Study on the optical properties dependence of annealing time in Er^{3+} coupled to Si nanoclusters rib-waveguides

D. Navarro Urrios, N. Daldosso, A. Pitanti, F. Gourbilleau, R. Rizk, P. Pellegrino, B. Garrido and L. Pavesi

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

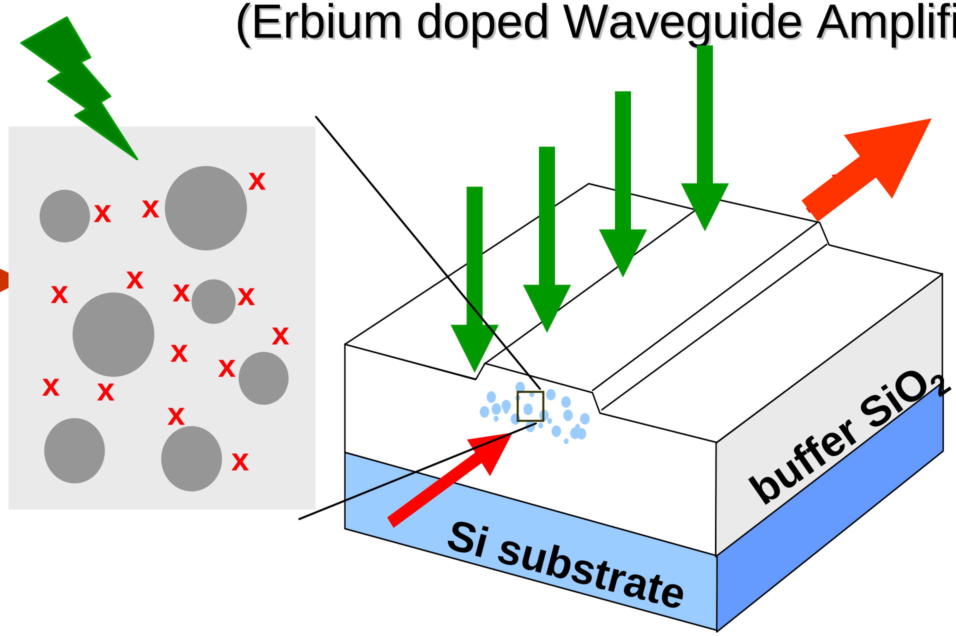
Usual EDFAs
(Erbium doped Fiber Amplifier)

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

Expensive pumping source

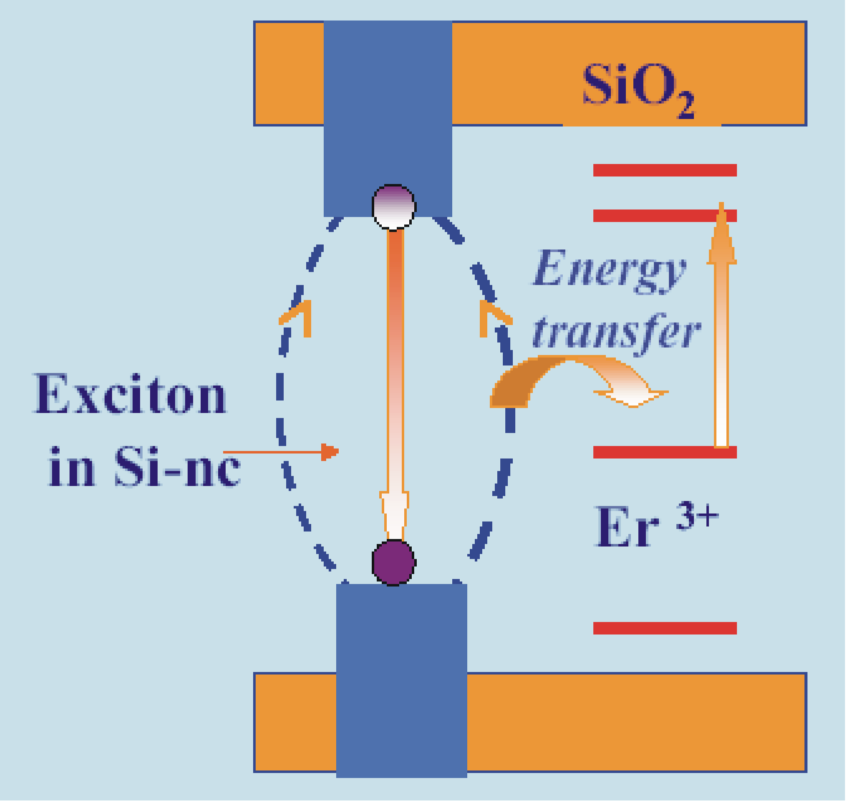
(resonant, intense and coupled)

EDWA
(Erbium doped Waveguide Amplifier)



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)

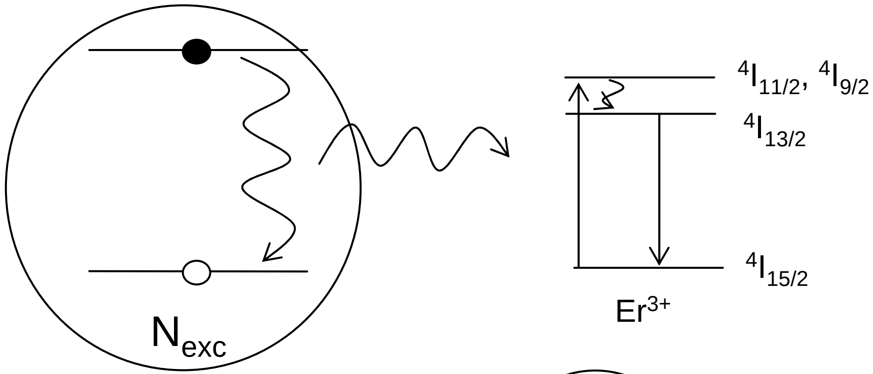
Fast (~ 1μs) and efficient (~55%) energy transfer from Si-nc to Er^{3+}

