Signal enhancement and limiting factors in waveguides containing Si nanoclusters and Er^{3+} ions

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Outline

- ✓ Introduction to the system under study.
- ✓ Characterisation and modelling of the studied samples.
- ✓ Signal enhancement setup and measurements.
- ✓ Conclusions

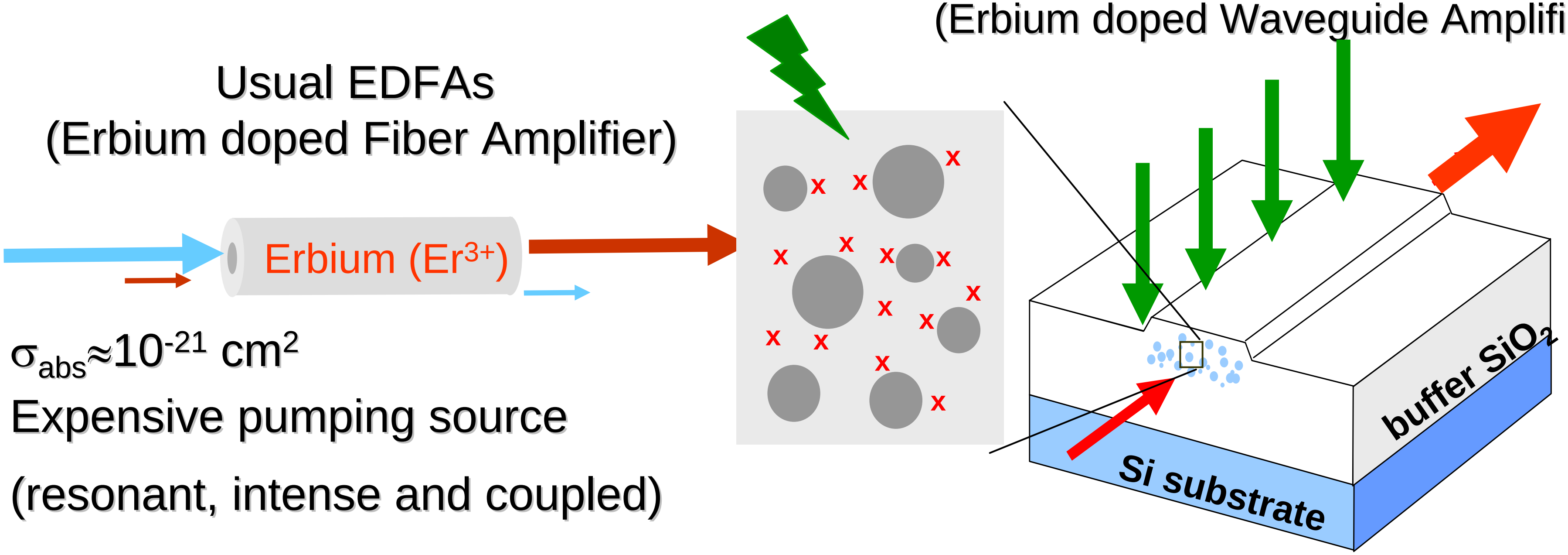
Introduction

We want to improve

by using

EDWA
(Erbium doped Waveguide Amplifier)

Usual EDFAs
(Erbium doped Fiber Amplifier)



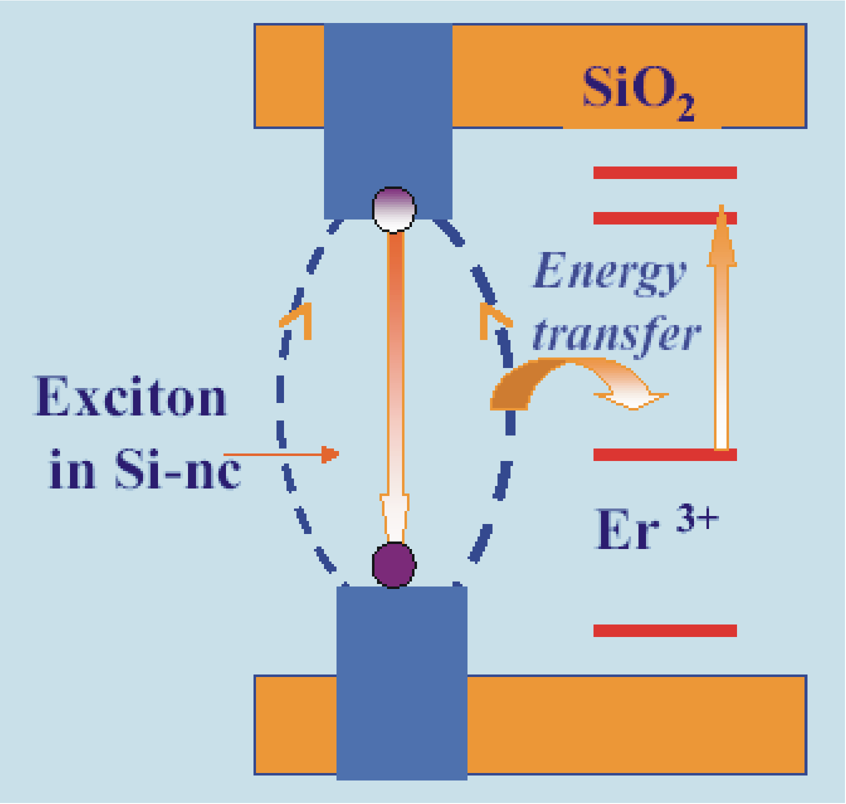
$\sigma_{abs} \approx 10^{-21}$ cm^2

Expensive pumping source

(resonant, intense and coupled)

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

Why Si-nc?



Broad band absorption (UV-VIS)

Increment of excitation for Er^{3+} : σ_{exc} from ~10^{-21} (in SiO_2) to 10^{-16}-10^{-18} cm^2 (with Si-nc)

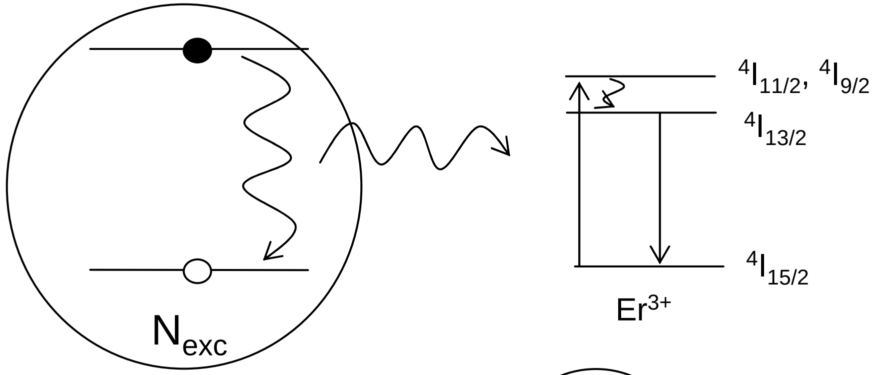
Fast (~ 1μs) and efficient (~55%) energy transfer from Si-nc to Er^{3+}

