IR to visible photon conversion in rare-earth doped chalcogenide fibers for all-optical gas sensing

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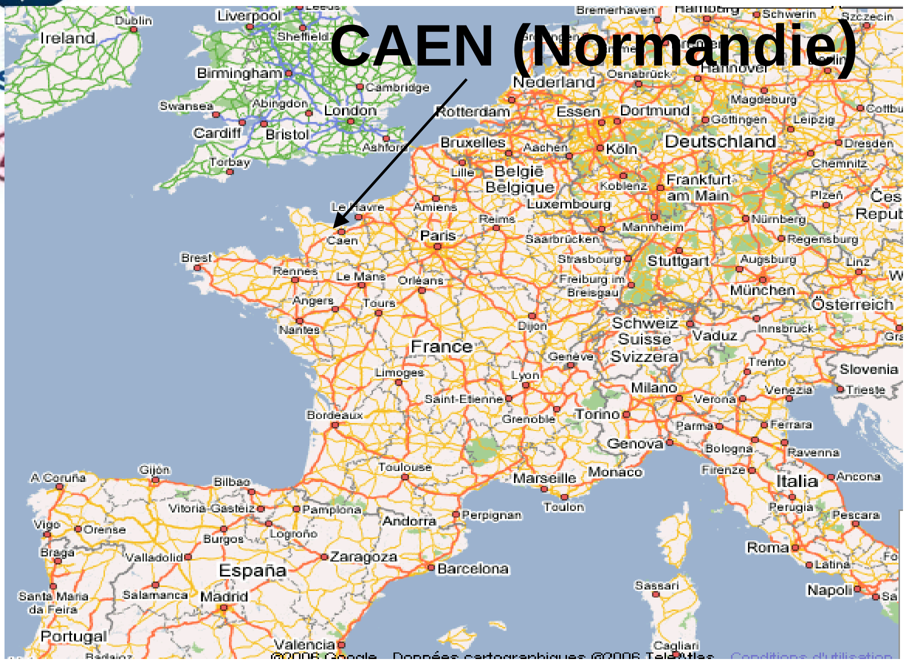
CIMAP laboratory : ~ 100 persons - 7 groups



Lasers and Materials for photonics and electronics

LIOA **MIL** NIMPH

13 persons

(Matériaux et Instrumentation Laser)

Ion-Matter interaction (heavy ions) and Defects

AMA MADIR SIMUL PM2E

http://cimap.ensicaen.fr

Group Matériaux et Instrumentation Laser (MIL)

(7 permanent + 4-5 PhD students/Post-docs)

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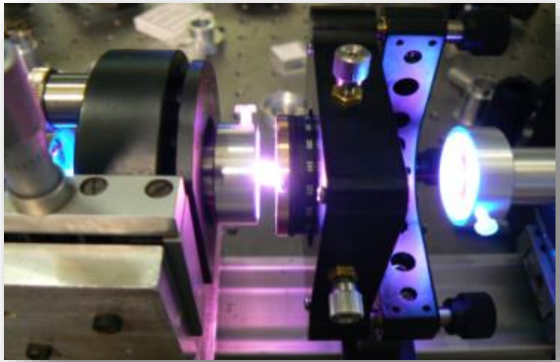
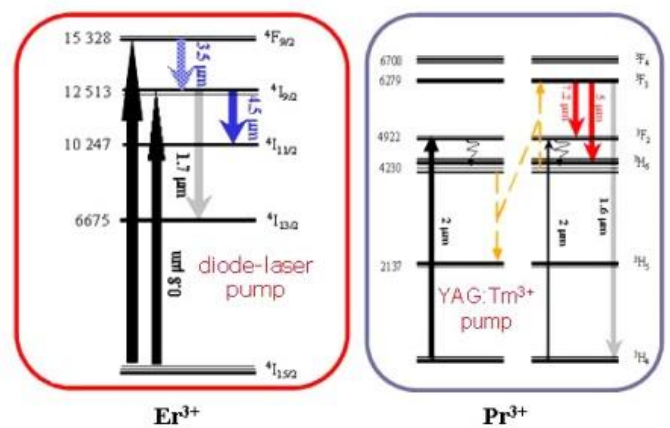
http://cimap.ensicaen.fr/spip.php?rubrique65

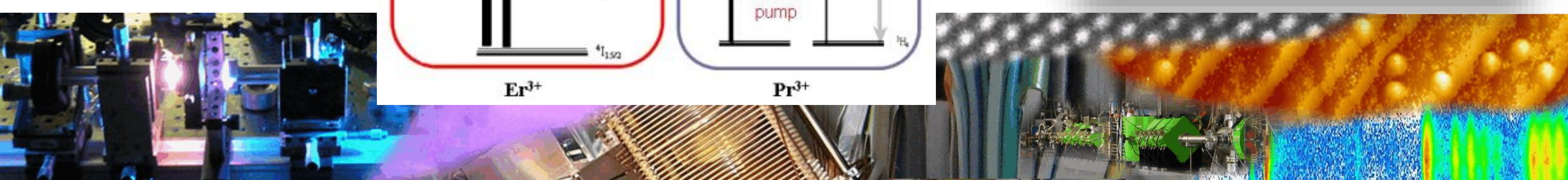
→ **Crystal growth** (low energy phonon crystals - Czochralski, Bridgman, LPE)

→ **Spectroscopy of ions in solids** and **laser instrumentation** in a wide spectral domain (nearUV→mid-IR)

→ **Prototype development** (lasers and **infrared gas detectors)**



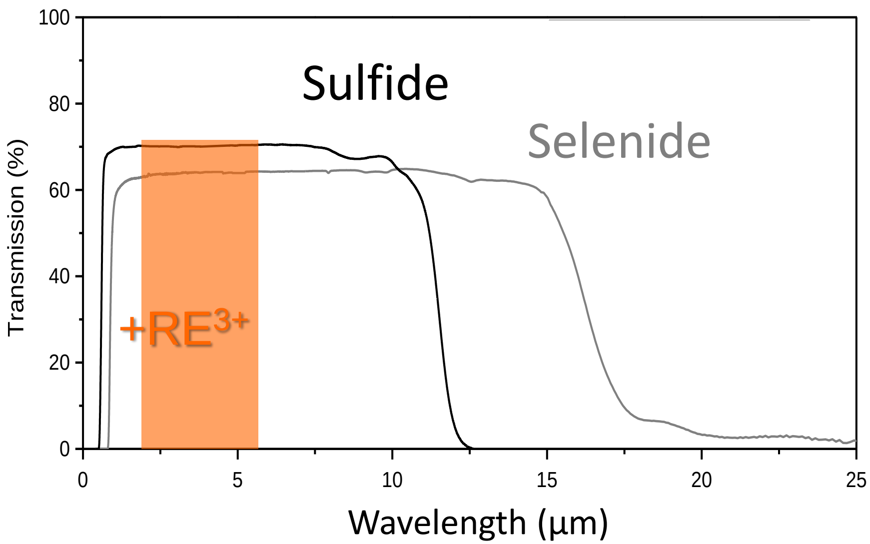


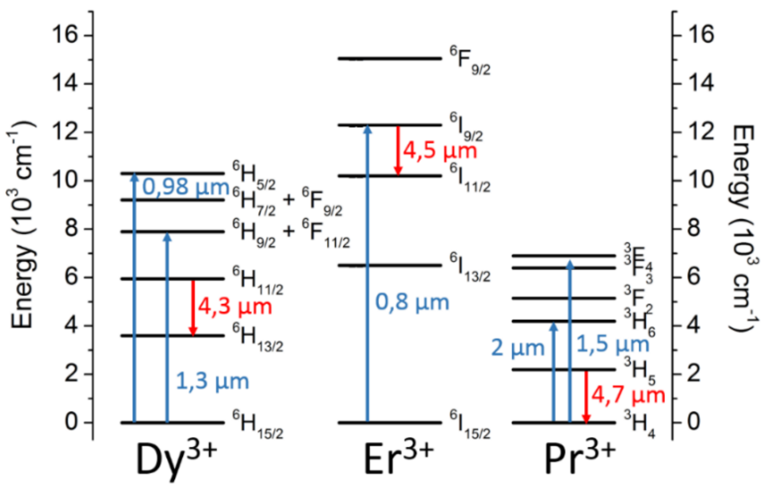


Rare earth embedded in a chalcogenide glass

- Phonon energies, transparency and quantum efficiency

Glass matrix	Phonons energy (cm^{-1})
Silica (oxide)	~1100
Tellurite (oxide)	~750
Fluoride	400-600
Sulfide	350-450
Selenide/Chlorides	200-300
Tellurides/Bromides	100-200





