



Workshop
Friday 30 June 2017
Räter Park Hotel, München, Germany

Breakthroughs in MIR fibre technology.
AB Seddon.
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The University of
Nottingham

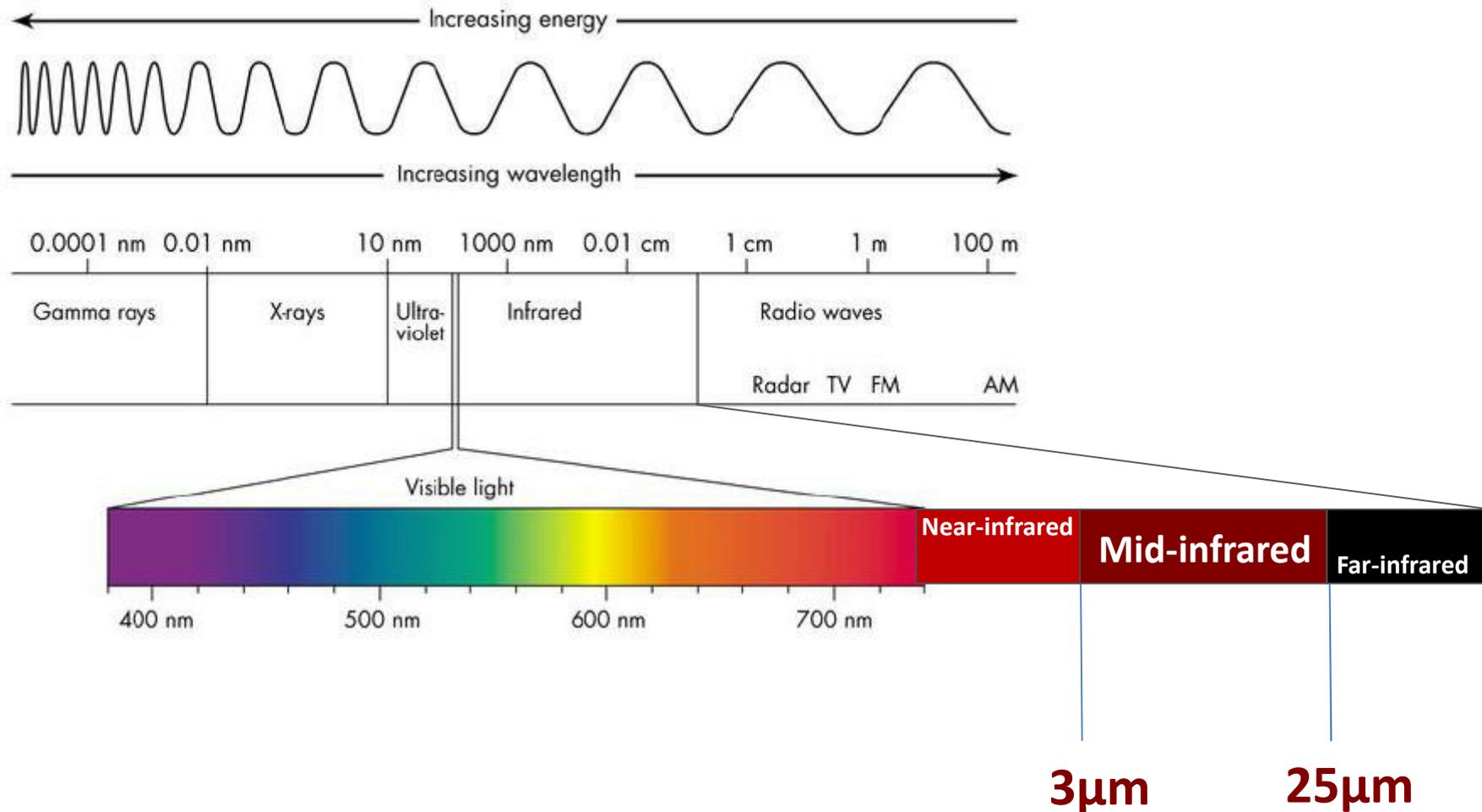
UNITED KINGDOM - CHINA - MALAYSIA

**Mid-Infrared Photonics
Group**

George Green Institute for
Electromagnetics Research
Faculty of Engineering

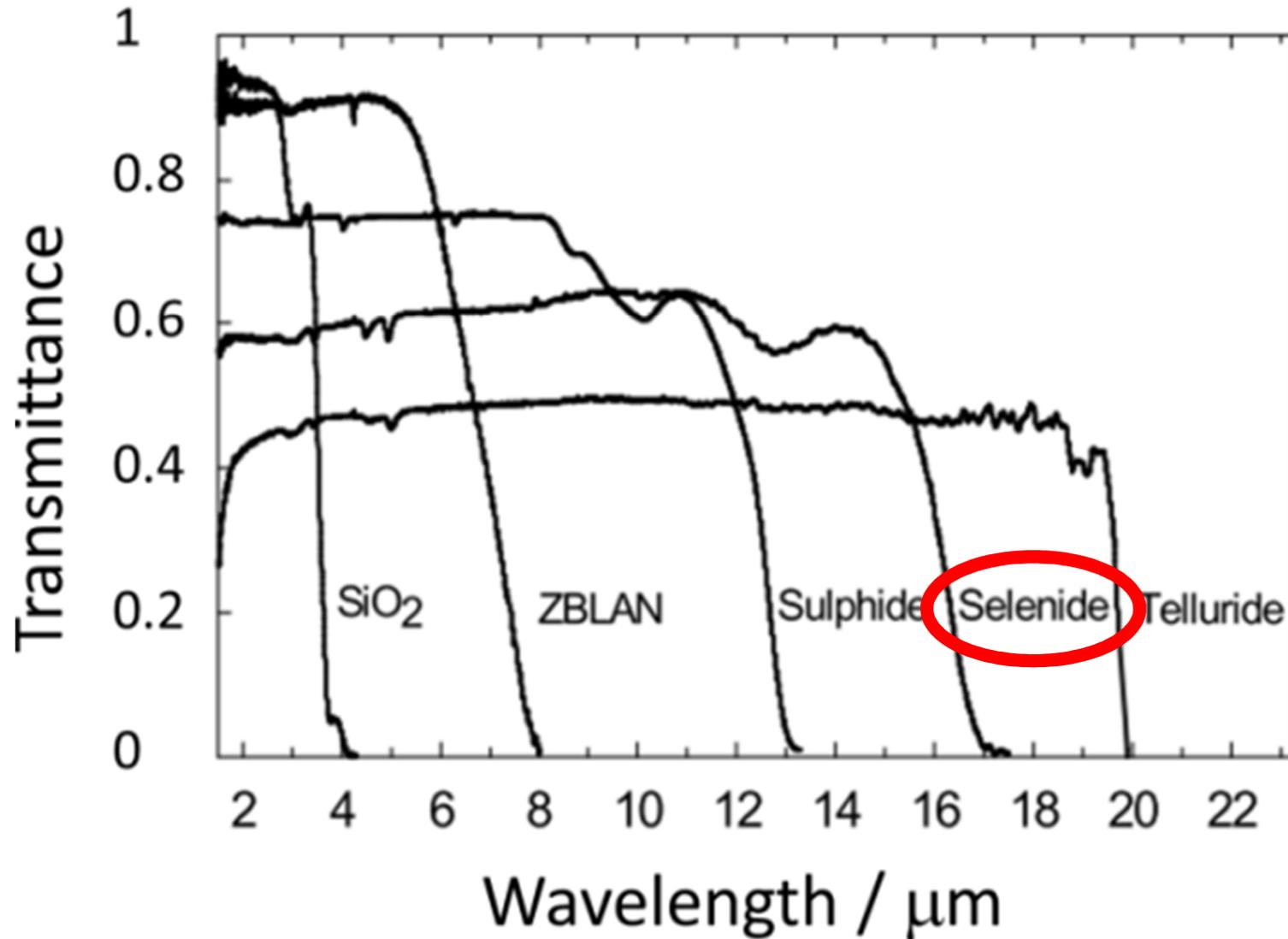


Definition of mid-infrared.

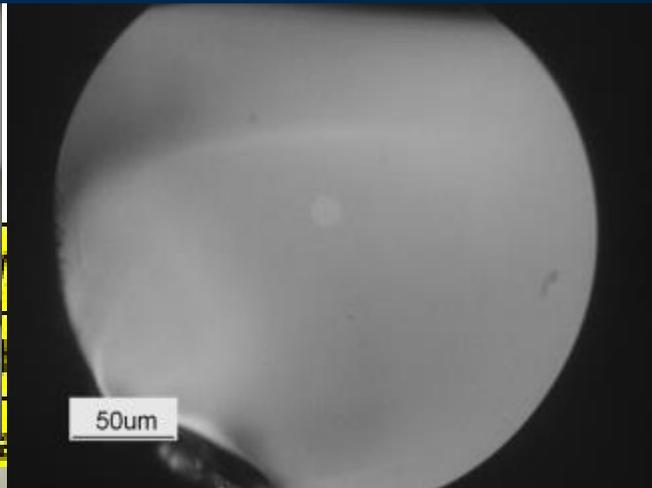


ELECTROMAGNETIC SPECTRUM

Mid-infrared (MIR) transmitting glasses.



Selenide fibres.

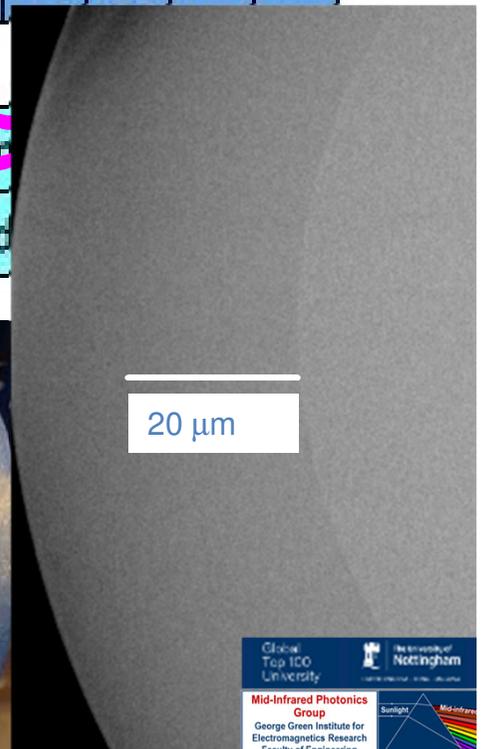


p-Block

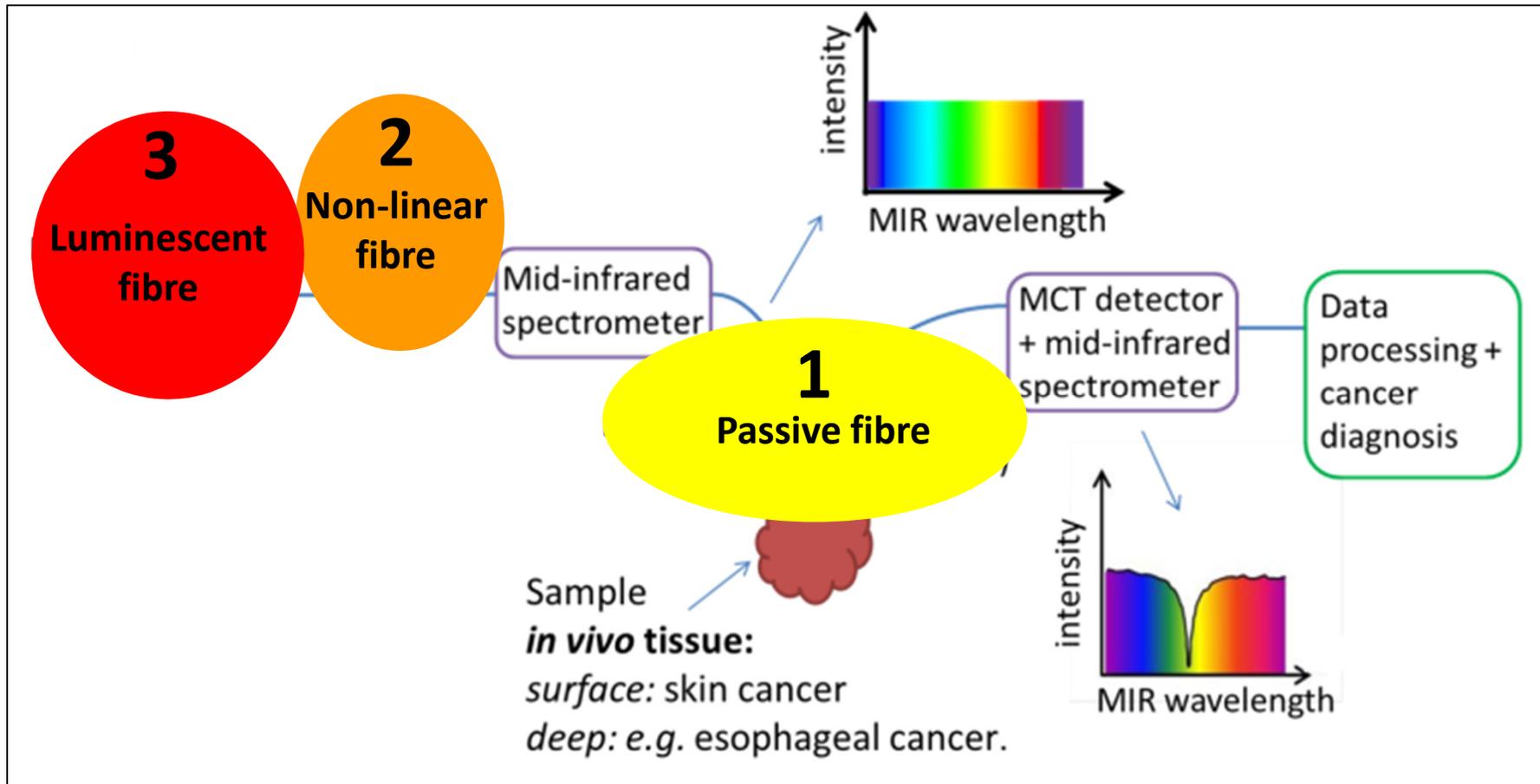
B	C	N	O	F	Ne
Al	Si	P	S	Cl	Ar
Ga	Ge	As	Se	Br	Kr
In	Sn	Sb	Te	I	Xe
Tl	Pb	Bi	Po	At	Rn
Uut	Fl	Uup	Lv	Uus	Uuo



g	Cn			
Dy	Ho	Er	Tm	
k	Cf	Es	Fm	Md



Motivation: *in vivo* cancer detection.

