Adaptive control of 3D ultrafast laser processing of optical glasses

R. STOIAN

Saint Etienne, France

LABORATOIRE Hubert CURIEN
UMR • CNRS • 5516 • ST-ETIENNE

MBI
Max-Born-Institut

activities:

Material processing:

Why ultrafast laser pulses???

-Energy localization
-Repressed diffusion

-Possibility of envelope design

Saint Etienne, France:

Laboratoire Hubert Curien, CNRS, University Jean Monnet

Optics & Photonics Department: Research directions

-Laser Matter Interaction

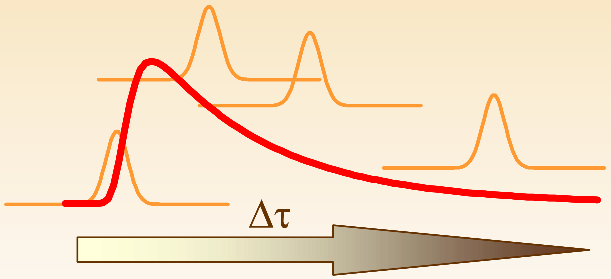
-Micro, nano-structuring

FUNDAMENTAL PLATFORM	⟷	INDUSTRIAL PLATFORM COMPETENCE POLE

Pole Optique Rhone-Alpes

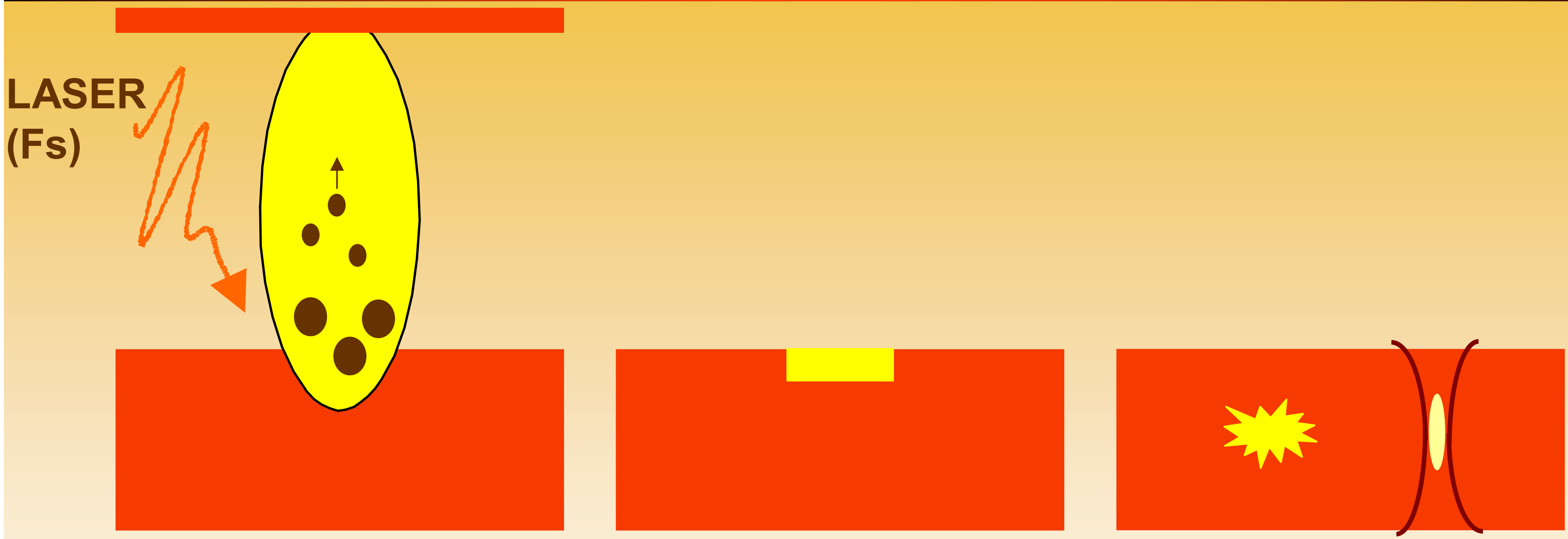
laser-matter interaction: research theme

- <u>Laser irradiation tool</u>: projects
  - ➪ Ablation products (material removal and transfer)
  - ➪ Material structuring on surfaces and bulk (2D and 3D)
  - ➪ Atomic scale structural changes: resistance in harsh environments
- Probing tool
  - – Ultrafast scale phenomena
  - – Non-equilibrium conditions
  - – Imaging and bio-sensing



Duality: fundamentals and applications

laser irradiation: enabling tool



-Laser ablation
-Material transfer
-Elemental spectroscopy
-Laser deposition

-Surface structuring
-Micro/nano texture
-Mechanical functions
-Optical functions

-3D processing
-Refractive index change
-Photonic functions

-Defect formation
-Resistance to damage

-TPA-imaging nm-µm

high intensity lasers:

short pulse power

flashlight

bomb

lightning

high field laser

1watt

etawatt
10^{15}W

electri

sun

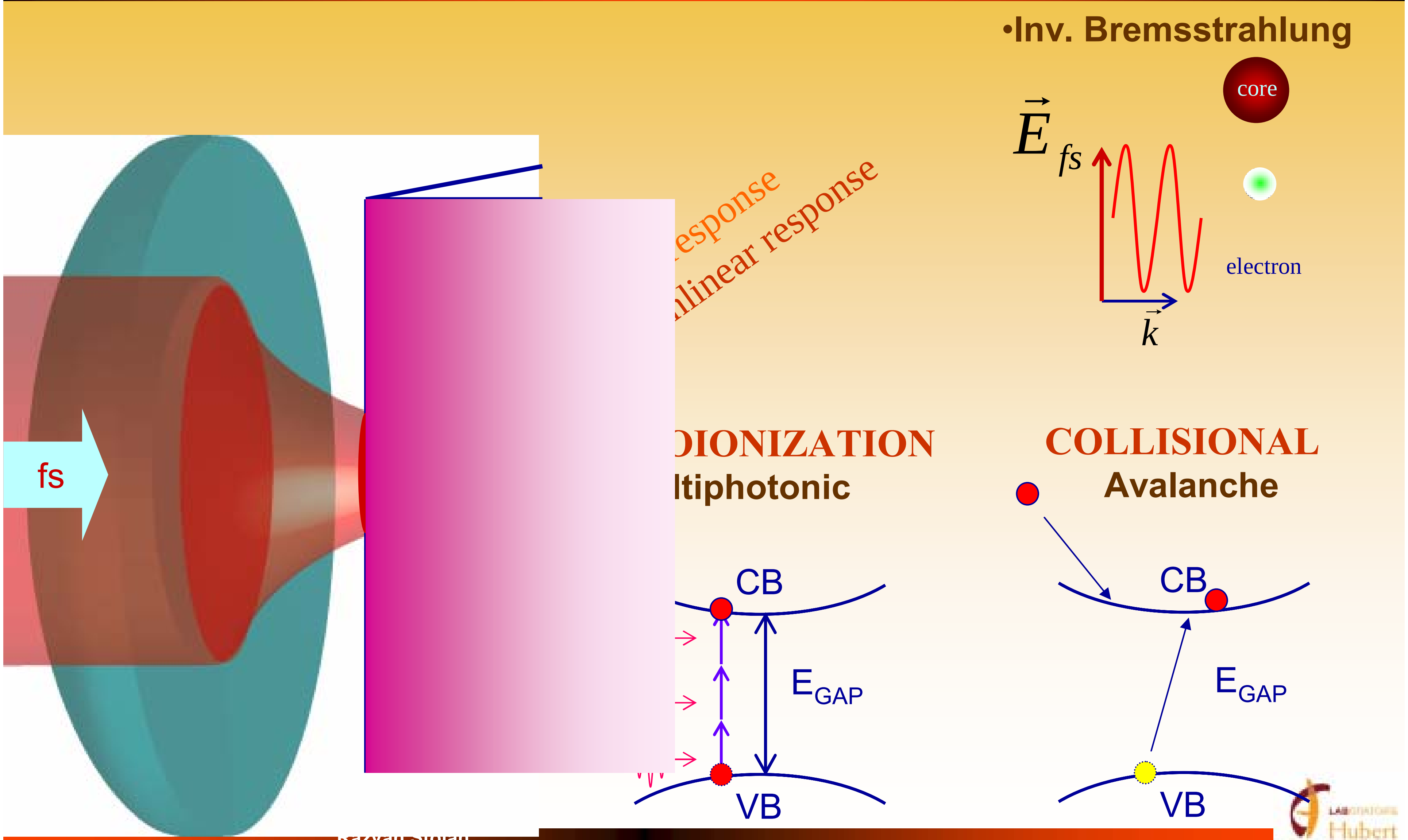
car

all power
in France

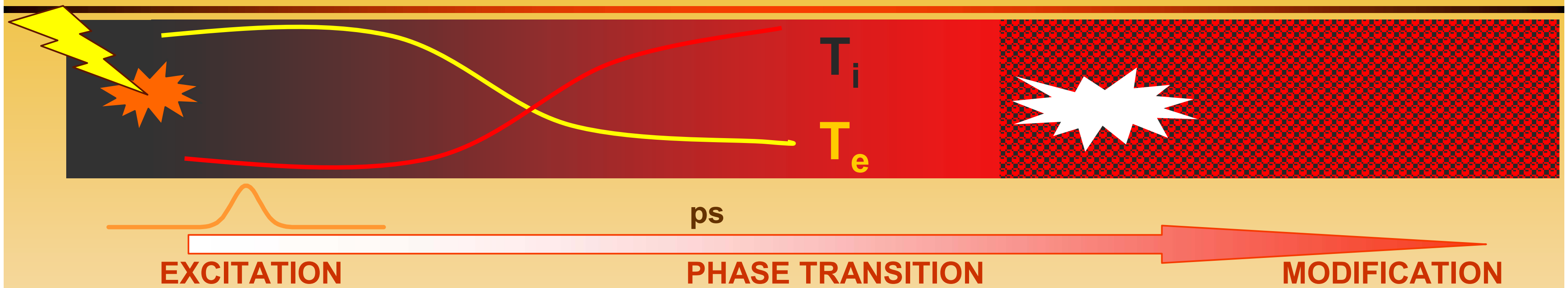
continuous power

Courtesy I.V. Hertel MBI

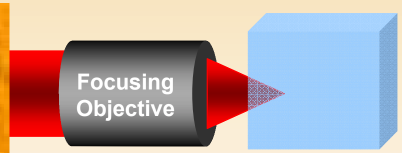
nonlinear excitation: ultrafast laser pulses

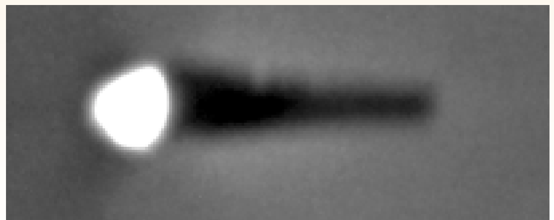


modification processes: ultrafast laser pulses



Electron plasma



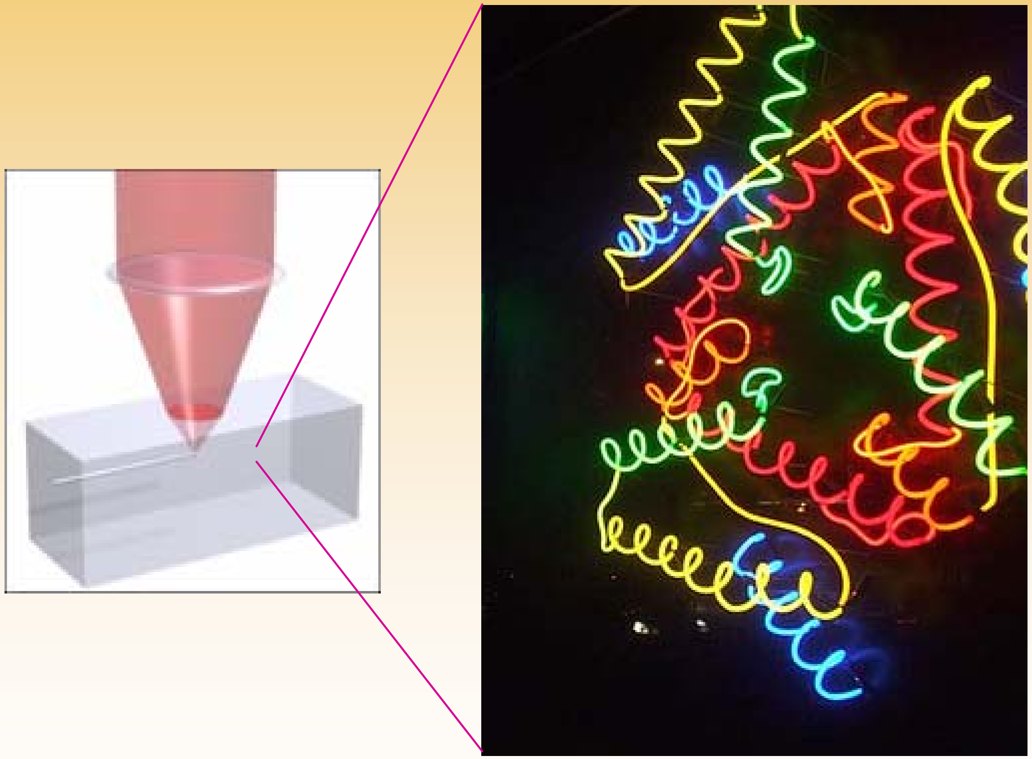


Result: refractive index change

3D material modifications

refractive index Δn

- Building block of embedded optical functions

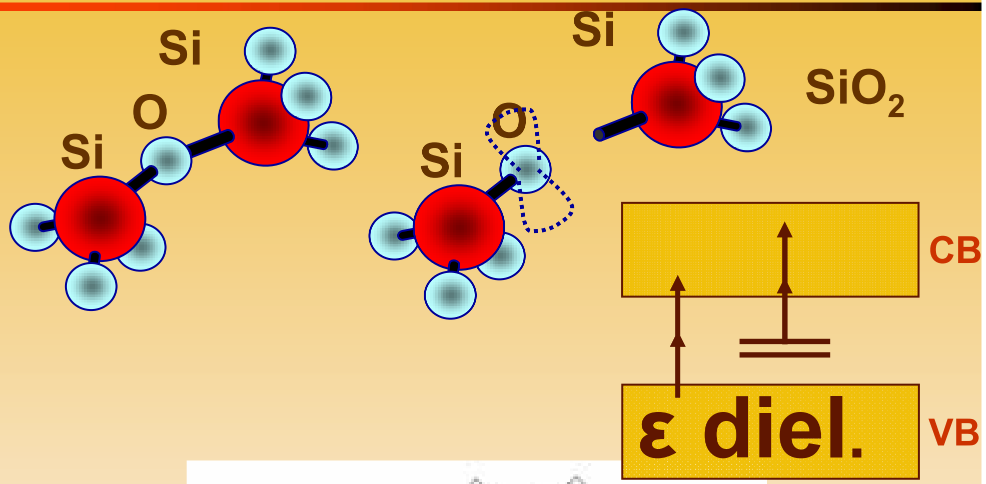


Integrated optical systems (waveguides, gratings, lenses, lasers…)

material modifications

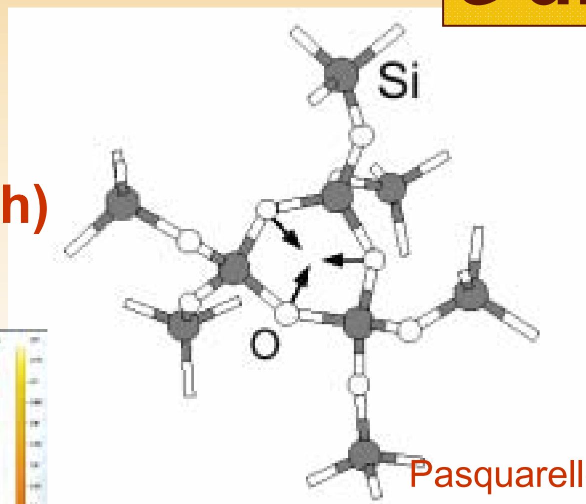
refractive index Δn

- interplay between



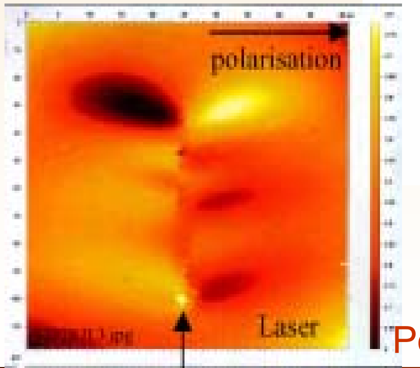
➪ **defects (energetic path)**

➪ **densification (thermodynamic path)**



Pasquarello PRL 1998

➪ **stress (mechanical)**



Poumellec OE 2003

material modifications

refractive index Δn

- interplay between
  - ➪ Defects → fs-ps
  - ➪ Densification → ps-ns
  - ➪ stress → ns-µs

Characteristic times:

fs-ps

ps-ns

ns-µs

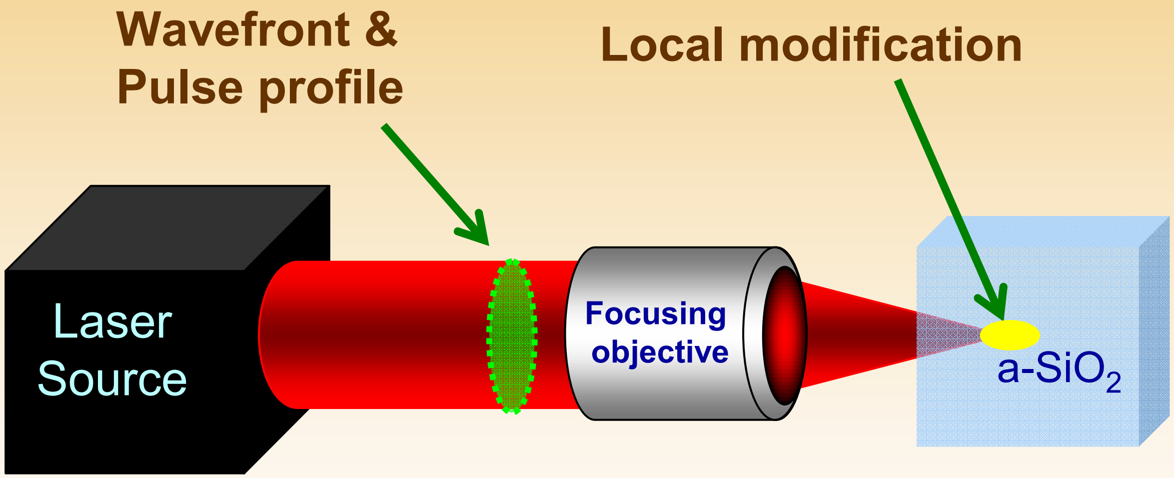
Possible control

- **I(r,t)**

space & time

- engineered refractive index
- design of integrated optical and photonic functions

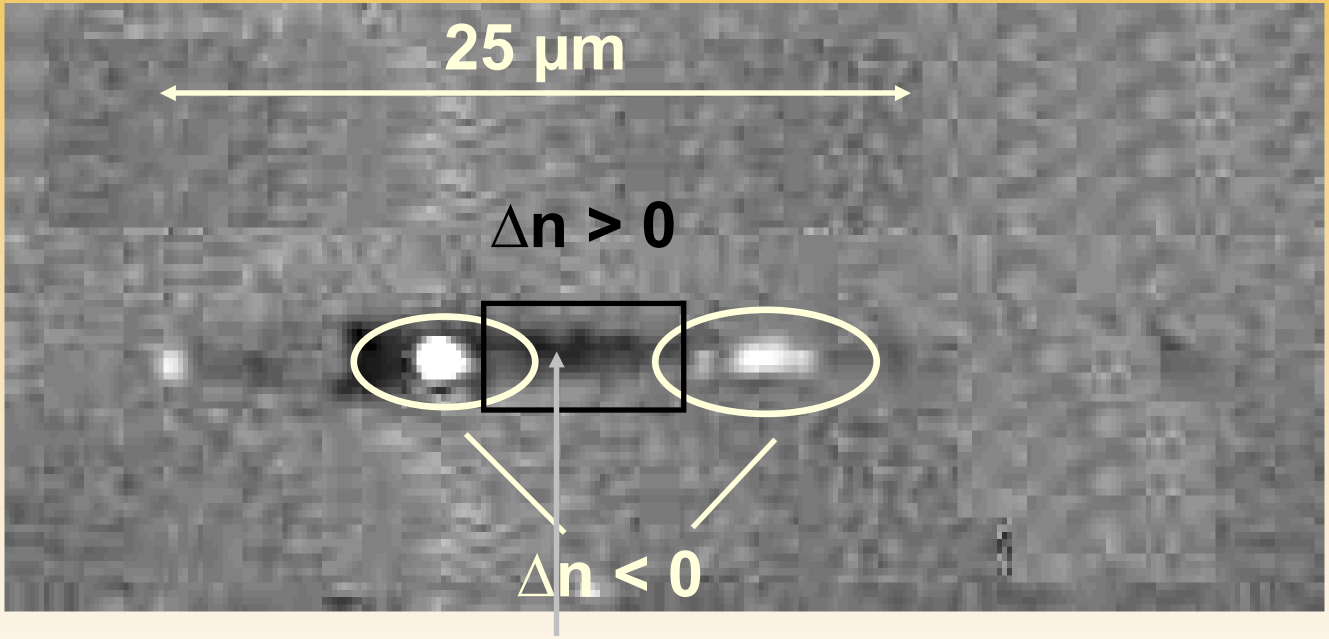
refractive index changes



Can this be improved (controlled)?

refractive index changes a-SiO_2

SINGLE PULSE EFFECT (N=1): a-SiO_2



PHASE-CONTRAST MICROSCOPY

FOCUS (NA= 0.4), 1µJ

Q1: how is the energy distributed?