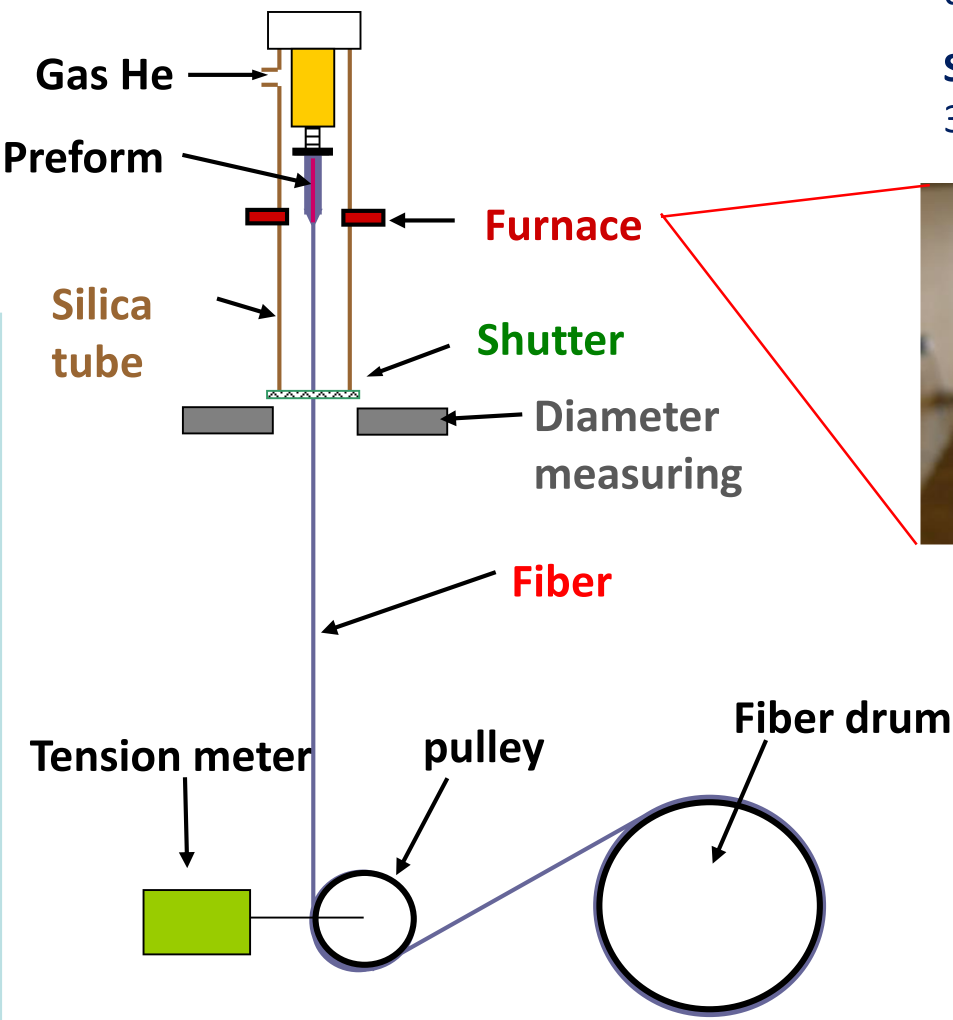
Matrix / Rare earth ion :

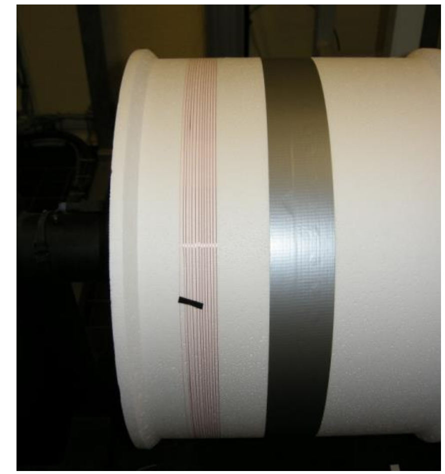
- Transparency for optical pumping
- Adapted phonon energies for an efficient mid-IR luminescence

Fiber drawing

Size of preform: 10 cm length and 1cm diameter

Size of fiber: several tens of meter for a 300 µm diameter fiber

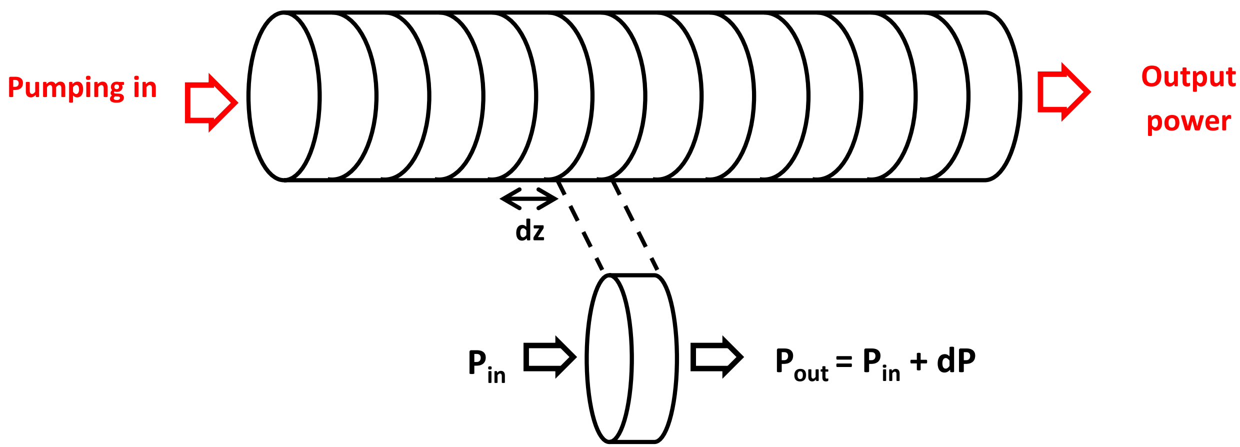




Fibered rare earth doped mid-IR sources

Dy^{3+}-doped mid-IR source : a model

- Simulation:
  - Simultaneous solving of population and propagation equations along the fiber



  - Fluorescence guided contribution : solid angle considerations

$$\eta = \frac{\Omega}{4\pi} = \frac{2\pi(1-\cos(\theta))}{4\pi}$$

$2\pi(1-\cos(\theta))$ → solid angle

4π → Isotropic emission basically

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Dy^{3+}-doped mid-IR source : a model

- Population equations :

Pump absorption

Energy transfer

$^6H_{5/2}+^4F_{7/2}$

$$\sigma_p.\phi_p(p).N_0 - \frac{N_4}{\tau_4} = 0$$

$^6H_{9/2}+^4F_{11/2}$

$$N_4.(A^R_{43} + A^{MP}_4) - \frac{N_3}{\tau_3} - W_{30}.N_3.N_0 = 0$$

$^6H_{11/2}$

$$N_4.A^R_{42} + N_3(A^R_{32} + A^{MP}_3) - \frac{N_2}{\tau_2} - W_{20}.N_2.N_0 = 0$$

$^6H_{13/2}$

$$N_4.A^R_{41} + N_3.A^R_{31} + N_2.(A^R_{21} + A^{MP}_2) - \frac{N_1}{\tau_1} + 2.W_{30}.N_3.N_0 + 2.W_{20}.N_2.N_0 = 0$$

$$N_T = N_0 + N_1 + N_2 + N_3 + N_4$$

- Propagation equations :

916 nm losses

Pump :

$$\frac{dP}{dz} = (-\sigma_p.N_0 - \alpha_p$$

4.4µm spontaneous emission within the solid angle

4.4µm losses

Fluorescence :

$$\frac{dP_{21}}{dz} = (\sigma_{21}.N_2 - \sigma_{12}.N_1 - \alpha_{p21}).P_{21} + A^R_{21}.\eta.h.\nu_{21}.S_f.N_2$$