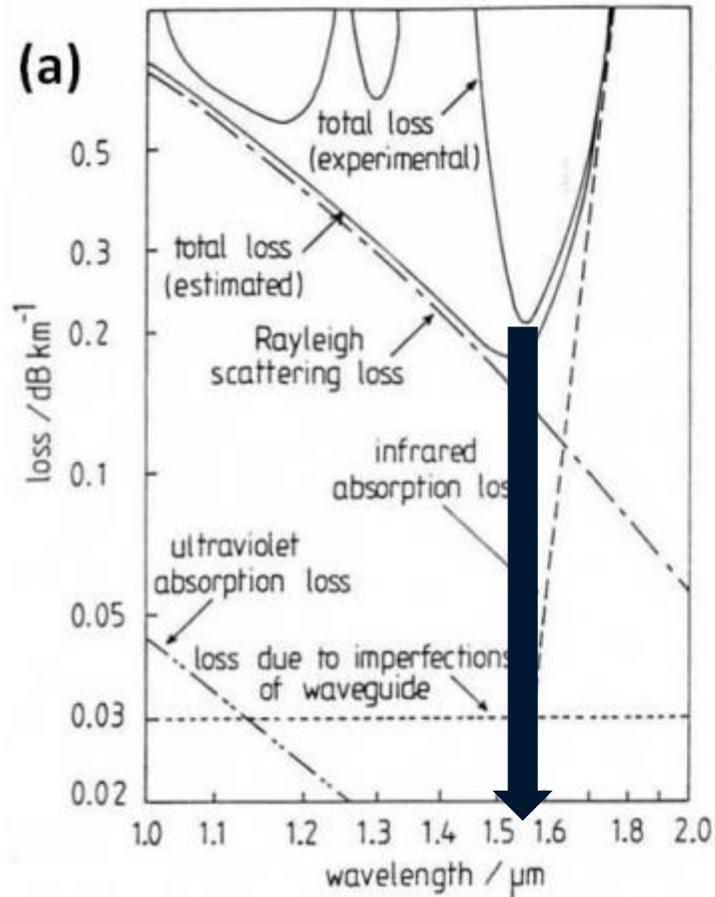


Seddon *et al.* *BioOptics World 2016.*

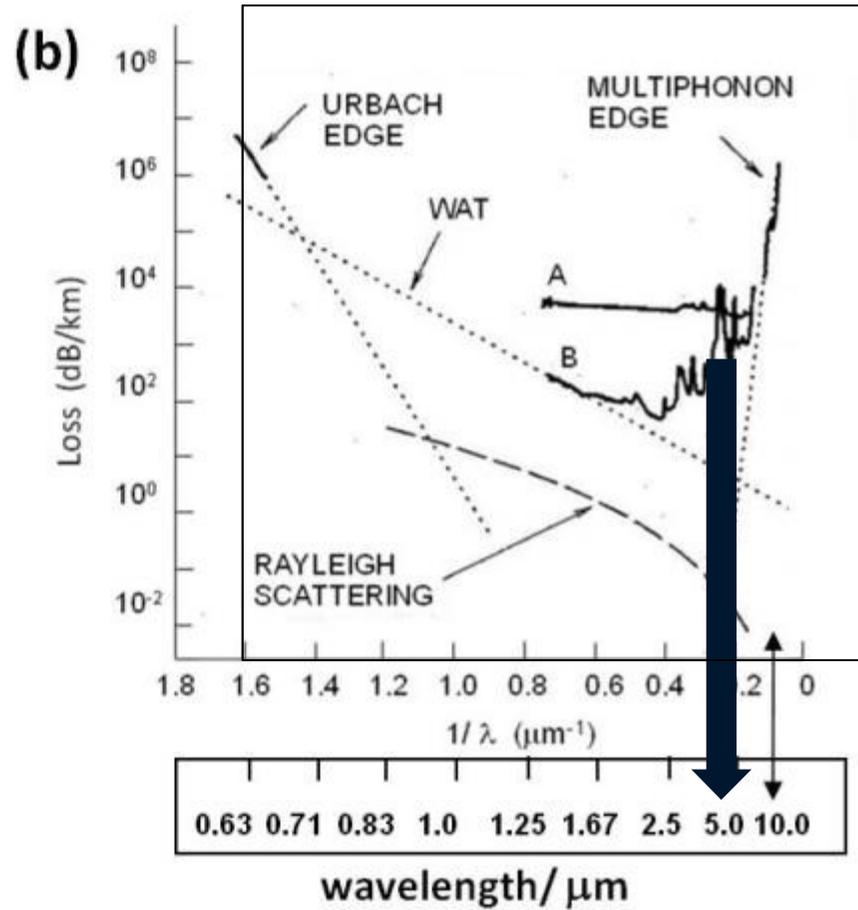
Passive fibre.

Silica fibre:

Chalcogenide fibre:

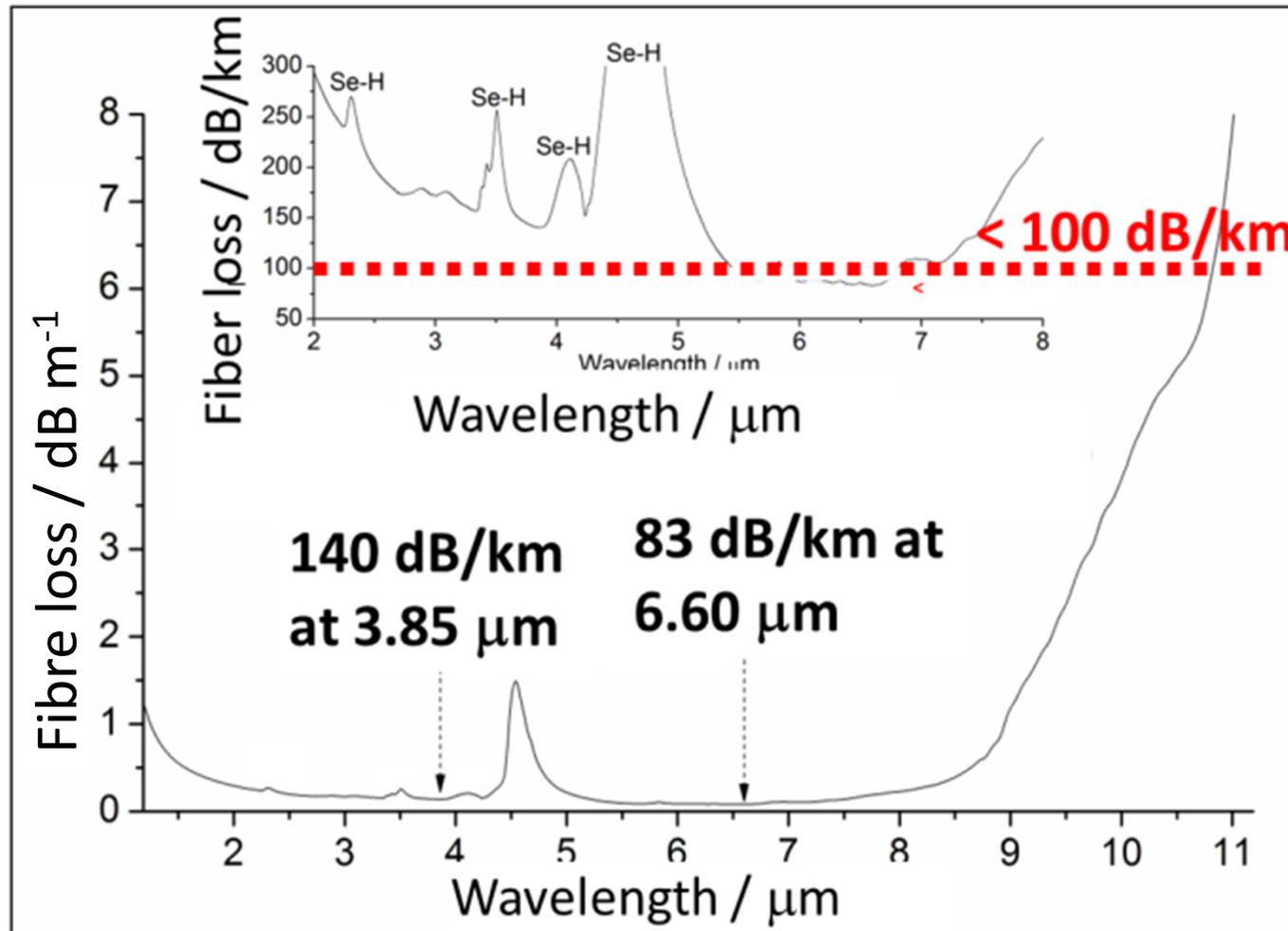


Miya et al., *Electron. Lett* 1979.



Sanghera et al. *J. Lightwave. Technol.*, 1996.

Record low-loss in Ge-As-Se fibre 83 dB / km.

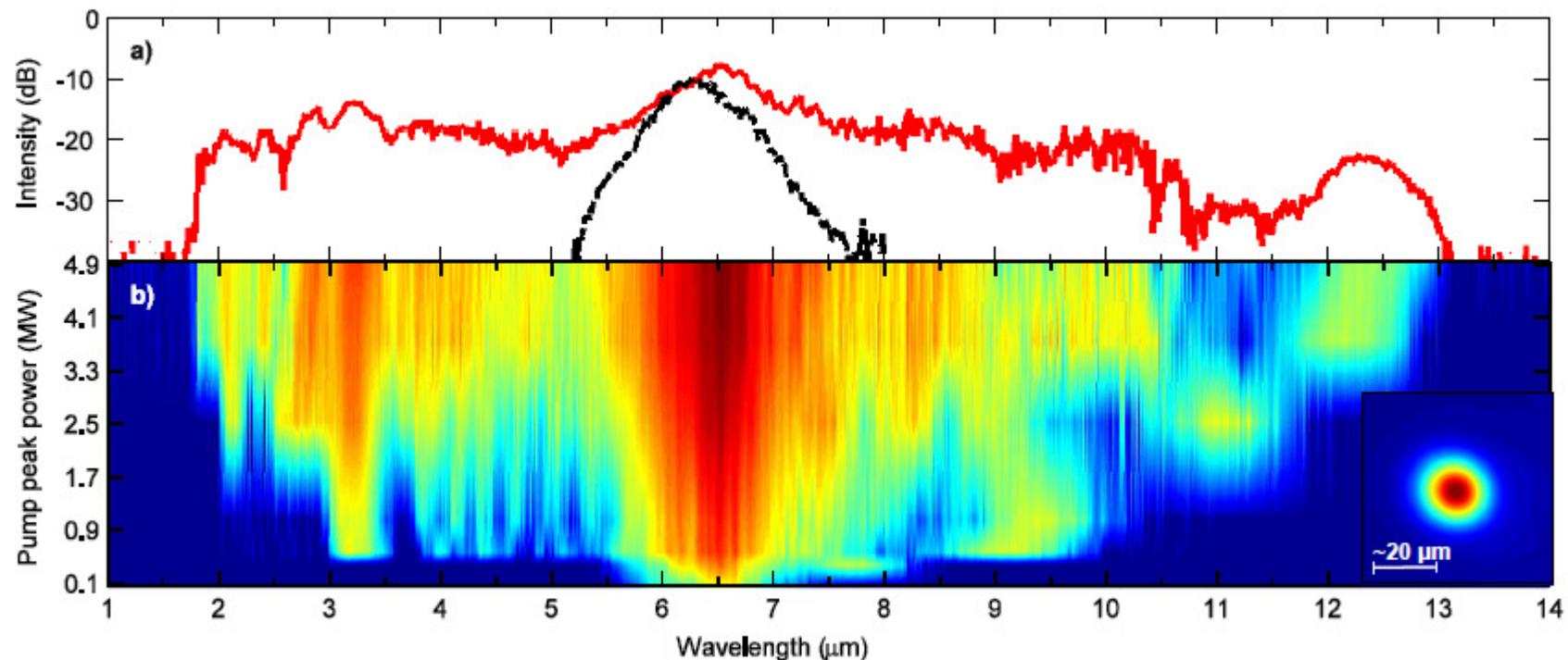


Transmission through 82 m fibre, Oct. 2016

Nonlinear fibre.

• *Petersen et al. NAT PHOTON 2014.*

A major achievement in MIR supercontinuum generation in fibre from 1.4 μm to 13.3 μm spectral range, to cover the fundamental biomolecular absorption bands.

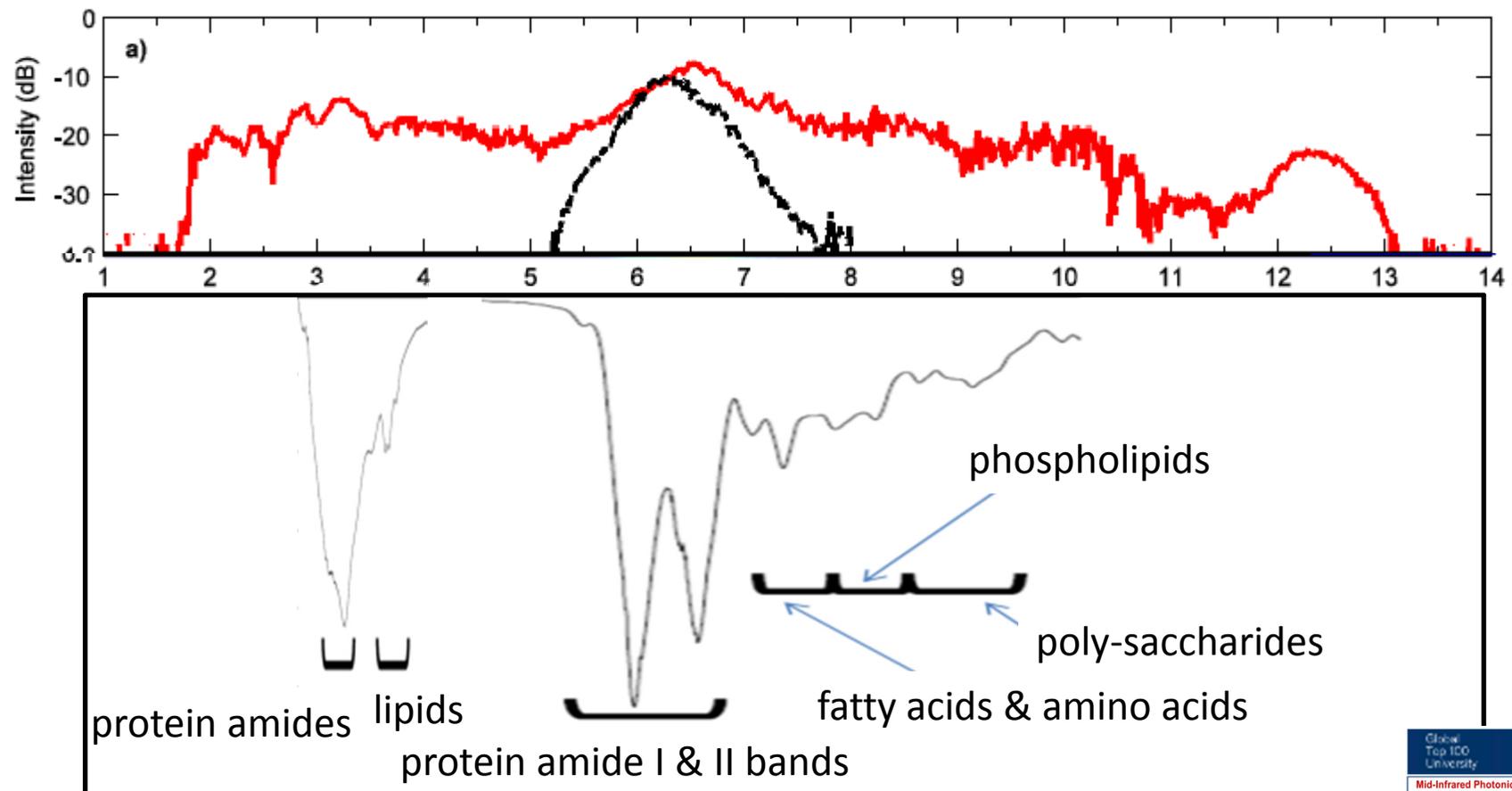


Pumped selenide fibre at 4.5 or 6.3 μm with OPA.

