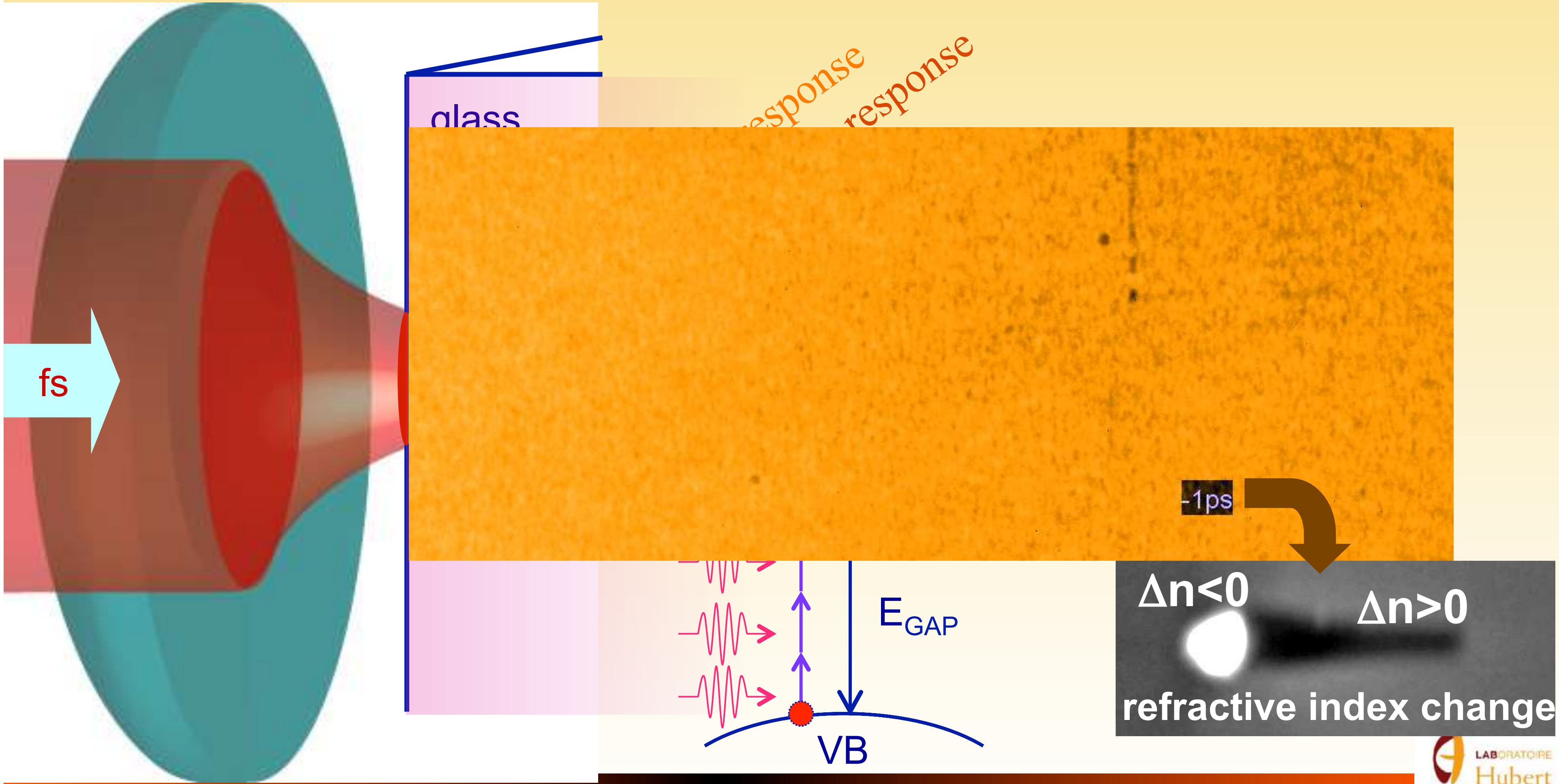
Ultrafast laser structuring beyond diffraction limit
applications in 3D photonics

R. STOIAN

LABORATOIRE Hubert CURIEN
UMR • CNRS • 5516 • ST-ETIENNE
Université Jean Monnet SAINT-ETIENNE
cnrs

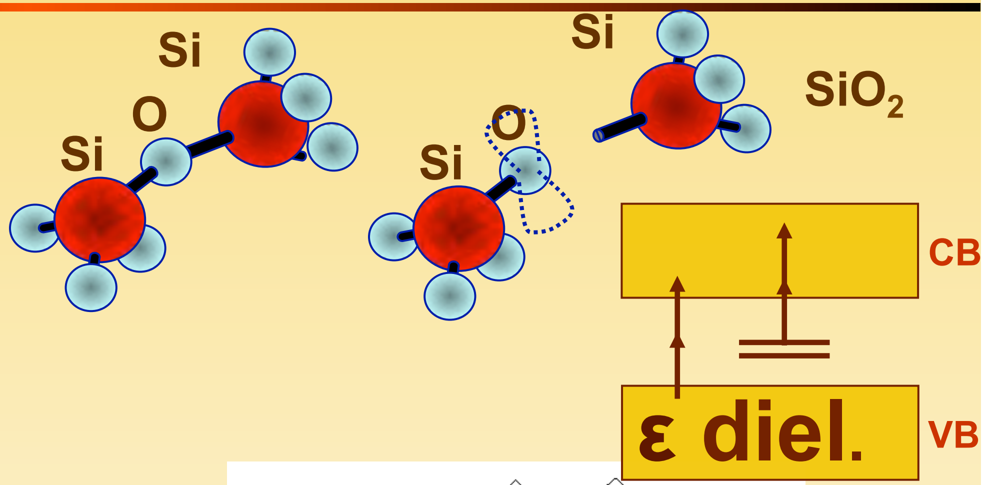
3D nonlinear excitation: ultrafast laser pulses



material modifications

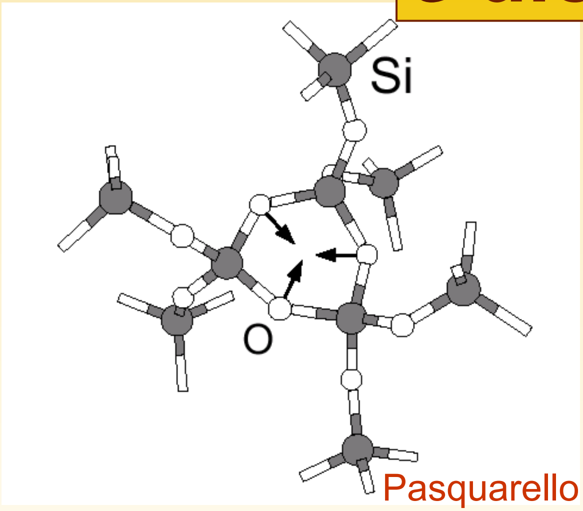
refractive index Δn

- interplay between



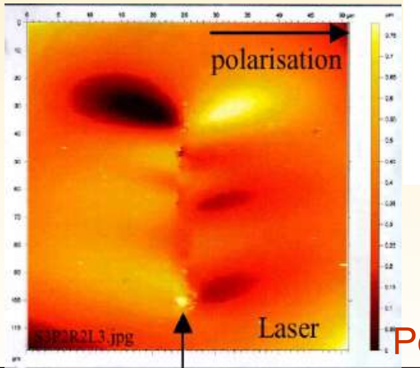
➪ defects (energetic path)

➪ densification (thermodynamic path)



Pasquarello PRL 1998

➪ stress (mechanical)

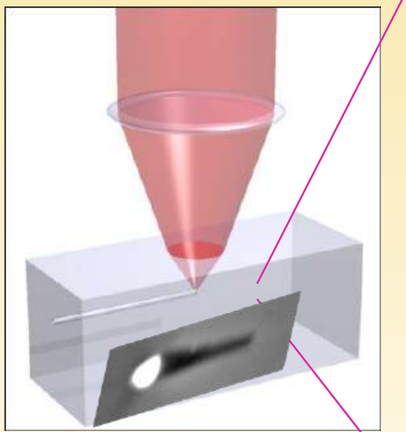


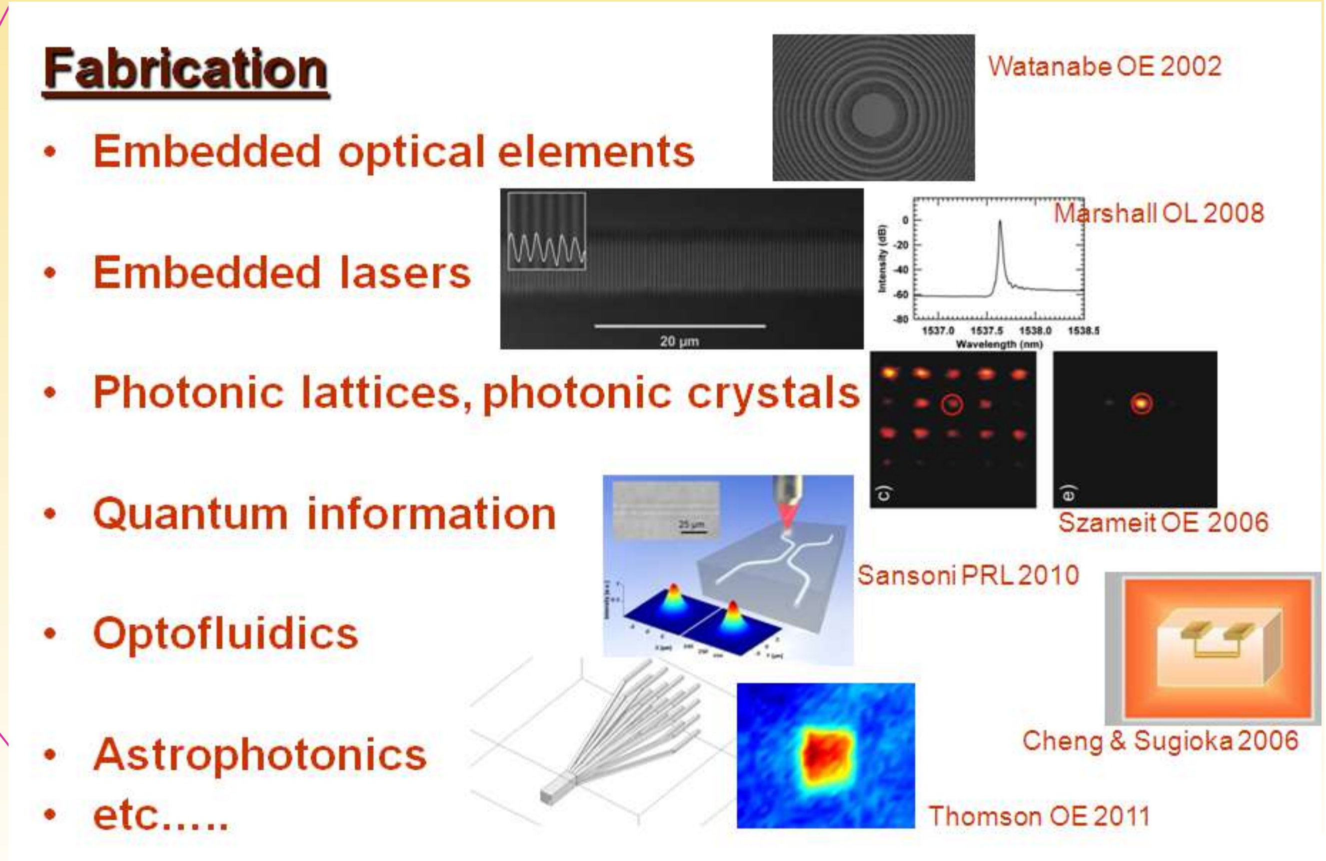
Poumellec OE 2003

3D material modifications: 3D optics

refractive index Δn

Building block of embedded 3D optical functions



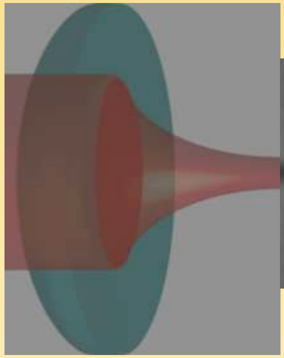


outline

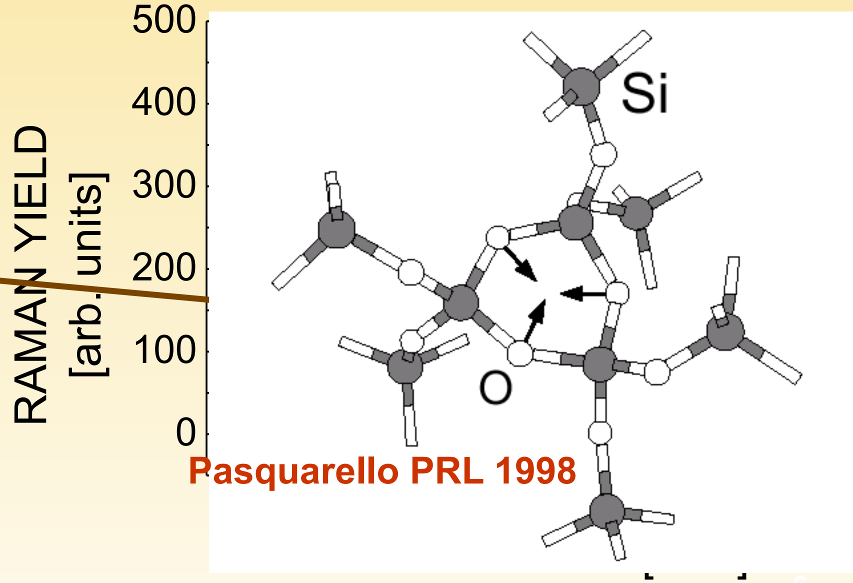
- **Index change**
- **Index control**
- **Applications in 3D photonics**

refractive index engineering: model a-SiO_2

Type I: Isotropic Δn>0



What does this represent?

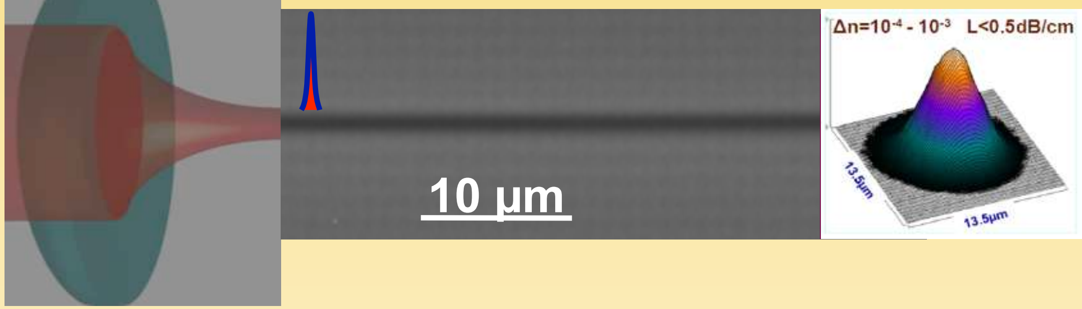


Accumulation of bond breaking

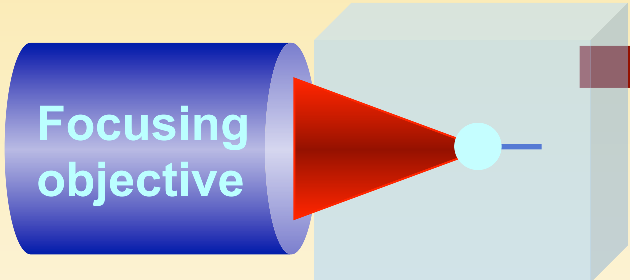
Densification

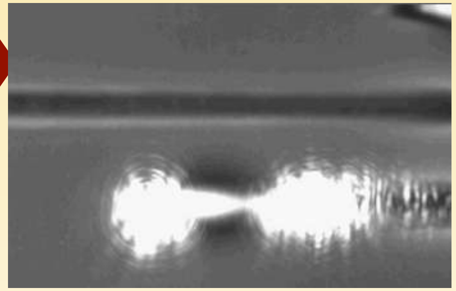
refractive index engineering: model a-SiO_2

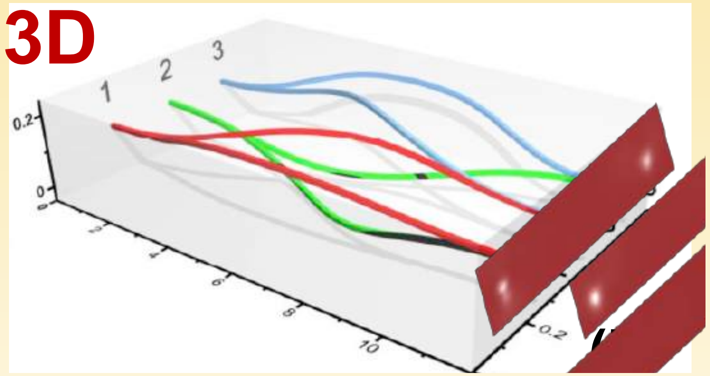
Type I: Isotropic Δn>0

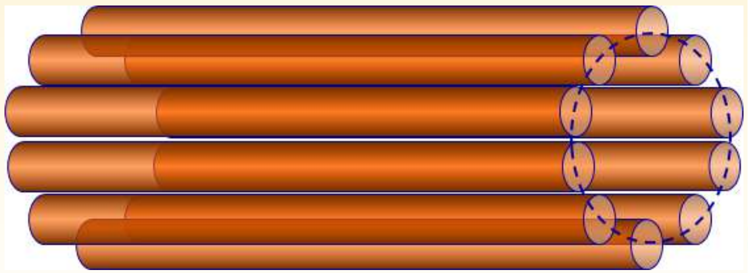


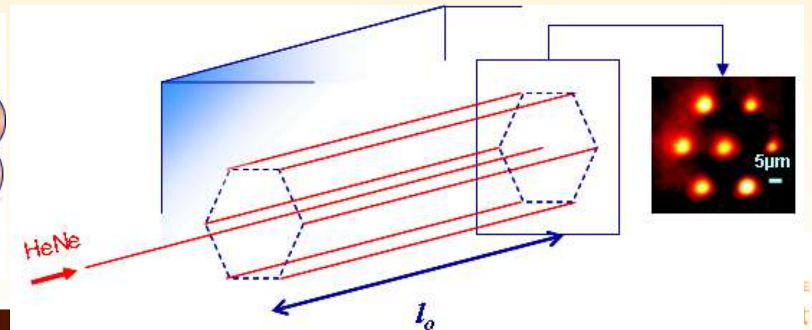
3D



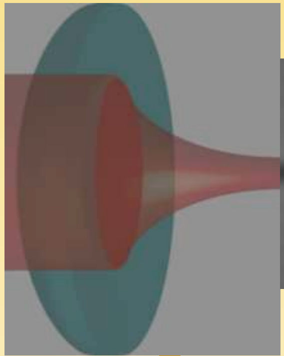






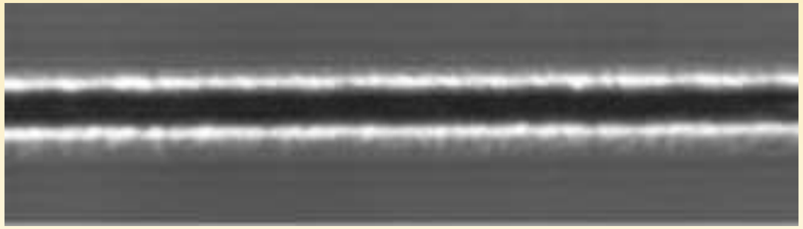


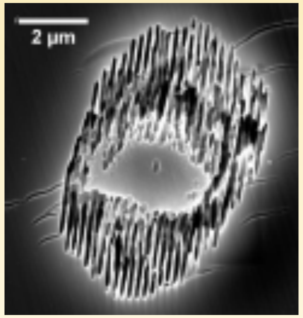
refractive index engineering: model a-SiO_2

