrotron radiation have pre-

However, the use of such materials in SCG has so far been limited by the lack of high peak power pump sources in the MIR. Coherent and broadband SCG is obtained by pumping in the anomalous dispersion regime close to the zero-dispersion wavelength (ZDW) of the fibre[17], but because bulk As_2Se_3 glass has a ZDW ~7.4 μm, it is challenging to fabricate fibres with a ZDW

Selected for *News & Views* Nature Photonics 8 (2014)

“The demonstration of chalcogenide fibre-based supercontinuum sources that reach beyond a wavelength of 10 microns is set to have a major impact on spectroscopy and molecular sensing.”

news & views

SUPERCONTINUA

Entering the mid-infrared

The demonstration of chalcogenide fibre-based supercontinuum sources that reach beyond a wavelength of ten micrometres is set to have a major impact on spectroscopy and molecular sensing.

Günter Steinmeyer and Julia S. Skibina

Supercontinuum generation is one of the most fascinating effects in nonlinear optics. Starting with a nearly monochromatic input beam, a rainbow of colours can be generated, continuously spanning more than one optical octave across the visible and near-infrared spectral region. Compared with conventional white-light sources (including the Sun), the resulting white light of these supercontinua may reach a spectral brightness that is up to a million times brighter. Furthermore, the excellent spatial coherence of fibre-based white-light sources allows for laser-like tight focusing while overcoming the monochromatic nature of conventional continuous-wave lasers.

Although supercontinuum generation has been explored since the early 1970s[1], a major breakthrough came with the discovery of a soliton fission scenario in optical fibres[2], which enables highly

are limited to visible and near-infrared wavelengths up to about 2 μm. However, employing fluoride fibres with enhanced infrared transmission properties has pushed this limit deeper into the infrared to around 6 μm (ref. 3).

Now, writing in *Nature Photonics*, Christian Rosenberg Petersen and colleagues[4] report fibre-based mid-infrared supercontinuum generation all the way up to a wavelength of 13.3 μm, exceeding previous record values by a factor of two and coming close to the best demonstrated infrared performance of bulk white-light generation schemes[5]. Moreover, given that their mid-infrared spectra encompass more than three octaves in bandwidth, the results of Petersen et al. also constitute one of the widest demonstrated supercontinua.

Two key ingredients are behind the achievements. The first is the use of pump lasers directly in the mid-infrared at wavelengths of 4.5 and 6.3 μm; the second

heavy elements like arsenic, selenium and germanium, which, combined in a glass, provide excellent infrared transmission properties due to their low phonon energies. An additional important property is a relatively high Kerr nonlinearity, which enables supercontinuum generation at relatively low peak powers. The idea of using chalcogenide glasses for mid-infrared white-light generation is certainly not new. In fact, over the past decade, various geometries have been explored to stimulate this process, including in bulk materials and nanoscale waveguides. Nevertheless, so far none of these approaches have been able to fully exploit the full bandwidth of these glasses, which reaches up to about 15 μm in the selenide glass system.

For the soliton fission process to work well it is important to launch near-monochromatic input light close to the zero-dispersion wavelength of the

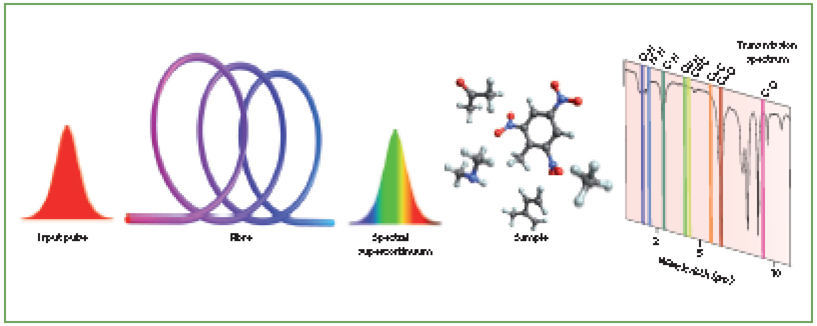


Figure 1 | Illustration of supercontinuum generation in the mid-infrared 'molecular fingerprint' region. Nonlinear processes in an optical fibre convert input pulses into broad-bandwidth white light that can then be used for molecular spectroscopy. The most common vibrational resonances in organic molecules are in the wavelength range from 2 to 10 μm. The example spectrum shown is for acetone, which is the top left molecule in the sample area.

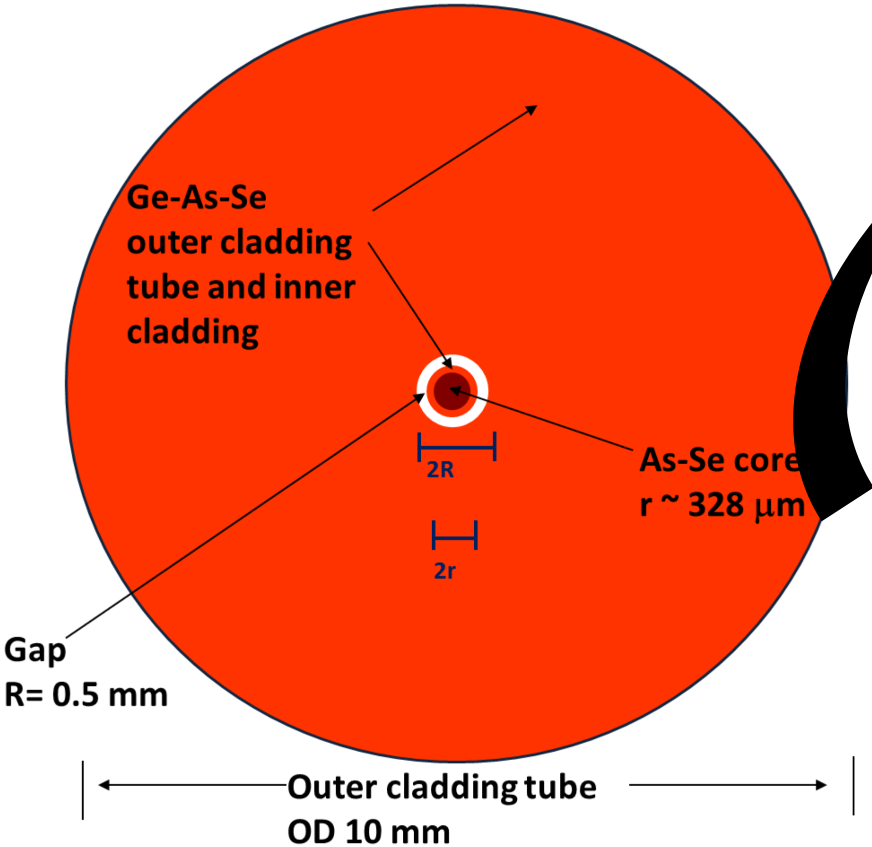
Record wide mid-infrared SC in fibre:

- we achieved with specially engineered, high numerical aperture, step-index mid-infrared fibre.

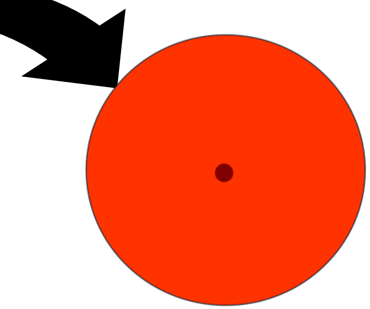
Dantanarayana et al. OPTICAL MATERIALS EXPRESS 4(7) 1444 2014.

Bang, Seddon et al. NATURE PHOTONICS 8 830-834 2014.

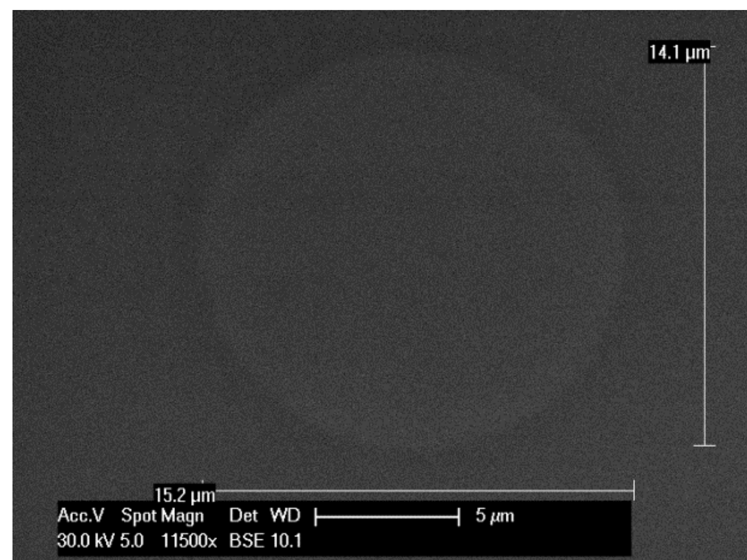
Schematic diagram preform, made *via* extrusion.



Drawn-down final-SC-fibre small-core



Core diameters aimed at: 10, 15, 20 μm



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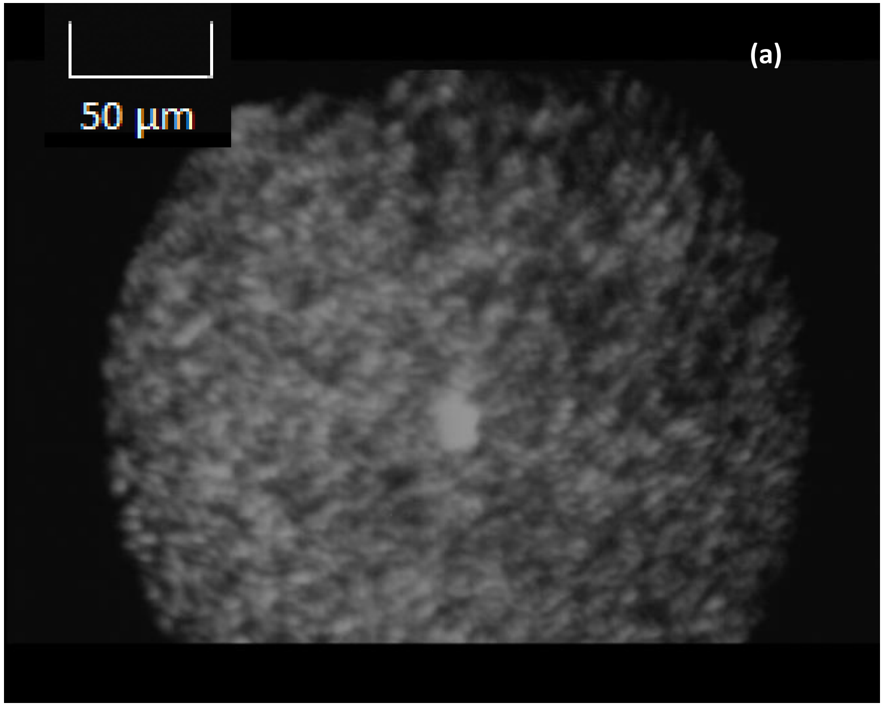
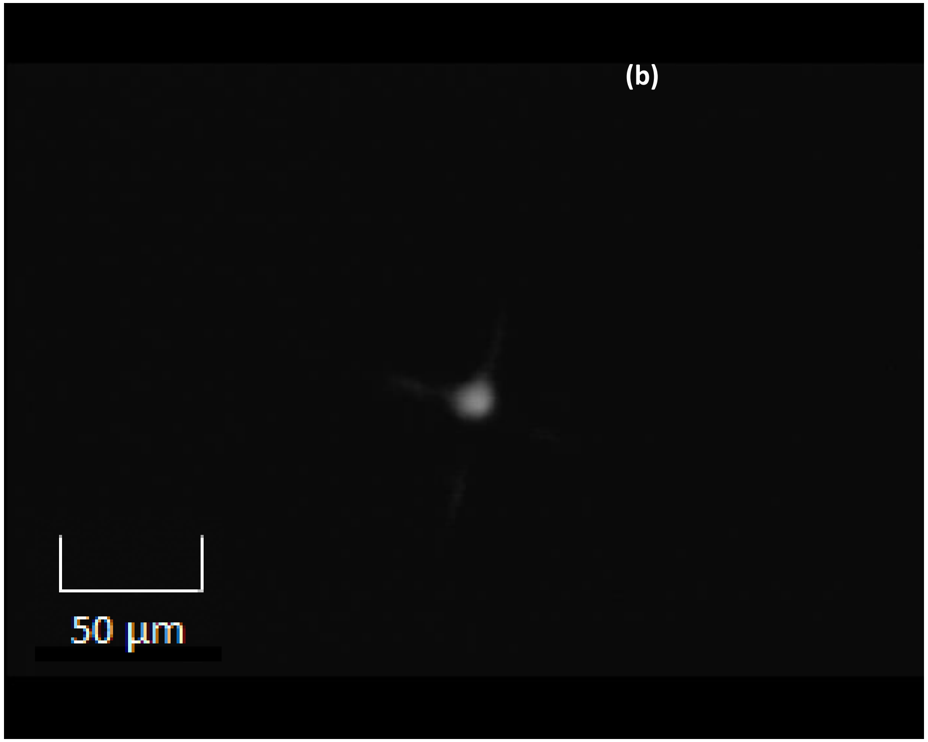
Faculty of Engineering

MINERVA
improved medical diagnostics

Near-field image of the small-core fibre (F006MINSCGNM)

at 1463 nm and 10 mW input power from a semiconductor tuneable laser.





(a) launching into the 14 µm core of the 270 µm outer diameter SCG fibre and
(b) focusing laser input to the 14 µm core of the 270 µm SCG fibre.