Q2: how fast is the material reaction?

refractive index changes

Q1: How is the energy distributed?

Collaboration:
IT, Novosibirsk

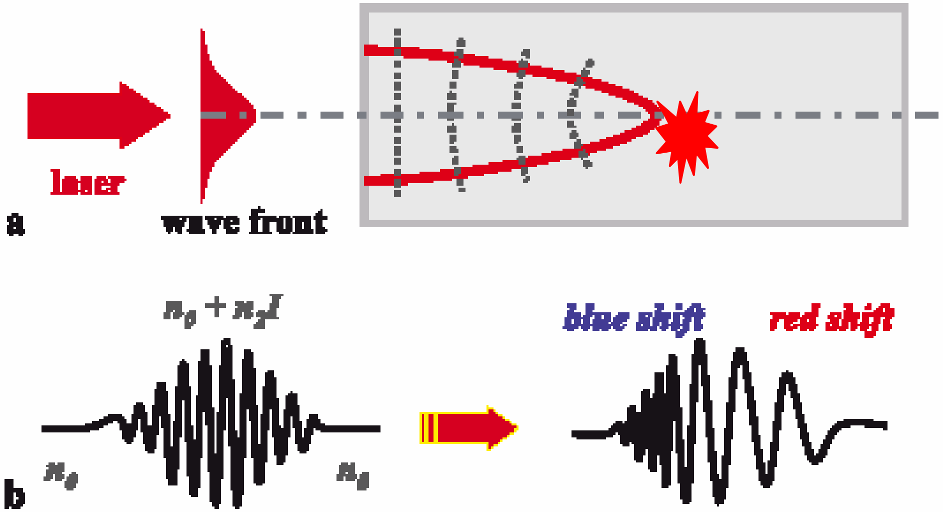
nonlinear pulse propagation

$$\frac{\partial \bar{\epsilon}}{\partial z} = \frac{i}{2k_0} T^{-1}\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)\bar{\epsilon} - \frac{ik''}{2}\frac{\partial^2 \bar{\epsilon}}{\partial t^2}$$

$$+ \frac{ik_0 n_2 T}{n_0}\left[(1-f_R)|\bar{\epsilon}|^2 + f_R \int_{-\infty}^{t} \mathrm{d}\tau\, R(t-\tau)|\bar{\epsilon}|^2\right]\bar{\epsilon}$$

$$- \frac{\sigma}{2}(1 + i\omega_0\tau_c)T^{-1}(\rho_e \bar{\epsilon}) - \frac{1}{2}\frac{W_{PI}(|\bar{\epsilon}|)E_g}{|\bar{\epsilon}|^2}\bar{\epsilon}.$$

NLSE-Schrödinger
E-field propagation

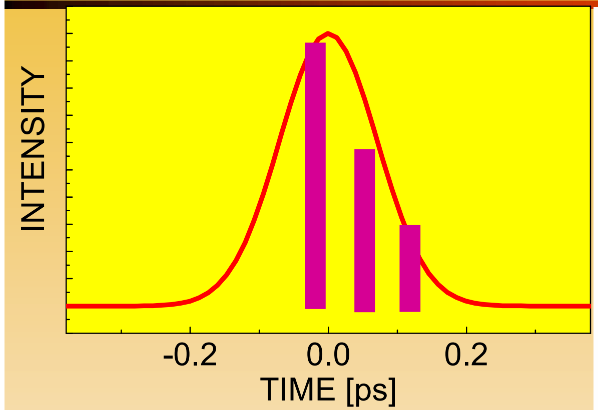


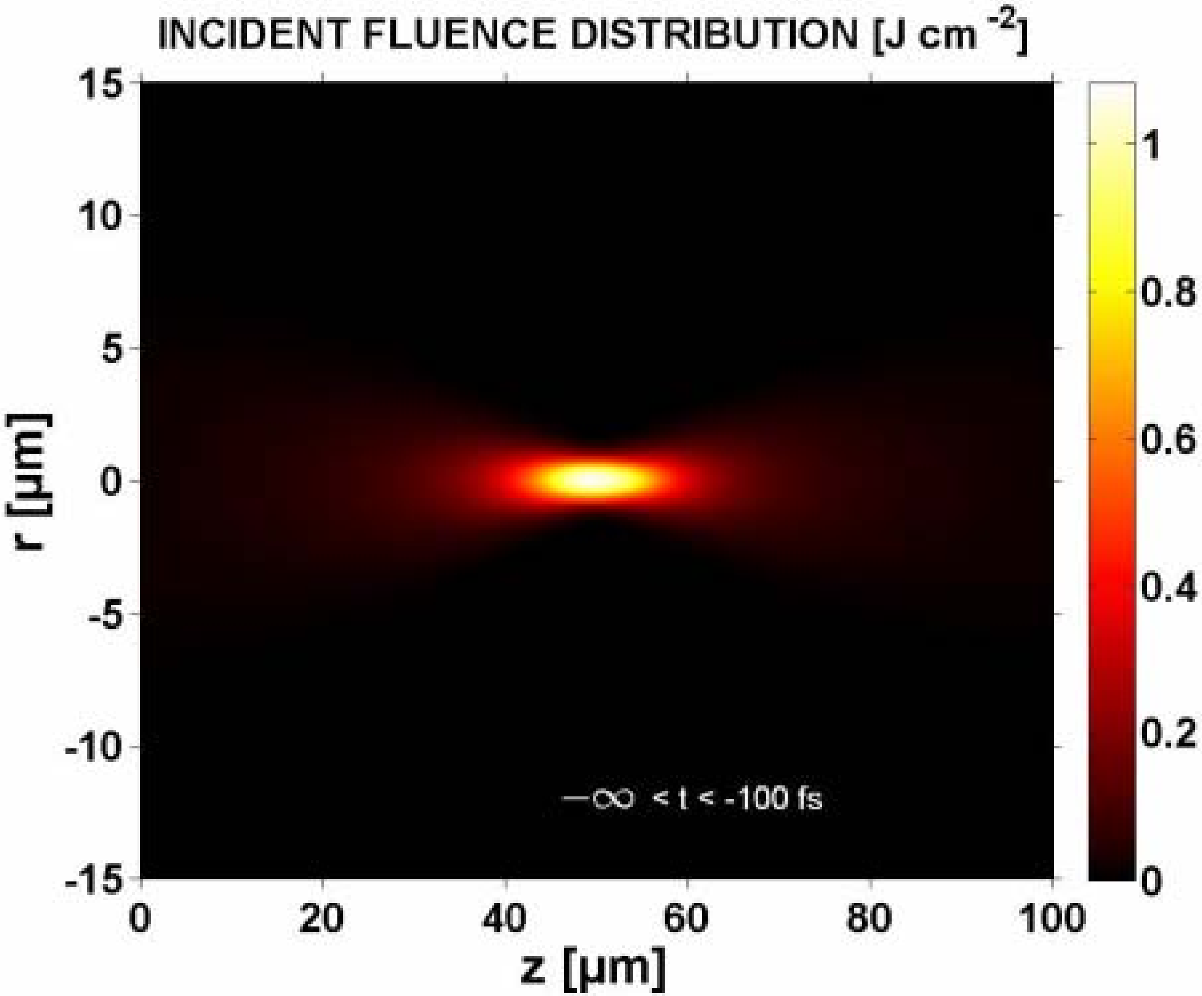
Plasma generation

$$\frac{\partial \rho_e}{\partial t} = \left[W_{\mathrm{PI}}(|\bar{\epsilon}|) + \frac{\sigma \rho_e}{\left(1 + \frac{m}{m_e}\right)E_g}|\bar{\epsilon}|^2\right]\frac{\rho_a}{\rho_0} - \frac{\rho_e}{\tau_{\mathrm{tr}}}.$$

Photoionization **Avalanche**

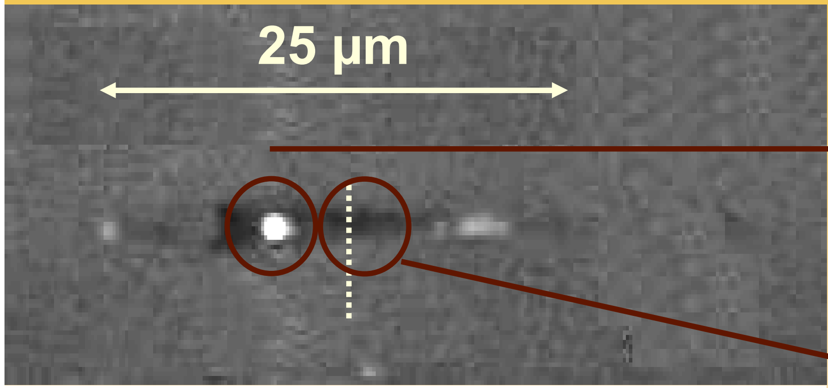
pulse evolution- sequential energy deposition





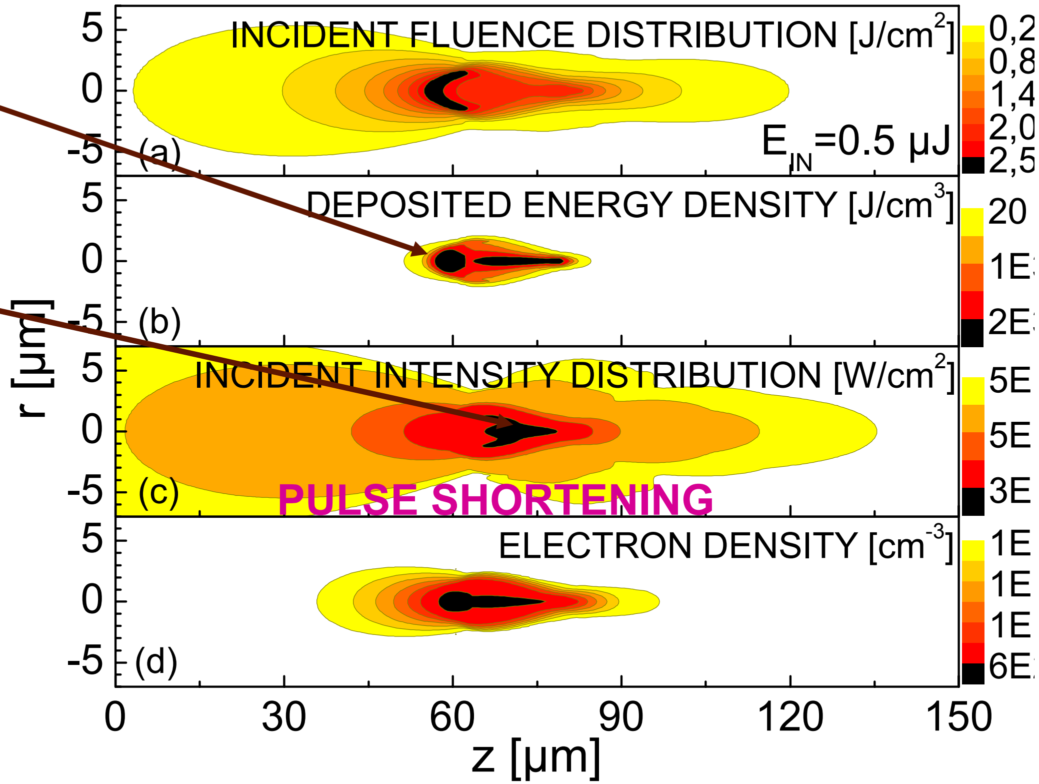
nonlinear excitation a-SiO_2

energy distribution: short pulses NA=0.4



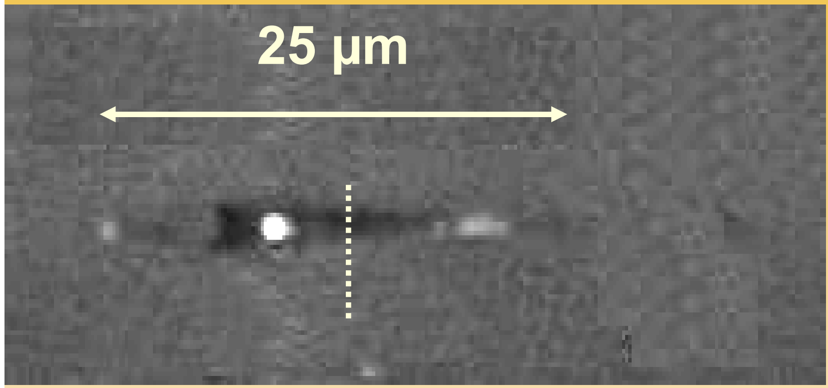
$$\nabla \times \nabla \times E + \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = -\frac{4\pi}{c^2}\frac{\partial^2 P}{\partial t^2},$$

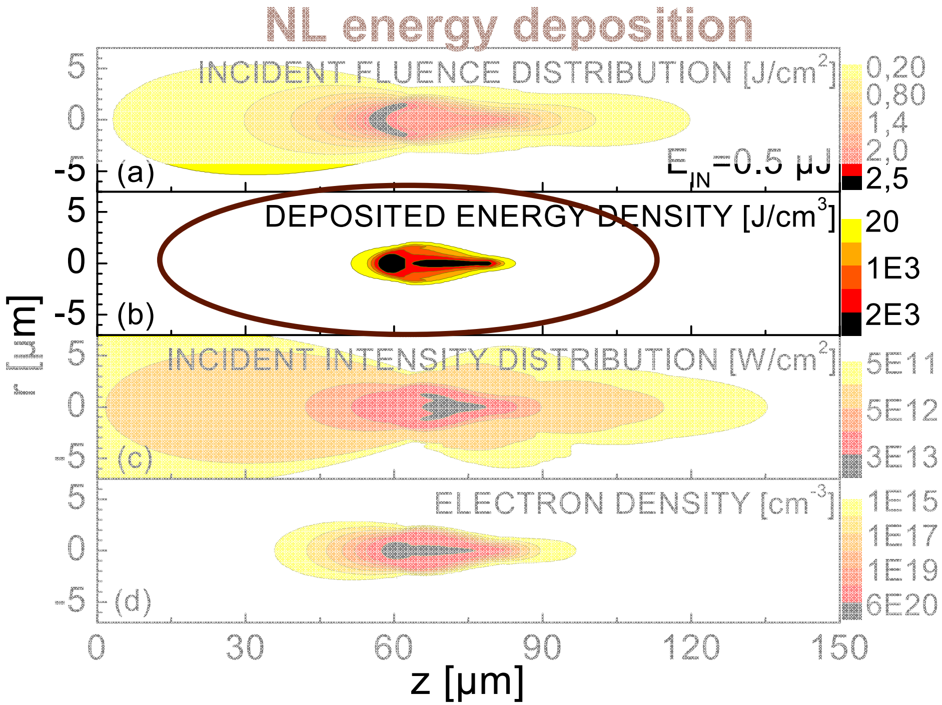
Burakov JAP 2007 NLSE formalism



bulk modifications in a-SiO_2; density change

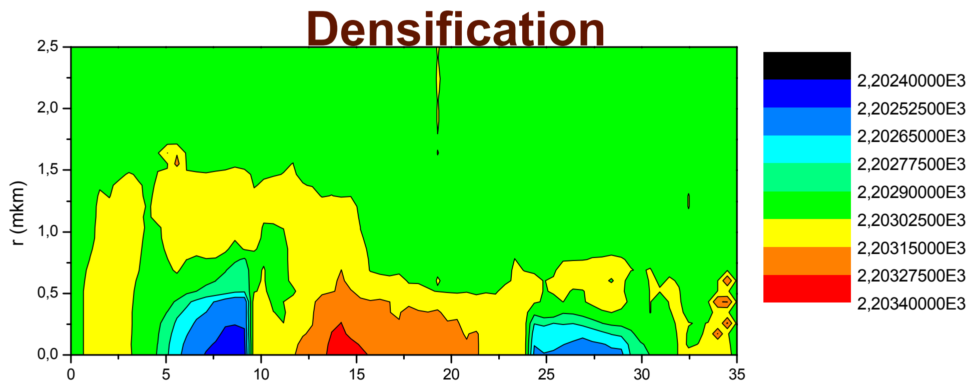
short pulses





THERMO-MECHANICAL ELASTO-PLASTIC MODEL

-Dynamic elasticity
-Heat transfer
-Yield criterion



Material deformation
Plastic yielding

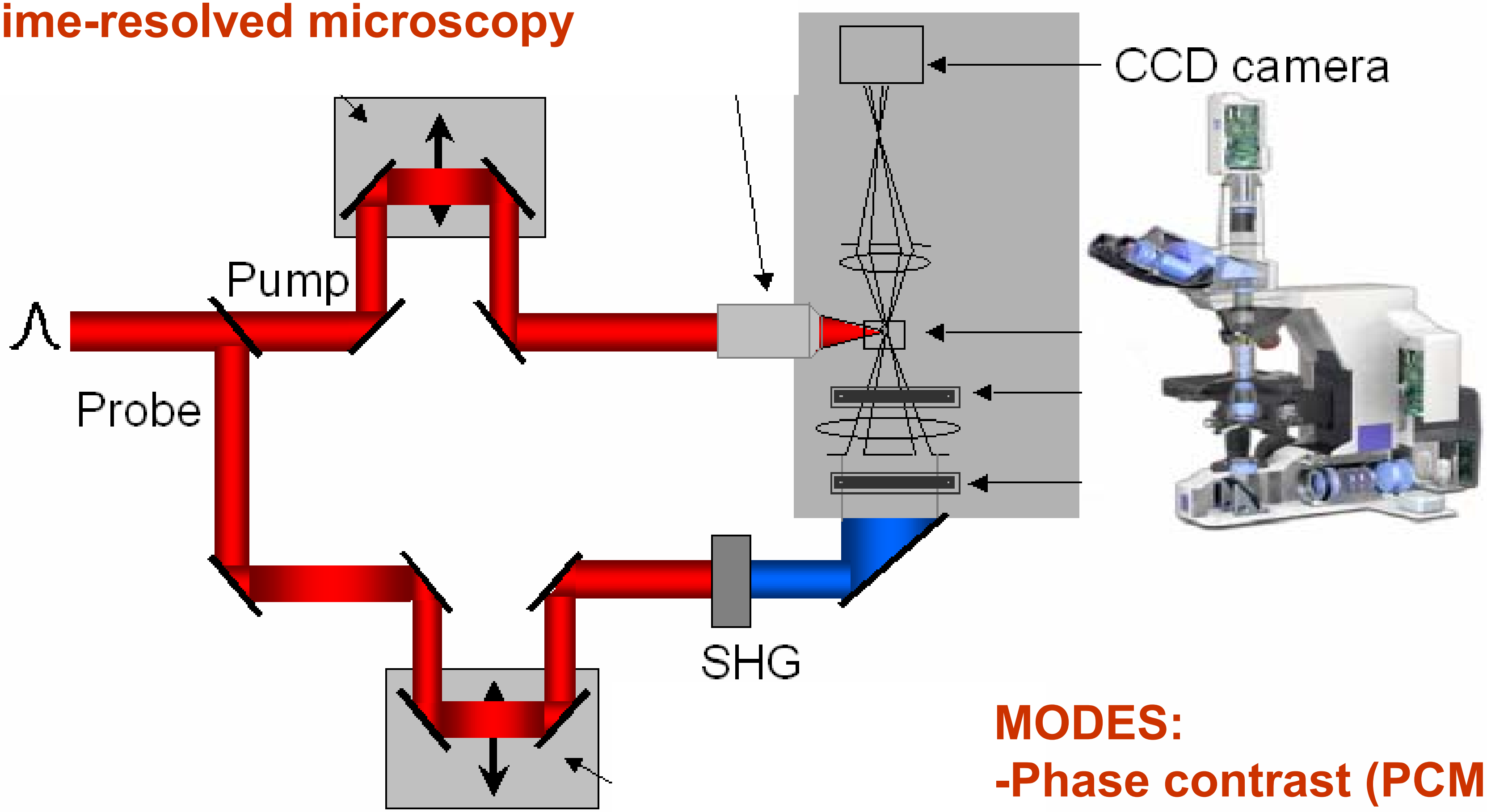
refractive index changes a-SiO_2

Q2: how fast is the material reaction?