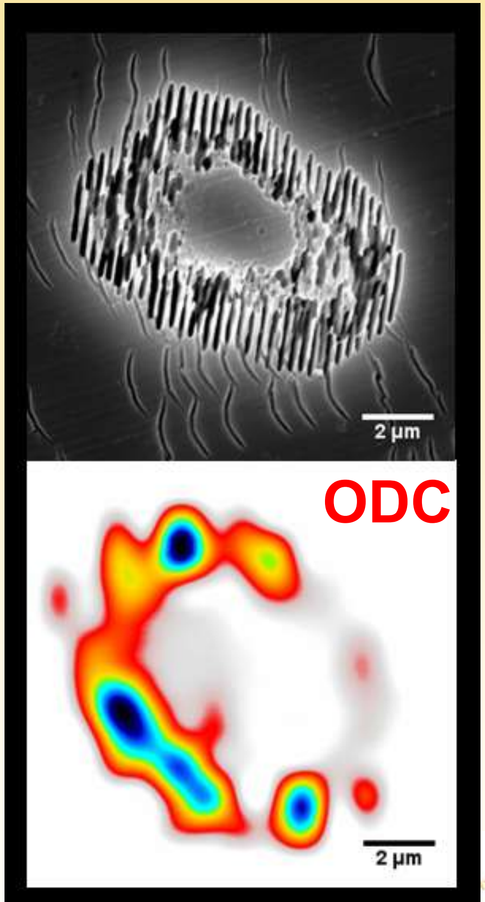


Type I: Isotropic Δn>0

Pulse manipulation
E, N, τ_p







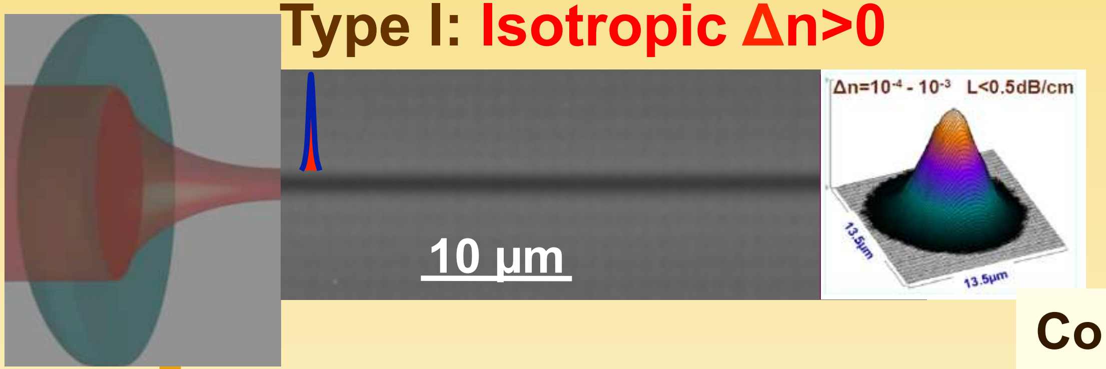
Type II
Anisotropic Δn

Nanogratings:
quasi-universal

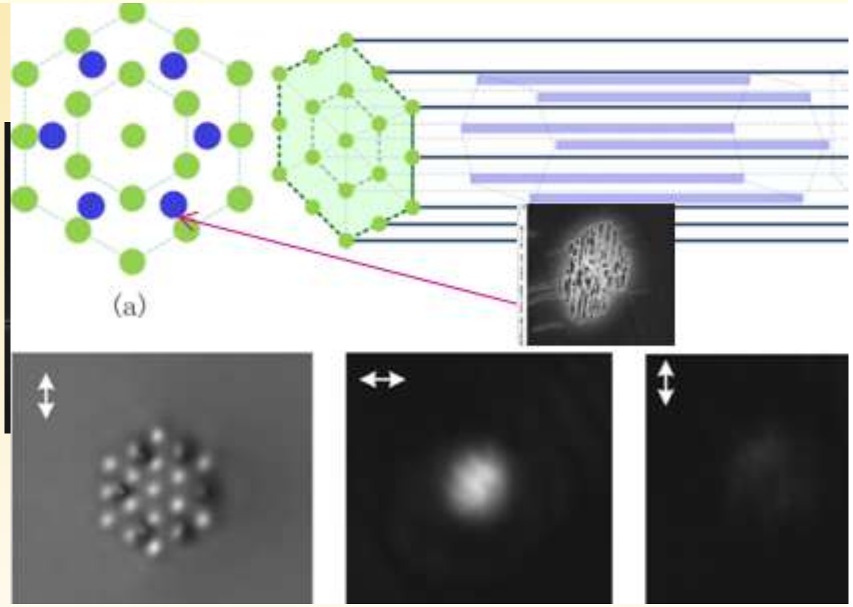
Mauclair Opt. Exp. 2009, Mishchik Opt. Exp. 2010, Cheng OL 2013

refractive index engineering: model a-SiO_2

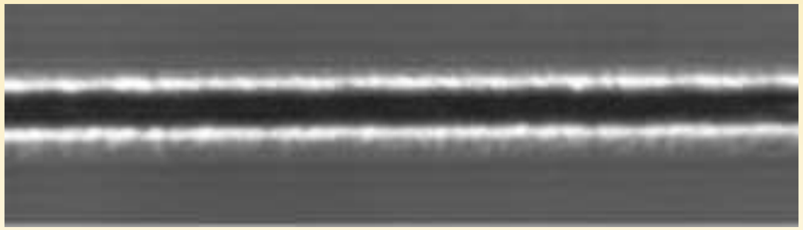
Type I: Isotropic Δn>0

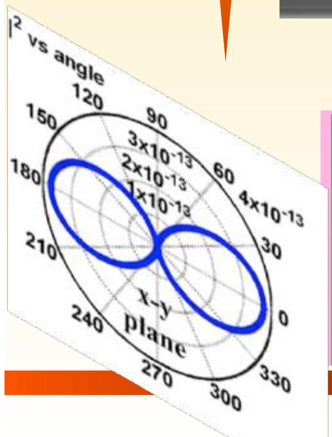


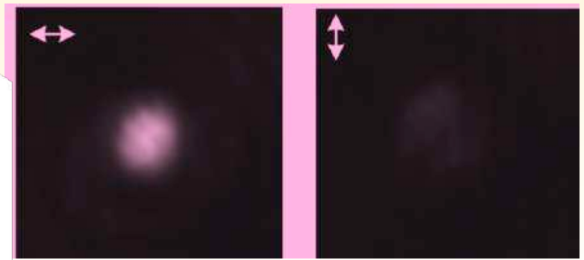
Combination: low loss polarization



Pulse manipulation
E, N, τ_p



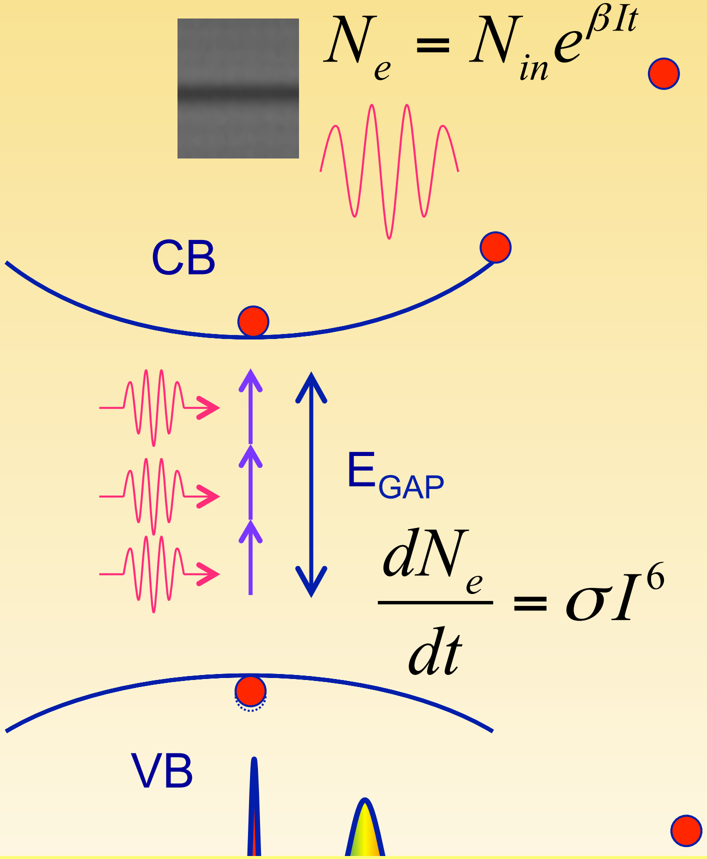




Polarization sensitivity

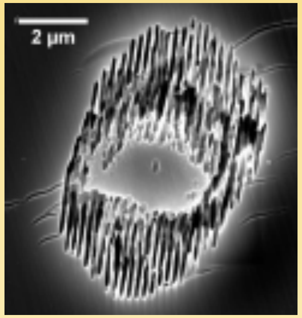
Mauclair Opt. Exp. 2009, Mishchik Opt. Exp. 2010, Cheng OL 2013

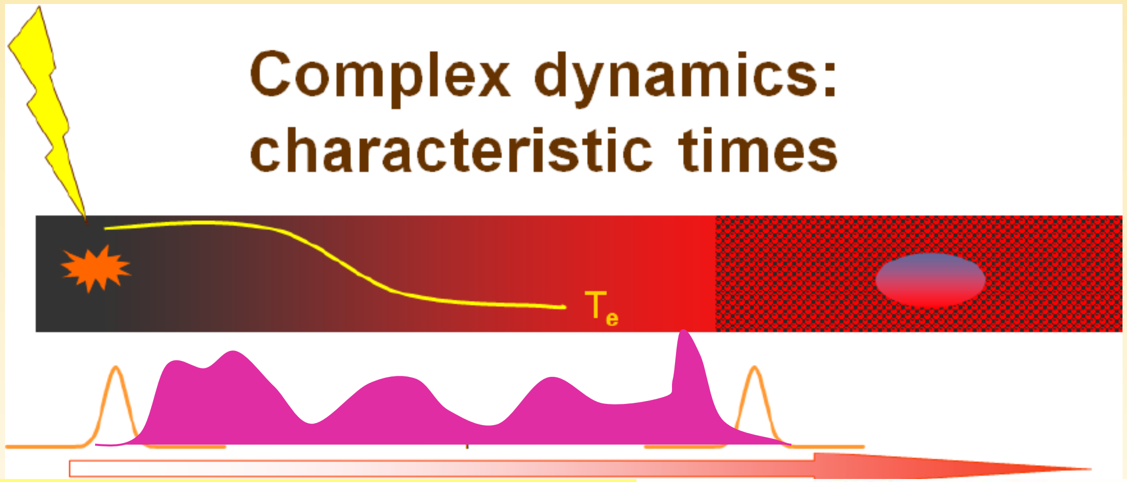
3D nonlinear excitation: ultrafast laser pulses



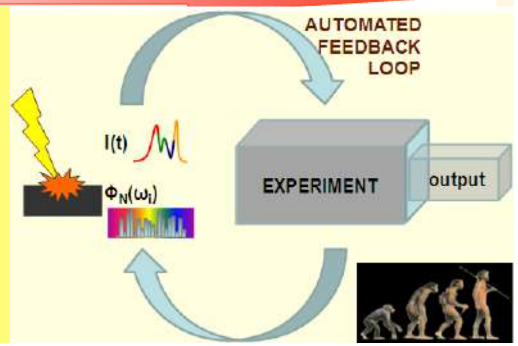
$$N_e = N_{in} e^{\beta I t}$$

$$\frac{dN_e}{dt} = \sigma I^6$$





Controlling light-matter interaction on smallest scales: spatio-temporal pulse design (index engineering)



optimizing the laser action

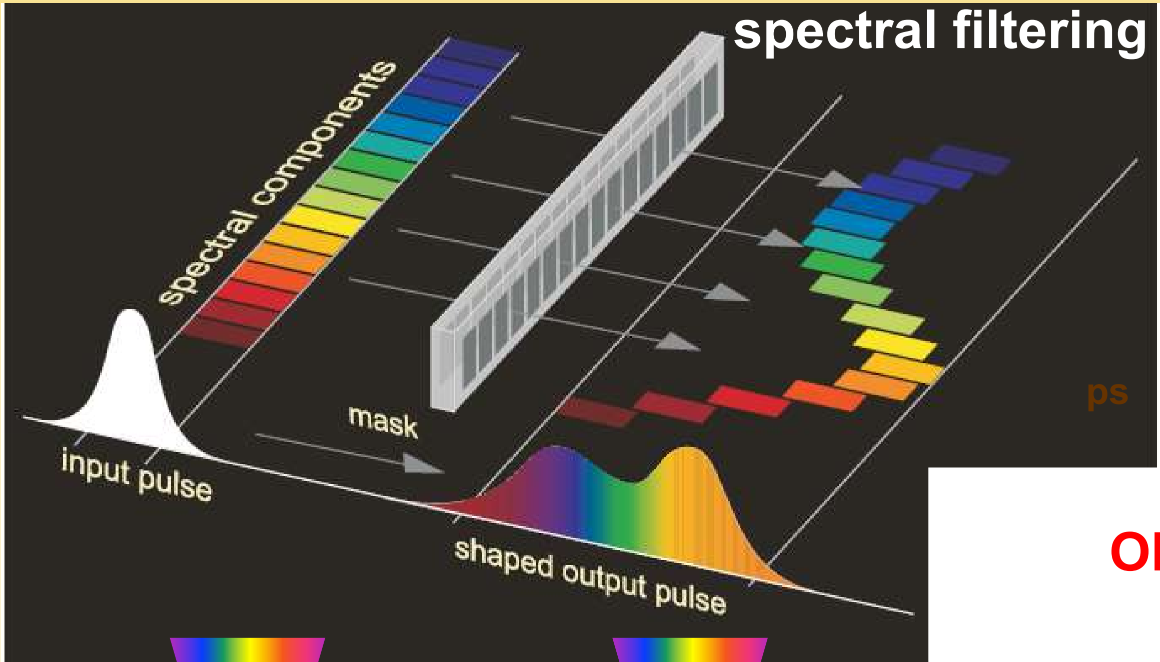
Idea

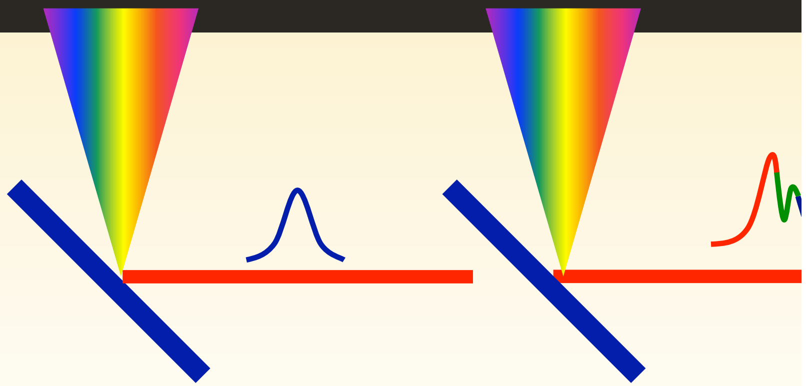
- Design radiation according to the material response

Technique

- Pulse temporal shaping

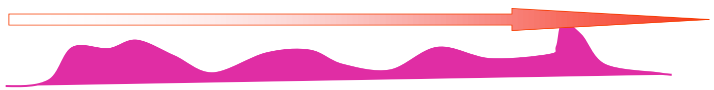
designing pulses in time





OPTIMAL CONTROL

PHASE TRANSITION



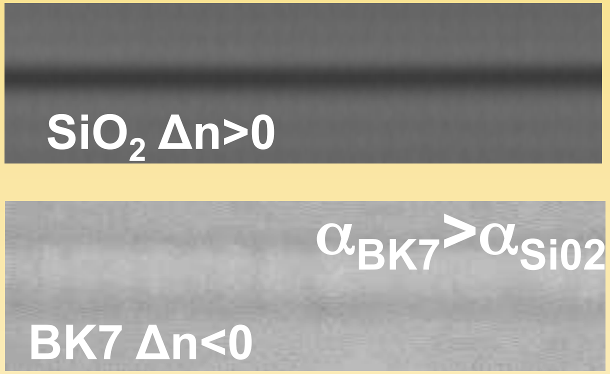
-synergetic design

evolution trajectories

IMPROVE PROCESS

Wollenhaupt et al. Springer 2007 Stoian et al Springe

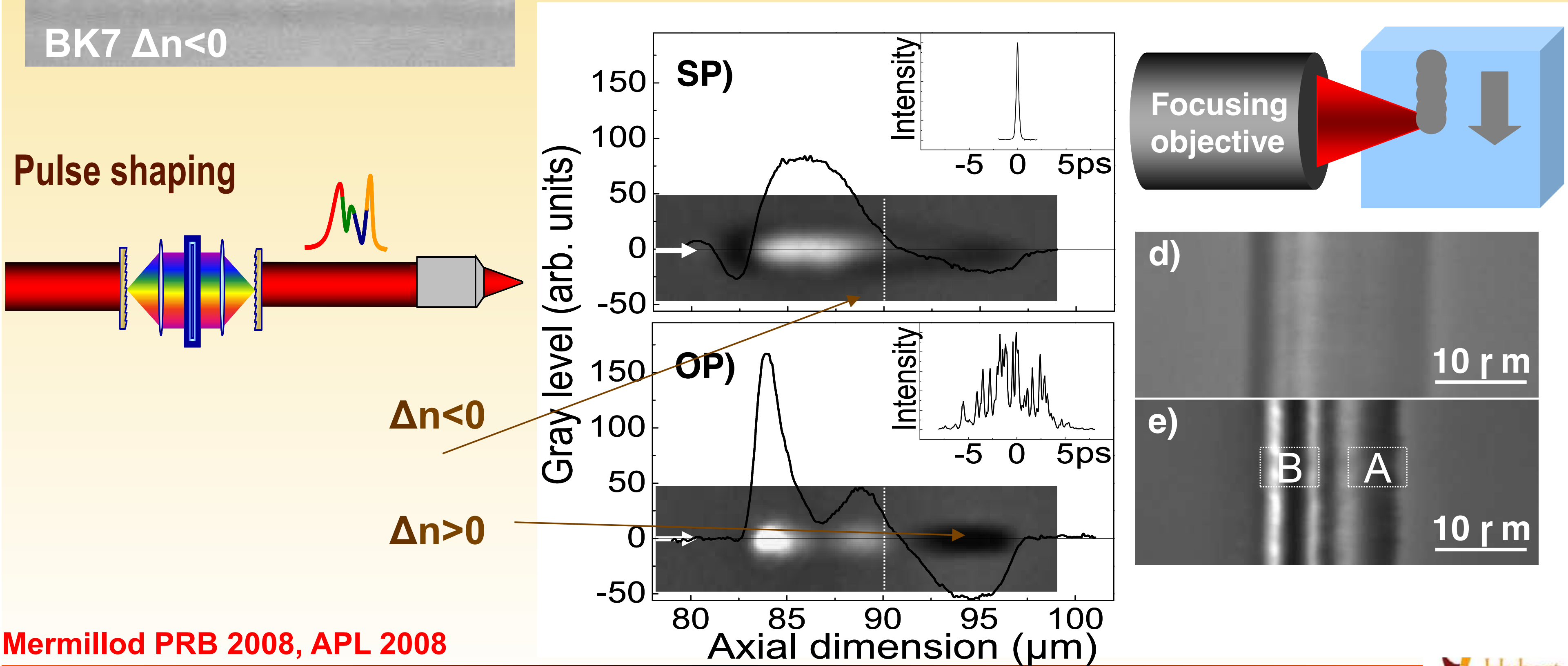
applications: change standard material reaction



Can we change this?