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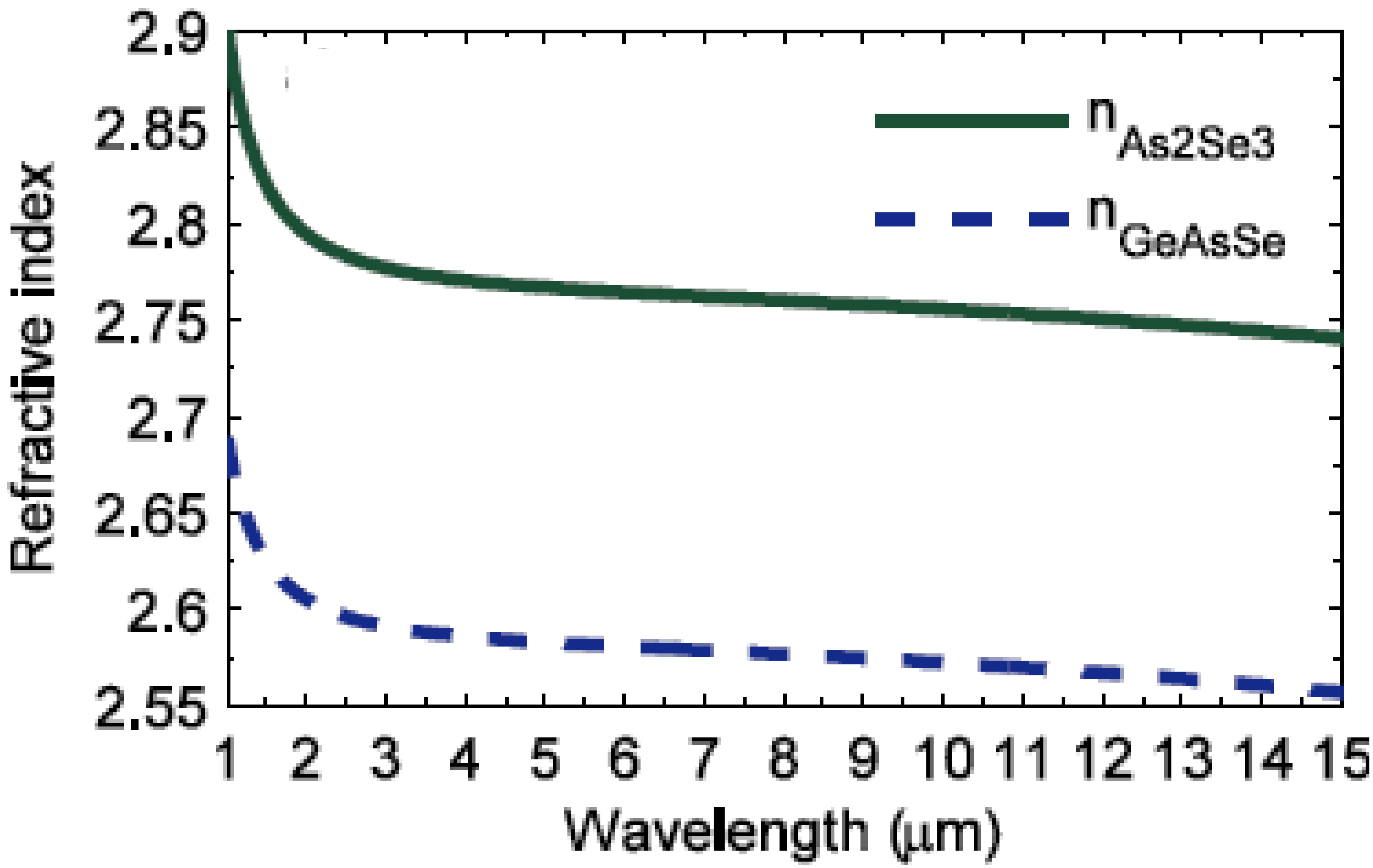
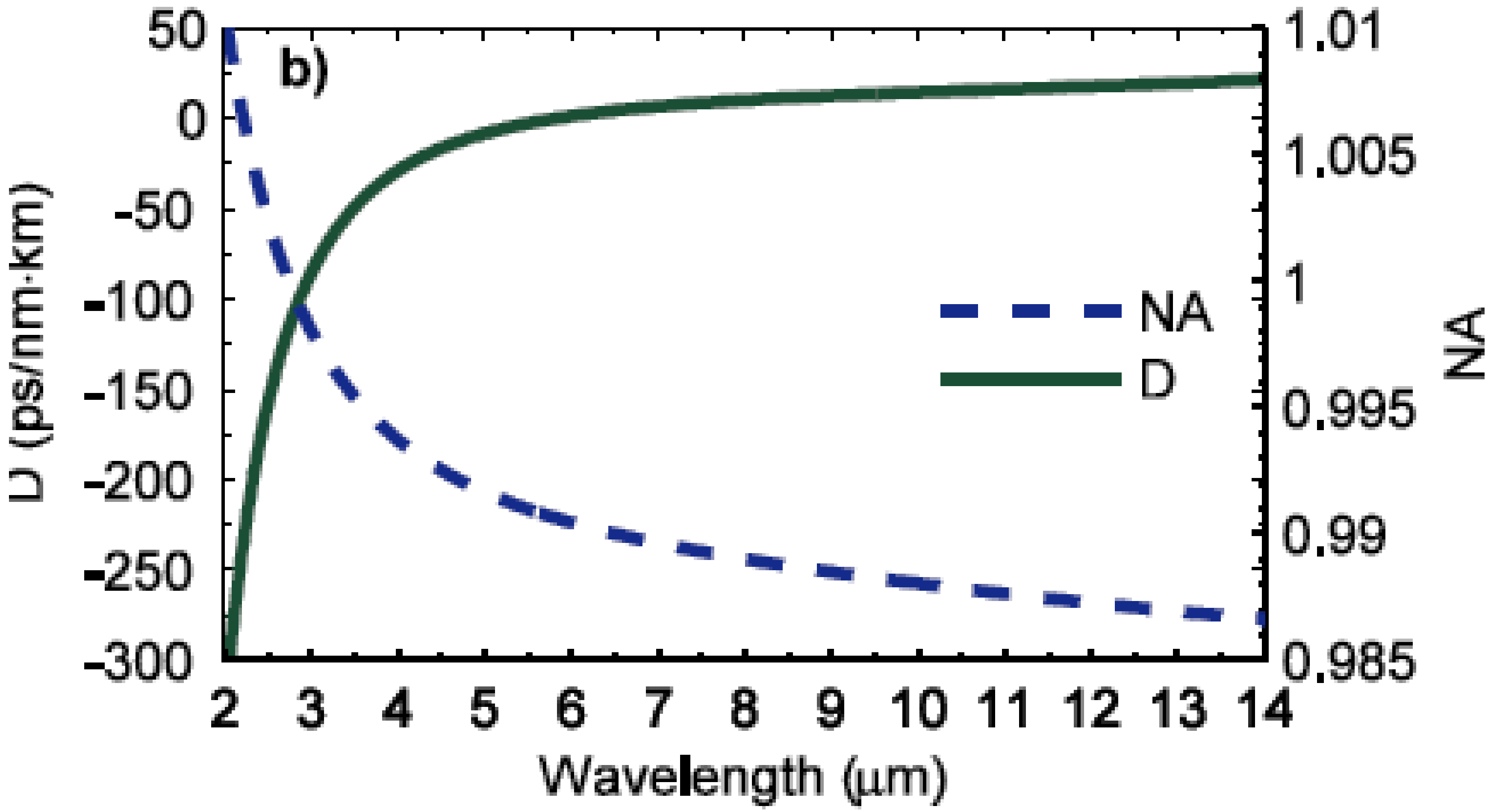
MINERVA improved medical diagnostics

Refractive index dispersion of core and cladding glasses, to make high numerical aperture, chalcogenide step-index mid-infrared fibre.



Dantanarayana et al. Opt. Mat. Exp. (2014)

High-NA and zero dispersion wavelength of chalcogenide glass step-index mid-infrared fibre for wideband MIR-SC.



Dantanarayana et al. Opt. Mat. Exp. (2014)

MIR SCG chalcogenide fibre sources reported, arranged in order of decreasing output wavelength-span.

MIR SCG fibre design		• SIF, NA=1.0 • core/cladding = AsSe/GeAsSe • core: φ ~16μm	• SIF, NA=1.3 • core/cladding = GeAsSe/ GeAsS • 110 mm long	• 'holey' MOF • air/AsSe • core: long	•SIF, NA = 0.3 •core/cladding='AsS' •2 m long	• SIF, NA=0.3 • core/cladding ='AsS' • core:	• 'holey' MOF • air/AsSe • core:
MIR SC span / μm		1.4 to 13.3	1.8 to 10	1.7 to 7.5	1.9 to 4.8[#]	2.5 to 4.1	3.65 to 4.9[#]
MIR SC average power out		'few 100 μW	'few' mW	15.6 mW	565 mW	550 mW	5 mW
Pump laser	Type	OPA pumped NDFG	customized OPA	OPA	Raman-shifted Er^{3+} SiO_2 mode-locked fibre laser	Yb:KGW→ OPO →OPA	Nd-YAG micro-chip pumped PPLN
	Center λ /μm	6.3	4.0	4.4	2.45	3.8 (& others)	3.82
	Pulse width /fs	100	330 ±15	320	-	300-450	-
	Pulse rate /kHz	1	21,000	21,000	10,000	(pulse energy 13 nJ)	20
	Peak power / kW	2290	~ 3	5.2	> 3.5	-	> 2
	Av. pump power	~760 μW	40 mW	100 mW	1.4 W	1 W	30 mW
Year , Authors		2014 MINERVA	2015 CUDOS	2015 Bang	2012 NRL	2015 Giessen	2014 NRL

MIR SCG chalcogenide fibre sources reported, arranged in downwards order of output wavelength-span.

MIR SCG fibre design		• SIF, NA=1.0 • core/cladding = AsSe/GeAsSe • core: φ ~16μm • 85 mm long		• SIF, NA=1.3 • core/cladding = GeAsSe/ GeAsS • core: φ=4.5μm • 110 mm long	• 'holey' MOF • air/AsSe • core: φ=4.5μm • 180 mm long	•SIF, NA = 0.3 •core/cladding='AsS' •core: φ=10 μm •2 m long	• SIF, NA=0.3 • core/cladding ='AsS' • core: φ= 9μm • 130 mm long	• 'holey' MOF • air/AsSe • core: φ=12μm • 2m long
MIR SC span / μm		**1.4 to 13.3**	**1.5 to 11.7**	**1.8 to 10**	**1.7 to 7.5**	**1.9 to 4.8#**	**2.5 to 4.1**	**3.65 to 4.9#**
MIR SC average power out		**'few 100 μW**		**'few' mW**	**15.6 mW**	**565 mW**	**550 mW**	**5 mW**
Pump laser	Type	OPA pumped NDFG		customized OPA	OPA	Raman-shifted Er^{3+} SiO_2 mode-locked fibre laser	Yb:KGW→ OPO →OPA	Nd-YAG micro-chip pumped PPLN
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	Pulse width /fs	100		330 ±15	320	-	300-450	-
	Pulse rate /kHz	1		21,000	21,000	10,000	(pulse energy 13 nJ)	20
	Peak power / kW	2290	1250	~ 3	5.2	> 3.5	-	> 2
	Av. pump power	~760 μW	~350 μW	40 mW	100 mW	1.4 W	1 W	30 mW
Year , Authors		2014 Minerva		2015 CUDOS	2015 Bang	2012 NRL	2015 Giessen	2014 NRL

journal

J. Am. Ceram. Soc., 1–4 (2016)
DOI: 10.1111/jace.14391

Rapid Communication

High Brightness 2.2–12 μm Mid-Infrared Supercontinuum Generation in a Nontoxic Chalcogenide Step-Index Fiber

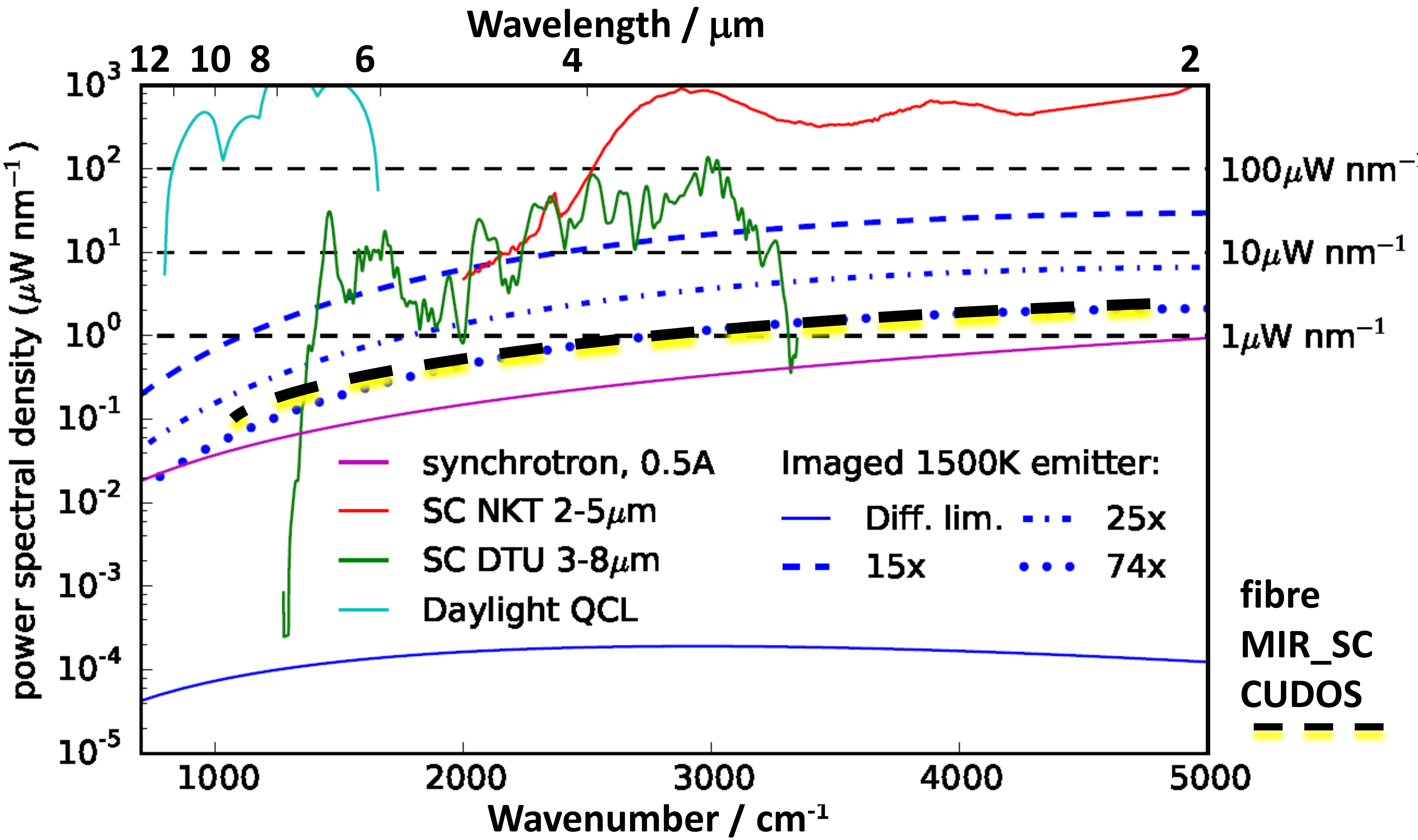
Bin Zhang,[‡] Yi Yu,[§,†] Chengcheng Zhai,[‡] Sisheng Qi,[‡] Yuwei Wang,[‡] Anping Yang,[‡] Xin Gai,[§] Rongping Wang,[§] Zhiyong Yang,[‡,†] and Barry Luther-Davies[§]

17 mW fibre MIR- SC power output

≡ “a few synchrotrons’ worth”

2016

Comparison of broadband mid-infrared sources: Blackbody at 1500 K; Quantum Cascade Lasers (QCL); Synchrotron, Supercontinuum fibre lasers (SC).