pump-probe apparatus

Follow dynamics

Time-resolved microscopy



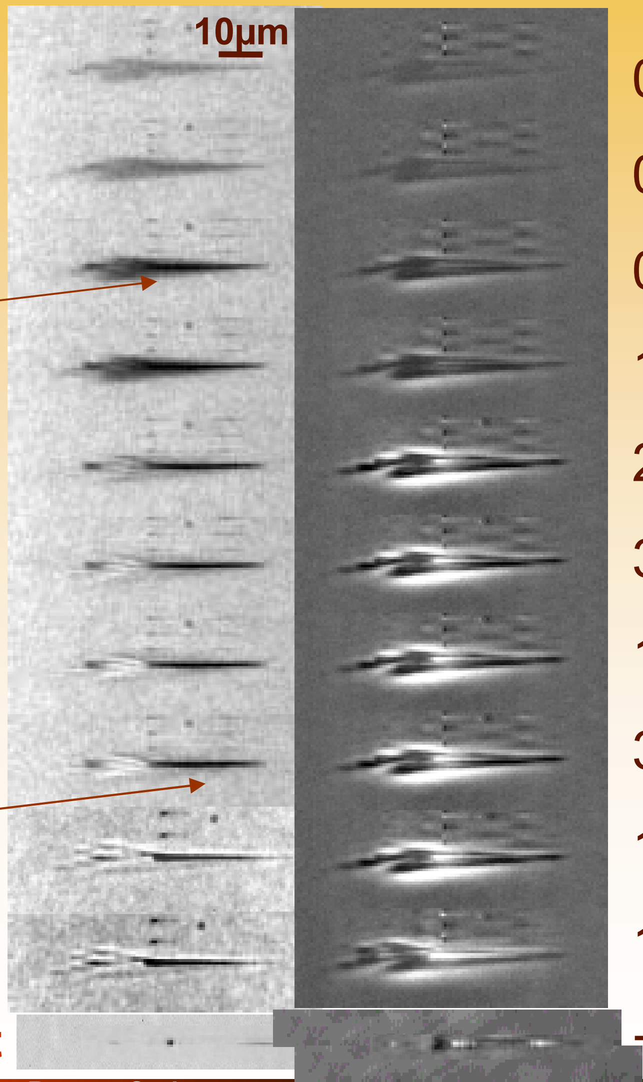
MODES:

-Phase contrast (PCM)

-Optical transmission (OTM)

refractive index changes a-SiO_2: time-sequence

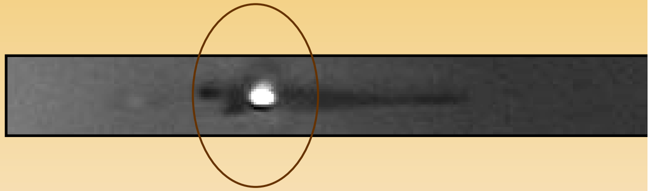
OTM PCM Time delay (ps)

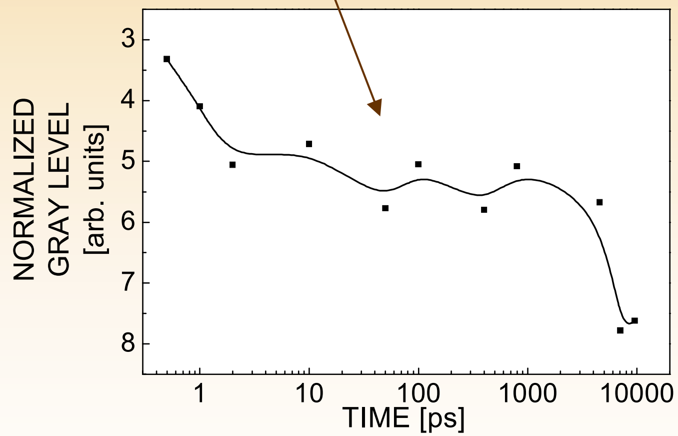


Fast (sub-ps) plasma decay
(low excitation)

Persistent absorptive zone (<u>ns</u>)
-electrons?
-liquid phase?
-defects**?**

But not permanent





Matrix response

Thermo-mechanics

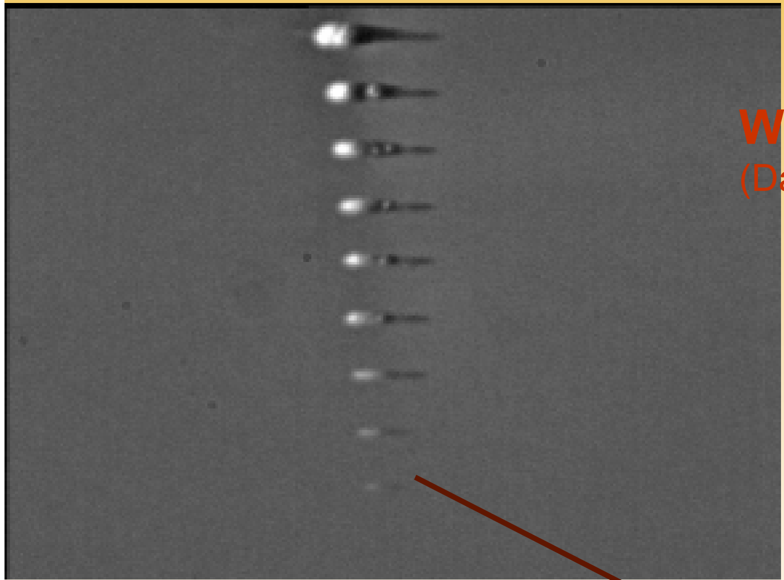
refractive index changes

Q3: the response is material dependent?

bulk modifications in a-SiO_2 and BK7

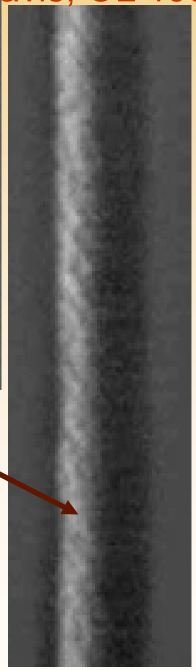
short pulses

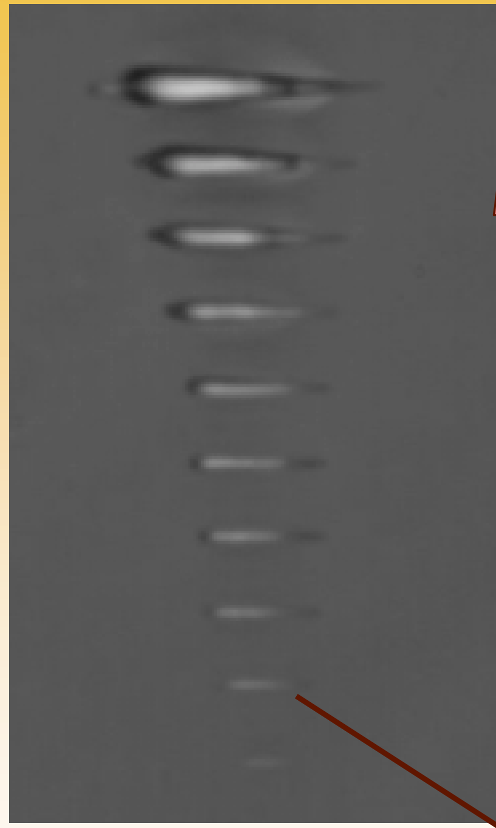
Multishots: N=1000



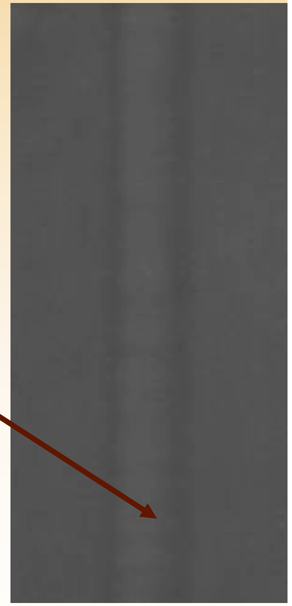
Waveguide

(Davis, OL 1999)