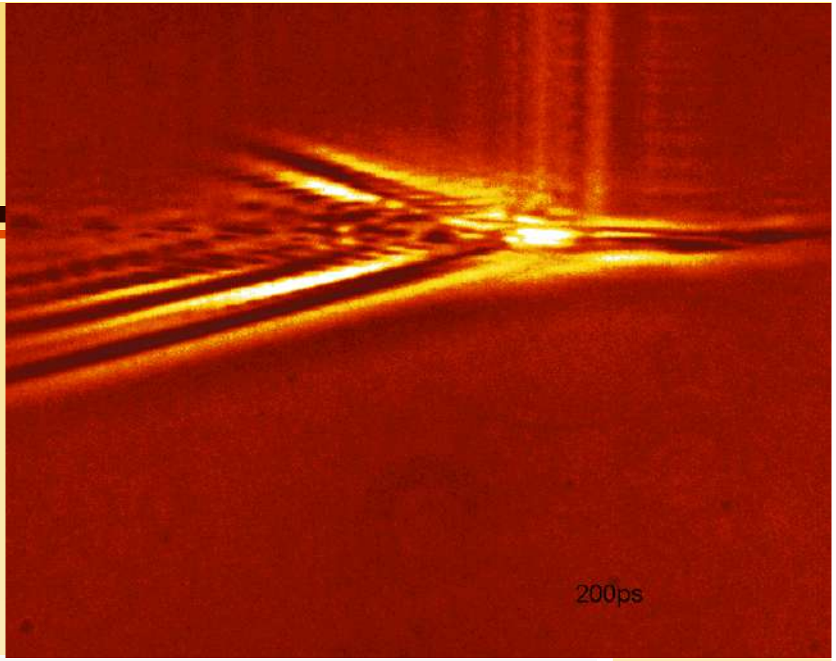
Index flip in BK7/difficult to process

Pulse shaping



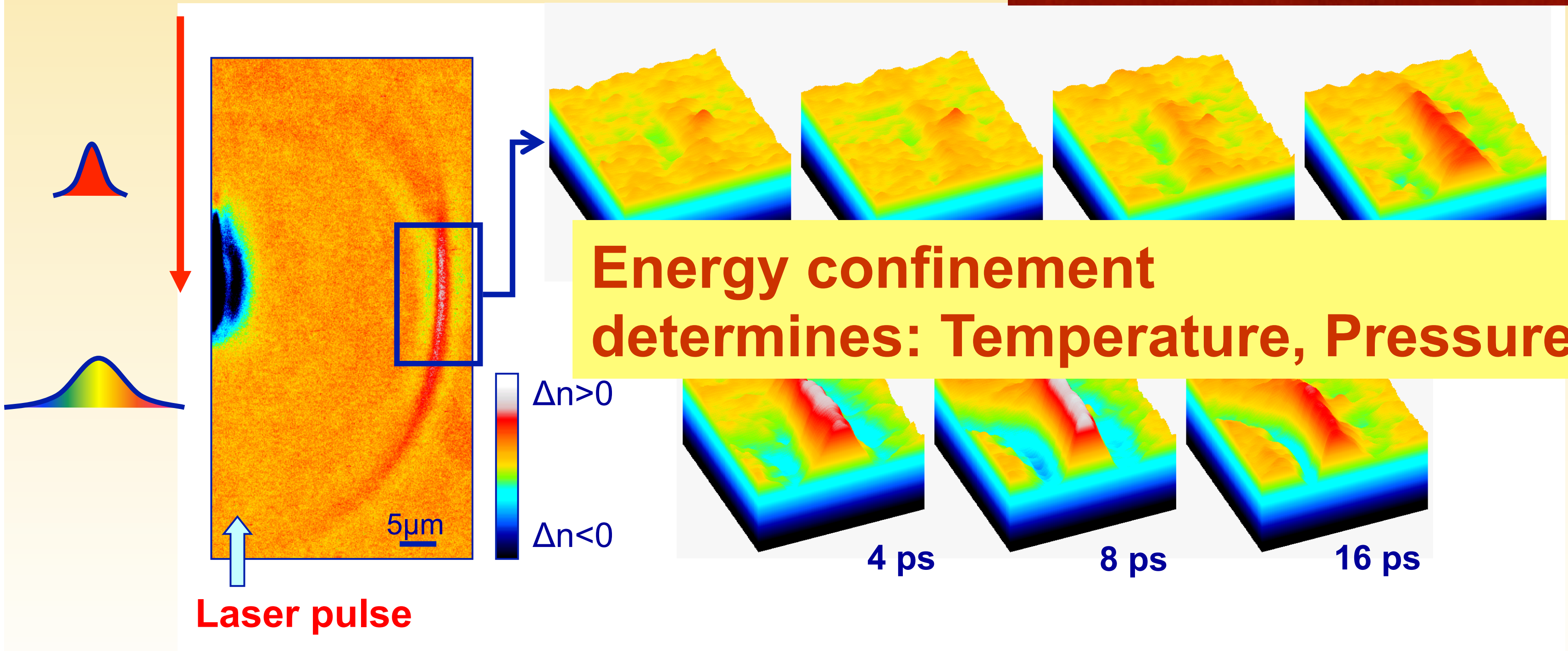
Mermillod PRB 2008, APL 2008

energy confinement
role of pulse duration



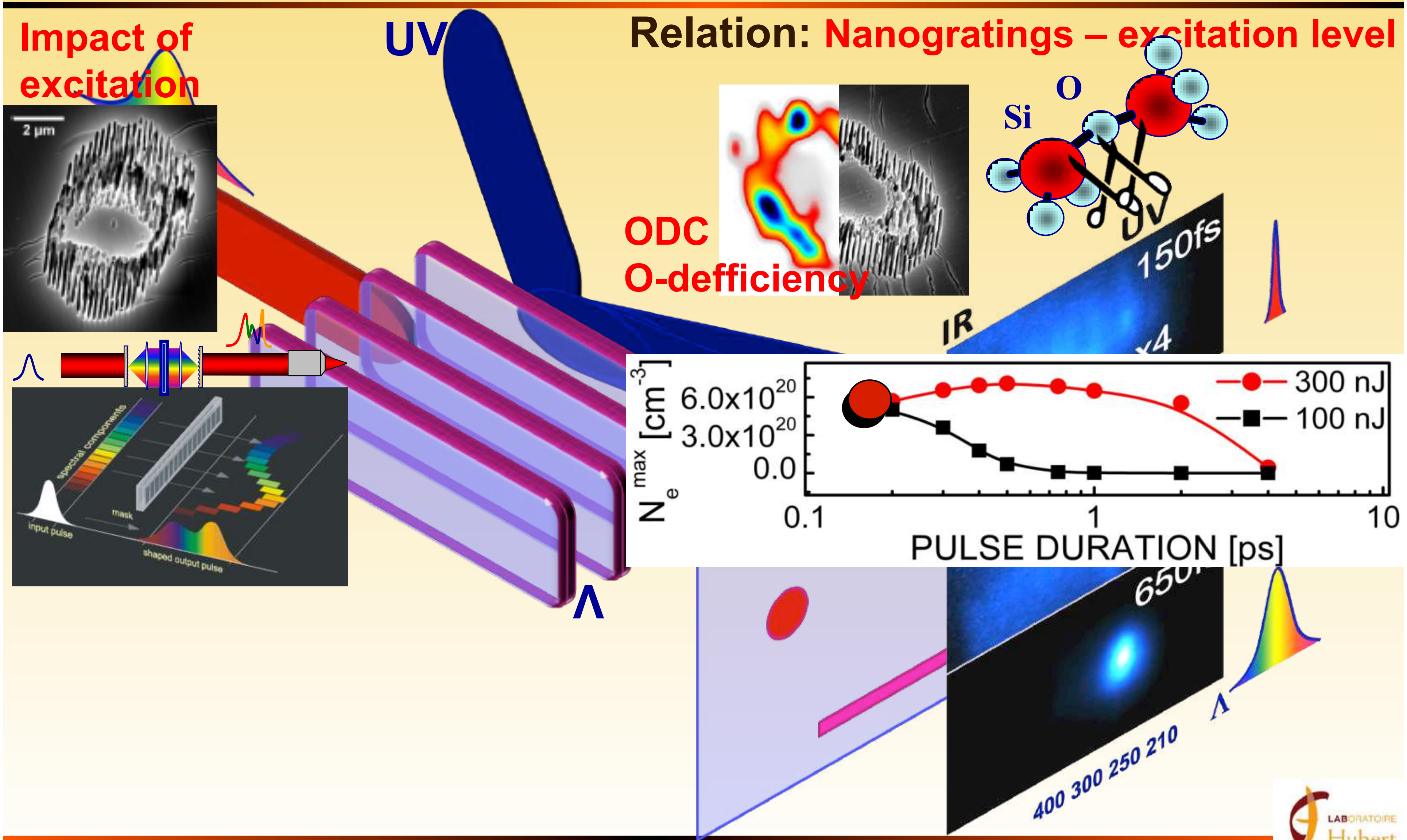
Pressure wave

- ps pulse – Stronger amplitude of the PW



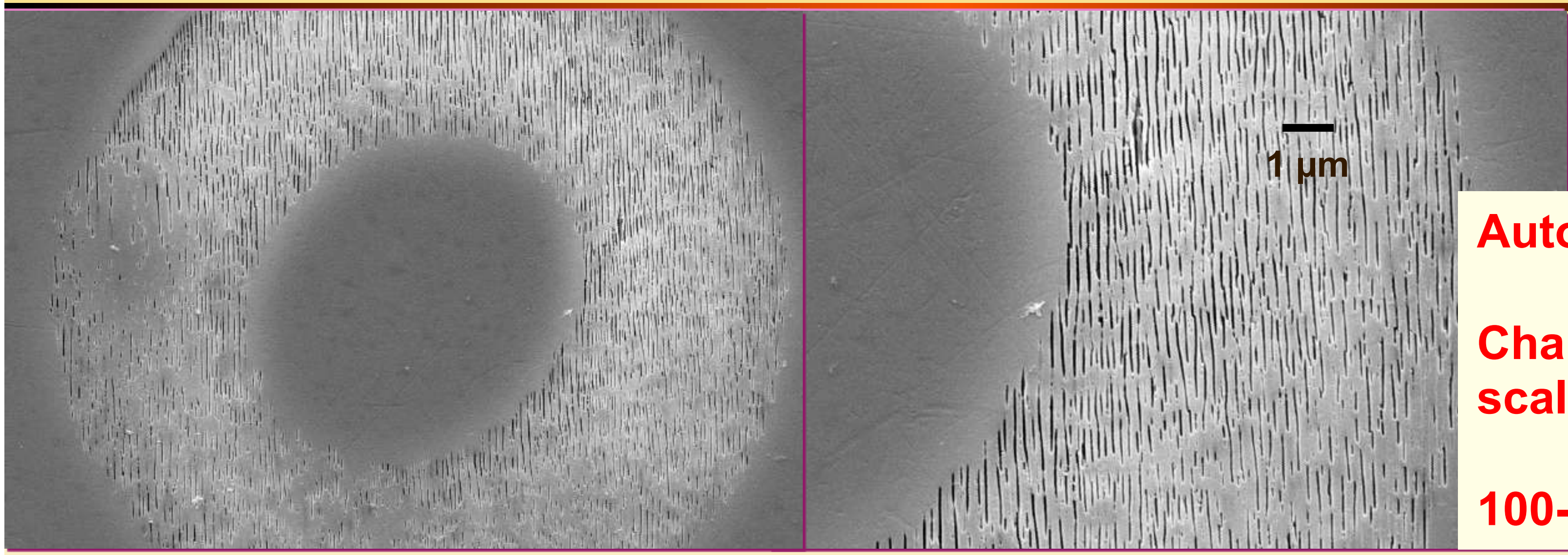
Energy confinement determines: Temperature, Pressure

nano-control via diffraction feedback: a-SiO_2



Mauclair Opt. Exp. 2012

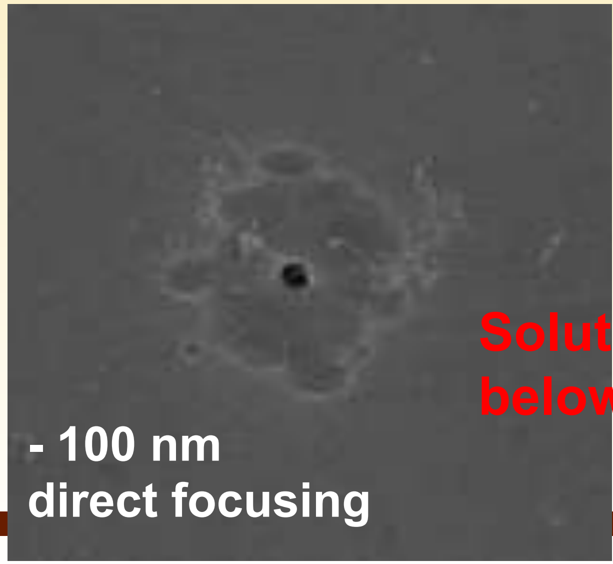
laser nanostructuring: beating the diffraction limit



Auto-organization

Characteristic scale

100-200nm

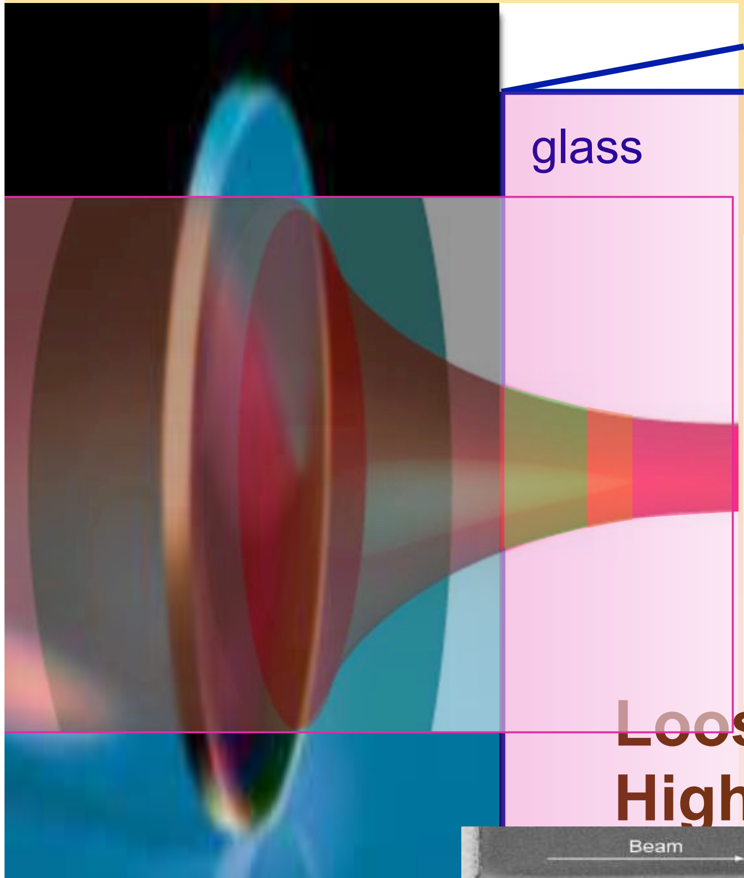


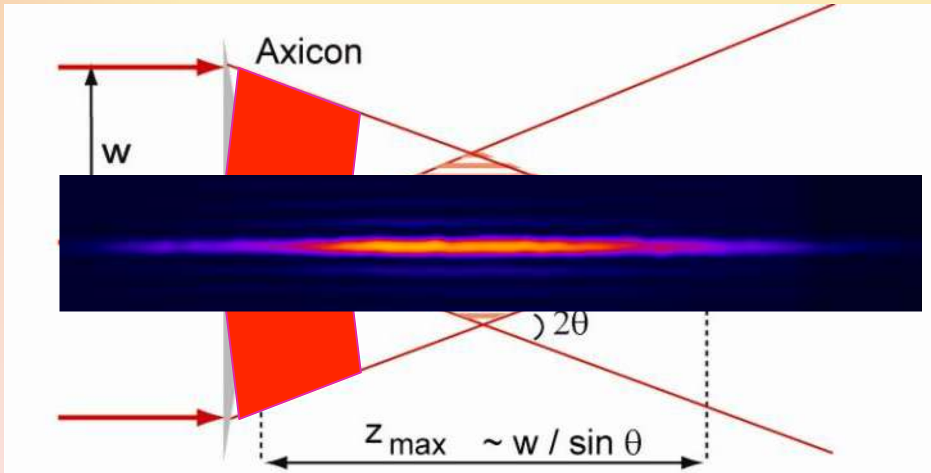
Solutions for energy confinement below the difraction limit

3D? giving-up dimensions

Bessel beams – a class of non-diffracting beams (2D)

$$E(r,z) = J_0\,(kr \sin\theta)\,\exp(ikz\cos\theta)$$



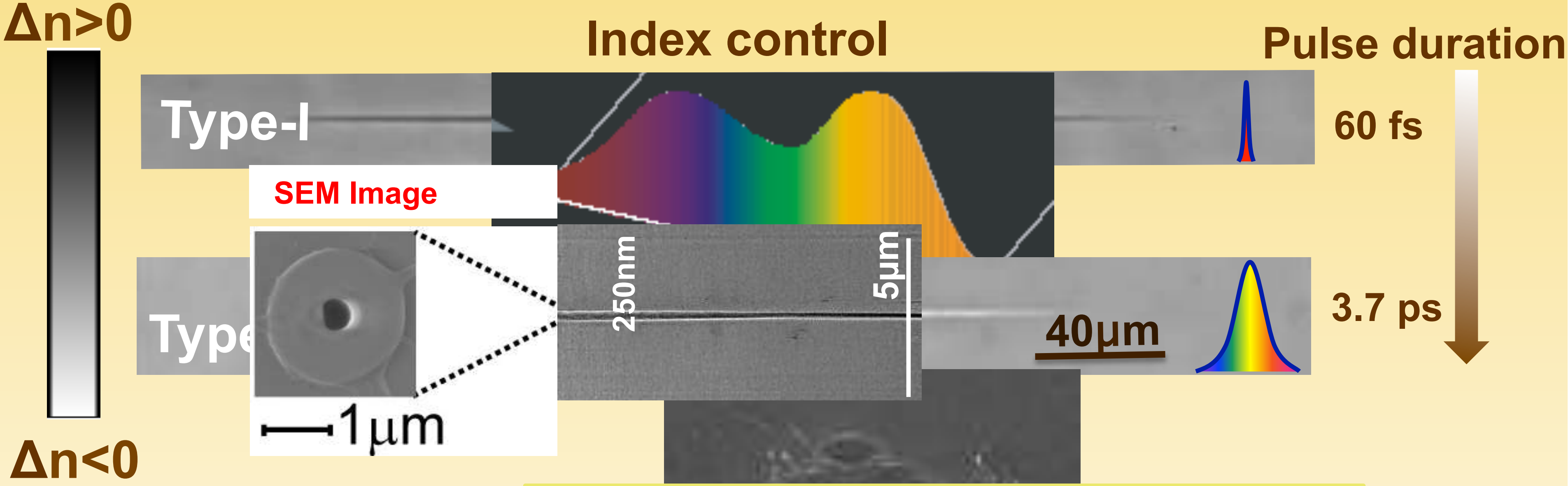


Loose focusing to maximize performance

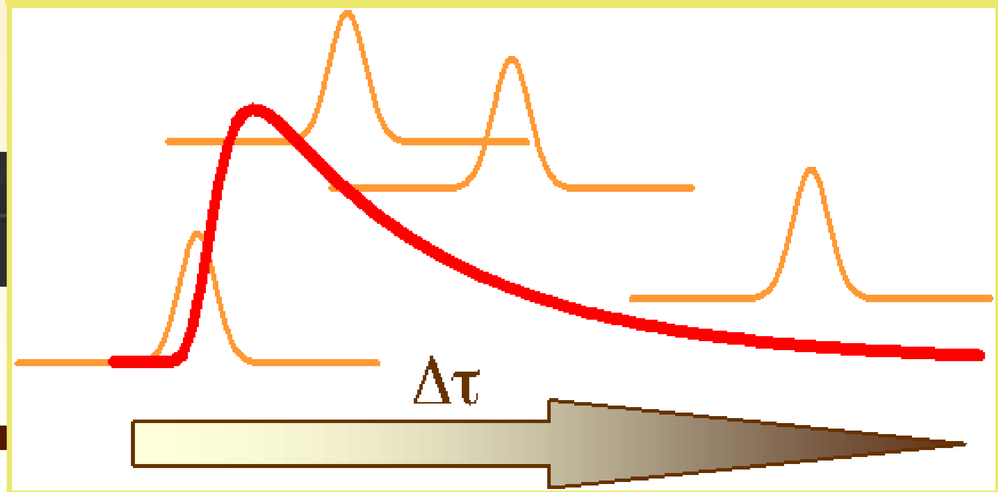
High aspect ratios: 1000-10000

FEMTO-ST
Bhuyan APL 2010

non-diffractive: space and time design



Q: how to identify processes?



Pulse duration is key

Bhuyan et al Appl. Phys.Lett. 2014

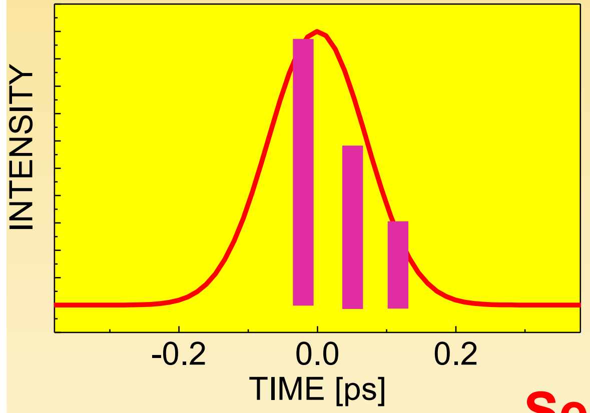
refractive index changes

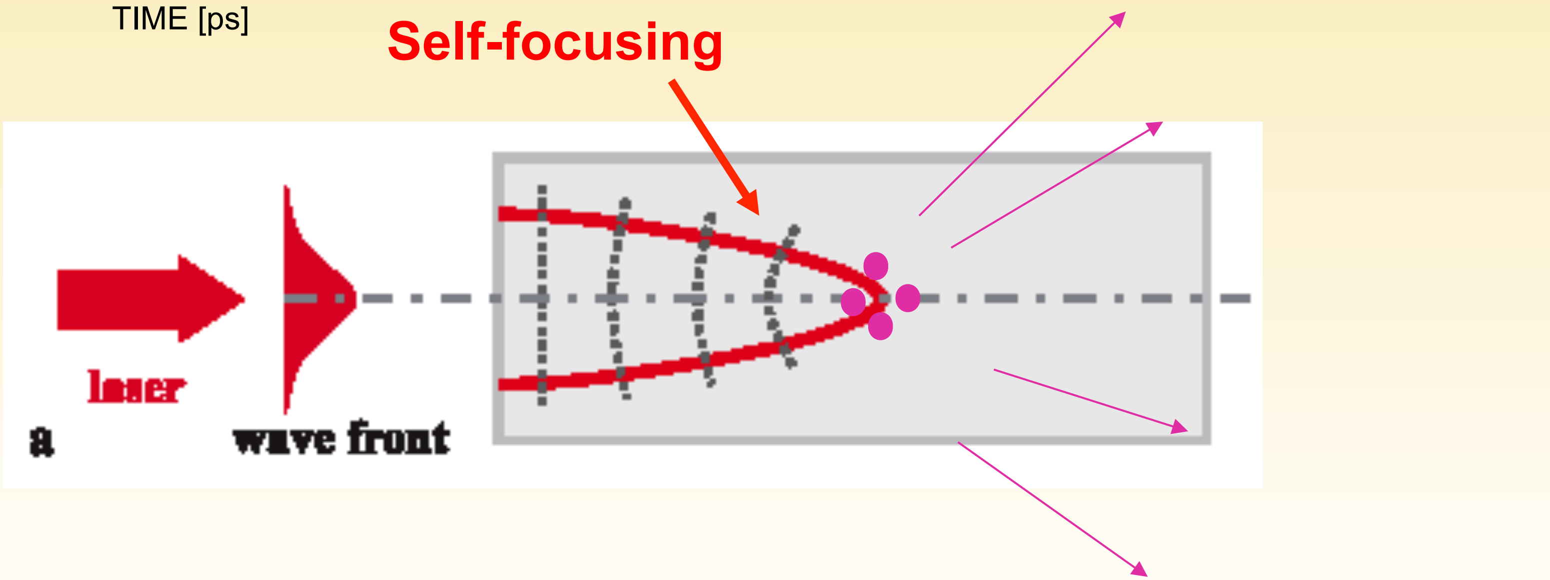
Q: How is the energy deposited?

Q: How does the material react?

role of pulse duration: energy confinement

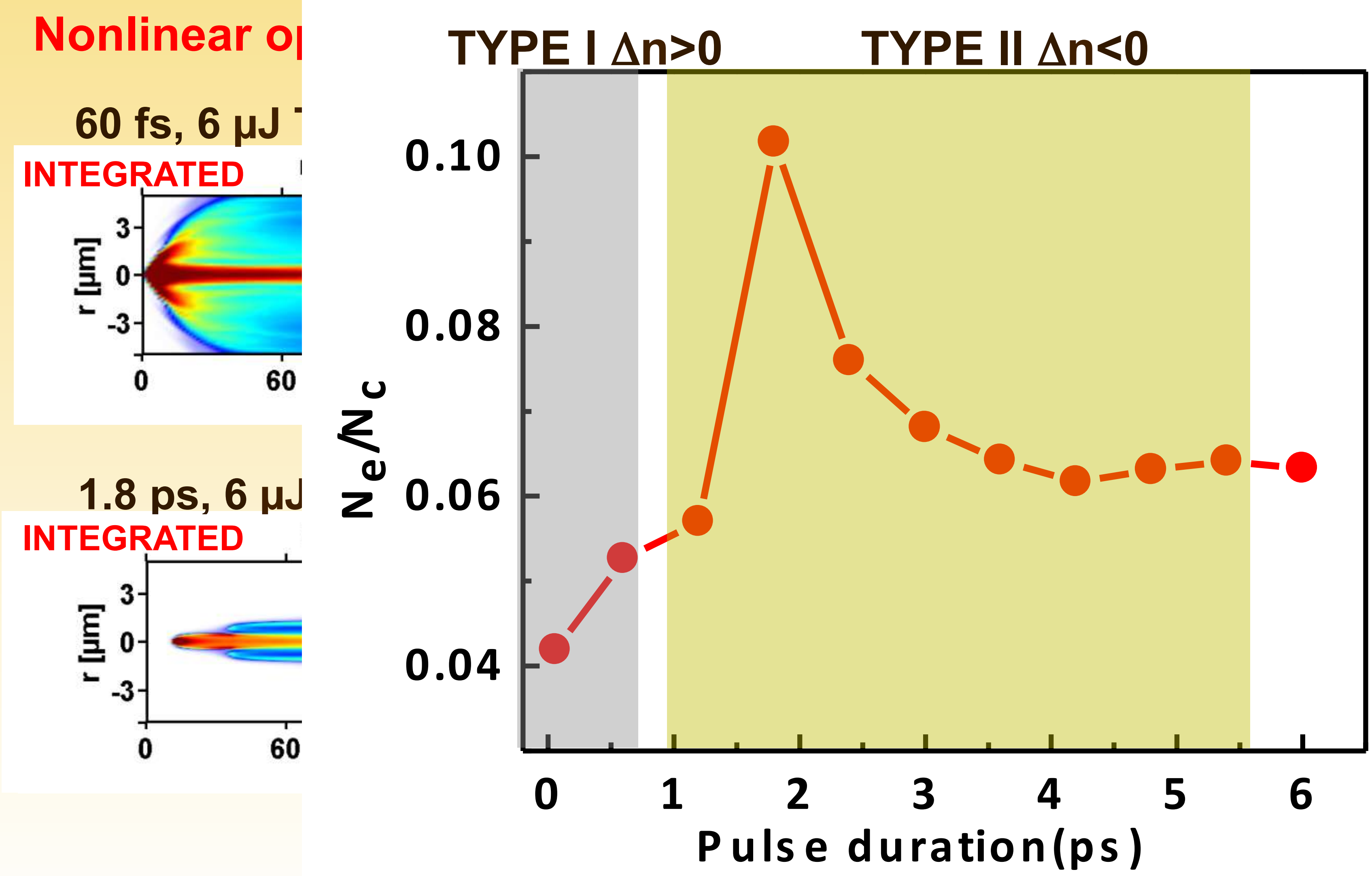
Nonlinear optical Schrödinger equation for propagation