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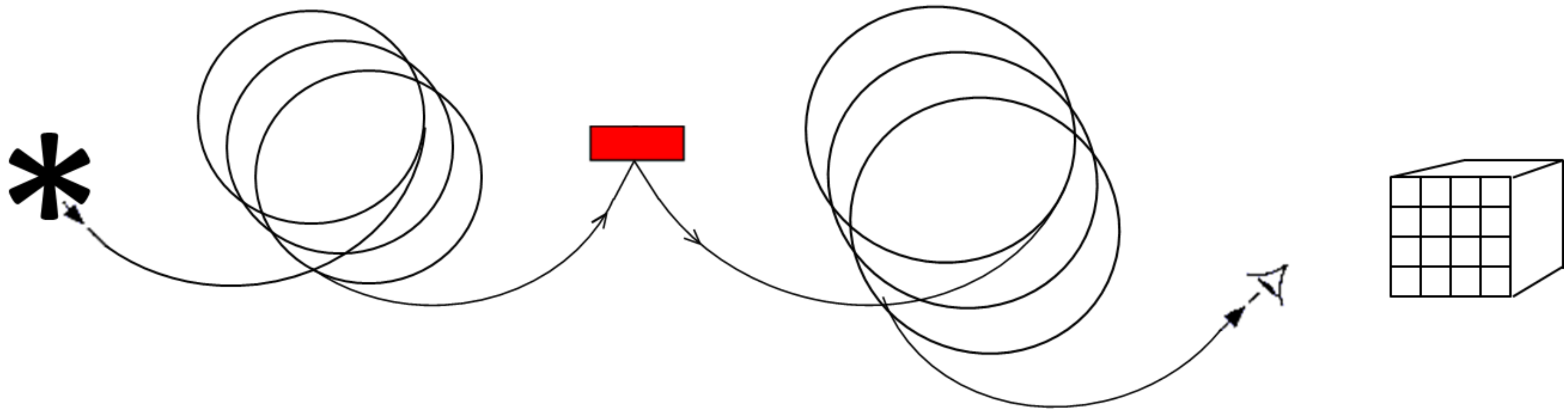
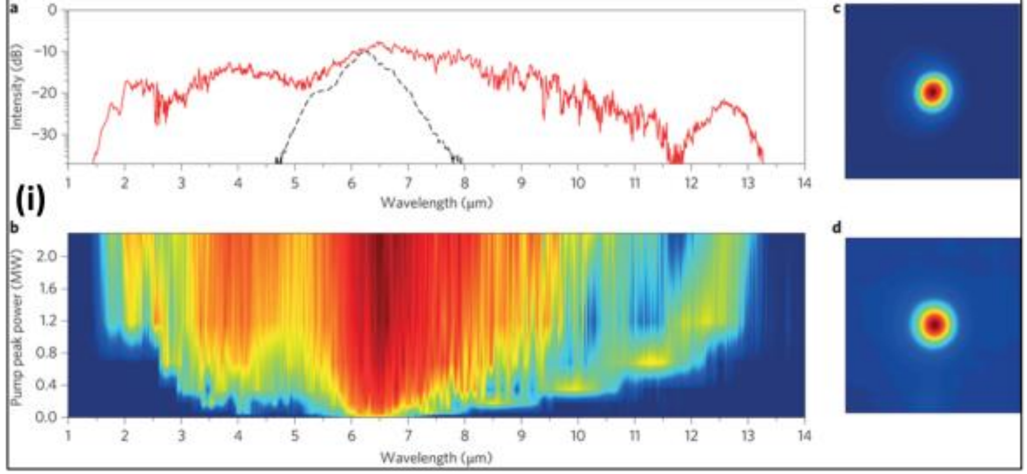
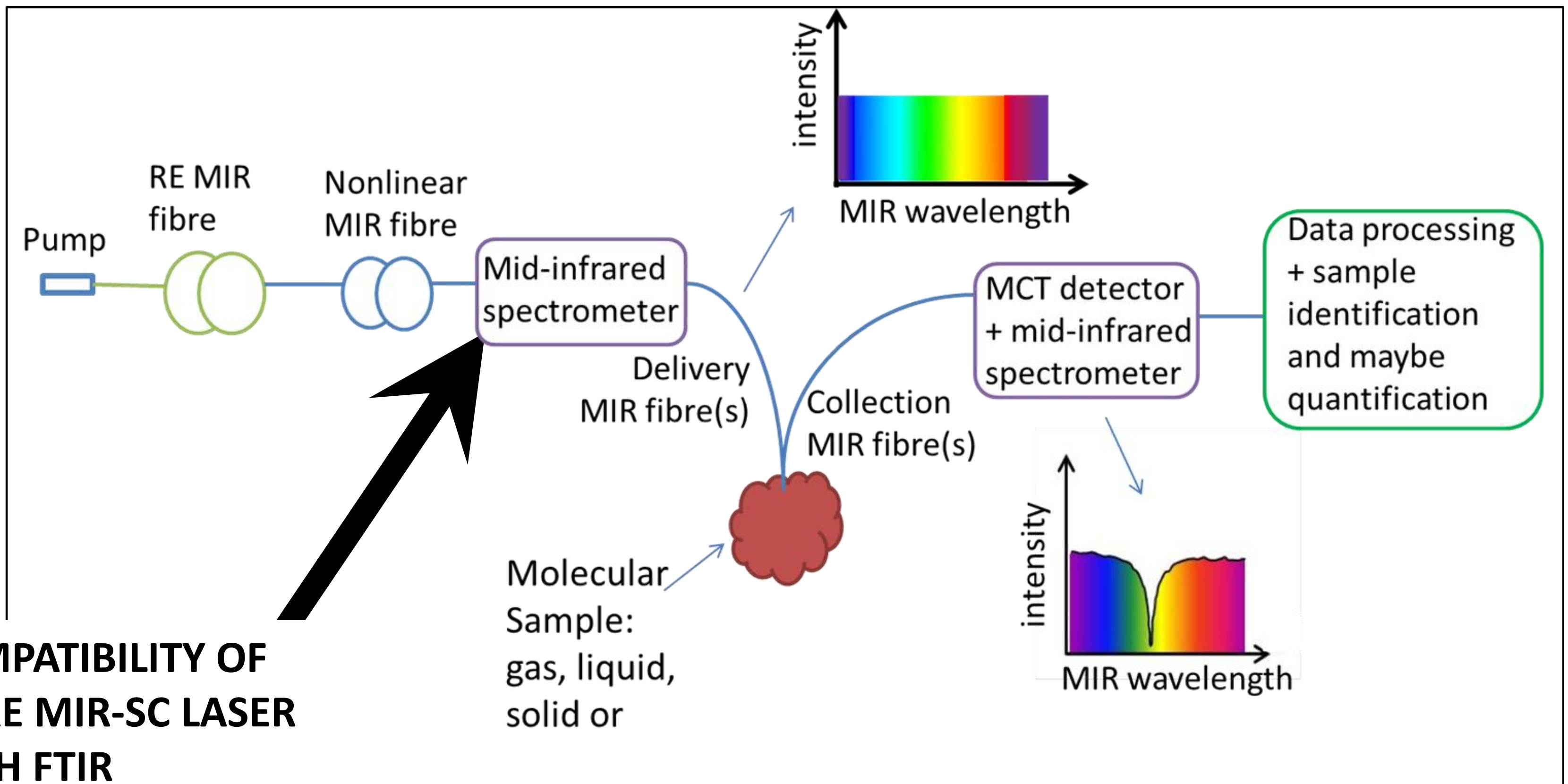
Wideband MIR fibre supercontinuum lasers

- progress and challenges



Challenge (I)
How to achieve this MIR sensing optical circuit in practice?





COMPATIBILITY OF FIBRE MIR-SC LASER WITH FTIR SPECTROMETER ?

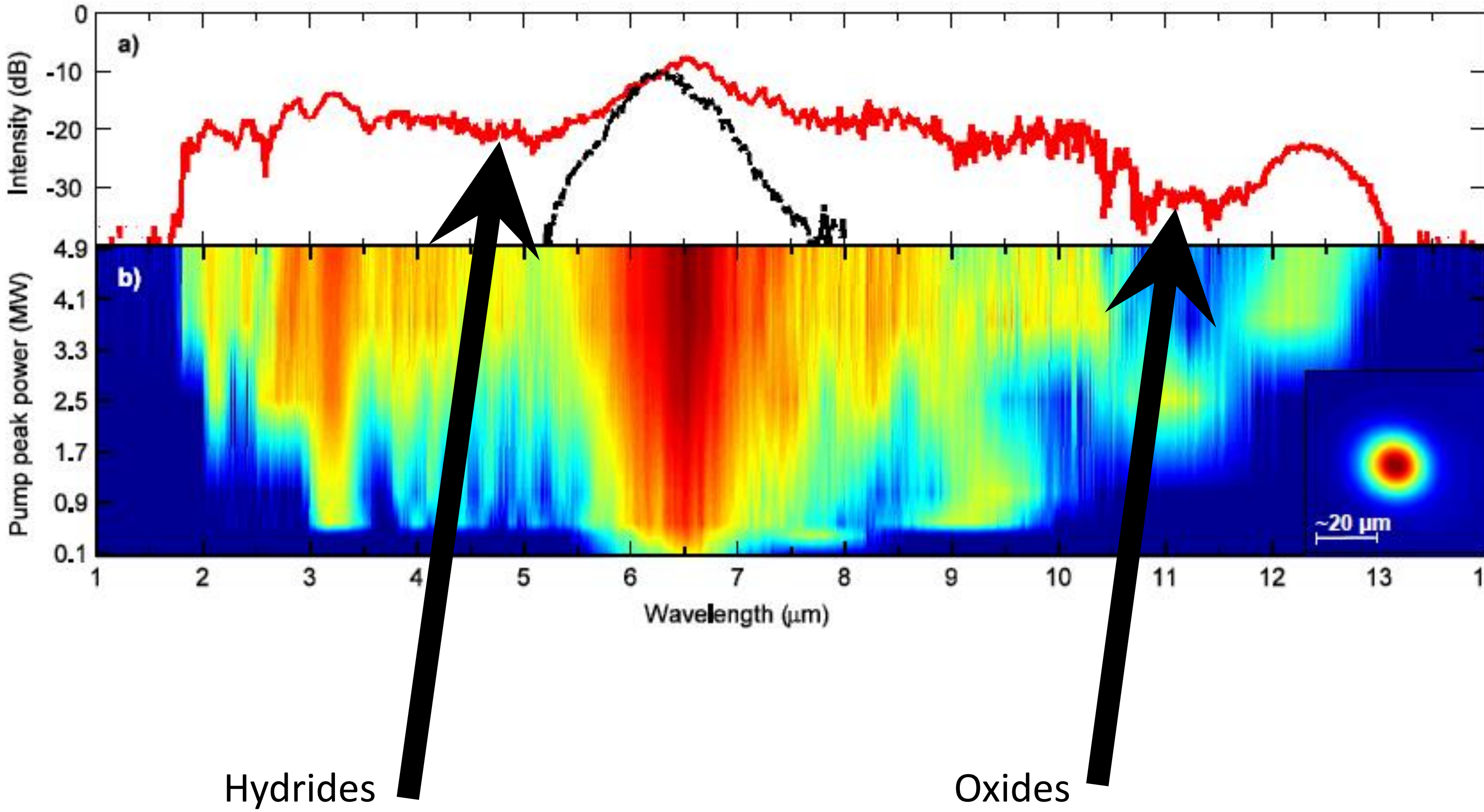
Challenge (II)

How to achieve fibre MIR-SC with flatter output?

MINERVA improved medical diagnostics

Mid-infrared fibre SC - pump centred at 6.3 μm.

Record: 1.3–13 μm mid-infrared SC



IMPURITIES IN THE GLASS ITSELF AFFECT THE FLATNESS OF THE FIBRE MIR-SC LASER OUTPUT

Bang, Seddon et al. NATURE PHOTONICS 8 830-834 2014.

Challenge (III)

How to achieve narrow-line, MIR fibre laser pump for compact, fibre MIR-SC ?