Possibility of electrical pumping

Higher index contrast for light confinement

CMOS compatibility

Introduction



Excitons:

$$\frac{dN_{exc}}{dt} = \sigma_{NC}\Phi(N_{NC} - N_{exc}) - \frac{N_{exc}}{\tau} - k_t N_{exc} C_{ind} N_{Er}$$

Transfer to Er^{3+}

Exciton generation and strong Auger

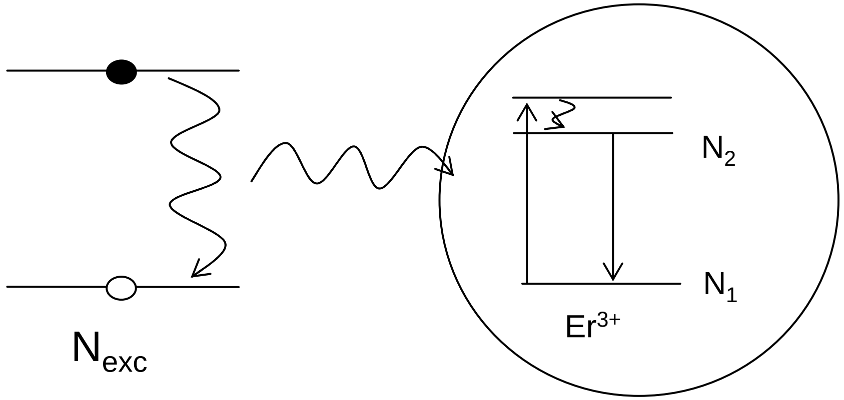
Intrinsic recombination

Steady state:

$$N_{exc} = \frac{\sigma_{NC}\Phi N_{NC}}{\sigma_{NC}\Phi + k_t C_{ind} N_{Er}}$$

N_{exc} : density of excitons
N_{NC}: total density of Si-nc
σ_{NC}: absorption cross section
τ: intrinsic lifetime of the exciton
k_t: average coupling rate
C_{ind}: percentage of Er^{3+} coupled to Si-nc

Introduction



$$\frac{dN_2}{dt} = KN_{exc}N_1 + \sigma_d\phi_p N_1 - \frac{N_2}{\tau_d} - C_{up}N_2^2 + \sigma_{abs}\Phi_s N_1 - \sigma_{em}\Phi_s N_2$$

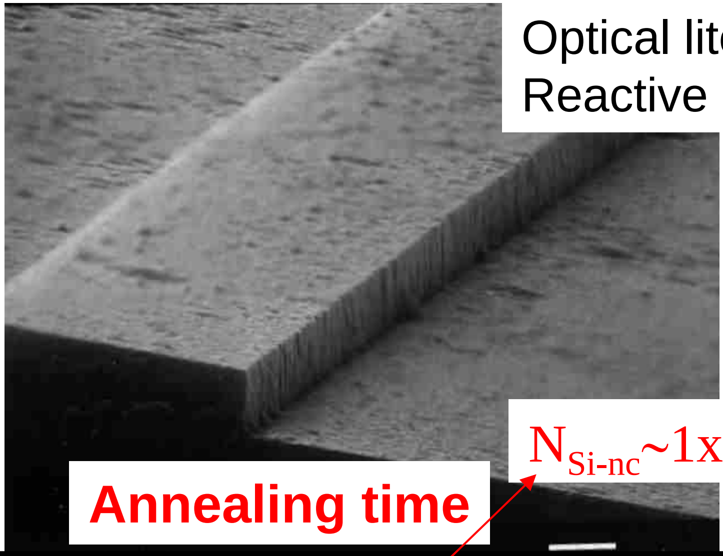
$$= \underbrace{\sigma_{exc}\phi_p N_1}_{\text{Excitation term}} \underbrace{- \frac{N_2}{\tau_d} - C_{up}N_2^2}_{\text{De-excitation mechanisms}} + \underbrace{\sigma_{abs}\Phi_s N_1 - \sigma_{em}\Phi_s N_2}_{\text{Absorption and stimulated emission term}}$$

σ_{abs}, σ_{em}, σ_{exc}, τ_d, C_{up} ?

Important for pump and probe measurements

The samples

Er:Si-nc produced by Reactive Magnetron co-Sputtering and successive annealing to get phase separation and reduction of non radiative defects



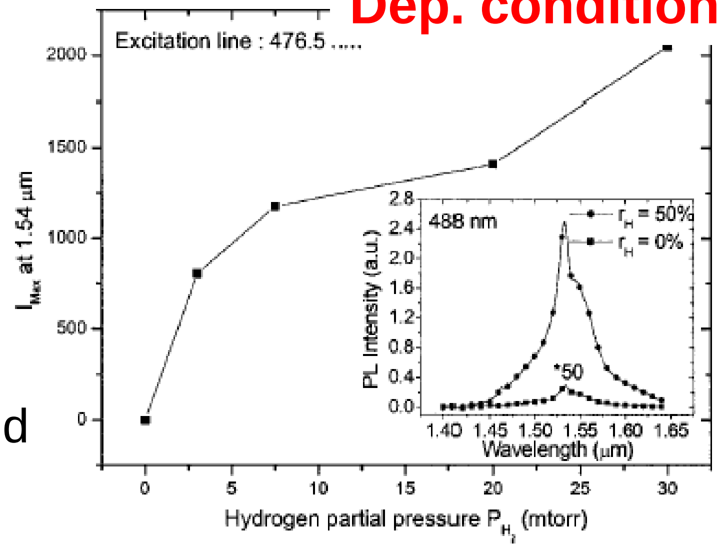
Optical litography and Reactive ion etching

Annealing time

$N_{Si\text{-}nc}$~$1x10^{17}cm^{-3}$

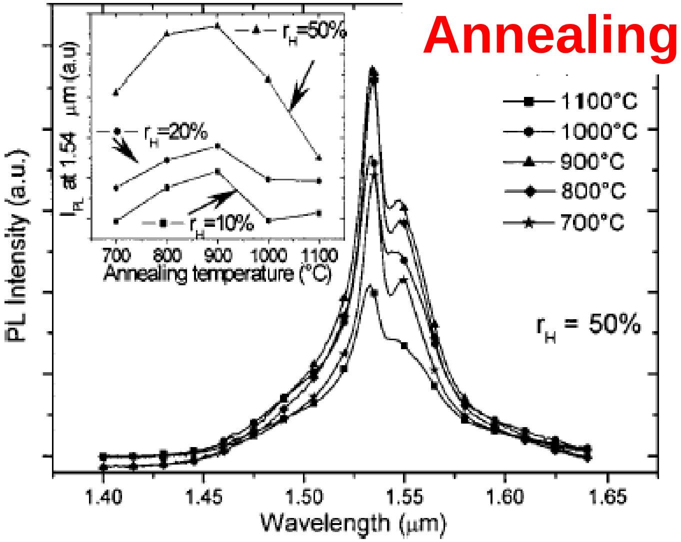
Waveguide Sample	Annealing time (min)	Si excess (at. %)	Er content ($x10^{20}$ cm^{-3})	*n*	Γ
A	240	7	3±0.1	1.61	0.62
B	60	7	4±0.1	1.545	0.51
C	30	6-7	5.4±0.2	1.516	0.48
D	10	6-7	5.4±0.2	1.48	0.28

