Quantification of the optically active Er^{3+} content and its direct excitation cross section in Er^{3+} doped SiO_2 sensitized by Si nanoclusters

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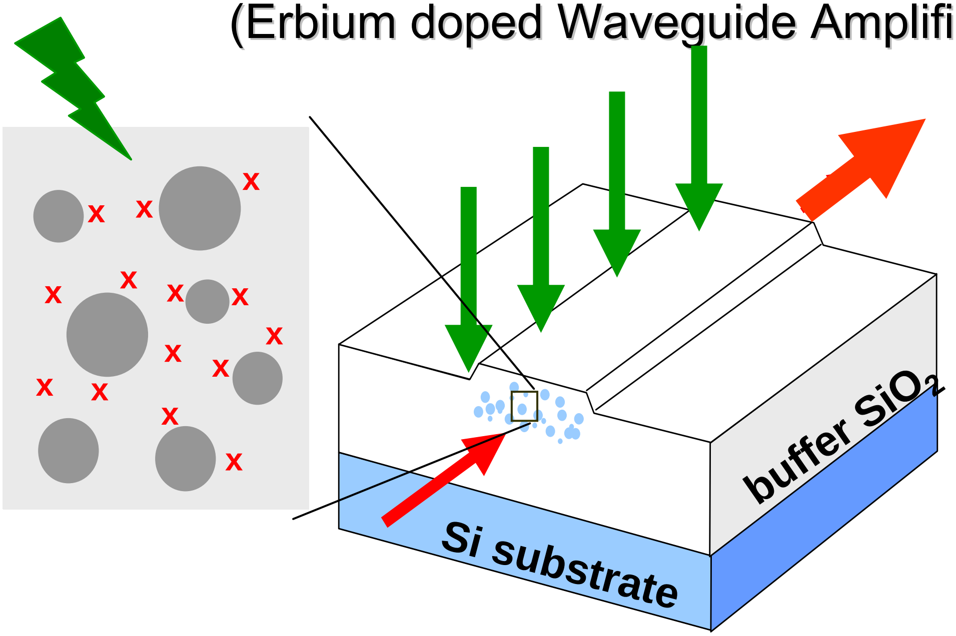
Silicon nanocluster based IR optical amplifier

Si-nc + Er^{3+} in SiO_2

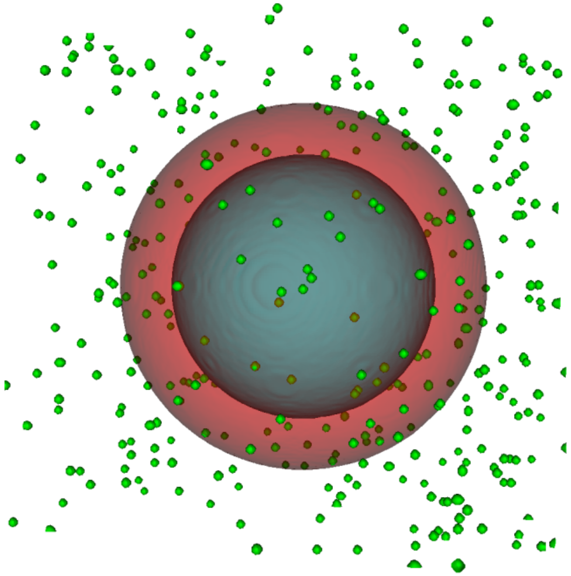
EDWA
(Erbium doped Waveguide Amplifier)



- ➢**Optimised Si-nc to Er^{3+} coupling to excite all the ions through indirect transfer without damaging the PL properties of Er^{3+}**

By taking advantage of the coupling between Si-nc and Er^{3+} ions

Motivations



Several reports show low percentages of coupled Er contents ranging from less than 1% to few tens percent (our case).

Apart from the indirect excitation problem, it has been proposed that up to several tens percent of the deposited Er content could not be even optically active, i.e. not able to emit light even if pumped directly.

⇓

Only a part of the total content will be potentially able to provide optical gain in an amplifier when inverted.

We wanted to study the optical properties of the optically active Er^{3+} content and quantify its concentration (**N_{Er}**).

How is it usually determined the active Er^{3+} content?

Resonant $\longrightarrow$ $N_2(488nm) \approx \sigma_{Si-nc,488}\tau_{PL}N^*_{Er}\varphi + \sigma_{d,488}\tau_{PL}N_{Er}\varphi$

Non resonant $\longrightarrow$ $N_2(476nm) \approx \sigma_{Si-nc,476}\tau_{PL}N^*_{Er}\varphi$

$\sigma_{Si-nc,488} \approx \sigma_{Si-nc,476}$

N^*_{Er} :Erbium content coupled to Si-nc

$N_2(488nm) - N_2(476nm) \approx \sigma_{d,488}\tau_{PL}N_{Er}\varphi$, at low fluxes

…but $\sigma_{d,488}$ assumed to be the same as in Er^{3+} in SiO_2 (~10^{-21} cm^2)

... and $\sigma_{Si\text{-}nc}=10^{-16}$-$10^{-17}$ cm^2, so even a small difference in the transfer term would be very important.

Our approach:

We pump Er^{3+} directly at 0.98μm (resonant with the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition):

$$N_2(\Phi) = \xcancel{\frac{\sigma_{Si-nc,980} N^*_{Er} \Phi}{\sigma_{Si-nc,980}\Phi + 1/\tau_{PL}}} + \frac{\sigma_d N_{Er} \Phi}{\sigma_d \Phi + 1/\tau_{PL}}$$

…no contribution from indirect excitation is observed pumping at 980nm since exciton formation within the Si-nc is very unlikely

τ_{PL}, $N_2(\Phi)$ and $\sigma_d(0.98\mu m)$????