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Narrow-line MIR rare earth fibre lasers

- progress and challenges

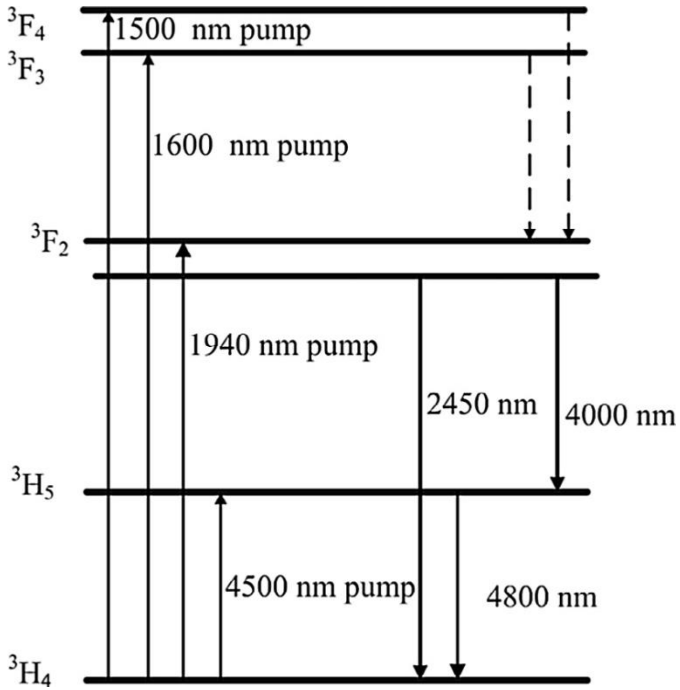
Building on the comprehensive studies of
rare earth ion emission in chalcogenide bulk glasses, :

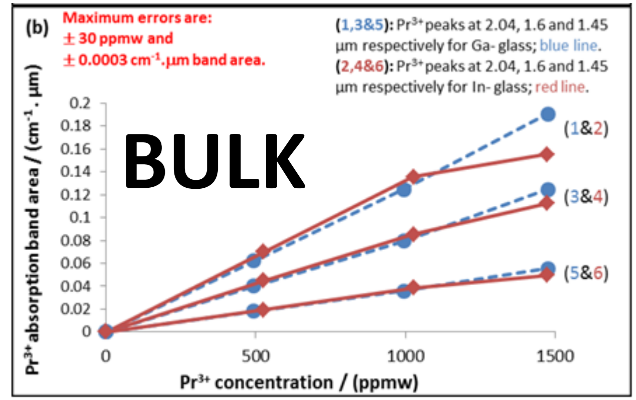
Sanghera	[*IEEE J. Quant. Electron. 2001)* FIBRE
Heo	[*J. Non-Cryst. Solids 1999; 2007*]
Tanabe	[*J. Non-Cryst. Solids 1999]*
Adam	[*Opt. Mat. 2008*] FIBRE
Frumar	[*Mat. Lett. 2008*] and
Aitken and Quimby	[*J. Non-Cryst. Solids 2003; CR Chemie 2002*]

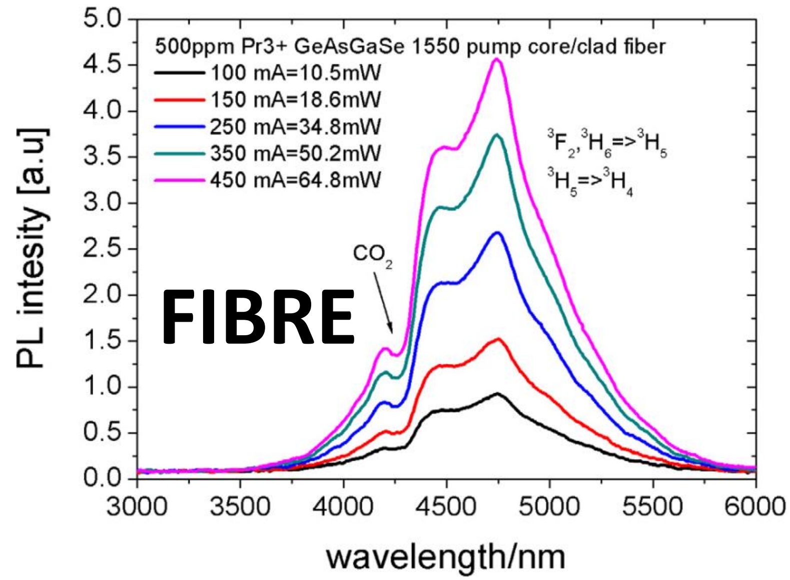
and also the rare earth ion modelling work of the Groups of:

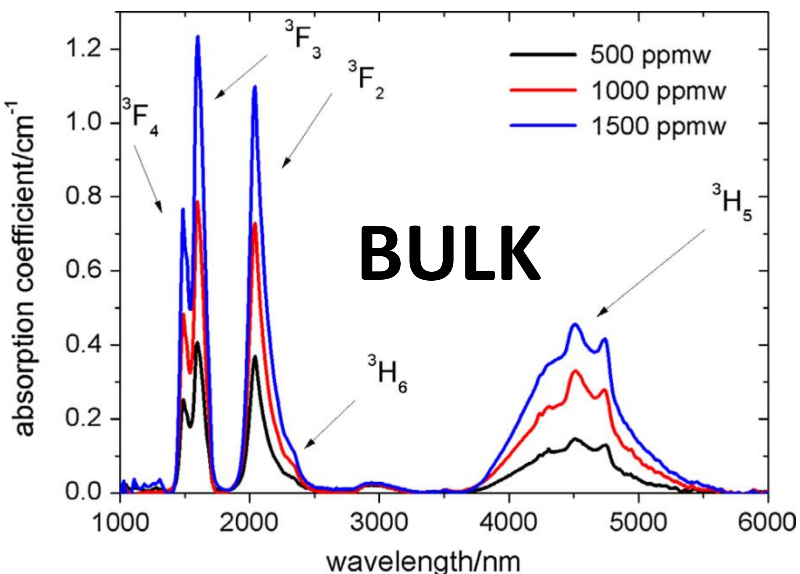
Prudenza	[*J. Non-Cryst. Solids 2009*]
Hu and Sanghera	[*Opt. Lett. 2015*]
Quimby and Shaw	[*IEEE Photon. Lett. 2008*] and
Sujecki *et al.*	[*Opt. Mat. Exp. 2012 etc.*]

Energy-levels Pr^{3+} - selenide







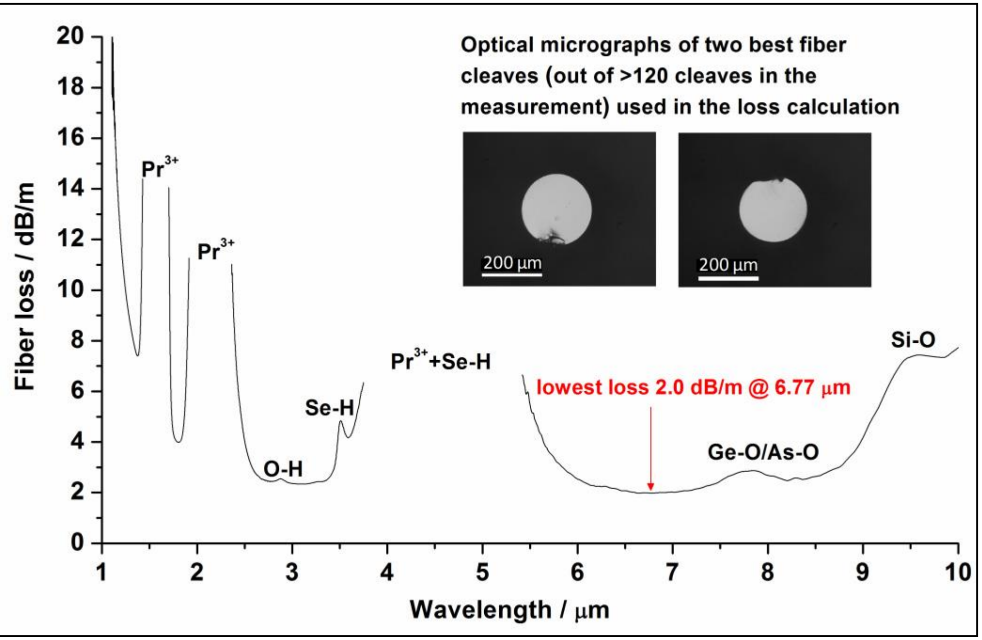


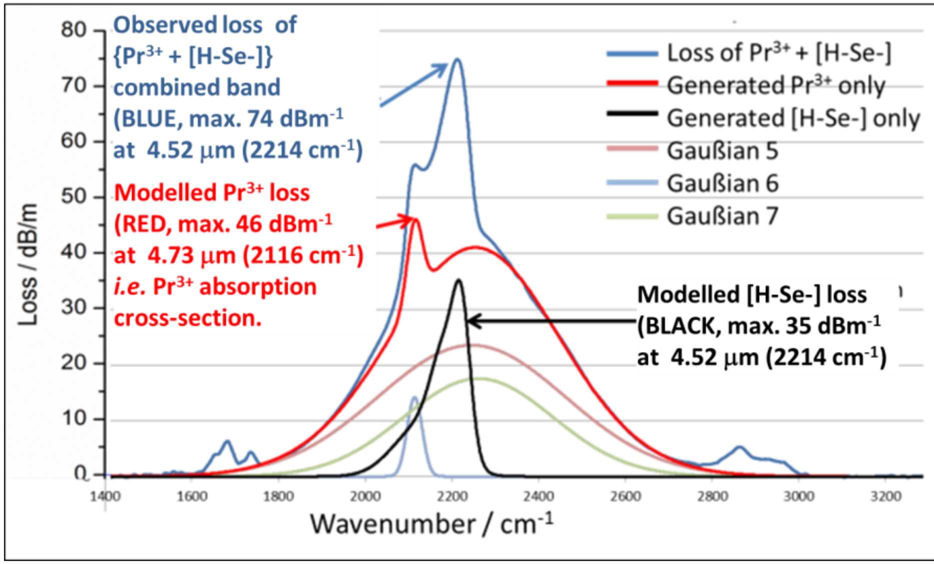
Experimental lifetime (τ_{exp}), calculated radiative lifetimes (τ_{rad}) from the J–O analysis for Pr^{3+}: GeAsGaSe core/GeAsGaSe cladding step-index chalcogenide glass fiber.

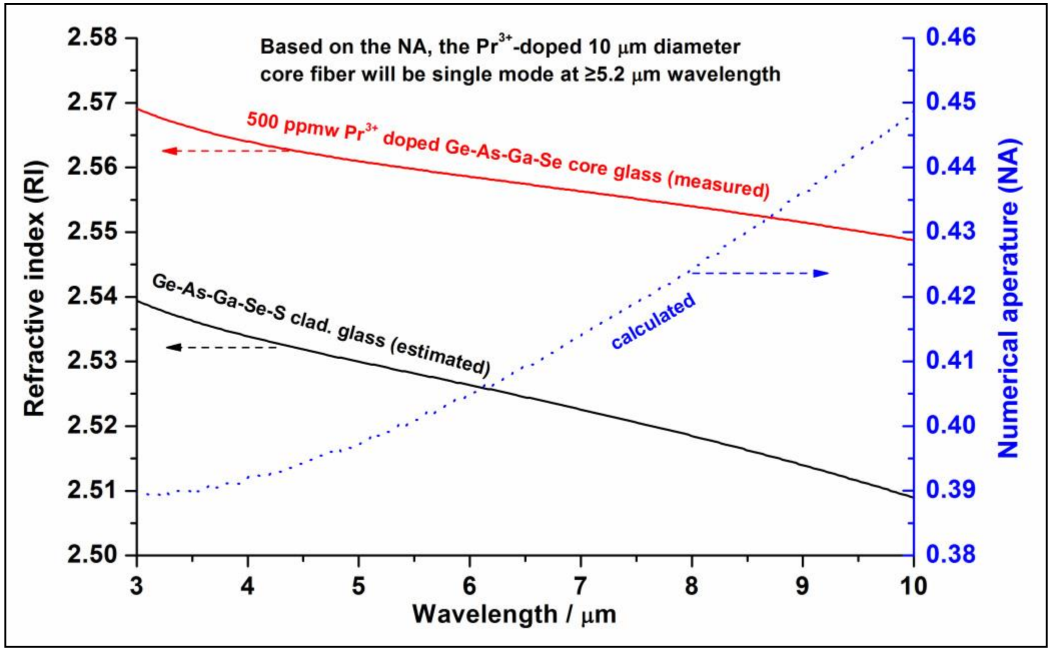
Upper state	τ_{exp} (ms)	τ_{rad} (ms)
($^3F_4$, $^3F_3$)	0.272 ± 0.003	0.23
$^3H_5$	11.5 ± 0.5	10.0

Seddon et al. Opt Exp. 2010
Sojka et al. Opt. Mat. 2014
Sakr et al. Opt. Exp. 2014