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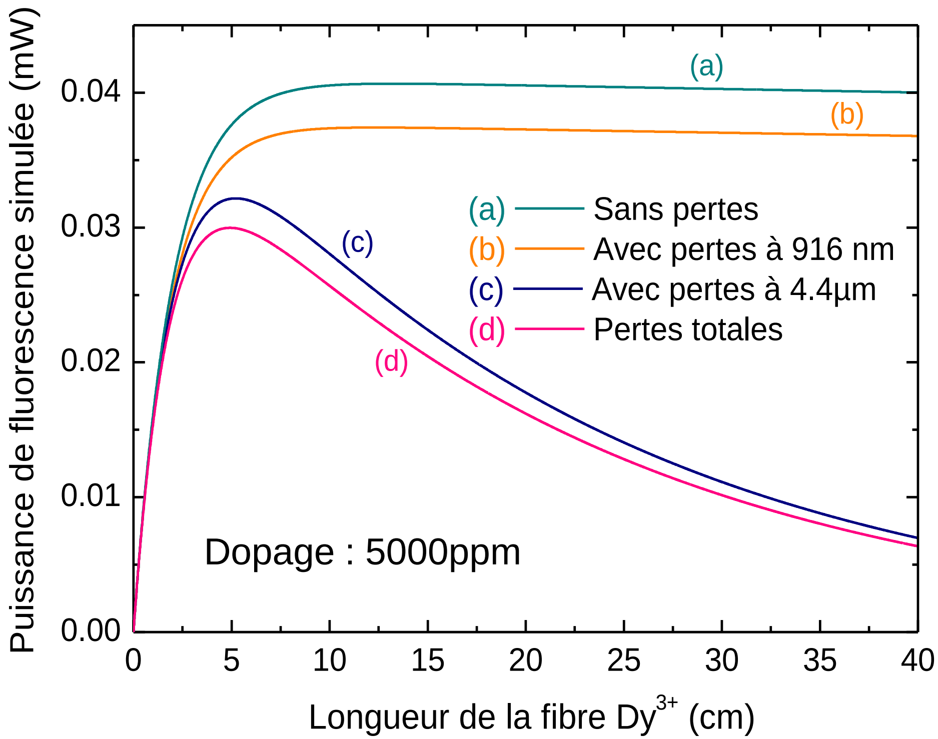
Dy^{3+}-doped mid-IR source : a model

- Results : 4.4µm output power
  - Propagation losses influence :



(a) - increase of P_{IR} until full pump absorption (Beer-Lambert)

(b) - **916 nm losses (19 dB/m)** : decrease of P_{IR}

(c) - **4.4µm losses (20 dB/m)** : not compensated by Dy^{3+} fluorescence → decrease of P_{IR}

(d) - **All losses included**

4.4 µm losses dominance in the process

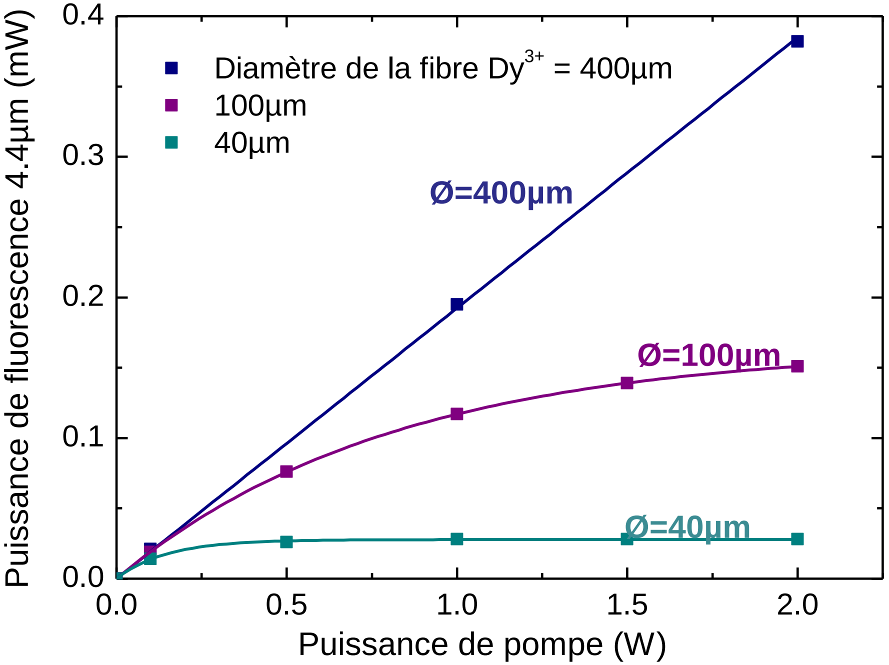
Dy^{3+}-doped mid-IR source : a model

- Fiber diameter influence :

- **$Ø_{fibre}$= 400 µm** : linear shift of P_{IR} with respect to P_{pump} → no ground state deplection

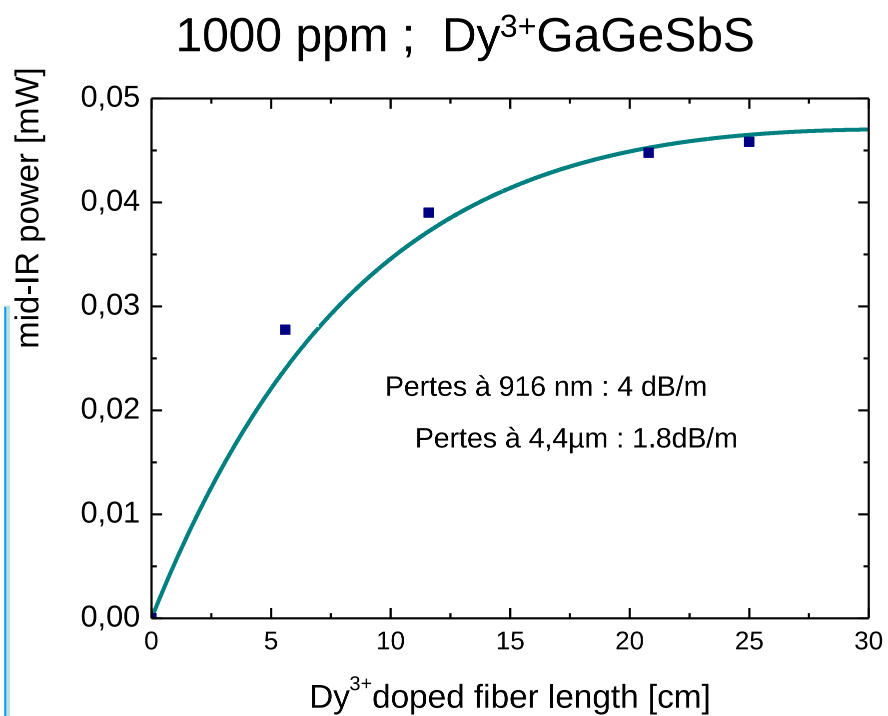
- **$Ø_{fibre}$= 40µm** : absorption saturation → P_{IR} ~ cste / P_{pump}

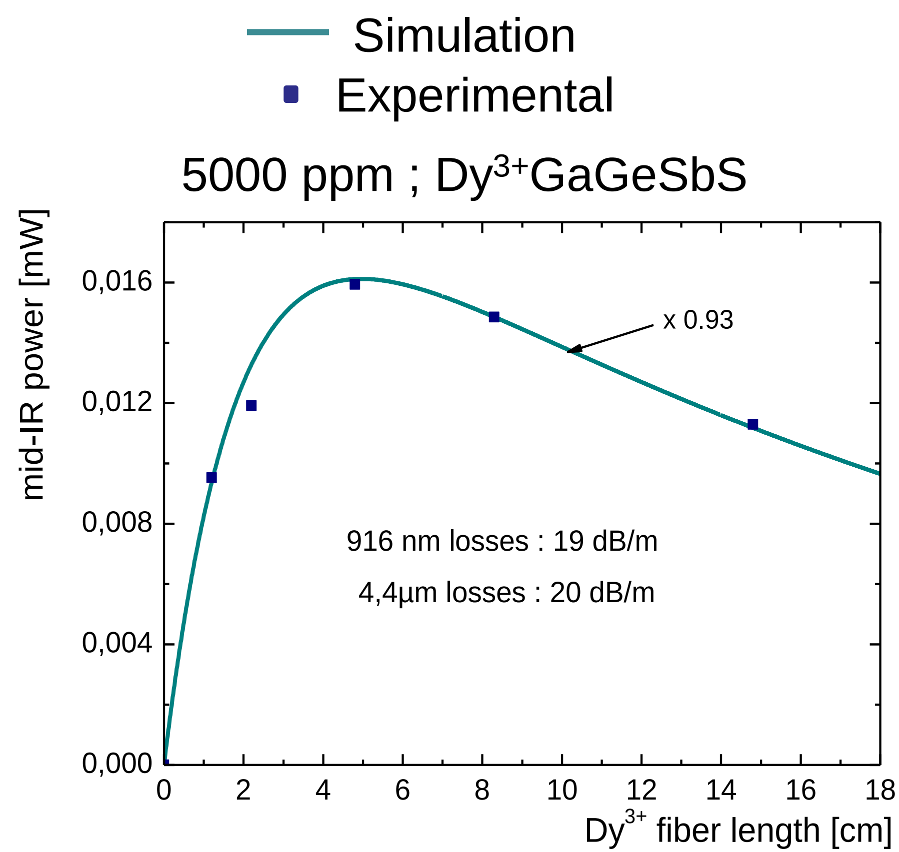
- **$Ø_{fibre}$= 100µm** (mixed case) :
  - low pumping power → linear variation of P_{IR},
  - high pumping power → saturation



400 µm diameter fibers

Dy^{3+}-doped mid-IR source : experimental





1000 ppm fiber fluorescence stronger than the 5000 ppm case : losses and desactivated ions.

