Micromachining and laser processing with ultrashort laser pulses

Eli Glezer
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Laser-Induced Electric Breakdown in Solids

NICOLAAS BLOEMBERGEN, FELLOW, IEEE

Abstract—A review is given of recent experimental results on laserinduced electric breakdown in transparent optical solid materials. A fundamental breakdown threshold exists characteristic for each material. The threshold is determined by the same physical process as de breakdown, namely, avalanche ionization. The dependence of the threshold on laser pulse duration and frequency is consistent with this process. The implication of this breakdown mechanism for laser bulk and surface damage to optical components is discussed. It also determines physical properties of selffocused filaments.

THE history of laser-induced electric breakdown is almost as old as the history of lasers itself. Early in 1963 Maker et al. [1] reported damage to transparent dielectrics and the production of a spark in air by focusing nulsed ruby laser beam. The importance of these the production of laser-induced dense anarted in part

plasmas and for the propagation characteristics of highpower laser beams through solids, liquids, and gases was quickly recognized. The subject of electric breakdown in transparent optical solids, including laser materials, windows, and other optical components, remained, until recently, largely an empirical or engineering science. Although a vast amount of theoretical and experimental effort was expended in the economically and technically important problem of optical damage, quantitative reproducible breakdown thresholds with unambiguous theoretical interpretations have been obtained only during the last two years. The situation was somewhat analogous to the development of our understanding of the problem of de breakdown in electrical insulators. There, too, the field developed largely by engineering trial and error. Basic quantitative understanding was not achieved until reproducible experimental results on well-defined materials were obtained [2]. The difficulties in de the influence of

Laser-Induced Electric Breakdown in Solids

SICOLANS BLOTAMERGES, WILLIAM, WAS

Orders, of action is fixed of derivat exferenceing adoptic on new undered the come breakdown or transcent in outro of south inspectable. A sum dams that breakdown therefored events about a translation for week material. The threshold to determine to the same threshold process as it breakdown, manufacture of occasionates on the same process of the fitting in last, paint that there was a constant of the constan on this breakdown may be anknown from Lynck Smile and surface damage to optical entitionality is granteed in their defectioning this real biologists of edge

 $\lim_{t\to\infty} Q_{m,k}(\hat{g},A_{m}^{-1}(t)) = Q_{m,k}(\hat{g},A_{m}^{-1}(t))$

Till bysants of hose material afection breakdown 1963 Maket at the all reported damage to the apparent Appetition will the medication in a small in its by the both maken the face beam. The impartance of these

plasmin and for the propagation characteristics of high being their housesty and anti- Equilibries and may was mark's reservered. The same of electric breakdown of transplaced special while, including laser states and done and dever option described remained, and Seattle, these in empired to a seatment sence Attorney of the annual of theoretical and experimental glint was expelled in the scongregation and rechnicity supertunt president of option damage automotives terreducible breakdown thresholds with unanaprimers

the record incorrectation have been almortal tally during the and the excess. The eduction was surregified attributed to the development of all mederalization of the problem breakdown in the transfer of the best of the tions developed forces in enconcernation and error

Rose whomen's understanding was not principle until reproducting experimental results in well-petitien more trade were contained (2) the difficulties in str were manifely the influence of

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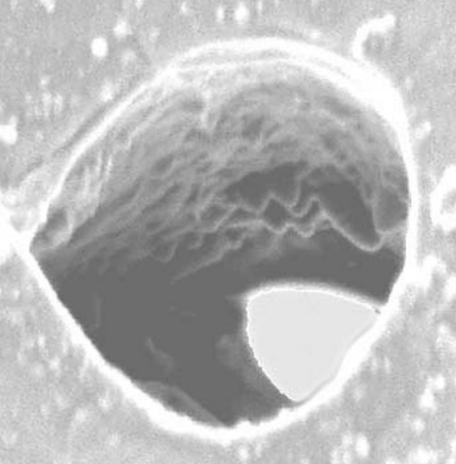
DAMAGED