Dep. conditions



F. Gourbilleau et al., JAP, 94, 3869 (2003) JAP 95, 3717 (2004).

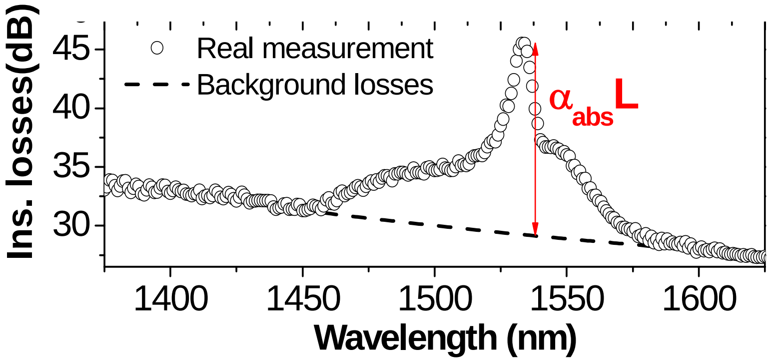
Annealing T



n increases with annealing time

Determination of σ_{abs} and σ_{em}

From transmission measurements

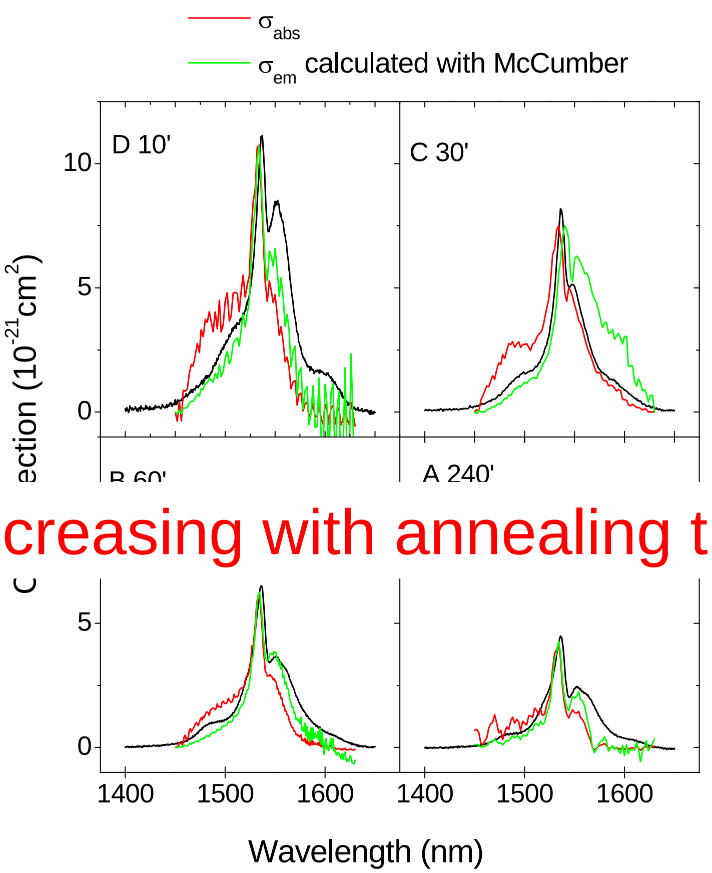


σ_{abs} and σ_{em} similar to that of Er^{3+} in SiO_2

σ_{abs} and σ_{em} ✓

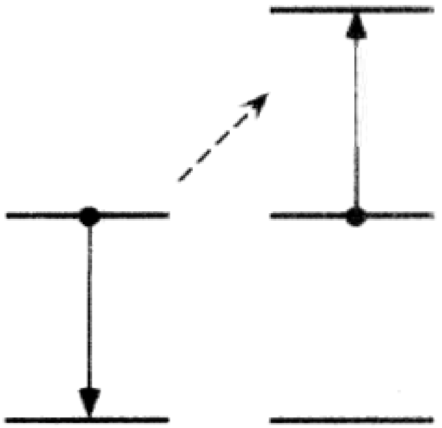
Mc Cumber relation:

$$\sigma_{em}\left(\upsilon\right)=\sigma_{abs}\left(\upsilon\right)e^{\frac{\varepsilon-h\upsilon}{kT}}$$