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

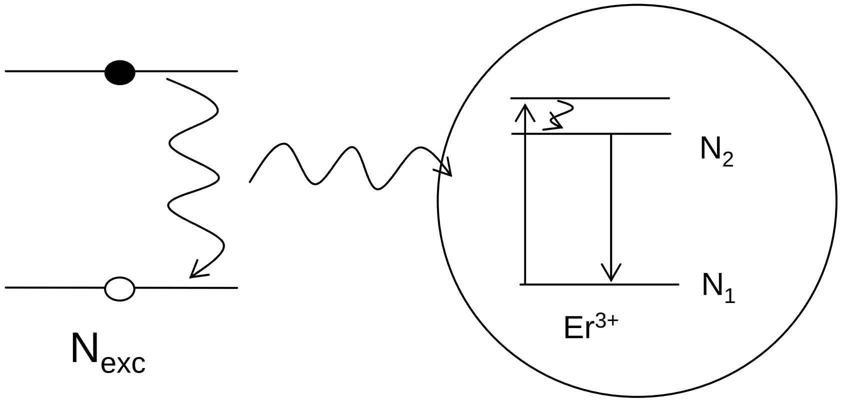
Intrinsic recombination

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



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

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

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

Excitation term

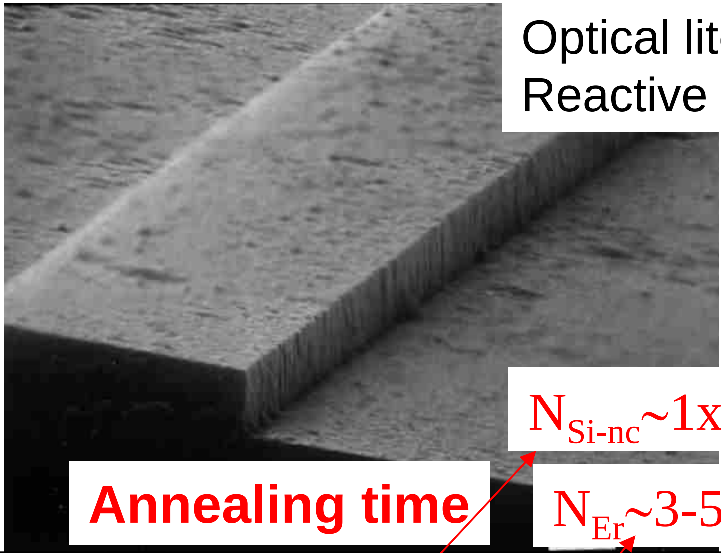
De-excitation mechanisms

Absorption and stimulated emission term

Important for pump and probe measurements

The samples

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



Optical litography and Reactive ion etching

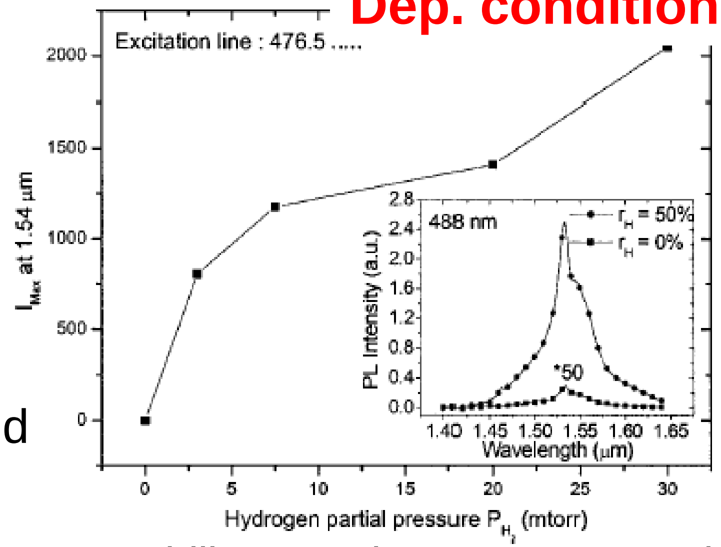
$N_{Si\text{-}nc} \sim 1x10^{17} cm^{-3}$