22nd ANNUAL BOULDER DAMAGE SYMPOSIUM
Proceedings



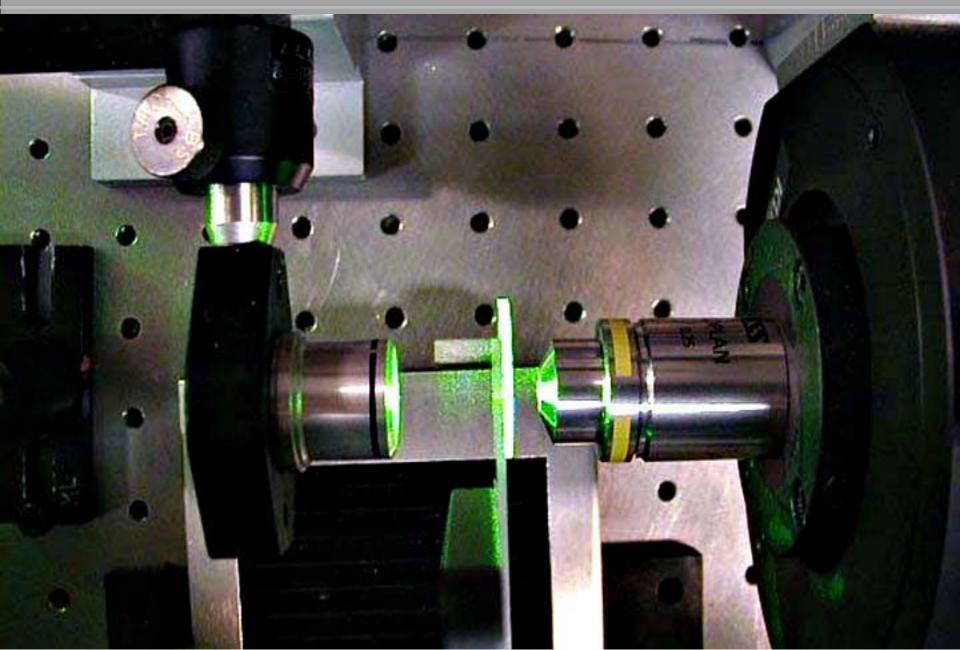
LASER-INDUCED DAMAGE
IN OPTICAL MATERIALS: 1990