Velpula et al Opt.Eng. 2014

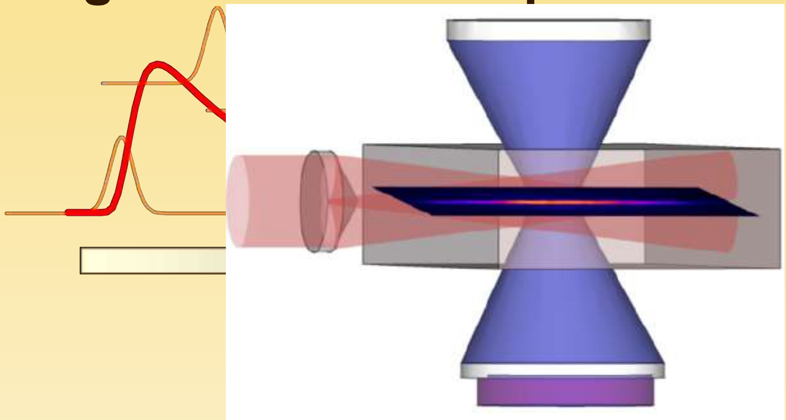
role of pulse duration: energy confinement

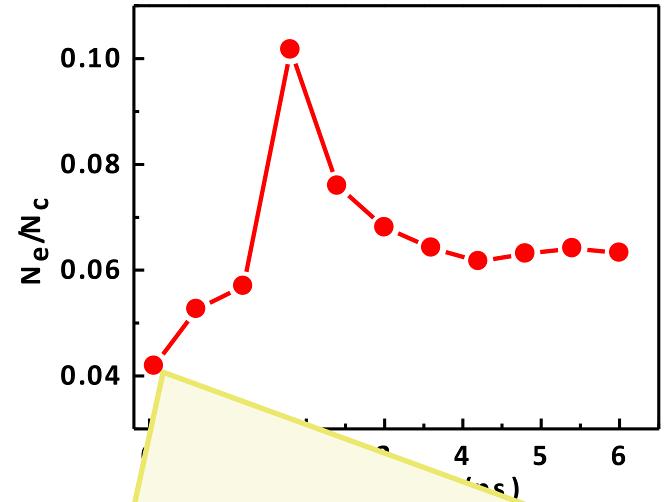


Velpula et al Opt.Eng. 2014

ultrafast dynamics: time-resolved imaging (fs)

Probing the material response:





Time-resolved microscopy

60 fs; Type-I smooth positive refractive index structures

1.25 µJ
(around the threshold)

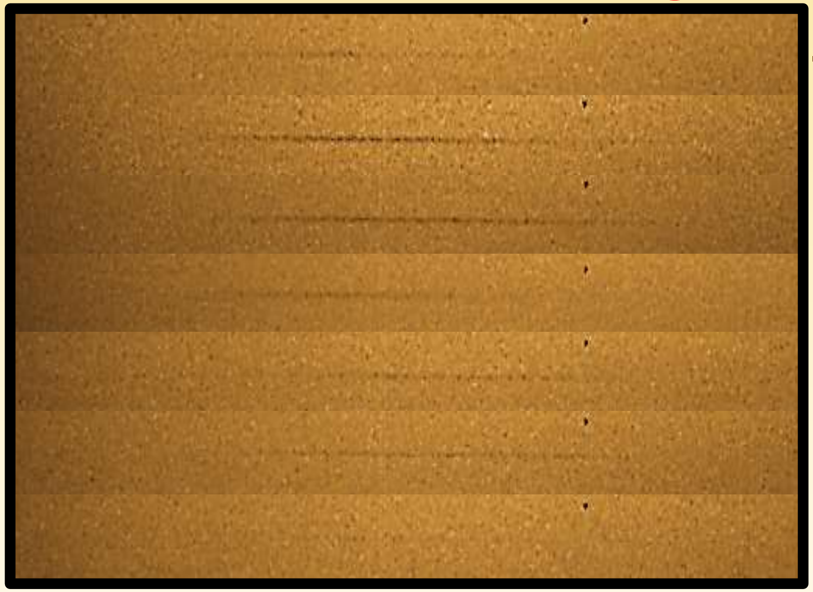
ultrafast dynamics: time-resolved imaging (fs)

Around the modification threshold

1.25µJ
60fs

Optical transmission

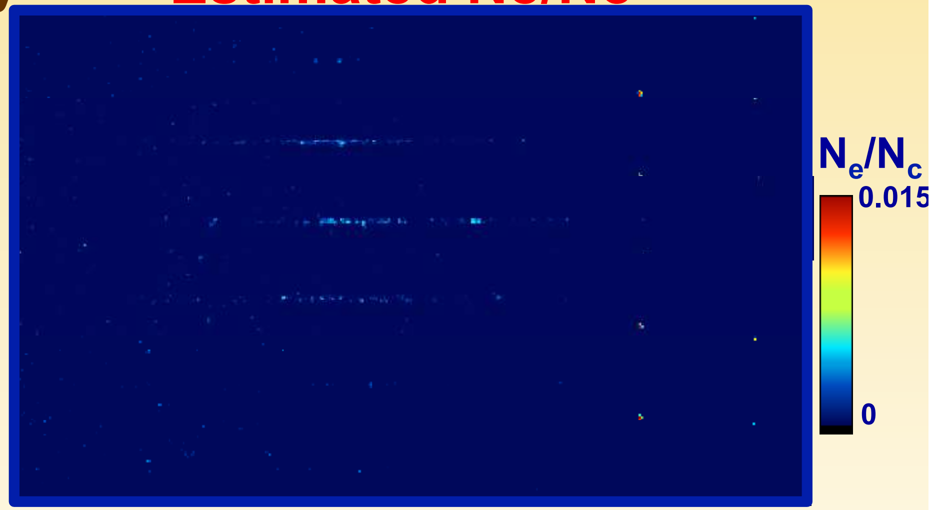
Optical transmission images



Delay

-0.4ps
0ps
0.3ps
0.6ps
0.9ps
1.2ps
5ps

Estimated Ne/Nc

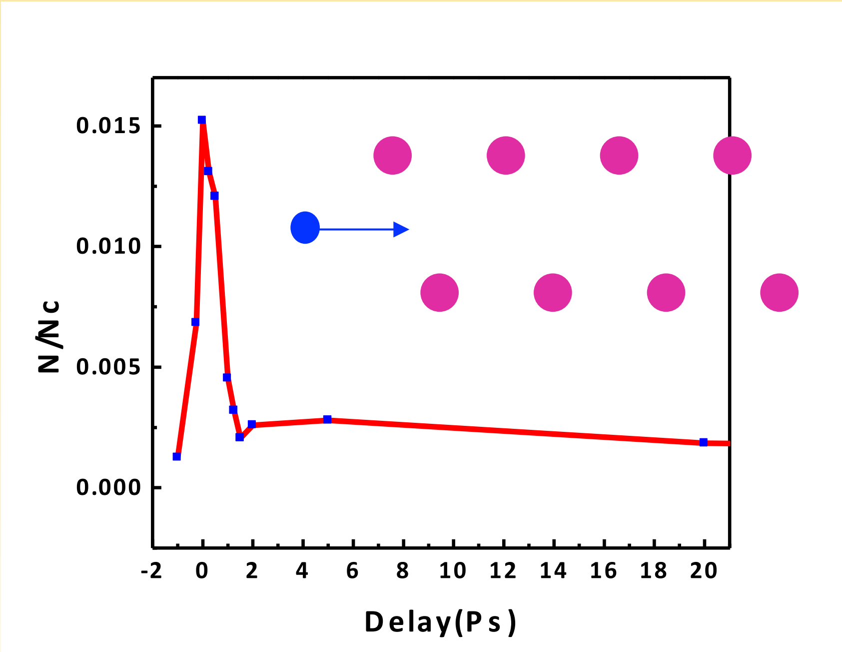


ultrafast dynamics: time-resolved imaging (fs)

Around the modification threshold

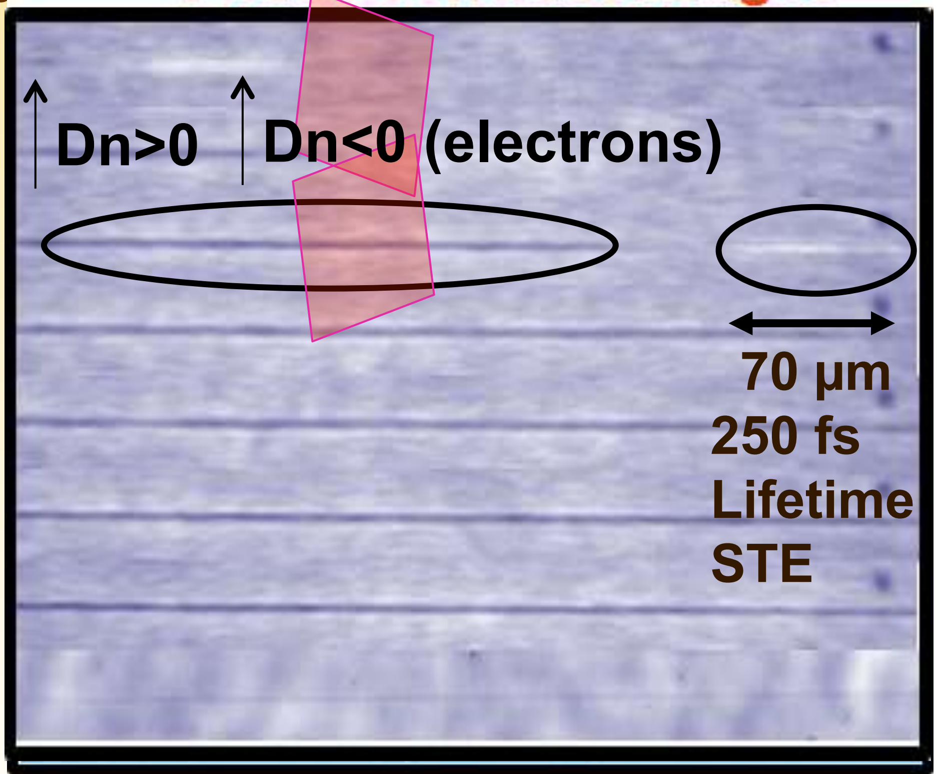
1.25µJ
60fs

Optical transmission



Delay
-0.4ps
0ps
0.3ps
0.6ps
0.9ps
1.2ps
5ps

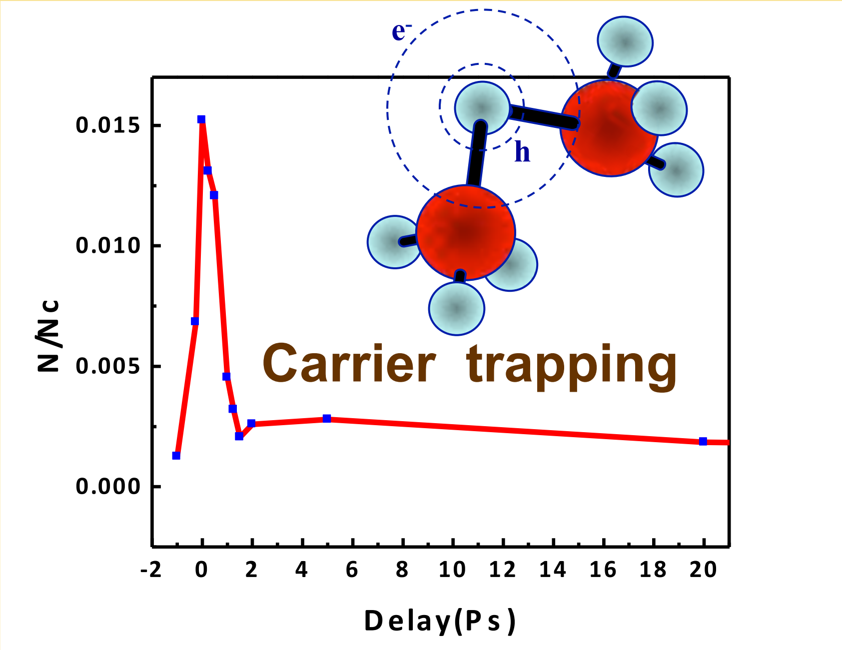
Phase contrast images



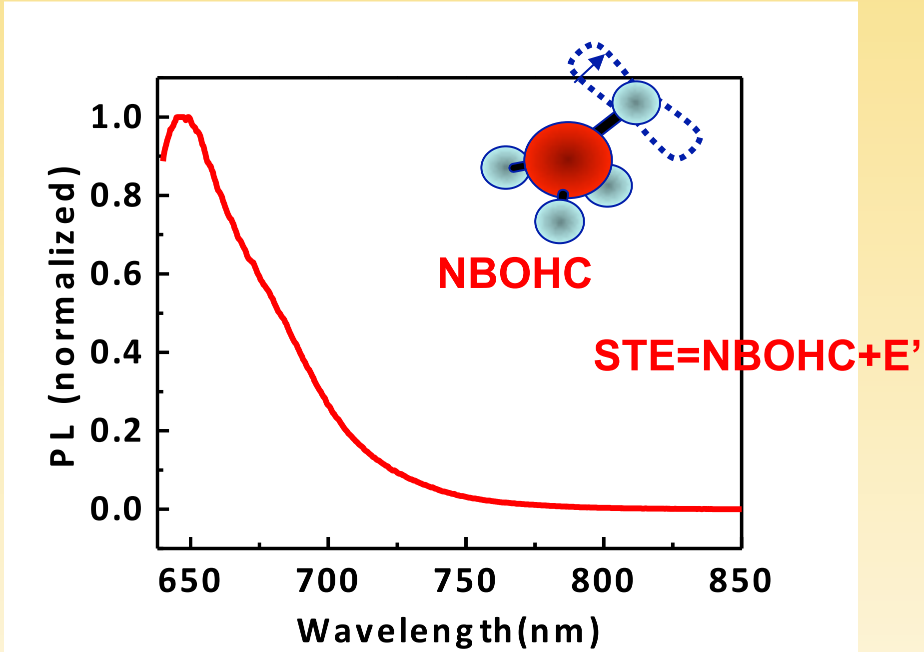
Fast decaying corresponds to

in brief: scenario for positive index (type I)

Time-resolved studies

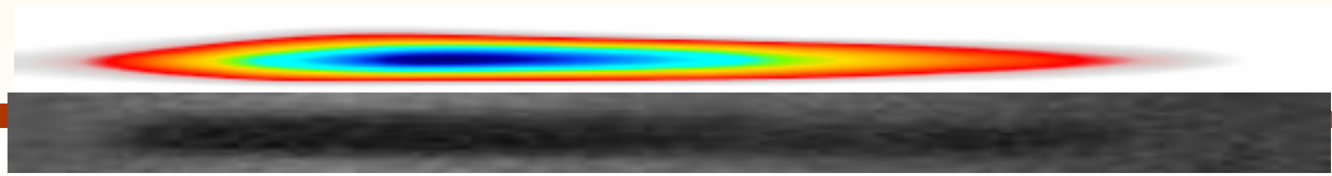


Photoluminescence studies



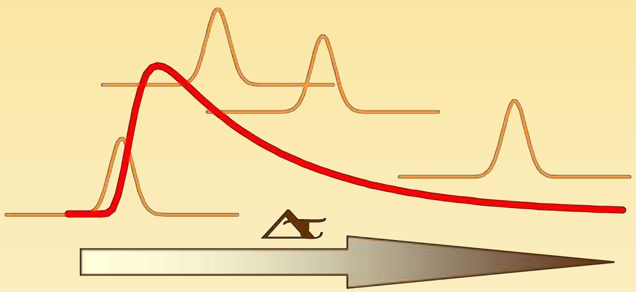
Carrier trapping ➡ bond breaking ➡ densification of Si-O rings

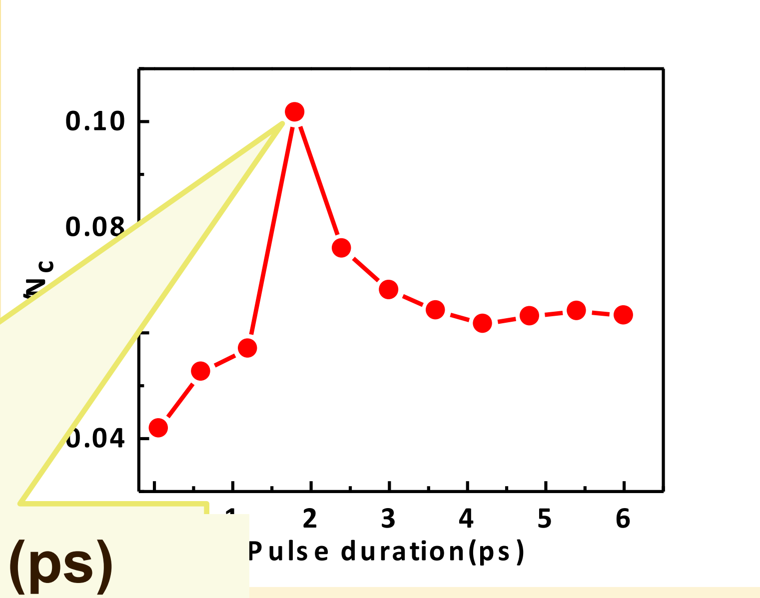
Defect assisted densification leads to the formation of type-I structures



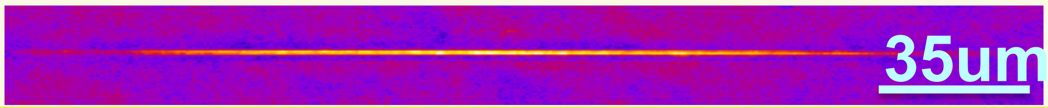
ultrafast dynamics: time-resolved imaging (ps)

Probing the material response:





Type-II uniform void structures (ps)



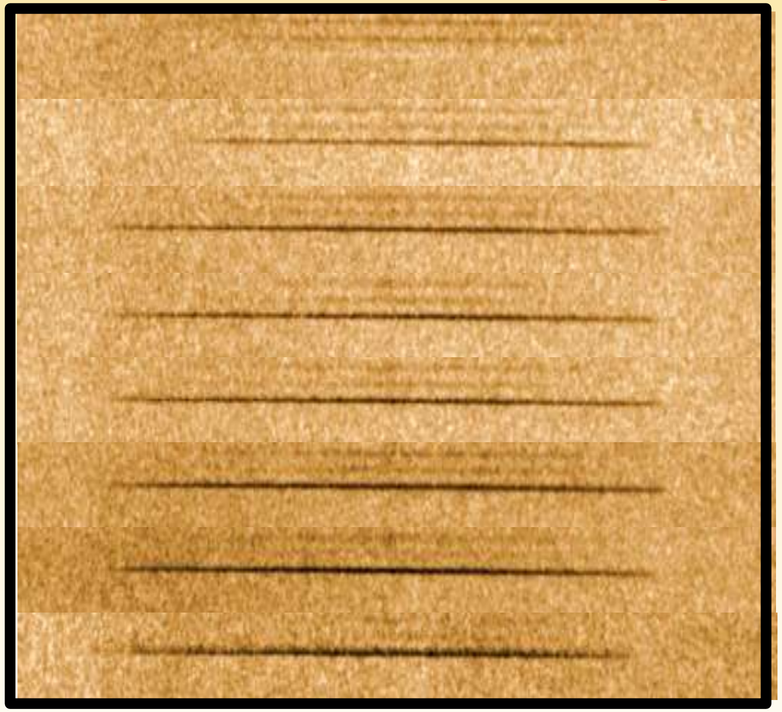
ultrafast dynamics: time-resolved imaging (ps)

Far above the modification threshold (type II)

7µJ
6ps

Optical transmission

Optical transmission images



Delay

-3ps

0ps

3ps

6ps

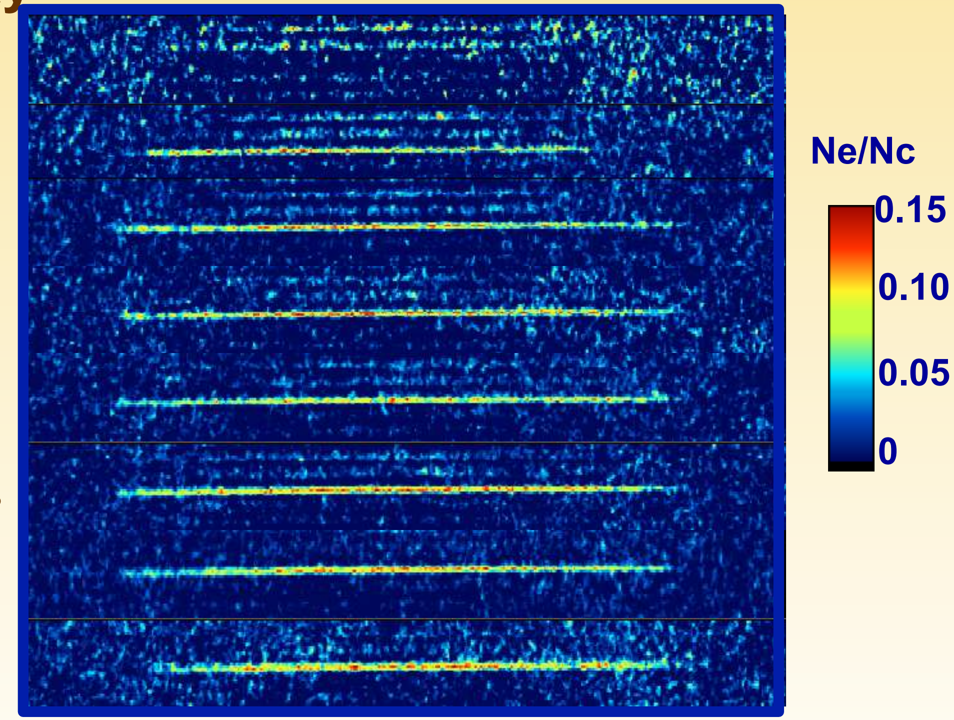
9ps

50ps

1.5ns

6.25ns

Estimated Ne/Nc

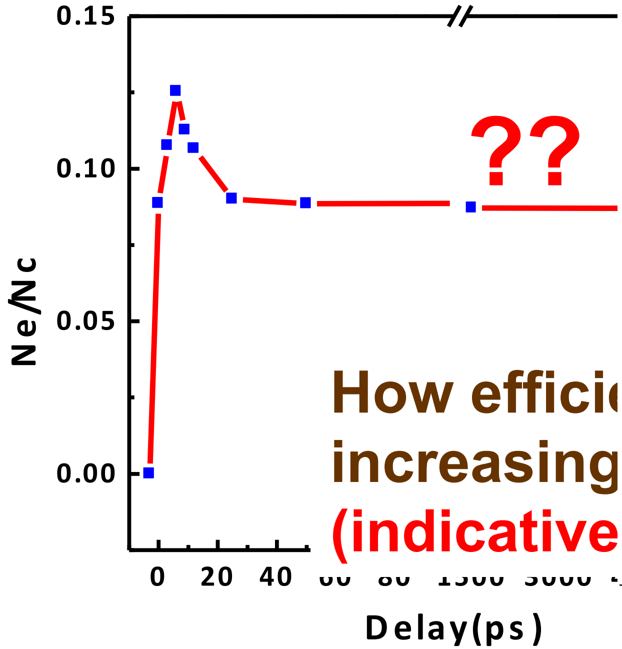


ultrafast dynamics: time-resolved imaging (ps)