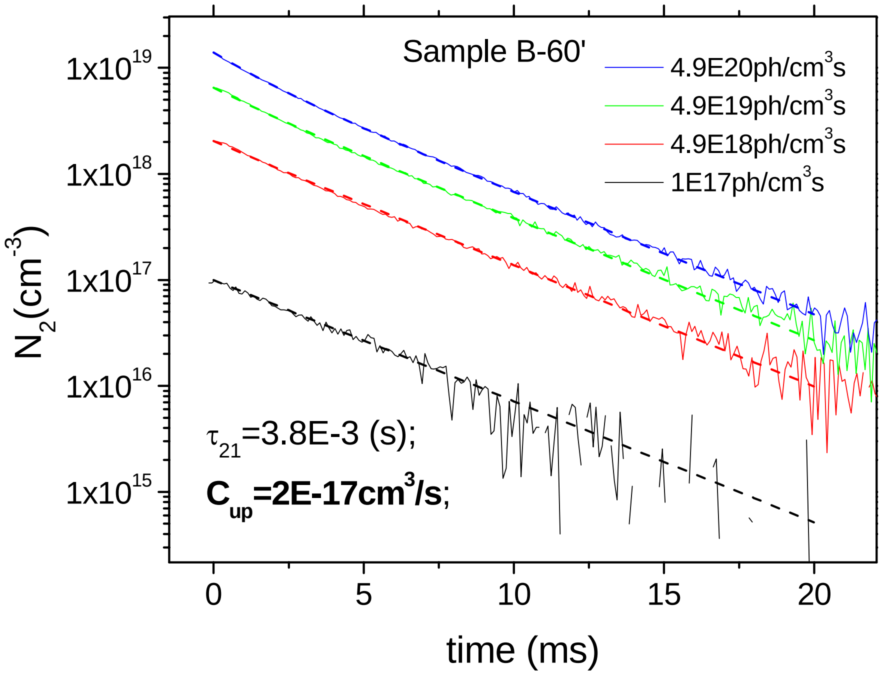
Decreasing with annealing time

Total lifetime and cooperative up-conversion

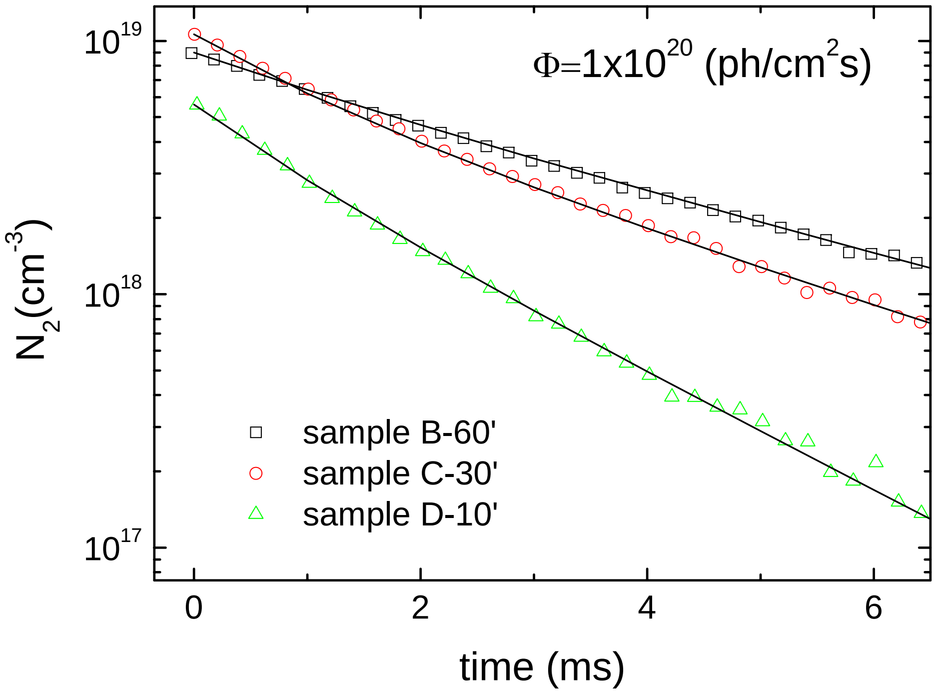


Quantitative measurements of the photon flux emitted from the samples. It is so possible to correlate the number of emitted photons with N_2

$$\frac{dN_2(t)}{dt} = -\frac{N_2(t)}{\tau_d} - C_{up} N_2(t)^2$$



Total lifetime and cooperative up-conversion



Decreases with annealing time

	N_2(t=0) (cm^{-3})	C_{up} (cm^3 s^{-1})	τ_{21}(ms)
Sample B	9.00E+18	2.0E-17	3.8
Sample C	1.06E+19	5.5E-17	3.2
Sample D	5.60E+18	8.0E-17	1.9

Increases with annealing time

τ_d and C_{up} ✓

Excitation cross section at low pump power

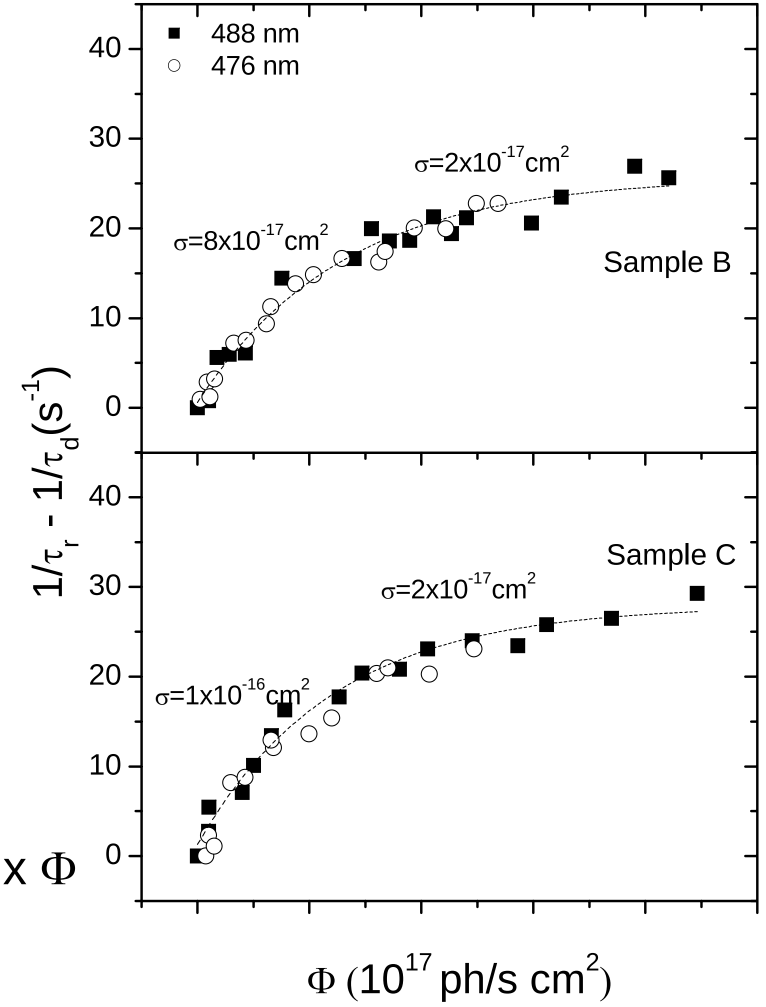
$$\frac{1}{\tau_r}-\frac{1}{\tau_d}=\sigma_{exc}\Phi$$

σ_{exc} ✓

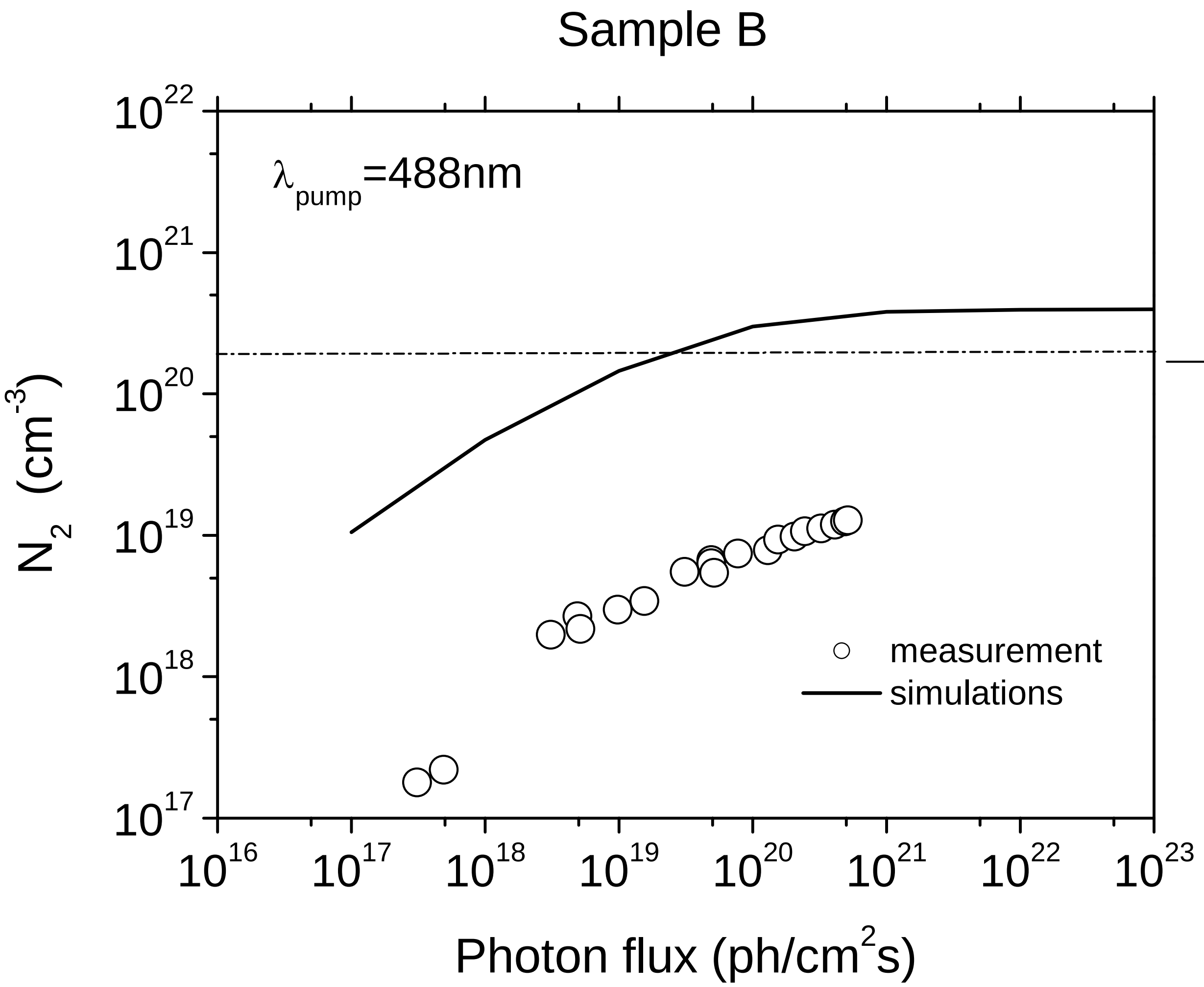
σ_{exc} is orders of magnitude higher than that of Er^{3+} in pure silica (~10^{-21} cm^2),