E



a-SiO_2

$\Delta n > 0$

BK7

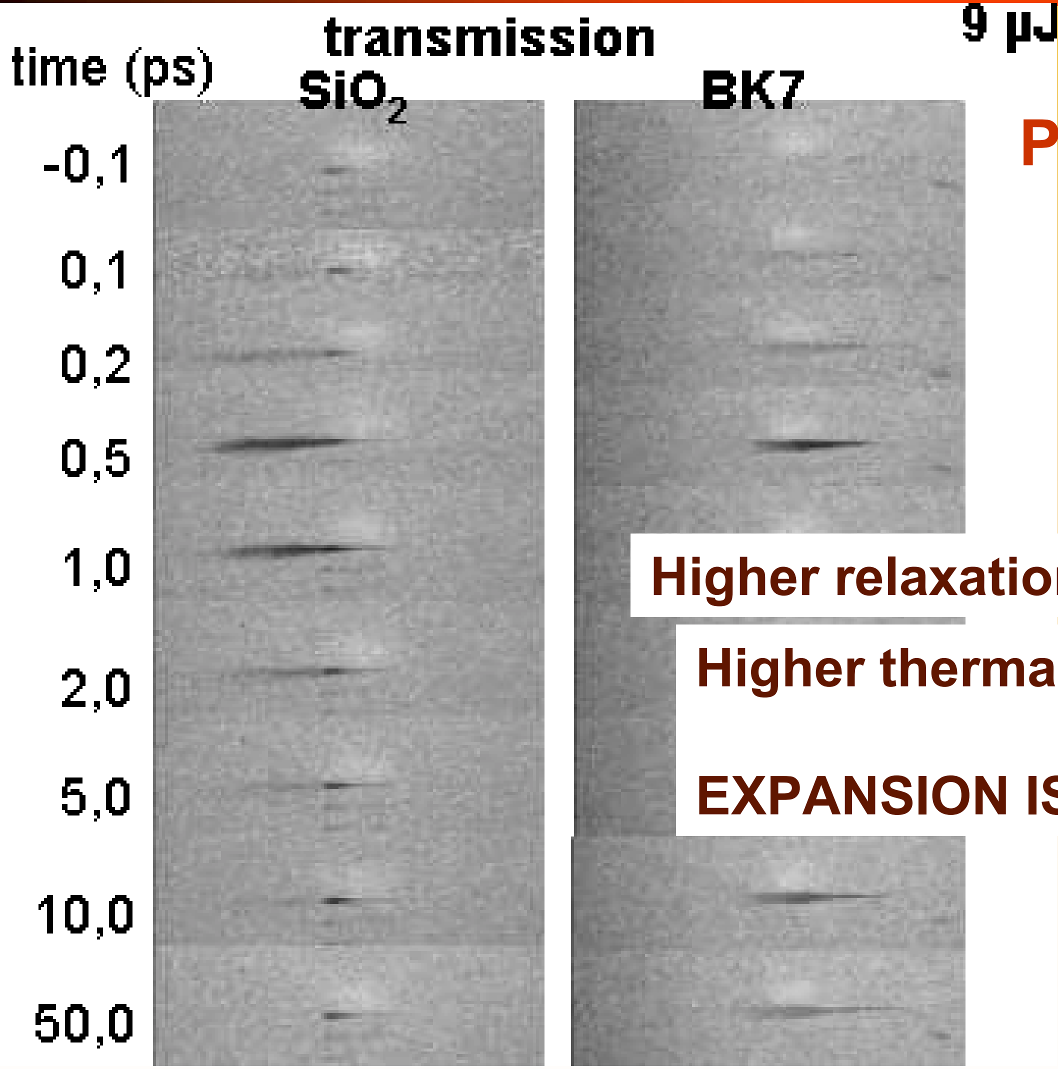
$\Delta n < 0$

Conditions: Focusing objective NA: 0.4

Energies: 0.25µJ-4.5µJ

investigations in dynamic regimes

a-SiO_2, BK-7



Plasma dynamics

Higher relaxation time for BK7

Higher thermal expansion coefficient 15x

EXPANSION IS THE NATURAL BEHAVIOR

optimizing the laser action

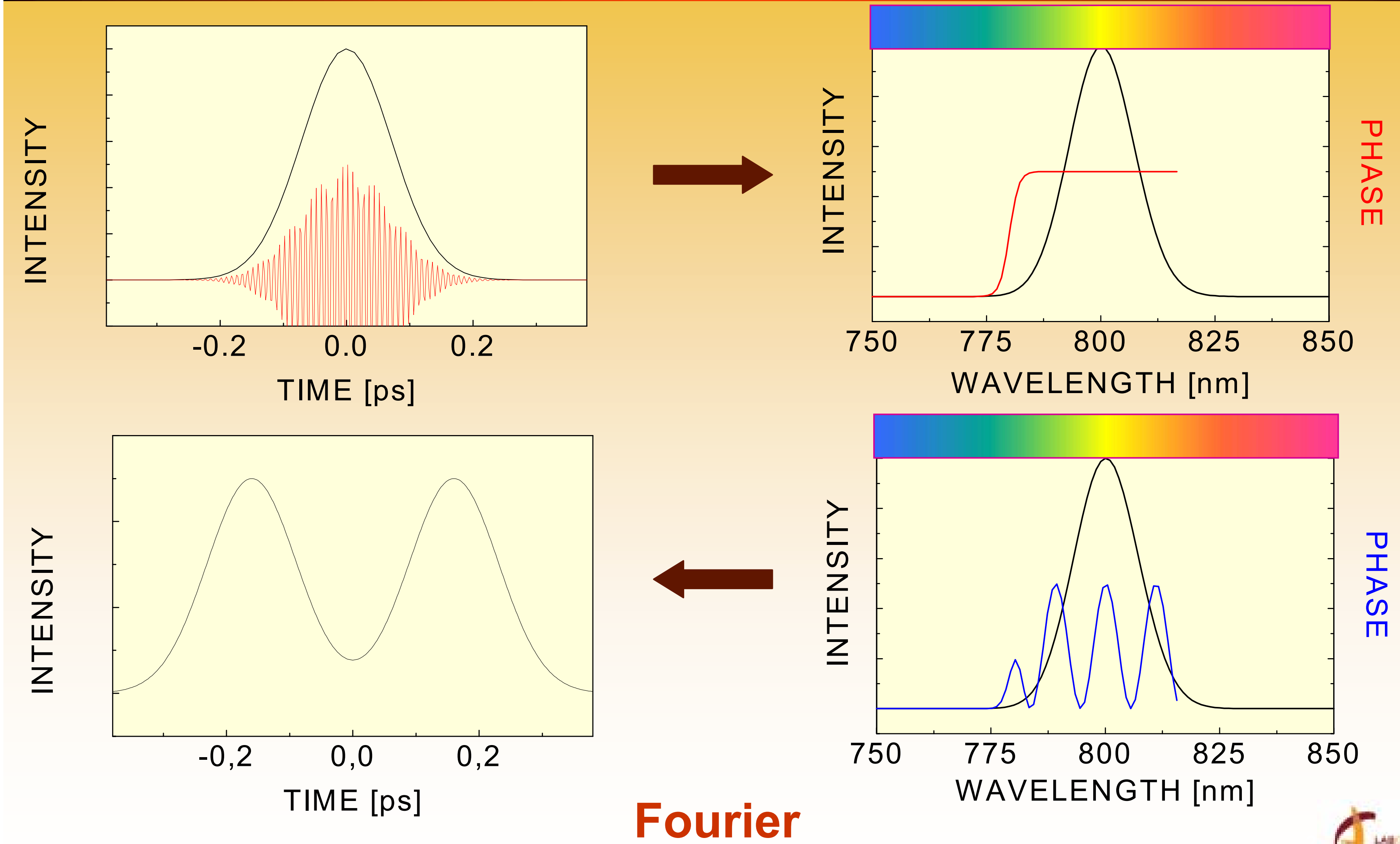
Idea

- ➪ Design radiation according to the material response

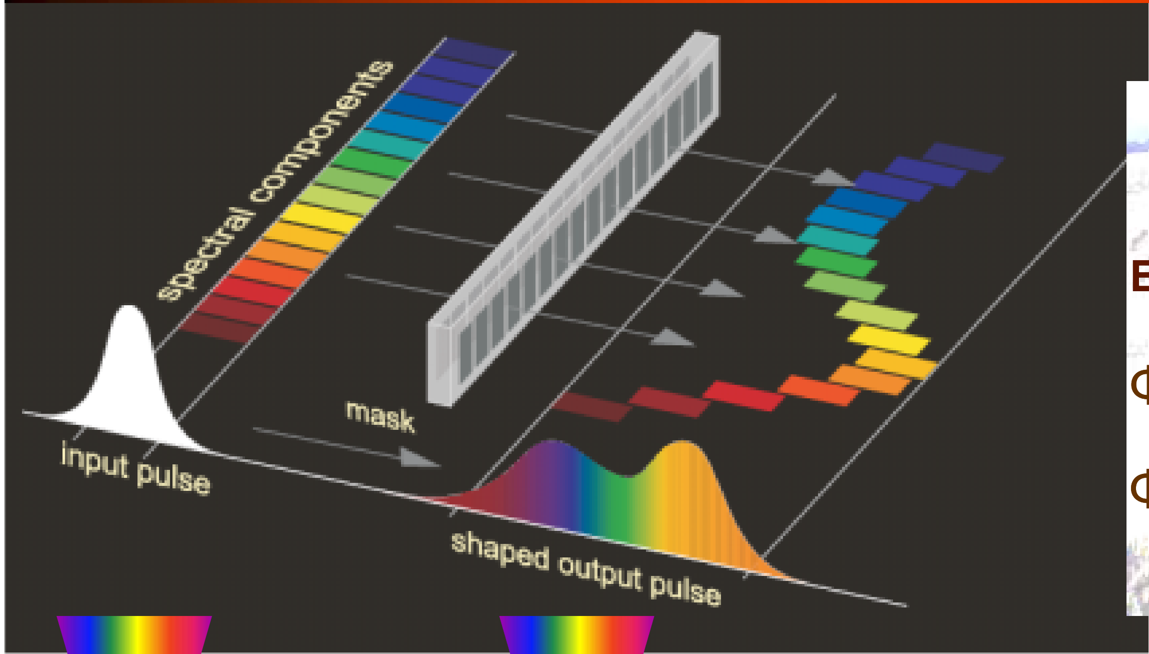
Technique

- ➪ Pulse shaping
- ➪ Optimization strategy : evolutionary algorithms

spectral modulation: temporal pulse shaping



tailoring temporal envelopes

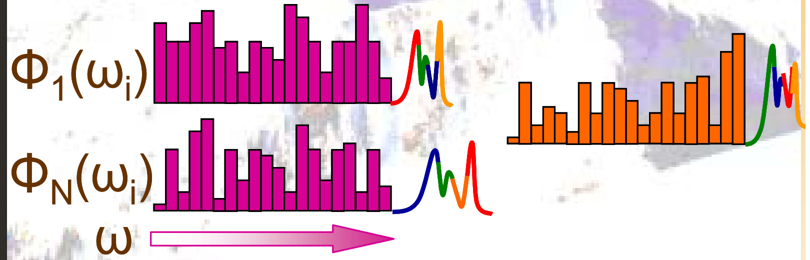


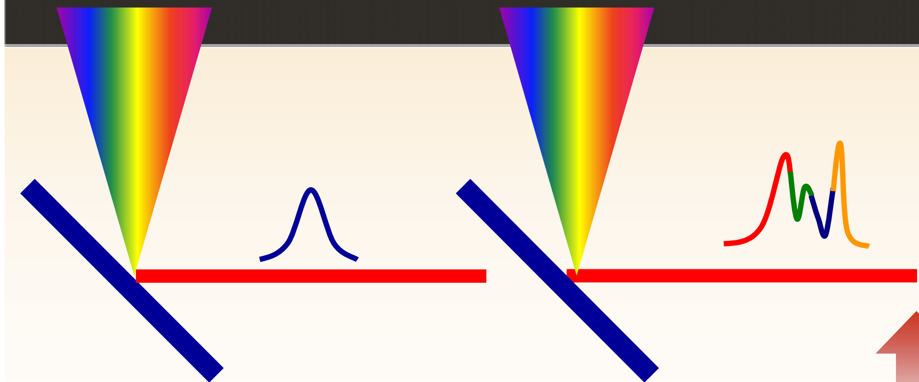
spectral filtering

complexity requires

- **-self-learning approaches for optimization**

Evolutionary approach for optimality



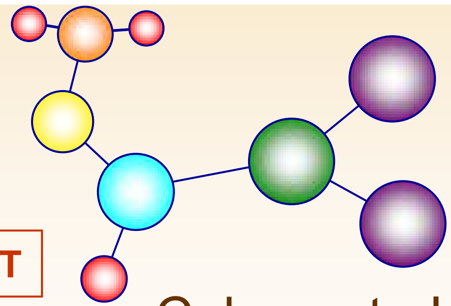


Feedback loop

EXPERIMENT

EVALUATION

PULSE SHAPER

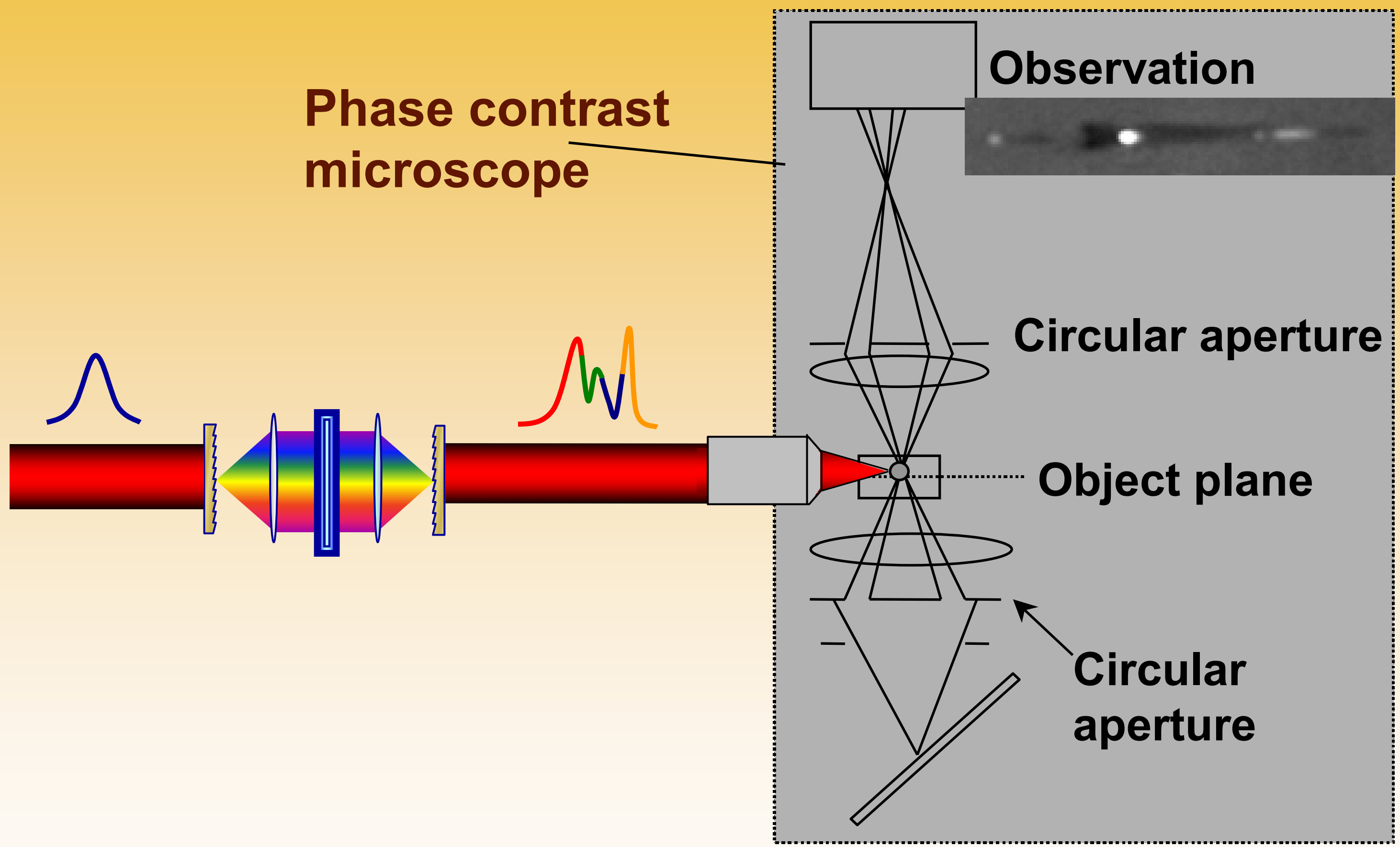


Coh. control

Wollenhaupt et al. Springer 2007

Courtesy:
T. Baumert KU
R. Trebino GT

optimizing the laser action: role of time delivery

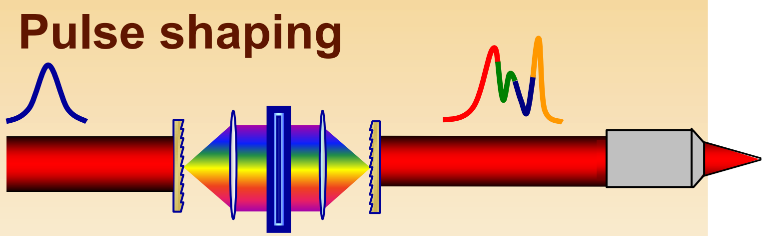


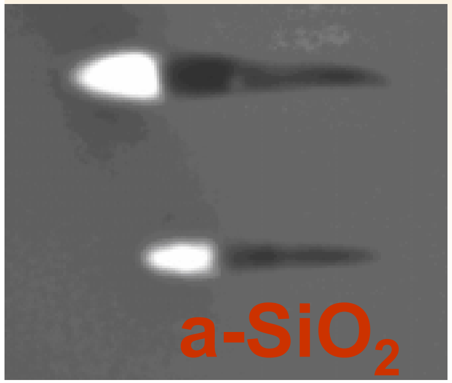
$\Delta n > 0$

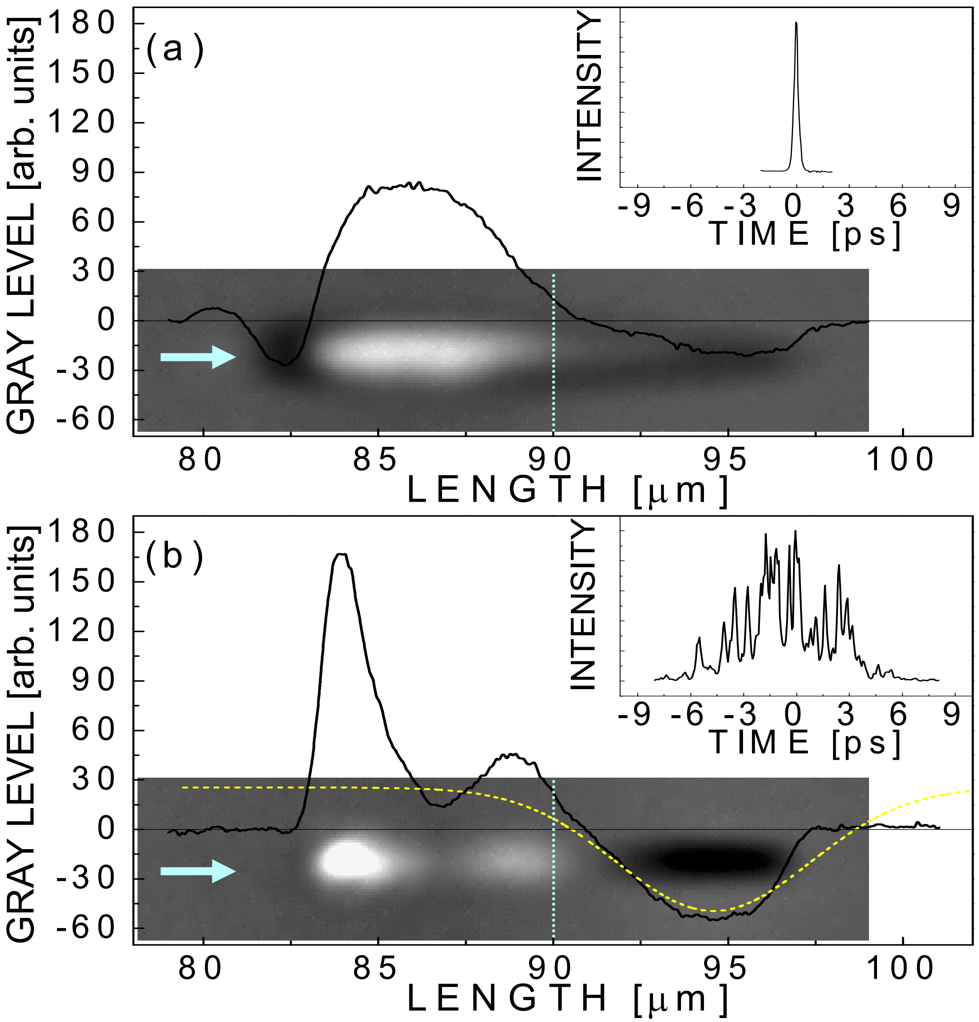
index flipping in borosilicate BK7

Experimental conditions:

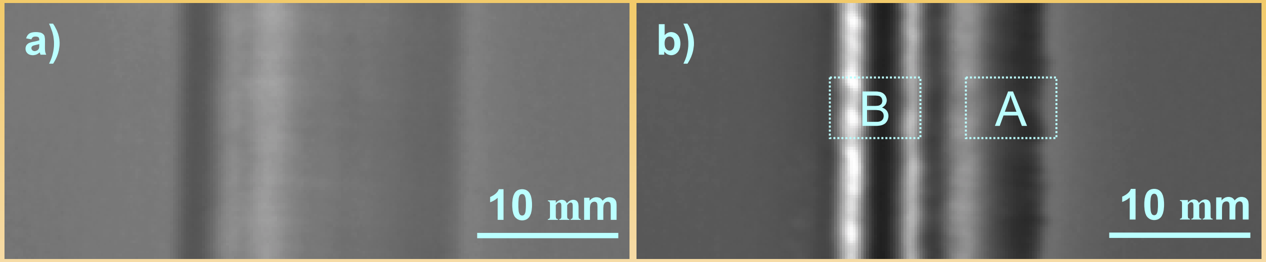
100 kHz optimization







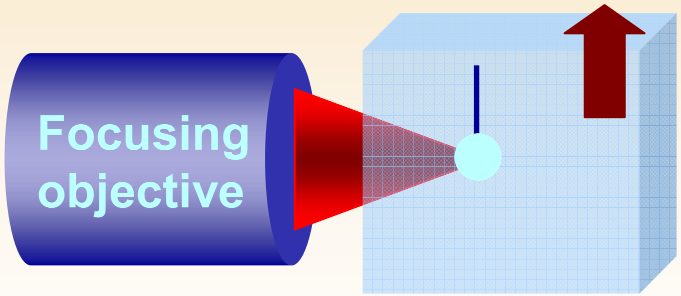
waveguide writing : BK7



SP-High E

OP-High E

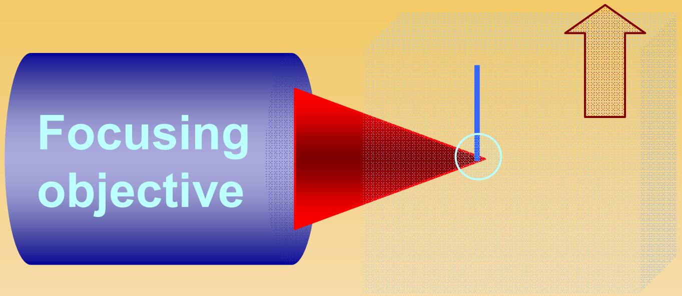
Δn>0



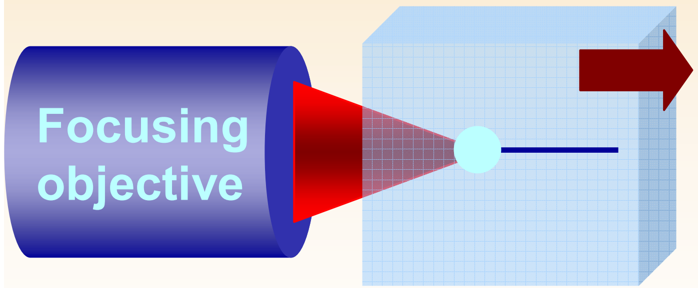
Transverse writing

IMPORTANCE OF GOOD ENERGY CONFINEMENT

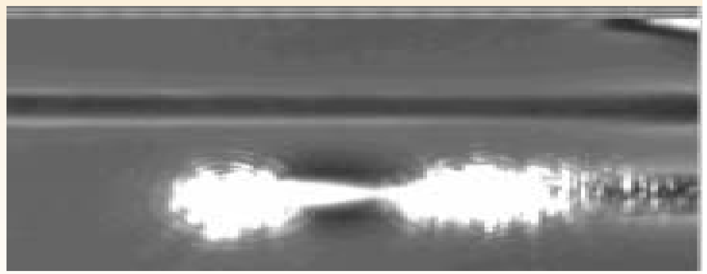
waveguide writing techniques



Transverse writing



Longitudinal writing

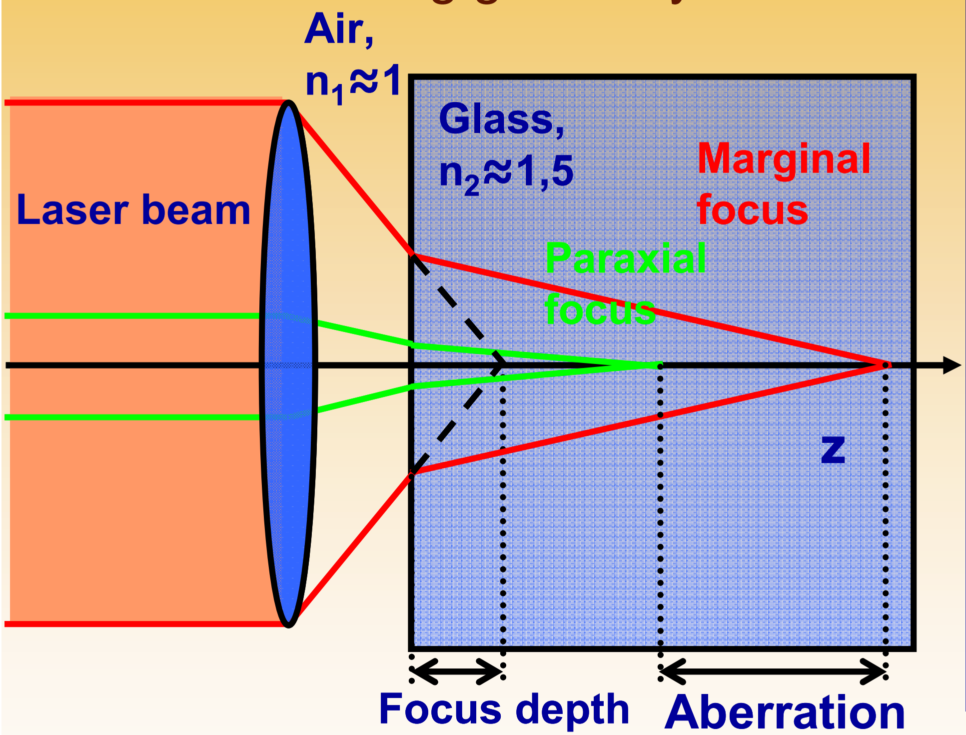


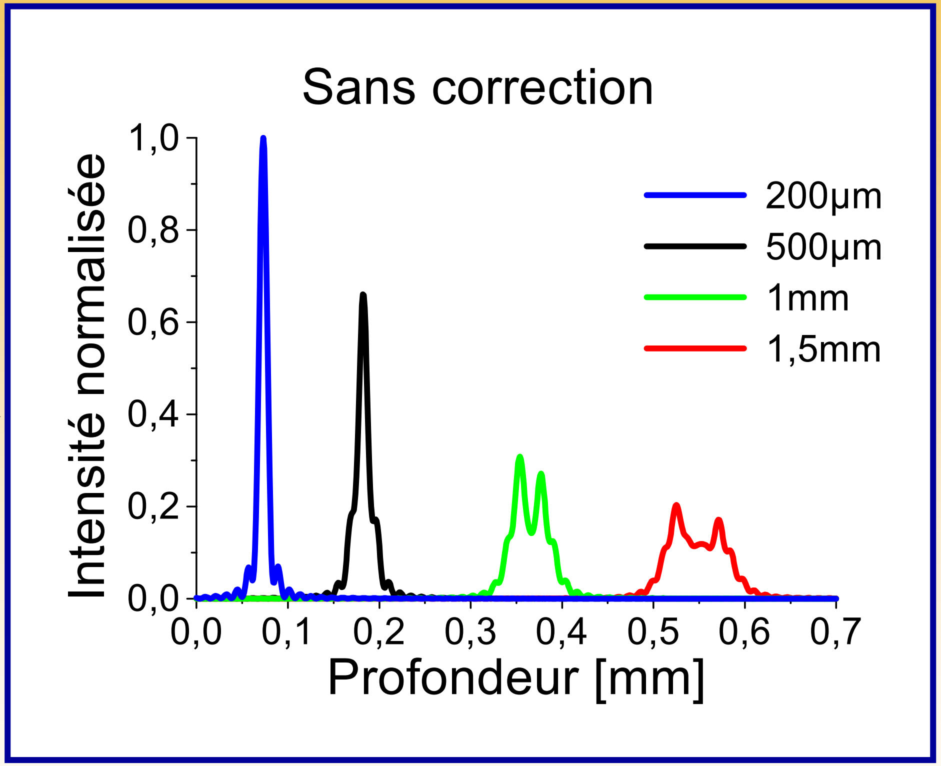
Keeps the symmetry of the beam

aberrations

Focusing air-dielectric :

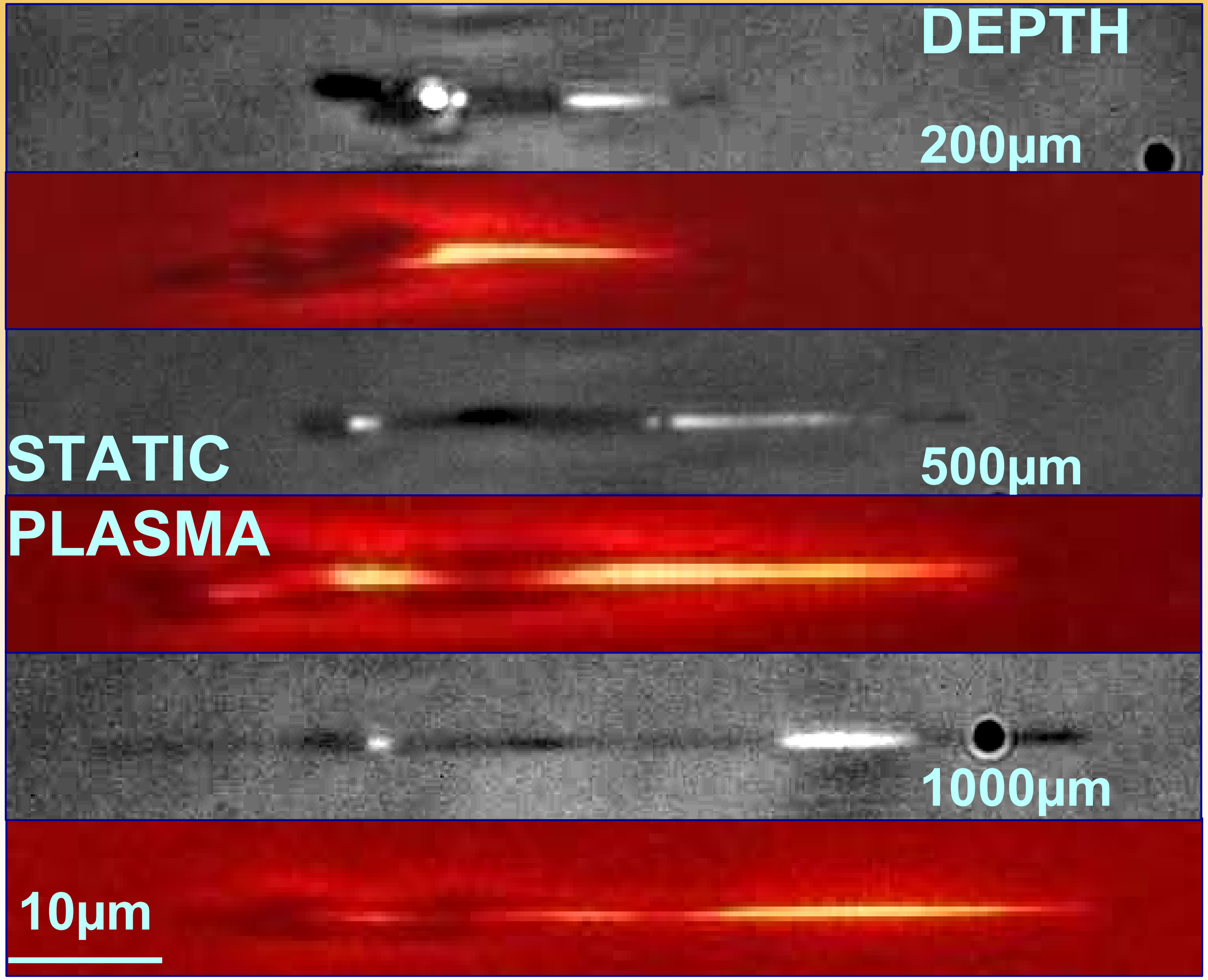
- Focusing geometry





Focus elongation: bad photoinscription quality

aberrations a-SiO_2

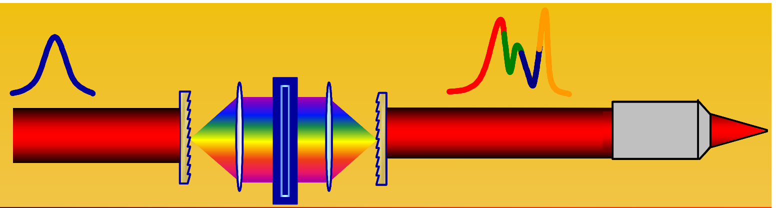


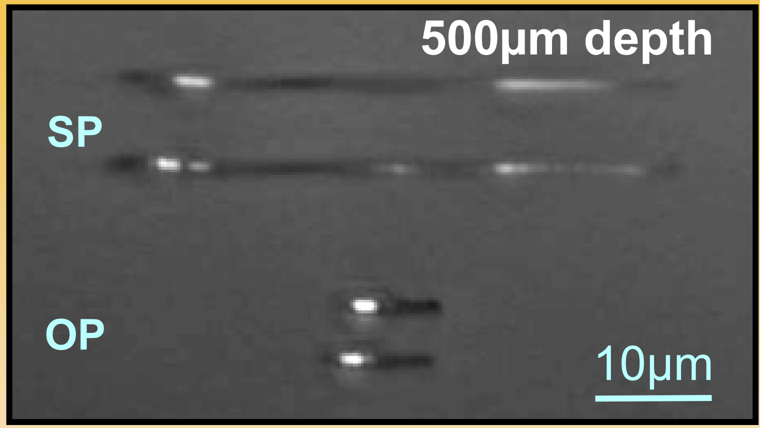
-Size: longitudinal aberration
-Modulation: NLO propagation