τ_{PL} is obtained from TR-PL measurements

The samples

Er:Si-nc produced by Reactive Magnetron co-Sputtering using three (SiO_2, Er_2O_3 and Si) and two cathodes (Er_2O_3 and SiO_2) approach and successive annealing

Two of the best samples obtained so far obtained by optimising the following figures of merit:

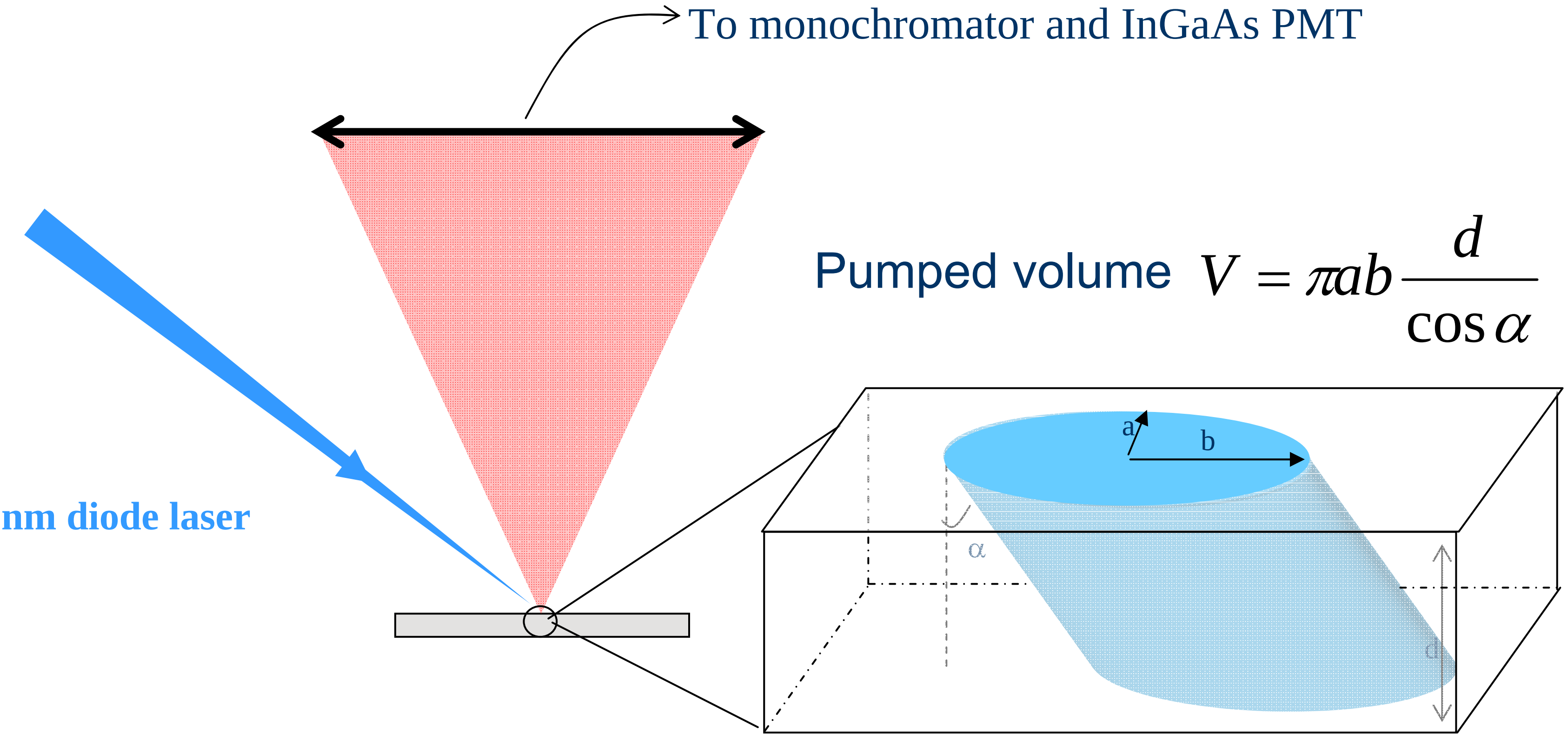
- $^4I_{13/2} \rightarrow {}^4I_{15/2}$ PL (@ 1535nm) under non-resonant pumping (476nm)
- $^4I_{13/2} \rightarrow {}^4I_{15/2}$ lifetime
- Carrier absorption

Khomenkova et al., Physica E, 2009
Hijazi et al., Physica E, 2009

Sample	Si excess [at %]	Er^{3+} conc [cm^{-3}]	Lifetime ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) [ms]
A *(3 cathodes)*	8.5 ± 2.0	3.6 ± 0.2 x 10^{20}	4.2 ± 0.2
B *(2 cathodes)*	5.0 ± 2.0	3.4 ± 0.2 x 10^{20}	4.8 ± 0.2