Pr^{3+} - selenide fibre



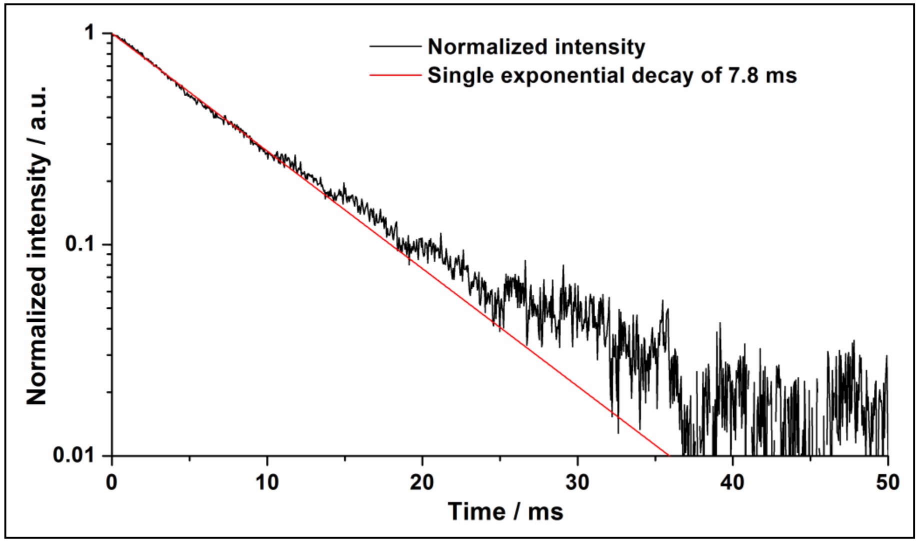


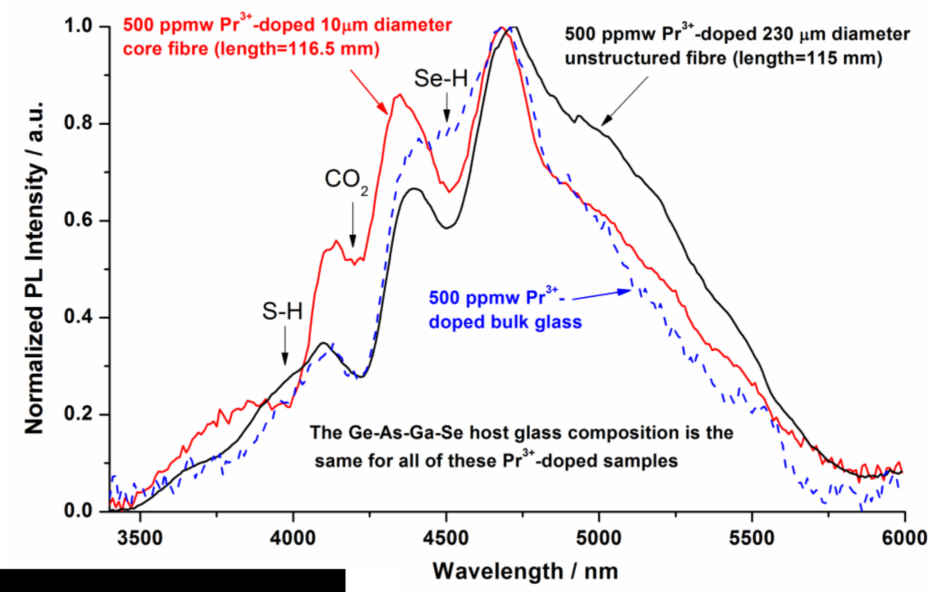


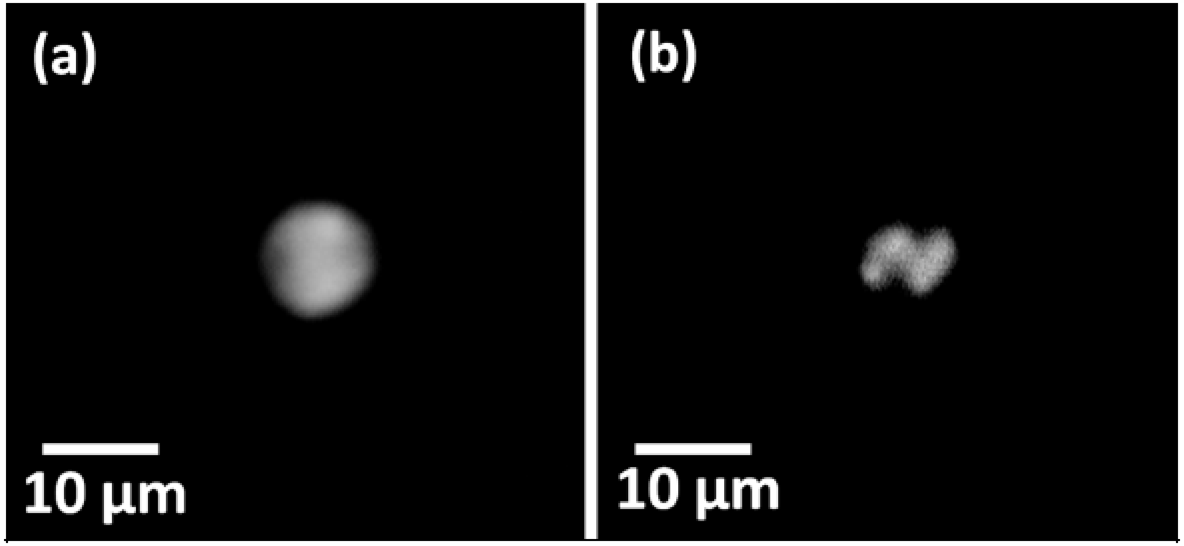
Tang et al. Opt. Mat. Exp. 2015
Seddon et al. IEEE Proc. ICTON 2016

Pr^{3+} - selenide fibre of 10µm core diam.

Pr^{3+} - selenide fibre of 10μm core







Tang et al. Opt. Mat. Exp. 2015

Near-field image of 10 μm core diameter step-index fibre at 1.319 μm wavelength. fibre is multi-moded at this wavelength.

Pr^{3+} - selenide fibre of 10µm core diam.

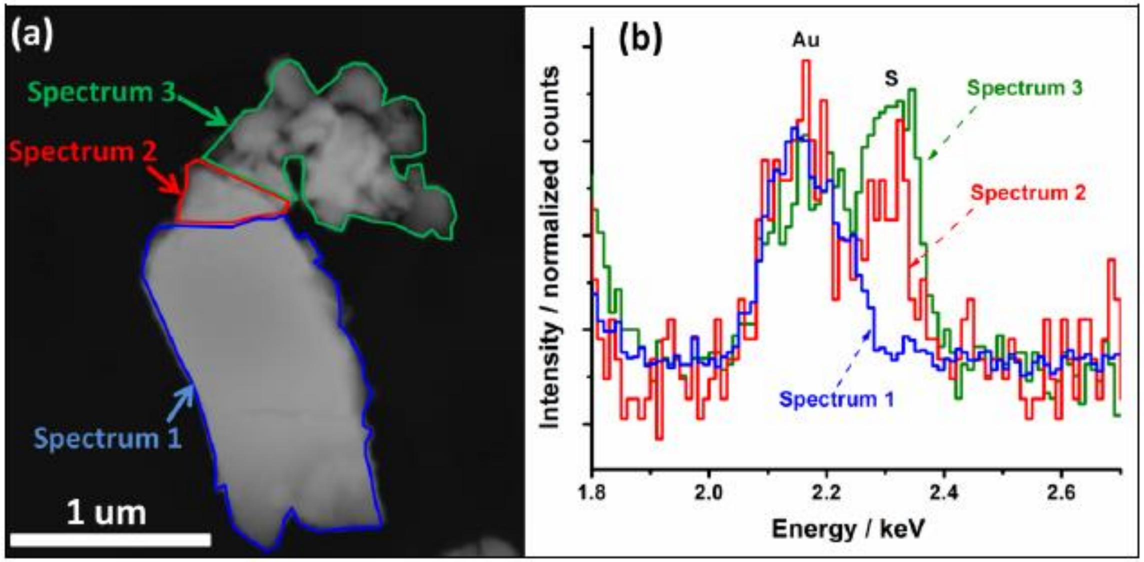


Fig. 7. (a) Scanning Transmission Electron Microscopy (STEM) image of core region (spectrum 1), core/clad. interfacial region (spectrum 2) and clad. region (spectrum 3) of the 500 ppmw Pr^{3+}-doped Ge-As-Ga-Se, step-index, 10 µm diameter core fiber. (b) TEM-EDX spectra of the three regions arrowed in Fig. 7(a).

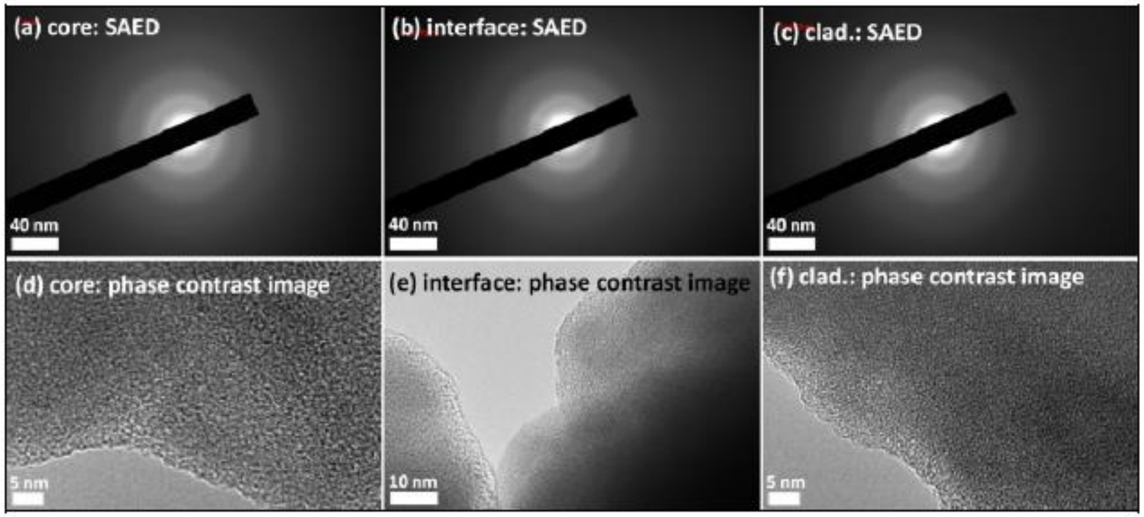
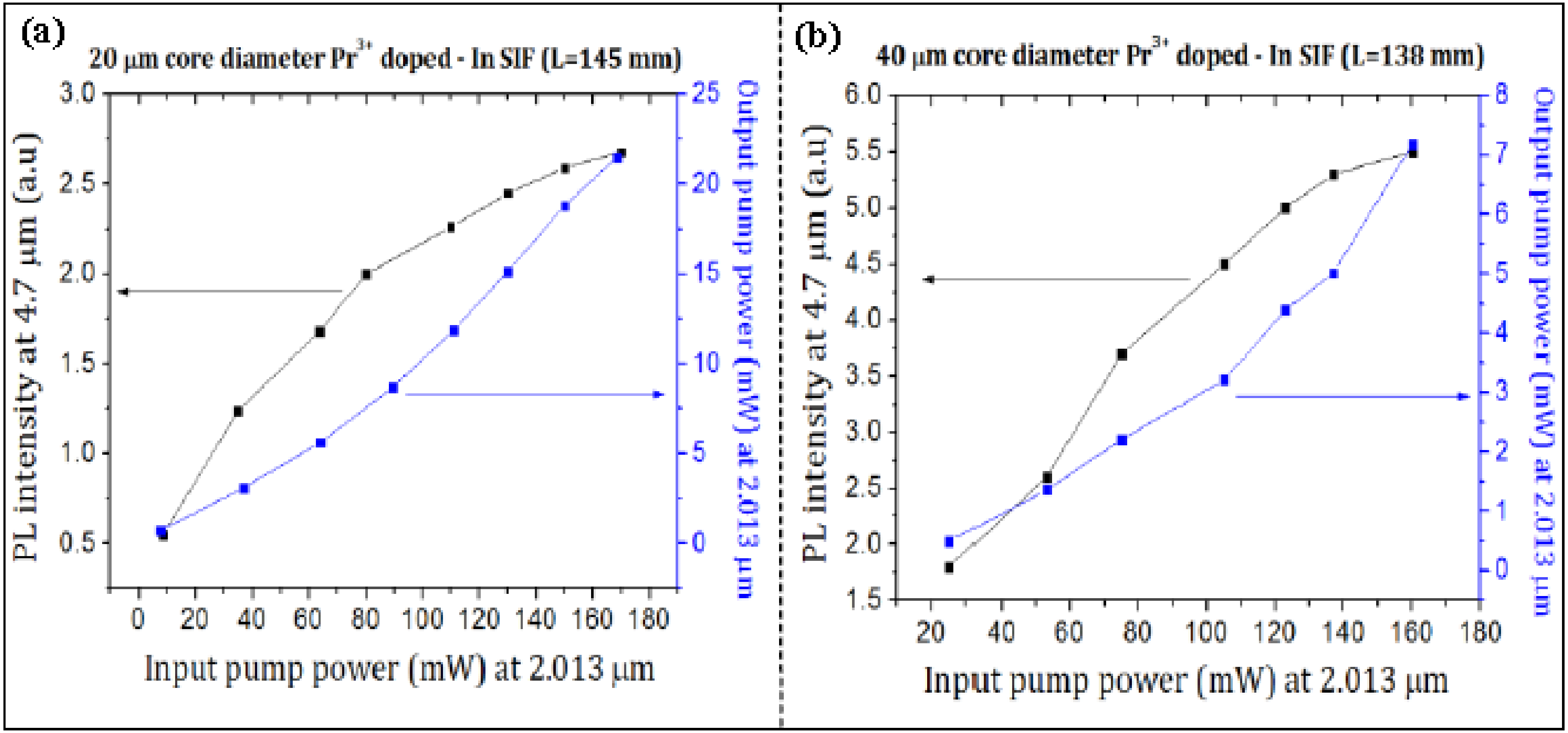


Fig. 8. HRTEM-SAED patterns and HRTEM phase contrast images of the core material region (spectrum 1 of Fig. 7(a)), the core/clad. interfacial region (spectrum 2 of Fig. 7(a)) and the clad. material region (spectrum 3 of Fig. 7(c)) indicating all fiber regions were amorphous.

HR (High Resolution) **TEM** (transmission electron microscopy) **SAED** (selected area electron diffraction) showing no devitrification of core.

