NATIONAL INSTITUTE for LASER, PLASMA and RADIATION PHYSICS
Laser Department

9th National Seminar of Nanoscience and Nanotechnology, Romanian Academy, 16.03.2010

RECENT CONTRIBUTIONS IN NONLINEAR NANOPHOTONICS

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OUTLINE

1. Electronic and thermal nonlinear refractive indices of periodically nano-patterned and un-patterned silicon-on-insulator (SOI)

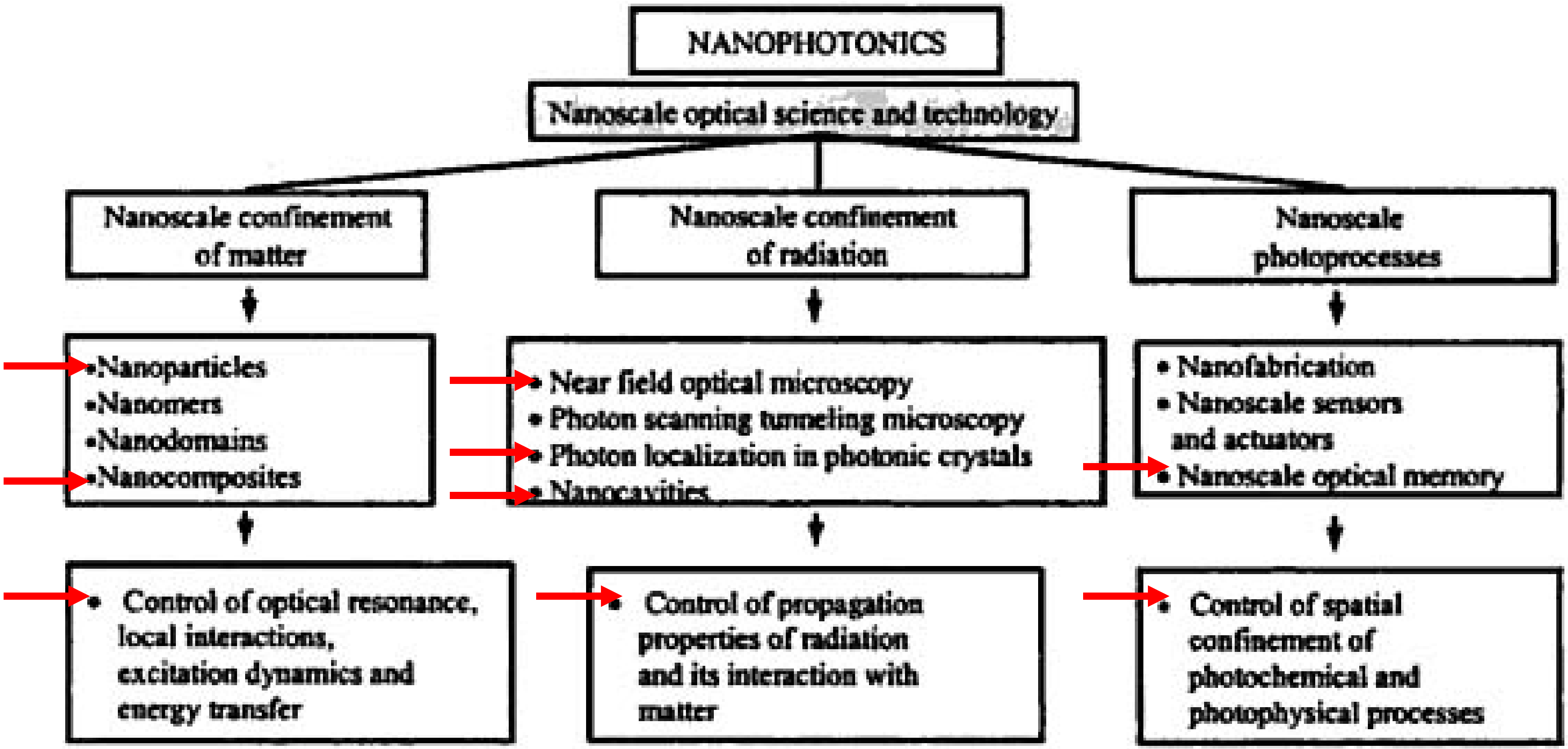
2. Theoretical and experimental dependence of effective optical linear and nonlinear refractive indices of nano-porous silicon (np-Si) on Si volume fill fraction, at different light wavelengths in visible and near-infrared

3. Experimental observation of huge, saturable and controlled nonlinear optical properties of CdTe quantum dots, in the case of strong quantum confinement (size ~ 2nm) and near resonant interaction with the excitation light

4. Fast spatial soliton creation in lithium niobate crystals with a low power c.w. laser blue-violet diode, near the absorption edge of the crystals. Parallel propagation of femtosecond impulse in IR in arrays of soliton waveguides

5. Experimental observation of highly efficient forward- and backward-random laser effect (without optical cavity) in dye infiltrated nematic liquid crystals.

Introduction. Definition and main fields. Our research in nanophotonics

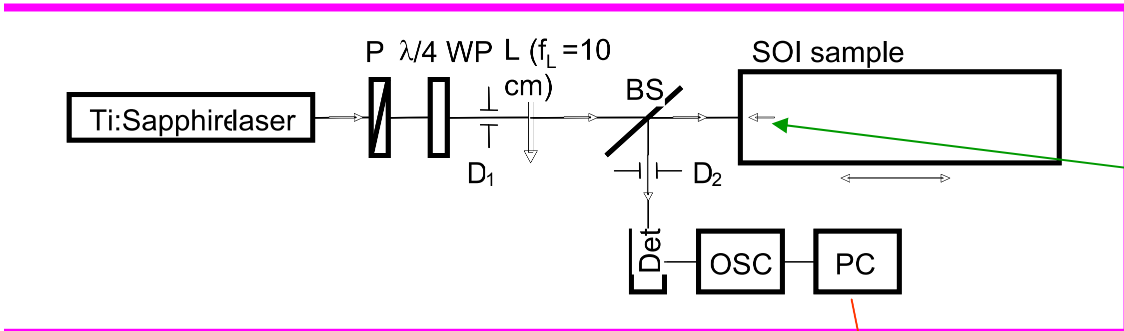


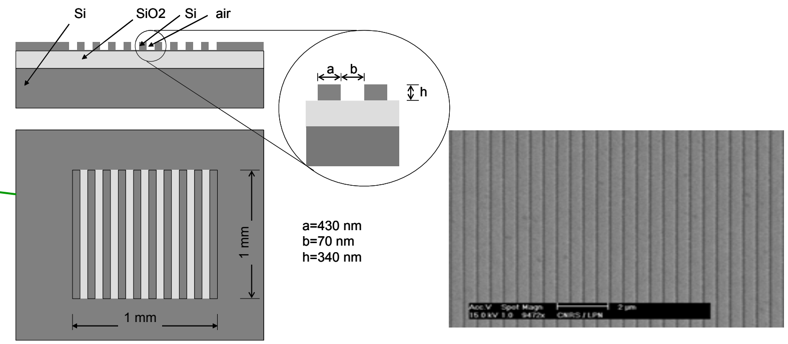
(Using the graph from P. Prasad, Nanophotonics, Wiley, 2004)

→ Research in NILPRP-NIP

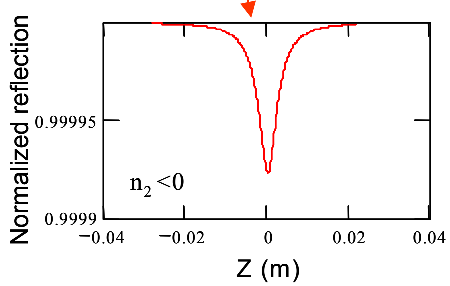
1.1. Strong enhancement of the fast nonlinear response of periodically nano-structurated SOI measured by double RZ-scan with a femto-laser