Nonlinear fibre.

• *Petersen et al. NAT PHOTON 2014.*

A major achievement in MIR supercontinuum generation in fibre from 1.4 μm to 13.3 μm spectral range, to cover the fundamental biomolecular absorption bands.



Nonlinear fibre.

• Petersen et al. NAT PHOTON 2014. **CITED 267 x**

LETTERS

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nature
photonics

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

Christian Rosenborg Petersen^{1*}, Uffe Møller¹, Iris Kubat¹, Binbin Zhou¹, Sune Dupont², Jacob Ramsay², Trevor Benson², Slawomir Sujecki², Nabil Abdel-Moneim², Zhuoqi Tang², David Furniss², Angela Seddan² 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-

vented the use of such materials in SCG because it has been limited by the lack of high-power pump sources in the MIR. Generally, efficient and broadband SCG is obtained by pumping in the anomalous dispersion regime close to the zero-dispersion wavelength (ZDW) of the fibre^{3,4}, but because bulk As_2S_3 glass has a ZDW of $\sim 9.8 \mu\text{m}$, it is challenging to fabricate fibres with a ZDW that

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 exciting 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 light focusing while overcoming the monochromatic nature of conventional continuous-wave lasers.

Although supercontinuum generation has been exploited since the early 1970s¹, a major breakthrough came with the discovery of a soliton fission scenario

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

Now, working in chalcogenide fibres, Christian Rosenborg Petersen and colleagues³ 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. Moreover, given that their mid-infrared spectra encompass more than two octaves in bandwidth, the results of Petersen et al. also constitute some 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

heavy elements (telluric, 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 telluride glass system.

For the soliton fission process to work well, it is important to launch near-monochromatic input light close

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.”

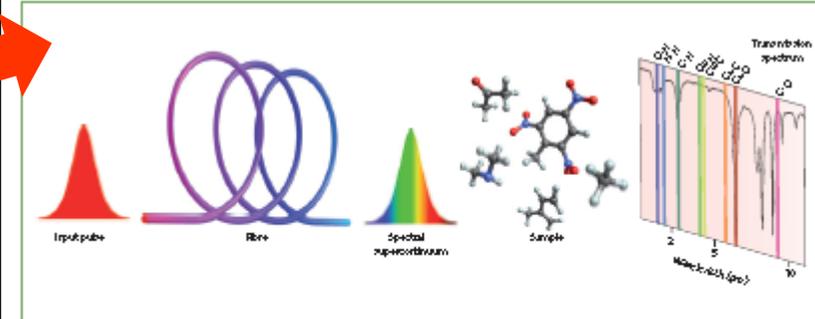


Figure 1 | Illustration of supercontinuum generation in the mid-infrared ‘molecular fingerprint’ region. Nonlinear processes in an optical fibre convert input pulses into broad-bandwidth white light that can then be used for molecular spectroscopy. The most common vibrational resonances in organic molecules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

014

NATURE PHOTONICS | VOL 8 | NOVEMBER 2014 | www.nature.com/naturephotonics

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Nonlinear fibre.

- *Petersen et al. NAT PHOTON 2014.*
- *Dantanarayana et al. OPT MAT EXP 2014.*

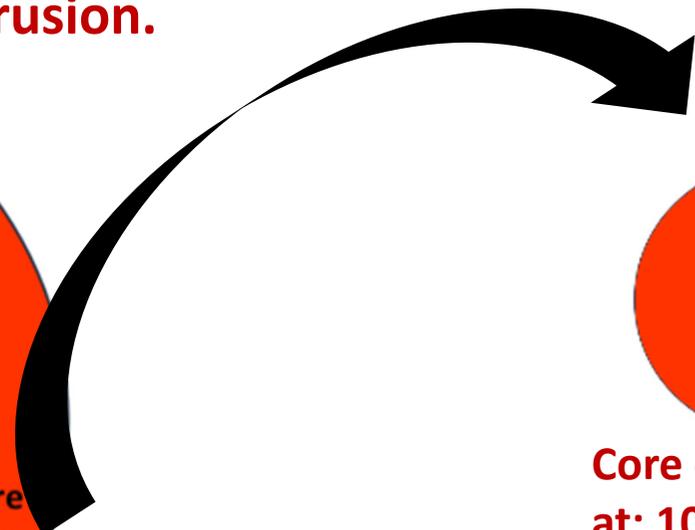
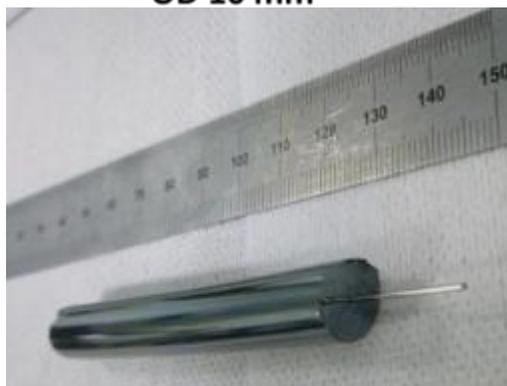
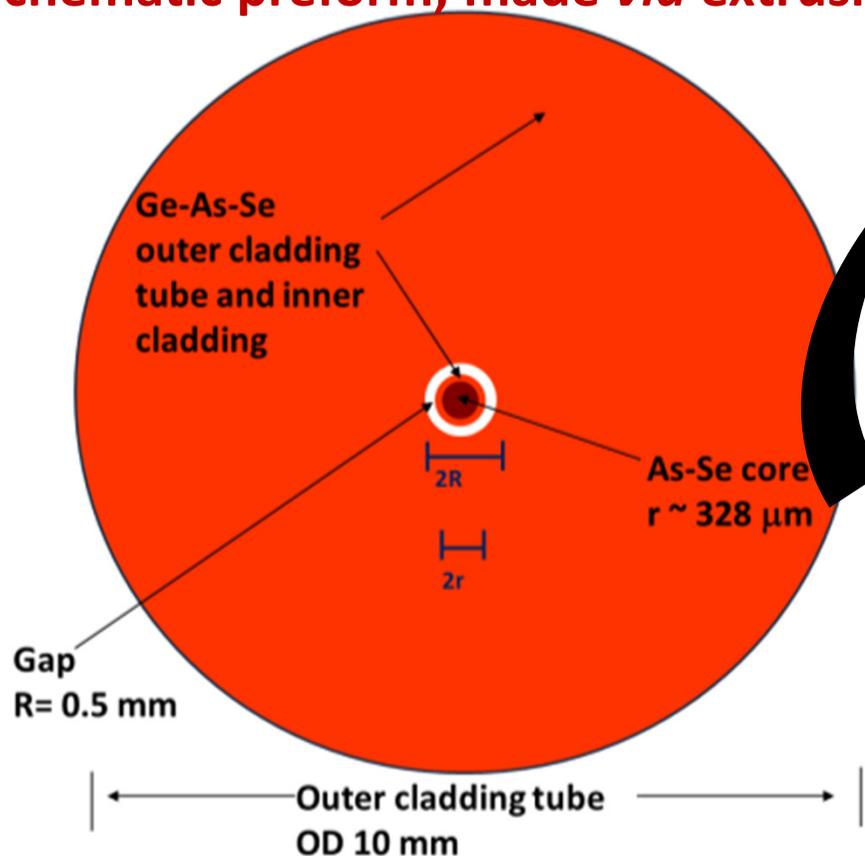
Record wide mid-infrared SC in fibre:

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

Nonlinear fibre.

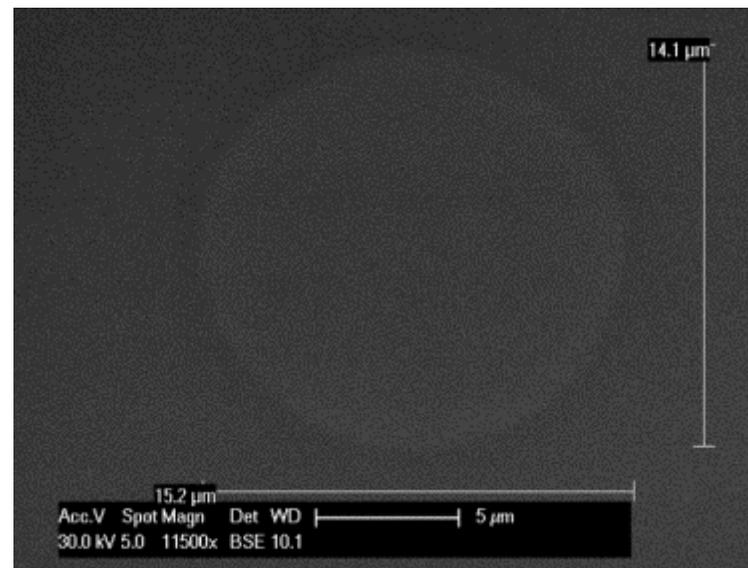
- *Petersen et al. NAT PHOTON 2014.*
- *Dantanarayana et al. OPT MAT EXP 2014.*

Schematic preform, made *via* extrusion.



Fibre-draw to small-core fibre.

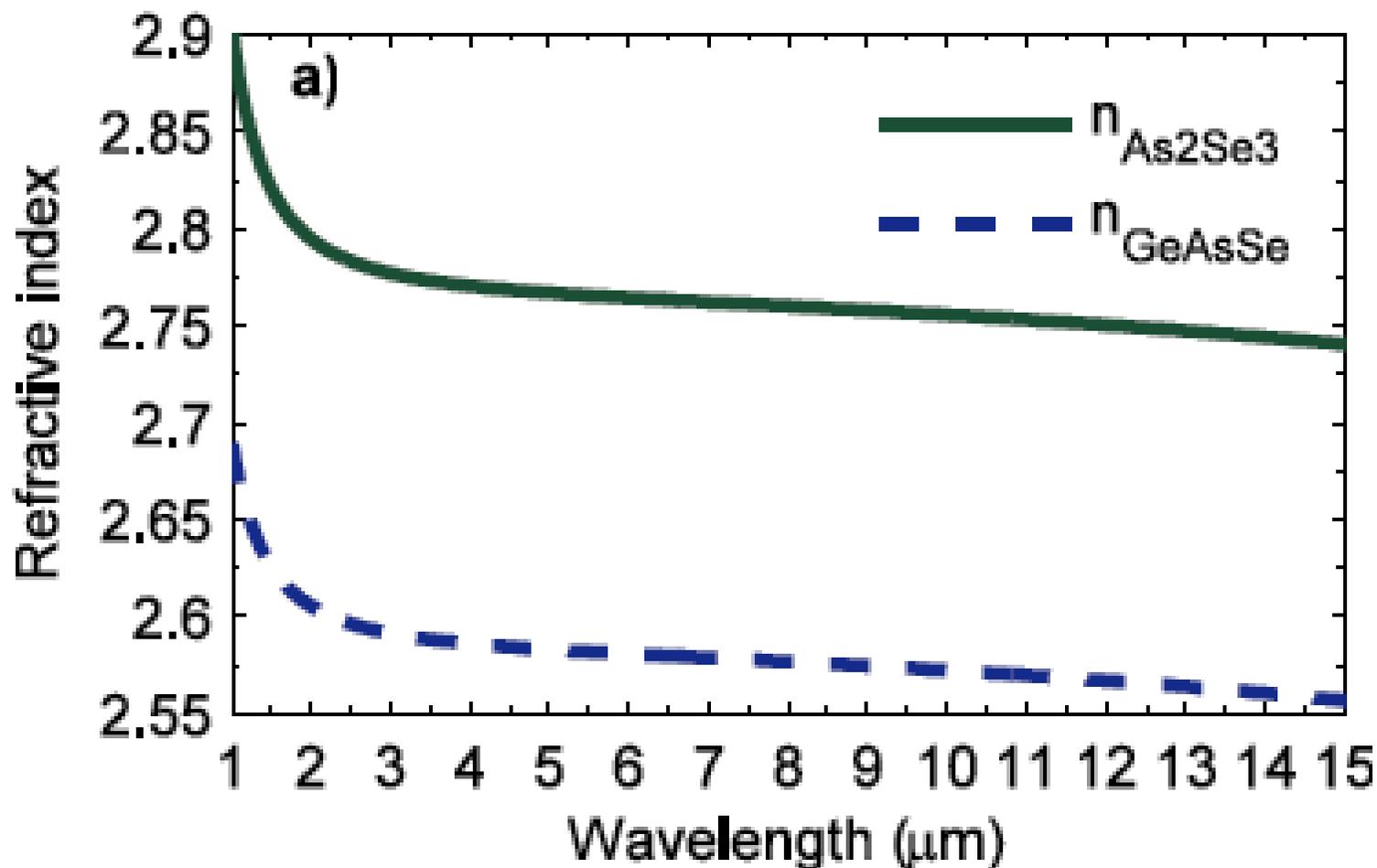
Core diameters aimed at: 10, 15, 20 μm



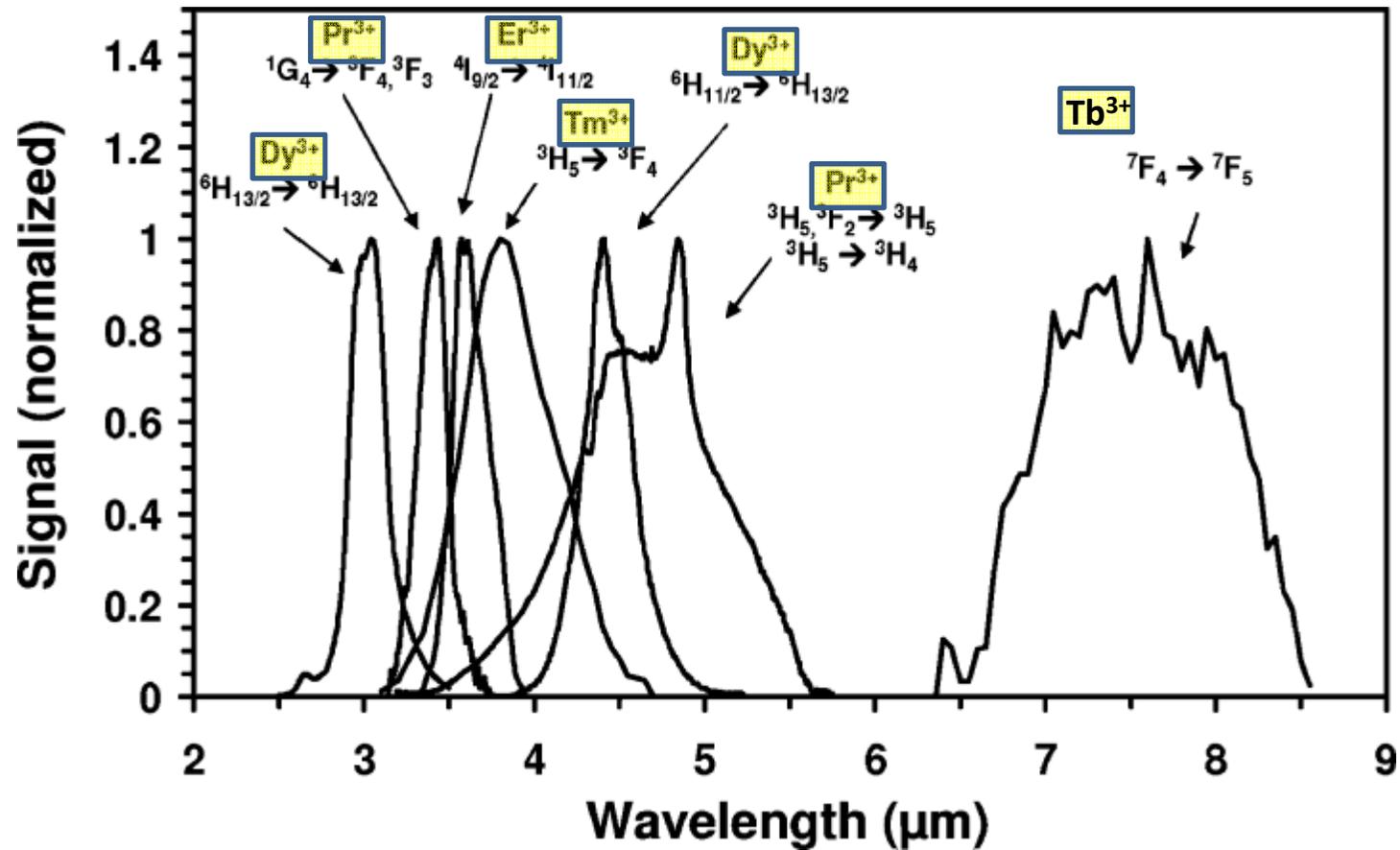
Nonlinear fibre.