Determination of $N_2(\Phi)$

Calibrated PL setup conditions



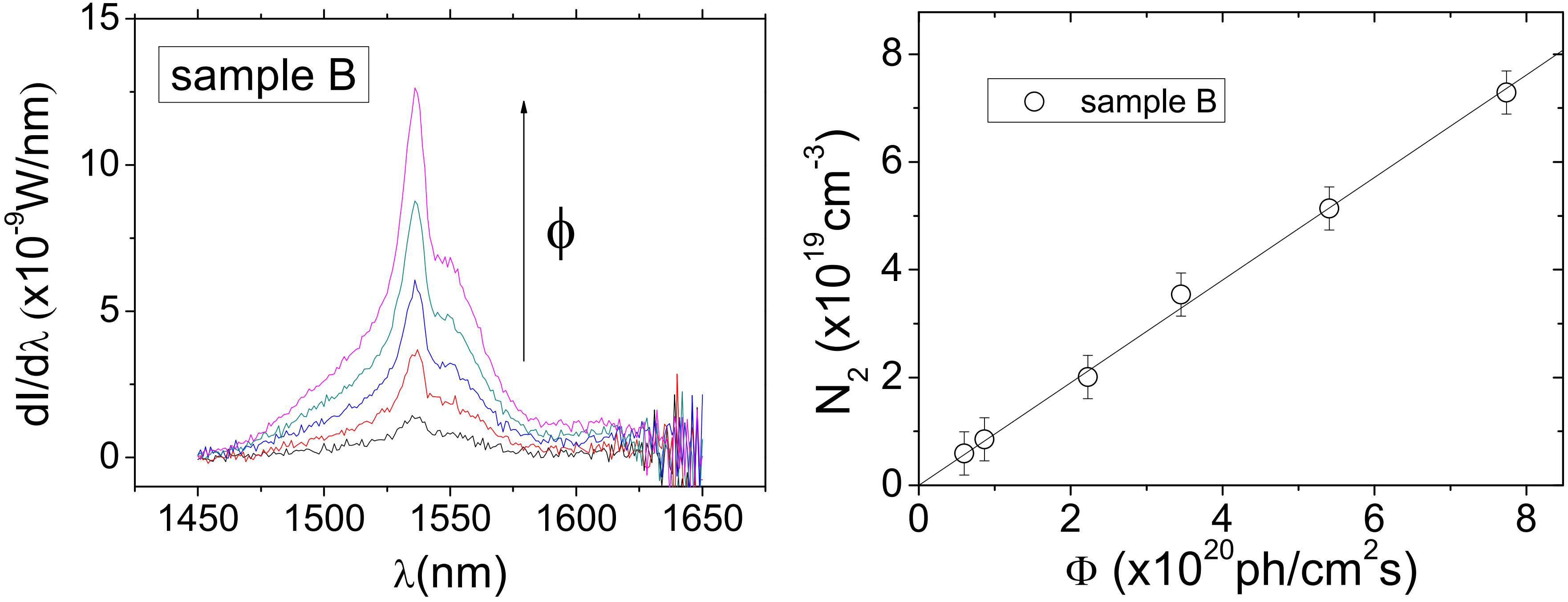
Pumped volume $V = \pi ab \dfrac{d}{\cos\alpha}$

We assume that the photon flux is constant within this pumped volume.

PL signals have been all normalised to the sample thickness

Case of sample B

$$\frac{\Phi_{em}\tau_{rad}}{V} = N_2 \qquad N_2(980nm) \approx \boxed{\sigma_{d,980}} N_{Er}\tau_{PL}\phi$$

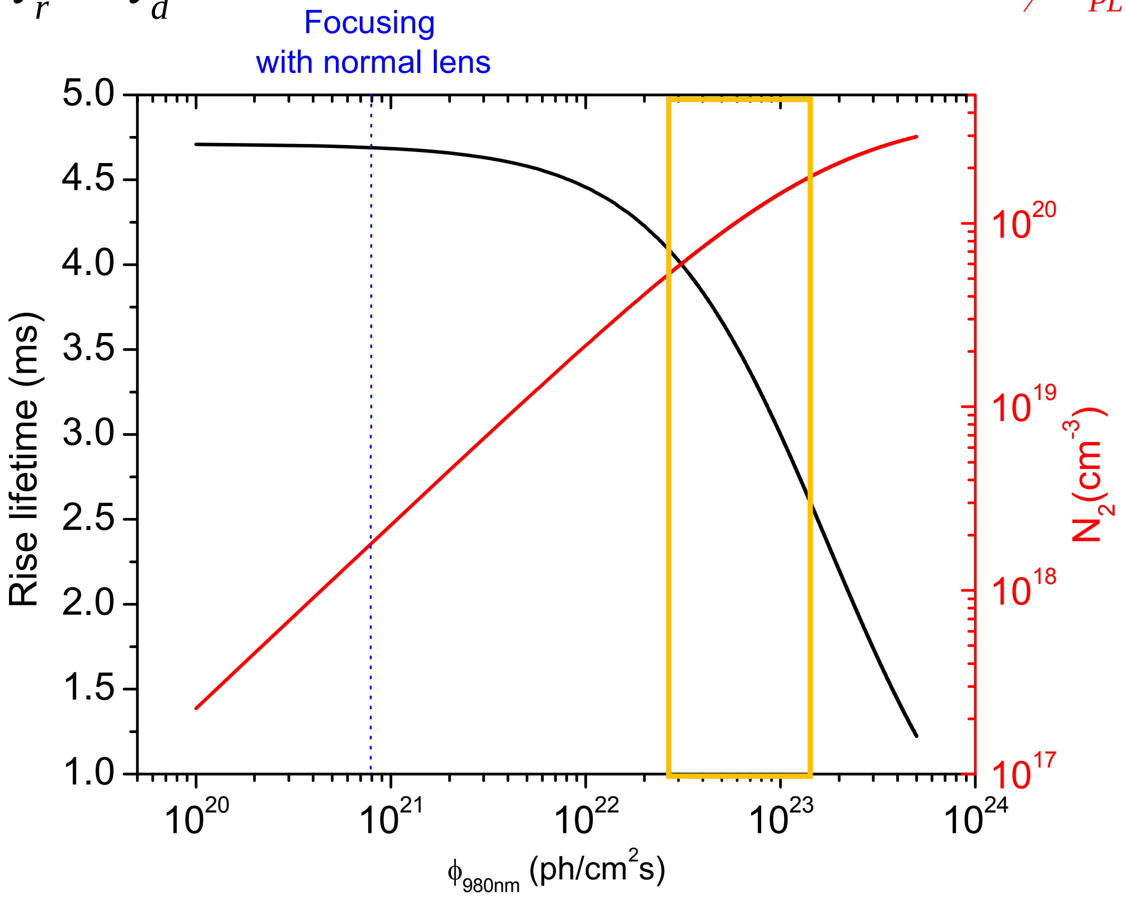


Determination of σ_d

In quasi-two level system:

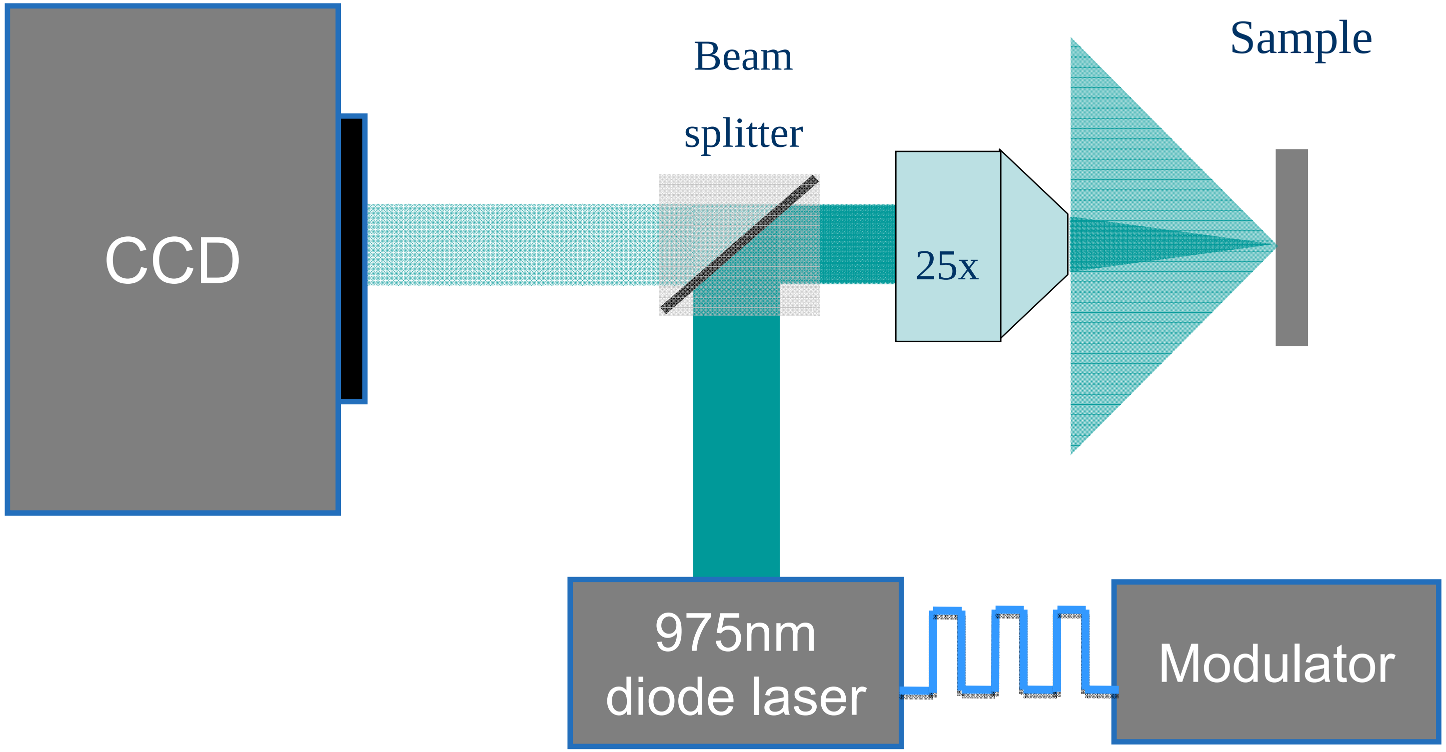
$$\frac{1}{\tau_r} - \frac{1}{\tau_d} = \sigma_d \Phi$$

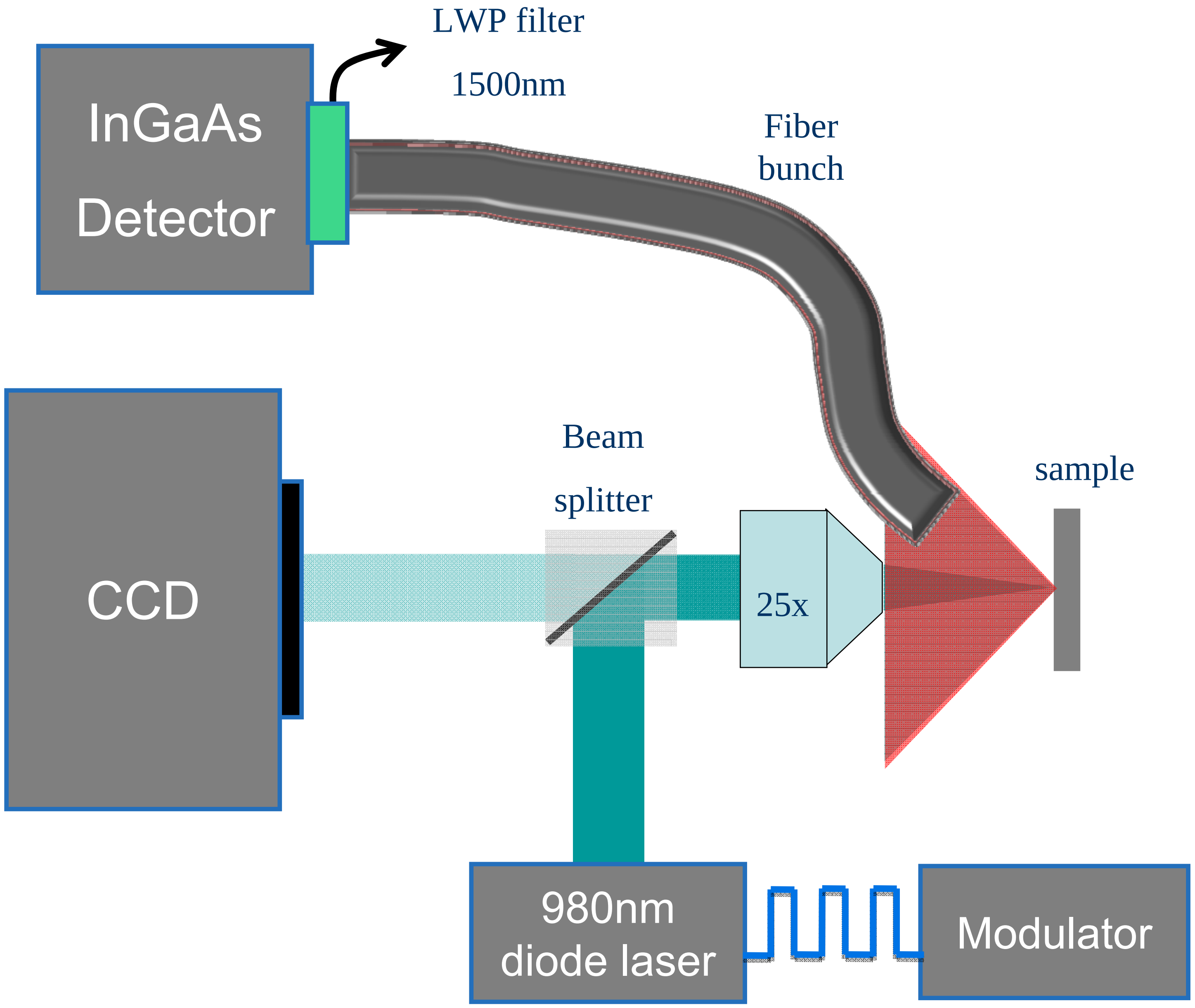
$$N_2 = \frac{\sigma_d N_{Er} \phi}{\sigma_d \phi + 1/\tau_{PL}}$$