Aim: High and ultra-fast photonic nonlinear response in SOI





Laser Ti:Sapphire : λ=800nm
P_{av}=265mW, 75 fs, 76 MHz



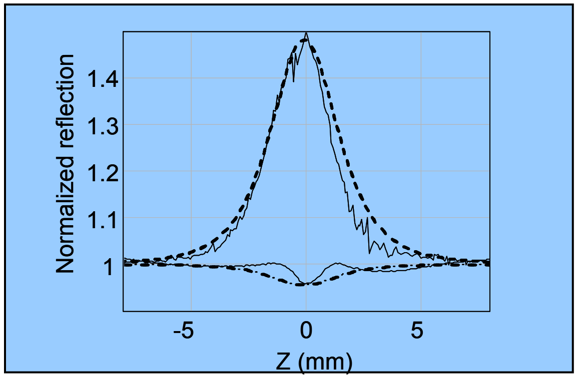
- SOI: Si (250μm)-SiO_2(2μm)-Si (340 nm)
- Periodic nano-structure: 430nm Si-70nm air (e-beam litho.+RIE)
- λ=800 nm: n_{Si}=3.7; n_{SiO2}=1.5; α_{Si}~1000 cm^{-1}

Normaliz. reflected power is: $P(z) \propto \Delta n = n_2 I$. Our formalism for RZ-scan leads to:

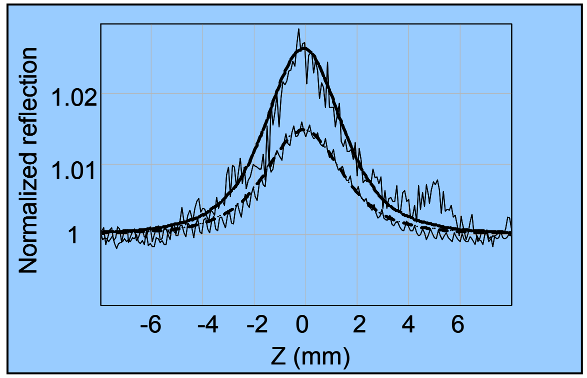
$$P(z) = 1 + \frac{2 n_2 I_0}{n_0^2 - 1} \cdot \frac{1}{1 + (z/z_0)^2} = 1 + \frac{2\Delta n}{n_0^2 - 1} \cdot \frac{1}{1 + (z/z_0)^2} \qquad (1)$$

Collab. NILPRP with Univ. "La Sapienza" di Roma and Ecole Normale Superieure Paris, in the frame of EU Network of Excellence in Nanophotonics "PHOREMOST"

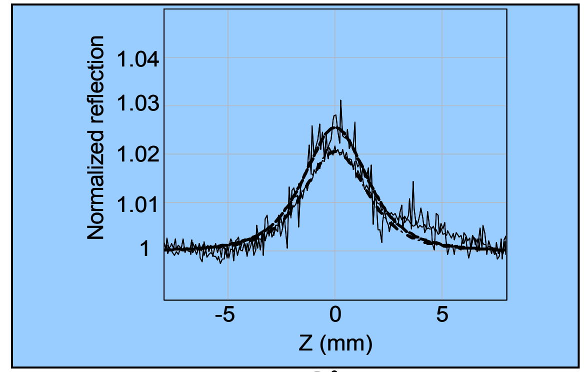
1.2. Double Z-scan (our method – separation of electronic and thermal NL)



SOI periodically nano-struct.



SOI



Si

c.w. Regime (sup. cont. graph): $\Delta n_{th} = n_{2,th} I_0$

Mode-locking Regime (inf. cont. graph): $\Delta n = \Delta n_{el} + \Delta n_{th} = n_{2,el} I_p + n_{2,th} I_{av} \rightarrow \Delta n_{el} = n_{2,el} I_p$

Best fit with (1) (dots, dash-dots)

Electronic and thermal eff. nonlinear coefficients of nano-structurated SOI, SOI and c-Si

n_2(m²/W)	SOI nano-struct.	SOI	Si
$n_{2,th}$ x 10^{10}	**36**	**7.5**	**7.5**
$n_{2,el}$ x 10^{15}	**- 21.2**	**- 1.8**	**- 1.0**

Fs Electronic Nonlinear Response (NR) of nano-structurated SOI > 20 x NR of cSi wafer.

=> **Fast nonlinear photonic devices with parameters controlled by simple nano-structures**

Ref:1. A. Petris, V. I. Vlad et al., Electronic and thermal nonlinear refractive indices of SOI and nano-patterned SOI measured by Z-scan method**, Proc. SPIE, 6785,** 67851F (2007)

2. **A. Petris, V. I. Vlad et al,** Femtosecond fifth order nonlinearities in SOI**, Proc. EOS Conf. "Optical Microsystems",** Capri, 2009

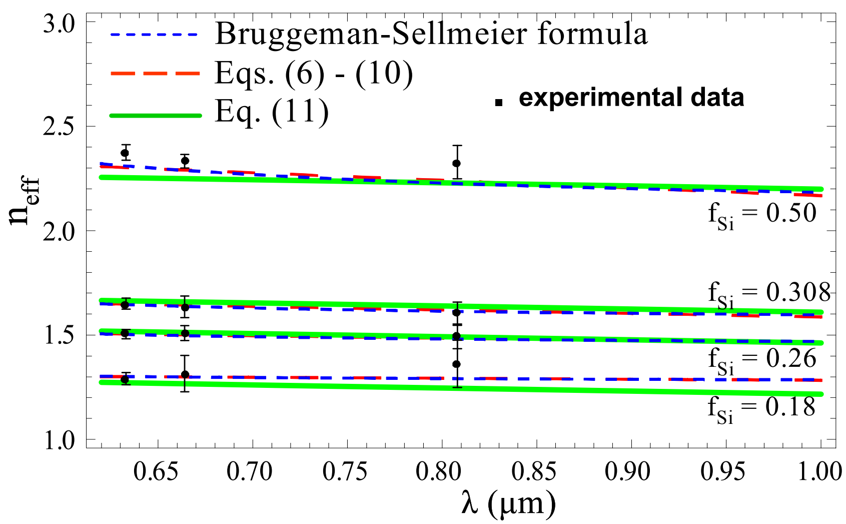
2.1. Effective linear refractive index of nano-porous silicon and its dependences on porosity and light wavelength

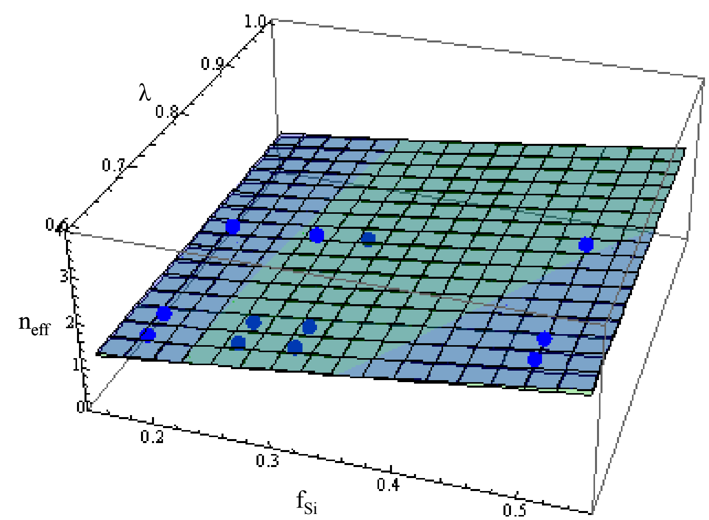
Aim: Control of optical nonlinearity by nanostructuring (at diff. laser wavelengths)

Bruggeman formalism: $n_{eff} = \sqrt{\varepsilon_{eff}} = \sqrt{\frac{1}{4}\left[2 - 3f_{Si} + \varepsilon_{Si}(3f_{Si} - 1) + \sqrt{8\varepsilon_{Si} + 2 - 3f_{Si} + \varepsilon_{Si}(3f_{Si} - 1)}\right]}$

Sellmeier formula: $n_{Si}^2 = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1^2} + \frac{A_2\lambda^2}{\lambda^2 - B_2^2} + \frac{A_3\lambda^2}{\lambda^2 - B_3^2} \quad (A_i, B_j = const, at\, T = 300K)$

Our approx. formula: $n_{eff} \approx 3.07 \cdot f_{Si} - 0.148 \cdot \lambda + 0.812$ (11)





Collab. NILPRP with IMT and NIMP; COST MP0702 "Towards Functional Sub-Wavelength Photonic Structures"- MC-member and WG 3 co-leader