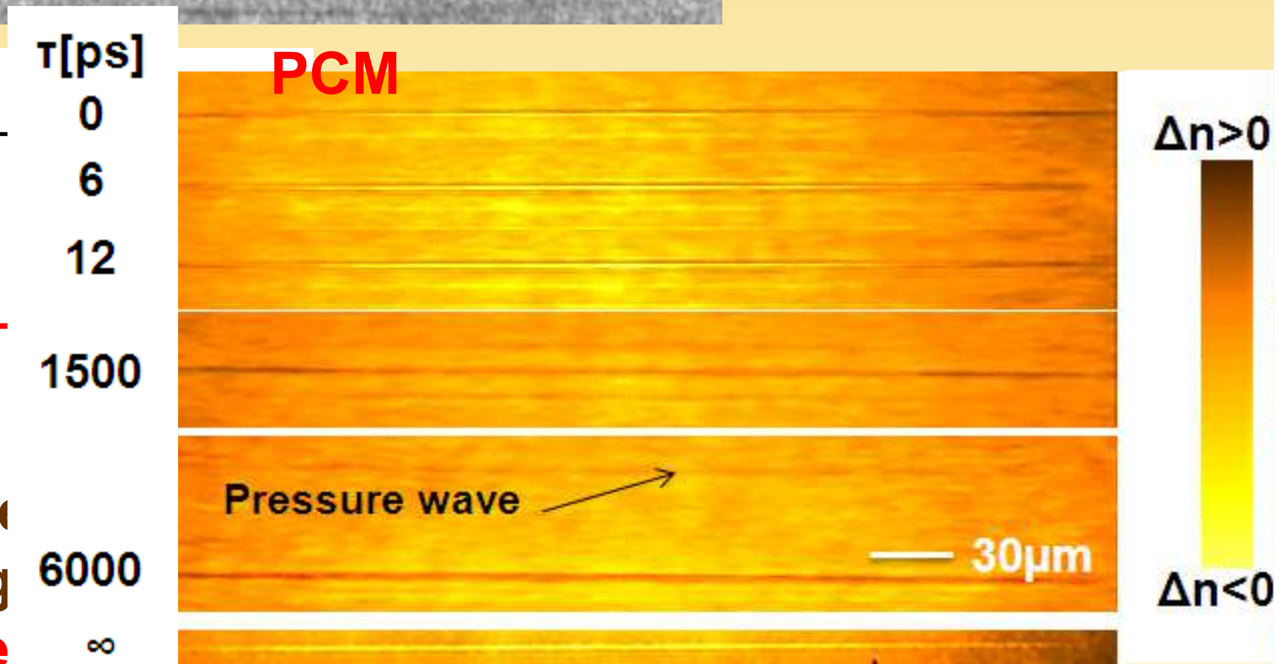
Far above the modification threshold (type II)

7µJ
6ps

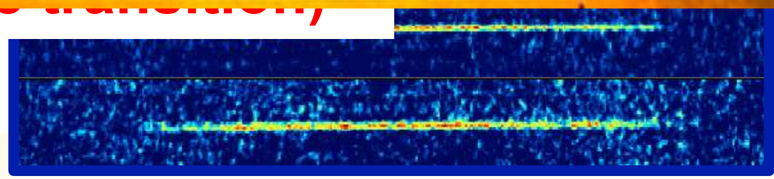
Optical transmission



How effici
increasing
(indicative



1.5ns



6.25ns

Residual absorption can be due to the existence of long-living electrons

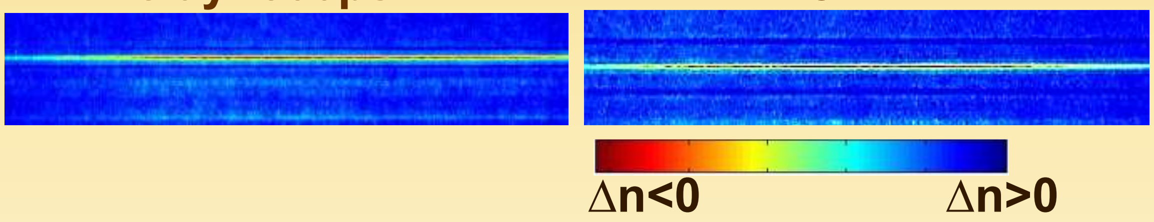
LABORATOIRE Hubert Curien

in brief: scenario for voids

Thermo-Mechanical activity

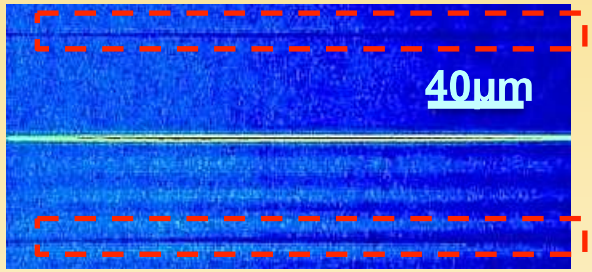
Delay: 500ps

Delay: 1.5ns

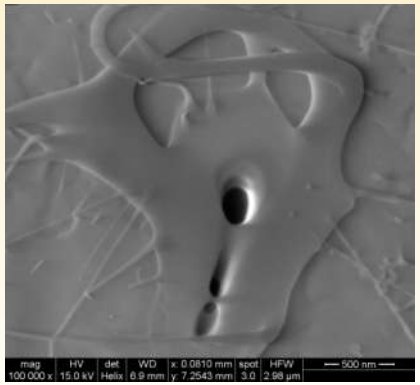


Delay: 6.25ns

Release of pressure wave



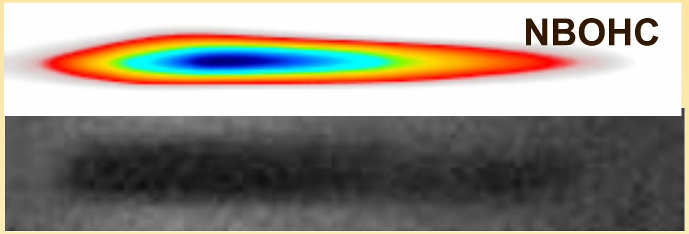
Hydrodynamic expansion and cavitation in the liquid phase
lead to the formation of void (type-II) structures

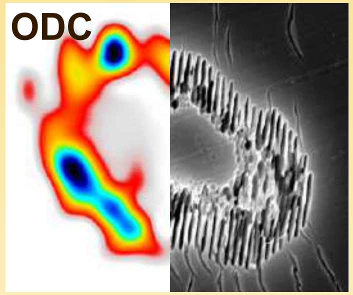


Bhuyan et al Appl. Phys.Lett. 2014

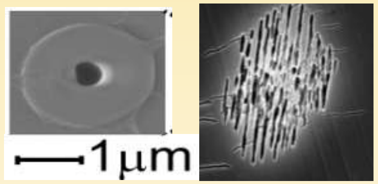
index control: mechanisms-dynamics/control-fabrication

➢ **Structural transitions (Δn>0 or Δn<0) are controllable via electronic density**

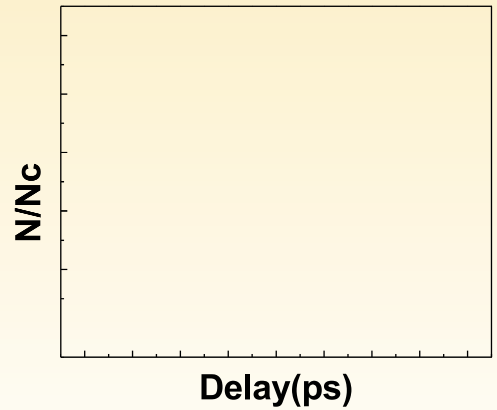




➢ **Nanoscale is achievable**



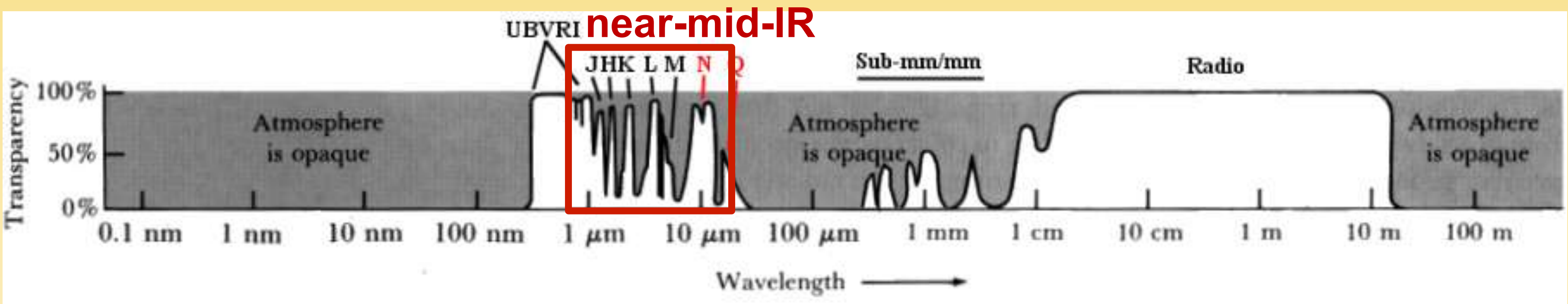
➢ **Transient dynamics**



➢ **Pulse duration/form is a key parameter**

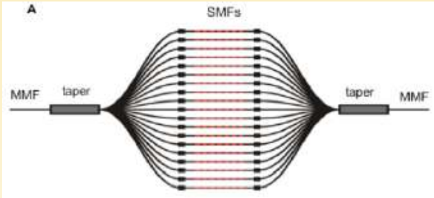
Applications to photonics

guided optics in the mid-IR (MIR photonics)

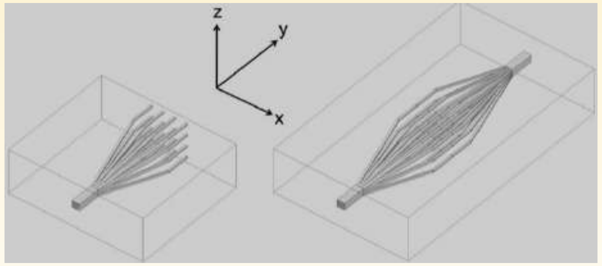


Mid-IR-Astronomy

Design requirements



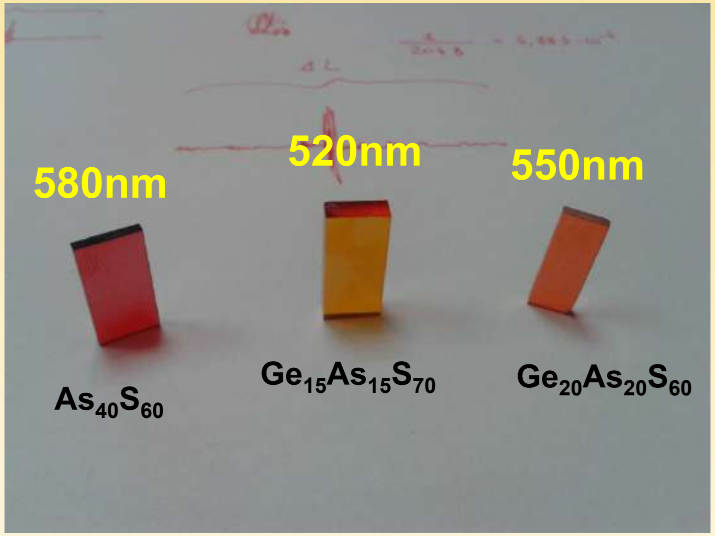
2D → 3D

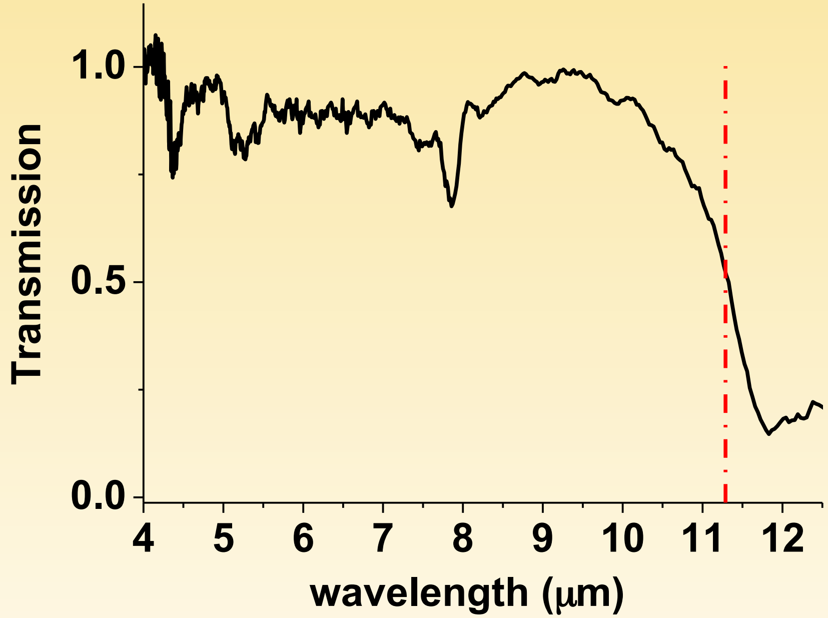


Material requirements

chalcogenide glasses for the mid-IR

Interesting class of materials : As-S; Ge-As-S systems



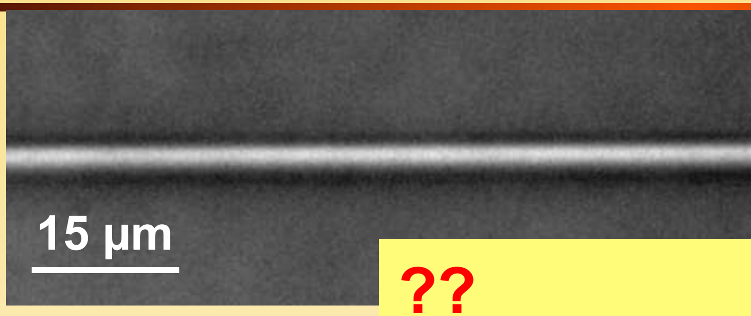


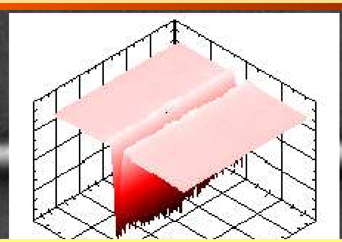
- Band-gap (two-photon absorption)
1.2 cm/GW@800

- High n_2 ($1000xn_2$-SiO_2)

photoinscription in S-based glasses

As_2S_3





Δn<0 TYPE II

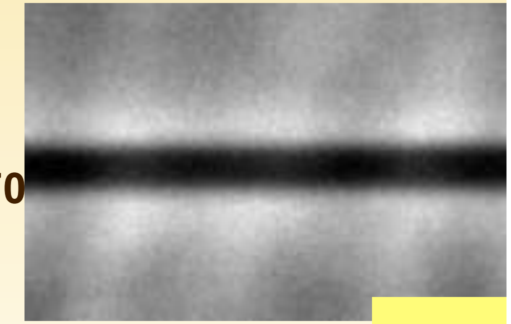
Thermomechanical

??

Quasi no guiding!

Solut

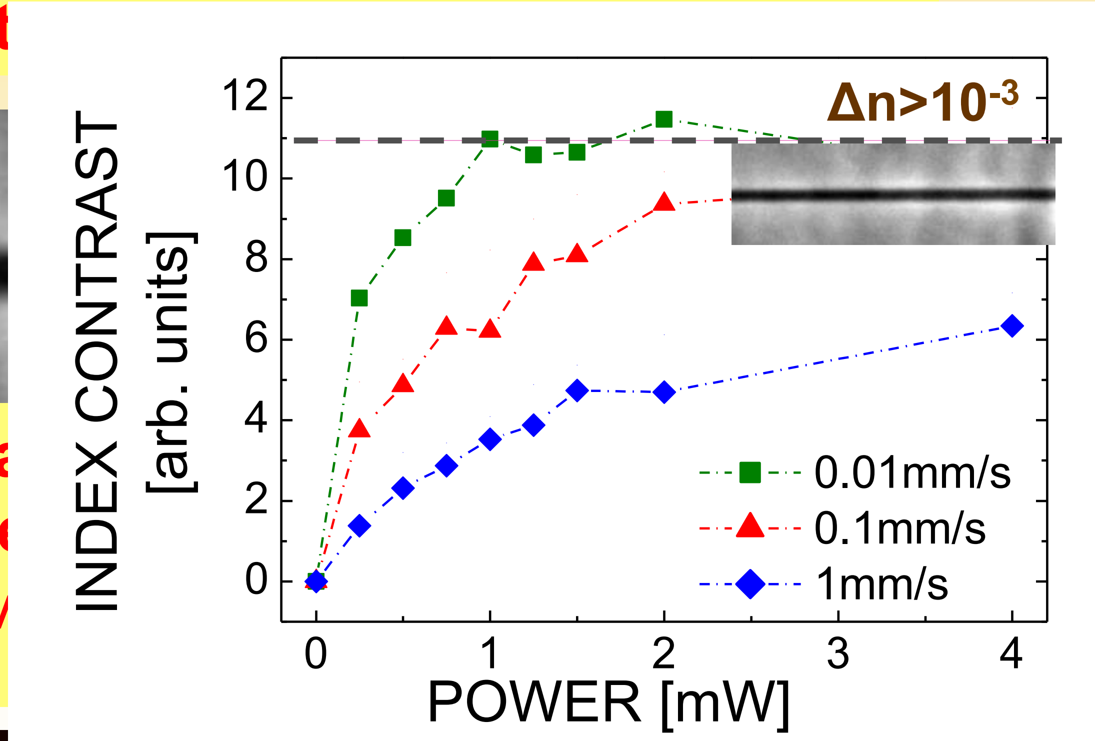
$Ge_{15}As_{15}S_{70}$



Wha

Rol

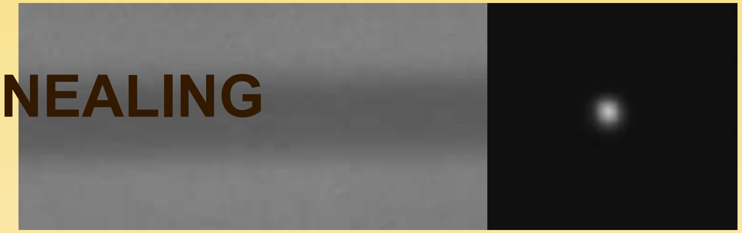
(cov



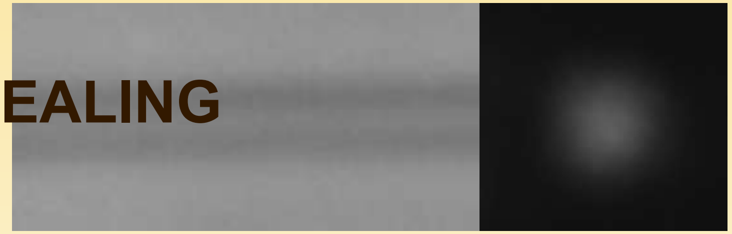
C. D'Amico Opt. Express 2014, OME 2015

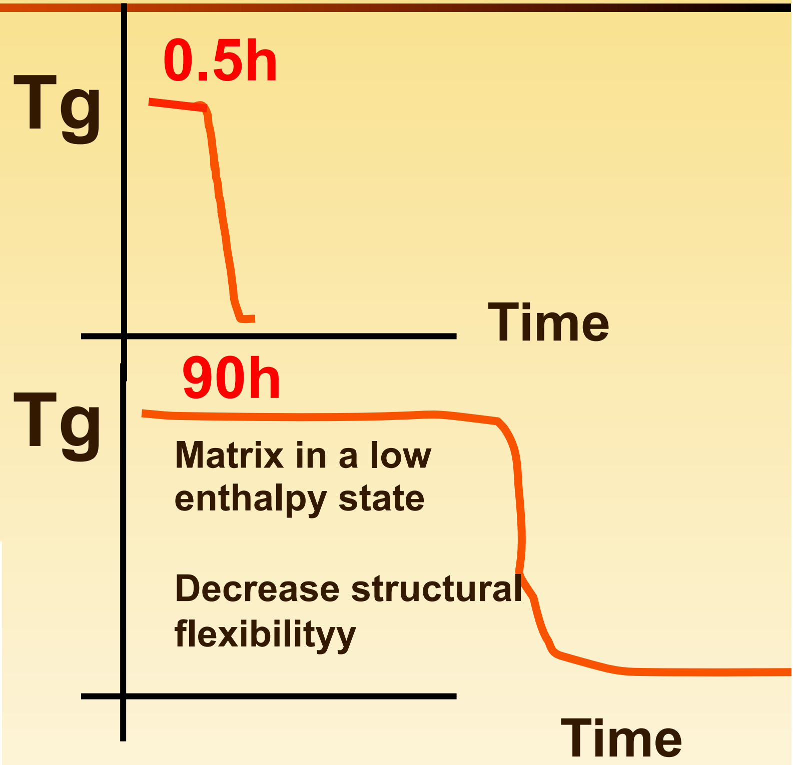
photoinscription in S-based glasses: T history