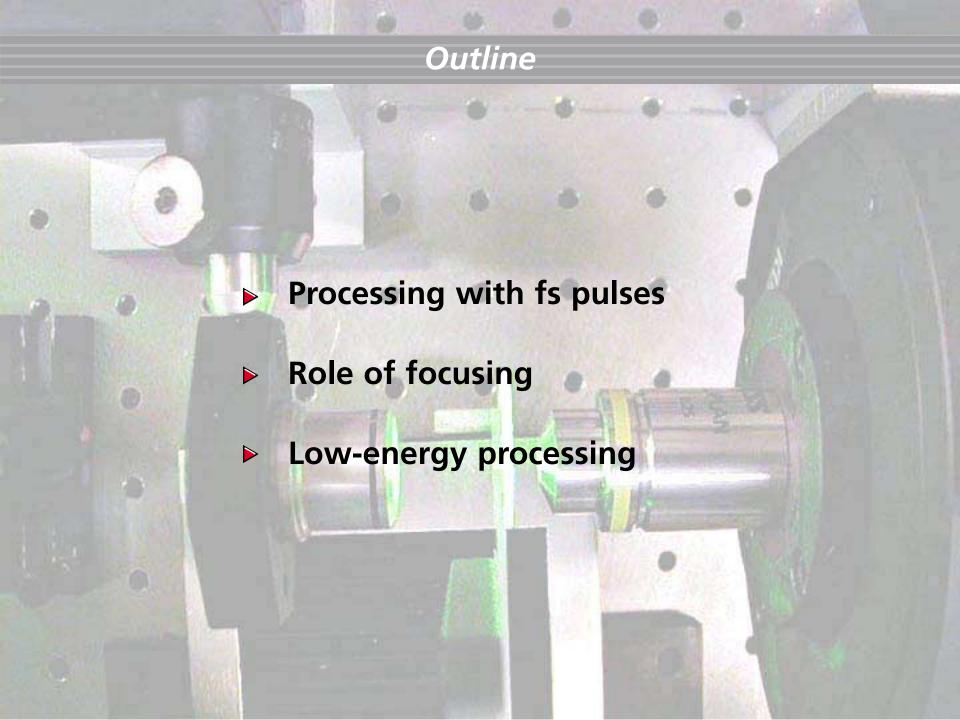
24-26 OCTOBER 1990 BOULDER, COLORADO

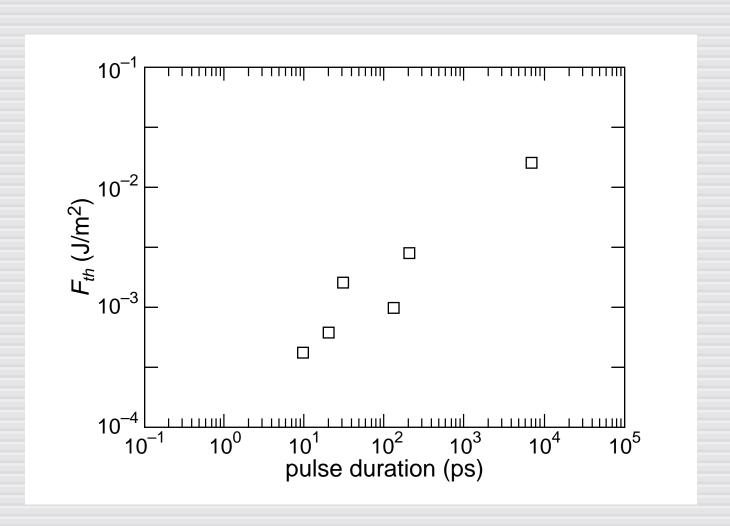


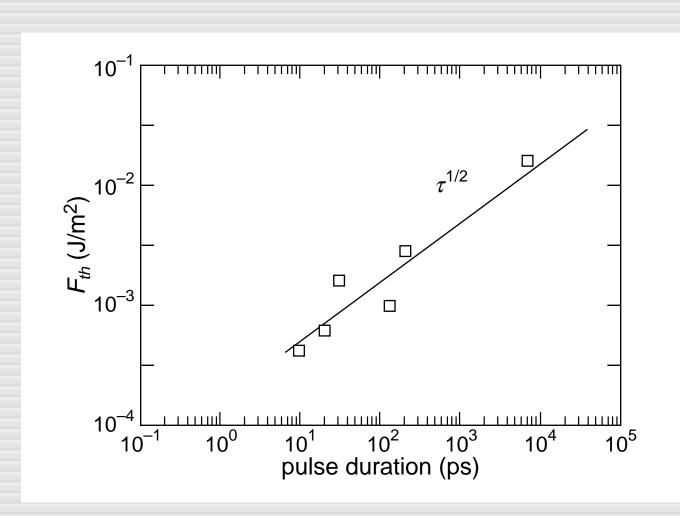
use damage for processing!