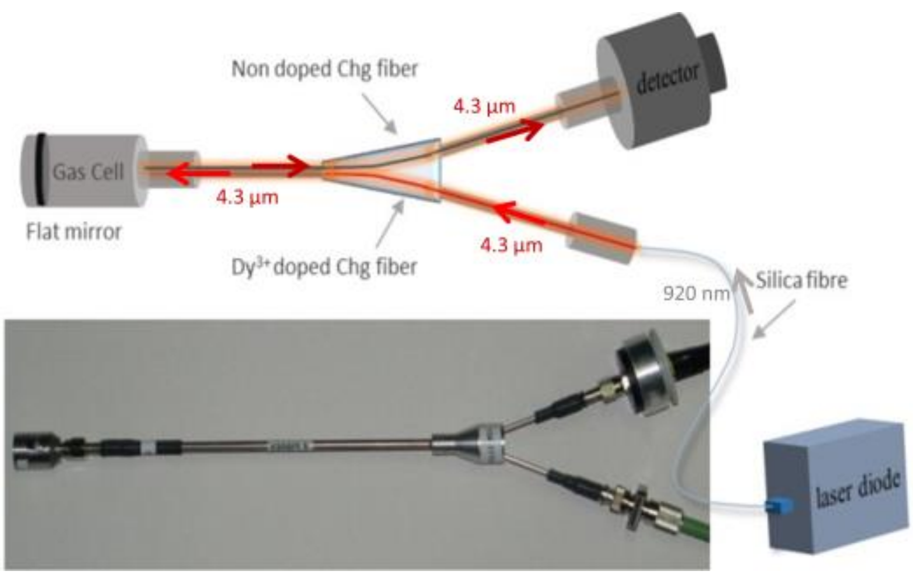
1000 ppm, 28 cm long, 400 µm diameter. Losses: 4 dB/m @916 nm and 1.8 dB/m @4.4µm

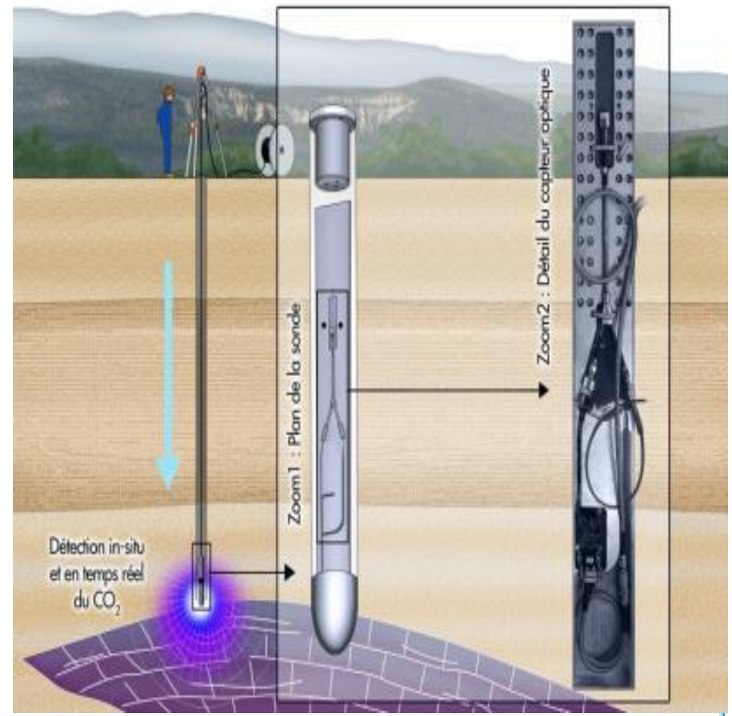
Projet ADEME

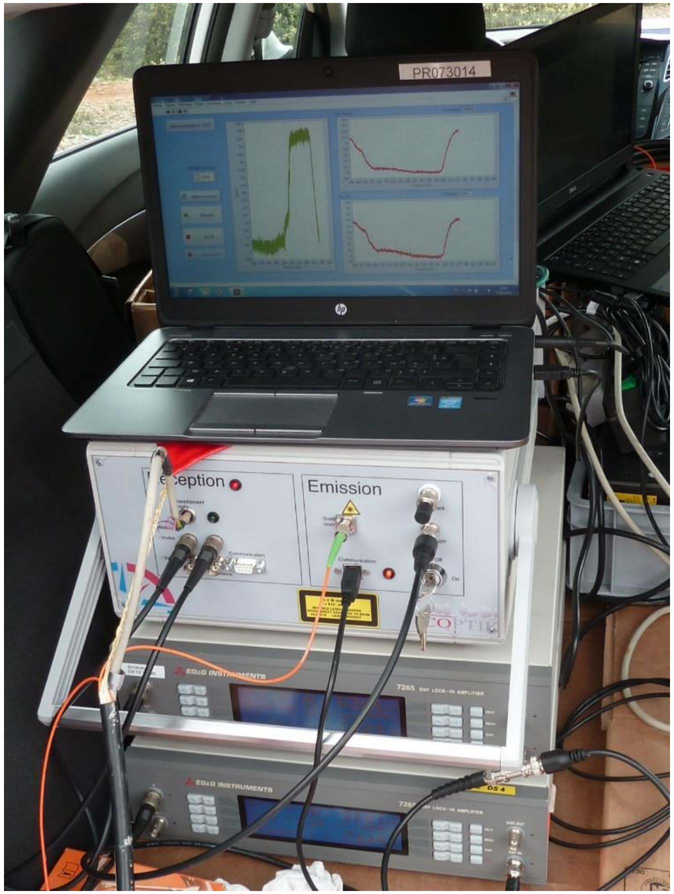
ADEME

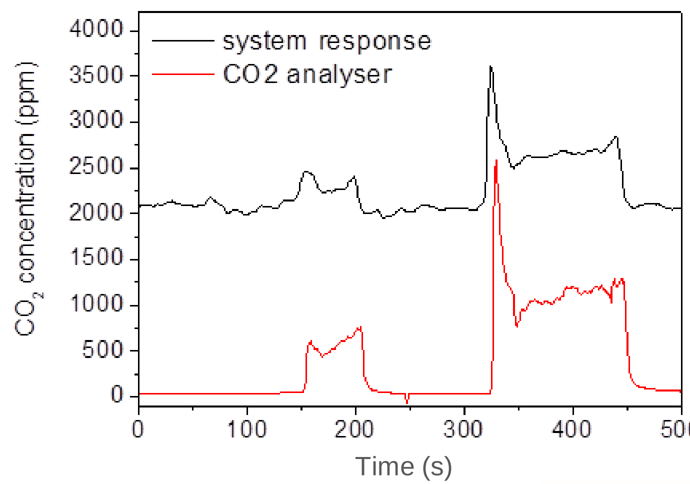
Agence de l'Environnement et de la Maîtrise de l'Energie

- applications examples
  - CO_2 leakage detection in gas pits









Achievements to date:

Detection by **fluorescence of Dy^{3+} in mid-IR** around 100 m depth

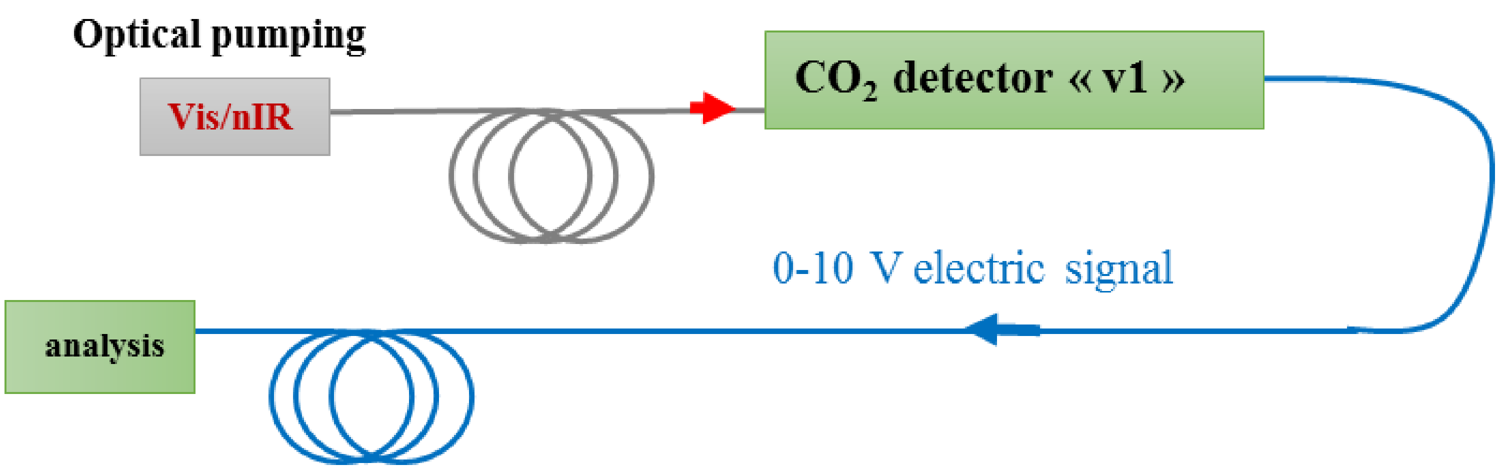
Detection threshold of **few hundreds of ppm**

$\sqrt{CO_2}$PTIK

Starecki, F., et al., Sensors and Actuators B-Chemical, 2015. **207**: p. 518-525.