Tang et al. Opt. Mat. Exp. 2015

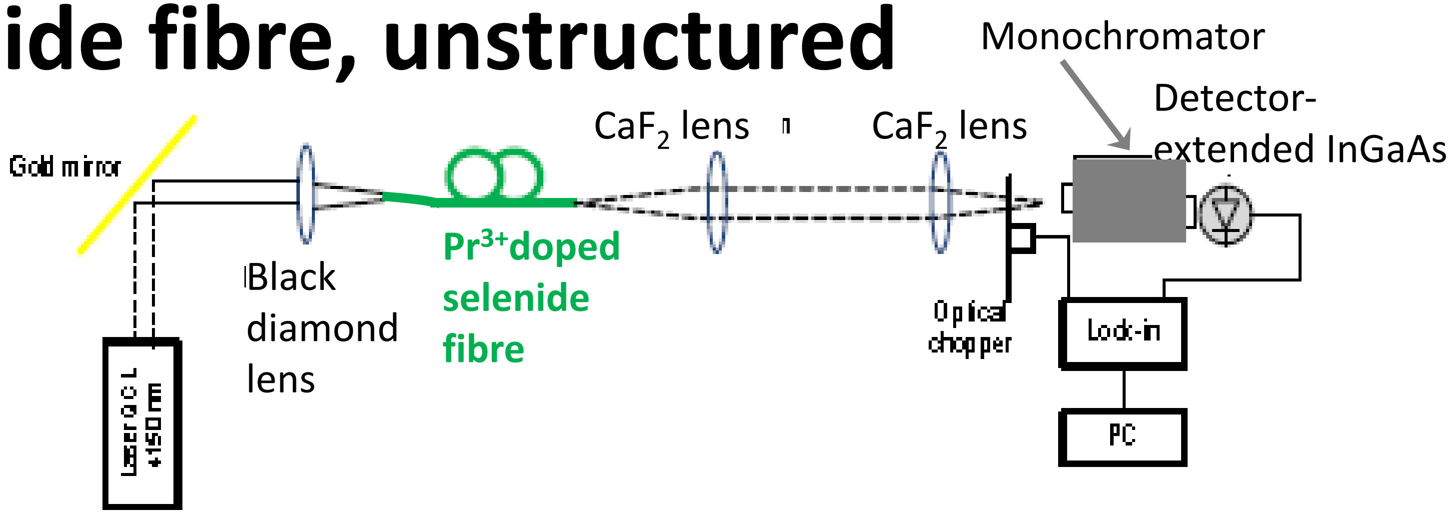
Pr^{3+} - selenide fibre of 20 μm and 40 μm core diameters:



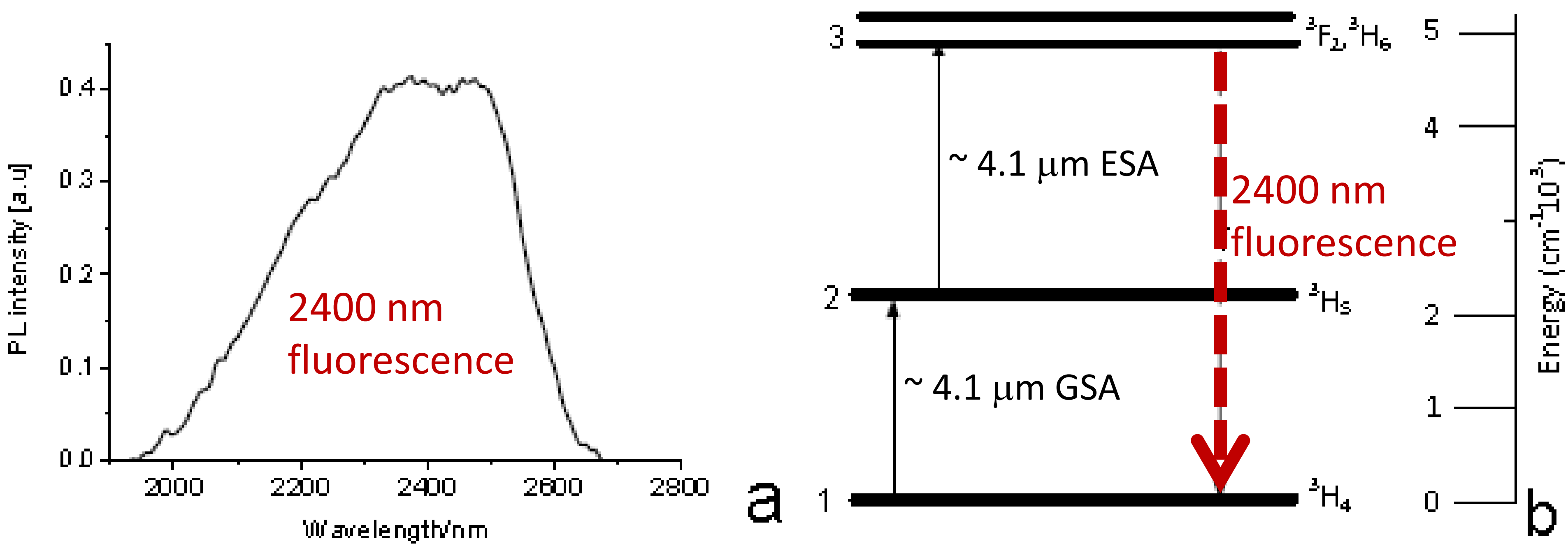
Evidence of upper-level saturation from sub-linear PL intensity out (black) with increasing pump power (blue).

Paper in preparation 2016

Pr^{3+} - selenide fibre, unstructured

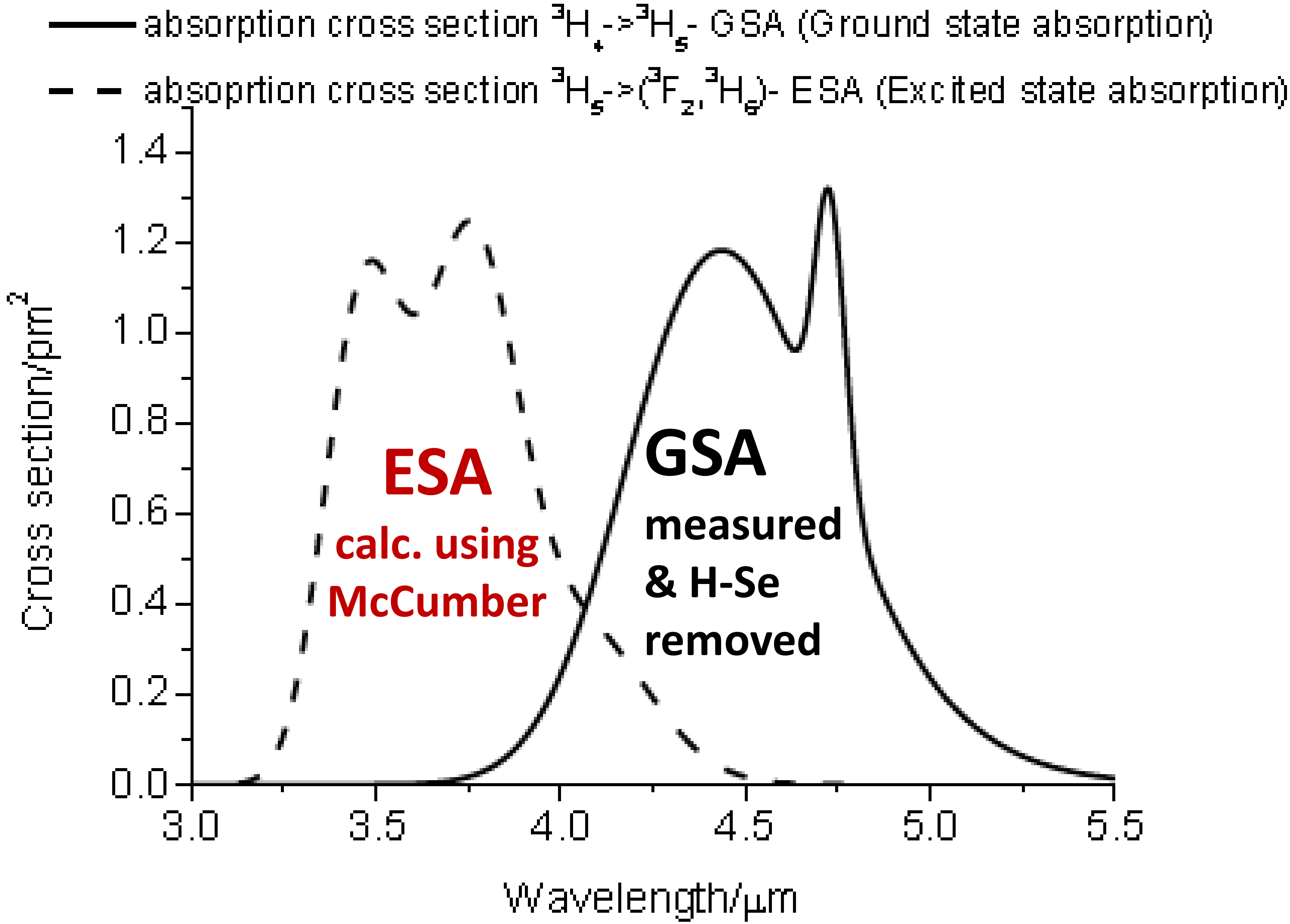


Experimental set-up for Excited State Absorption (ESA) measurement: **pump ~ 4.1 µm wavelength.**



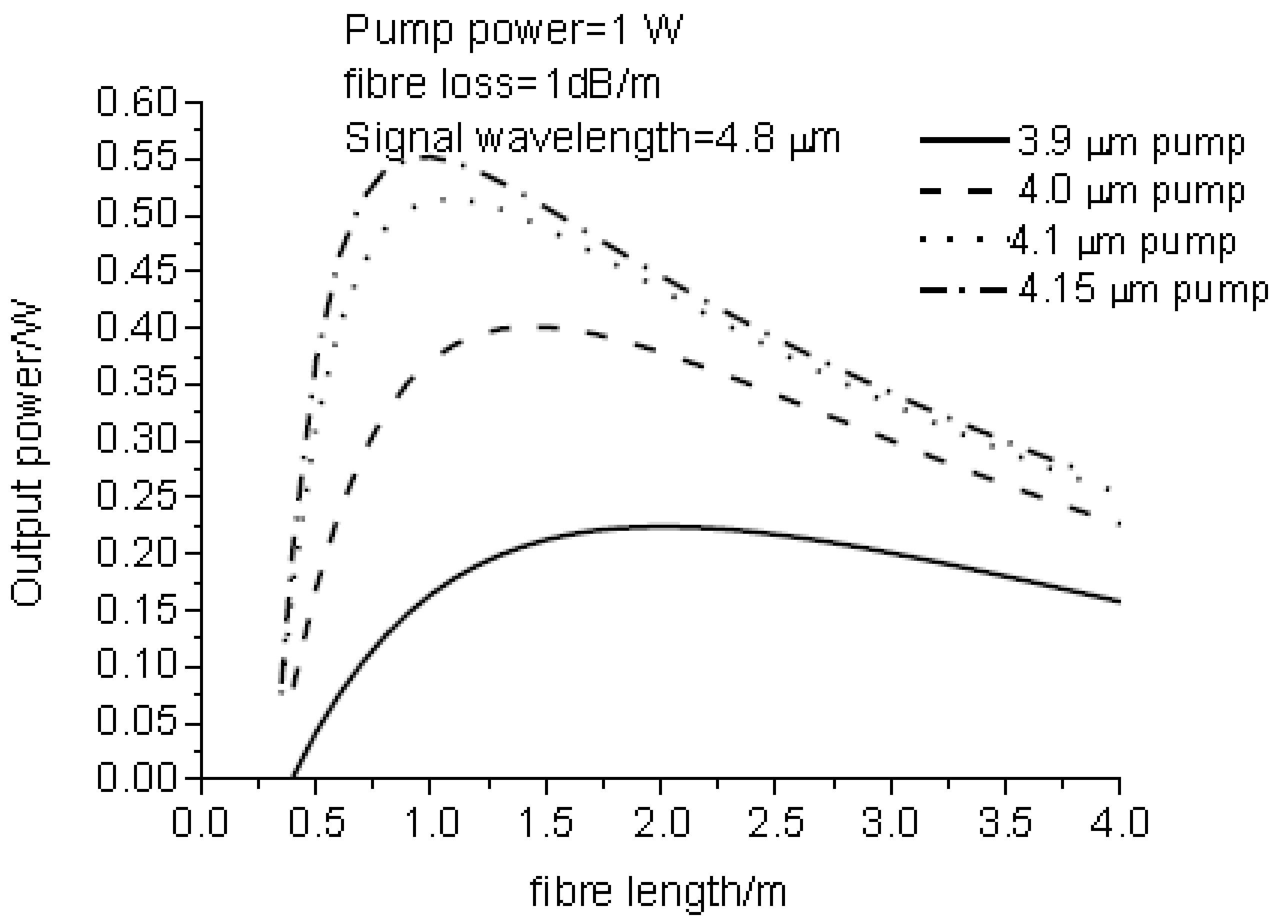
Sojka, Sujecki et al. Opt. Quant. Electron. 2016 Special Issue, submitted.

Pr^{3+} - selenide fibre, unstructured



Sojka, Sujecki et al. Opt. Quant. Electron. 2016 Special Issue, submitted.

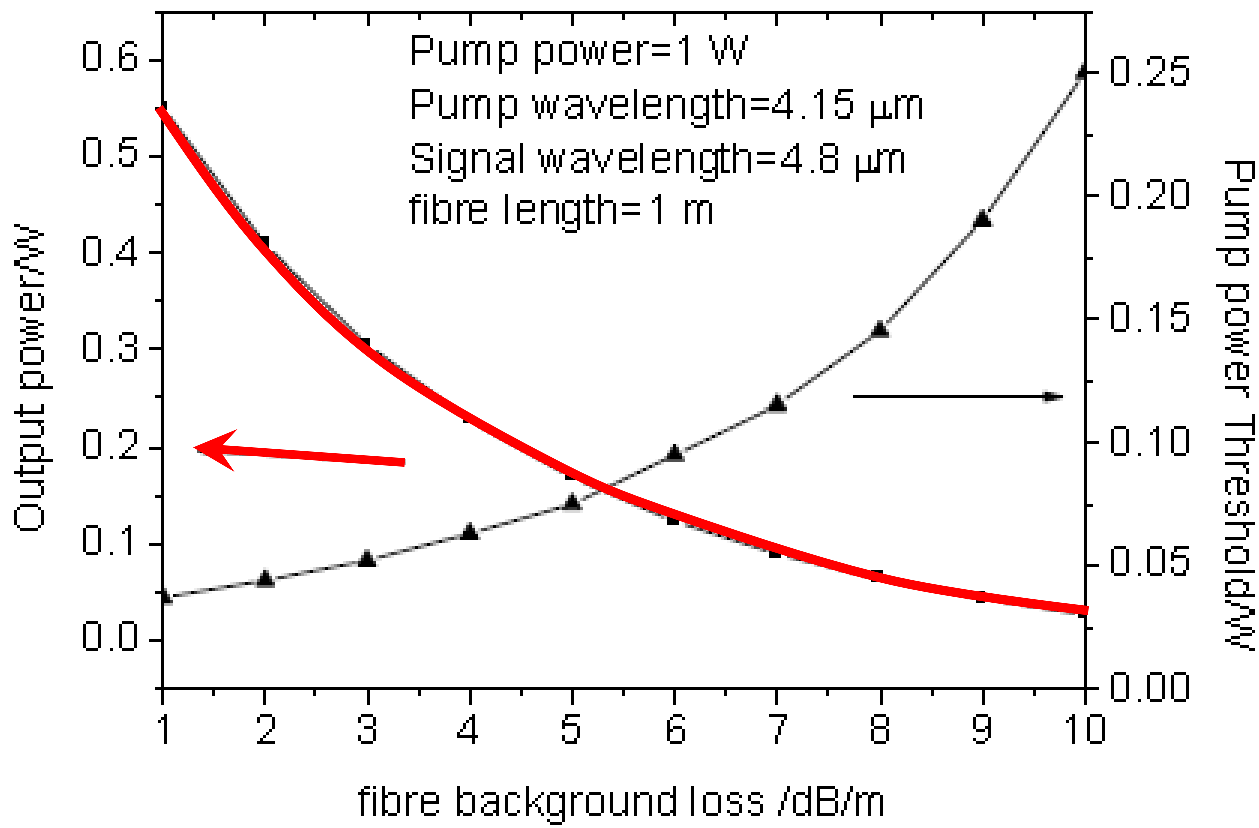
Pr^{3+} - selenide fibre, 30 μm core diam., modelling



Calculated signal power at 4.8 μm as a function of fibre length for different pump wavelengths around 4.0 μm. (*Results were obtained with an input power of 1 W, background loss assumed 1 dB/m*.)