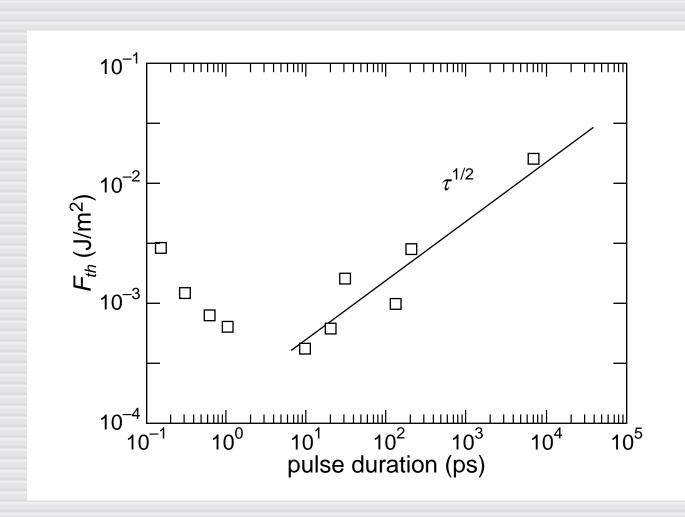
Outline



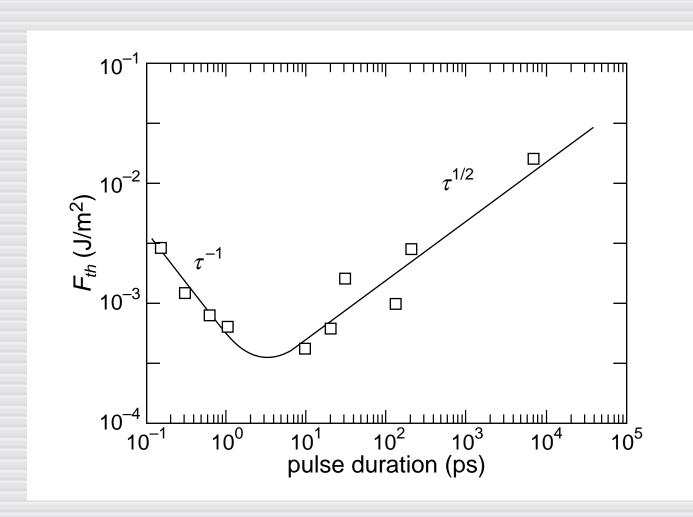








Du et al., Appl. Phys. Lett. 64, 3071 (1994)



Du et al., Appl. Phys. Lett. 64, 3071 (1994)

D. von der Linde and H. Schüler

Breakdown threshold and plasma formation J. Opt. Soc. Am. B/Vol. 13, No. 1/January 1996 in femtosecond laser-solid interaction

Institut für Laser- und Plasmaphysik, Universität Essen, D-45117 Essen, Germany

Combining femtosecond pump—probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. Combining femtosecond pump—probe techniques with optical microscopy, we have studied laser-induced. The threshold of optical breakdown in optically transparent solids with high temporal and spatial resolution. Plasma formation has been determined from measurements of the changes of the optical reflectivity associated. optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. plasma formation has been determined from measurements of the changes of the optical reflectivity associated.

We have observed.

We have observed the changes of the optical reflectivity associated with the developing plasma.

It is shown that plasma generation occurs at the interaction of femtosecond has a remarkable resistance to optical breakdown and material damage in the interaction. with the developing plasma. It is shown that plasma generation occurs at the surface.

We have observed
a remarkable resistance to optical breakdown and material damage in the interaction
pulses with bulk optical materials. a remarkable resistance to optical breakdown and material damage in to pulses with bulk optical materials. 1996 Optical Society of America

The interaction of intense femtosecond laser pulses with 1. INTRODUCTION

solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great particularly from the point of view of general-To produce such a the rise from the intensity level formation to the

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau et al., carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic

Thus far, the issue of breakdown thresholds in femtosecond laser-solid interaction has barely been touched.

The state out laser-induced breakforced silica with pulses ranging in 150 fs. They reported threshold on

"... clear evidence that no bulk plasmas ...

[and] ... no bulk damage could be produced

 D_{c} was der Limbe and H_{c} we hader

One of the key points in the research of Bloembergen and his co-workers was the use of very rightly focused

Laser beauty which allowed them to reach the breakdown threshold of the nuterials while staying well below the errical power of self-focusting. Self-focusing is one of the make happens in the measurement of pulk predylows thresholds. In a more special review Solicina et al., carefully examined the role of self-focusing in experiments

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Thus for, the issue of breakdown thresholds in femtoteend laser with internation has barrly been touched. an one man one recovery one tower more than tower or tower towers to be a control of the control

though after with pulsers ranging in

150 fs. They reported

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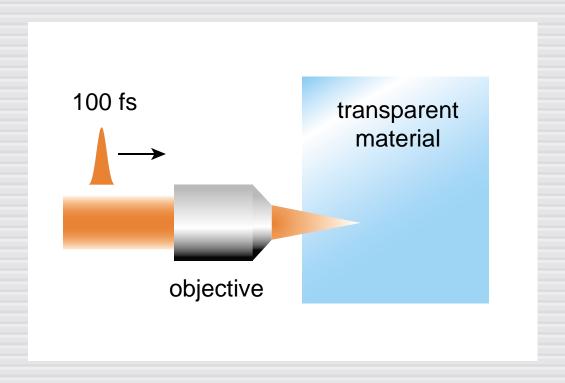
with femtosecond laser pulses." plasmic formation has been determined from managements of the changes of the operation with the deschaper plasmic. It is shown that plasma is necessarily in the internation a vectorial demands in the internation a vectorial decided because to indicat because and material demands in the internation. with the deschquag the-min. It is shown that pinema is contribute at the interaction of final a wearstable resistance to system because it makes a sometime of America pulses with bulk outlied resistance. optical becaution in applically Linnaparent while with high temporal angular plants of the change of optical bacadeliant in applically transparent solids with high its Compinions goldsonermy formit-factor recpuidness

a remarkable resistance to optical materials. Limb Optical Society of Americal polace with bulk optical materials.