2.2. Effective nonlinear refractive index of nano-porous silicon and its dependences on porosity and light wavelength

Boyd-Bruggeman formula:

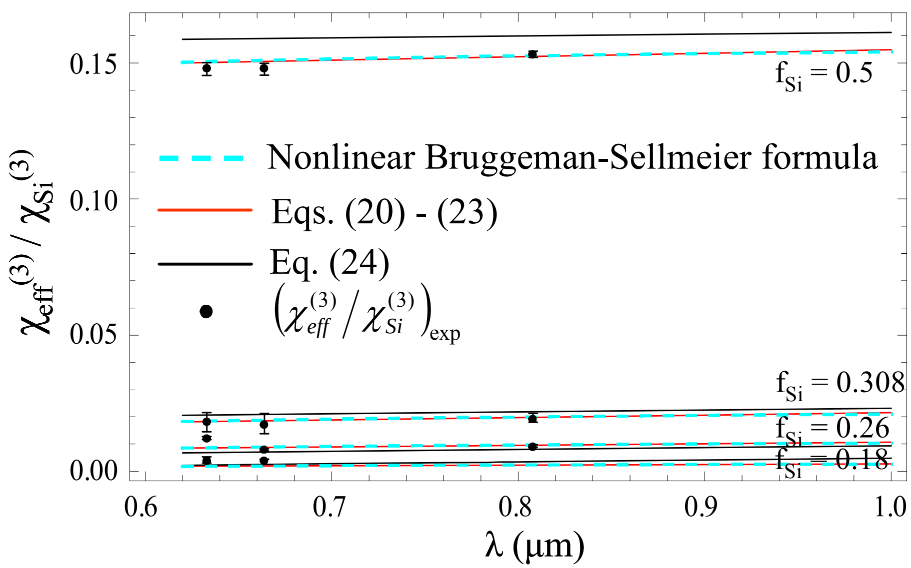
$$\frac{\chi_{eff}^{(3)}}{\chi_{Si}^{(3)}} = \frac{1}{f_{Si}}\left(\frac{\partial \varepsilon_{eff}}{\partial \varepsilon_{Si}}\right)^2 = \frac{1}{f_{Si}}\left[\frac{1}{4}\left(3f_{Si} - 1 + \frac{2 - 9f_{Si}(f_{Si}-1) + \varepsilon_{Si}(1-3f_{Si})^2}{\sqrt{8\varepsilon_{Si} + (2 - 3f_{Si} + \varepsilon_{Si}(3f_{Si}-1))^2}}\right)\right]$$

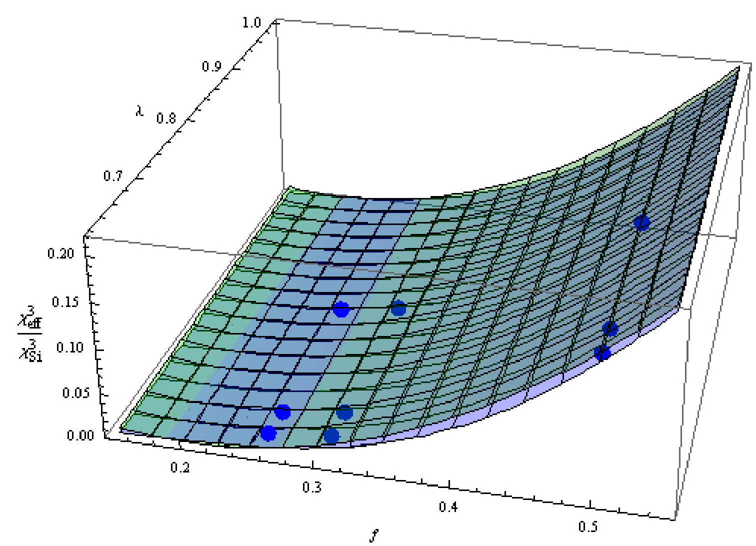
Sellmeier formula:

$$\varepsilon_{Si} = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1^2} + \frac{A_2\lambda^2}{\lambda^2 - B_2^2} + \frac{A_3\lambda^2}{\lambda^2 - B_3^2}$$

Our approx. formula:

$$\frac{\chi_{eff}^{(3)}}{\chi_{Si}^{(3)}} \approx 1.8 \cdot f_{Si}^2 - 0.735 \cdot f_{Si} + 0.0068 \cdot \lambda + 0.072 \qquad (24)$$

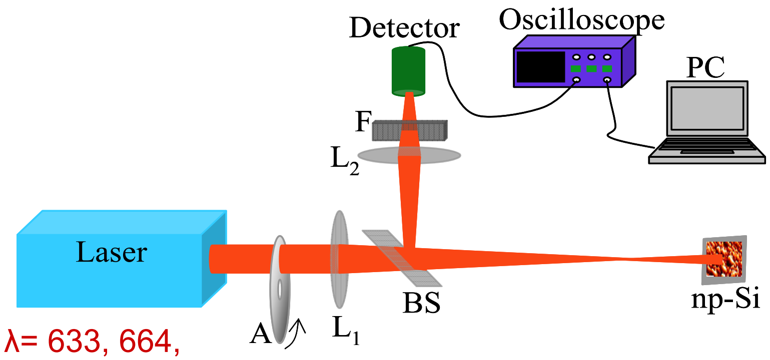




2.3. Effective nonlinear refractive index of nano-porous silicon and its dependences on porosity and light wavelength- Experiments

Reflection I-scan - our formalism leads to:

$$R(I) \approx 1 + \frac{0.04}{n_{eff}^2} \cdot \frac{\chi_{eff}^{(3)} \cdot I}{\left(n_{eff}^2 - 1\right)}$$



λ= 633, 664, 808 nm

where: I is the laser beam intensity at distance z_R from the focus, z_R is the Rayleigh length of the beam (for $w_0 = 4.827 \cdot 10^{-5}$ m and $\lambda = 633$ nm, we get $z_R = 1.2$ cm), w_0 is the beam waist,

$$\chi_{eff}^{(3)}[esu] \approx 12.7 \cdot n_0^2 \cdot n_2[cm^2/W]$$

is the third-order nonlinear optical susceptibility of the sample and n_2 is the nonlinear refractive index of the sample.

In the case of measurements on bulk Si sample, $n_{eff} = n_{0Si}$ and

$$\frac{\chi_{eff}^{(3)}}{\chi_{Si}^{(3)}} \approx 4.785 \cdot 10^{-3} \cdot \frac{R_{np-Si} - 1}{R_{Si} - 1} \cdot \left(3.16 \cdot f_{Si} + 0.71\right)^2 \cdot \left[\left(3.16 \cdot f_{Si} + 0.71\right)^2 - 1\right]$$

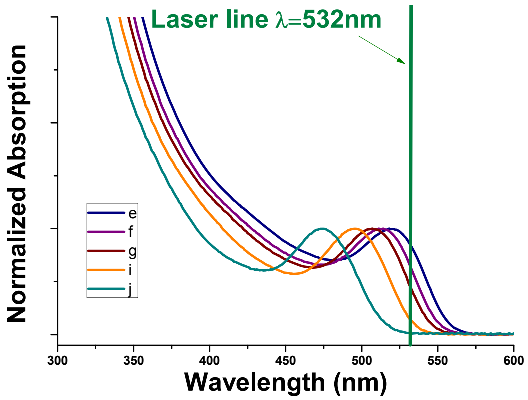
for $\lambda = 633$nm

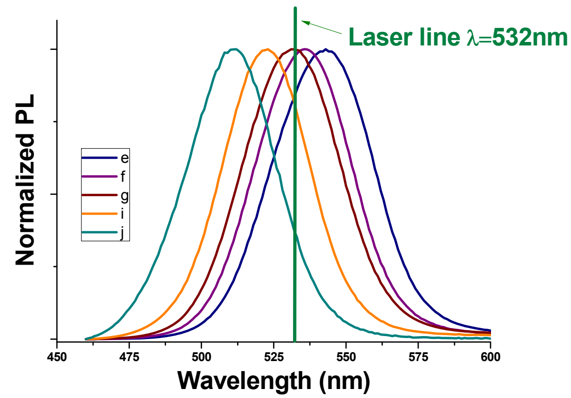
Ref: 1.T. Bazaru, V. I. Vlad, A. Petris, M. Miu, **J. Optoelectron. Adv. Mat. 12** (1), 43-47 **(2010)**