$N_{Er} \sim 3\text{-}5x10^{20} cm^{-3}$

Annealing time

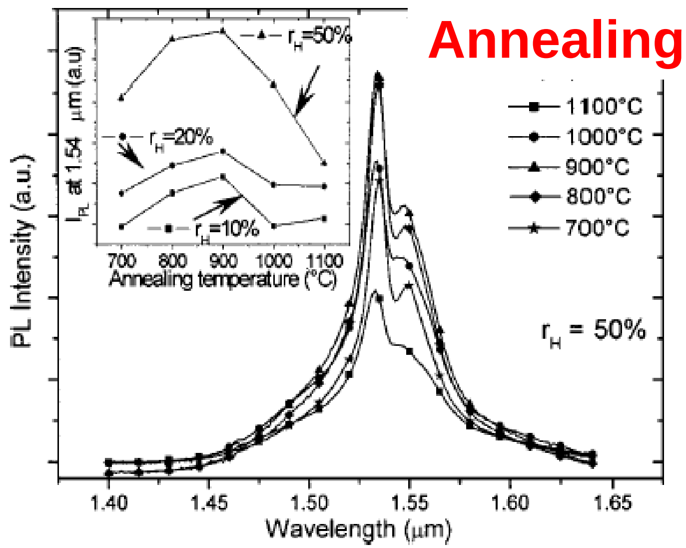
Waveguide Sample	Annealing time (min)	Si excess (at. %)	Er content ($x10^{20}$ cm^{-3})	*n*	Γ
A	240	7	3±0.1	1.61	0.62
B	60	7	4±0.1	1.545	0.51
C	30	6-7	5.4±0.2	1.516	0.48
D	10	6-7	5.4±0.2	1.48	0.28

Dep. conditions



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

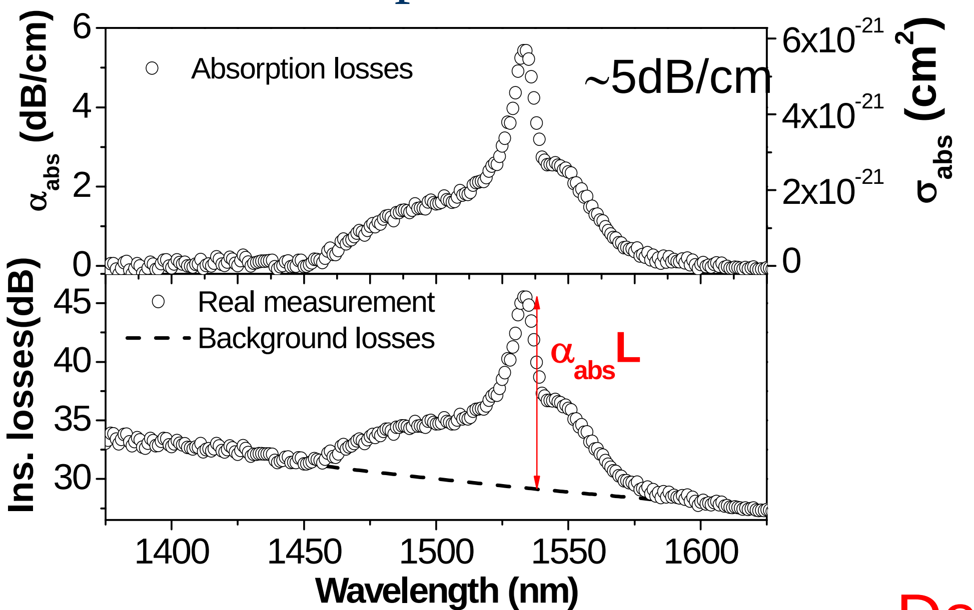
Annealing T



Determination of σ_{abs} and σ_{em}

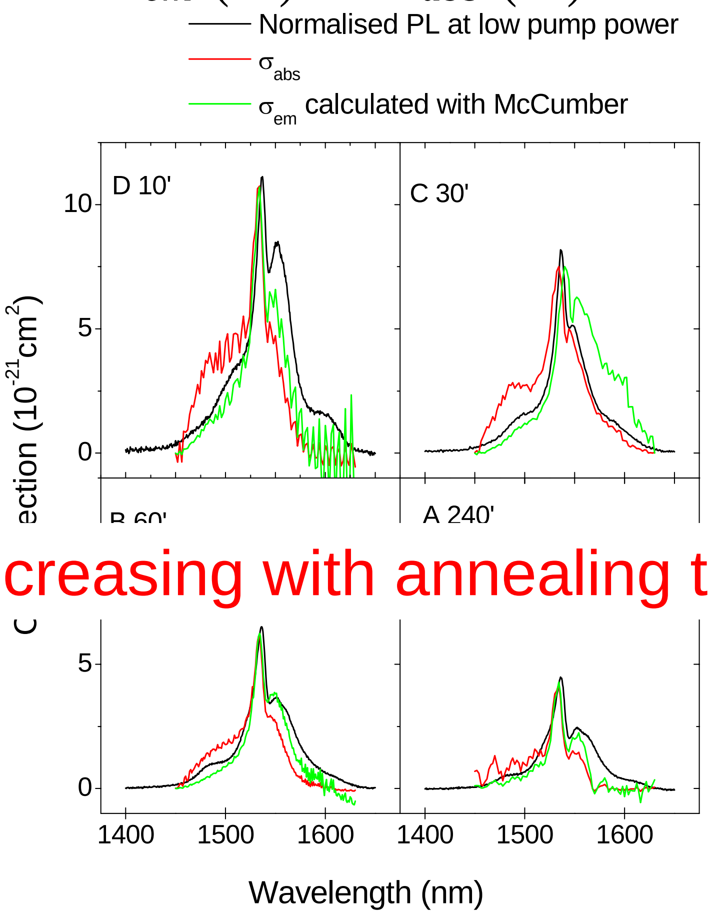
From transmission measurements

Prop losses ~ 1dB/cm



Mc Cumber relation:

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

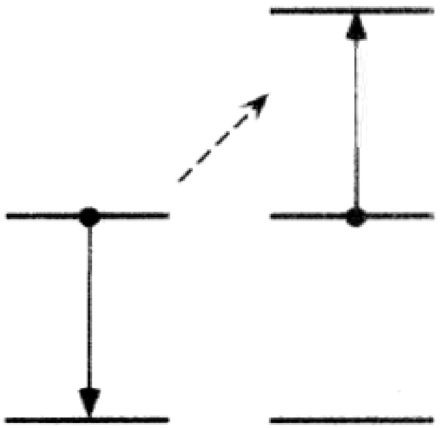


Decreasing with annealing time

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

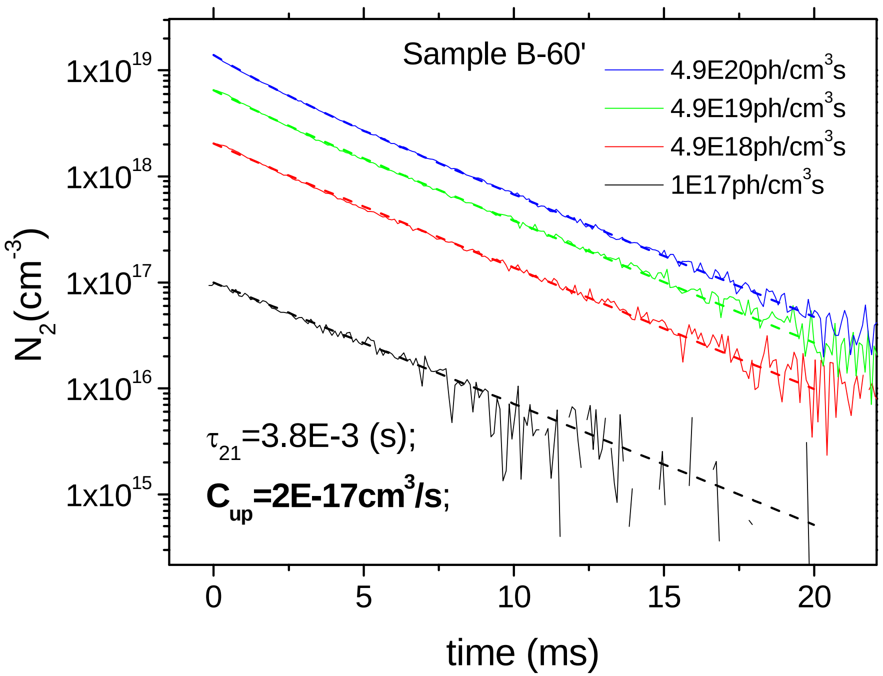
σ_{abs} and σ_{em} ✓

Total lifetime and cooperative up-conversion

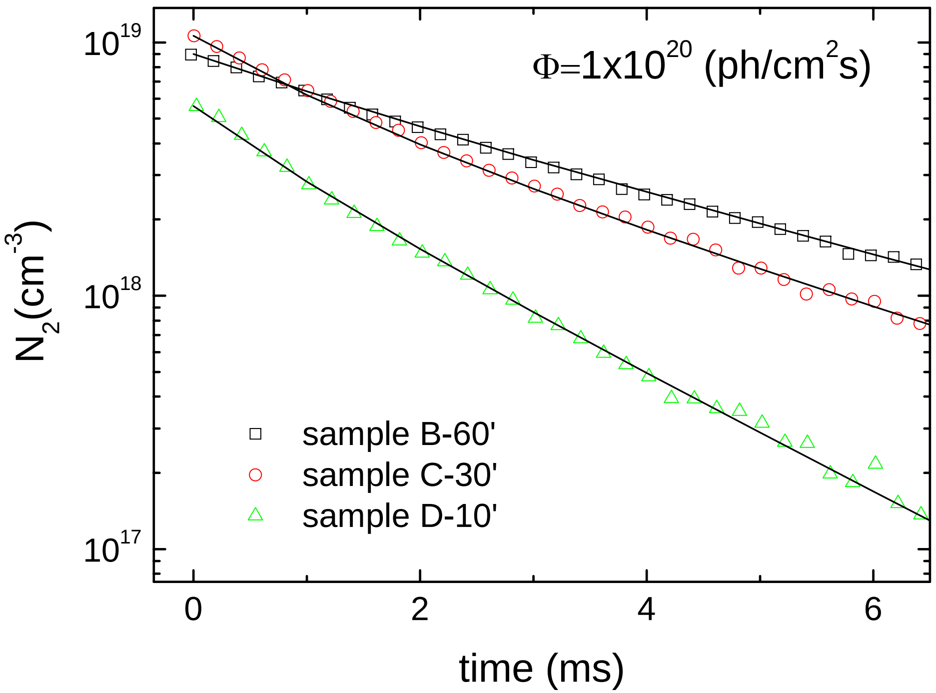


Quantitative measurements of the photon flux emitted from the samples. It is so possible to correlate the number of emitted photons with N_2