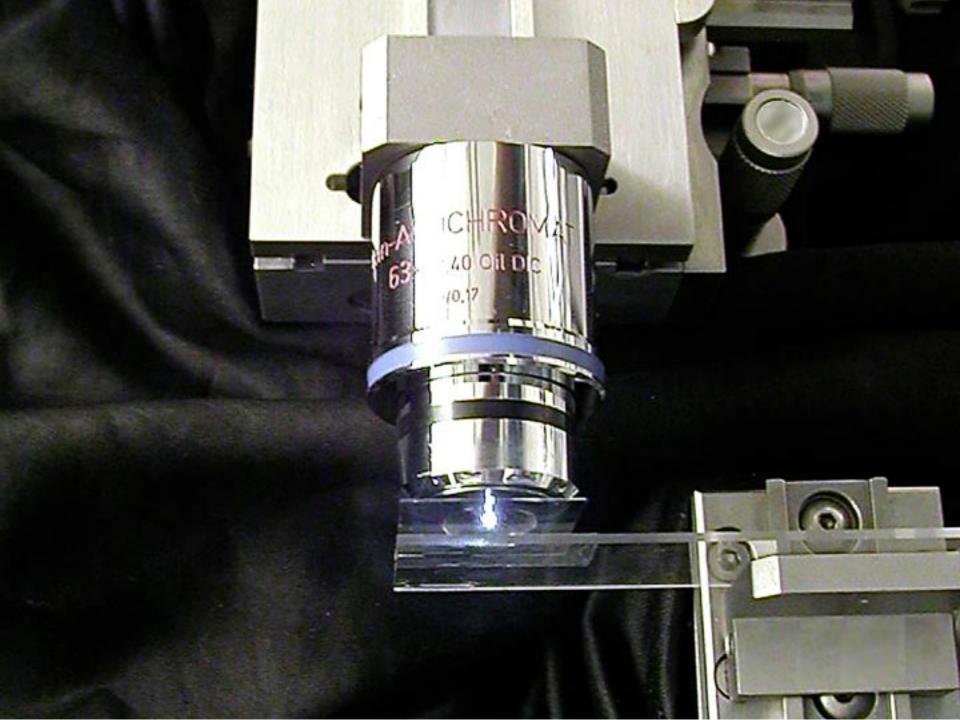
The interaction of intense feminescond laser pulses with measuring laser-induced breakdown of bulk dielectric masolids often the Postbility of Producing a new class of terials. They concluded that the breakdown and damhaving approximately solid-attite throatly and von der Linde, et al., J. Opt. Soc. Am. 13, 216 (1996)