- *Petersen et al. NAT PHOTON 2014.*
- *Dantanarayana et al. OPT MAT EXP 2014.*

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



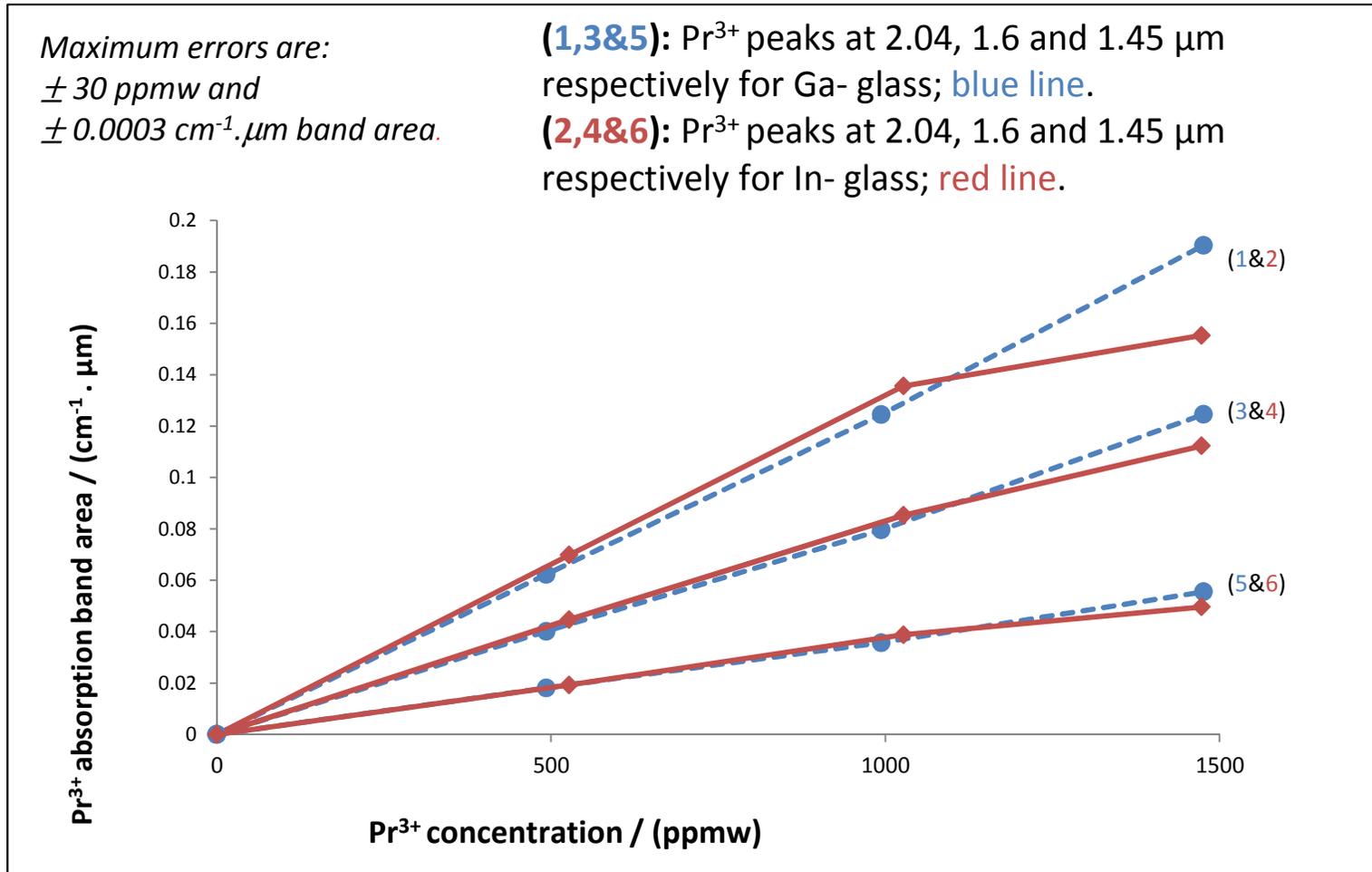
Luminescent fibre.



Sanghera *et al.* IEEE J Selected Topics in Quant. Elect 2009

Luminescent fibre.

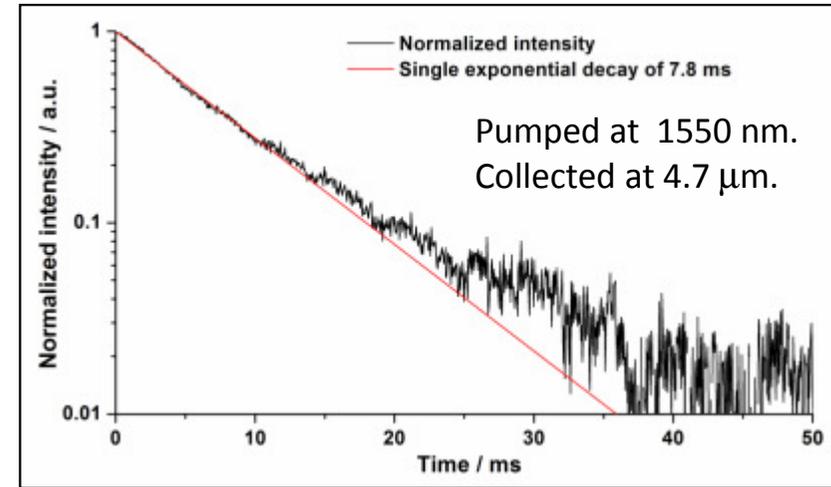
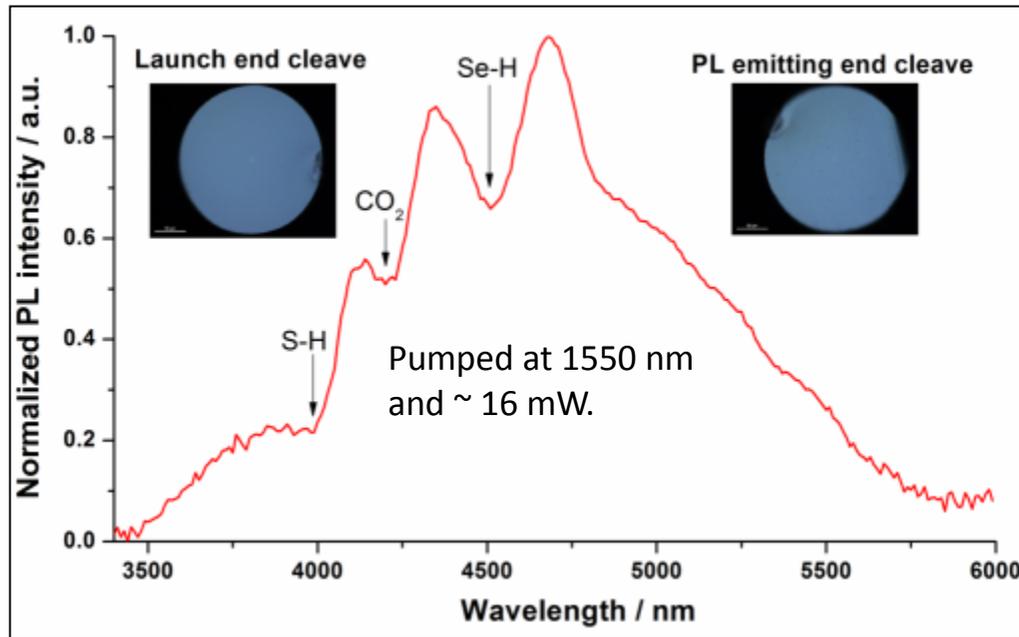
• Sakr *et al.* OPT. EXP. 22 2014.



Beer-Lambert plots of Pr³⁺ solubility limit in selenide glasses.

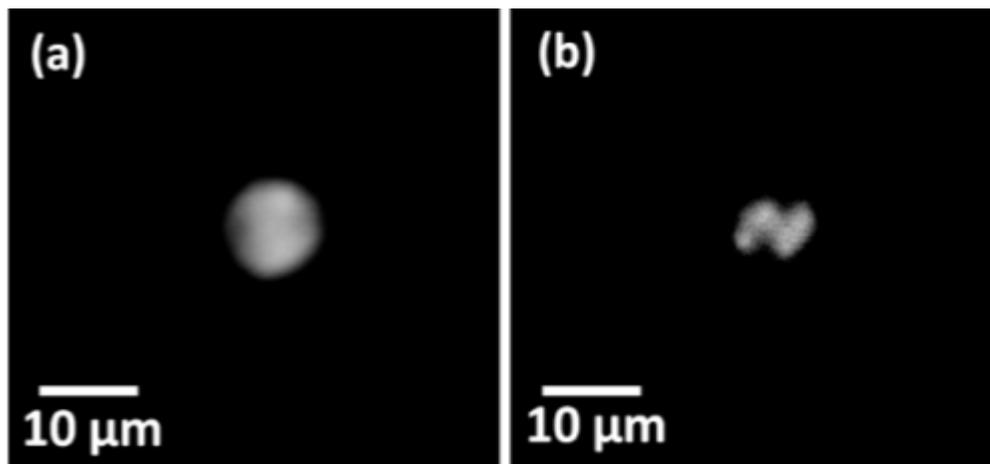
Luminescent fibre.

- Tang *et al.* OPT. MAT. EXP. 5 2015.



First reported long PL lifetime in small-core selenide fibre.

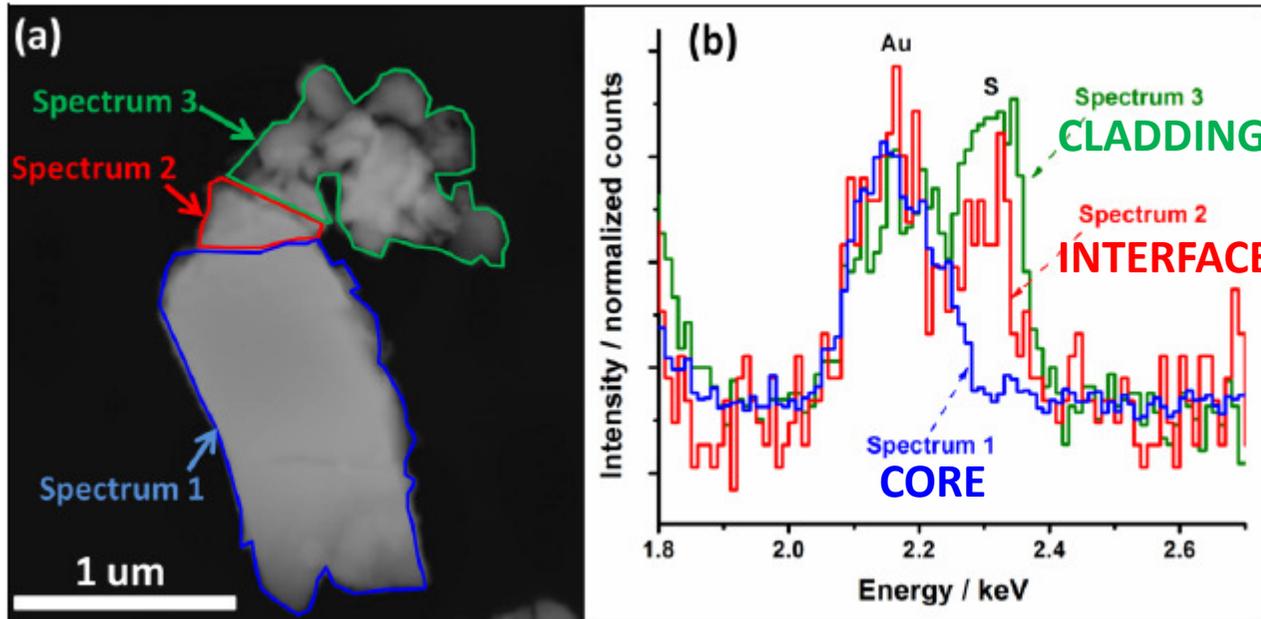
= 7.8 ms at 4.7 μm in 500 ppm Pr³⁺doped selenide chalcogenide fibre with 10 μm core-diameter.



Near-field images, multimoded at 1.319 μm .

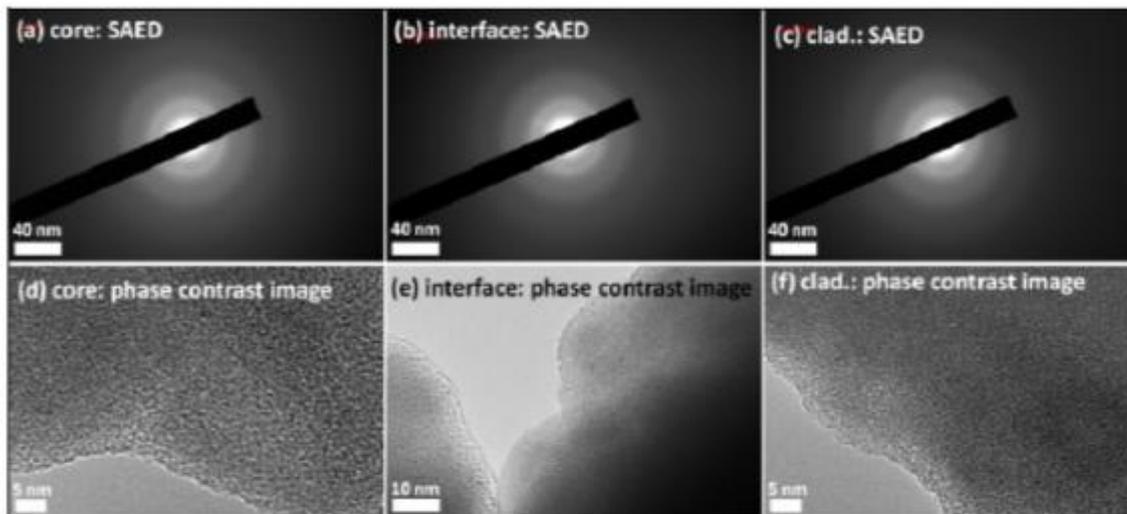
Luminescent fibre.

• Tang *et al.* OPT. MAT. EXP. 5 2015.