for samples B and C, resonant (488 nm) and non-resonant (476 nm) result in the same σ_{exc}

…but seems to be flux dependent,
the slope is changing with increasing pump flux Φ

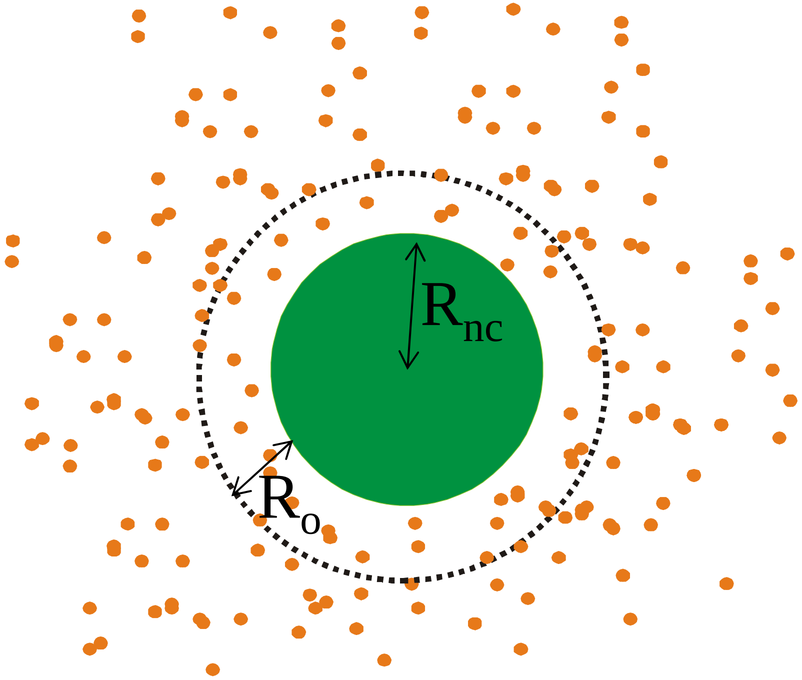


Excited erbium population vs photon flux



→ Population inversion

Modelling



Er^{3+} ions near the Si-nc are efficiently coupled to them, whereas Er^{3+} ions far away behave more and more as Er^{3+} in SiO_2 that can be excited only directly.

Model for σ_{exc}

$$\sigma_{exc}(R) = \sigma_o e^{\frac{R-R_{nc}}{R_o}} + \sigma_d$$

We consider that the first Er to be excited and therefore the strongest coupled would be the closest to the Si-nc

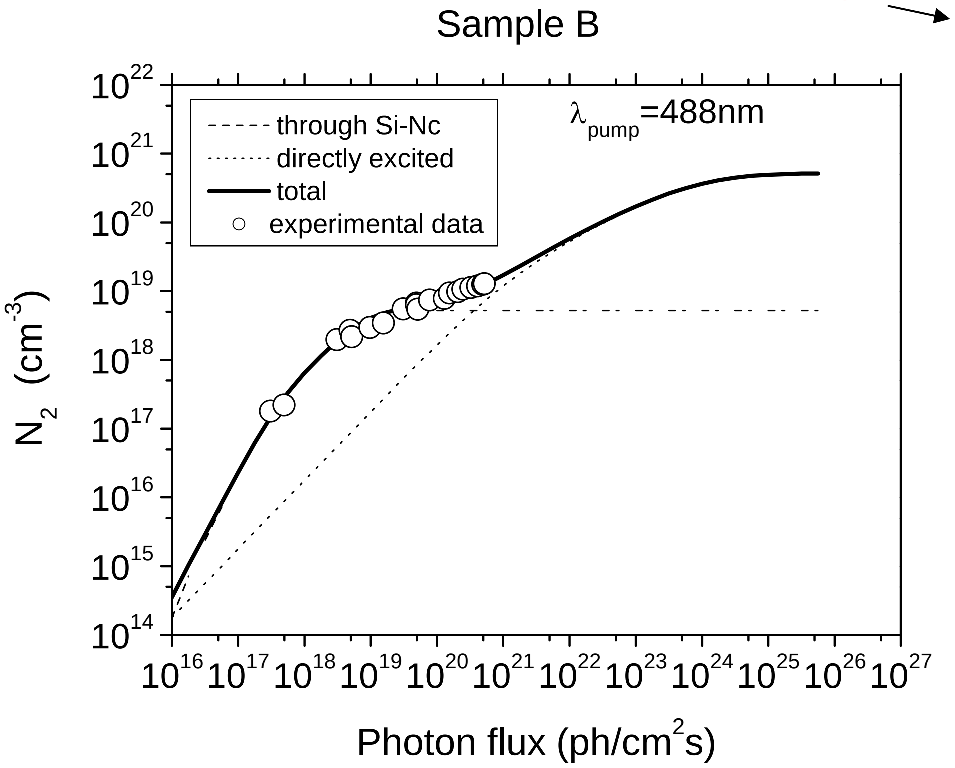
The coupling diminishes with the distance

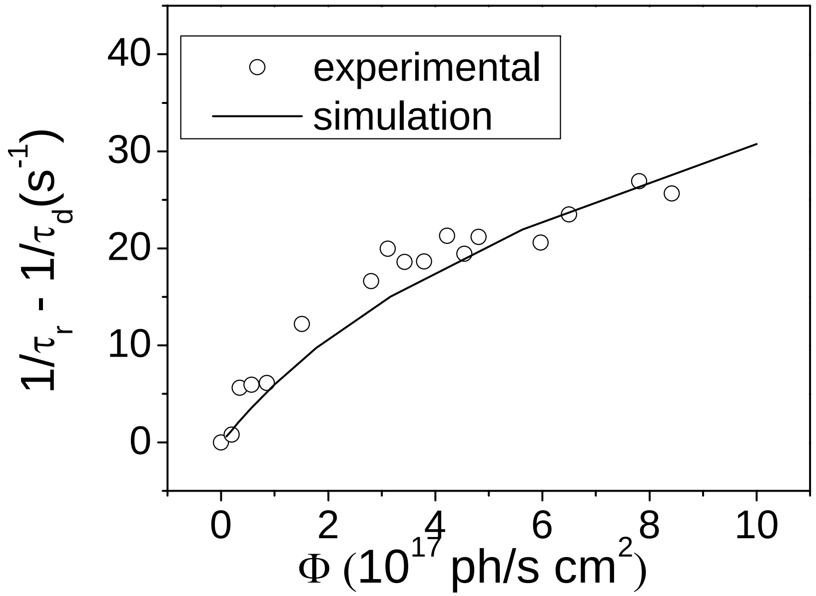
Simulations

Doing this for each flux we obtain....