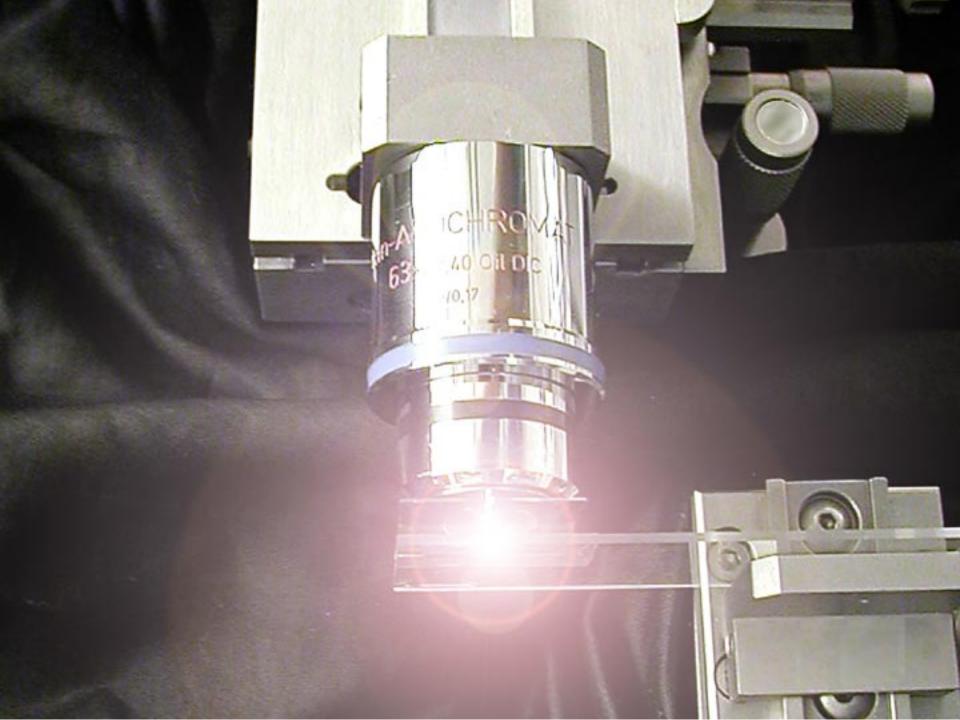
1. INTRODUCTION

focus laser beam inside material



Glezer, et al., Opt. Lett. 21, 2023 (1996)

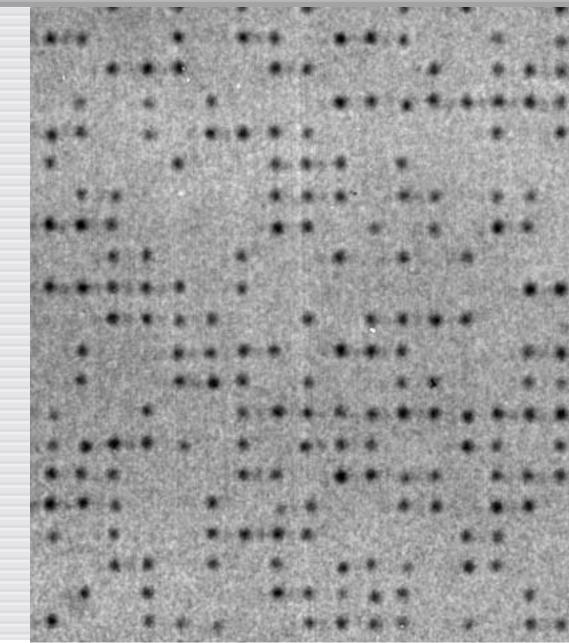




2 x 2 µm array

fused silica, 0.65 NA

0.5 μJ, 100 fs, 800 nm

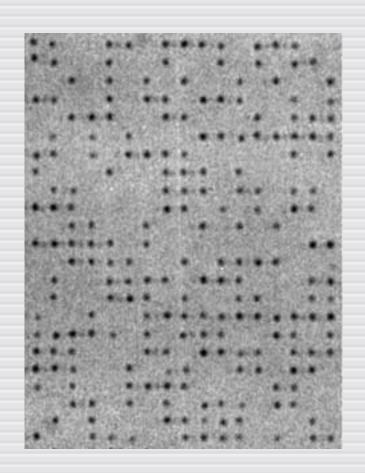


Opt. Lett. 21, 2023 (1996)