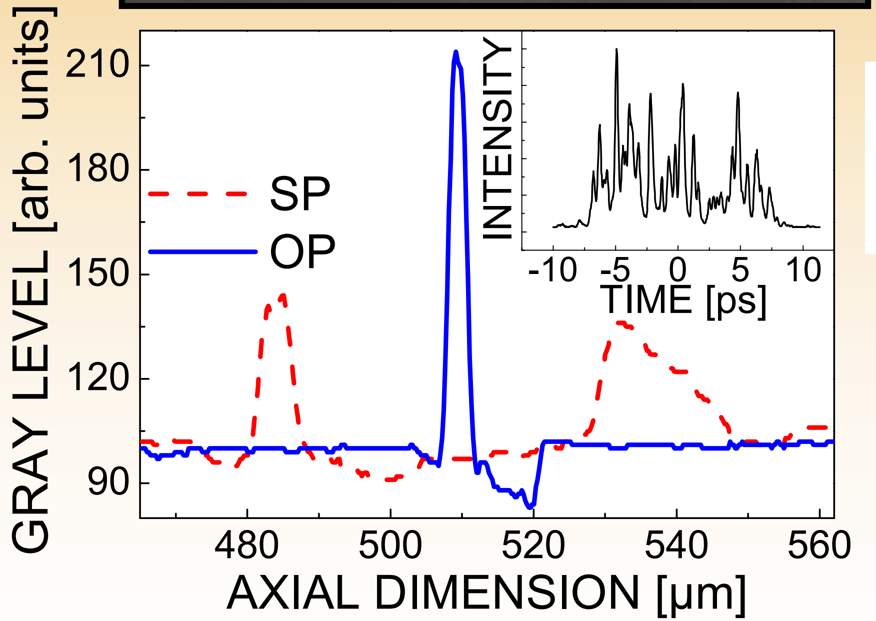
↓

Intensity factor

energy confinement







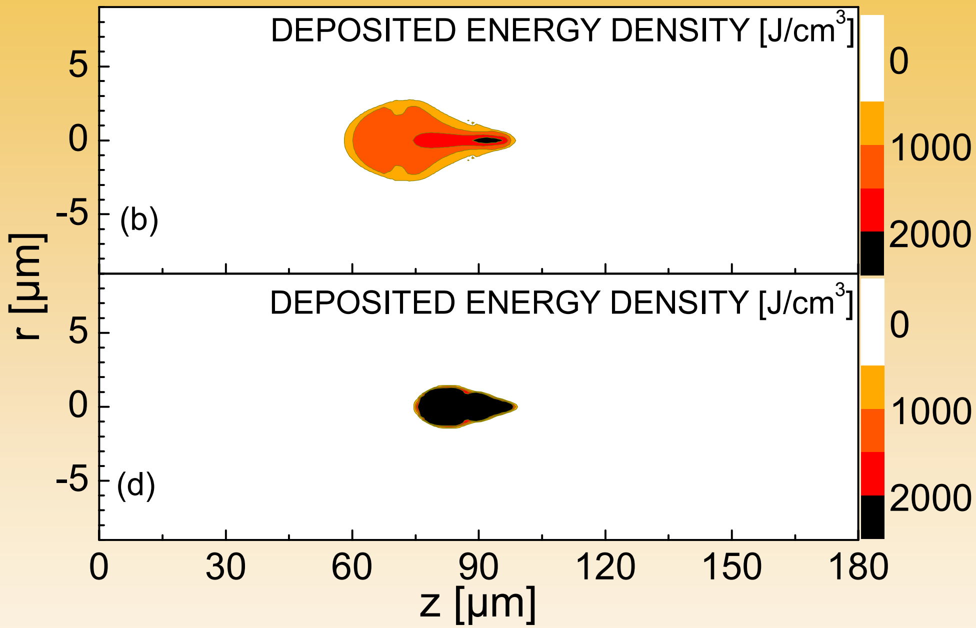
TIME CONTROL

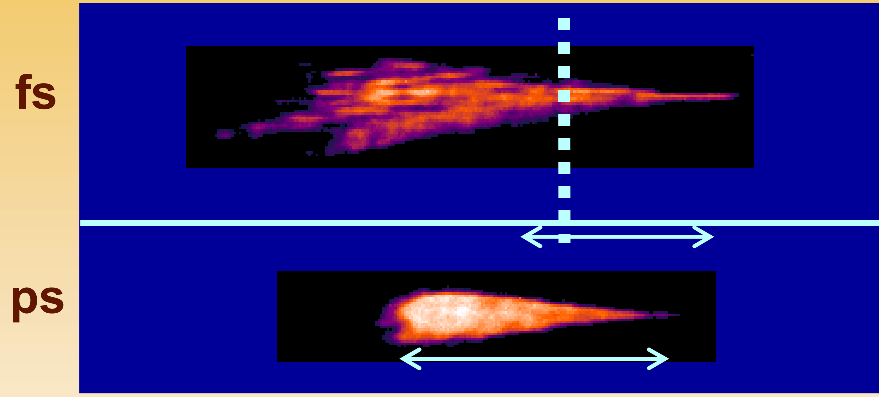
Features:
-multi peaks
-long envelope

Mermillod et al. APL 2008

propagation control

NLO propagation code





Reduced nonlinearity

-Less self focusing
-Higher threshold

Delayed plasma

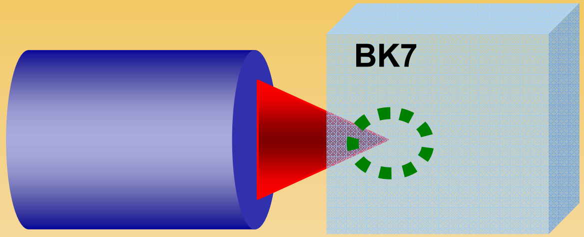
-less defocusing

Energy confinement determines: Temperature, Pressure

Q4: again, how about other glasses?

energy density regimes: BK7

Huot et al. OE 2007
Mauclair et al. OE 2007



Compression shell

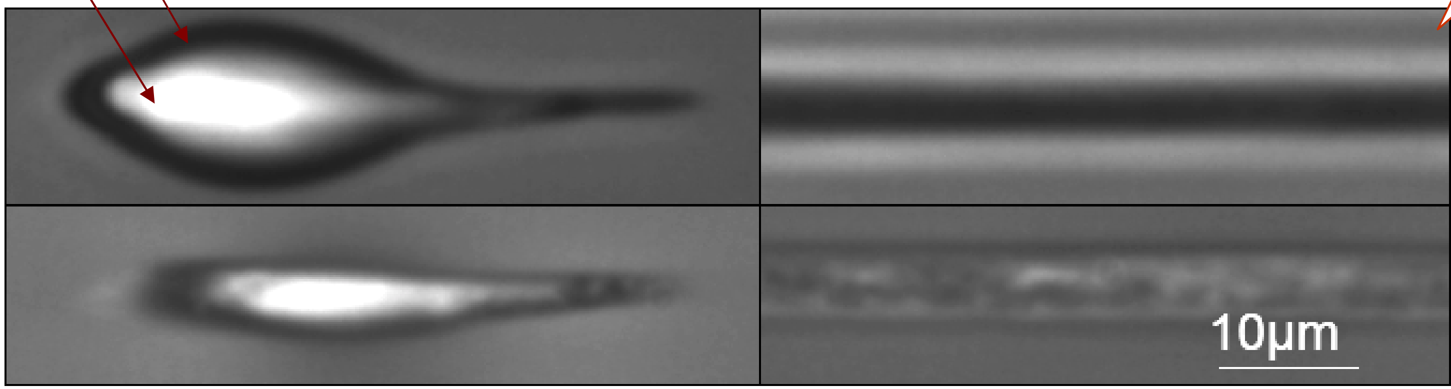
Rarefaction core

Requires high energy density

Keep it

190mW

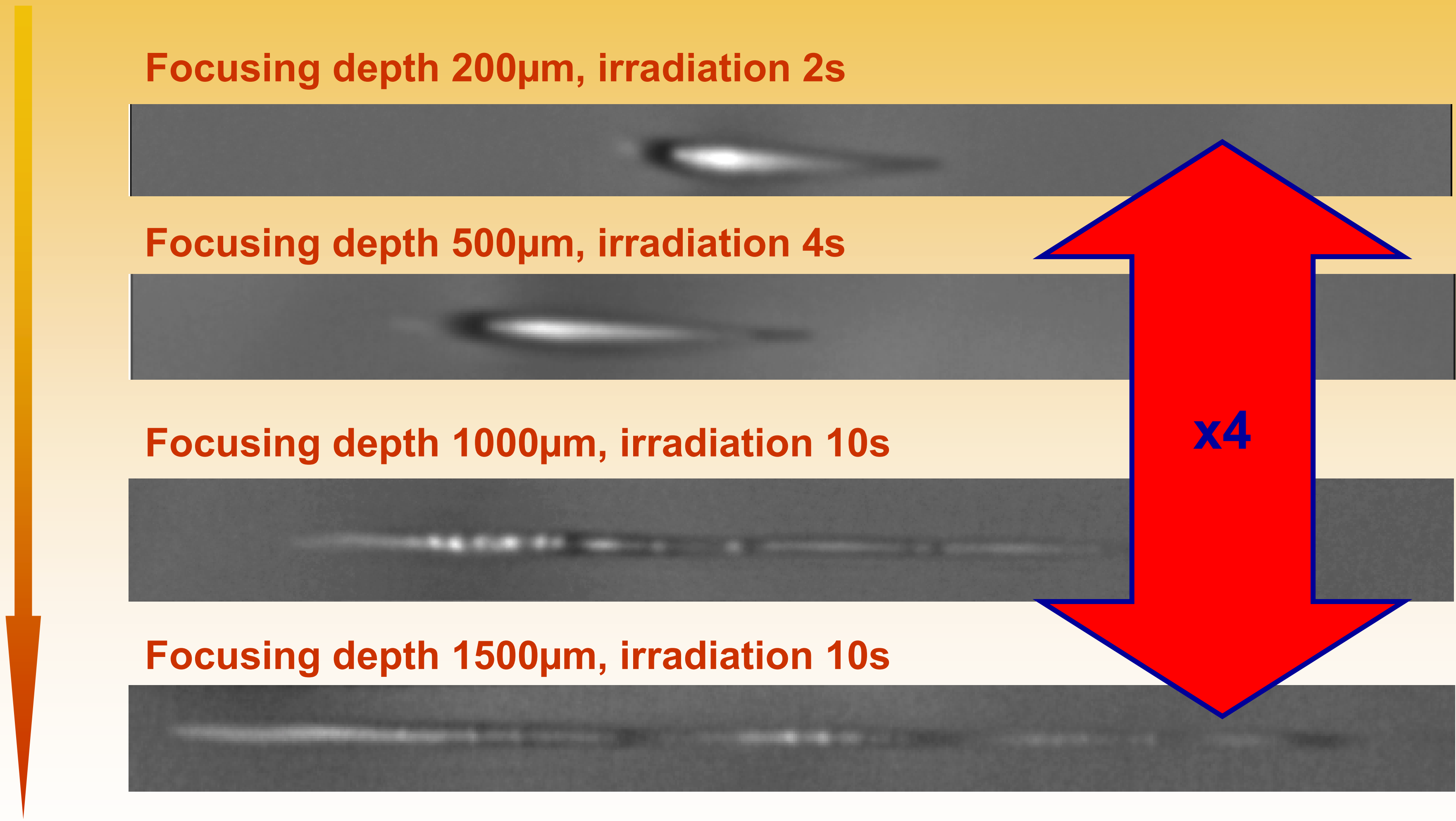
125mW



Δn>0

Δn<0

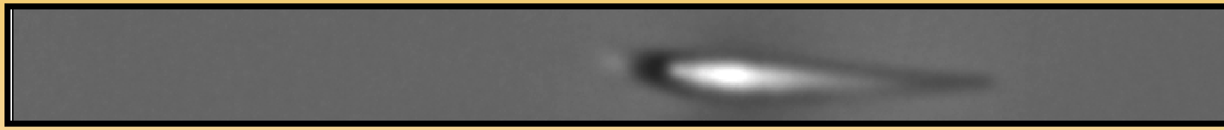
aberrations BK7: deep focusing

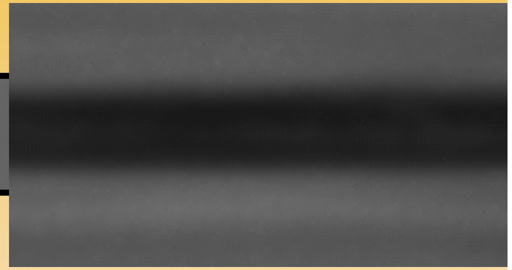


Energy density gets lower

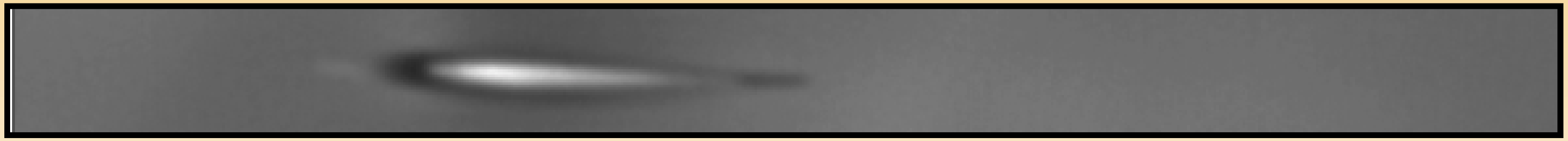
aberrations BK7: deep focusing

Focusing depth 200µm, irradiation 2s

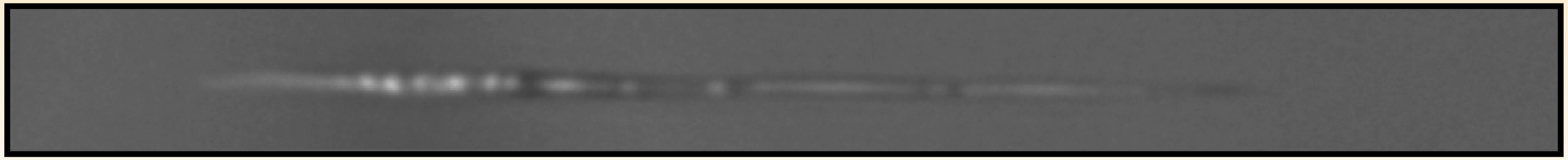




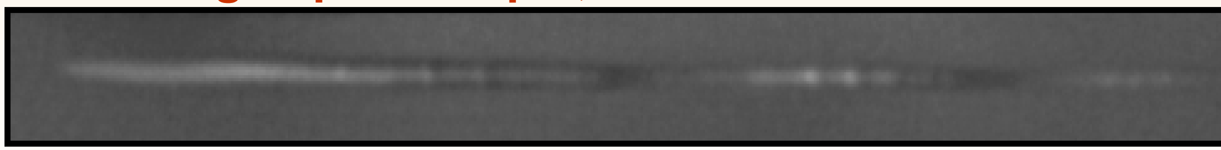
Focusing depth 500µm, irradiation 4s

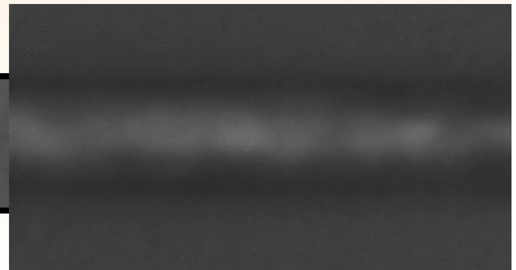


Focusing depth 1000µm, irradiation 10s



Focusing depth 1500µm, irradiation 10s





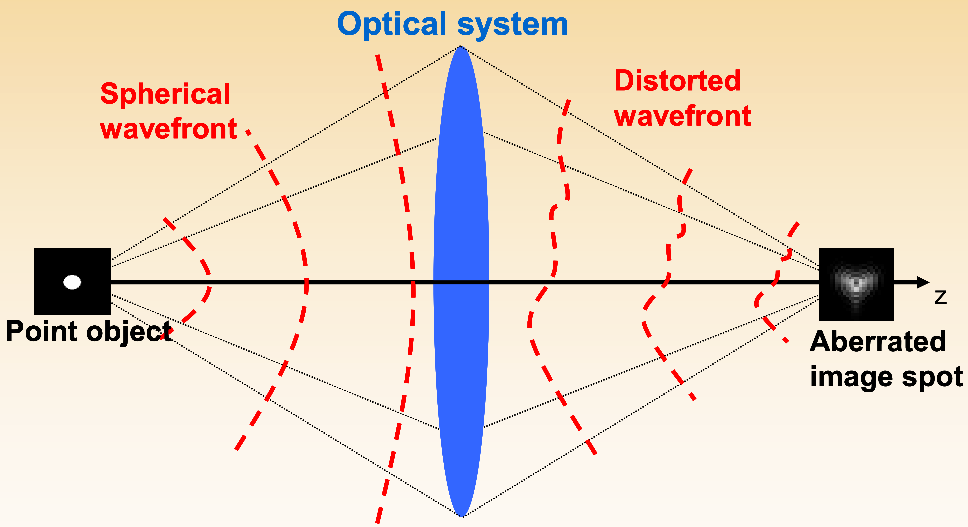
Energy density gets lower

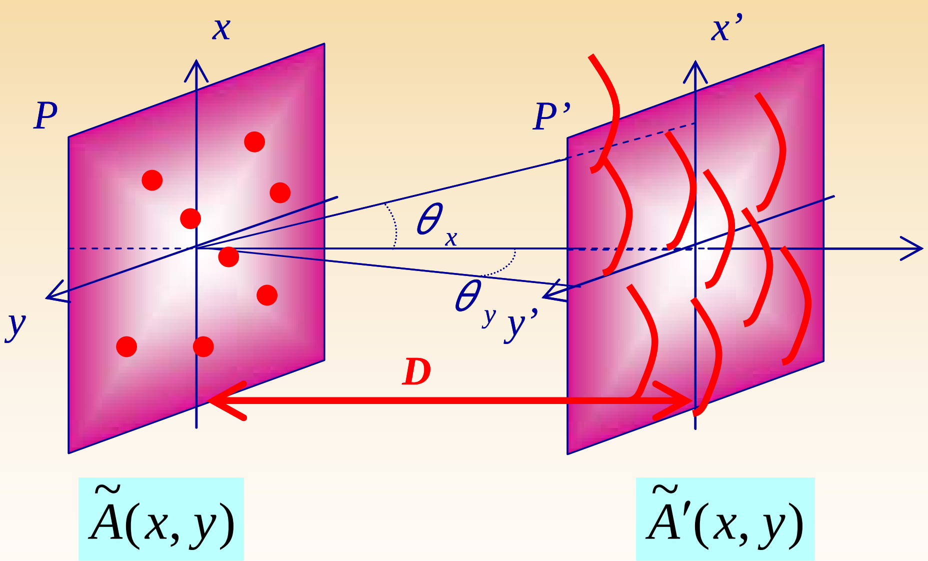
Spatial beam shaping

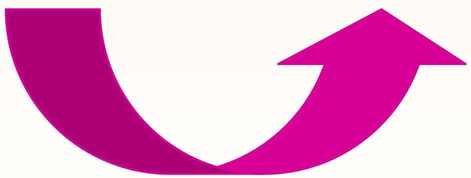
Since: wavefront distortion!!!