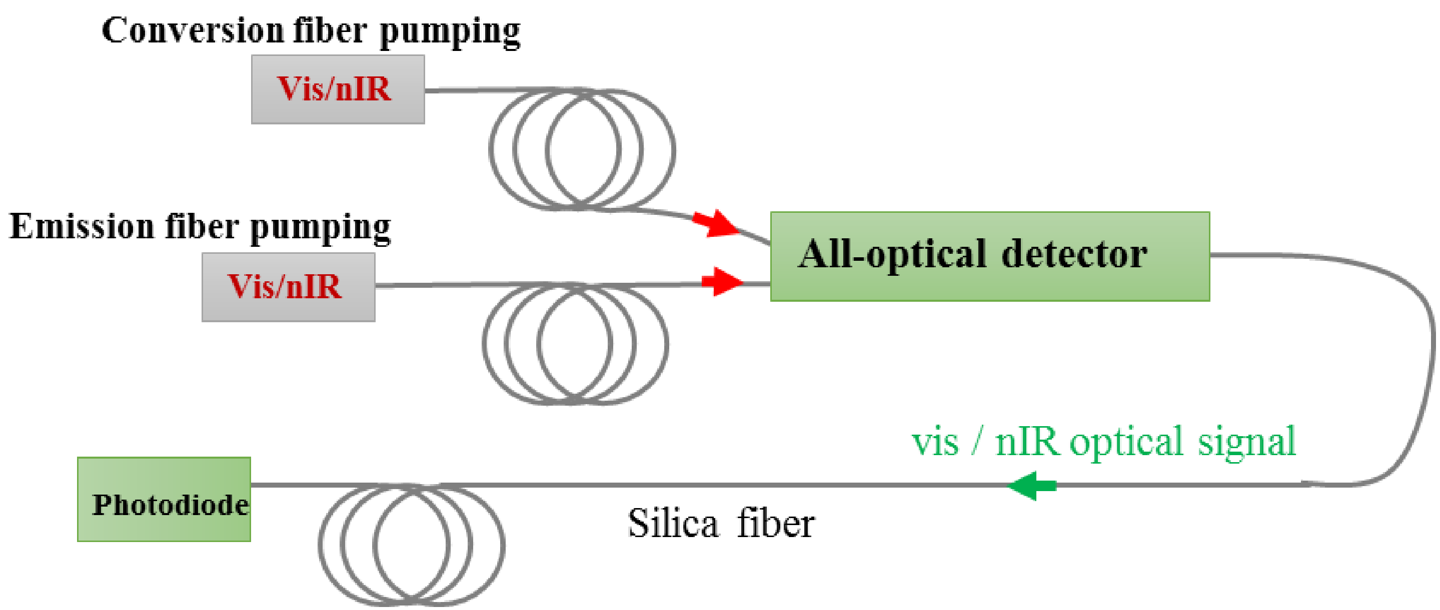
All-optical detector

- Today : electronic parts remains in-situ



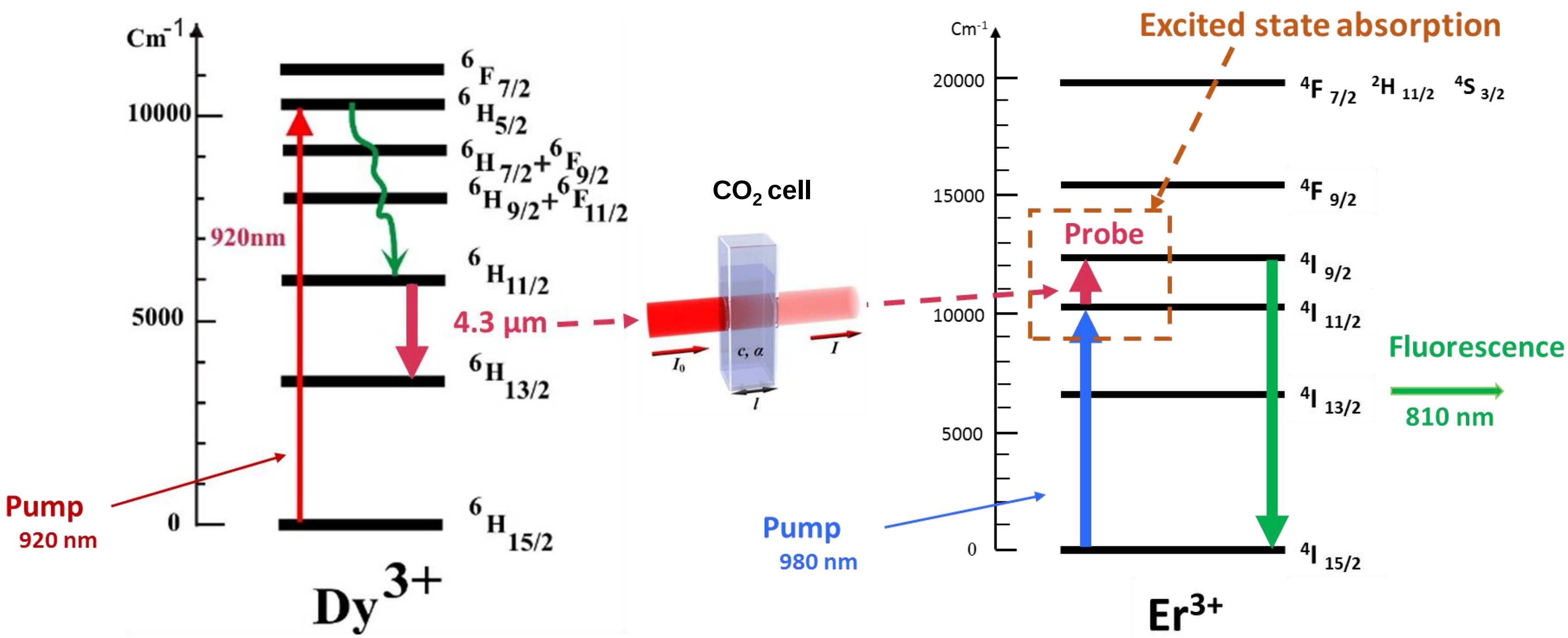
All-optical detector

- **Rare earth doped converter** from **m-IR** to **vis-nIR** optical signal



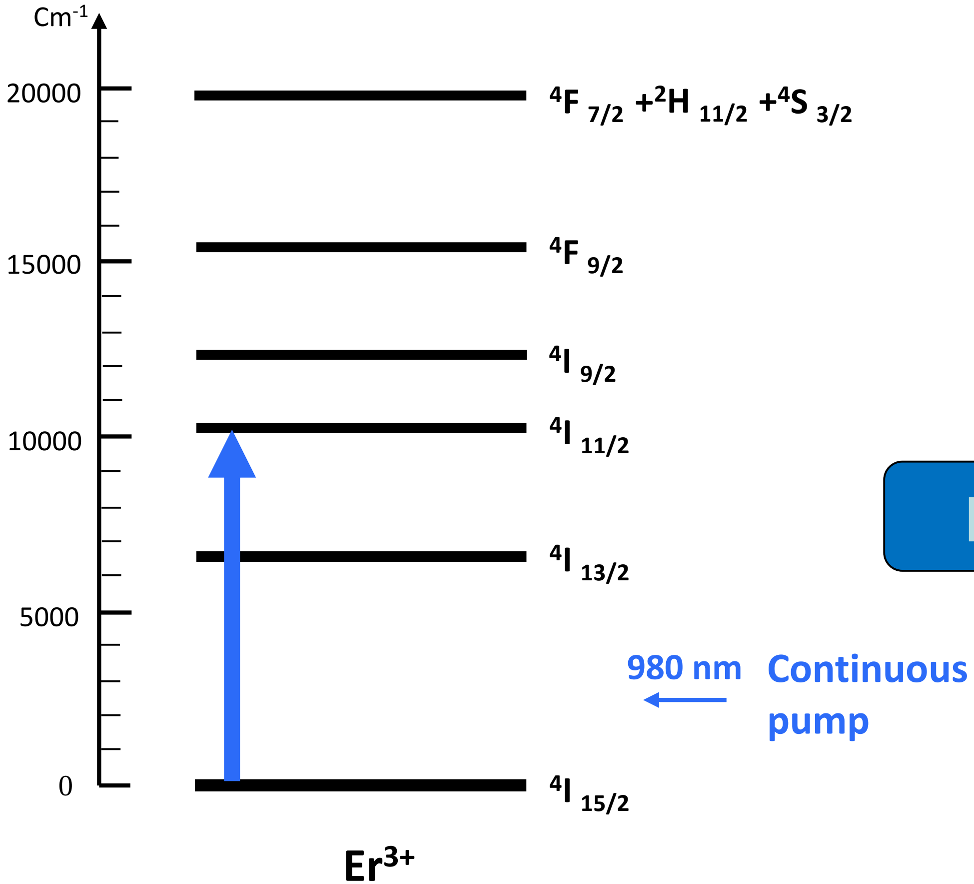
AEE based energy conversion

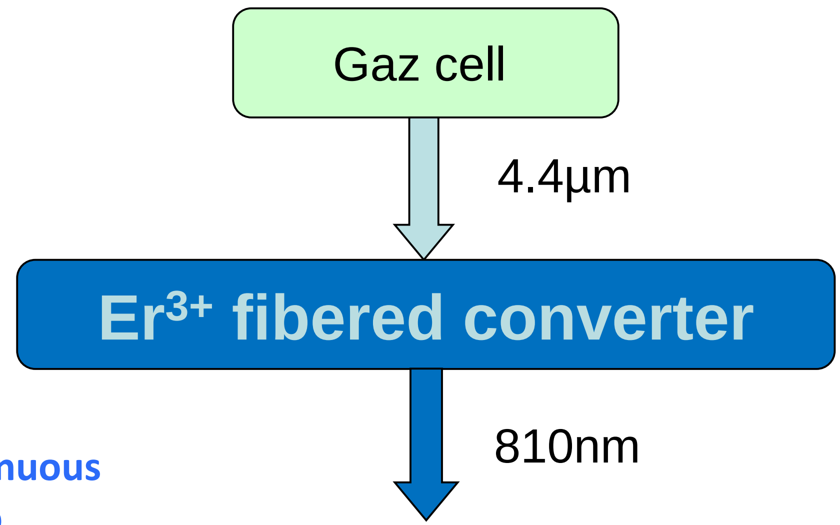
- CO_2 case : **4,3 µm → 810 nm** conversion
  - Using an **Er^{3+} excited state absorption**



AEE based energy conversion

- Erbium – Er^{3+} (from 4.4µm to 810 nm)





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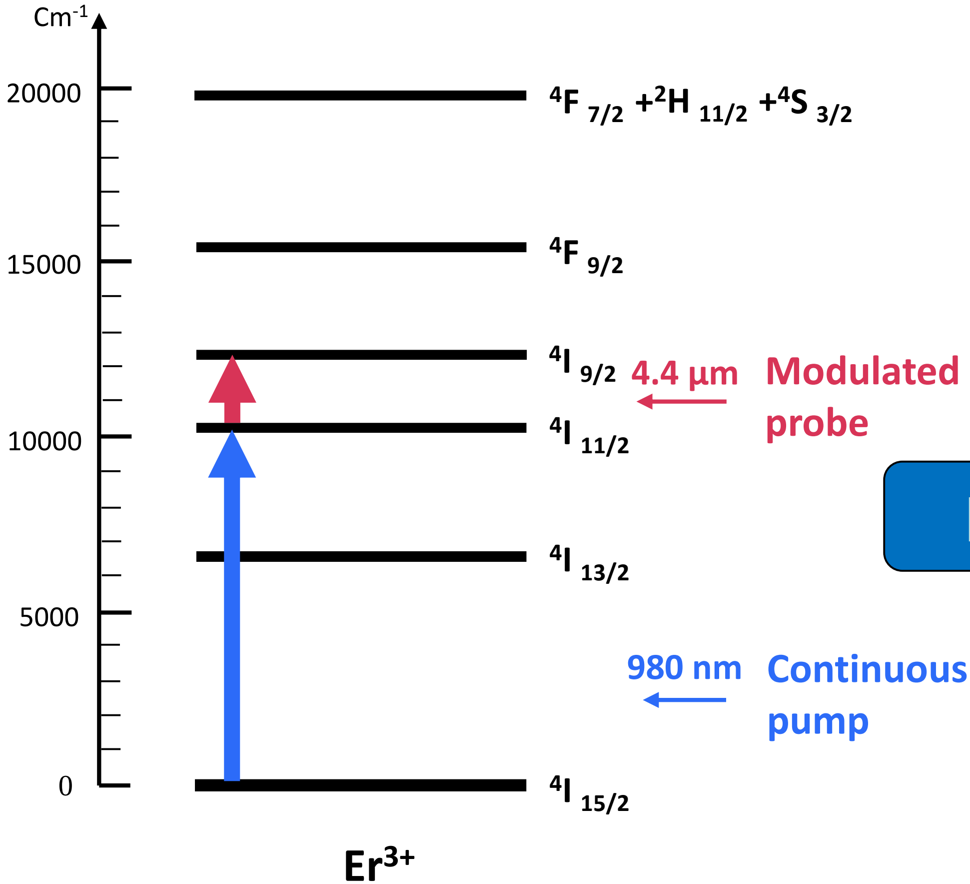
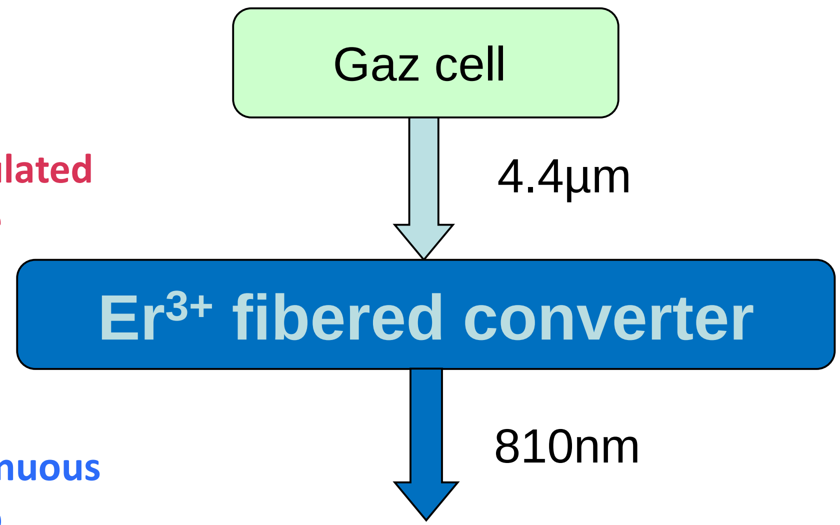
AEE based energy conversion

- Erbium – Er^{3+} (from 4.4µm to 810 nm)