τ_d=3.8ms, C_{up}=2x10^{-17}cm^{3}s^{-1}, σ_o=3x10^{-16}cm^2, σ_d=5x10^{-21}cm^2,
R_{nc}=4nm , R_o=0.5nm, N_{NC}=1x10^{17}cm^{-3}.

Short range interaction

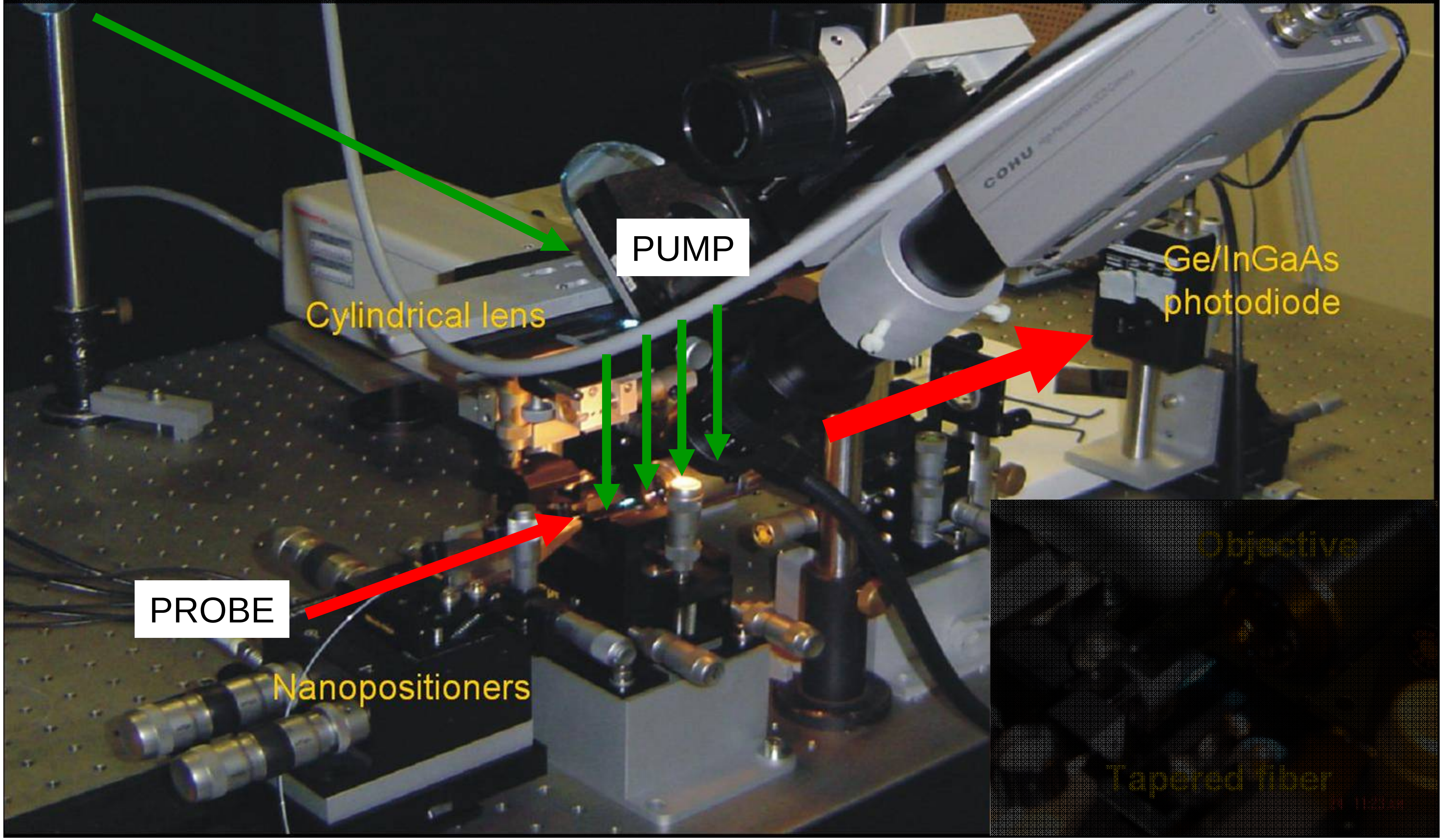




And this means that only 2-3% of the whole erbium population
can be excited trough transfer from Si-nc. The rest can only be excited directly because simply it is too far

In any case it is about **10-100** excitable Er^{3+} per Si-nc

Signal enhancement
(Pump&Probe experimental setup)