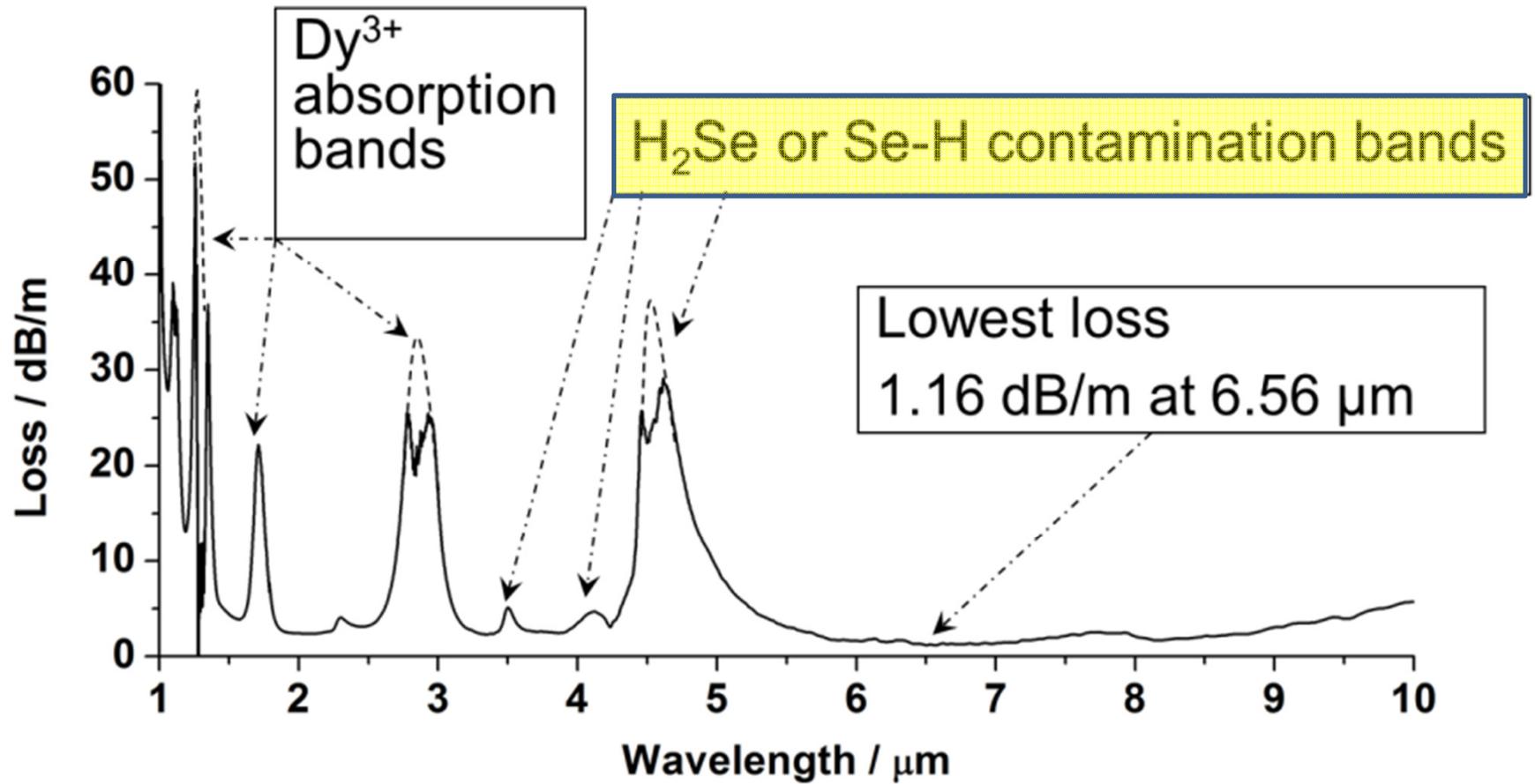
SAED (selected area electron diffraction) showing no devitrification of small-core fibre.

‘Needle in haystack’ small particle identified composed of S (cladding) and Se (core) glass.



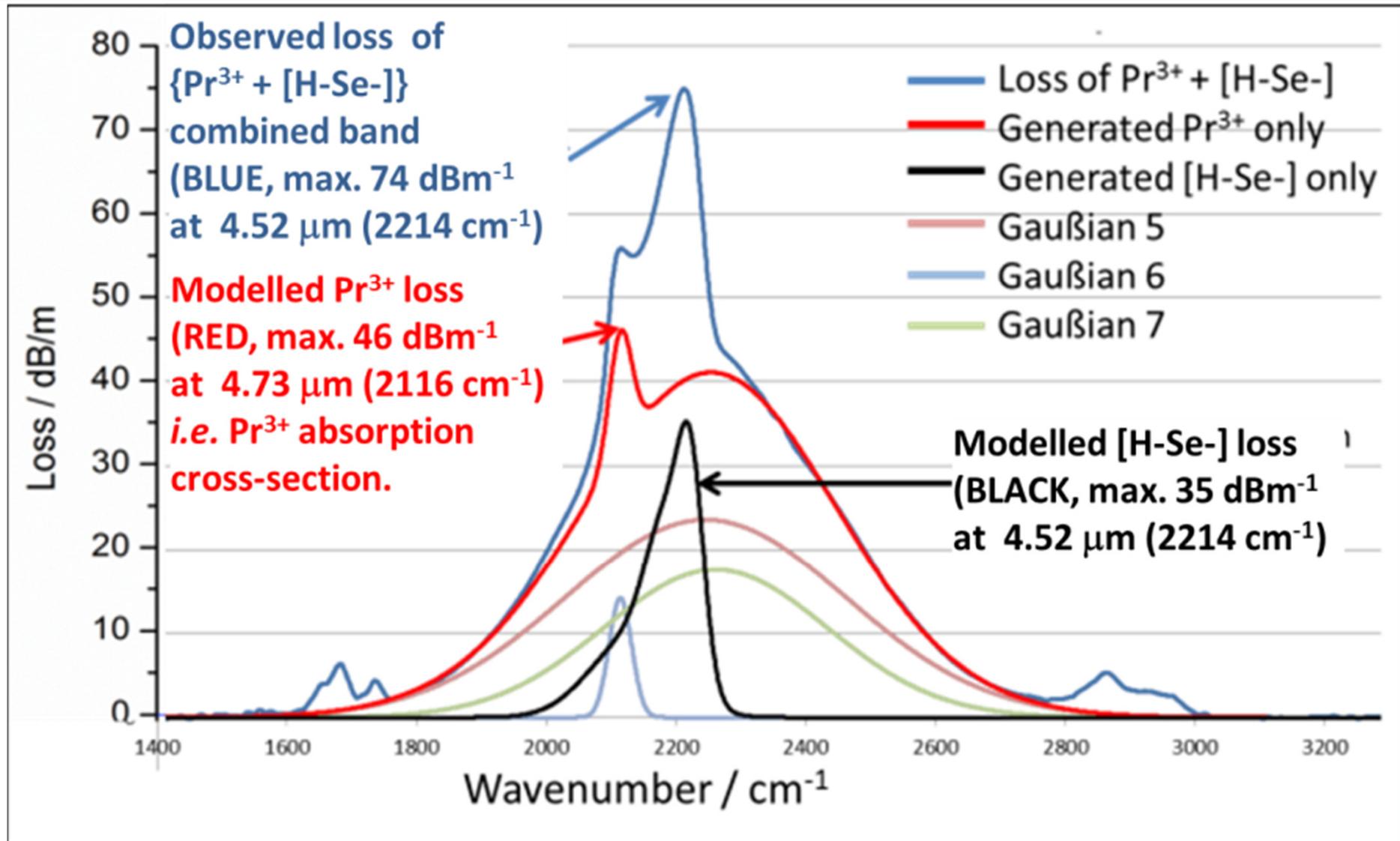
Luminescent fibre.

• Tang *et al.* CERAM. TRANS. 2012.



Luminescent fibre.

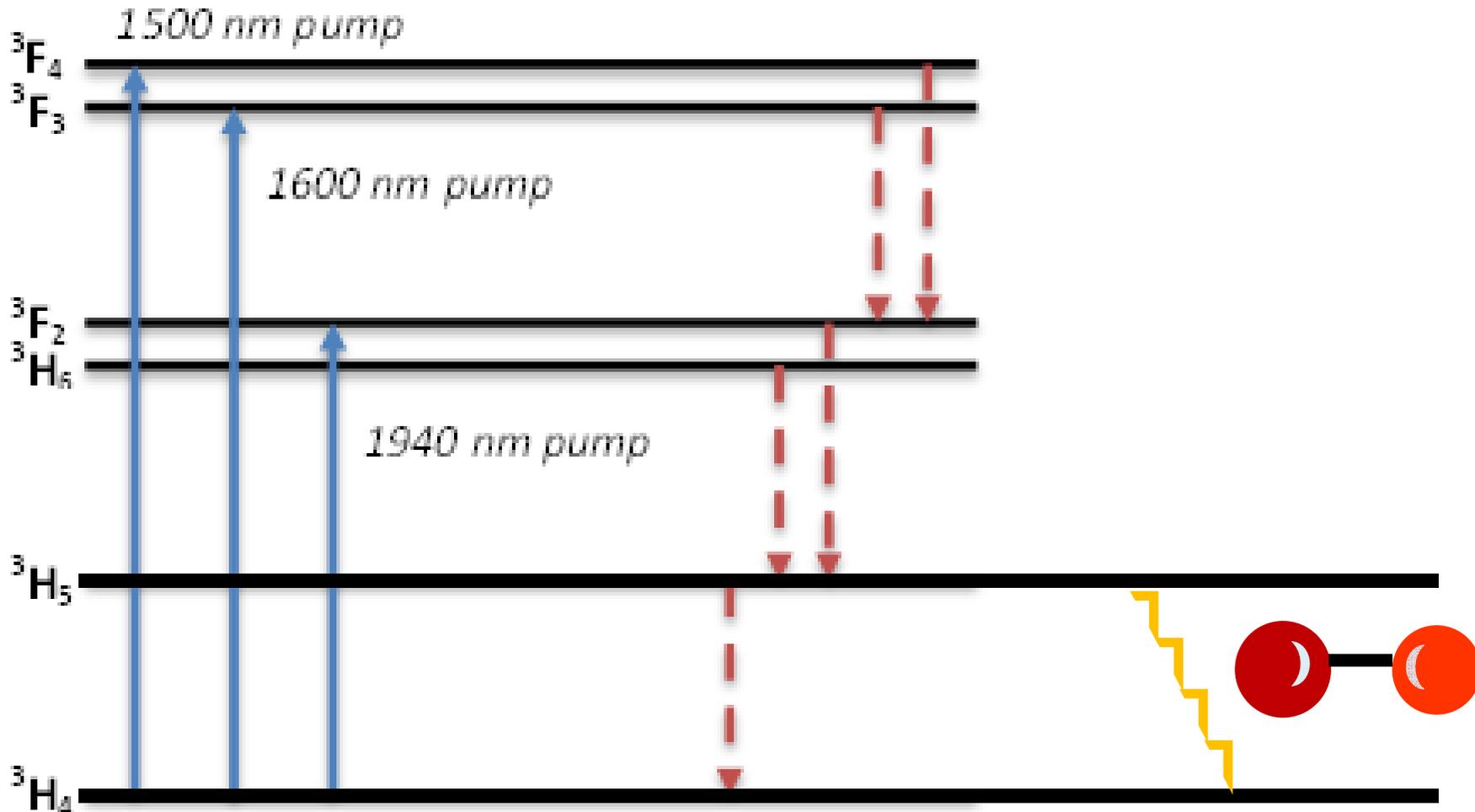
• Seddon *et al.* ICTON 2016.



Luminescent fibre.

- Seddon: *paper in preparation...*

Multiphonon decay competes with photoluminescence:

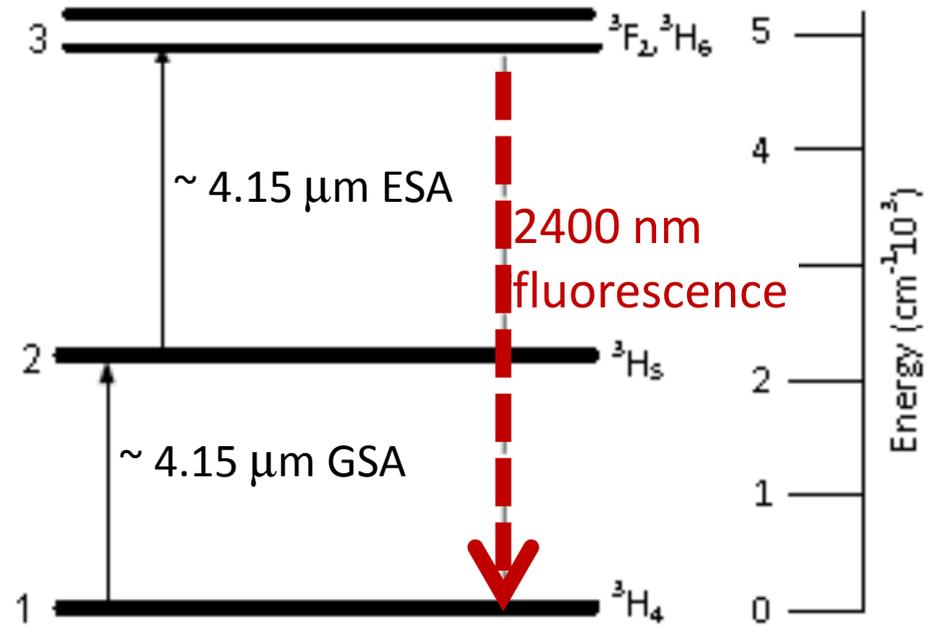
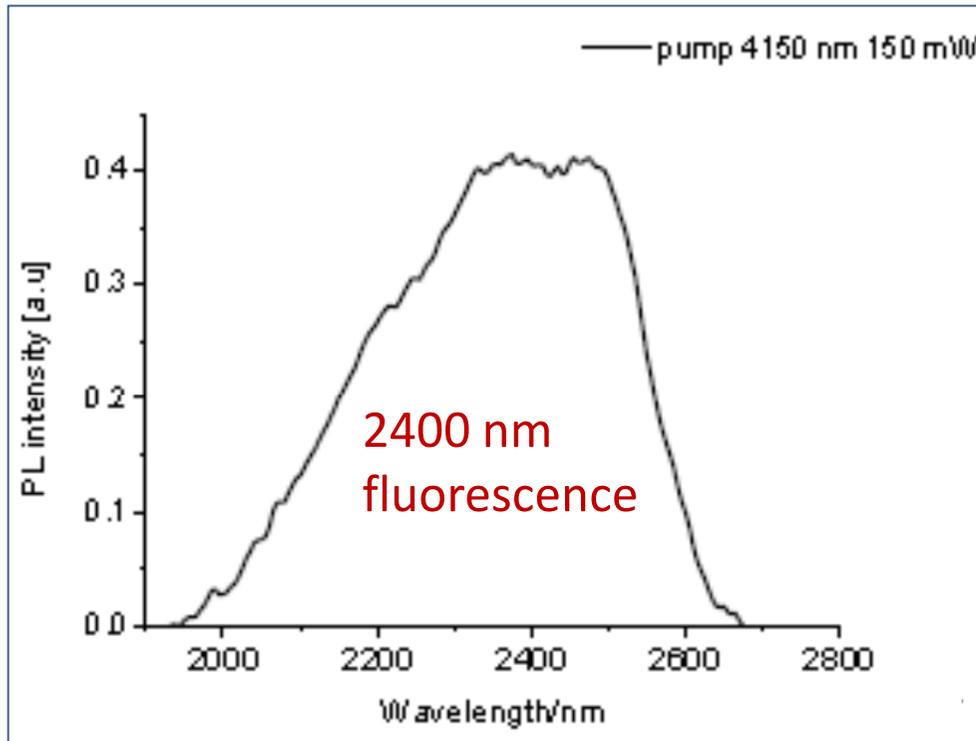


Pr^{3+} energy levels in a selenide chalcogenide glass host.