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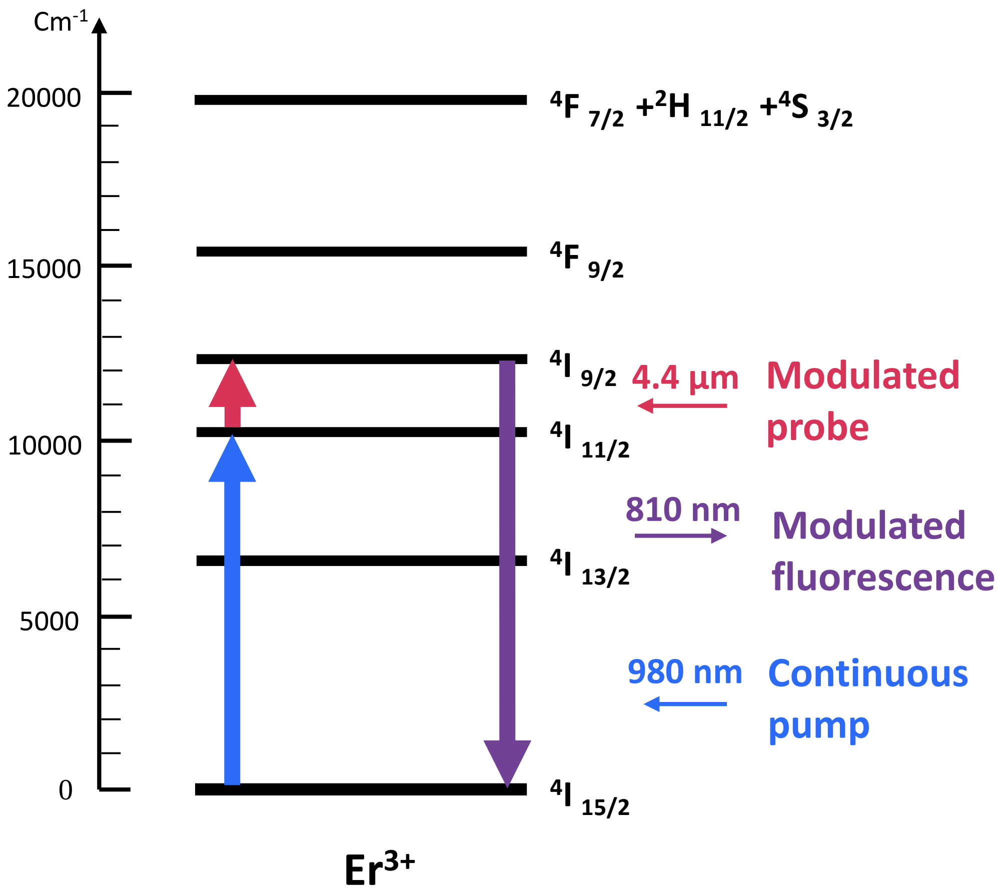


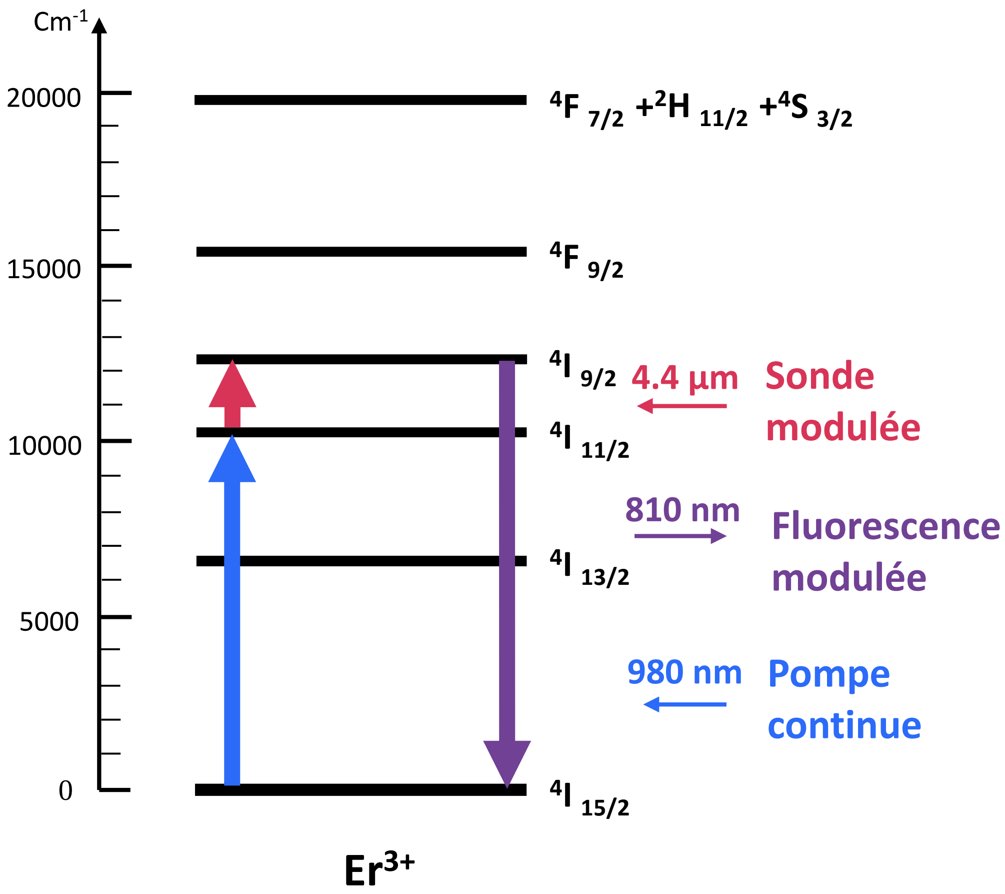
- quantum process: IR photon turned into nIR or visible photon

↓

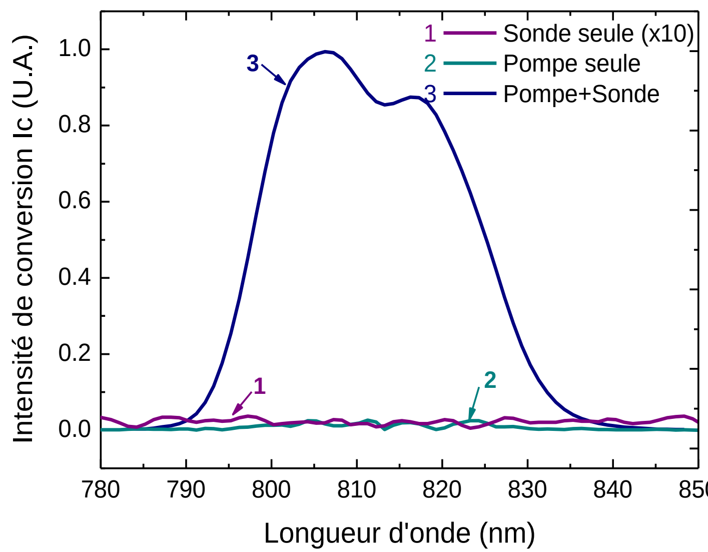
Excited stated absorption (ESA)

AEE based energy conversion

- Erbium – Er^{3+} (from 4.4µm to 810 nm)



Experimental proof



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810 nm conversion in Er: GaGeSbS : a model

- Steady state population equations

Energy transfer

$^4S_{3/2} + ^2H_{11/2} + ^4F_{7/2}$

$$-\frac{N_5}{\tau_5} + W_{22}.N_2^2 - W_{50}.N_5.N_0 = 0$$

$^4F_{9/2}$

$$N_5.\left(A_{54}^R + A_5^{MP}\right) - \frac{N_4}{\tau_4} = 0$$

$^4I_{9/2}$

$$N_4.(A_{43}^R + A_4^{MP}) + A_{53}^R.N_5 - \frac{N_3}{\tau_3} + \sigma_{esas}.\phi_s.N_2 + W_{11}.N_1^2 + W_{50}.N_5.N_0 = 0$$

$^4I_{11/2}$

$$N_3.(A_{32}^R + A_3^{MP}) + A_{42}^R.N_4 + A_{52}^R.N_5 - \frac{N_2}{\tau_2} + \sigma_p.\phi_p.N_0 - \sigma_{esas}.\phi_s.N_2 - 2.W_{22}.N_2^2 = 0$$