Natural solution: wavefront engineering

SPATIAL ADAPTIVE OPTICS





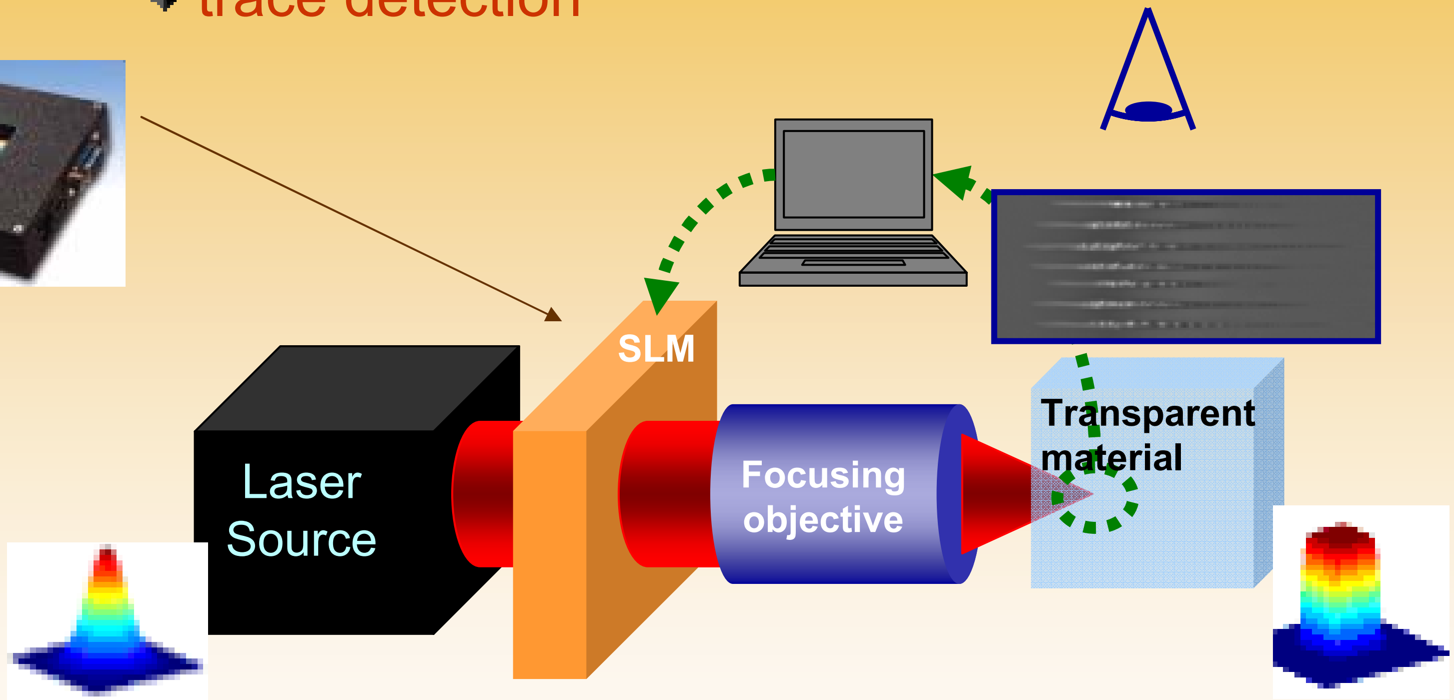


corrections of aberrations: spatial phase

Spatial shaping

Evaluation:

- trace detection

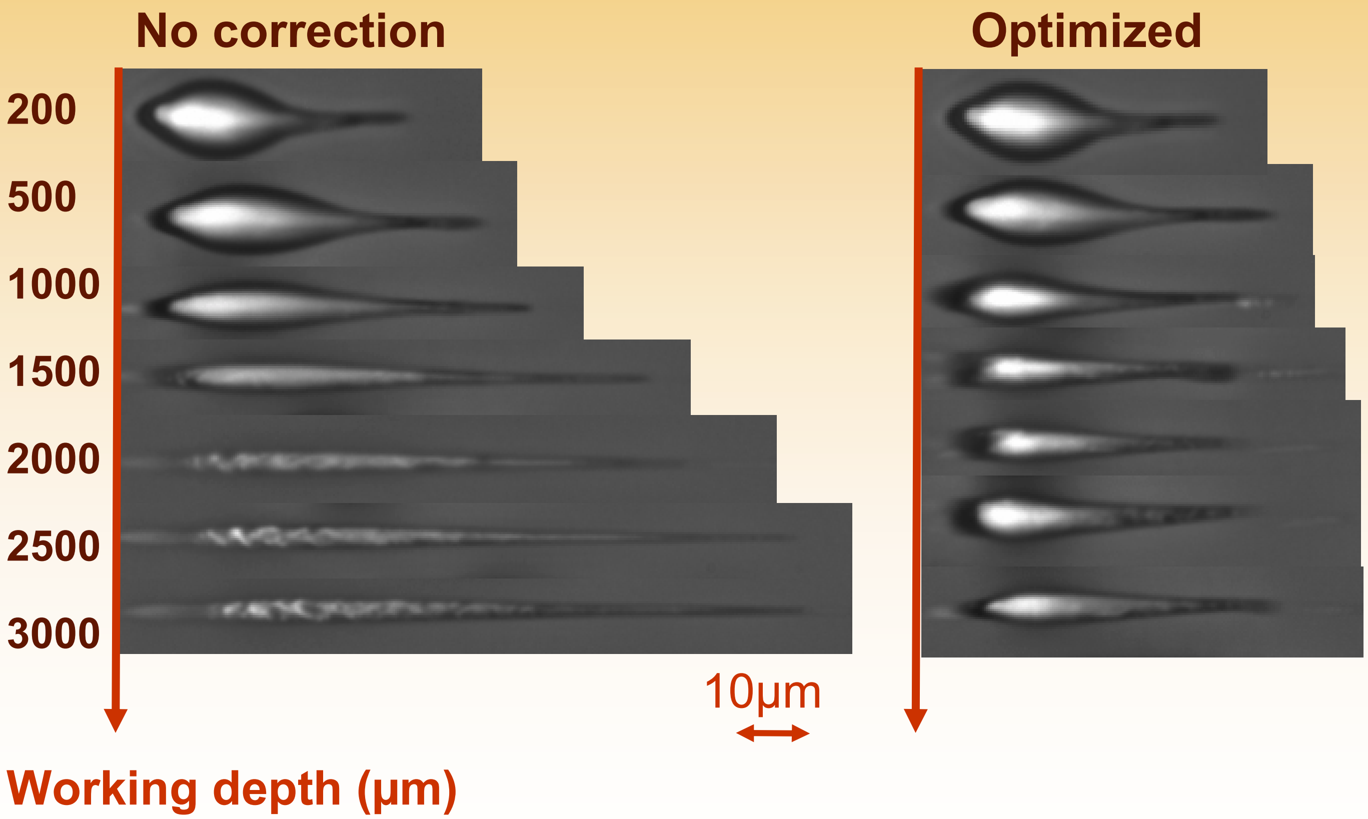


Correction of spherical aberrations:

- Image treatment
  - Length of the trace=fitness

corrections of aberrations BK7

Power:	≈200mW
Pulse duration:	180fs
Repetition rate:	100kHz
Exposition:	1s

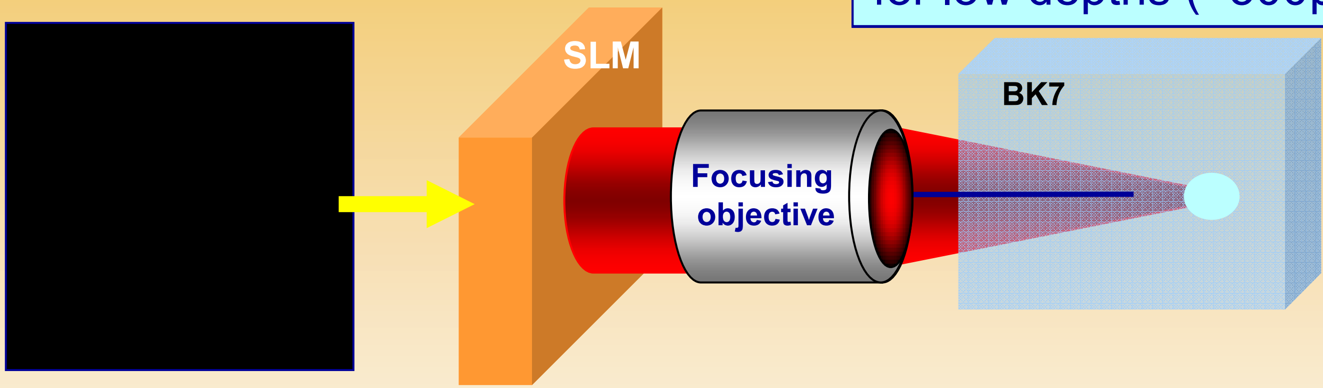


corrections of aberrations BK7

Photowriting waveguide with dynamic correction

- Time-evolutive phase mask

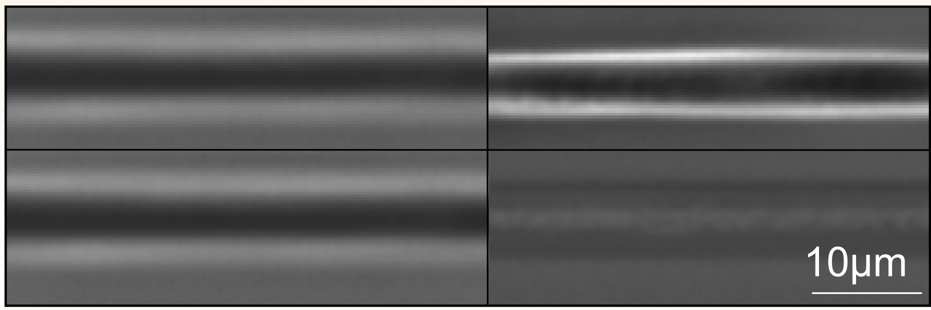
Displaying gray phase mask for low depths (<500µm)



200µm deep | 3mm deep

Corrected

Non-corrected



Mauclair et al. OE 2008

refractive index changes

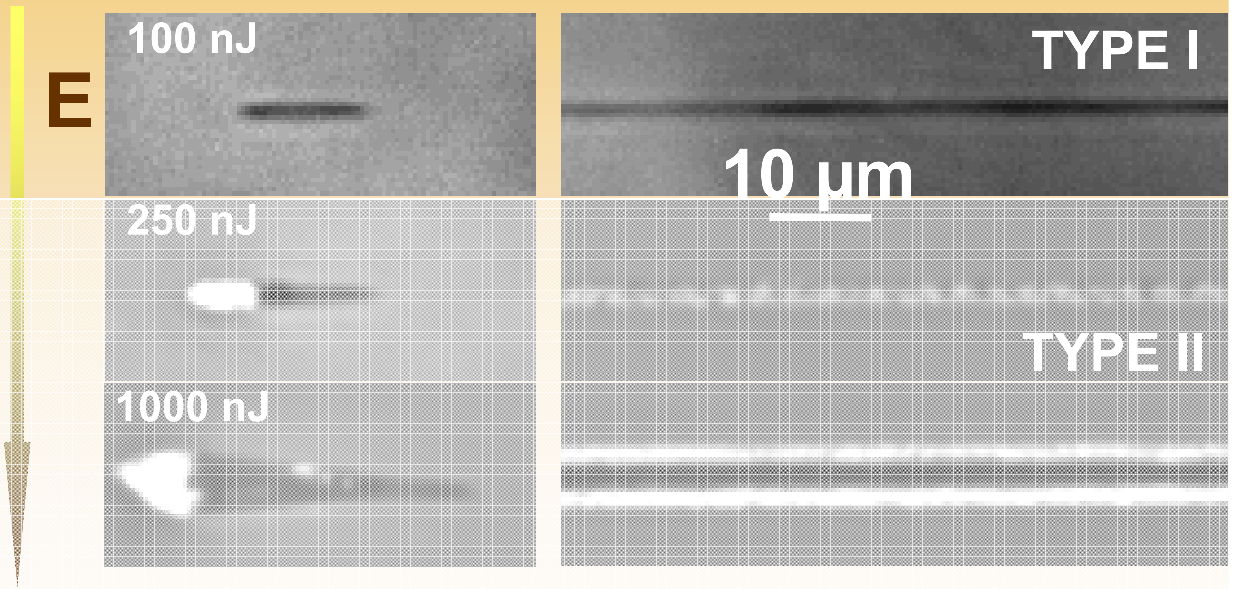
Q5: the energy density is important

Energy density is important!!!
-regulates the physical excitation
-determines relaxation paths

energy density regimes: a-SiO_2

Phase contrast

NA: 0.45 - 150 fs



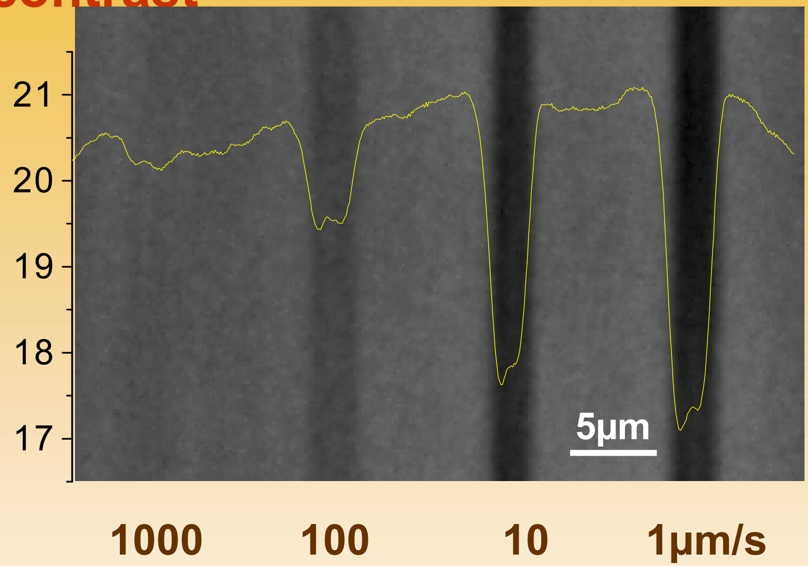
Black $\Delta n>0$ enables guiding - core

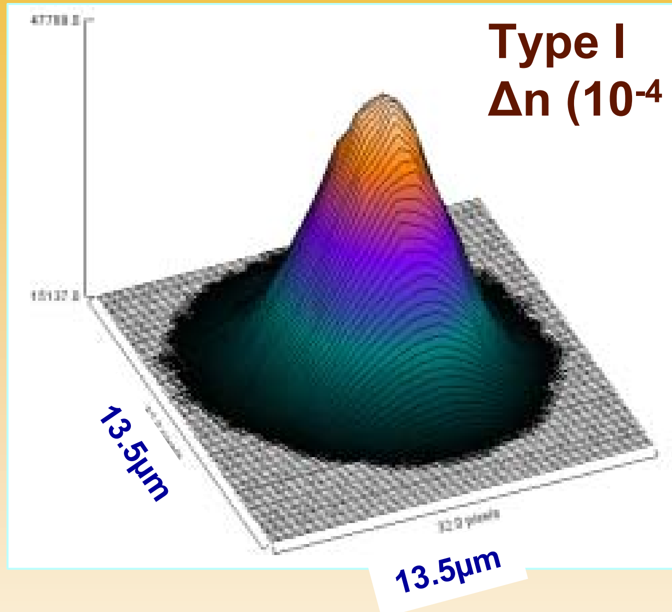
White $\Delta n<0$ defines guiding -cladding

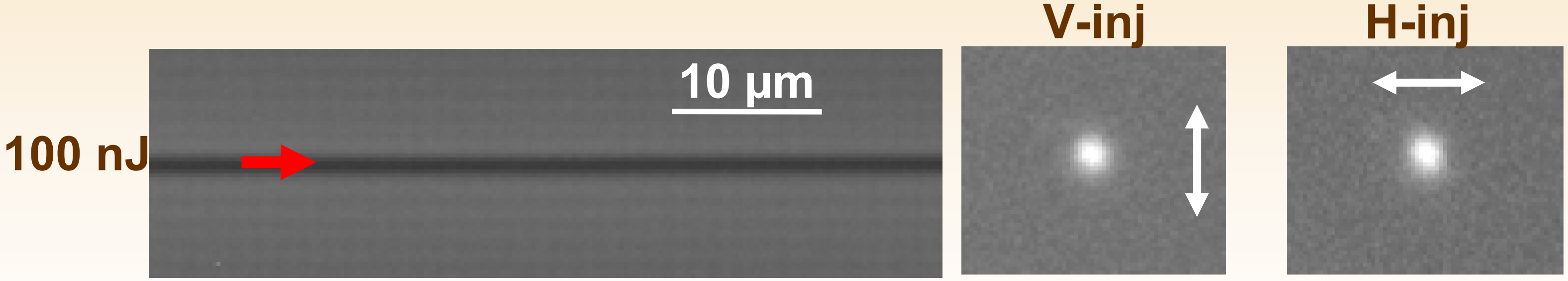
type I regime: a-SiO_2

Optical functions

Phase contrast





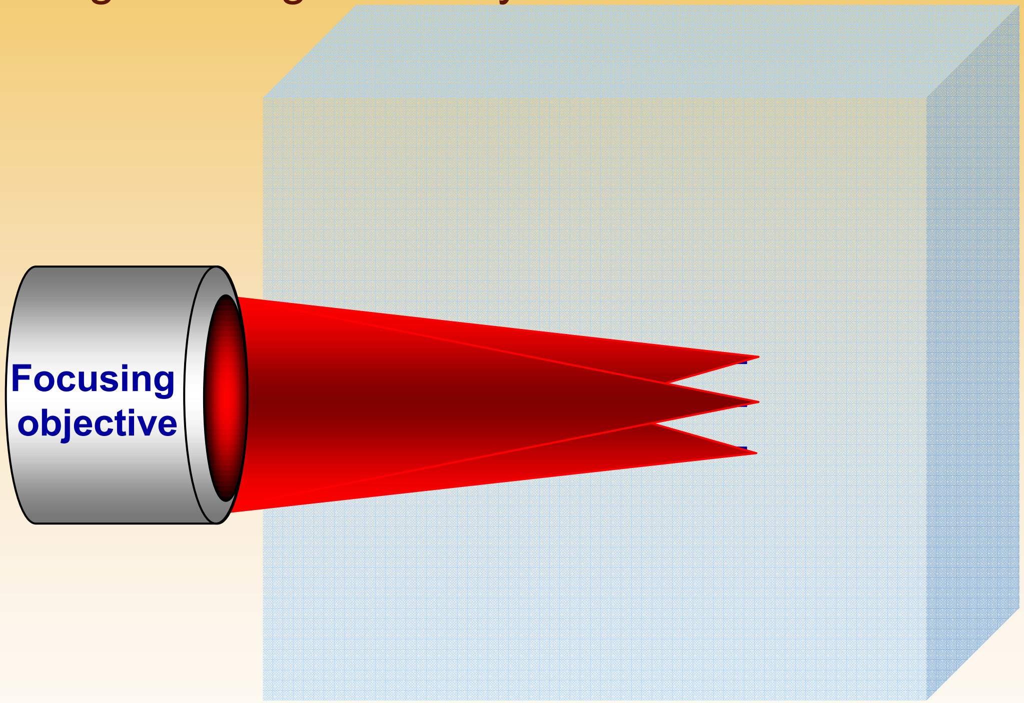


NO STRONG POLARIZATION SENSITIVITY
ISOTROPIC OPTICAL GUIDING
LOW LOSSES <0.5dB/cm

multispot processing: efficiency

Multispot operation (MSO):