Decrease the spot size by two orders of magnitude

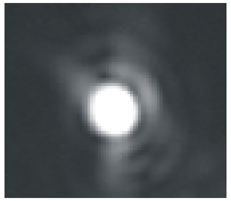
Experimental setup

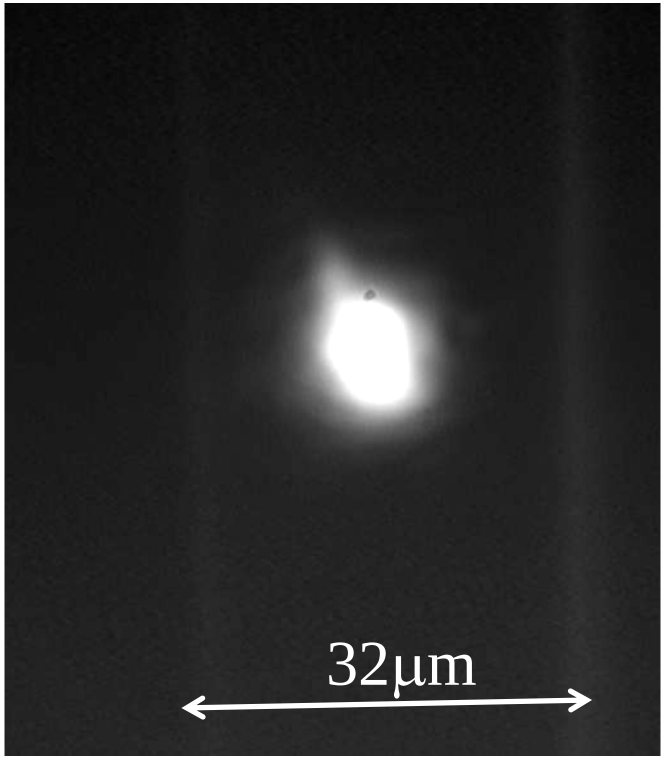


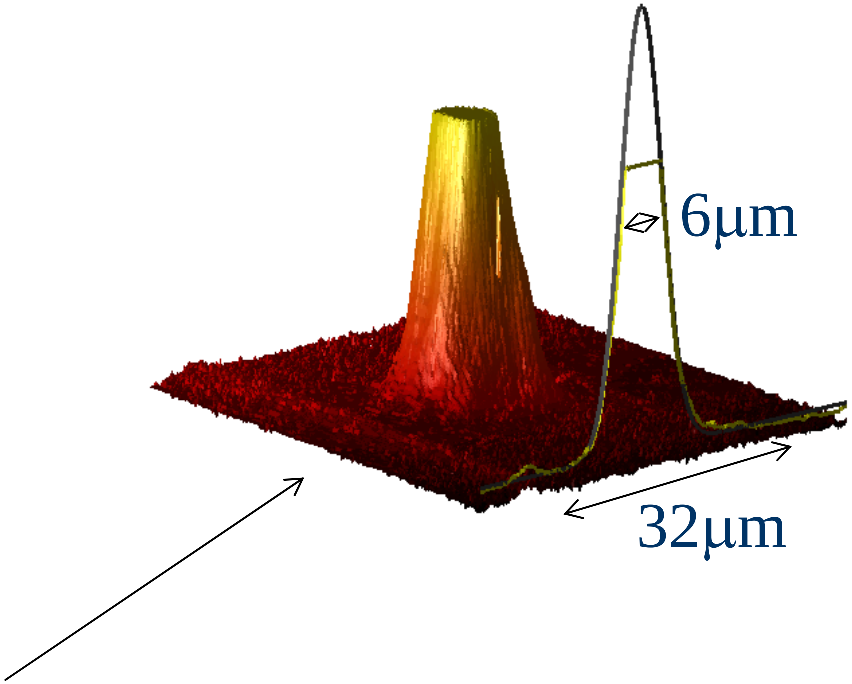

LWP filter
1500nm
InGaAs
Detector
Fiber
bunch
Beam
splitter
sample
CCD
25x
980nm
diode laser
Modulator