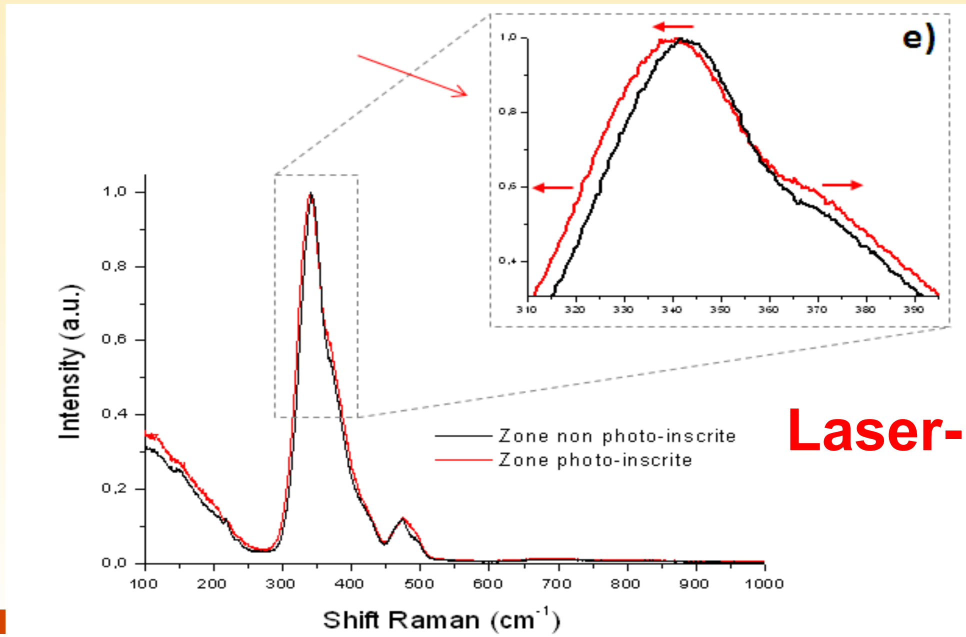
SHORT ANNEALING



LONG ANNEALING

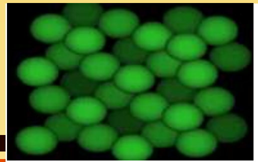






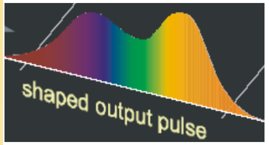
Laser-induced structural disorder

optical design



Material design:

Matrix connectivity (Ge)

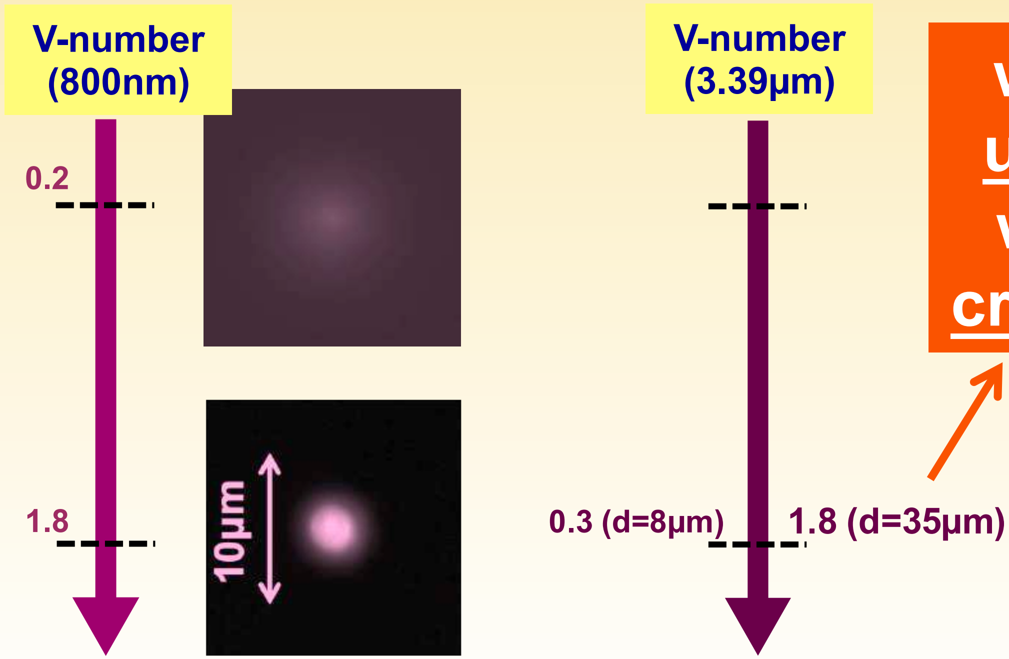


Pulse design:

Optimally adapted

Material response:
-structural
(role of metastability)

Design of waveguides: normalized frequency (SM)

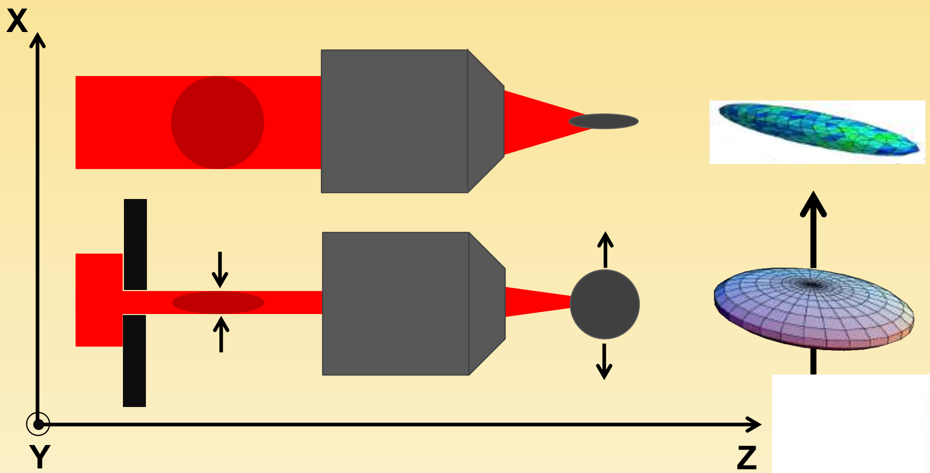


we need to <u>upscale</u> the waveguide <u>cross-section</u>

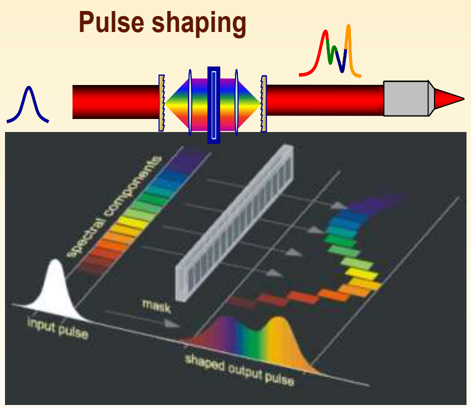
upscaling the mode-section

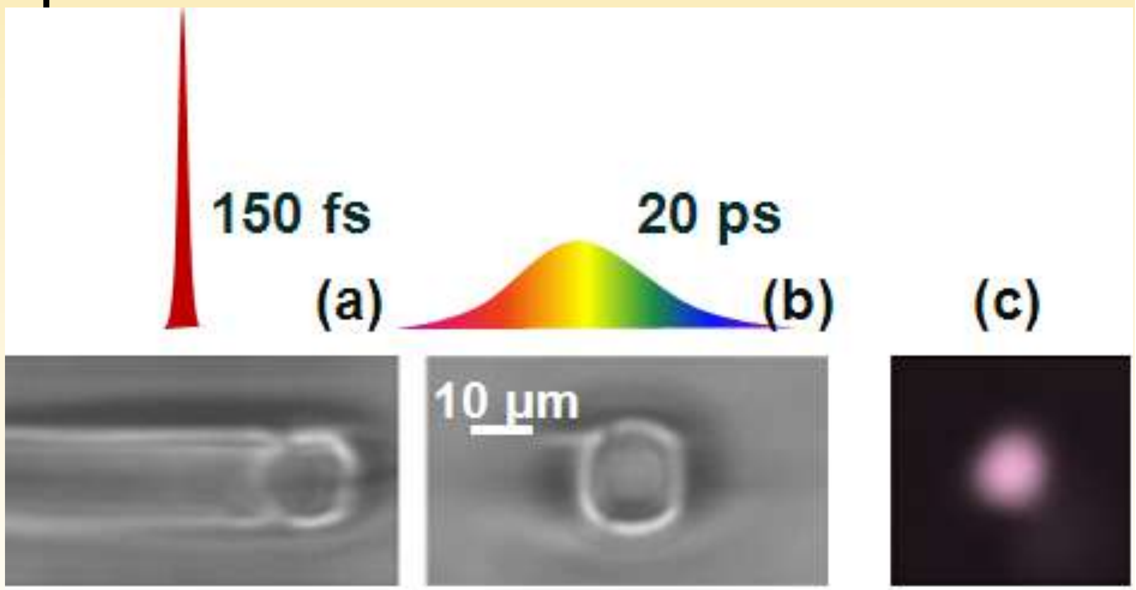
Slit-Shaping (Transversal)

Cheng&Sugioka OL 2003



➡ **Larger circular cross-section**





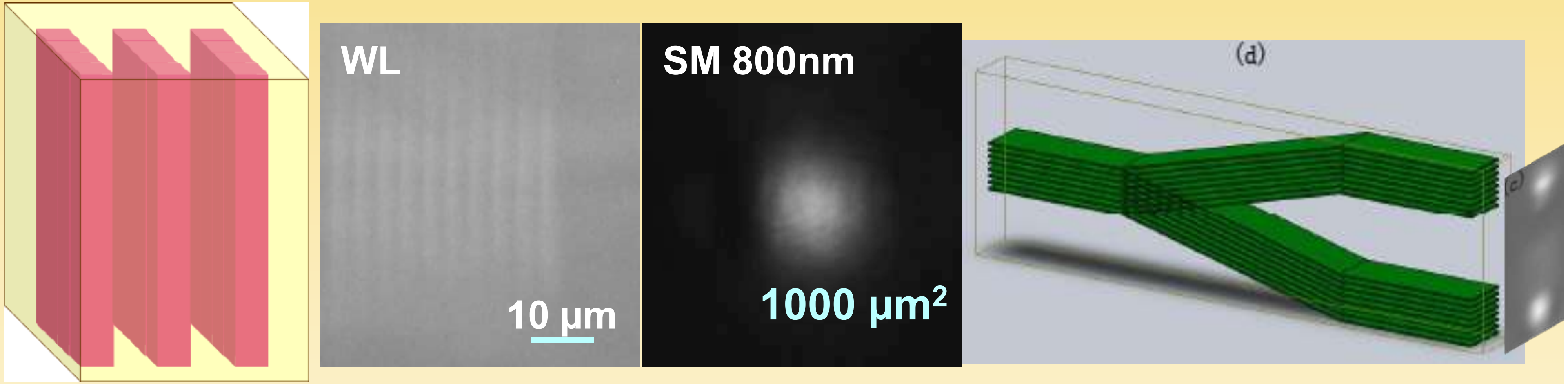
NLO distortion

D'Amico, R. Stoian, J. Troles, P. Kern OE 2013

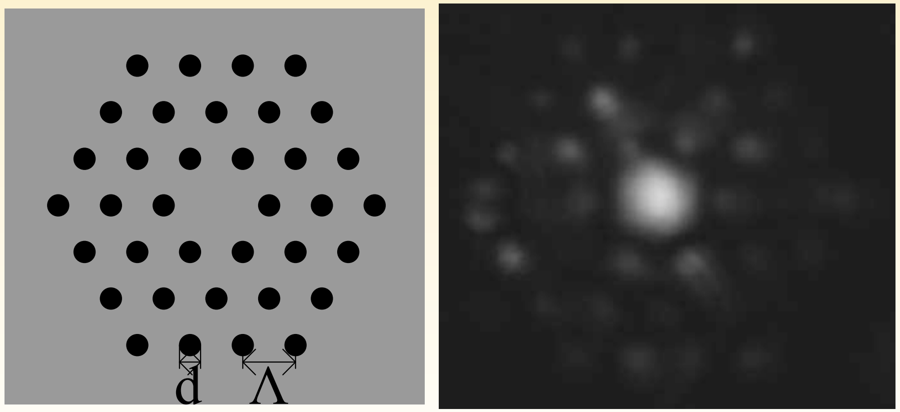
LABORATOIRE Hubert Curien

upscaling the mode-section (LMA concepts)

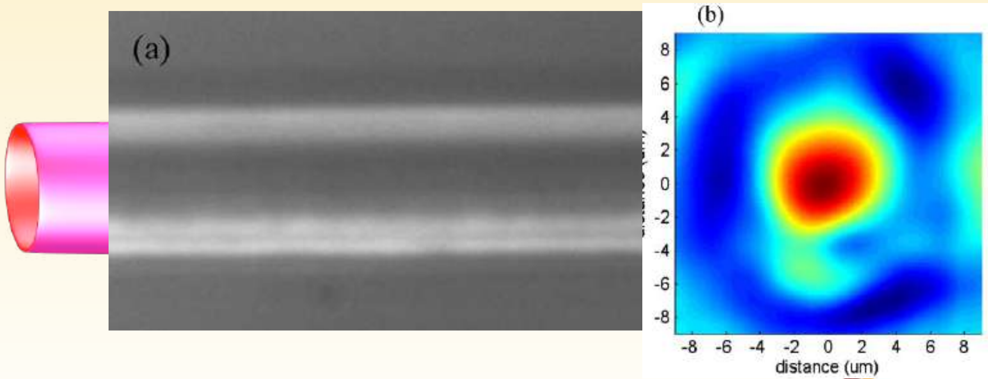
Exteded core waveguide



PCF core waveguide



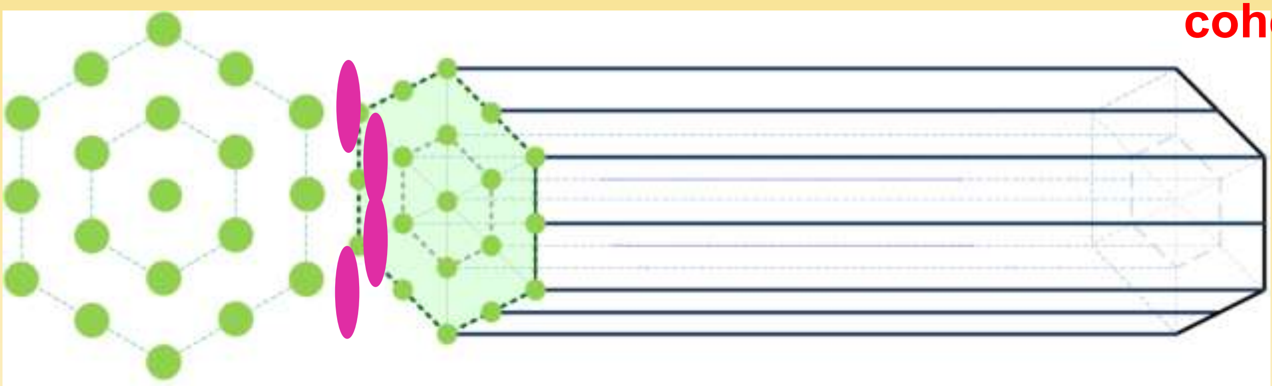
Vortex HO Bessel waveguide



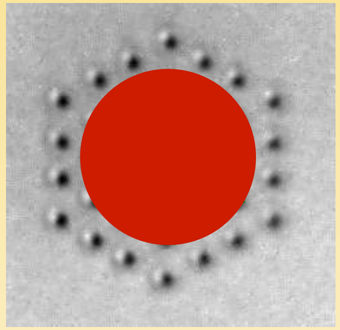
X. Liu OE 2014, X. Long OL 2014, **collaboration XiAn Institute of Optics & Photonics**

upscaling the mode section

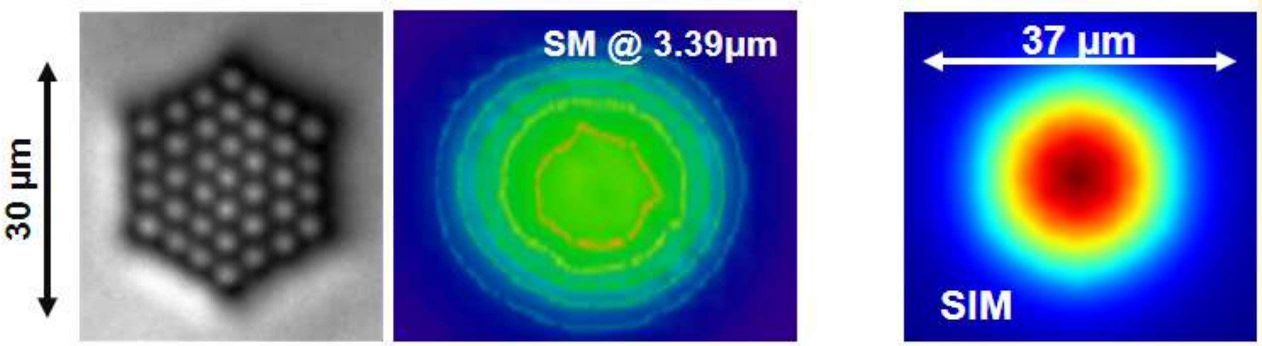
Multicore & evanescent coupling

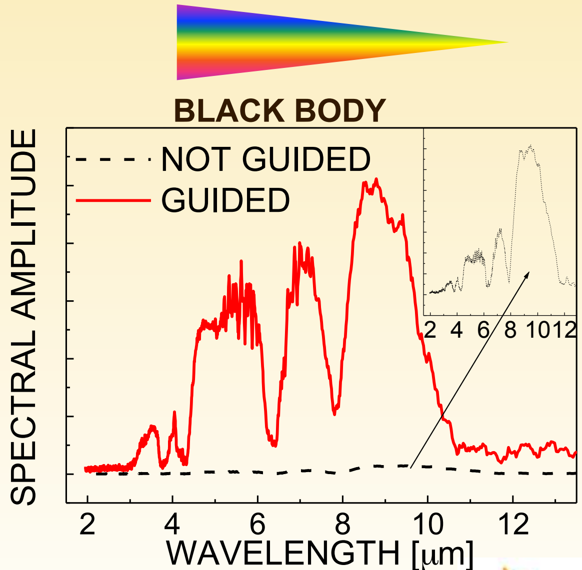


Multicore waveguide:
coherent mode superposition



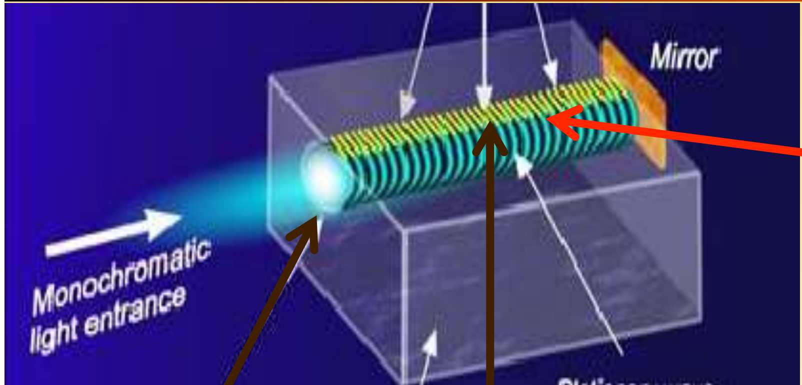
MIR test of multicore waveguides



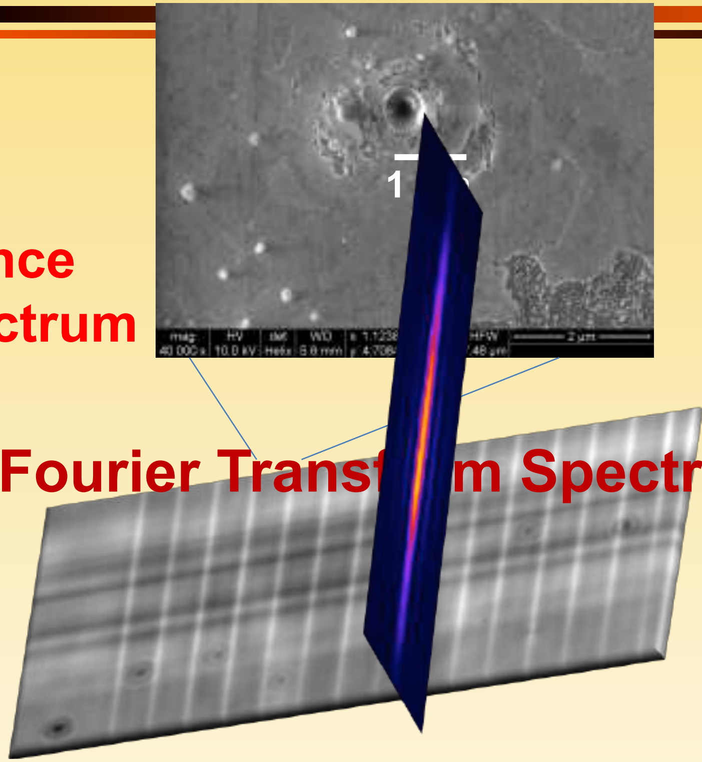


G. Cheng, R. Stoian OL 2013, C. D'Amico Opt. Express 2014

embedded spectrometers



Interference
=FT=spectrum

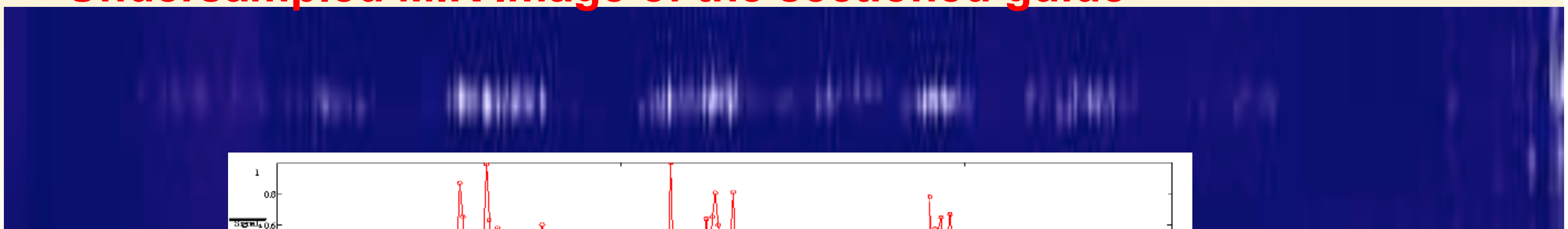


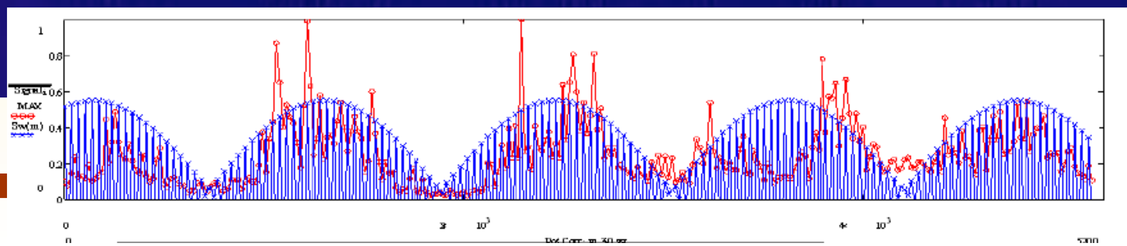
SWIFTS: Stationary wave integrated Fourier Transf m Spectromete
E Coarer Nat. Phot 2007

waveguide

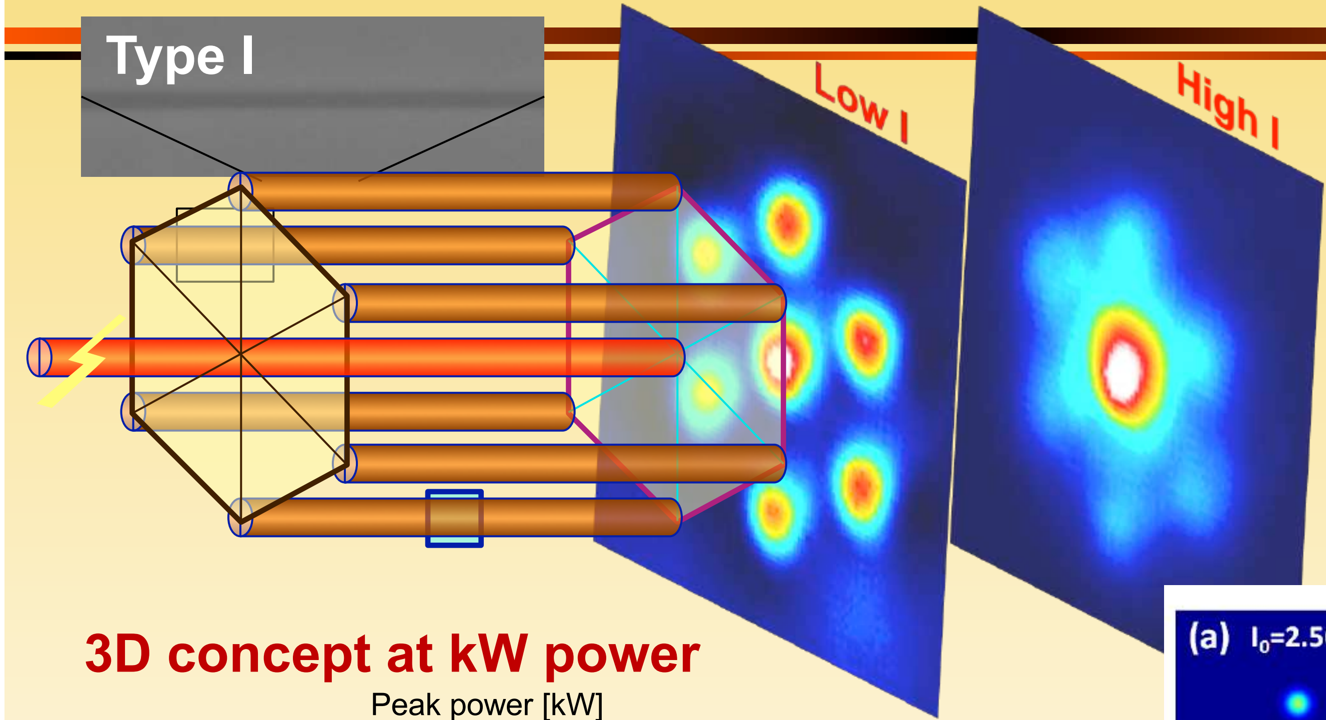
Nonperturbative acces to
evanescent field