Sojka, Sujecki et al. Opt. Quant. Electron. 2016 Special Issue, submitted.

Pr^{3+} - selenide fibre, 30 μm core diam., modelling



Calculated output power and threshold pump power as a function of fibre background loss.

Sojka, Sujecki et al. Opt. Quant. Electron. 2016 Special Issue, submitted.

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EAGLES

International Conference on Rare-Earth Doped Glass Materials and Fibre Lasers

MPNS COST Action MP1401

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COST is supported by the EU Framework Programme Horizon 2020

October 18th – 19th, 2016 | Trento, Italy

Rare earth narrow-line MIR fibre lasers

- progress and challenges

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Sunlight
Mid-infrared

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International Conference on
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MPNS COST Action MP1401

cost
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IFN

Rare earth narrow-line MIR fibre lasers

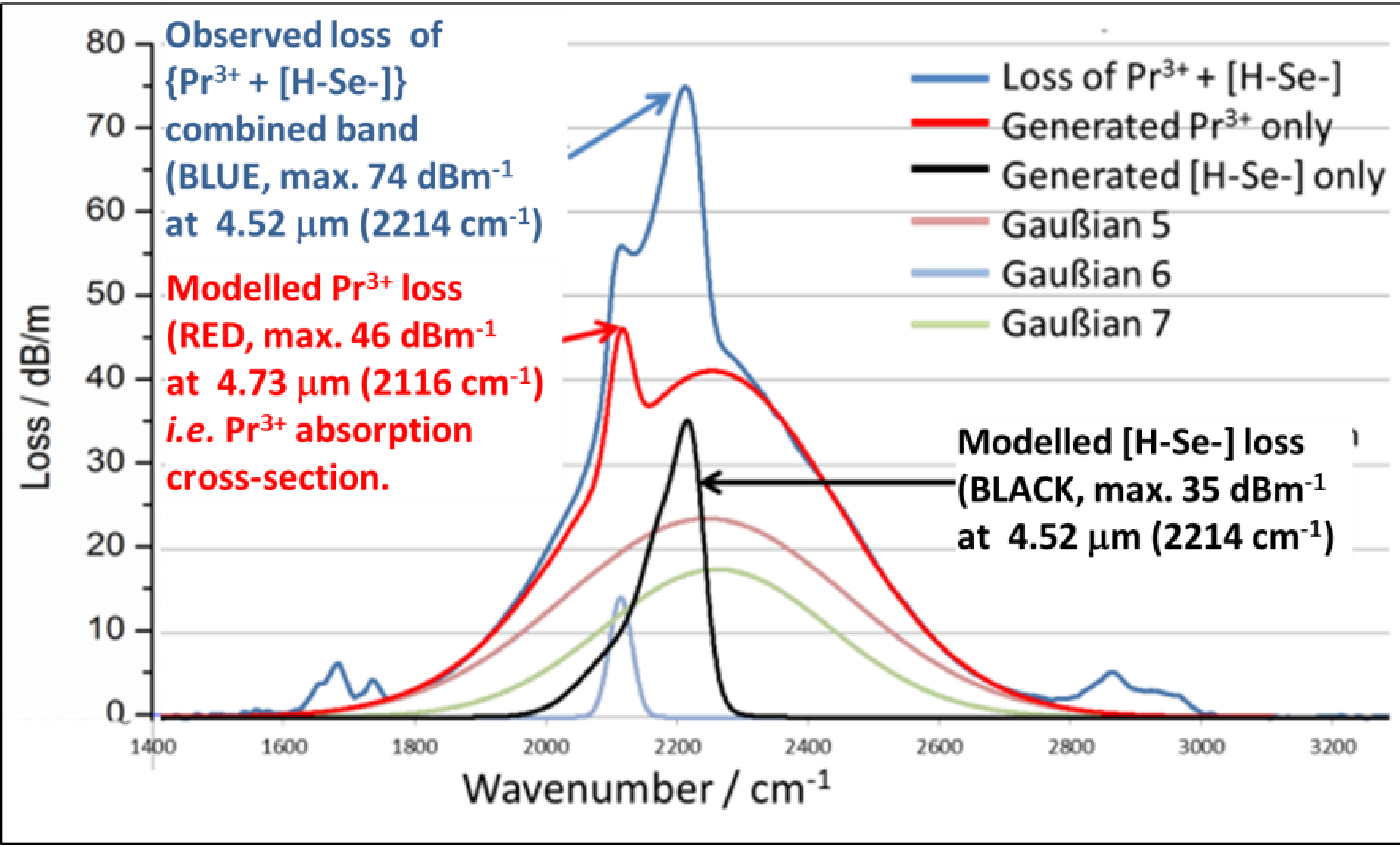
- progress and challenges

Challenges (I) + (II)

- **(I)Resonant absorption and**

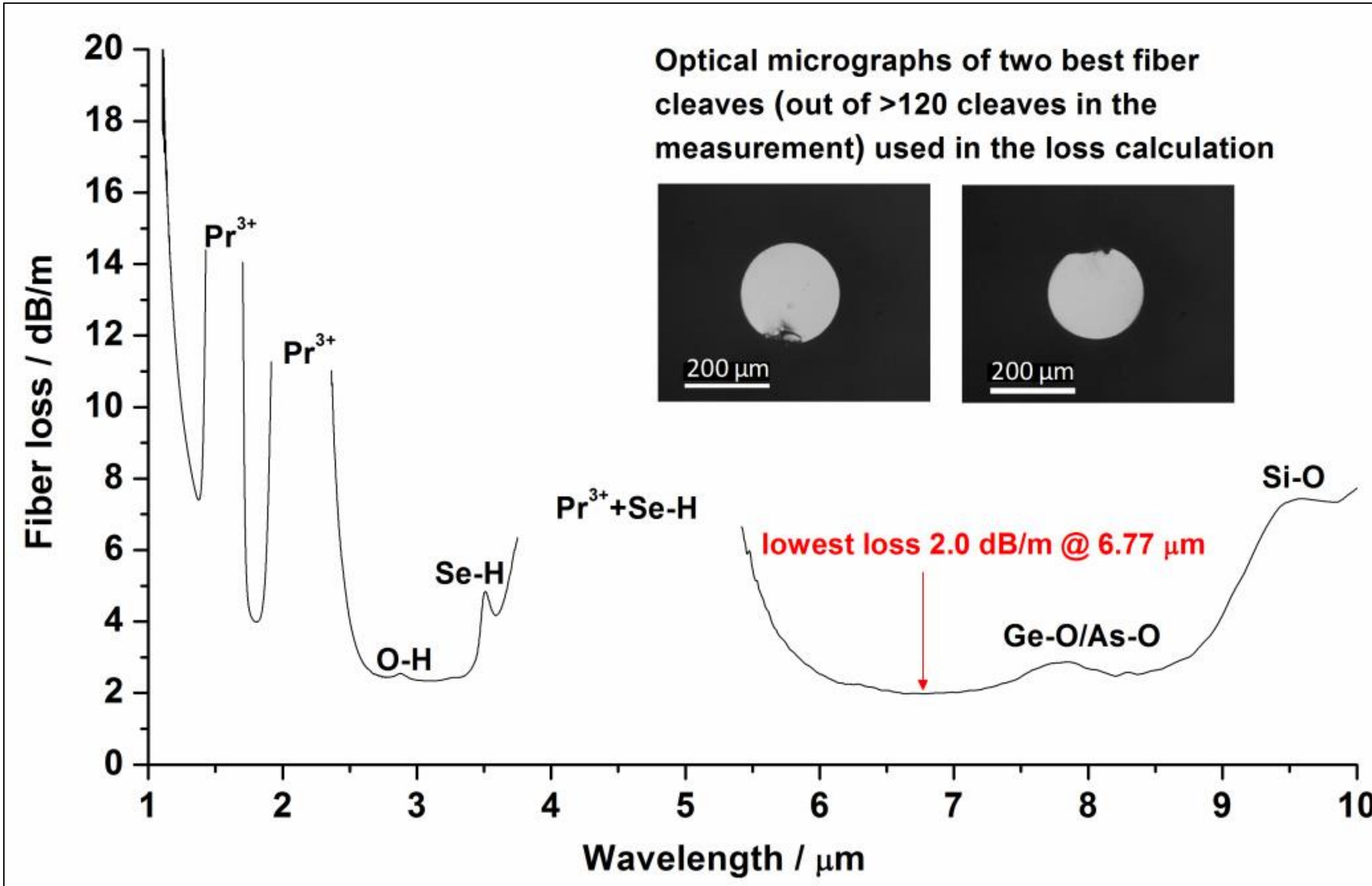
  (II)*Resonant extrinsic non-radiative-decay of the excited state.*

Pr^{3+} - selenide fibre :



Seddon et al. IEEE Proc. ICTON 2016

Pr^{3+} - selenide fibre :



Challenge (III)

- **Achieve gain and lasing in narrow-line, rare earth ion doped MIR fibre.**

Mid-infrared (MIR) photonics:

1. Introduction
   - *I. Definitions & introduction*
   - *II. Portable, real-time MIR sensing*
2. **Wideband MIR fibre** supercontinuum **lasers** – progress and challenges
3. **Narrow-line MIR** rare earth **fibre lasers** – progress and challenges
4. Summary and future prospects

Summary and future prospects

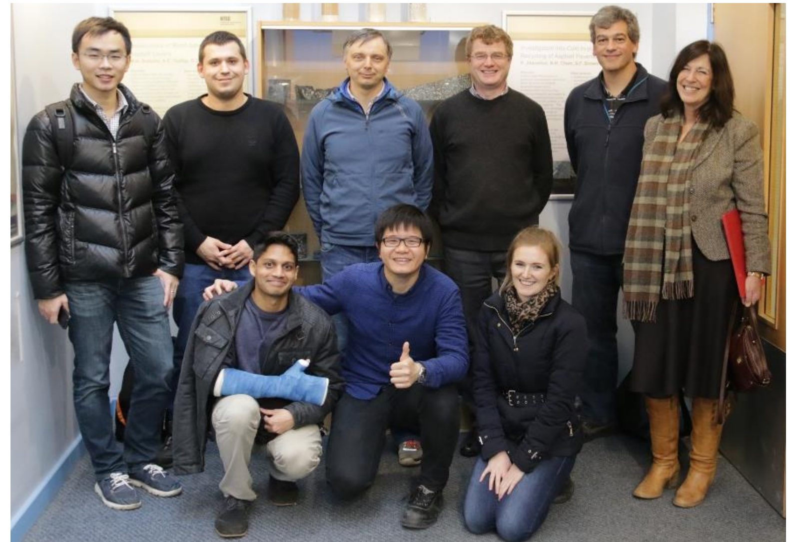
1. Wideband MIR fibre supercontinuum lasers – progress and challenges

2. Narrow-line MIR rare earth fibre lasers – progress and challenges

world-changing research
from The University of Nottingham

Yuanrong Fang, Lukasz Sojka, Slawek Sujecki

Dinuka Jayasuriya Harriet Parnell.



Vladimir Shiryaev, --- Anna Loth, Jess Butterworth, **Trevor Benson**, Emma Barney, David Furniss
Hesham Sakr & Zhuoqi Tang Najla Najeeb

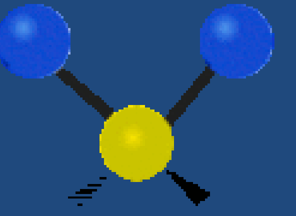
I sincerely thank my Colleagues at the University of Nottingham, UK, for very hard work in the lab. and wonderful discussions.

Table 3. Pr^{3+} doped chalcogenide glass fibre laser modelling parameters.