2 x 2 µm array

fused silica, 0.65 NA

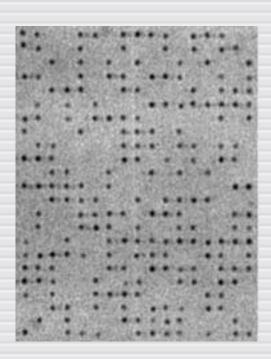
0.5 μJ, 100 fs, 800 nm



2 x 2 µm array

fused silica, 0.65 NA

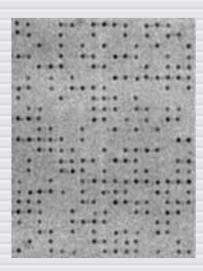
0.5 μJ, 100 fs, 800 nm

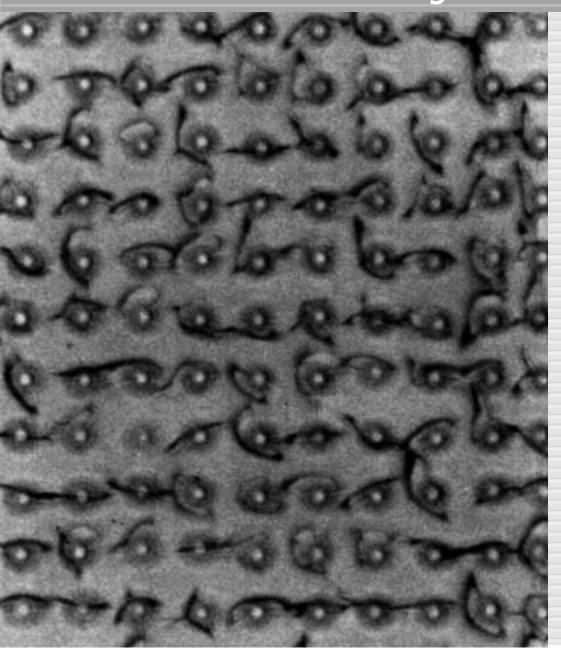


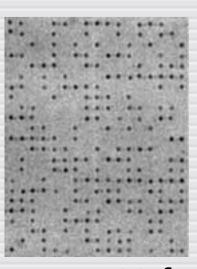
2 x 2 µm array

fused silica, 0.65 NA

0.5 μJ, 100 fs, 800 nm







100 fs 0.5 μJ

200 ps 9 μJ

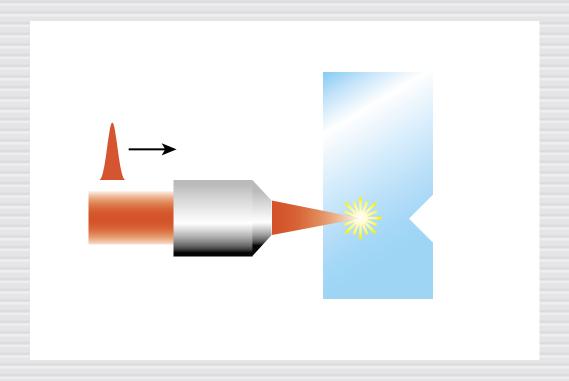
100 nm

5 x 5 μm array

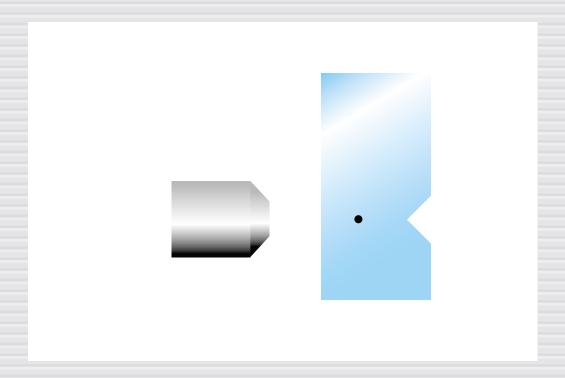
fused silica, 0.65 NA

0.5 μJ, 100 fs, 800 nm

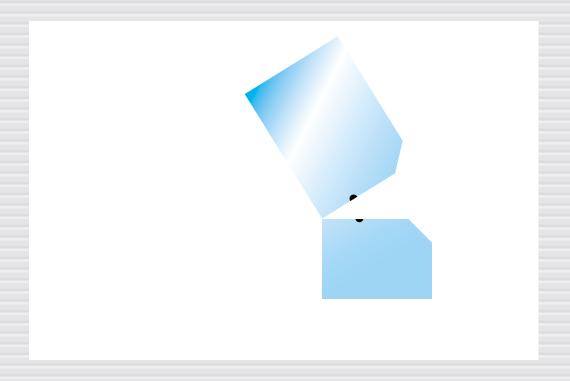
Opt. Lett. 21, 2023 (1996)