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



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

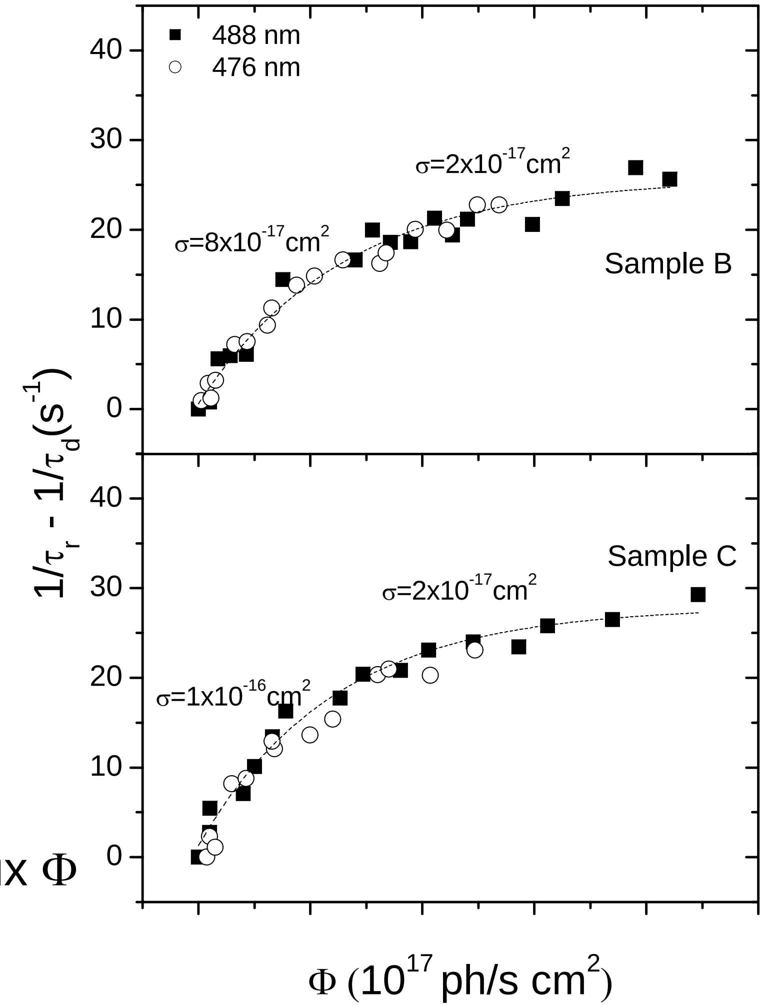
$$\frac{1}{\tau_r} - \frac{1}{\tau_d} = \sigma_{exc}\Phi$$

σ_{exc} ✓

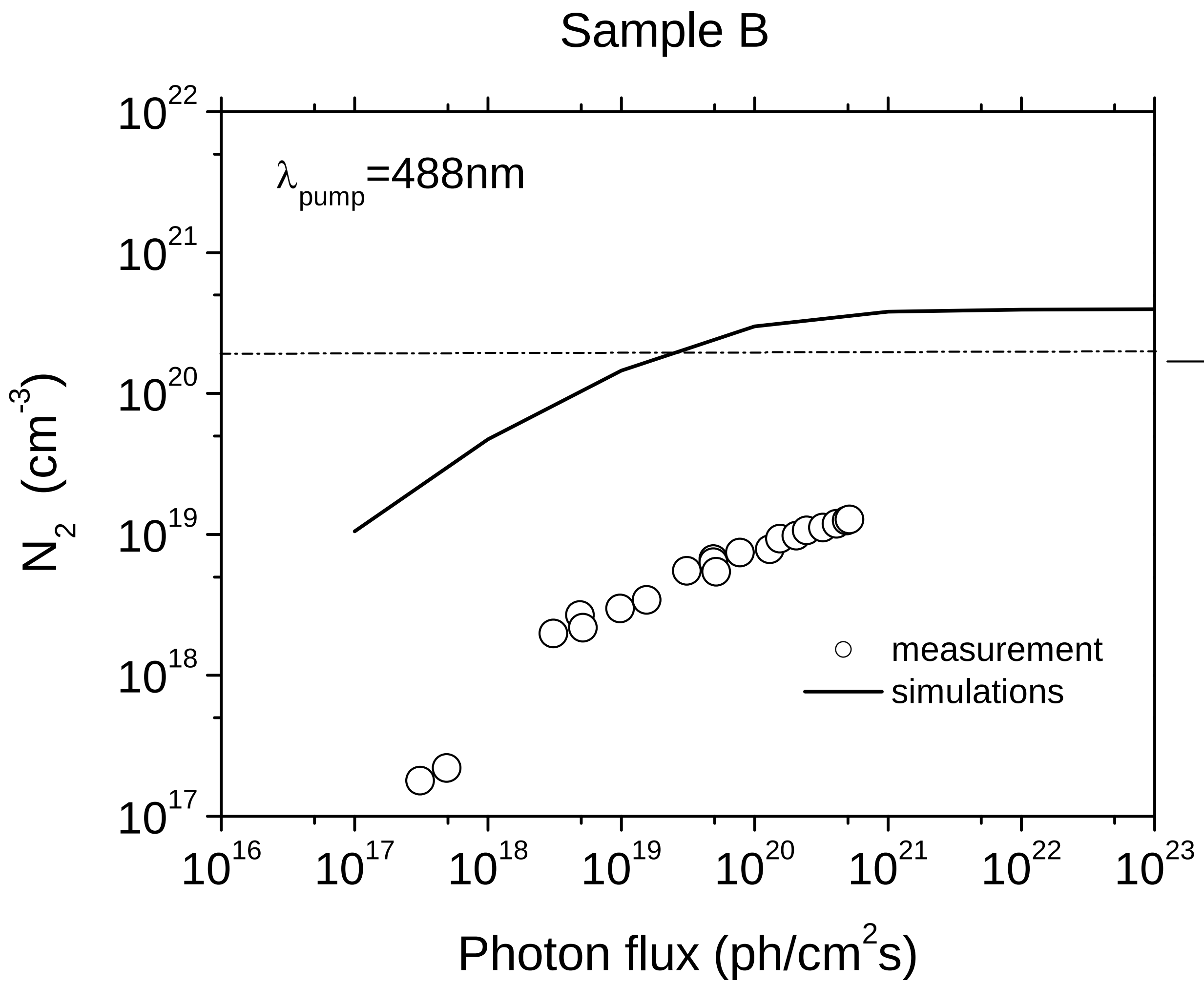
σ_{exc} is orders of magnitude higher than that of Er^{3+} in pure silica (~10^{-21} cm^2),