2. T. Bazaru, V. I. Vlad, A. Petris, M. Miu**, Proc. SPIE, Micro- to Nano-Photonics, 2010**

3.1. Giant and controlled nonlinear optical properties of CdTe quantum dots in strong confinement regime – QD characterization

Aim: Synthesis and measurement of giant tunable optical nonlinearity in QDs for switching and new photonic functionalities





All samples have the same QD concentration:

~2.65×10⁶ NC/l

We used A. L. Rogach et al, J. Phys.Chem. C (2007) , for size calculation from the 1s-1s transition

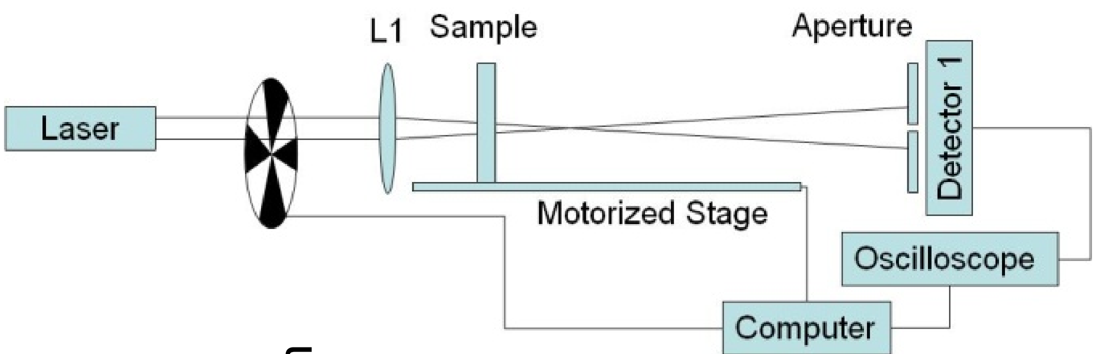
Sample	*1s-1s Abs. Peak (nm)*	*PL max (nm)*	*Size (nm)*	*n_2 ($10^{-7}cm^2/W$)*	*I_{sat} (W/cm^2)*
v108j	*474*	*510.4*	*1.8*	*-1.36*	*-*
v108i	*495*	*522.4*	*2.0*	*-3.09*	*3409.9*
v108g	*507*	*531.3*	*2.1*	*-7.72*	*1424.4*
v108f	*511*	*535.4*	*2.2*	*-9.57*	*1111.7*
v108e	*518*	*542.1*	*2.2*	*-14.65*	*674.5*

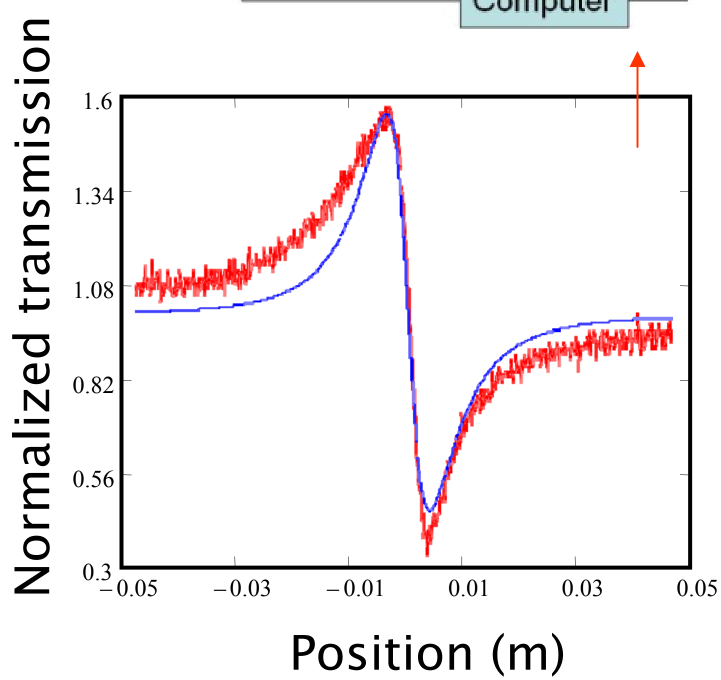
Collab. NILPRP with Univ. Dresden, EU Network of Excellence in Nanophotonics "PHOREMOST" and COST MP0702

3.2. Giant and controlled nonlinear optical properties of CdTe quantum dots in strong confinement regime –TZ scan experiments

TZ-scan –Sheik-Bahae & van Stryland formula:

$$T_{\beta=0}(z,\Delta\phi_0) \cong 1 + \frac{4\Delta\phi_0 Z}{(z^2+1)(z^2+9)}$$





where:

$x=z/z_0$ is the normalized distance;

z_0 – the Rayleigh distance;

$\Delta\phi_0 = k\Delta n_0 L_{eff}$;

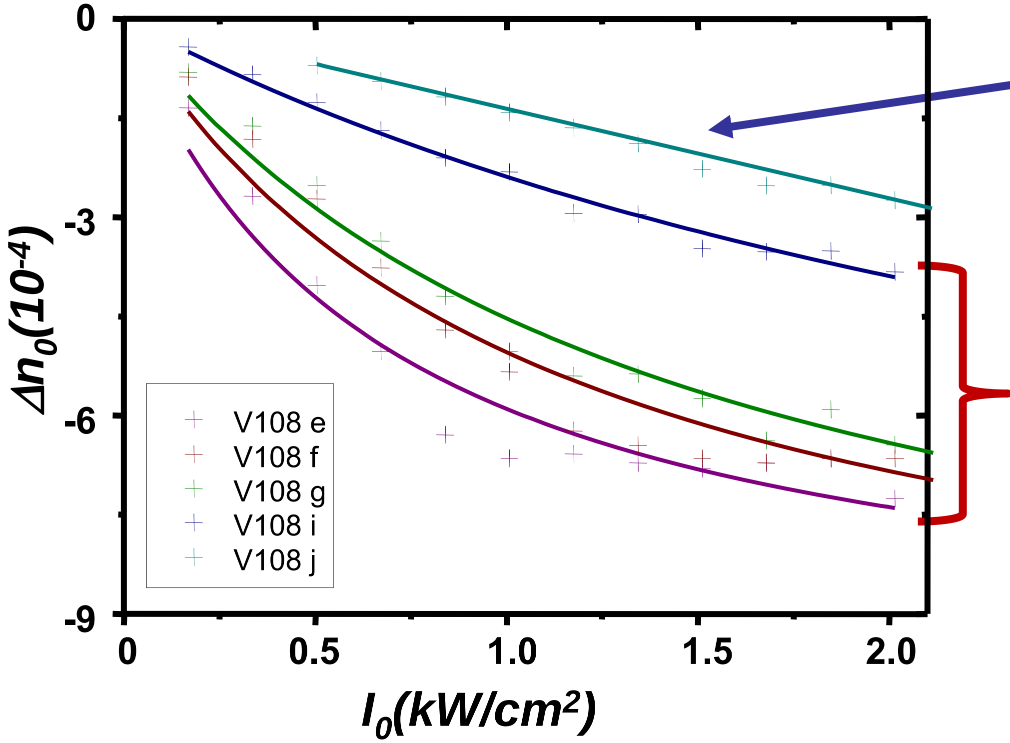
Δn_0 – the **nonlinear induced refractive index change** in the focal plane;

$L_{eff} = (1-e^{-\alpha L})/\alpha$ – the effective length of the medium;

α– the linear absorption and

L – the thickness of the medium.