Quantifying the dimensions of the pumping spot

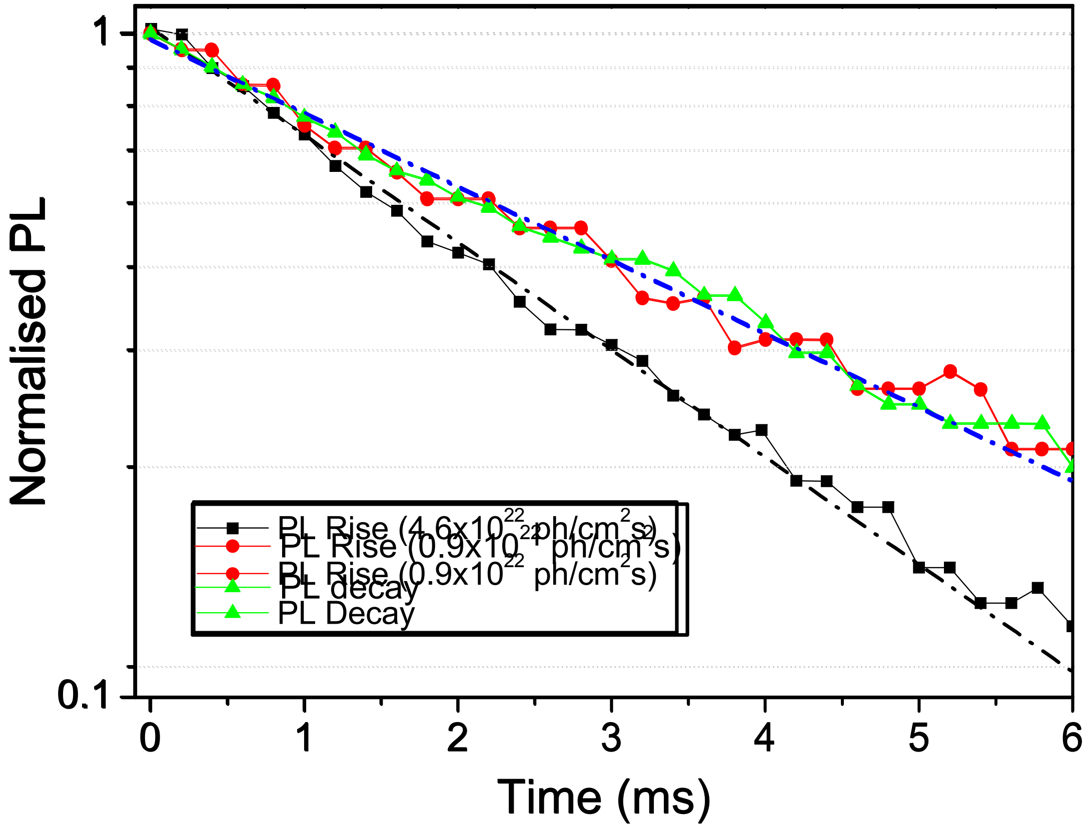
Spot on the surface of a waveguide
of known width







Rise and decay lifetimes



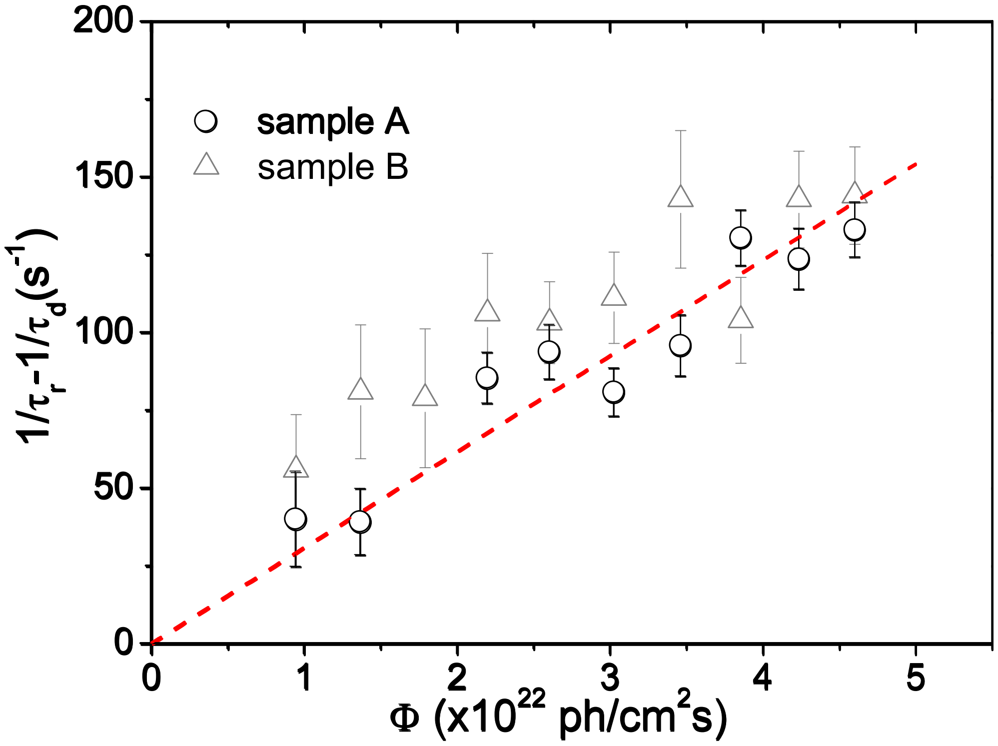
The experimental PL rises are inverted and normalized for clarity.

At high flux the rise lifetime is lower.

Estimation of $\sigma_{exc,975nm}$

$$\frac{1}{\tau_r}-\frac{1}{\tau_d}=\sigma_{exc,975}\Phi$$

$\sigma_{exc,975}=3.1\text{x}10^{-21}\text{cm}^2$



Both samples showed similar results, i.e. σ_{exc} is roughly the same.