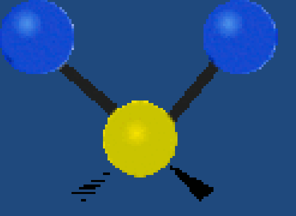
Quantity	**Value**	**Unit**
Ion concentration:	9.46×10^{24}	$ions/m^3$
Fibre length:	1	m
Fibre core diameter:	30	μm
Fibre clad diameter:	200	μm
Fibre numerical aperture:	0.4	-
Confinement factor for pump wavelength:	0.9	-
Confinement factor for signal wavelength:	0.9	-
Signal emission cross-section at 4.8 μm:	1.14×10^{-24}	m^2

The three fundamental vibrations of the water molecule

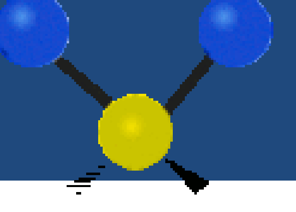
v_1,O-H symmetric stretching
3657 cm^{-1} (2.734 μm)



v_2, H-O-H bending
1595 cm^{-1} (6.269 μm)



v_3, O-H asymmetric stretching
3756 cm^{-1} (2.662 μm)



The three fundamental vibrations of the water molecule

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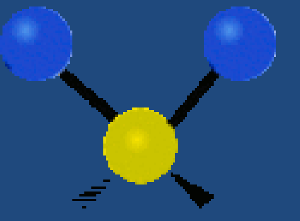

v_2, H-O-H bending
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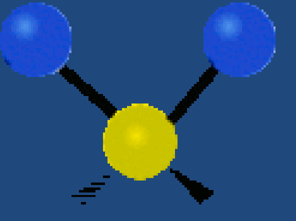

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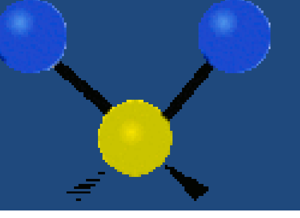
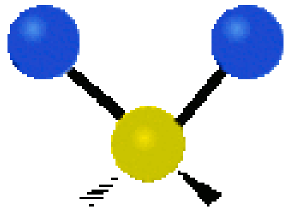
3756 cm^{-1} (2.662 μm)



Szigeti:

$$\nu \propto (f/m)^{1/2}$$



ν = frequency of simple oscillator

$m = (m_1 m_2/(m_1+m_2))$

f is (chemical) bond force constant.

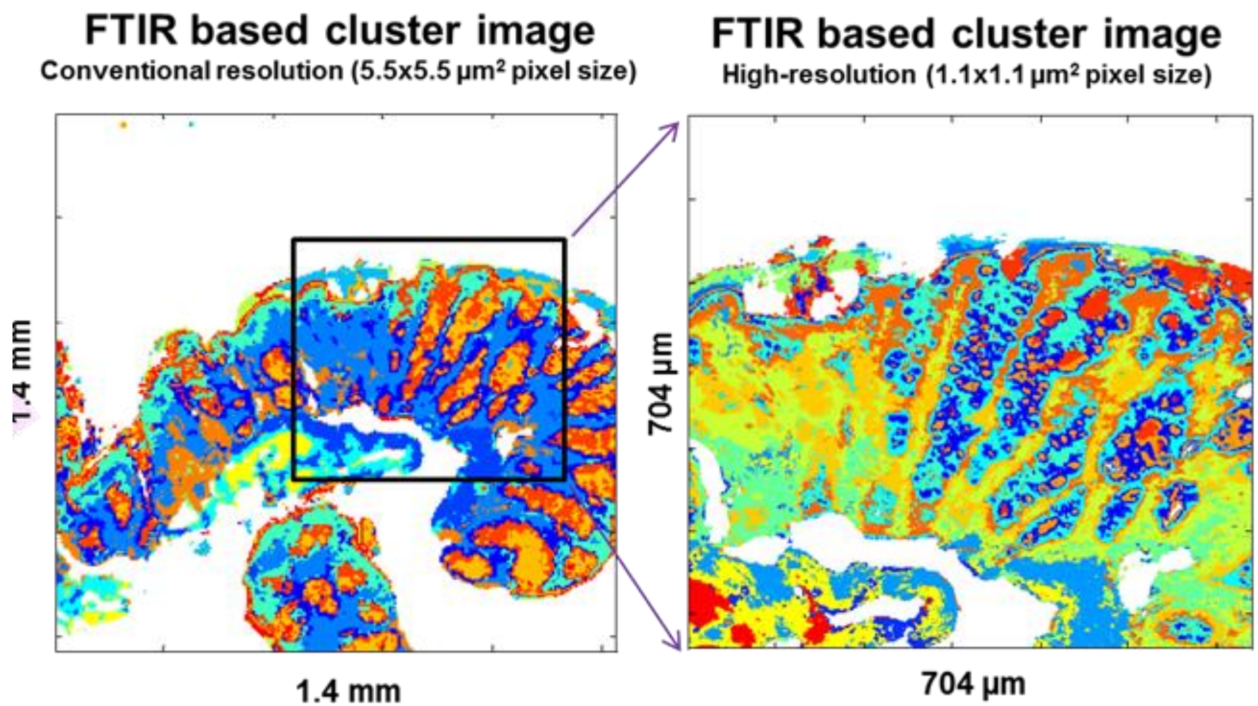
Planck:

$$E = h\nu$$

E = photon energy

h = Planck's constant

How was this MIR imaging of tissue captured?



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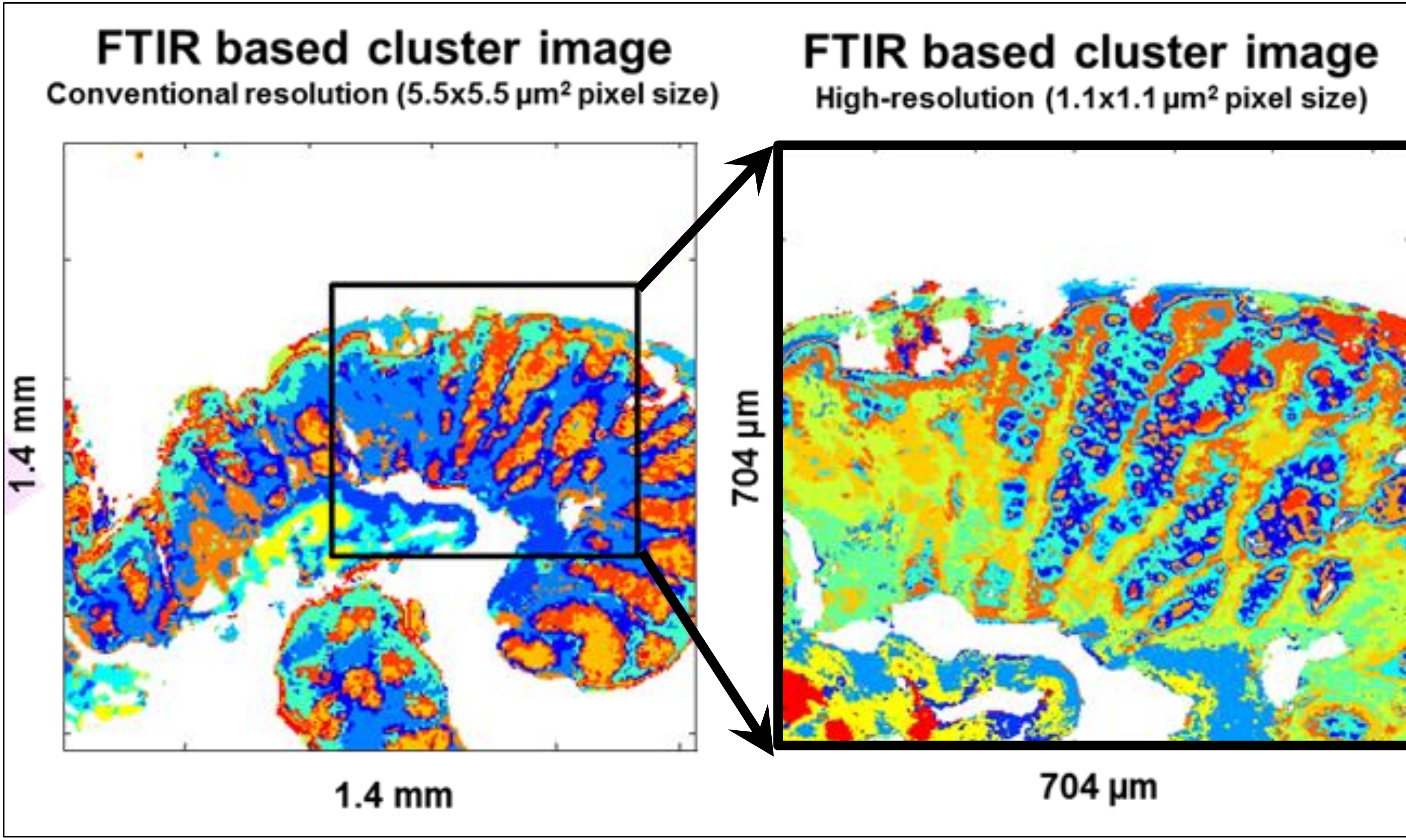
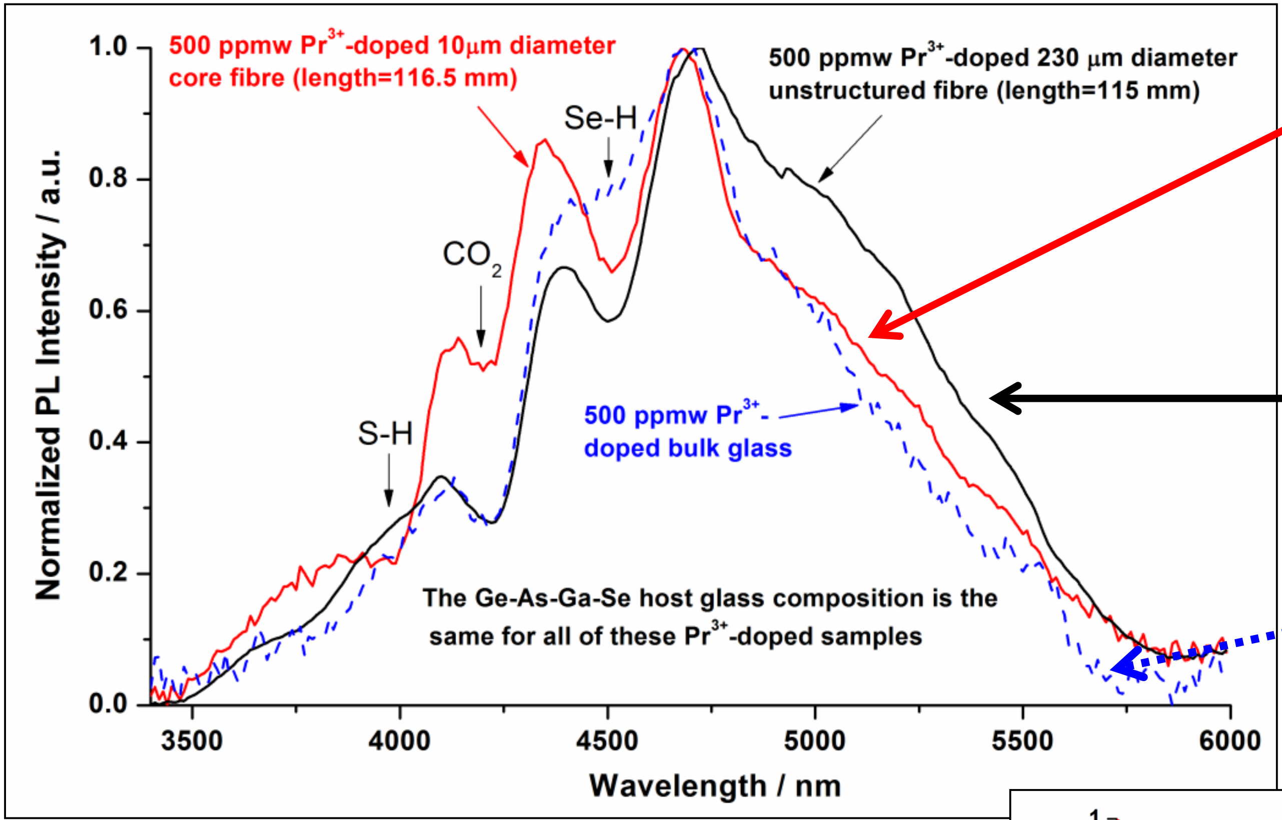


*Nallala, Stone et al. Analyst (**2016**) .*

(MIR is mid-infrared)

Rare earth ion doped mid-infrared small-core fibre



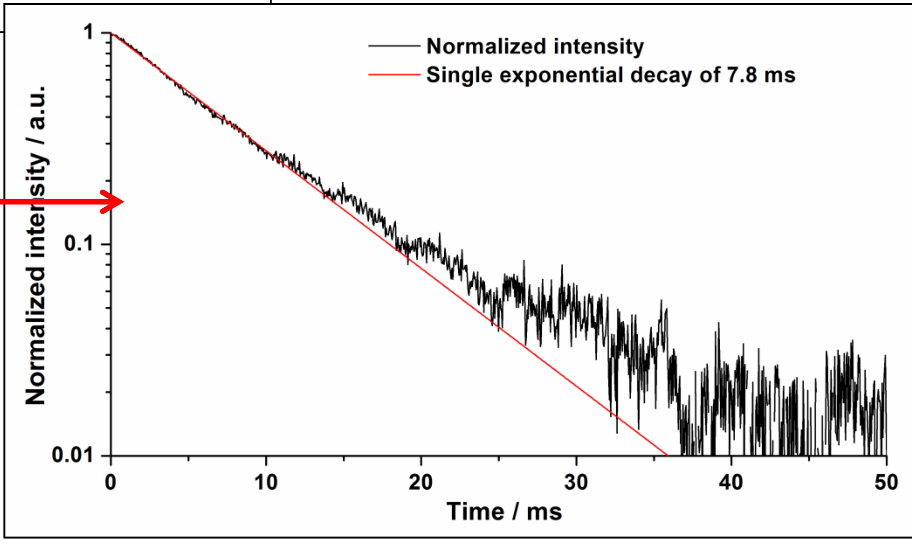
SMALL-CORE fibre.
PL spectrum of 500 ppmw Pr^{3+}-doped, 10 μm diameter core fibre (continuous solid curve).

LARGE-CORE fibre.
PL spectrum of 500 ppmw Pr^{3+}-doped 230 μm diameter unclad./intermediate fibre (continuous solid curve).

BULK GLASS
PL spectrum of 500 ppmw Pr^{3+}-doped bulk glass (dashed curve).

Pumped at 1550 nm

SMALL-CORE fibre: PL lifetime = 7.8 ms for 500 ppmw Pr^{3+} doped Ge-As-Ga-Se, step-index, 10 μm diameter core fibre, at wavelength of 4700 nm. Nominally, 64.8 mW pump power at 1550 nm wavelength was used.
SAME LIFETIME OBSERVED AS FOR BULK GLASS.



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Tang et al. Opt Mat Exp (**2015**).