3.3. Giant and controlled nonlinear optical properties of CdTe quantum dots in strong confinement regime – Saturated NL at low intensity



$$\Delta n_0(I_0) = n_2 I_0$$

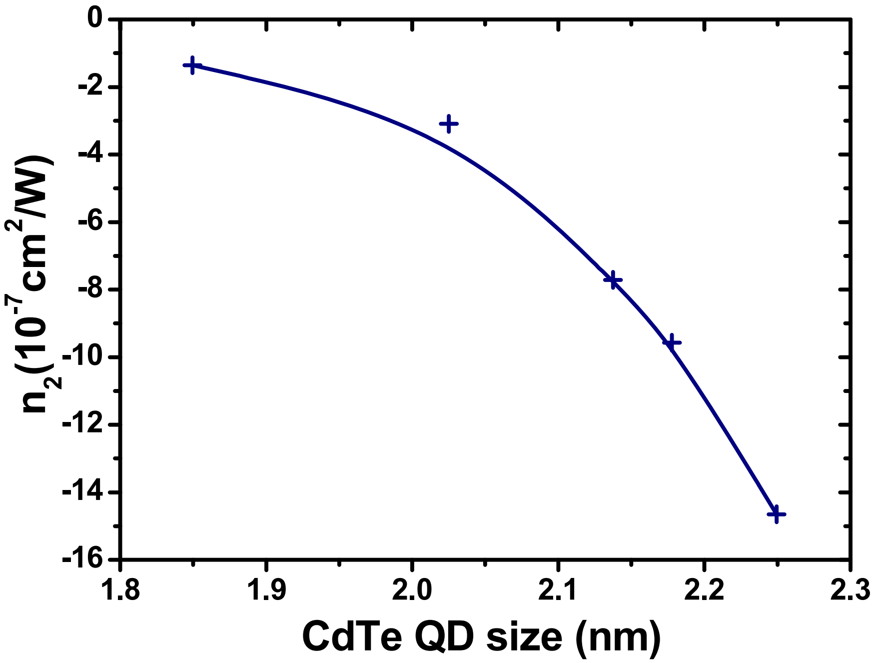
$$\Delta n_0(I_0) = \frac{n_2 I_0}{1 + \frac{I_0}{I_{sat}}}$$

Giant saturated optical nonlinearity at low intensity

G.L. Tan et al. in Opt. Mat. (2004) obtained ***n_2~-10^{-11} cm^2/W;***
L. Pan et al. in Appl. Phys. Lett. (2007) obtained ***n_2~-10^{-12} cm^2/W;***
J. T. Seo et al. in Phys. Stat. Sol (c) (2004) obtained ***n_2~-10^{-9} cm^2/W;***

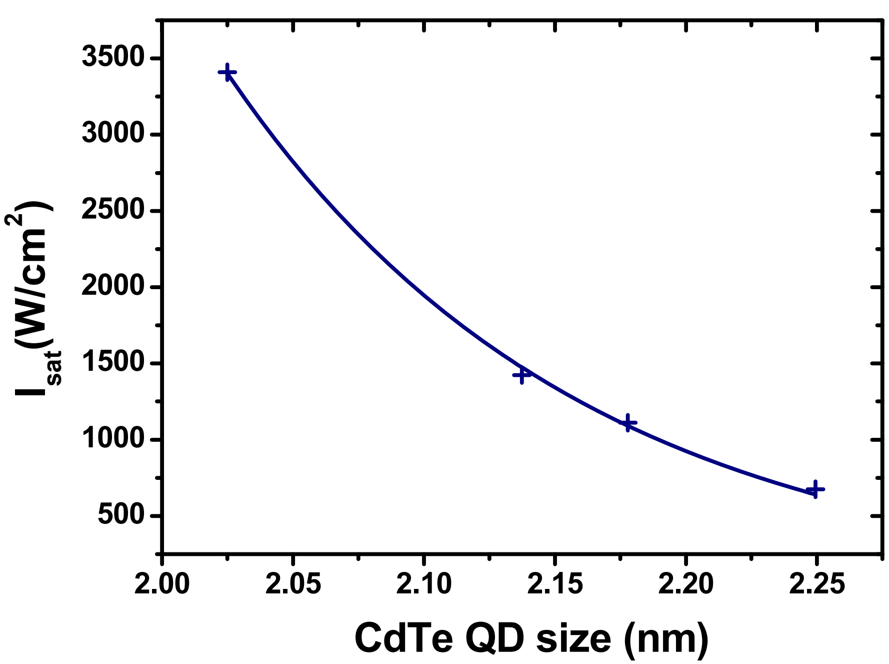
I. Dancus, V.I. Vlad et al, Opt. Lett., March 2010: *n_2~-10^{-6} cm^2/W*

3.4. Giant and controlled nonlinear optical properties of CdTe quantum dots in strong confinement regime – Size dependent NL effects



Experimental nonlinear refractive index, n_2, shows an exponential decrease with the increase of the size, *a*, of the QDs

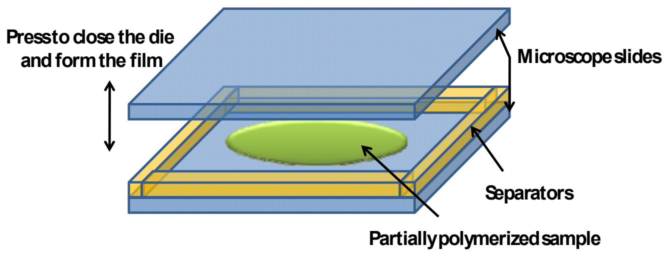
$$n_2(a) = 0.18 - 1.69 \cdot e^{\frac{a}{0.16}}$$



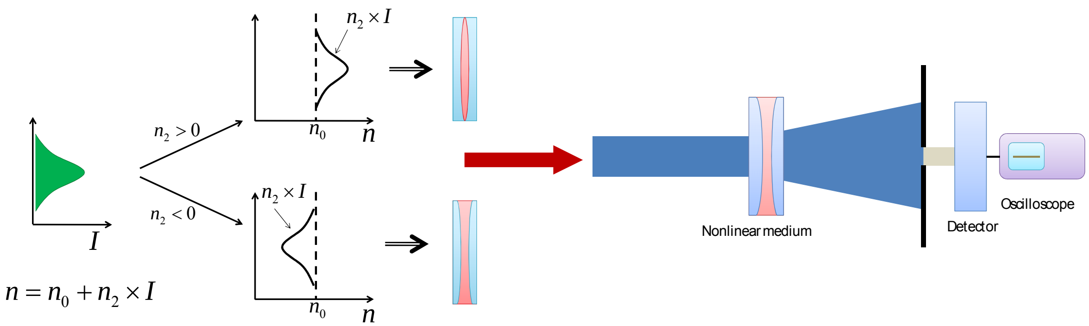
Experimental dependence of the saturation intensity shows an exponential decrease with the increase of the size of the CdTe QDs

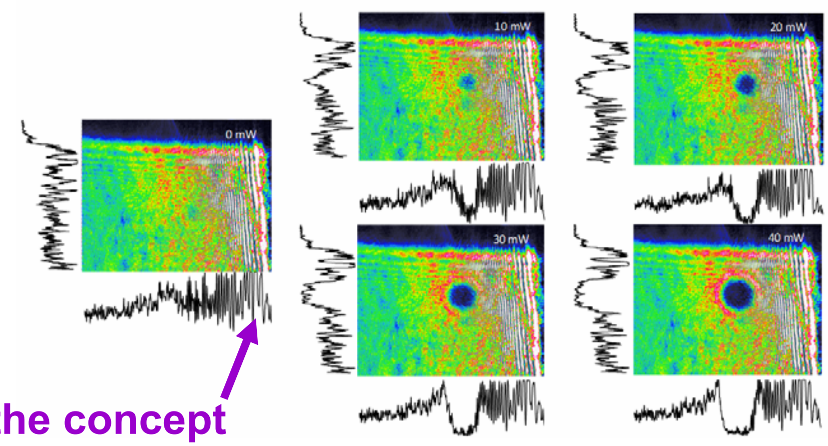
$$I_{sat}(a) = 201.73 + 8.45 \cdot e^{-\frac{a}{0.12}}$$

3.5. Giant and controlled nonlinear optical properties of CdTe QDs in polystyrene – Eye exposure limiting to laser beams



Concept of optical limiting device based on the induced nonlinear refractive index lens. The divergence of the lens is intensity dependent.