Example: writing a waveguide array



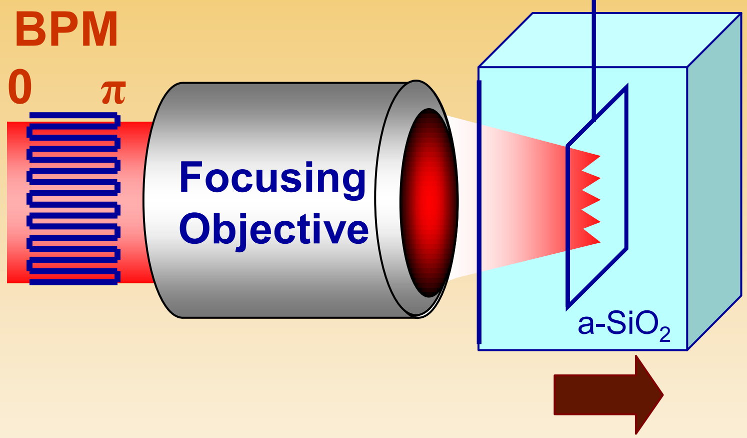
Lower processing time

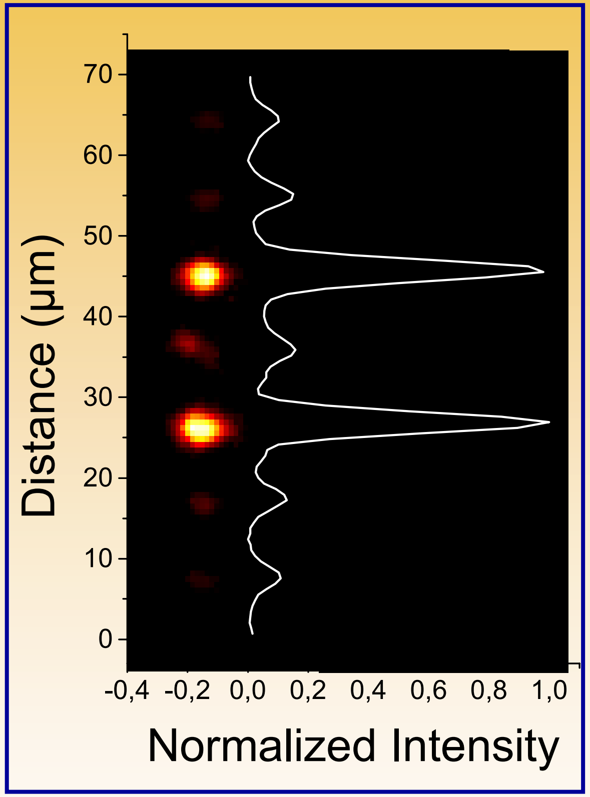
Simplify the motion scheme

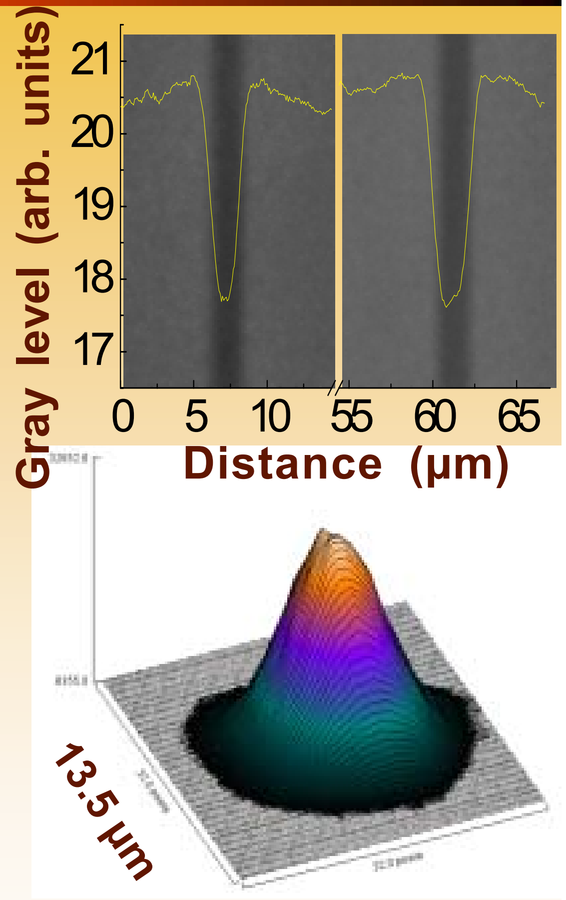
Interesting propagation effects in discrete spaces

Szameit et al, OE, OL, PRL, Nat. Photonics 2005-2009

multispot processing: a-SiO_2



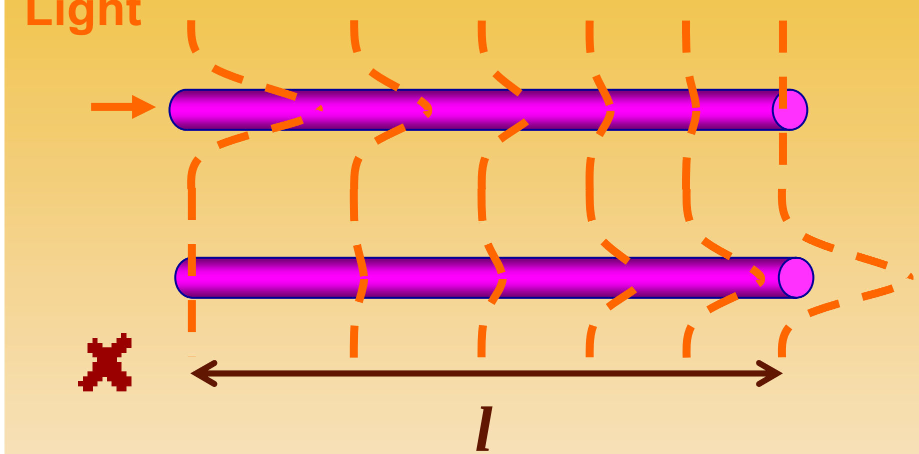




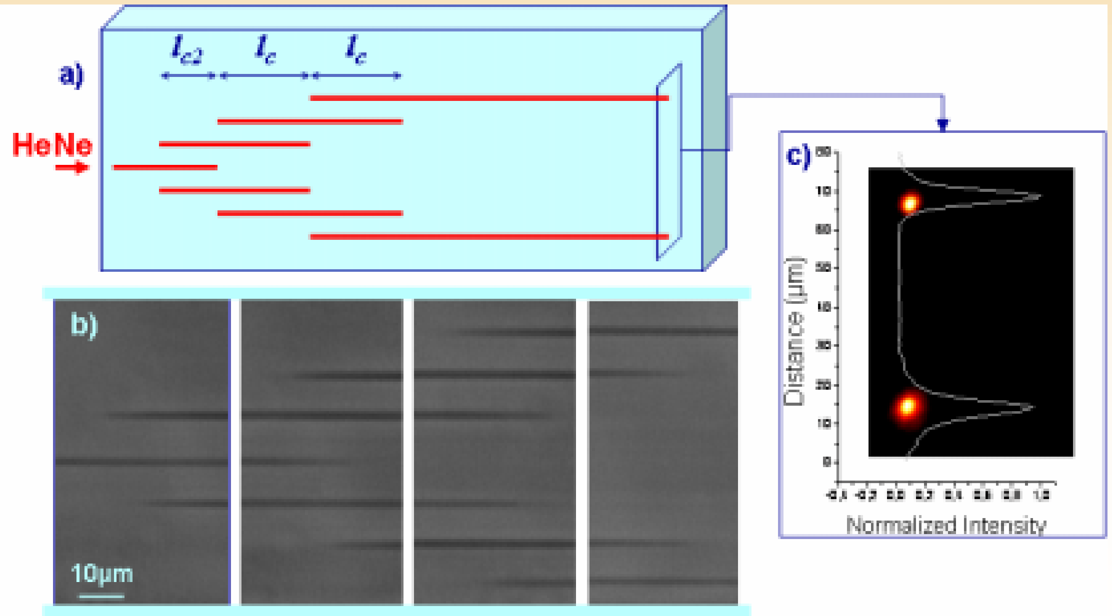
Losses < 0.7 dB/cm

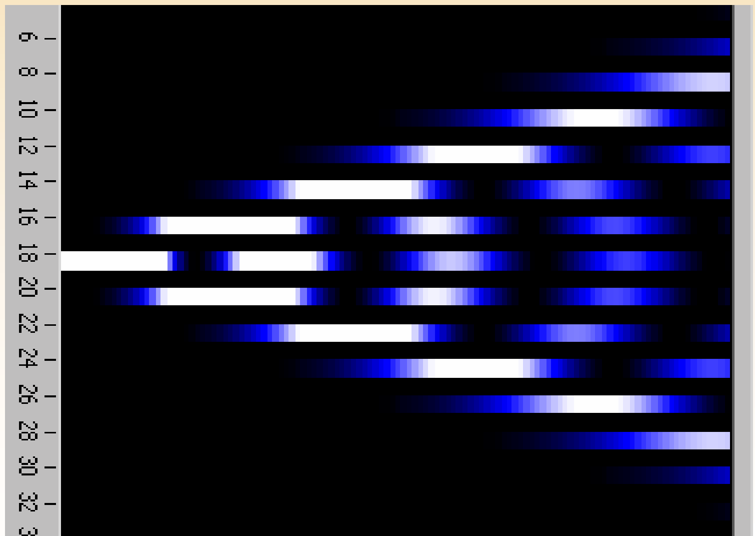
Mauclair et al. OE 2009

optical functions: light coupling & division

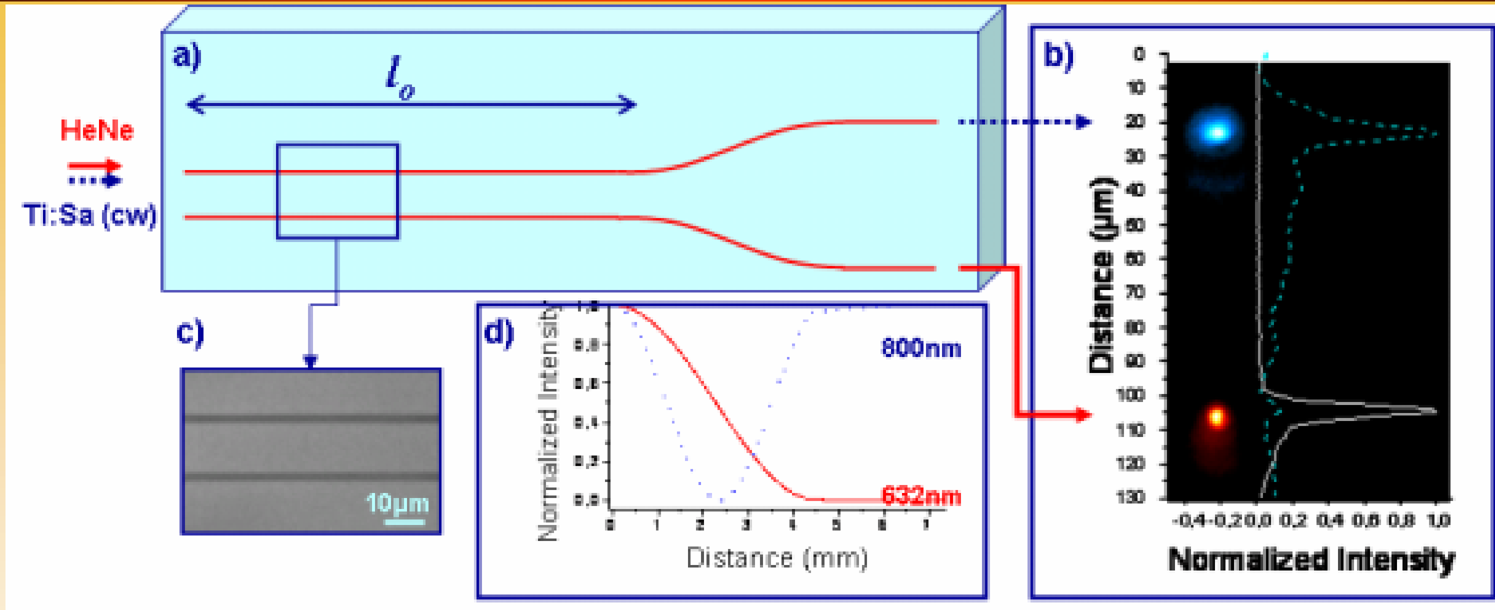


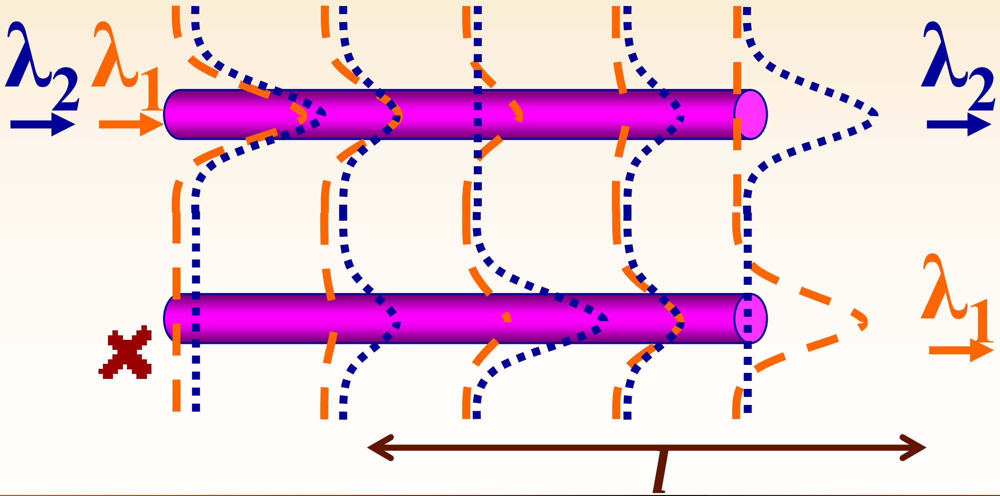
Evanescent mode coupling





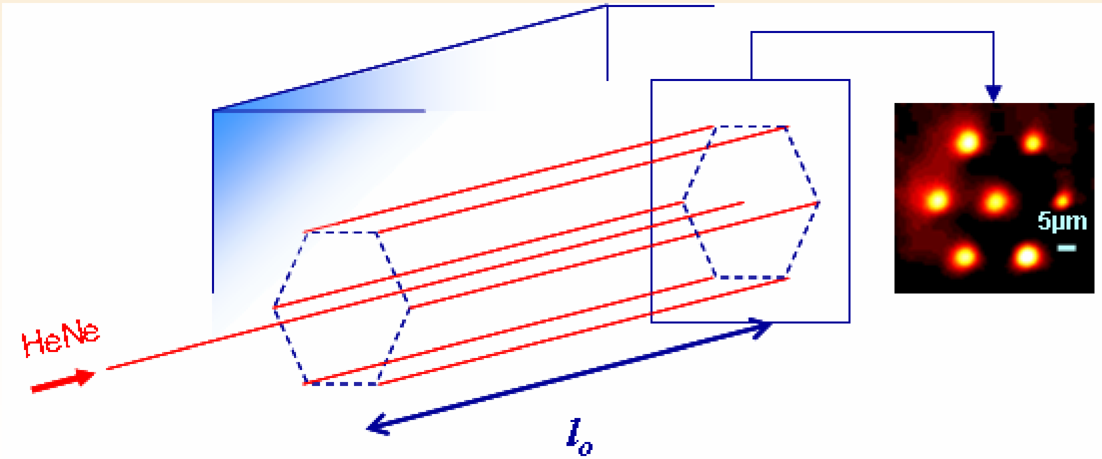
optical functions: light coupling & multiplexing