Dieke & Crosswhite, Appl. Optics 1963.

Luminescent fibre.

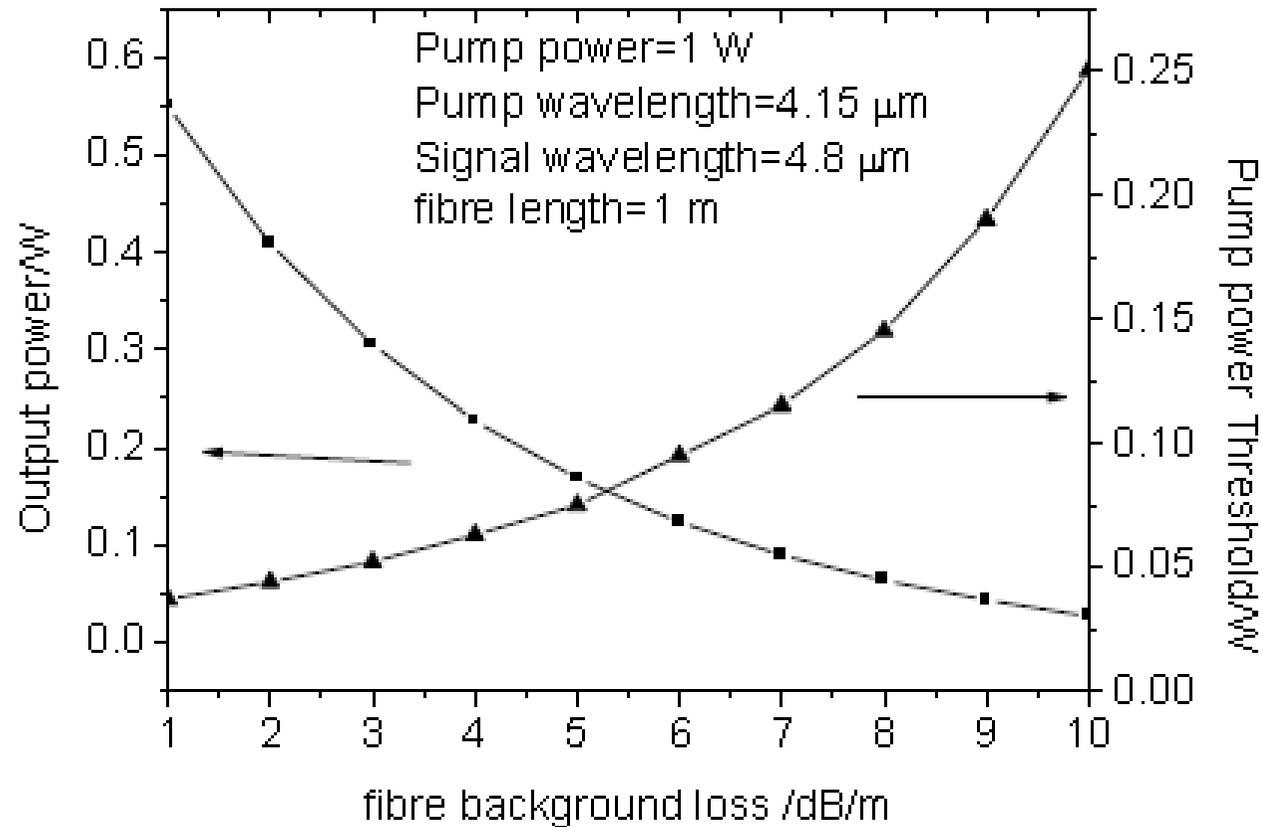
• Sojka *et al.* OPT. QUANT. ELECTRON. 2017.



Measured: resonant pumping 500 ppmw Pr^{3+} selenide fibre also emitted 2400 nm.

Luminescent fibre.

• Sojka *et al.* OPT. QUANT. ELECTRON. 2017.



Calculated output power and threshold pump power as a function of fiber background loss: 500 ppmw Pr³⁺ selenide fibre.

Summary.

- Record low loss Ge-As-Se passive fibre.
- Record MIR supercontinuum span for As-Se/ Ge-As-Se nonlinear fibre.
- First long lifetime in small core rare earth ion doped Ge-As-Se Ga/In luminescent fibre.

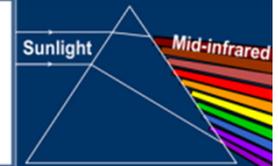


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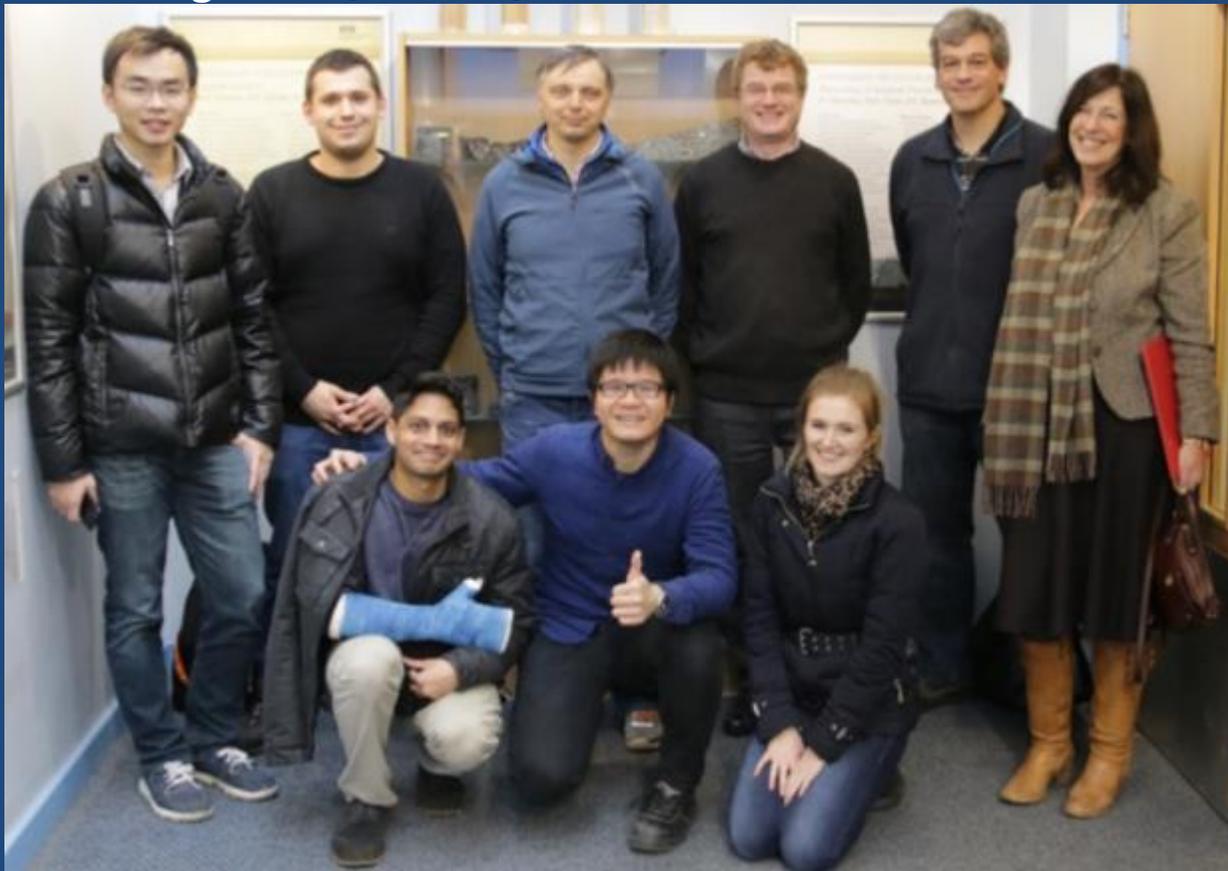
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**Mid-Infrared Photonics
Group**

George Green Institute for
Electromagnetics Research
Faculty of Engineering



Yuanrong Lukasz Slawek Trevor David
Fang. Sojka. Sujecki. Benson. Furniss..



Angela Seddon.



Hesham Sakr & Zhuoqi Tang.

Dinuka Zhuoqi Harriet
Jayasiura. Tang. Parnell.

Thank you!

Mid-infrared narrow-line rare earth fibre lasers.

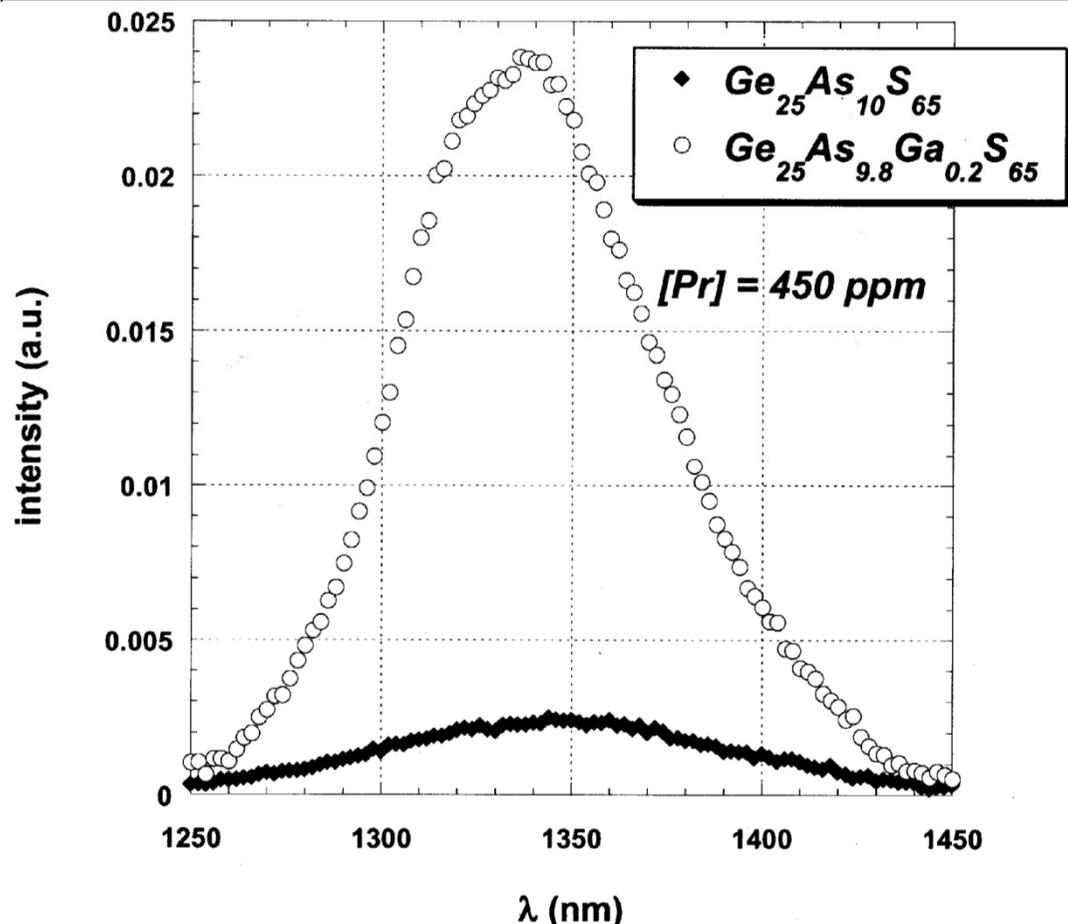
Building on the comprehensive studies of rare earth ion emission in chalcogenide bulk glasses:

Sanghera [*IEEE J. Quant. Electron.* 2001] **including fiber**
Heo [*J. Non-Cryst. Solids* 1999; 2007]
Tanabe [*J. Non-Cryst. Solids* 1999]
Adam [*Opt. Mat.* 2008] **including fiber**
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.]

Overcoming the low solubility of rare earth ions in chalcogenide glass hosts:

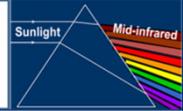


$^1\text{G}_4 \rightarrow ^3\text{H}_5$ emission spectra of Pr^{3+} -doped GeAs sulfide glasses with (open circles) and without (solid diamonds) Ga^{III} co-dopant.

“p-block” chalcogenide glass compositions like Ge-Sb-S and Ge-As-Se, exhibit extremely low intrinsic rare earth ion solubility.

Addition of Ga^{III} to the host in a concentration ratio of $[\text{Ga}^{\text{III}}] : [\text{rare earth ion}] \geq 10:1$ can increase the radiative emission by two orders of magnitude for the same nominal concentration of rare earth ion dopant.

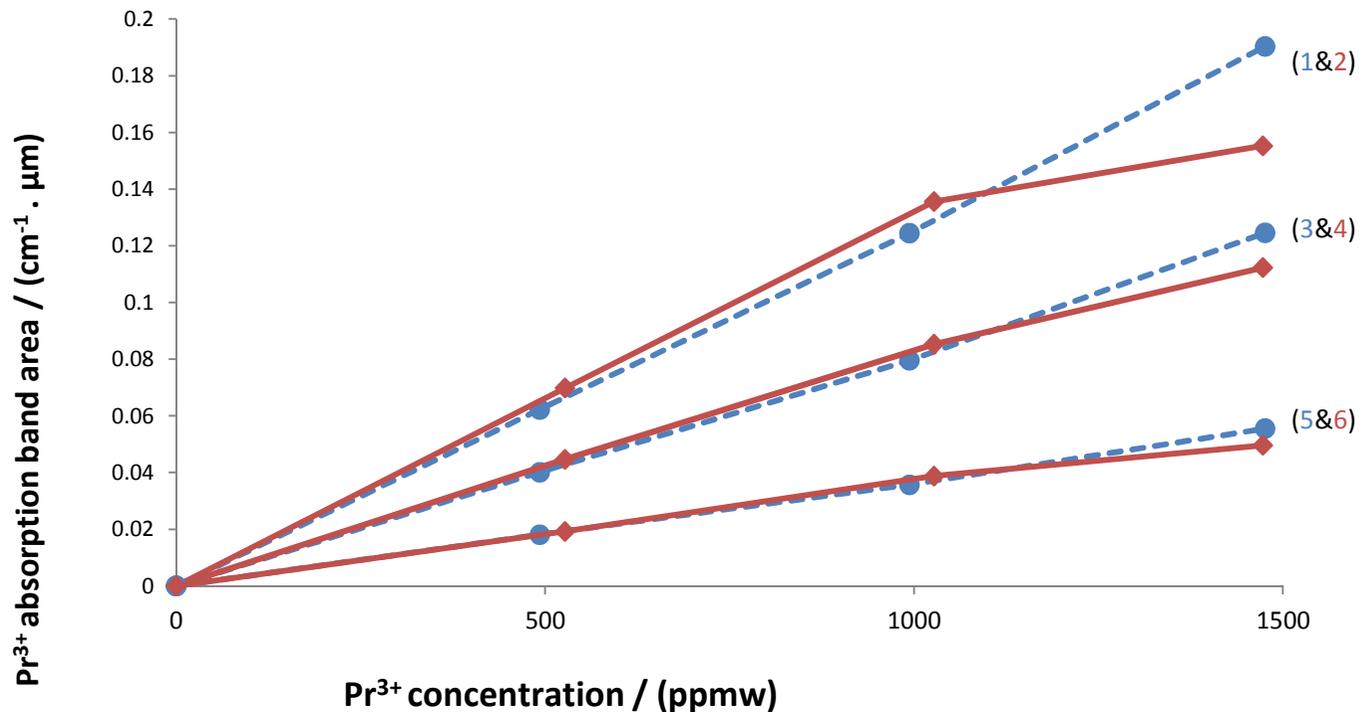
Experimental Beer-Lambert plots of Pr³⁺ doped BULK selenide glasses.