Proof of the concept

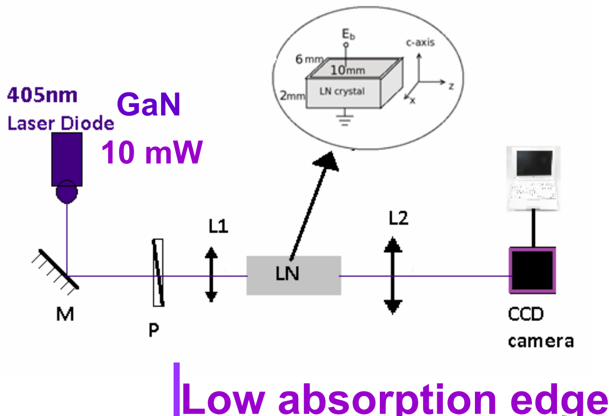
For laser beam diameter of 1mm, the threshold intensity for this optical limiting device is ~ 1W/cm^2 and switching time ~ 1μs

Ref: 1. I. Dancus, V.I. Vlad et al, Sat. near-resonant refractive NL in CdTe QDs, **Optics Lett., 2010**
2. I. Dancus, V. I. Vlad et al, **J. Optoelectron. Adv. Mat. 12** (1), 149-151 **(2010)**
3. I. Dancus, V. I. Vlad et al, **Proc. SPIE, Micro- to Nano-Photonics, 2010**
4. I. Dancus, V. I. Vlad et al, Size-dependent NL propeties of Cd-Te QDs, **CLEO/Europe-EQEC Conf.**, **Munich, 2009**

4.1. Fast spatial soliton and soliton waveguide creation in lithium niobate (LN) crystals with a low power c.w. laser blue-violet diode

First Bright Spatial Solitons in LN crystals: E. Fazio, A. Petris, V. I. Vlad et al, "Screening-photovoltaic bright solitons in $LiNbO_3$ and associated single-mode waveguides", Appl. Phys. Lett. 85, 2193 (2004)

Aim: Fast SWG creation with low power lasers at the absorption edge of LN-Fs propagation



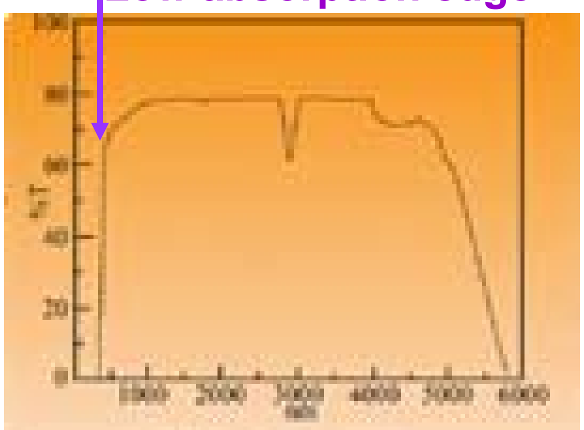


Fig.1. LN Transmission

(www.sp3plus.co.uk/lithium-niobate)

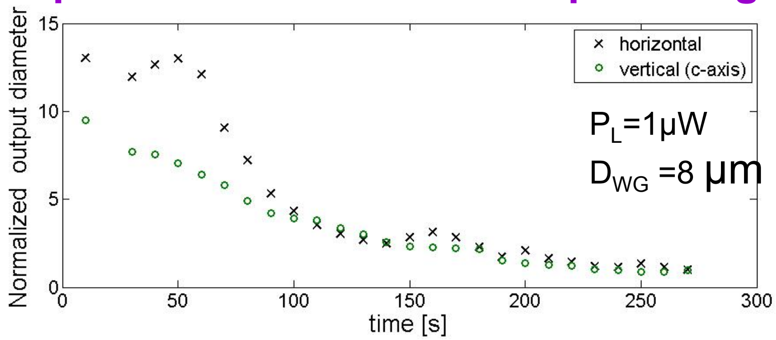
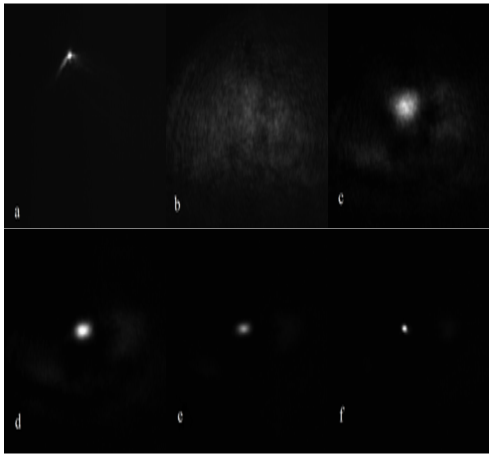
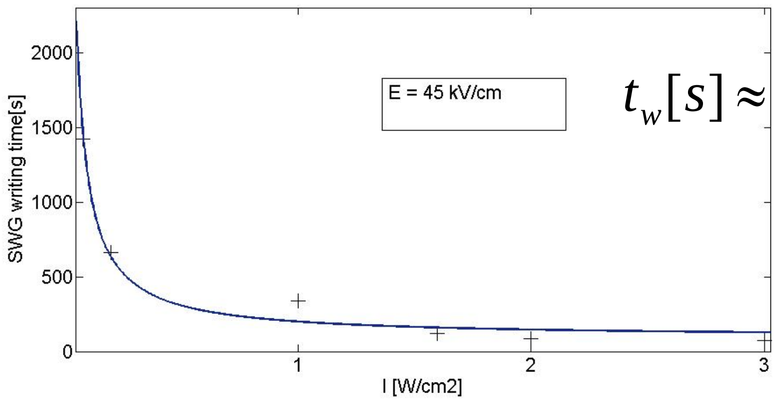


Fig.2.Time evolution of normalized output beam diameter at 405nm (single mode fiber after ~ 2 min; at 533nm, t_w ~ 30 min)





$$t_w[s] \approx \frac{107}{I[W/cm^2]} + 92$$

Fig.3. Writing time at 405nm vs. laser intensity

Collab. NILPRP with Univ. "La Sapienza" di Roma, in the frame of COST MP0702

4.2. Fast soliton waveguide creation in lithium niobate crystals with a low power laser blue-violet diode – Fs pulse propagation in SWG arrays

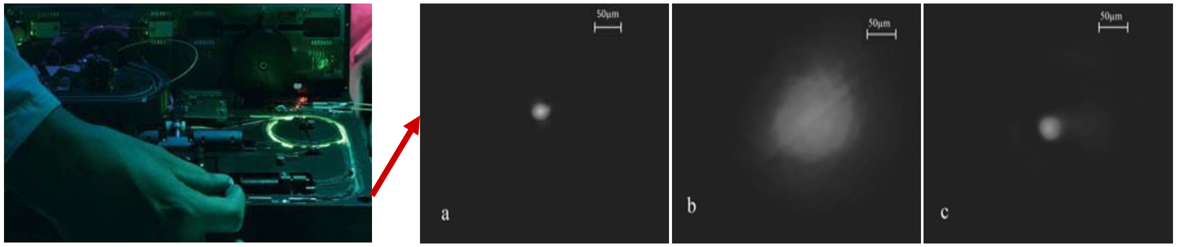


Fig. 4. Propagation of 150 fs laser pulses from ultrafast fiber lasers (1.03µm and 1.55 µm) in SWG

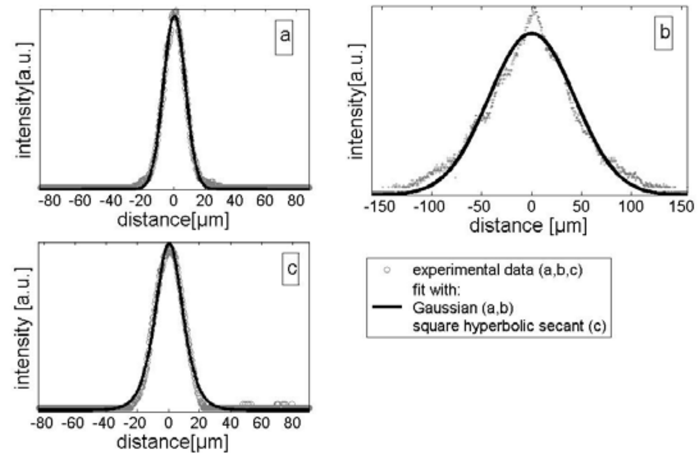


Fig. 5. (a) The beam profile along its diameter on the input face of the LN crystal;
(b) The beam profile on the output face of the LN crystal after free propagation;
(c) The beam profile on the output face of the LN crystal when propagating through a SWG