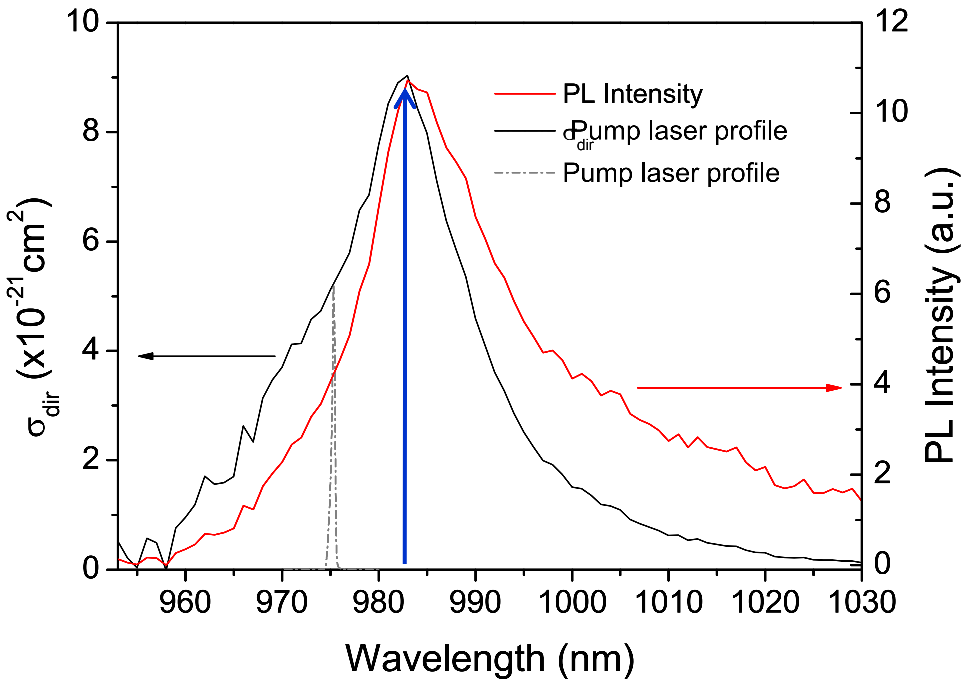
Some considerations

1) Rough approximation: $I_{PL} \alpha \sigma_{em}$

2) $$\sigma_{dir}(\lambda) = \sigma_{em}(\lambda)\exp\left[\frac{hc}{kT}\left(\frac{1}{\lambda} - \frac{1}{\lambda_m}\right)\right]$$

3) We normalise the resulting curve, taking into account that

σ_{dir} (975)=3.1x10^{-21}cm^2

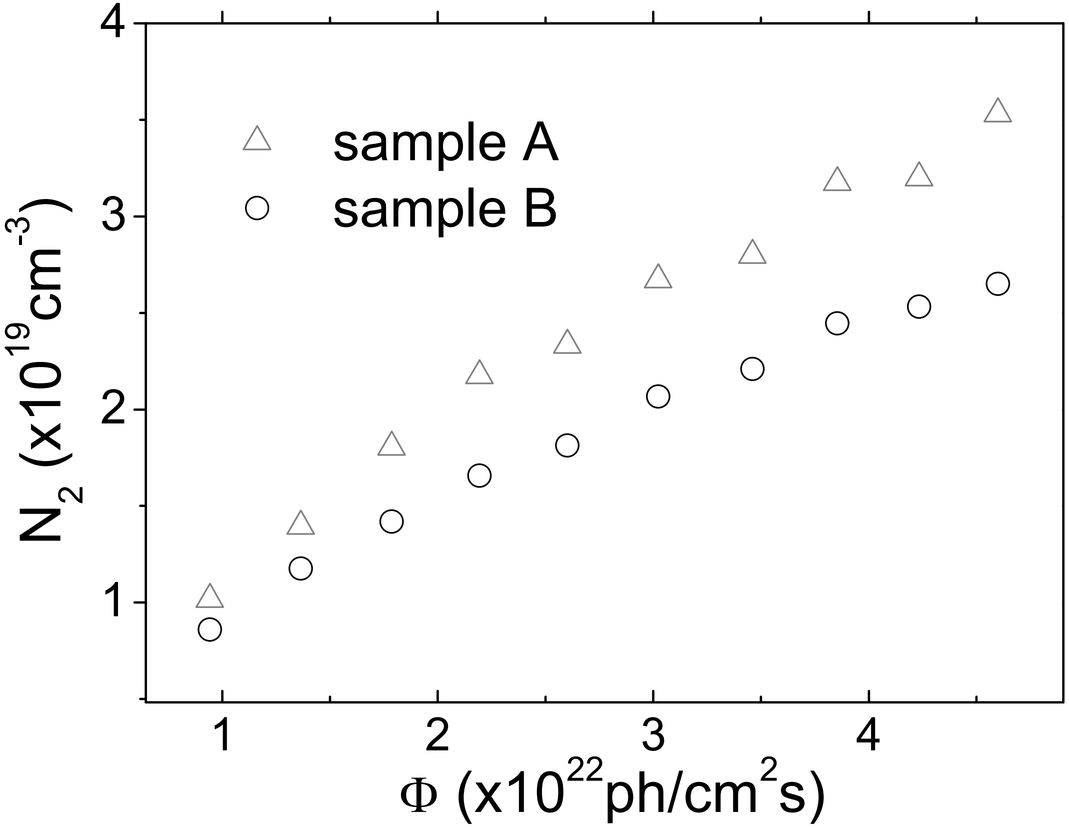


σ_{dir} (983nm)= 9.0x10^{-21}cm^2

In silicate glasses without Si excess are about 2-5x10^{-21}cm^2 at the peak wavelength

Quantification of the optically active content

$$N_2 = \frac{\sigma_d N_{Er} \phi}{\sigma_d \phi + 1/\tau_{PL}}$$



Sublinear behaviour with Φ.