Maximum errors are:
 ± 30 ppmw and
 $\pm 0.0003 \text{ cm}^{-1} \cdot \mu\text{m}$ band area.

(1,3&5): Pr³⁺ peaks at 2.04, 1.6 and 1.45 μm respectively for Ga- glass; blue line.

(2,4&6): Pr³⁺ peaks at 2.04, 1.6 and 1.45 μm respectively for In- glass; red line.



Beer-Lambert plots show Pr³⁺ solubility limits.

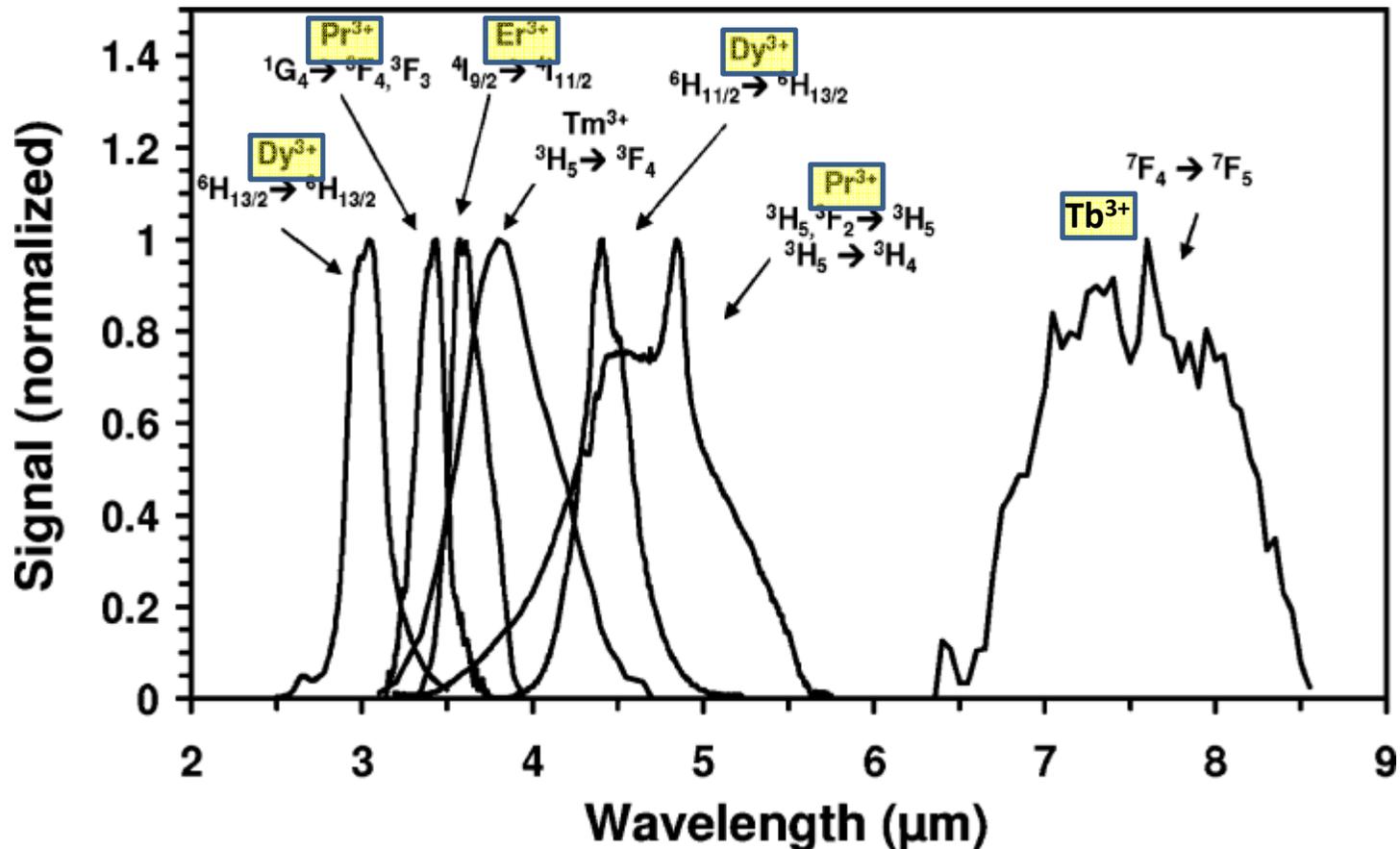
Sakr, Seddon *et al.* Opt. Exp. 22 2014.

Ref.:

“Chalcogenide glass-fiber –based mid-IR sources and applications.”

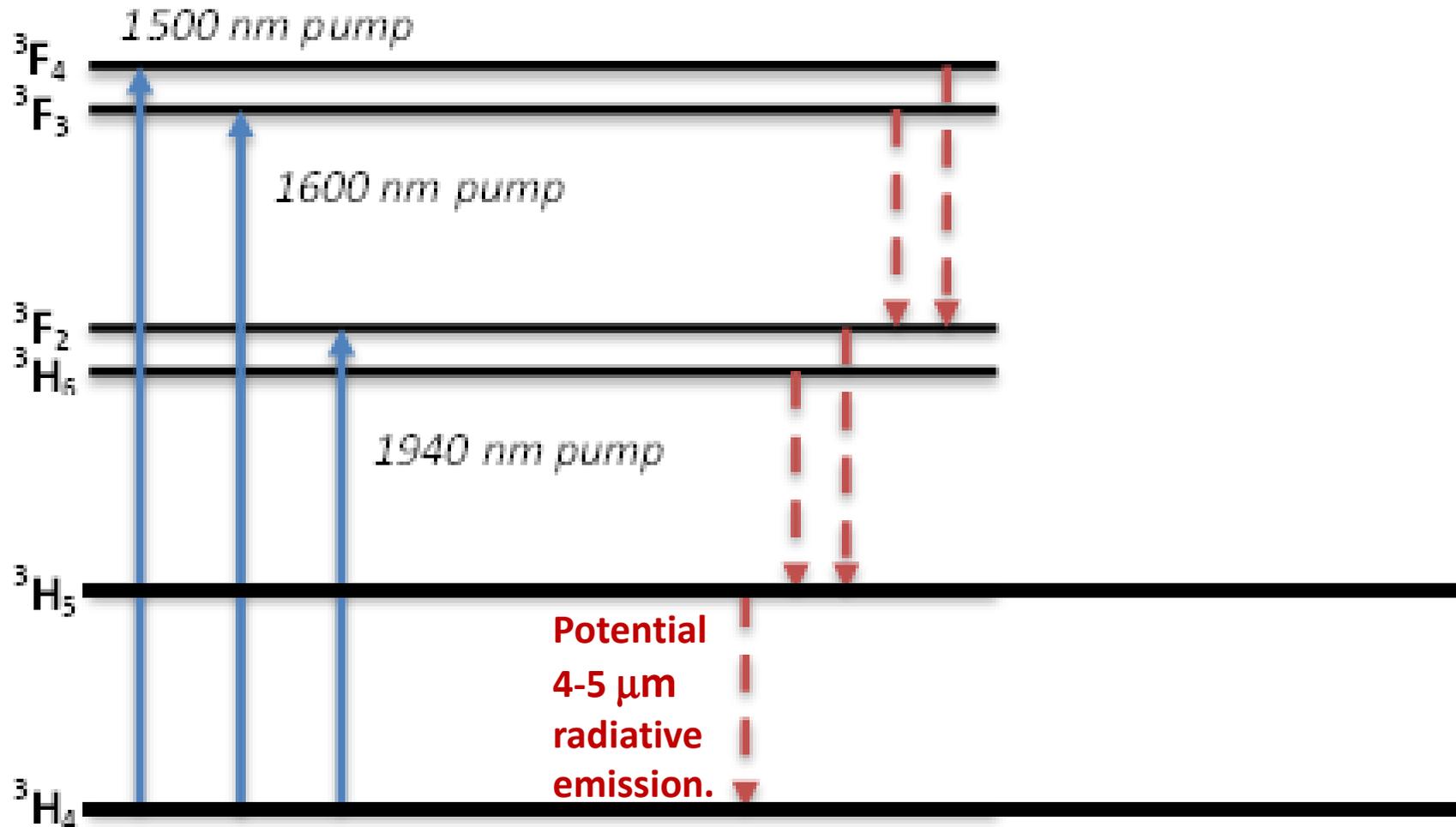
JS Sangera, L B Shaw and I Aggarwal.

IEEE J Selected Topics in Quant. Elect 2009



Rare-earth-doped chalcogenide (Ge-As-Ga-Se) glass mid-IR transitions in the 3-5 micron window and the ~ 8 micron transition of Tb^{3+} .

Multiphonon decay competes with photoluminescence.



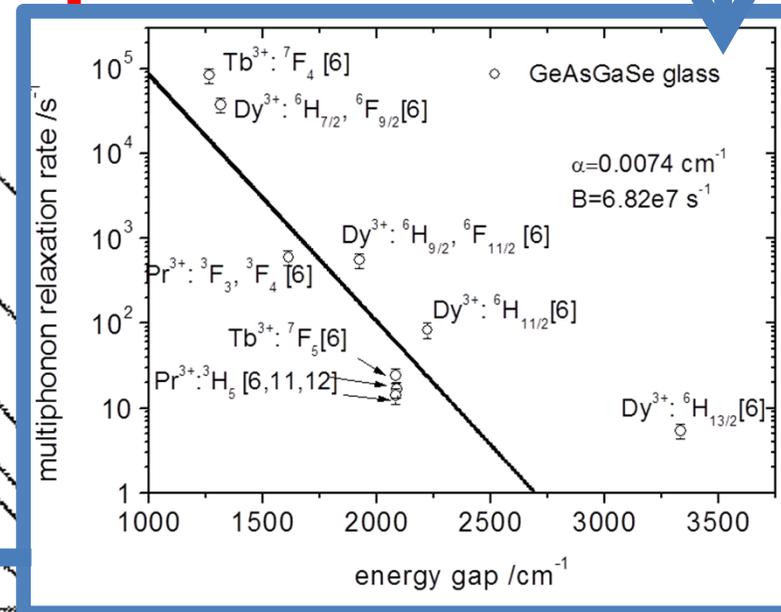
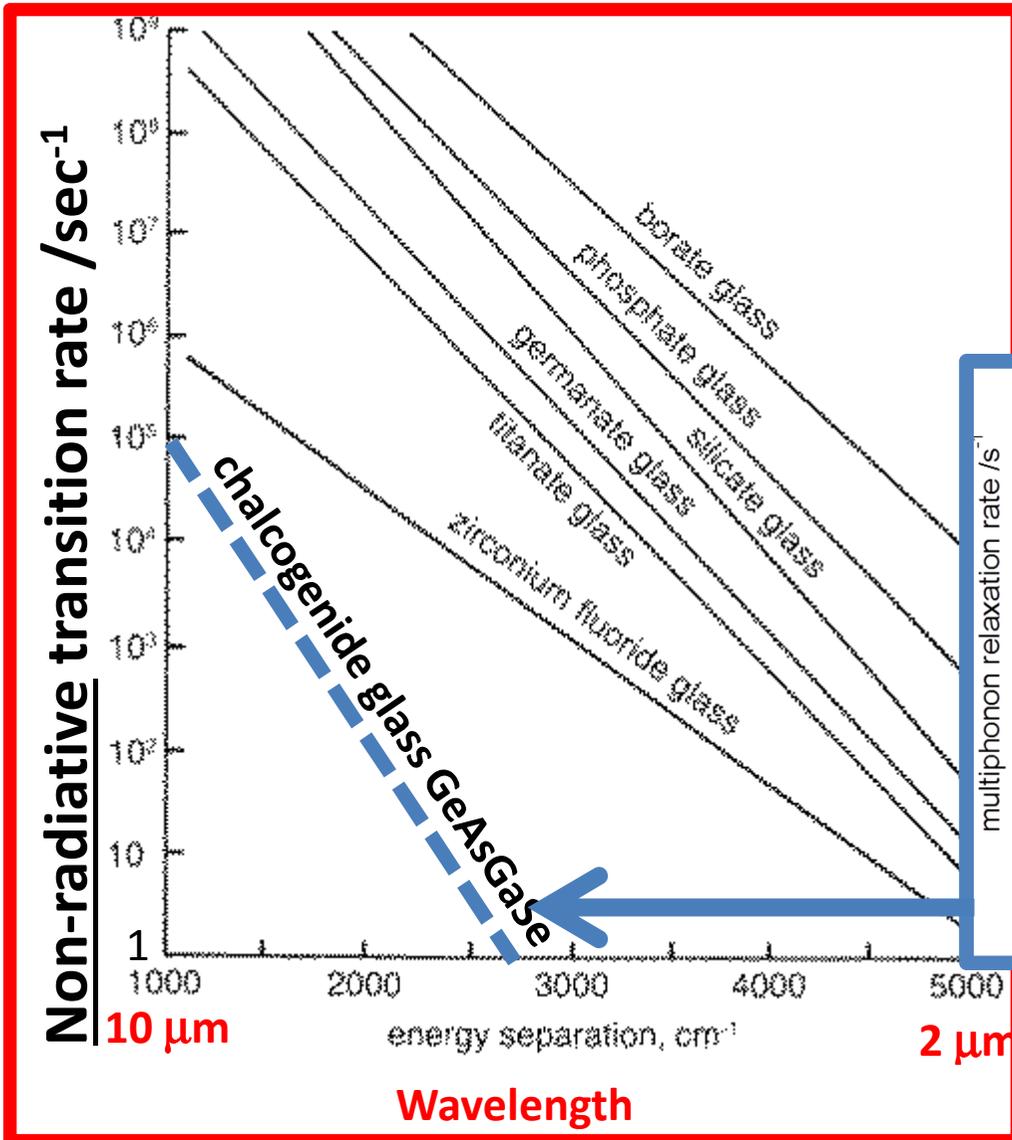
Pr³⁺ energy levels in 'isolated ion'.

Dieke & Crosswhite, Appl. Optics 2 1963.

Very low phonon energy of selenide mid-IR fibre.