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

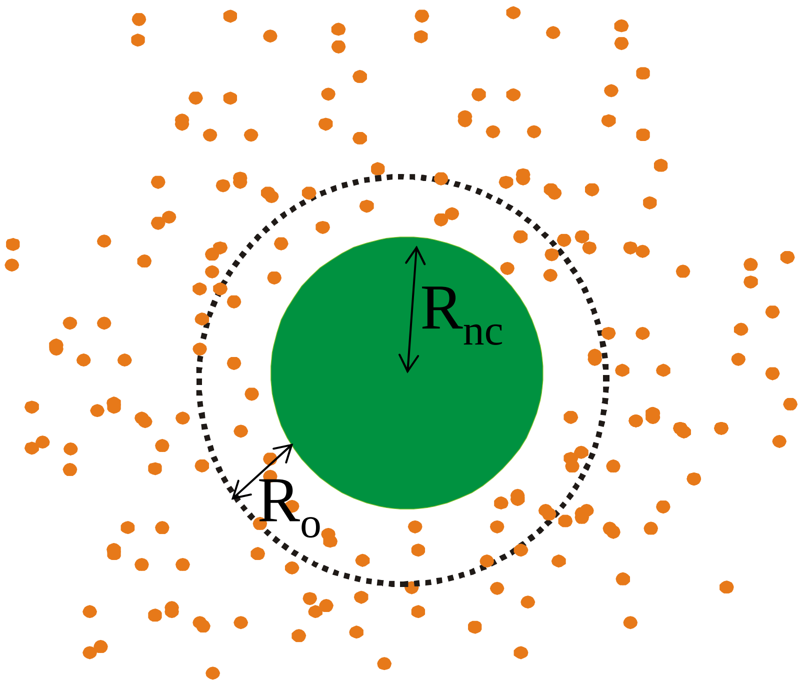


Excited erbium population vs photon flux



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

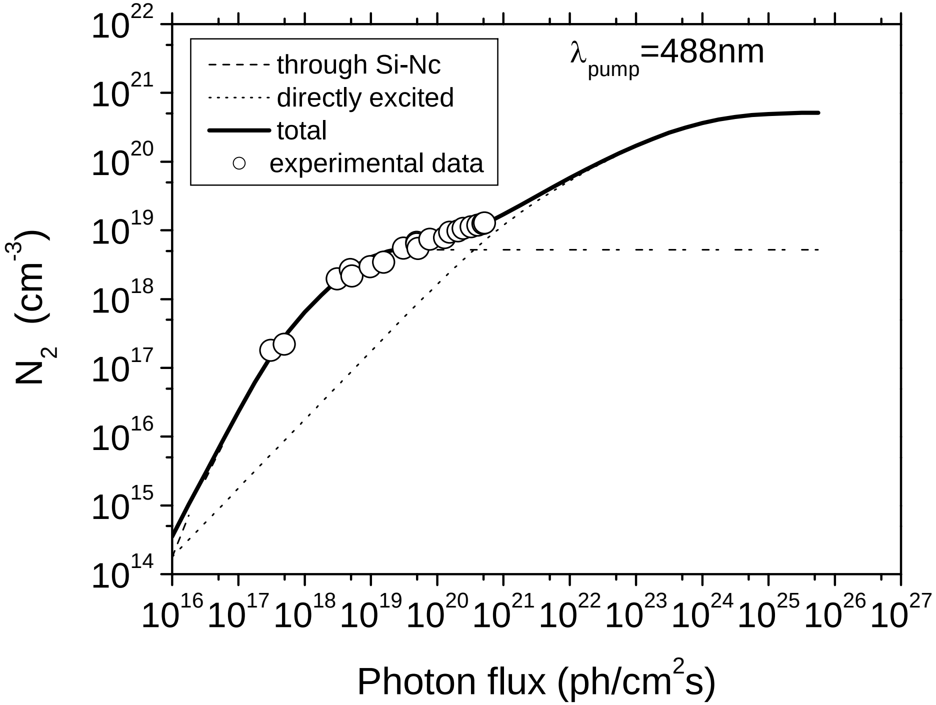
The coupling diminishes with the distance

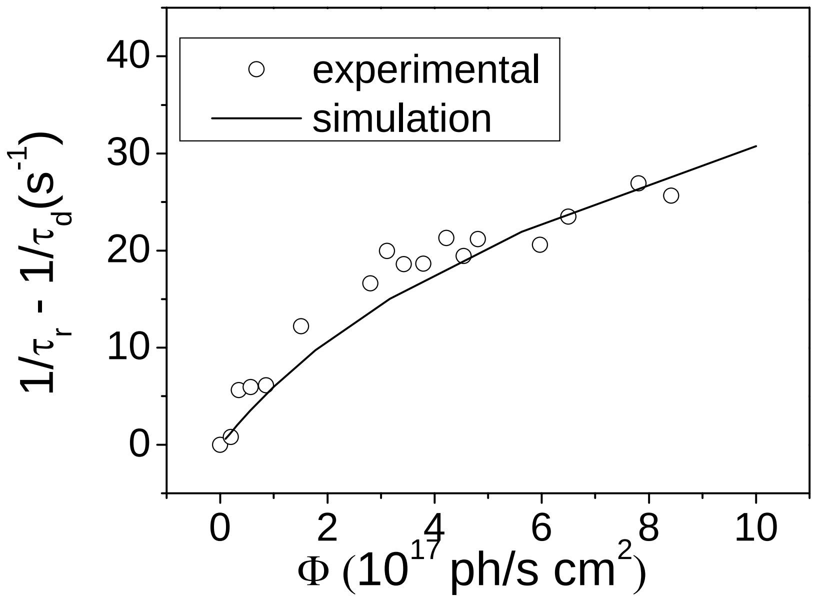
Simulations

τ_d=3.8 ms, 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}.