Undersampled MIR Image of the sectioned guide



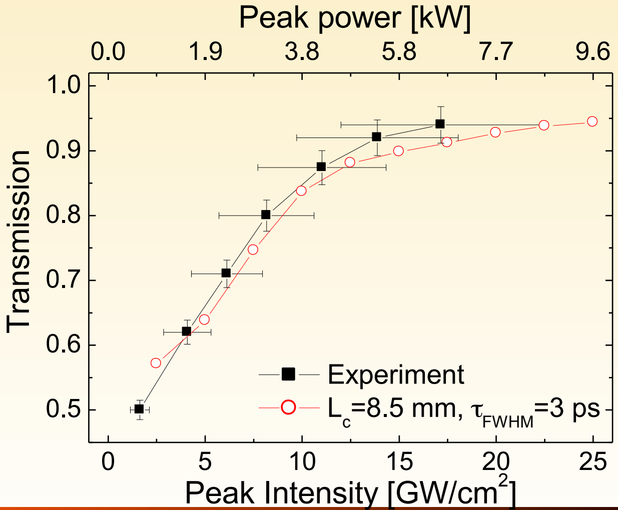


nonlinear functions

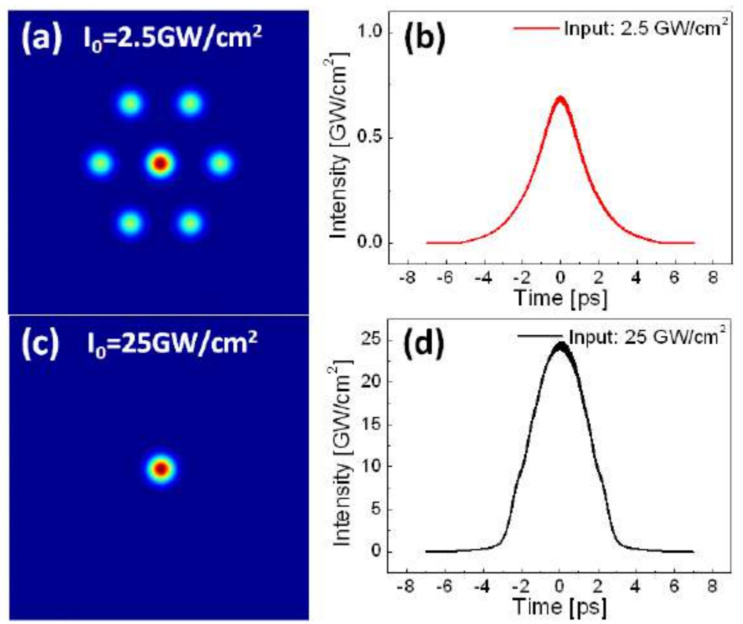


Saturable absorber
$n=n_0+n_2 I$ (Kerr)

3D concept at kW power



Discrete NLO Schrödinger



S. Minardi&R.Stoian, Opt. Lett. 2014

conclusions

- Controllability / Optimality in laser-matter interaction
  design of structural modifications

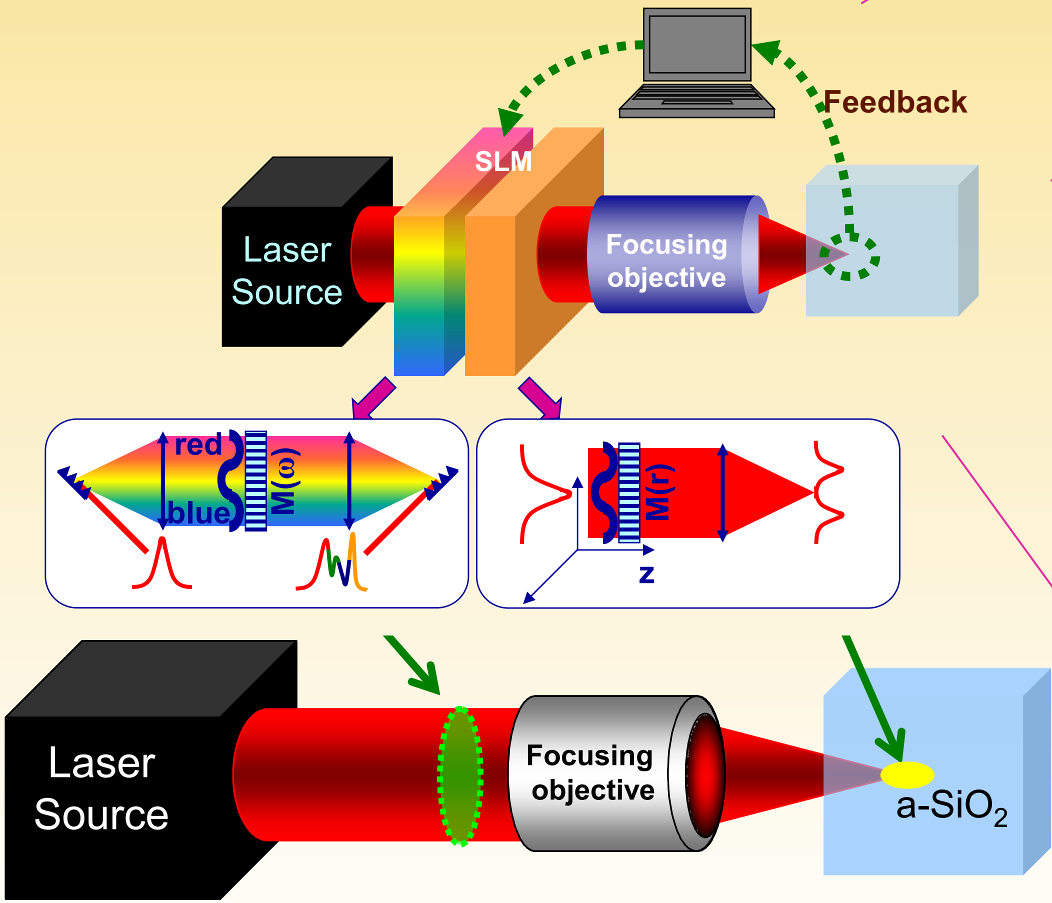
- Dispersion design: breaking the diffraction limit

- 3D Photonics:
  Linear and nonlinear LMA guiding functions

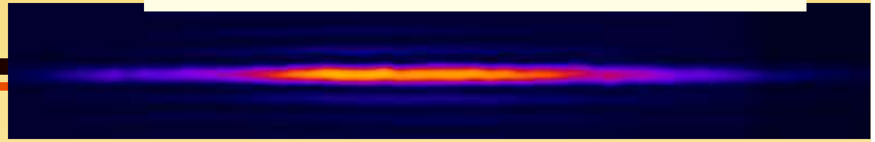
conclusions

High flexibility!

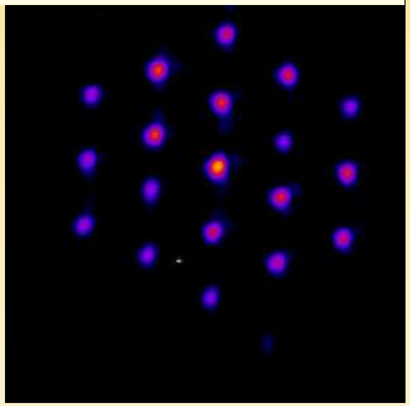
Designing light-matter interaction



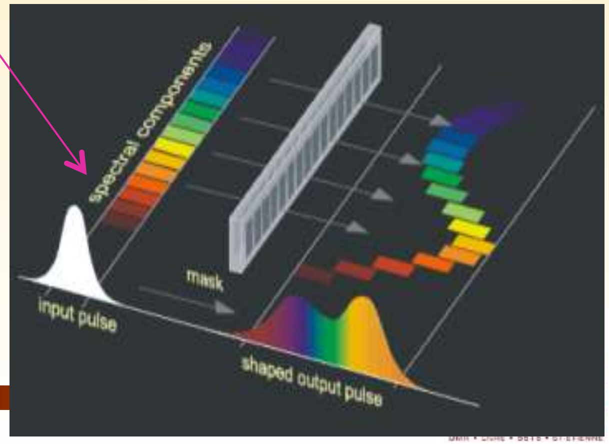
Non-diffractive beams



Parallel processing



Time-shaping



thanks to:

LHC, St. Etienne

C. Mauclair
G. Cheng
K. Mishchik
P. K. Velpula
M. Bhuyan

MBI, Berlin

A. Mermillod

IAP, Jena

S. Minardi

NIPLRP, Bucharest

M. Zamfirescu

EVC Rennes

J. Troles
L. Calvez
V. Nazabal

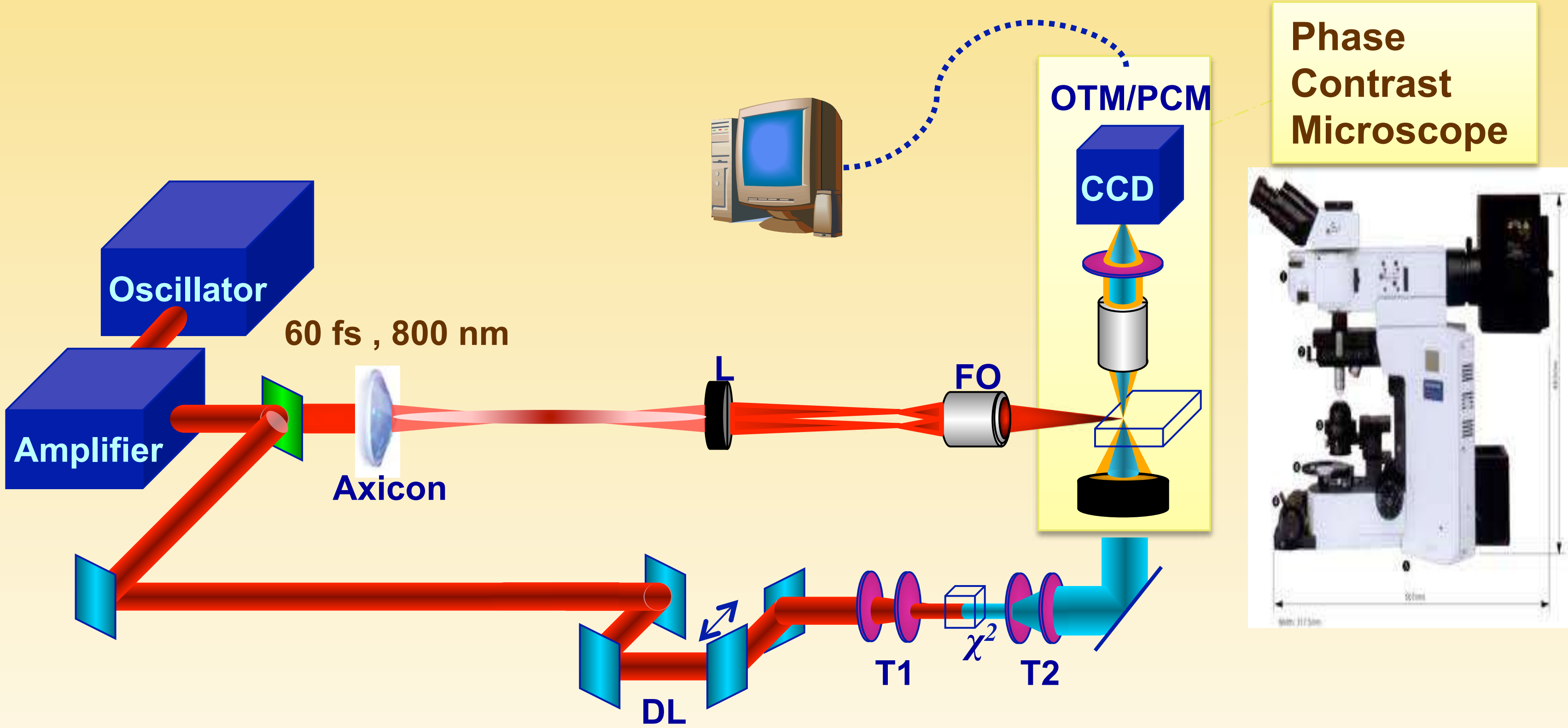
XIOPM, XIAN

G. Cheng

IPAG Grenoble

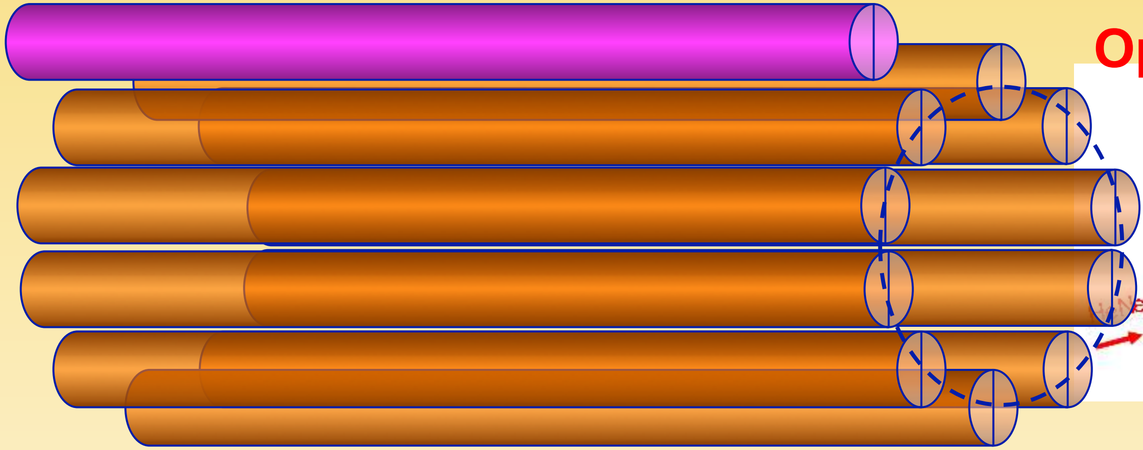
G. Martin
E. LeCoarer
P. Kern

Ultrafast dynamics: time-resolved imaging

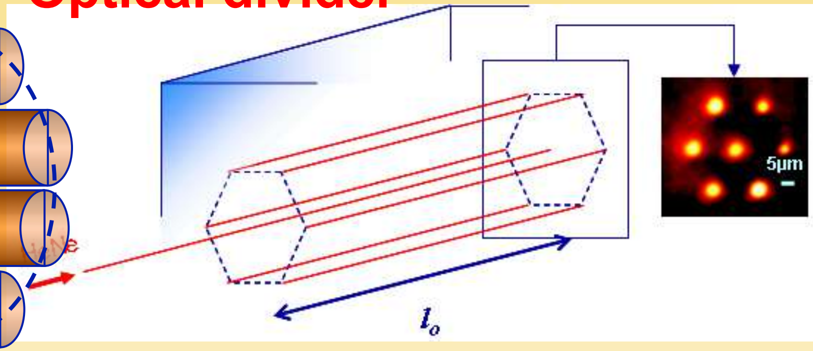


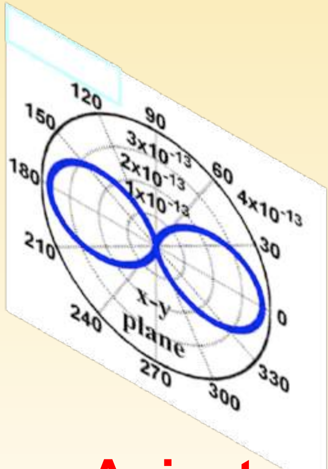
Time resolved microscopy setup; sub picosecond temporal resolution