Evanescent mode coupling ~ λ

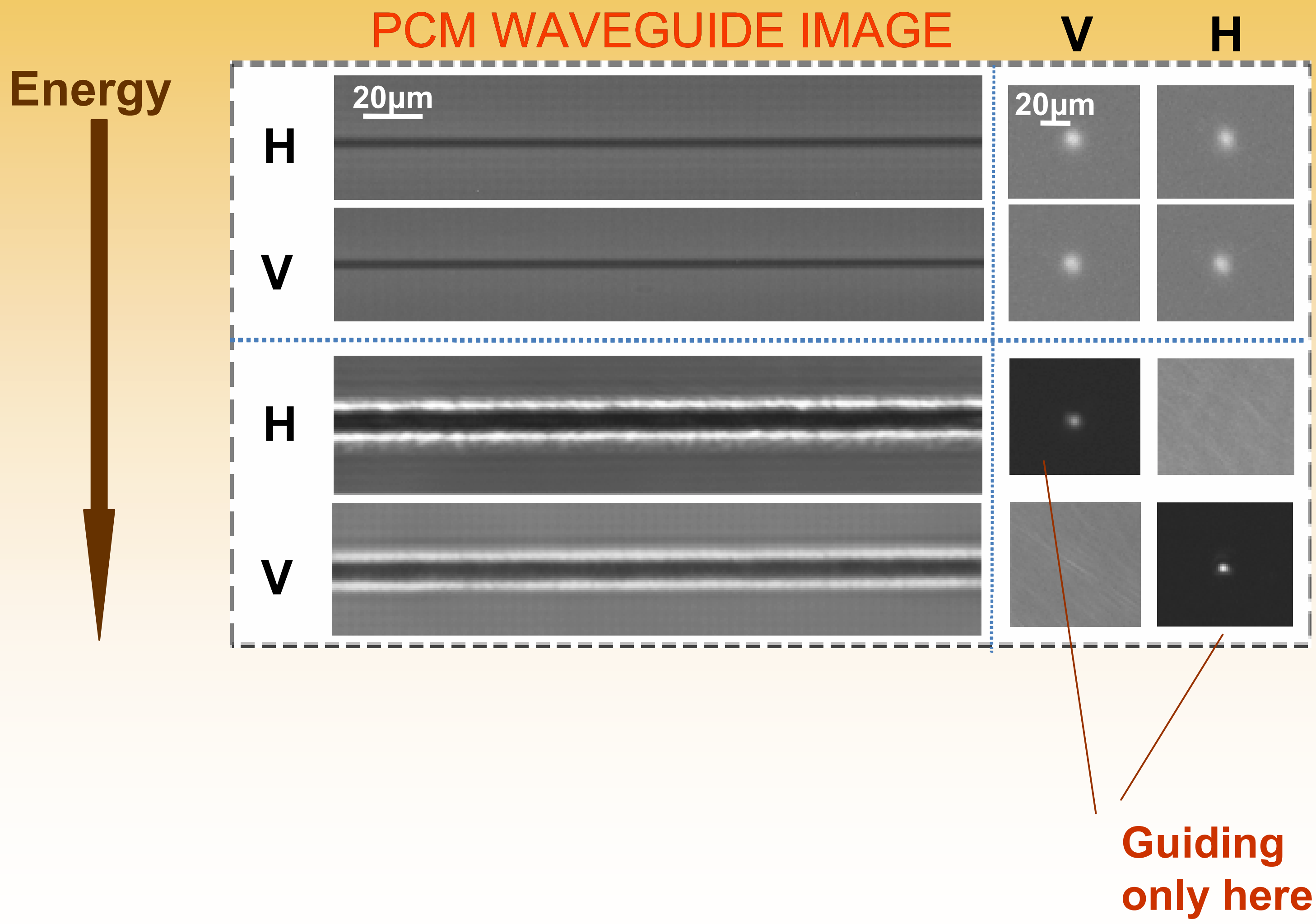
3D periodic structure



refractive index changes

Q6: not the whole story

role of polarization: a-SiO_2



Type I
Isotropic guiding

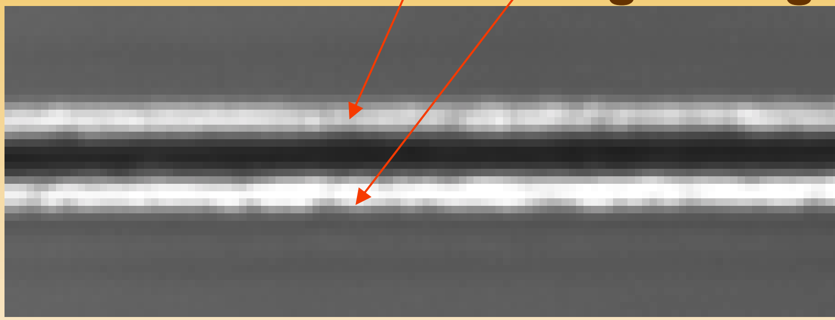
Type II - WG
Polarization sensitive

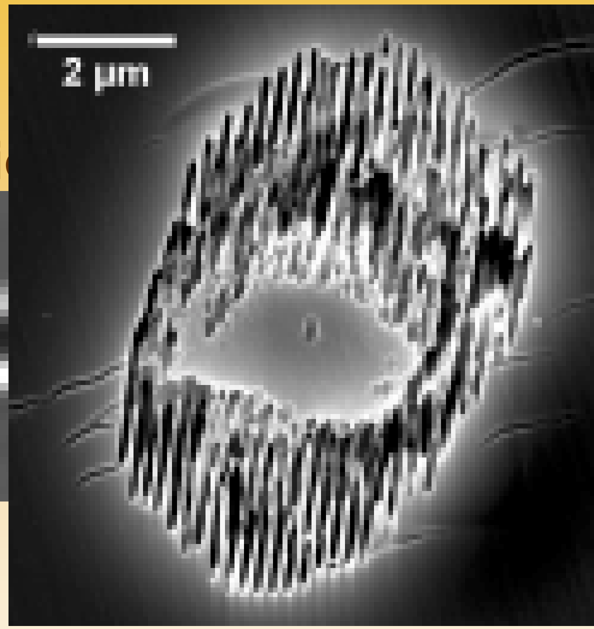
anisotropic regimes: a-SiO_2

ore $\Delta n>0$

Birefringent regi

125 mW





Type II

Λ=250 nm

$\lambda/2n$

E

20 mW

Shimotsuma PRL 2003
Bhardwaj PRL 2006

Guiding when E is parallel to the planes

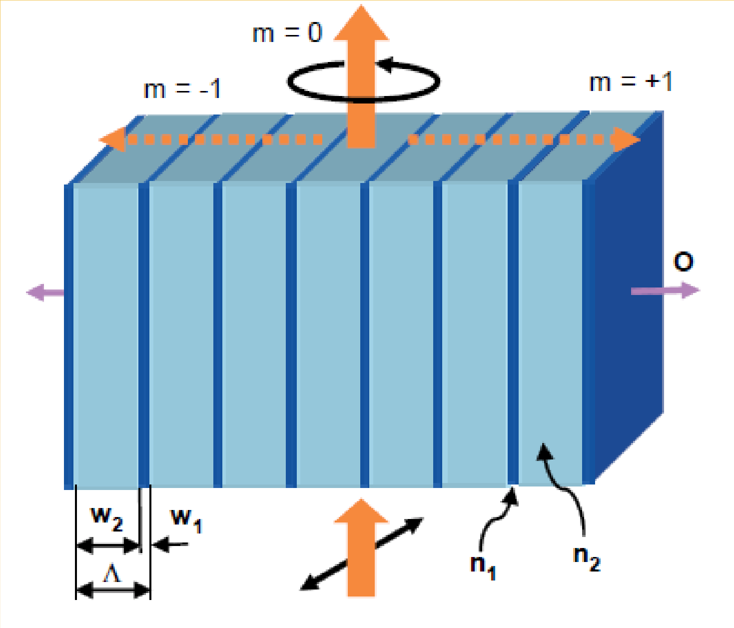
Cladding: form birefringence

Cheng et al. OE 2009, 2010

optical functions: a-SiO_2

•Birefringence: subwavelength structures

-define ordinary, extraordinary axes



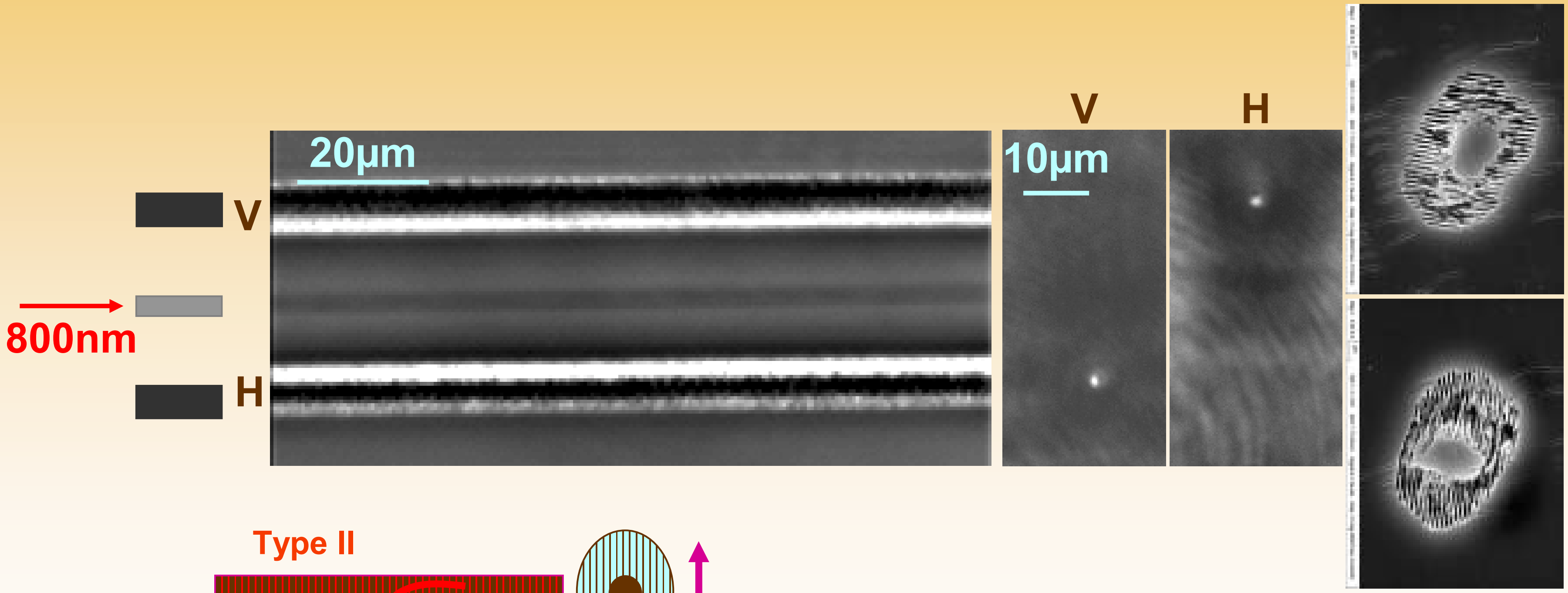
Taylor et al: LPR 2008
Shimotsuma et al

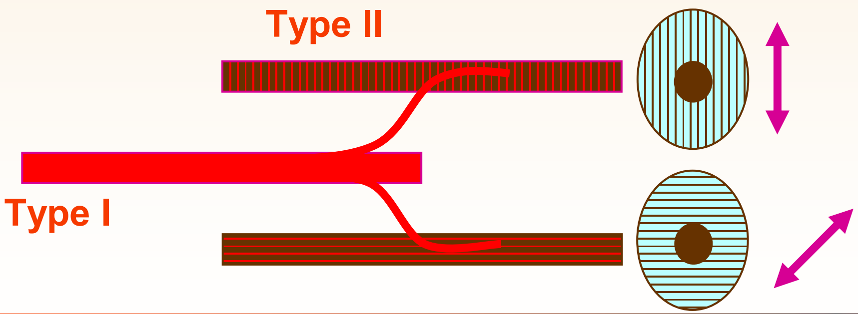
TE, TM control
$n_e < n_O$

Retardation
Polarization

optical functions: a-SiO_2

- Polarization switch
- Optical router (combining type I and type II)

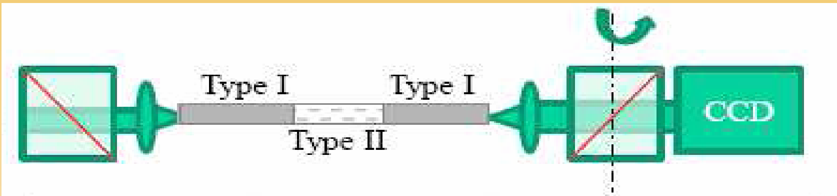


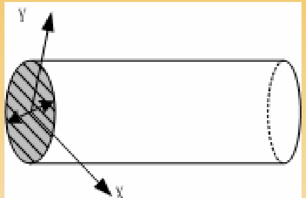


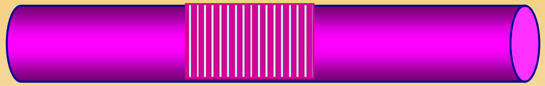
Cheng et al. OE 2009, 2010

optical functions: a-SiO_2

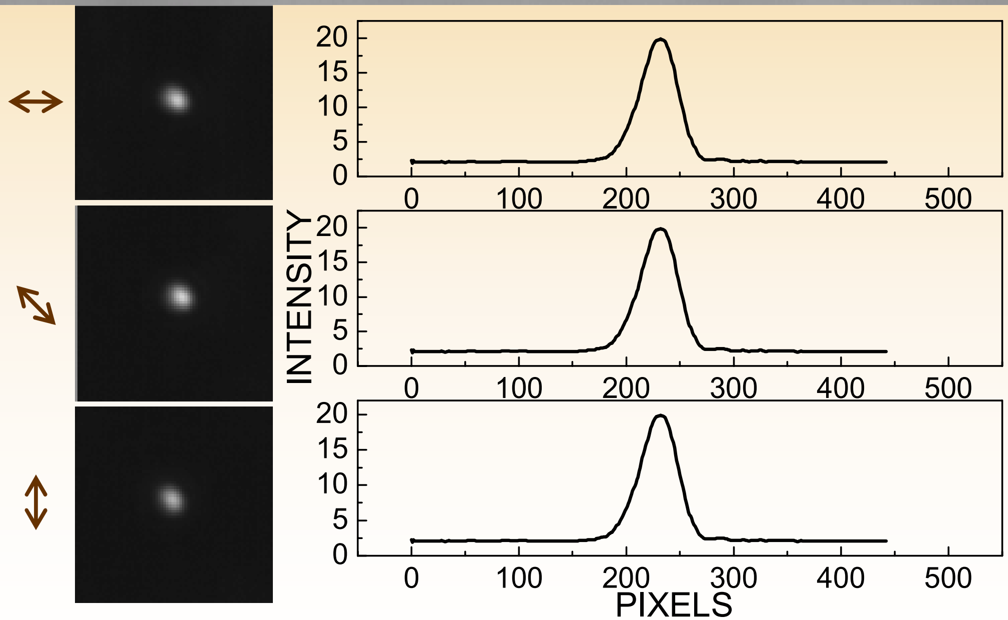
- Polarization maintaining waveguides
- Birefringent phase retardation properties

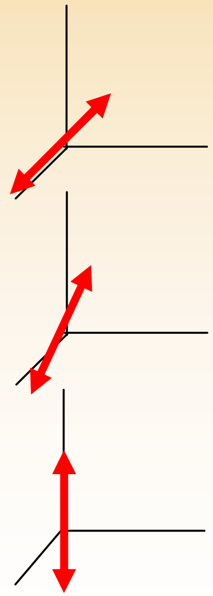






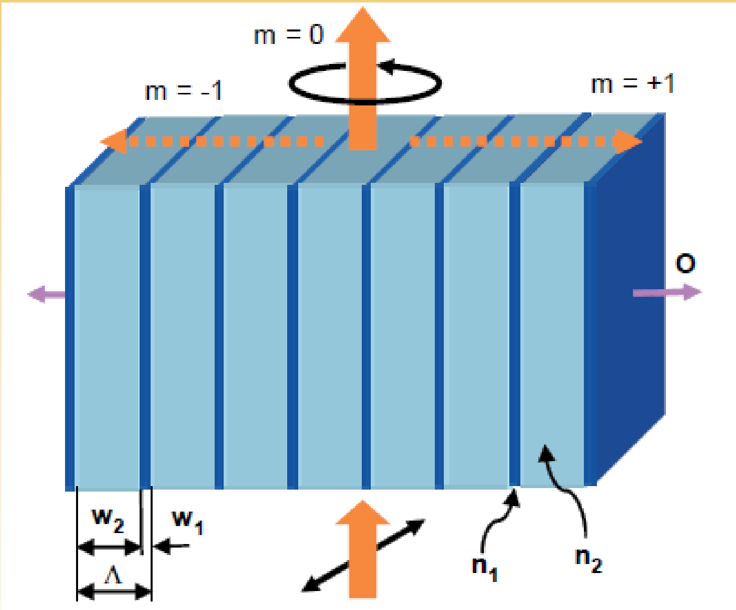
Quarter Wave Plate





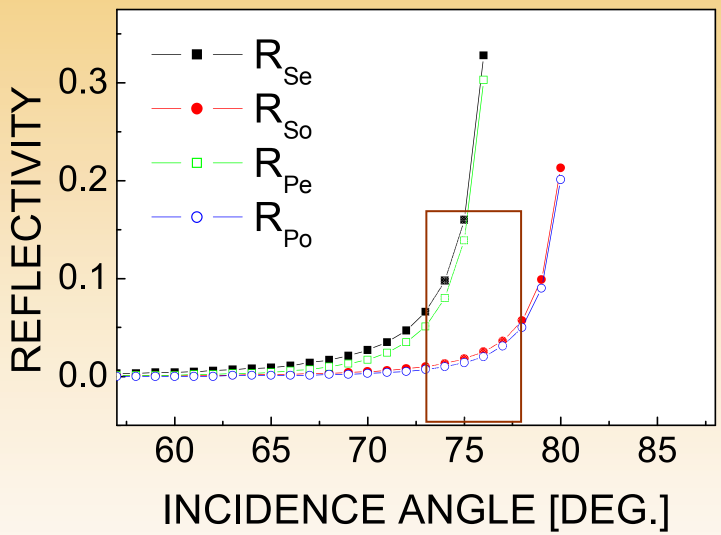
3D type II nanopatterned structures: a-SiO_2

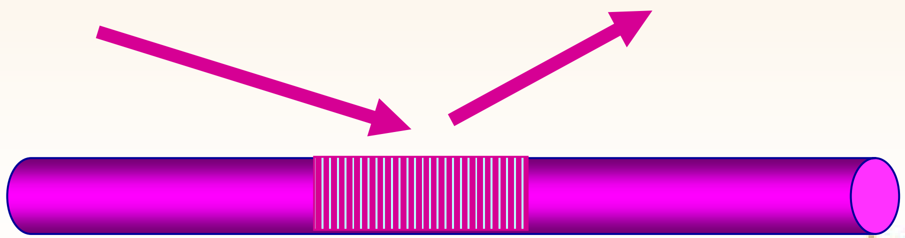
REFRACTIVE INDEX WALL



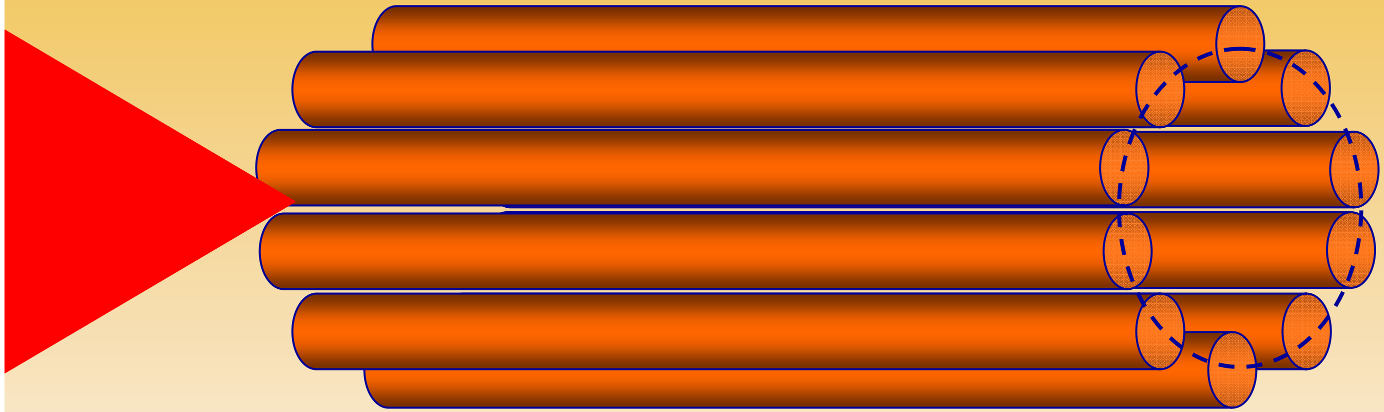
Taylor et al: LPR 2008

800 nm



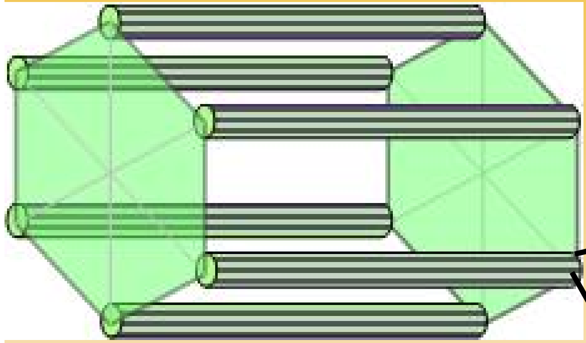


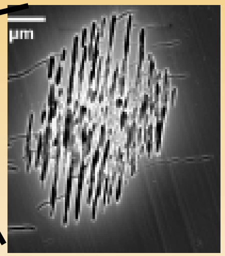
3D periodic structure



3D type II nanopatterned structures: a-SiO_2

REFRACTIVE INDEX WALL

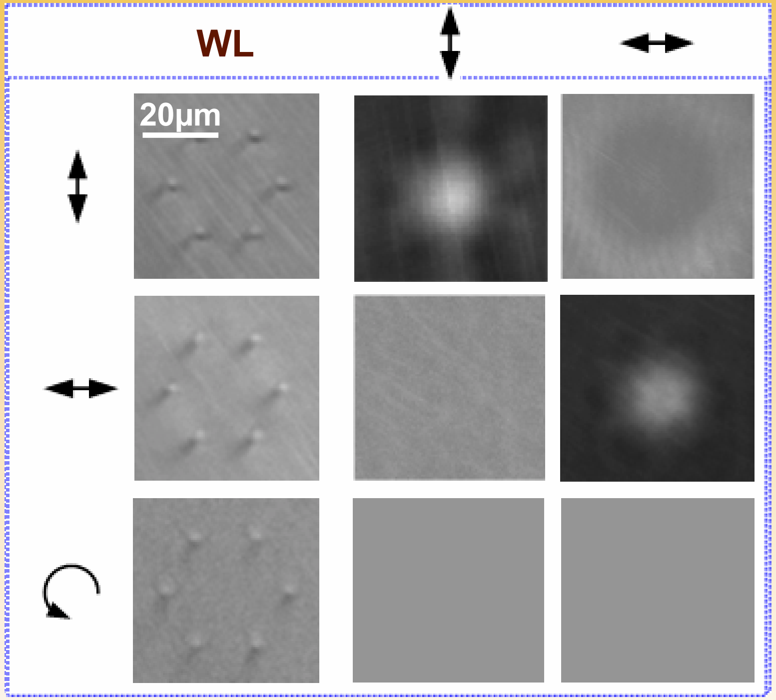


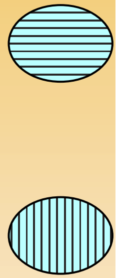


Selective reflection

$n_e < n_o < n$

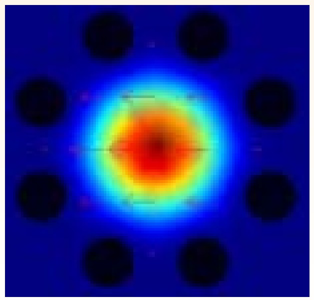
800 nm





Type II

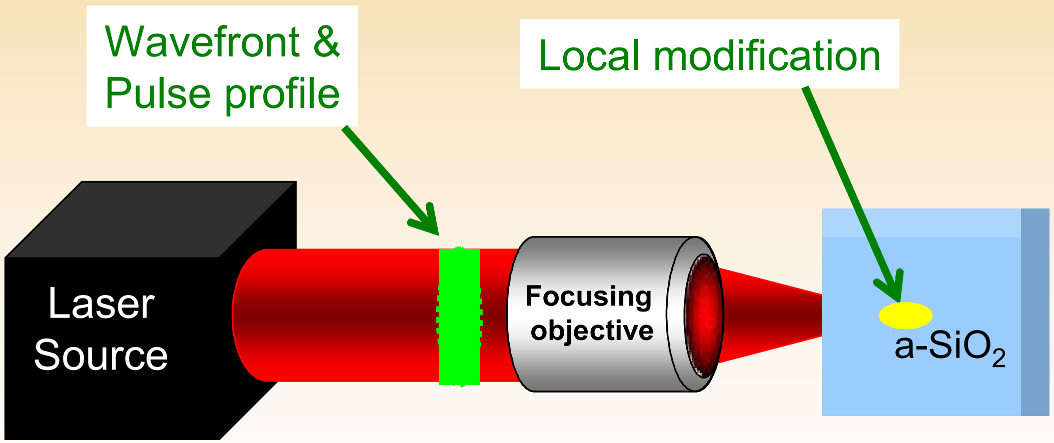
Confinement for specific polarizations



possible applications

What do we want to achieve ?

- **Flexibility in designing refractive index changes**



summary:

Material response characteristic times

↓

Tailored pulses

↓

The potential for quality processing

Adaptive "intelligent" machines

thanks to:

LHC, St. Etienne

C. Mauclair
G. Cheng
K. Mishchik
E. Audouard

MBI, Berlin

A. Mermillod
A. Rosenfeld
A. Husakou
J. Bonse
I. V. Hertel

IT, Novosibirsk

I. M. Burakov
N. M. Bulgakova
Y. Meschcheryakov

Max-Born-Institut