$^4I_{13/2}$

$$A_{21}^R.N_2 + A_{31}^R.N_3 + A_{41}^R.N_4 + A_{51}^R.N_5 - \frac{N_1}{\tau_1} - 2.W_{11}.N_1^2 + W_{50}.N_5.N_0 = 0$$

$$N_0 + N_1 + N_2 + N_3 + N_4 + N_5 = N_T$$

810 nm conversion in Er: GaGeSbS : a model

- Propagation equations

Pump (980nm): $$\frac{dP}{dz} = (-\sigma_p . N_0 - \alpha_p$$

982 nm losses

Probe (4.4µm) : $$\frac{dP_s}{dz} = (-\sigma_{ESAS} . N_2 - \alpha_{ps}) . P_S$$

4.4µm losses

Ic (810nm converted) : $$\frac{dP_{21}}{dz} = (\sigma_{21} . N_2 - \sigma_{12} . N_1 - \alpha_{p21}) . P_{21} + A^R_{21} . \eta . h . \nu_{21} . S_f . N_2$$

810 nm losses

810 nm spontaneous fluorescence emitted within the crictical angle

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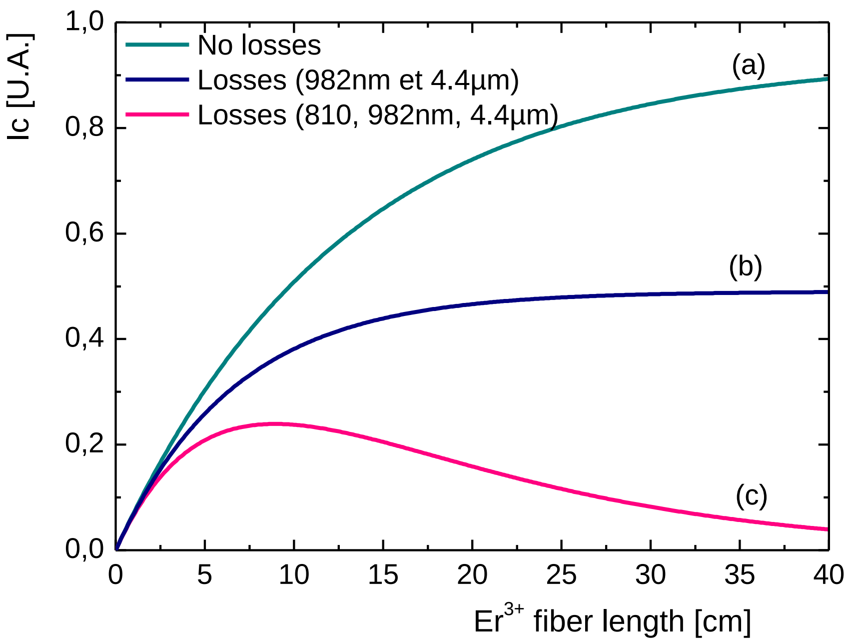
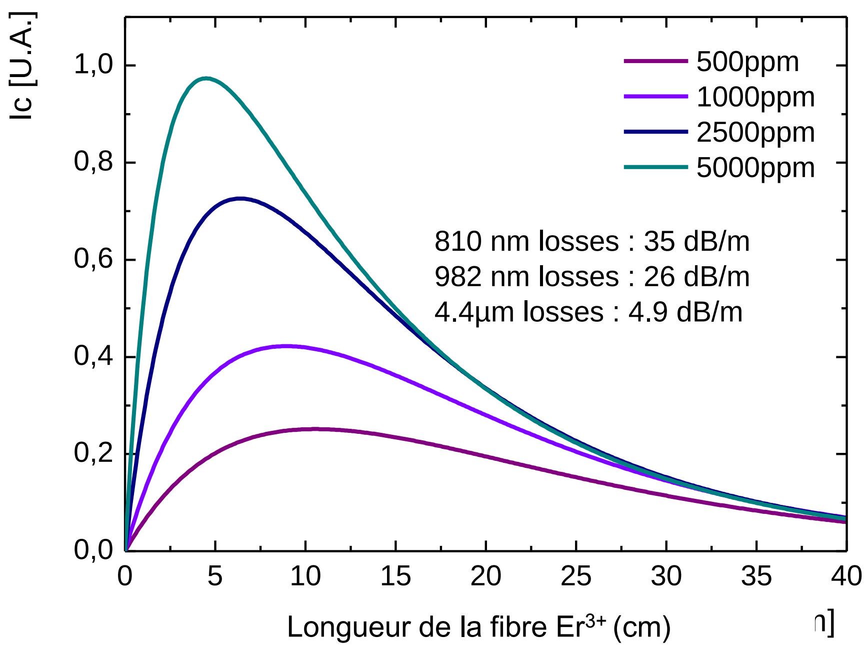
810 nm conversion in Er: GaGeSbS : a model

- 810nm converted intensity

Propagation losses influence



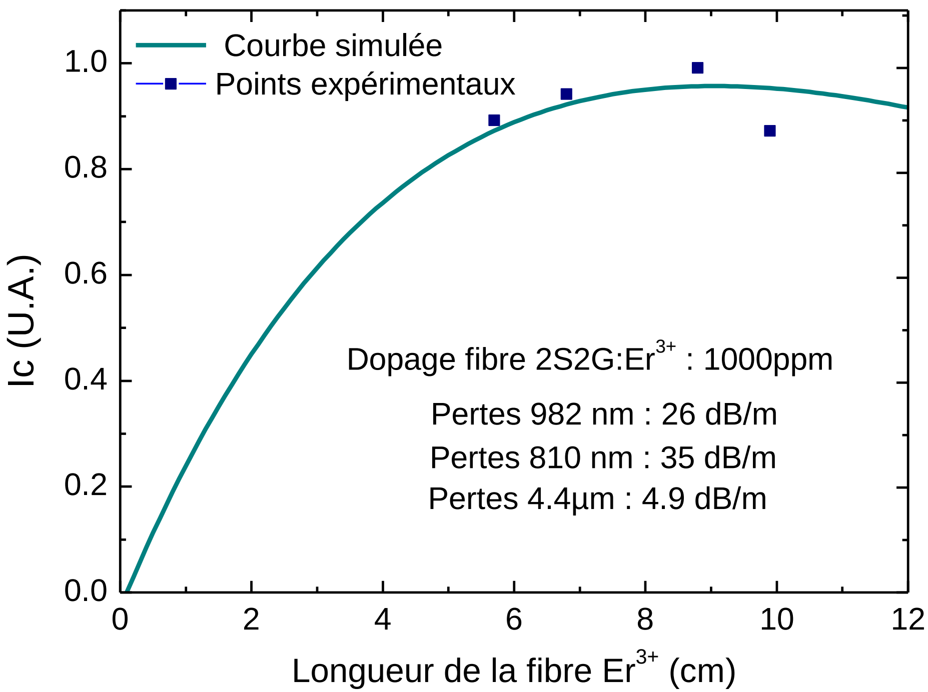
Er3+ doping rate influence



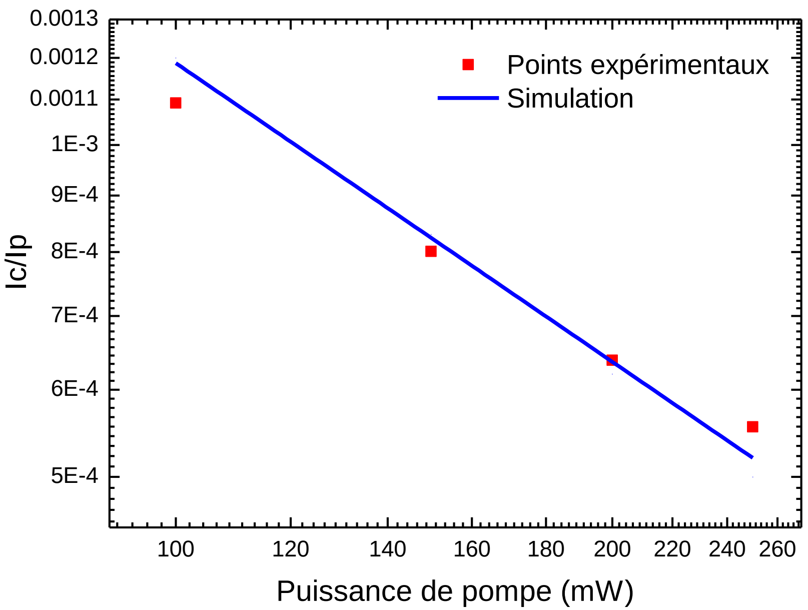
A good compromise: **2500ppm** doping rate, **6 cm** long corresponding to attenuation values of : **35 dB/m @810 nm, 26 dB/m @982 nm et 4.9 dB/m @4.4 µm**

Simulation / experiments

- 1000ppm Er^{3+} GaGeSbS fiber ; 810 nm converted intensity



Signal to noise ratio as a function of the 980 nm pumping power



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Thanks for your attention