3D periodic structure: evanescently coupled

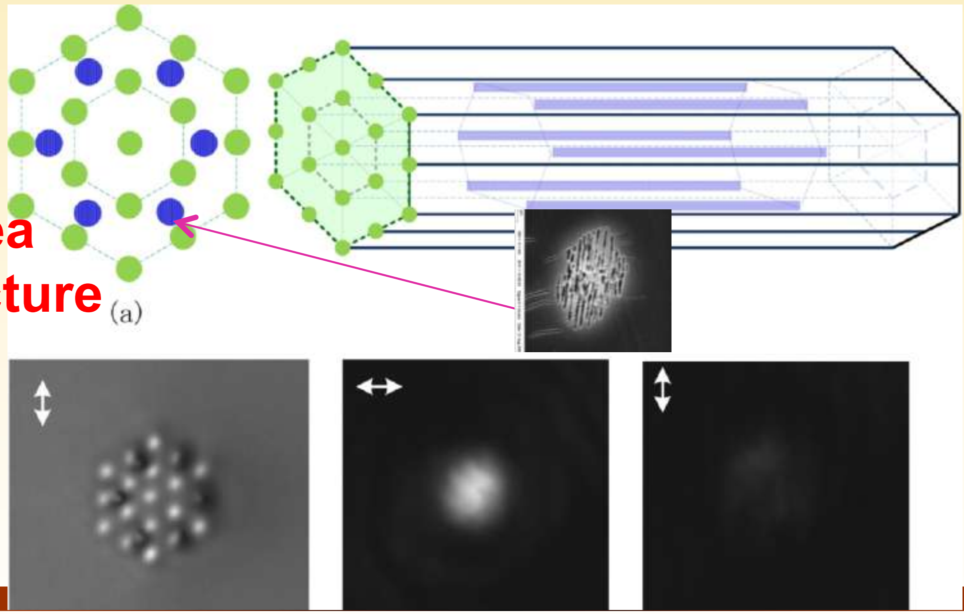


Optical divider





LMA
large-mode-area
Multicore structure



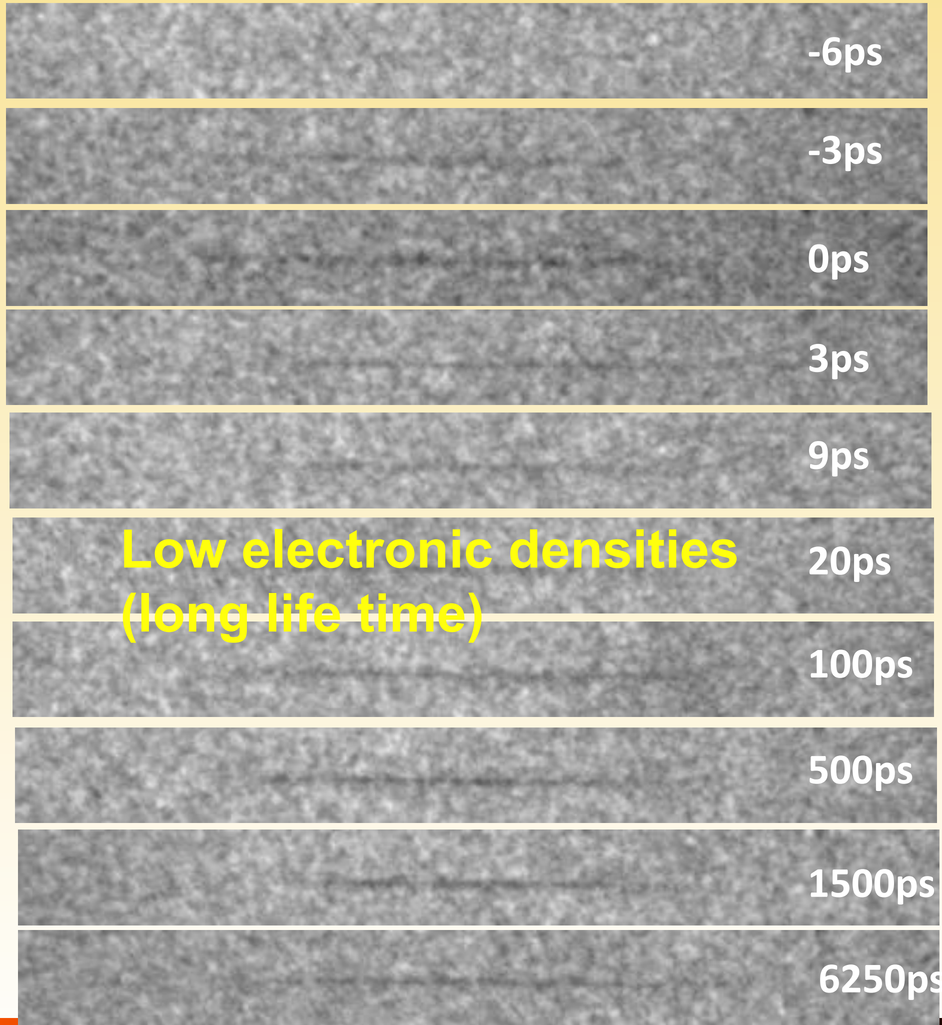
Anisotropic light transport

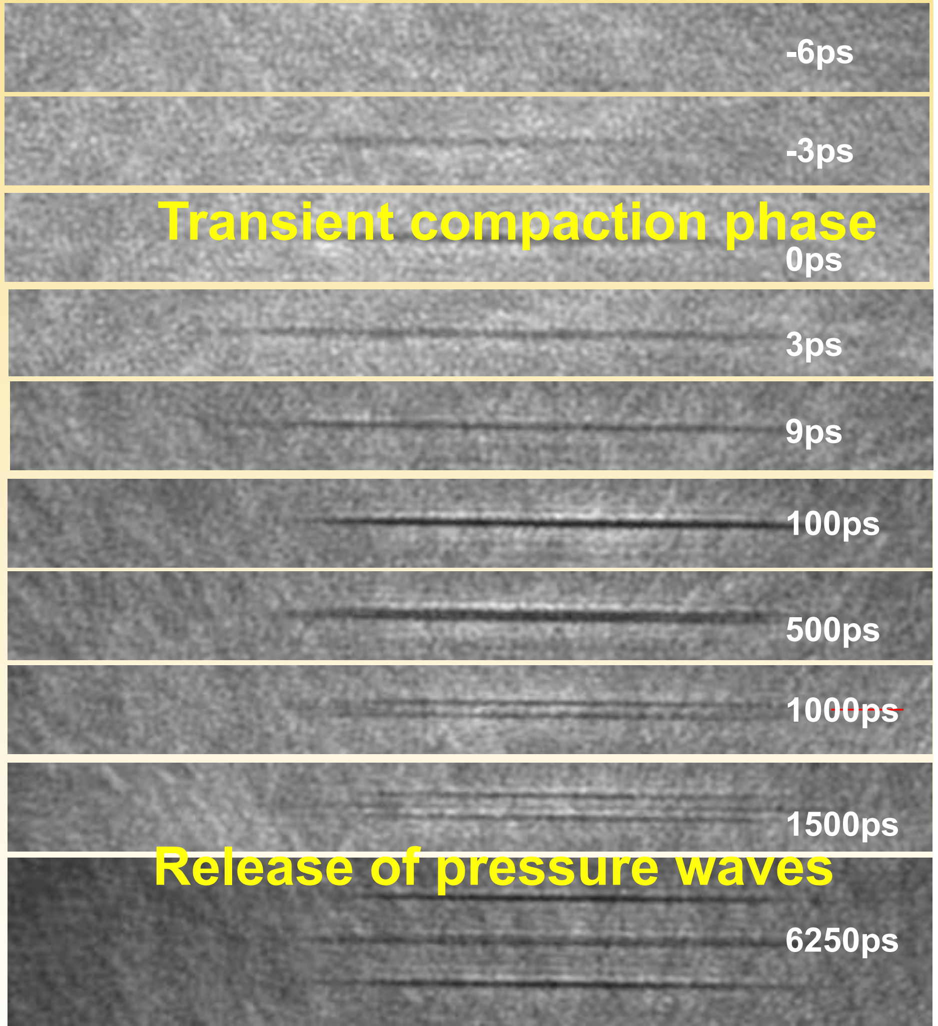
Cheng et al. Opt.Lett 2013

Dynamics of structural transformations

Transmission

Phase

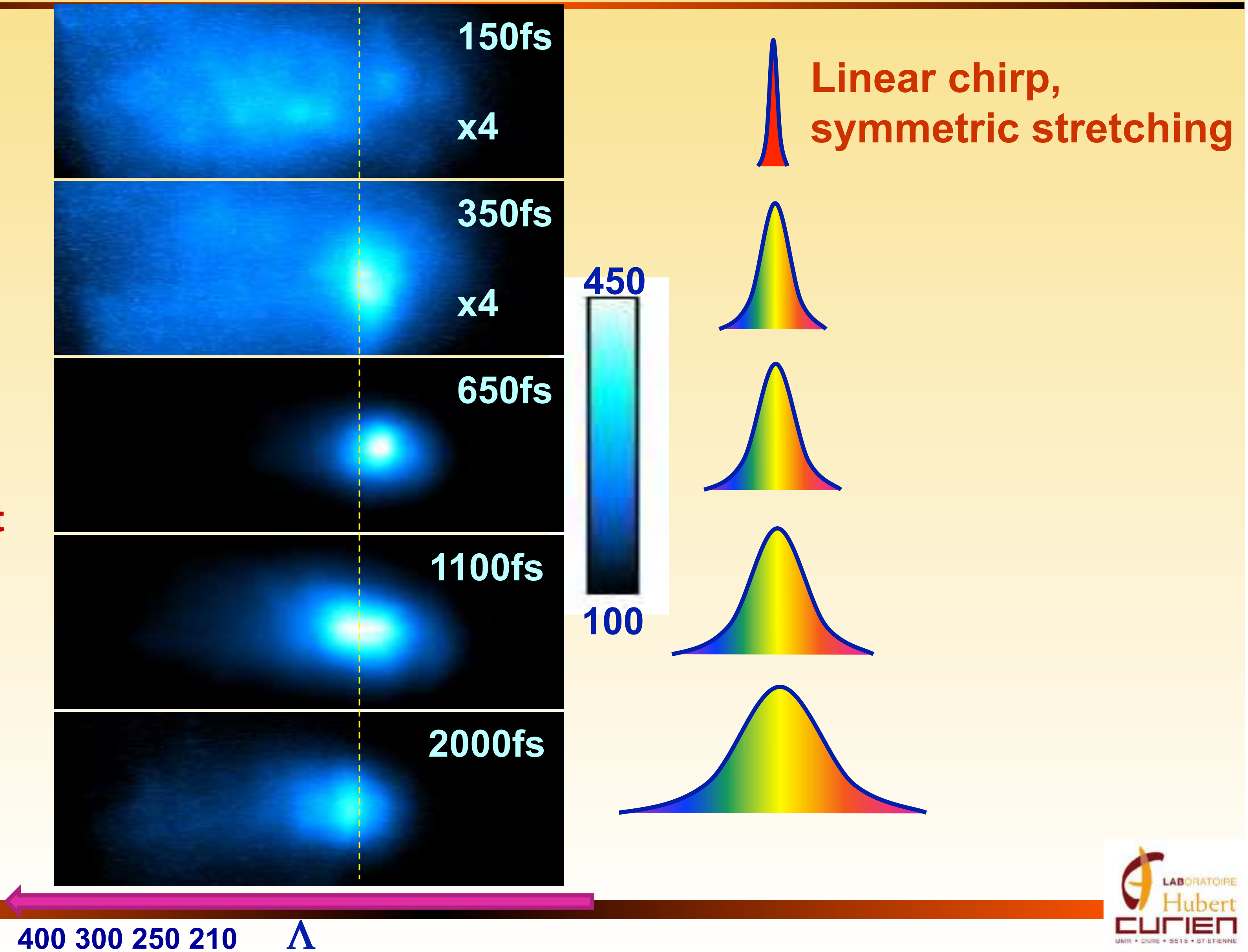




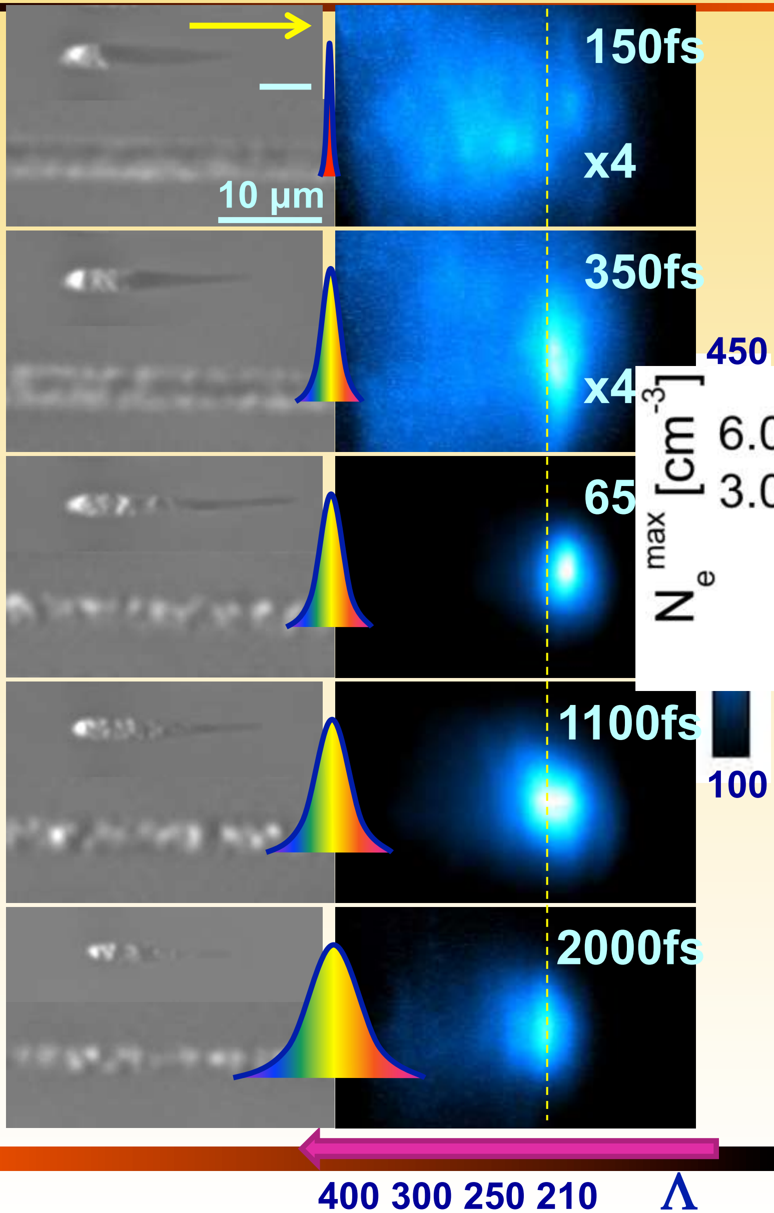
nano-control via diffraction feedback: a-SiO_2

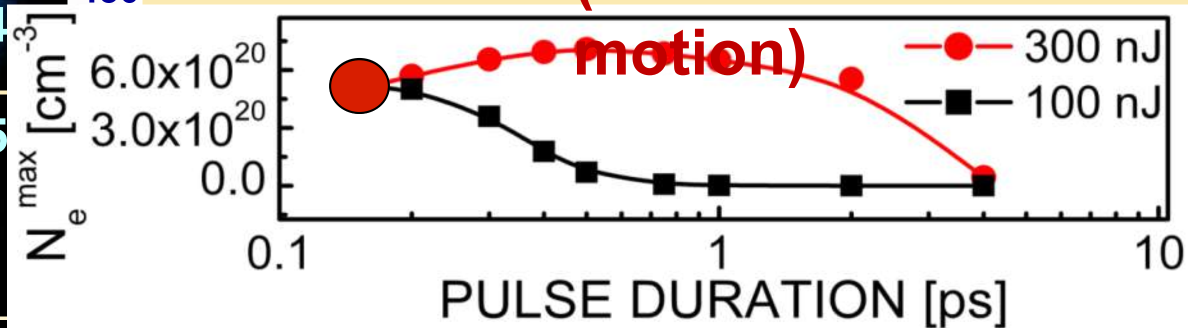
Controllable Periodicity

Controllable arrangement



nano-control via diffraction feedback: a-SiO_2

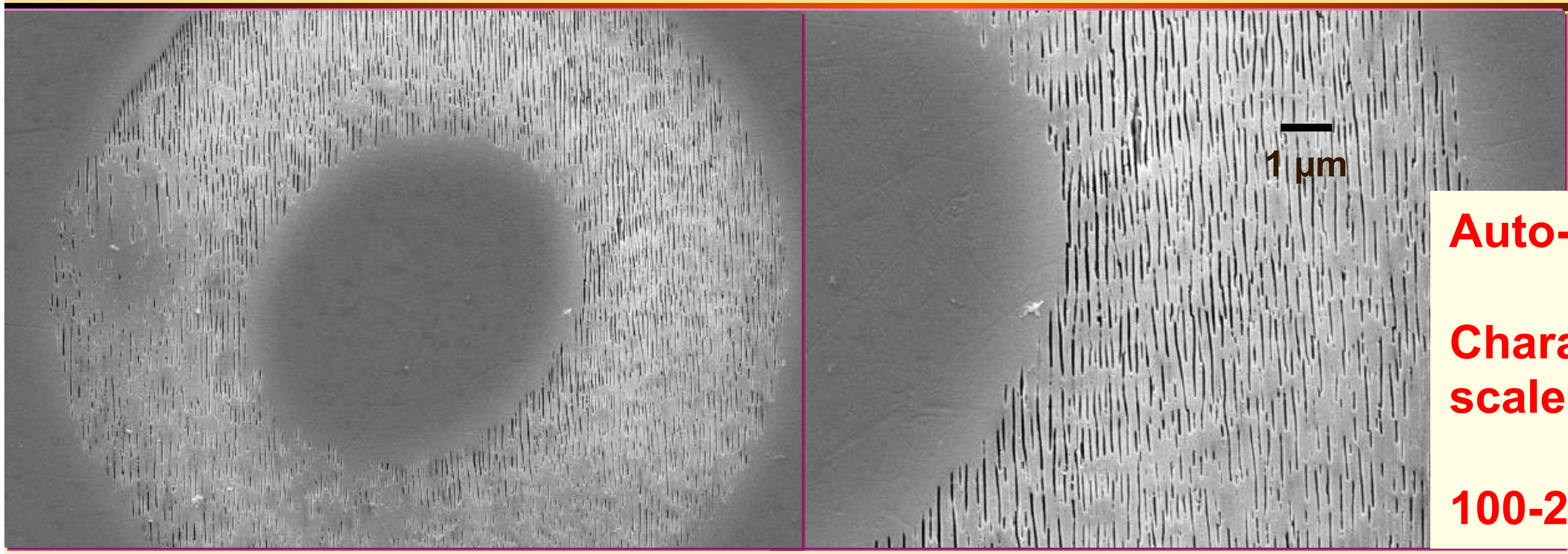




Electron density
control enabled (collective electron motion)

Non monotoneous N_e
-max 0.6ps

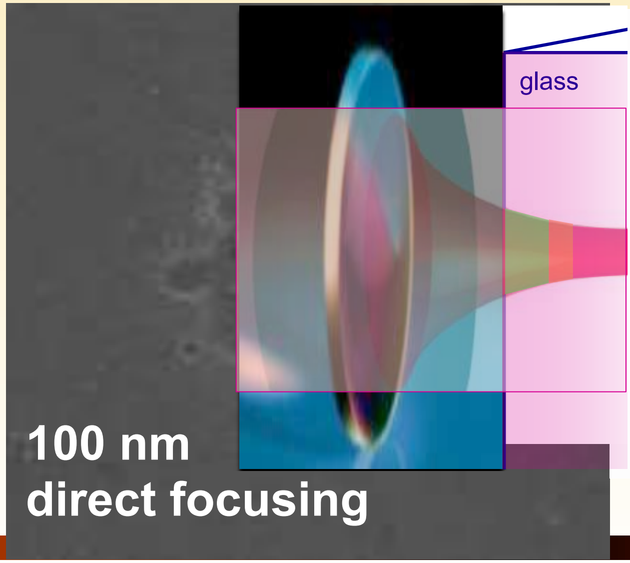
laser nanostructuring: beating the diffraction limit

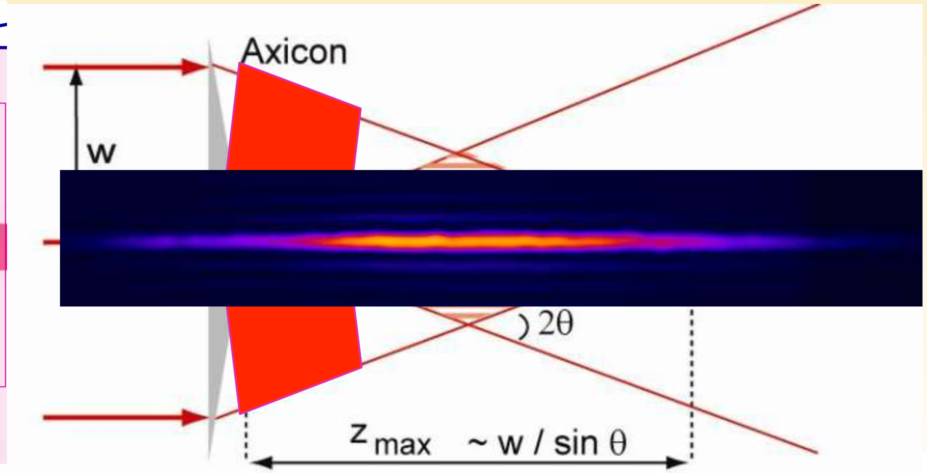


Auto-organization

Characteristic scale

100-200nm



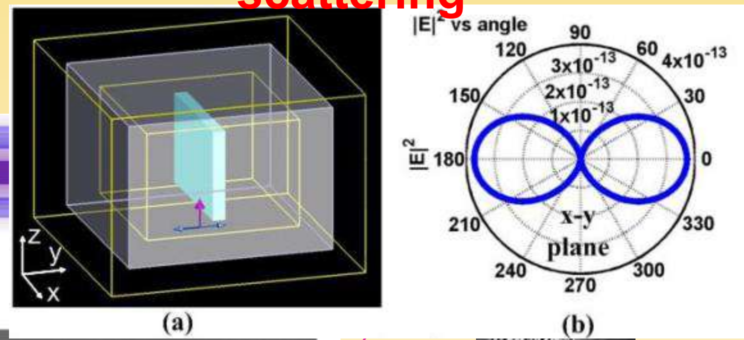


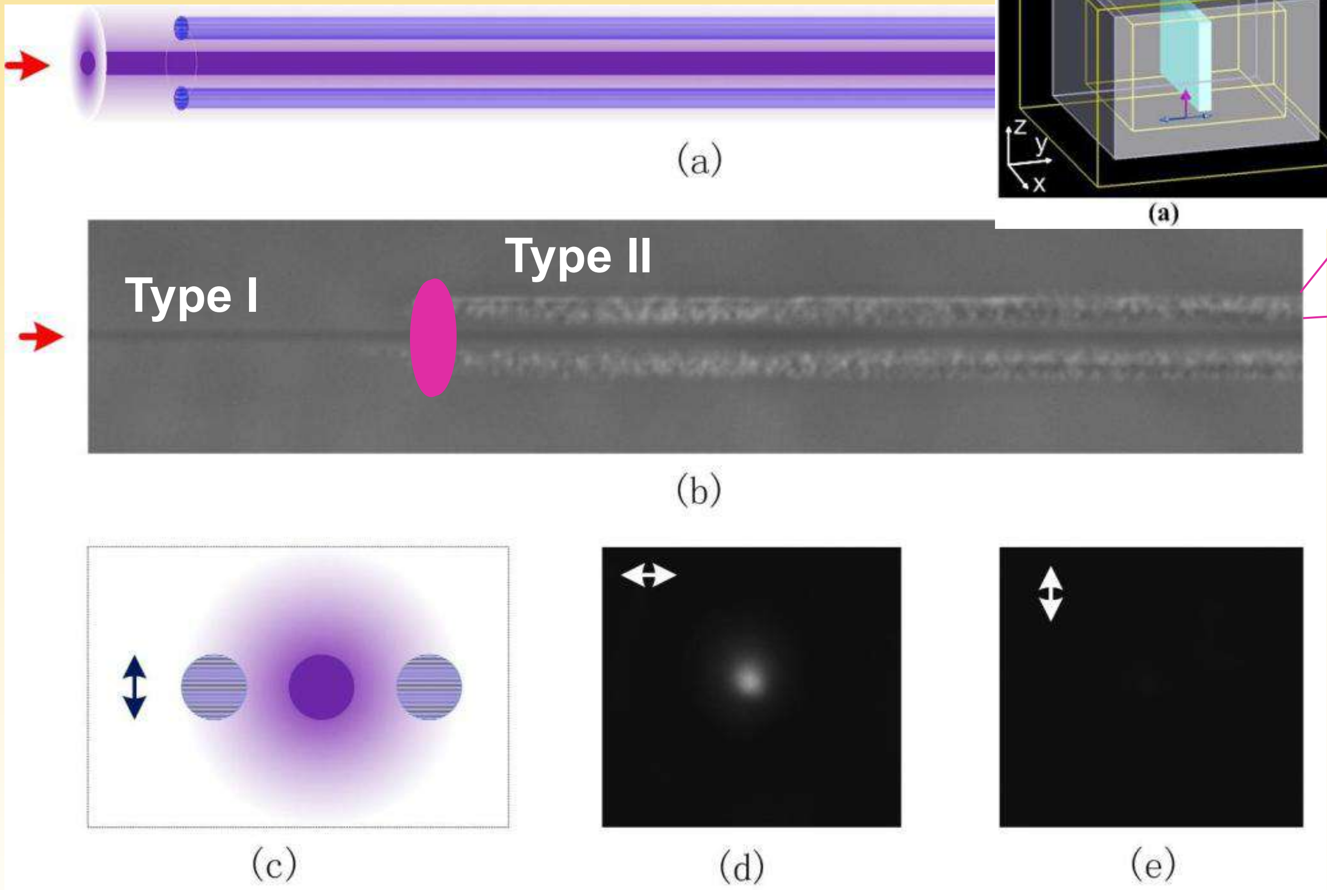
ANRNanoFlam, LaHC, Femto-ST

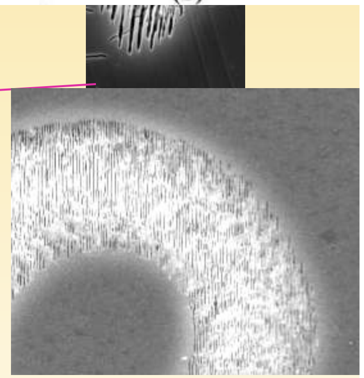
optical functions: a-SiO_2

•Polarization maintaining waveguides
low-loss + anisotropy

scattering







Mishchik et al. OE 2010