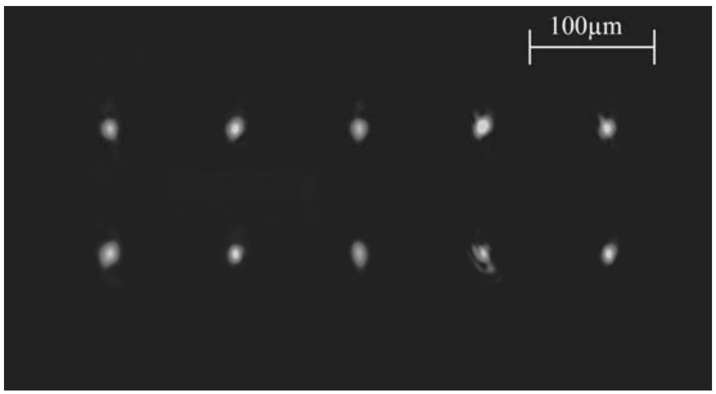


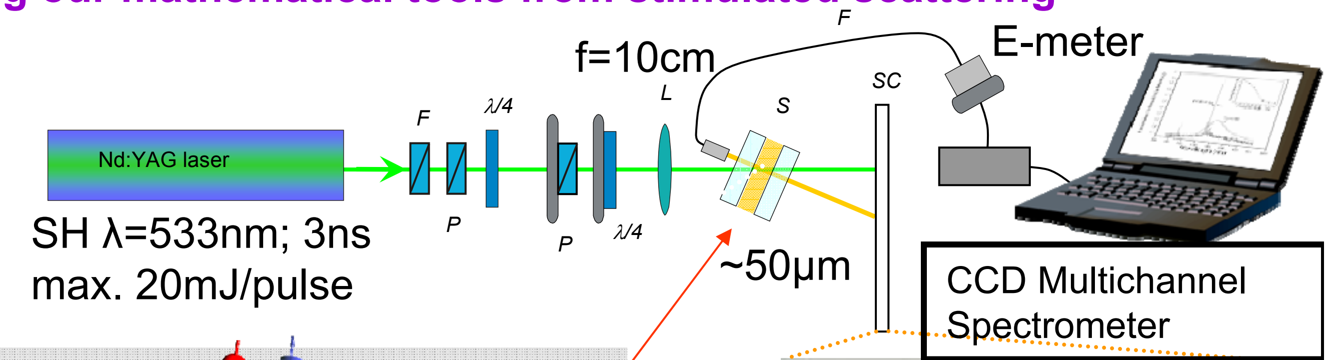
Fig. 6. SWG array 2x5 recorded in LN crystal at λ=405nm ; 1µW input power; writing time < 1h

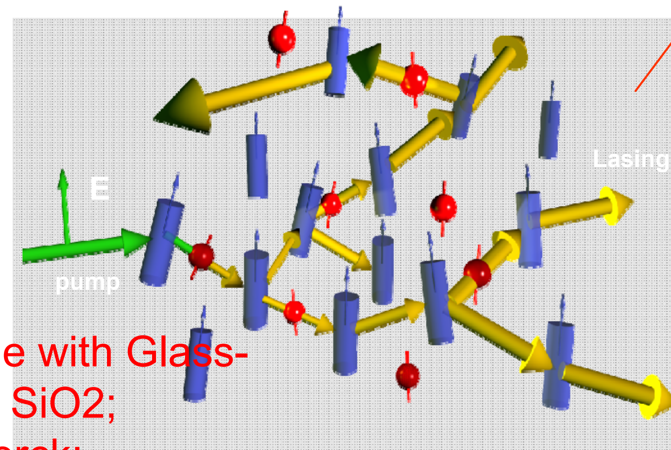
Ref: 1. F. Petazzi, A. Petris, V. I. Vlad et al, **Phys. Rev. A**., **76**, 063818 (2008);
2. E.Fazio, V. I. Vlad, A. Petris, Ch. 5 in « Micro-/Nano-engineering and Characterization of Ferroelectric Crystals for Photonic Applications », P. Ferraro et al. (Eds), **Springer,** 2008 (50 pag).
3. Petris, Vlad et al, Self-confined beams in Er-doped lithium niobate, **J. Optics, 12,** Paper 015206 (2010); and **J. Optics, 12,** Paper 015205 (2010)
4. S. Popescu, A. Petris, V.I. Vlad**, J.Optoelectr. Adv Mat, Jan. 2010;** and **Proc. SPIE, 2010**

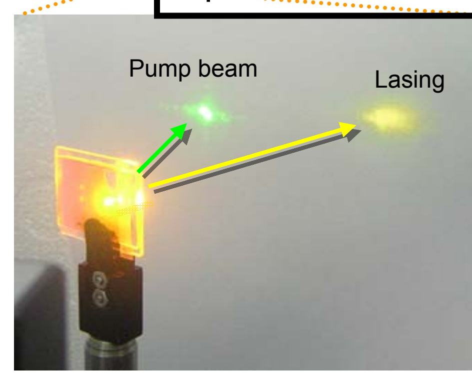
5.1. Highly efficient forward- and backward- random laser effect (without optical cavity) in dye doped nematic liquid crystals

First "random laser" in NLC: G. Strangi, S. Ferjani, V. Barna, et al, Random lasing and weak localization of light in dye-doped nematic liquid crystals, **Optics Express, 14**, 7737 **(**2006)

AIM: Experimental characterization of random laser in dye-doped nematic LC and theoretical modeling of laser effect using our mathematical tools from stimulated scattering



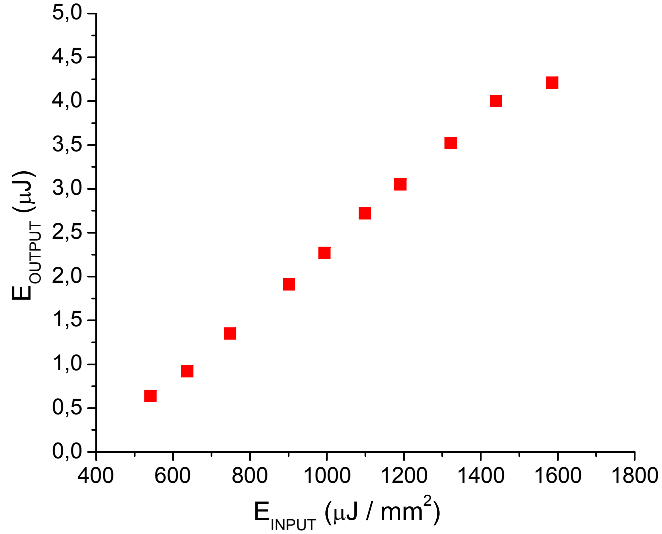


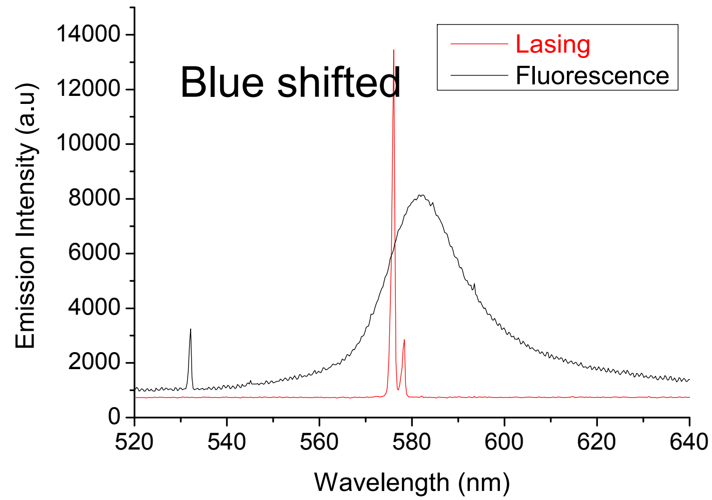


Material: Sandwich cell done with Glass-ITO plates; Align. Layers: SiO_2;
Nematic LC: ZLI 2659 by Merck;
Dye: PM597 by Exciton (0.5 wt%)

Collab. with Bucharest Univ.- Fac. Physics, University of Calabria - Center of Excellence CEMIF.CAL of Dept. Physics, Italy and NIMP

5.2. Random laser in dye doped nematic liquid crystals
Efficiency and Spectrum





Efficiency ~ 10% (quite high for a mirrorless laser!)
Threshold ~ 30 μJ/ mm^2; E_{out}X 2 (forw+backw)