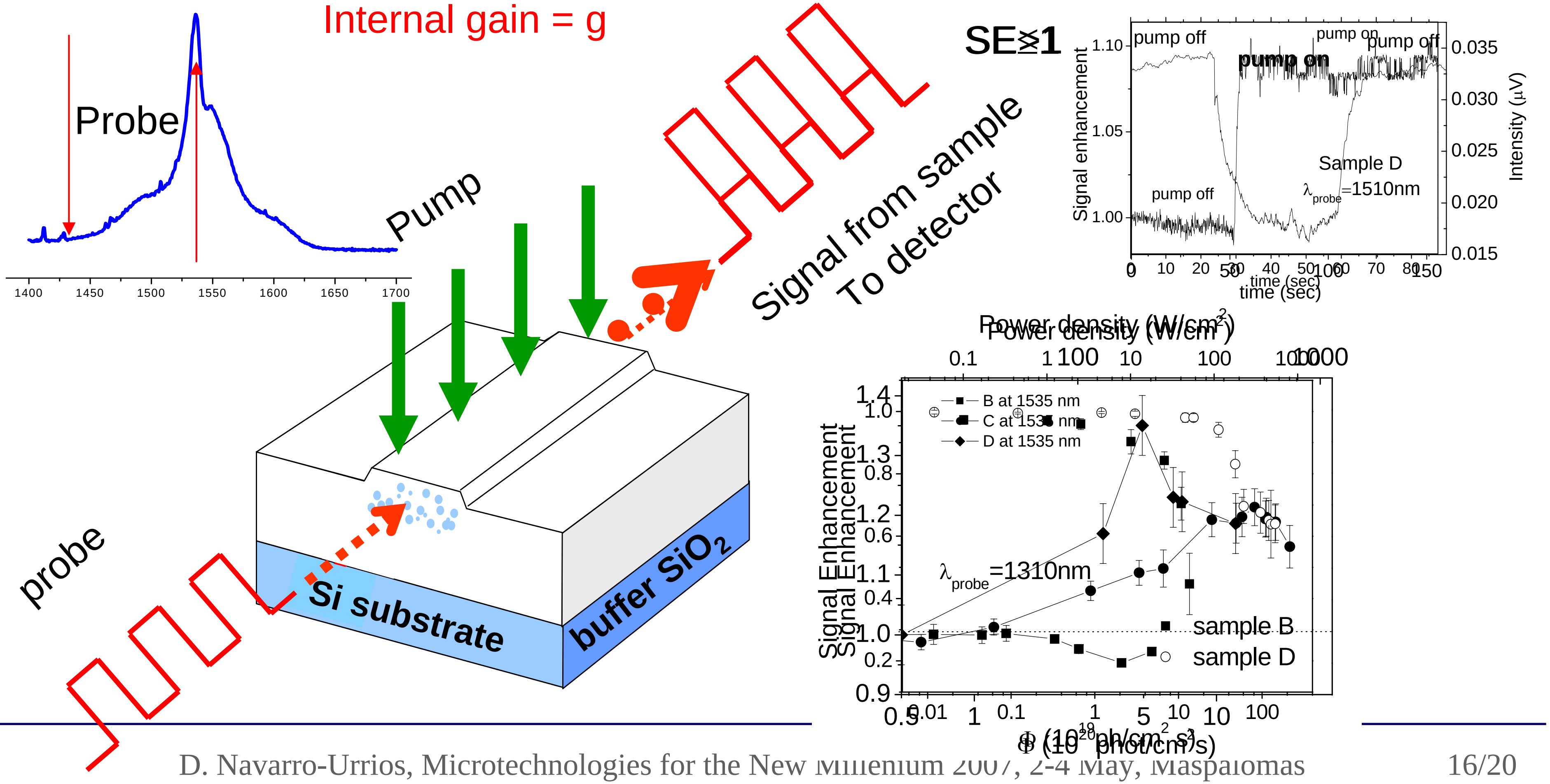


Signal enhancement

$$SE = \frac{I_{pump\&probe}}{I_{probe}} = \exp(2\sigma_{em} N_2 \Gamma L) \approx \exp\left[\left(\frac{2\Phi\ \sigma_{exc}}{\frac{1}{\tau_d(\Phi\ )} + \Phi\ \sigma_{exc}}\right)\sigma_{em} N_{Er} L\Gamma\right]$$

Internal gain = g

SE≥1



Signal enhancement

Sample	Max SE (dB/cm)	Propagation Losses (dB/cm)	Absorption Losses (dB/cm)	Max internal gain (CA corrected) (dB/cm)	Φ needed (ph/cm^2 s)
B-60’	0.12	**1.2**	**5.4**	**0.6**	1x10^{22} (488nm)
C-30’	0.65	**1.6**	**8.5**	**0.76**	5x10^{20} (488nm)
D-10’	0.45	**2.0**	**7.5**	**0.56**	1x10^{21} (532nm)

Signal enhancement

- ✓ From maximum gain value:

$$\frac{g}{\alpha} = \frac{\sigma_{em} N_2}{\sigma_{abs} N_{Er}} \approx \frac{N_2}{N_{Er}}$$

Sample	Max N_2/N_{Er}
B-60’	11%
C-30’	9%
D-10’	7%

…but only 2-3% is being excited thorugh transfer from the Si-nc

Conclusions

- We have measured and quantified reliable values for:

  Absorption and emission cross sections
  Total lifetimes and cooperative up-conversion coefficients
  Effective excitation cross sections at low pump power
  Indirectly excitable Er^{3+} population through Si-nc energy transfer (2-3% of the Er^{3+} concentration)

- Using a pump and probe technique we have demonstrated values of internal gains of around 0.7dB/cm

We still have to optimize the Si-nc:Er^{3+} ratio and the characteristics of the Si-nc in order to excite the whole Er population through indirect energy transfer

THANK YOU!

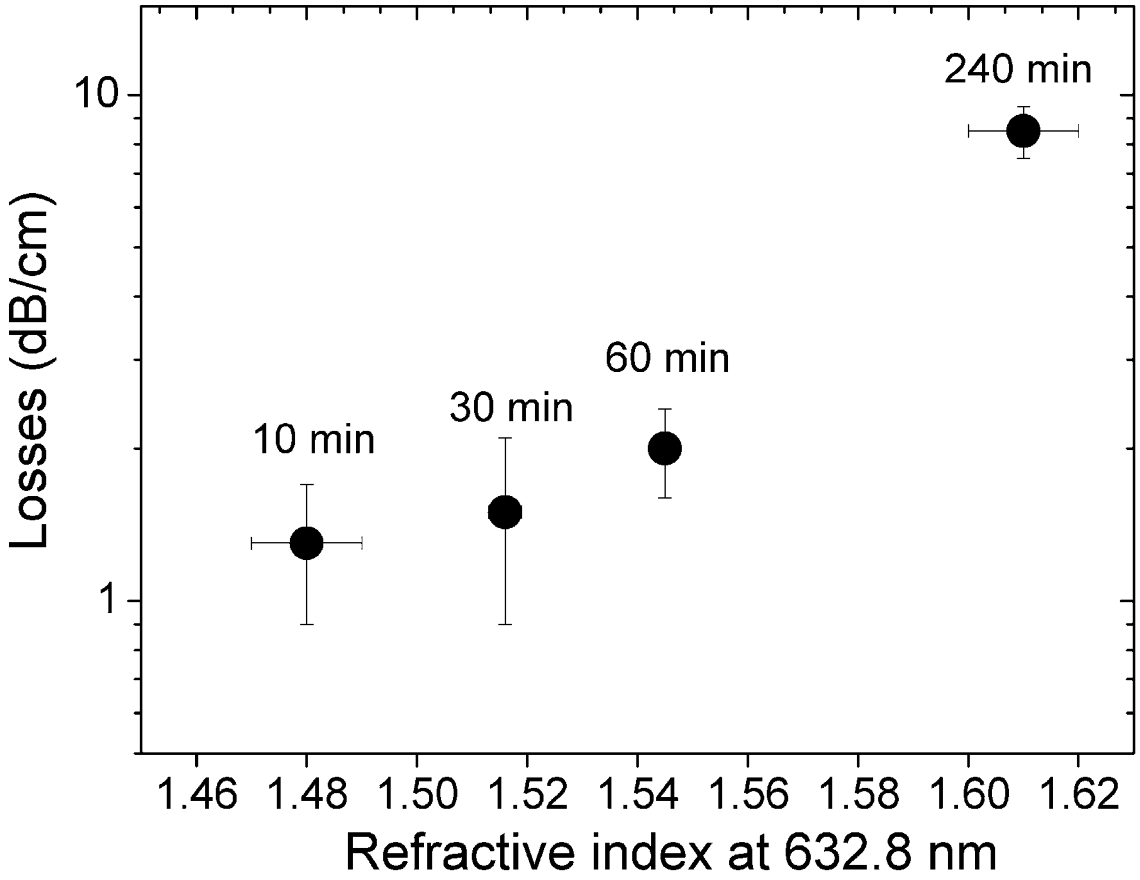
Gain favouring

- As much Er^{3+} as possible (avoiding up-conversion phenomena, $N_{Er} \leq 4\text{-}5 \times 10^{20} cm^{-3}$)
- Enough Si-nc to excite all the Er^{3+} ions
- Good modal confinement
- Low waveguide losses (not that due to absorption of Er^{3+})