Sample B

Short range interaction

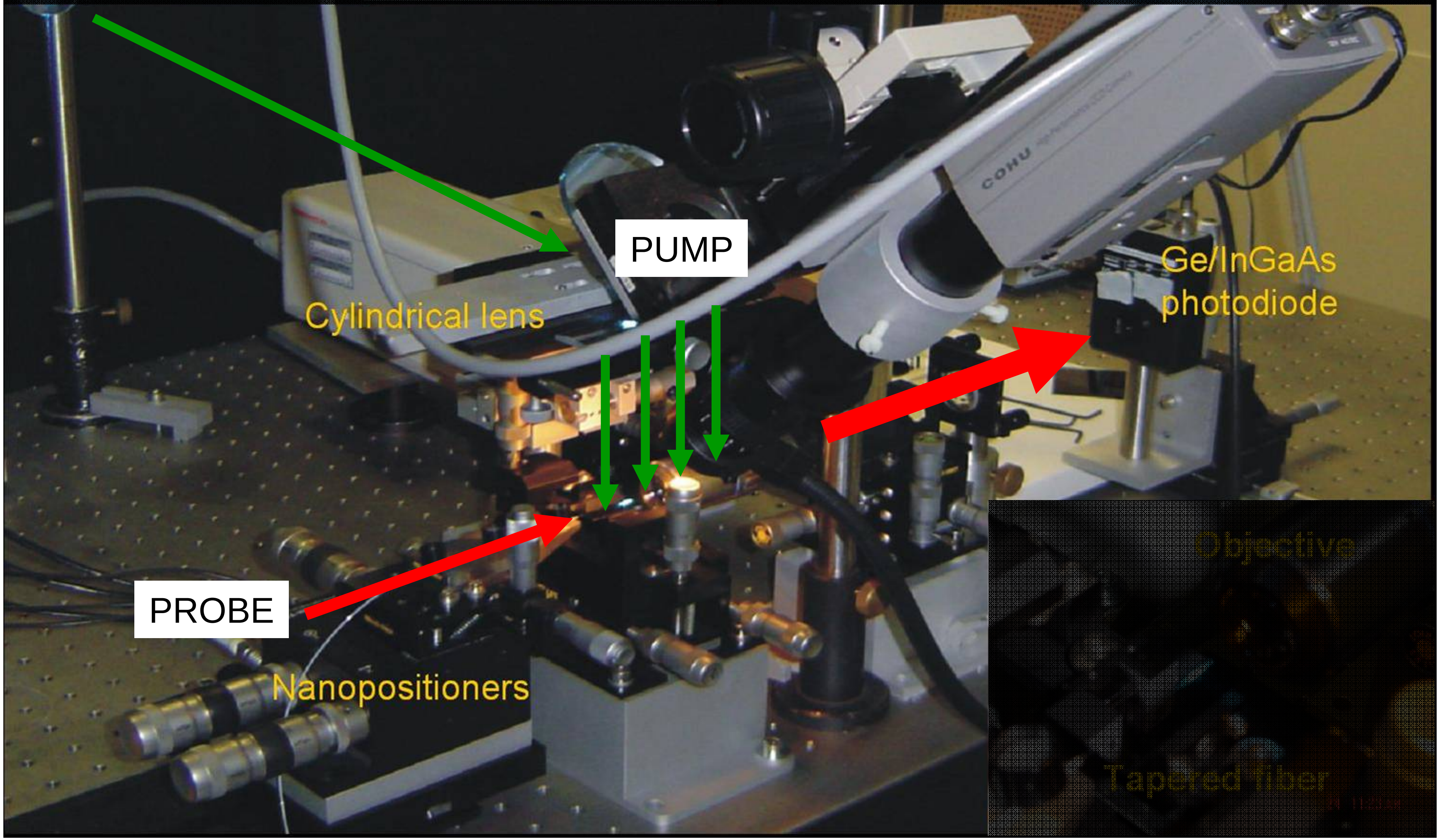




And this means that only 2-3% of the whole erbium population
can be excited trough transfer from Si-nc. The rest can only be excited directly because simply it is too far