Spectral properties (low pump en.)
Sharp peaks < 0.5 nm

Stimulated Scattering - Damzen, Vlad, Babin, Mocofanescu**, S.B.S., IOP Publ, London, 2003**

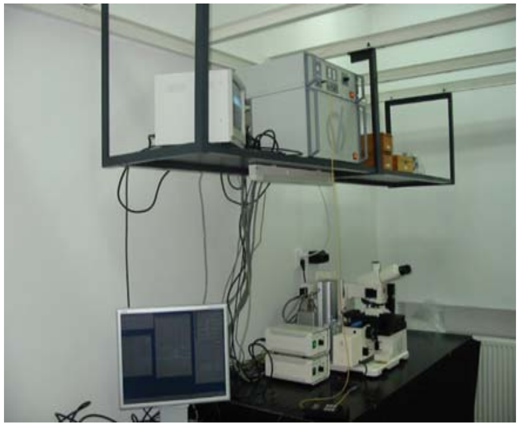
$$\frac{\partial E_P(z,r)}{\partial z} - \frac{i}{k}\left(\frac{\partial^2 E_P(z,r)}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial E_P(z,r)}{\partial r}\right) = -(k\sigma_{dye})\cdot\left|E_{LBackw}(z,r)\right|^2 \cdot E_P(z,r)$$

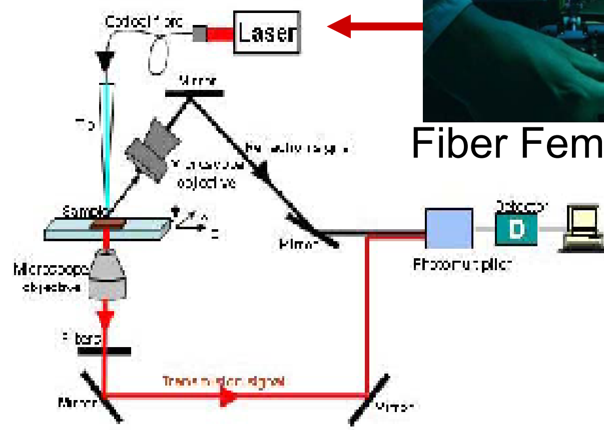
$$\frac{\partial E_{LBackw}(z,r)}{\partial z} + \frac{i}{k}\cdot\left(\frac{\partial^2 E_{LBackw}(z,r)}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial E_{LBackw}(z,r)}{\partial r}\right) = -(k\sigma_{dye})\cdot\left|E_P(z,r)\right|^2 \cdot E_{LBackw}(z,r)$$

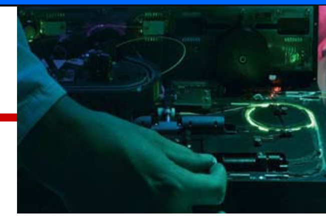
$$\sigma_{dye} = g_{dye} I_0 L$$

Ref: 1. V. Barna et al, **J. Nonlinear Optical Phys. & Mat., 18,** 349-365(2009)
2. V. Barna et al, **Opt. Express, 17,** 13435-13440(2009)
3. V. Barna et al**, Phys. Rev. Lett, 102,** Article Number:167801, Apr. 24 (2009)
4. V. Barna et al, **Opt. Express, 17,** 2042-2047(2009)

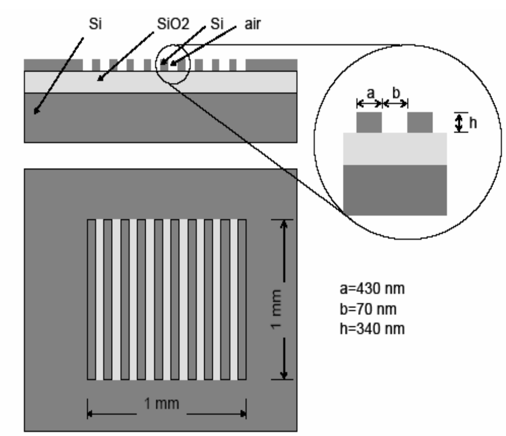
6.1. Imaging SOI nanostructures



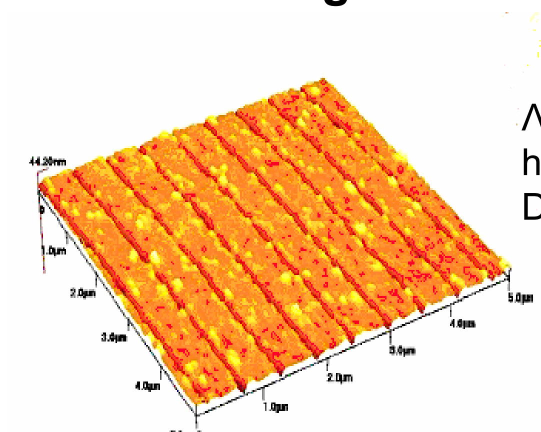




Fiber Femto-laser

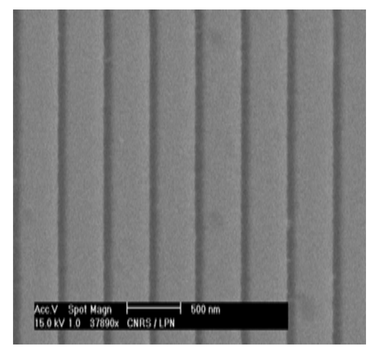


AFM Images

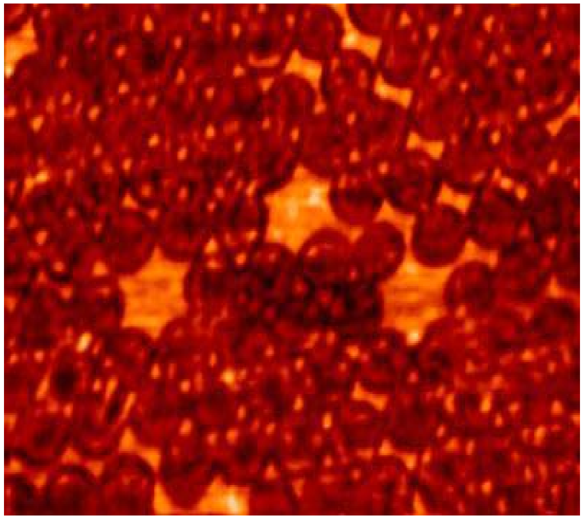


Λ_2= 530 nm
$h_{stripes}$=430 nm
D_{stripe}=70nm

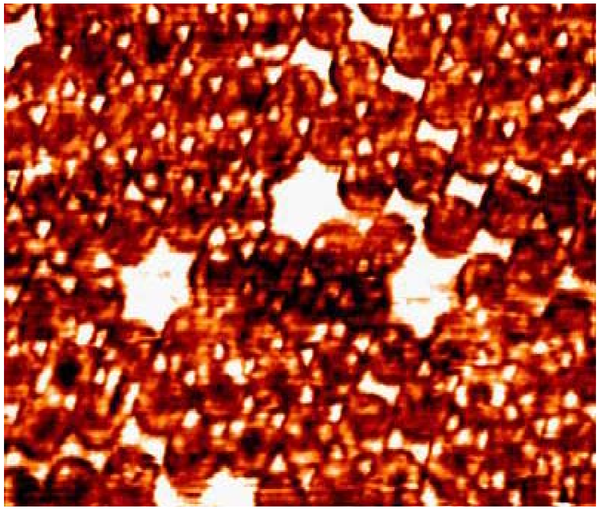
SEM Images



6.2. AFM si SNOM Imaging - Polystyrene nanospheres



AFM



SNOM

Polystyrene sphere (Omicron) diameter ~ 280 de nm,
Interstitial distance ~ 70 de nm.

The series of International Conferences "**ROMOPTO**", with Proceedings published by The International Society for Optical Engineering, USA (SPIE Digital Library – ISI)

Intl. Conf. "Micro- to Nano-Photonics III. ROMOPTO 2012" will be organized in Sept. 2012

+JOAM,1/2010 Special Issue

"NONLINEAR AND INFORMATION PHOTONICS" TEAM

Missing V. Barna, M. Udrea, M. Stoica

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to the other organizers of the 9th National Seminar of Nanoscience and Nanotechnology

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