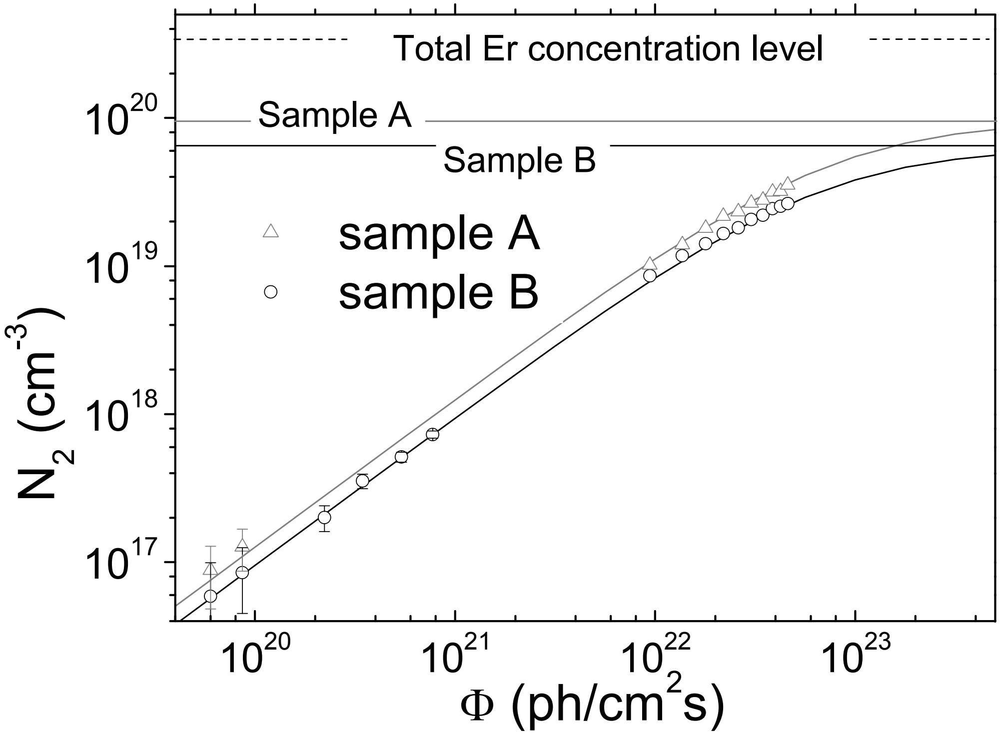
Saturation of N_2 is starting to be achieved

Sample A has more optically active Er content than sample B

Quantification of the optically active content

$$N_2 = \frac{\sigma_d N_{Er} \phi}{\sigma_d \phi + 1/\tau_{PL}}$$

Combining high and low Φ results:



Sample A:

$N_{Er}=0.93 \times 10^{20}$cm^{-3} (26% of the total Er^{3+} content)

Sample B:

$N_{Er}=0.64 \times 10^{20}$cm^{-3} (19% of the total Er^{3+} content)

Is the remaining Er content totally unactive (**not absorbing and not emitting**) or just the light emission mechanism is quenched (**not emitting but absorbing**) ???

If it is the second possibility then more than half of the population will "always" be found in the fundamental state (only contributing to optical losses)

In general: $N_{Er} \leq N_{Er,abs} \leq N_{Er,total}$

Absorption losses spectrum at 1.55μm (low contribution from Si-nc)

+

Measurement of σ_{dir} at 1.48μm …work in progress

Conclusions

- We have done an estimation of the direct excitation cross section of Er^{3+} evaluating the rise and decay lifetimes of the 1.55μm PL as a function of the photon flux. This magnitude is useful for determining the optically Er^{3+} content in a sample.
- Only 20-25% of the Er^{3+} present in the samples is able to emit light and, thus, potentially able to provide optical gain in an amplifier when inverted, i.e. the potential gain will be reduced by at least a factor of 4 with respect to what would be given by the total Er^{3+} content.
- It remains open the role of the remaining Er present in the samples.

Acknowledgments

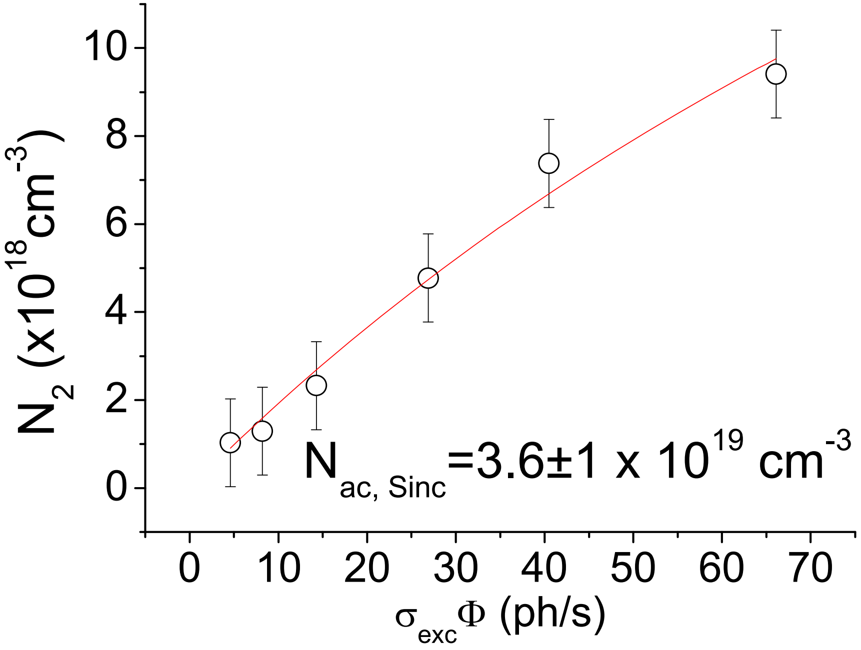
This work has been founded by EC through FP 6 – Lancer project

THANK YOU!

Quantification of the erbium coupled to the Si-nc

Sample B

$$N_2 = N_{ac,Sinc}\frac{\sigma_{exc}\Phi}{\sigma_{exc}\Phi + 1/\tau_{PL}}$$



The coupled Er^{3+} content should be compared to $\mathbf{N_{Er}}$ and **not** to the total content.

Around 53% of the optically active erbium (11% of the total Er concentration).