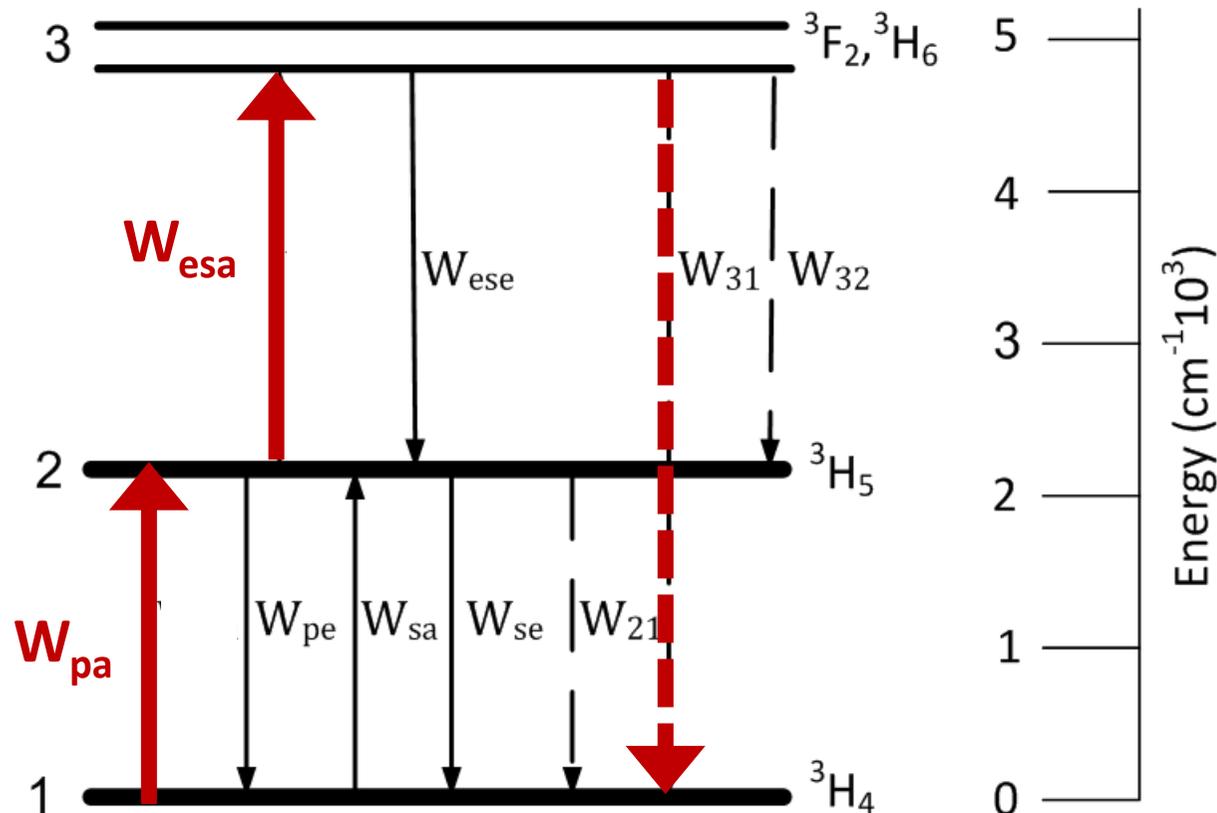
Data from Nottingham:
Sojka et al. Opt Mat Exp 2012
 and
Tang et al. Opt Mat Exp 2015

and also that of
Shaw et al. JQE 2001:



Fuxi Gan et al. Chinese Physics 6 978, (1986).

Simplified Pr³⁺ energy diagram in Se glass host: transition rates shown.

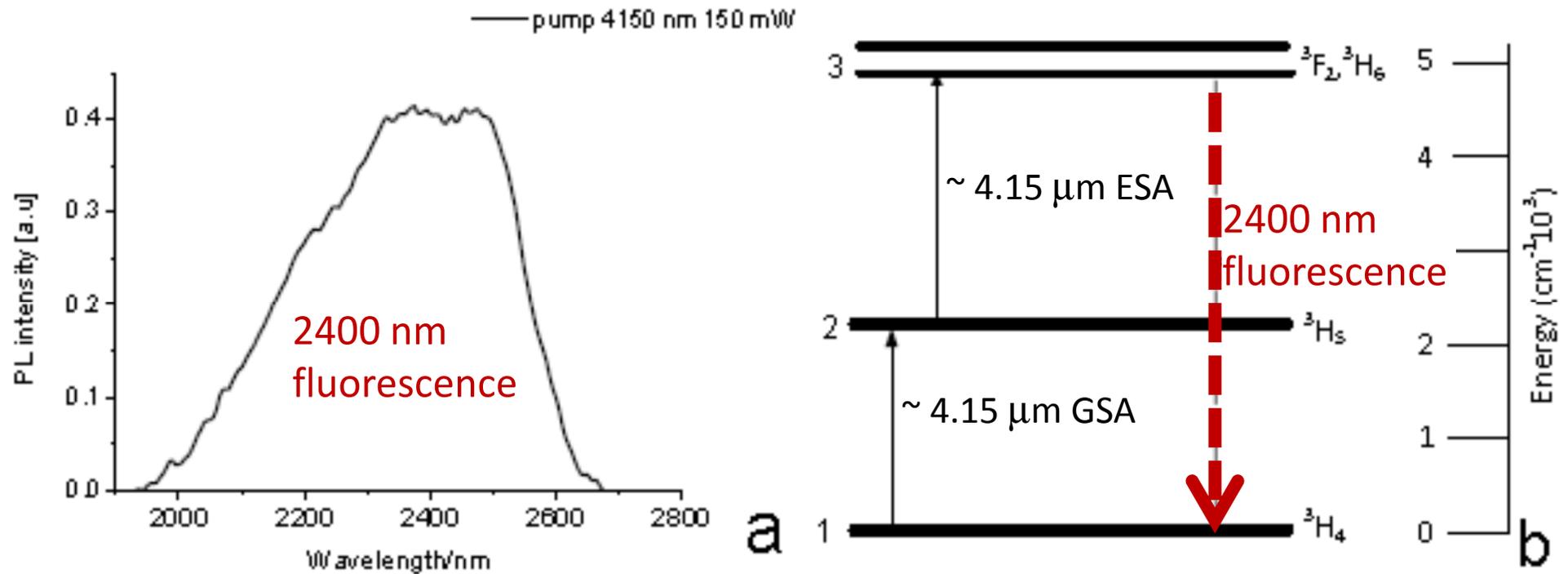


Sojka *et al.*
Opt. Quant. Electron. 2017.

W_{pa} rate of pump
absorption – resonant
absorption of
Pranalytica QCL: 4.15 μm

- Absorption and emission rates W_{pa} , W_{pe} , W_{sa} , W_{se} of the pump and signal, respectively.
- W_{esa} the ESA of the pump from $^3H_5 \rightarrow (^3F_2, ^3H_6)$.
- W_{ese} the emission of the pump from $(^3F_2, ^3H_6) \rightarrow ^3H_5$.
- $W_3 = W_{31} + W_{32}$ is spontaneous decay rate of level 3.
- W_{21} is spontaneous decay rate of level 2.

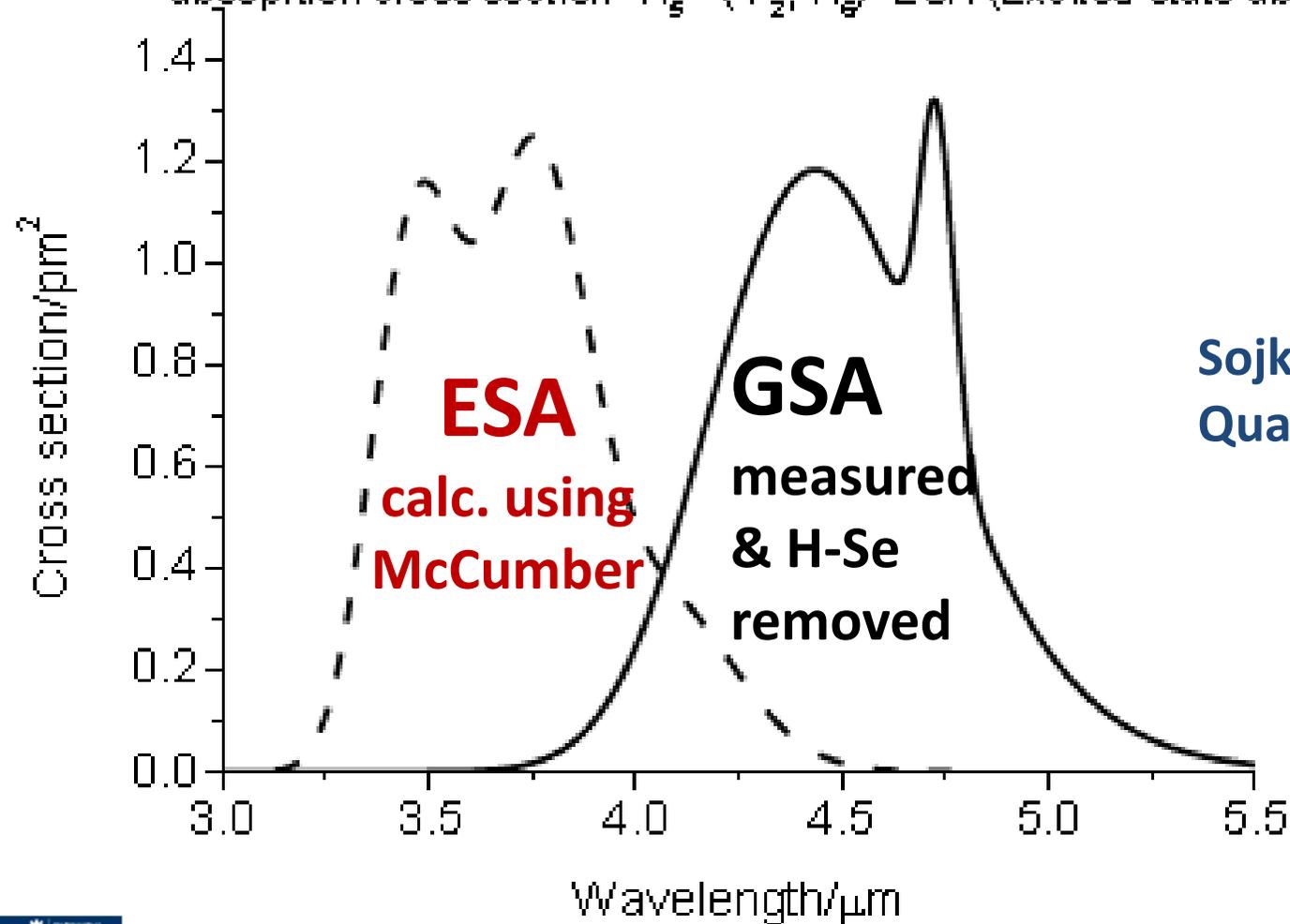
First reported resonant pumping at 4.15 μm wavelength gives excited state absorption.



Sojka *et al.* Opt. Quant. Electron. 49 2017.

First reported resonant pumping at 4.15 μm wavelength gives excited state absorption.

- absorption cross section ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ - GSA (Ground state absorption)
- - absorption cross section ${}^3\text{H}_5 \rightarrow ({}^3\text{F}_2, {}^3\text{H}_6)$ - ESA (Excited state absorption)

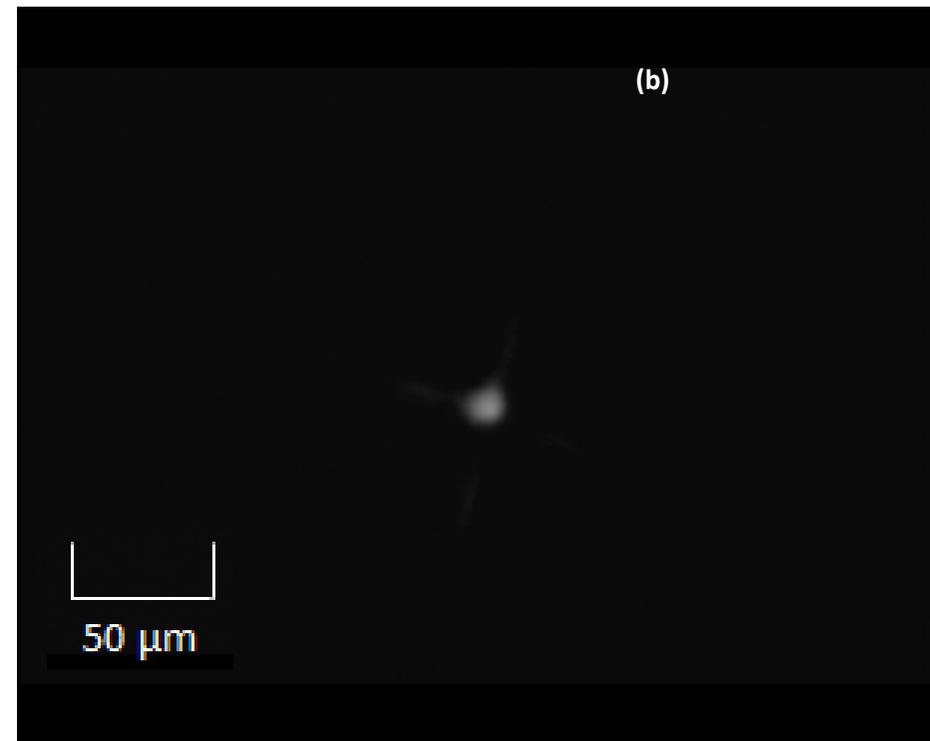
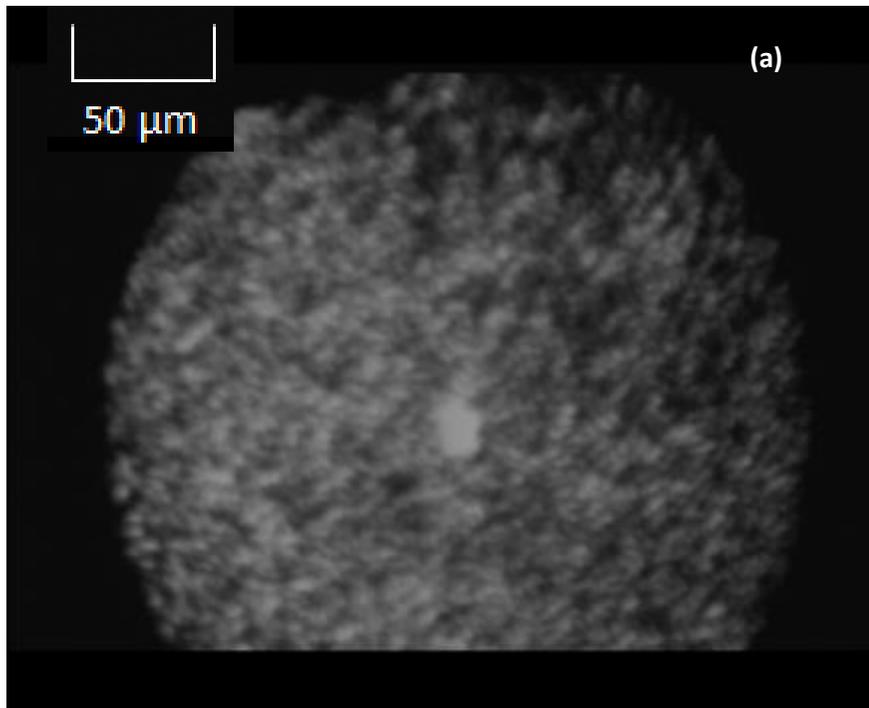


Sojka et al. Opt. Quant. Electron. 2017.

Mid-infrared (MIR) photonic sensing: bright MIR-SC fibre sources.

Near-field imaging 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.

Nonlinear fibre.

- *Petersen et al. NAT PHOTON 2014.*
- *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.