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

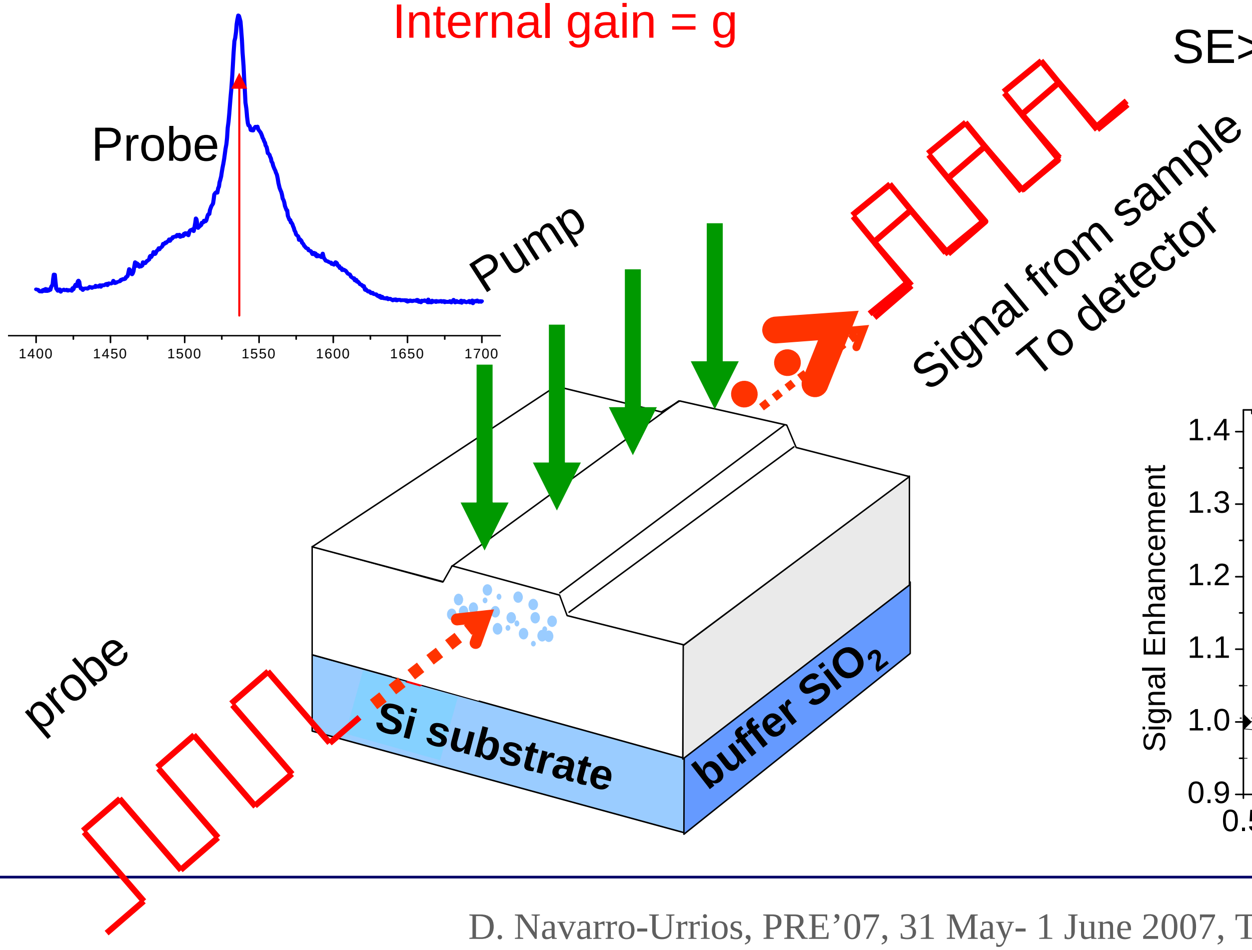
Signal enhancement
(Pump&Probe experimental setup)



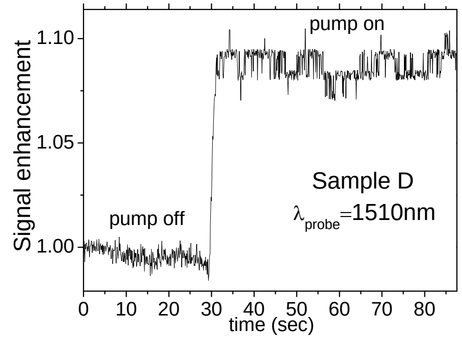
Signal enhancement

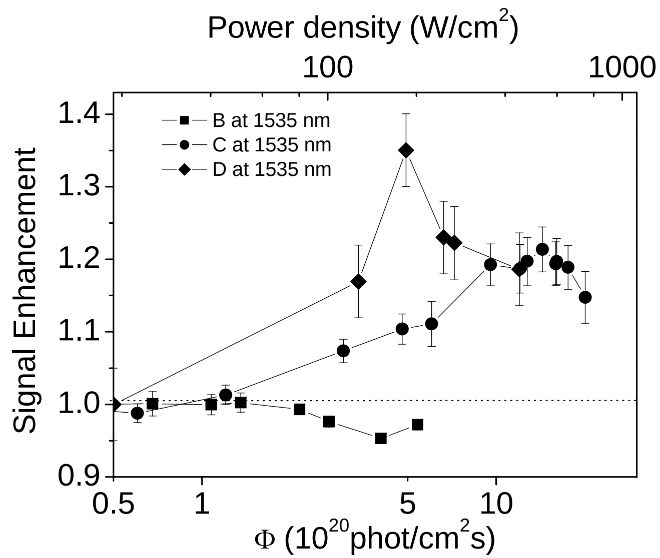
$$SE = \frac{I_{pump\&probe}}{I_{probe}} = \exp(2\sigma_{em} N_2 \Gamma L) \approx \exp\left[\left(\frac{2\Phi\ \sigma_{exc}}{\frac{1}{\tau_d(\Phi\ )} + \Phi\ \sigma_{exc}}\right)\sigma_{em} N_{Er} L\Gamma\right]$$

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/cm² 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 through 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!