Gain limiting

- Up-conversion (shifts the pump threshold for population inversion towards higher pump energies)
- Excited state absorption
- Non radiative de-excitation (Auger de-excitation with a nearby exciton)
- Carrier absorption in Si-nc (decreases the signal and blocks the transfer to Er ions)

Propagation losses at 1600nm

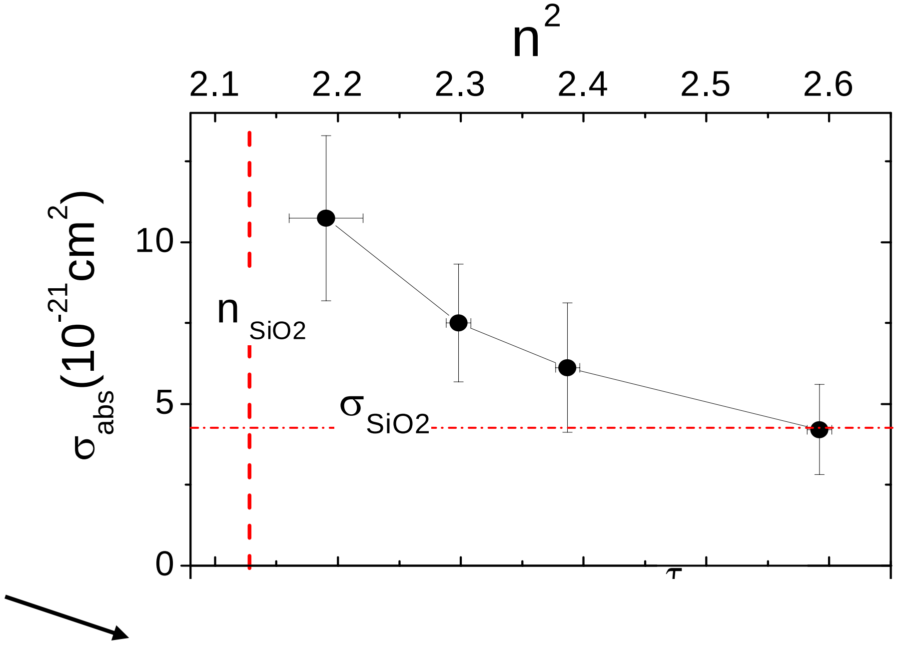


Losses at 1600 nm are essentially propagation losses of the rib loaded waveguide

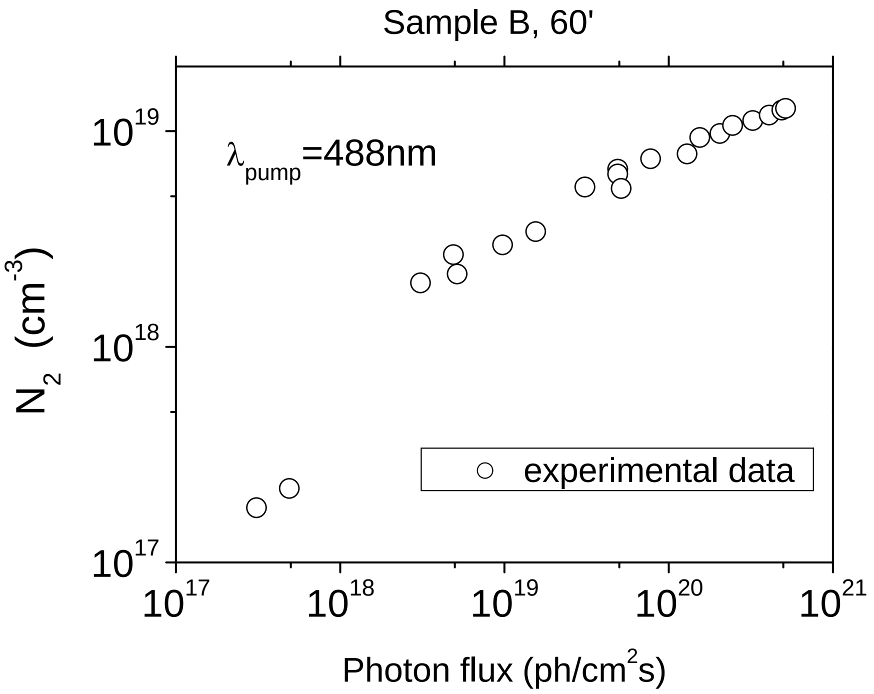
Radiative lifetime determination

Also, from Mc Cumber analysis:

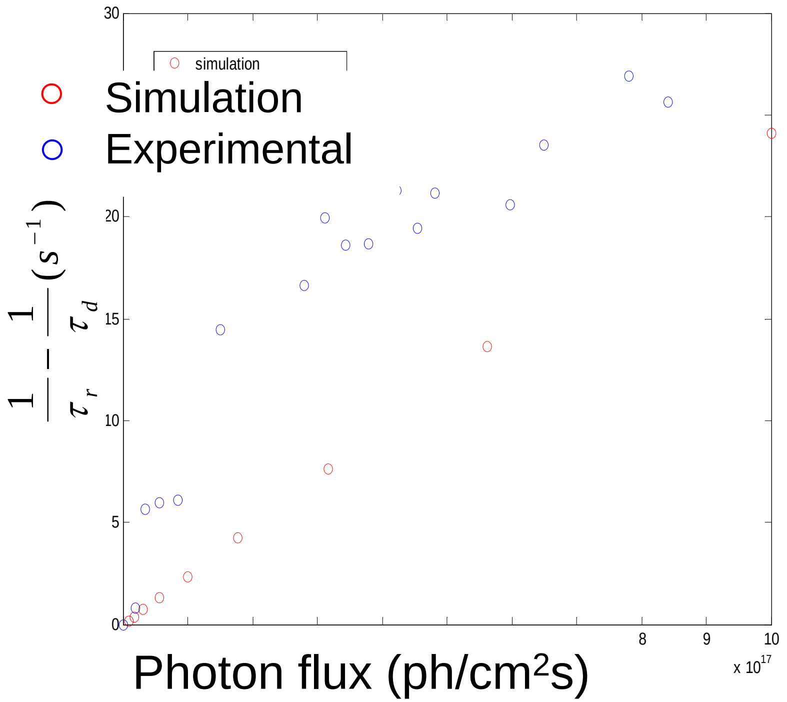
$$\frac{1}{\tau_{rad}} = \frac{8\pi n^2}{c^2}\int_0^\infty \nu^2 \sigma_e(\upsilon)\, d\upsilon$$



Excited Er^{3+} vs pump flux



…but



- ✓ Around 96% of the total volume of the sample is occupied by Er^{3+} that are only excitable through direct photon excitation, because simply they are too far from a Si-nc.