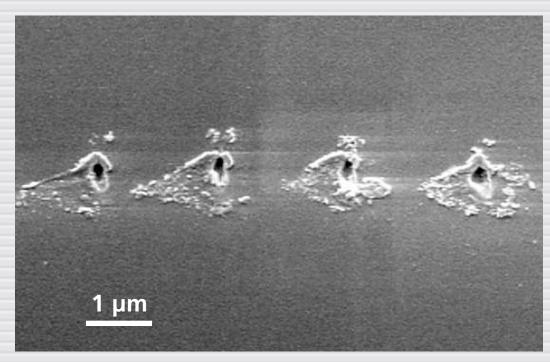
microstructure scribed sample



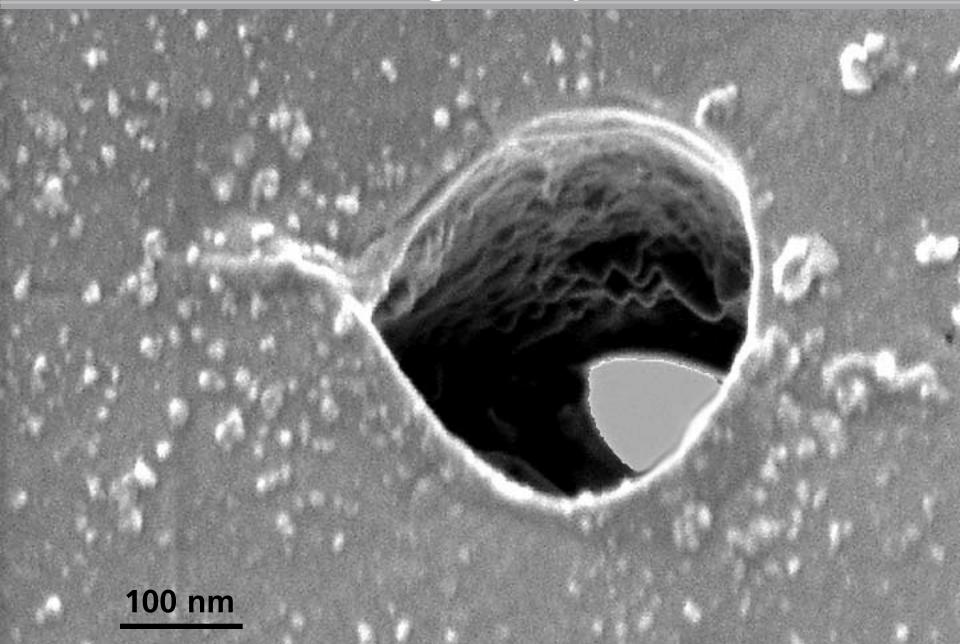
microstructure scribed sample

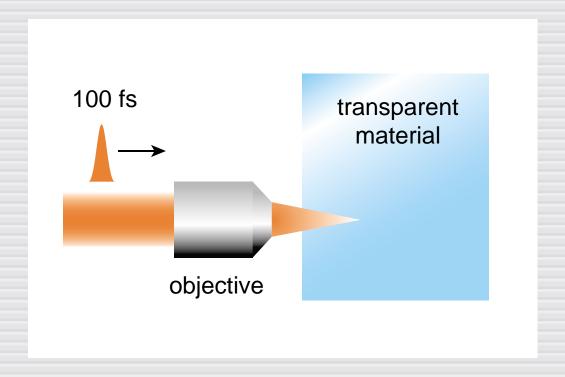


fracture along scribe line

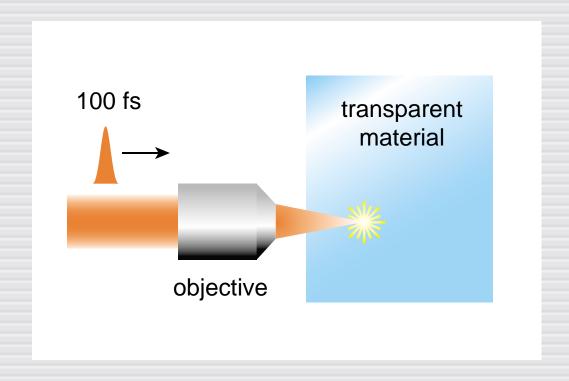


Corning 0211 1.4 NA, 140 nJ

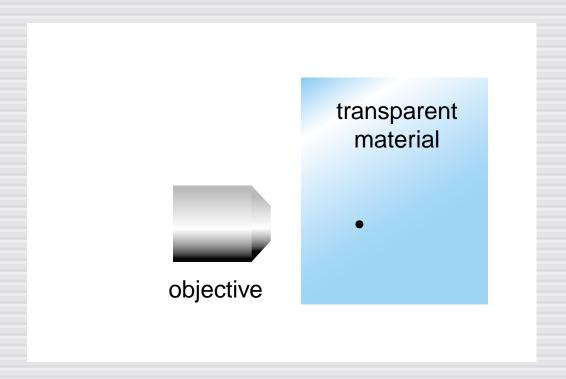




high intensity at focus...

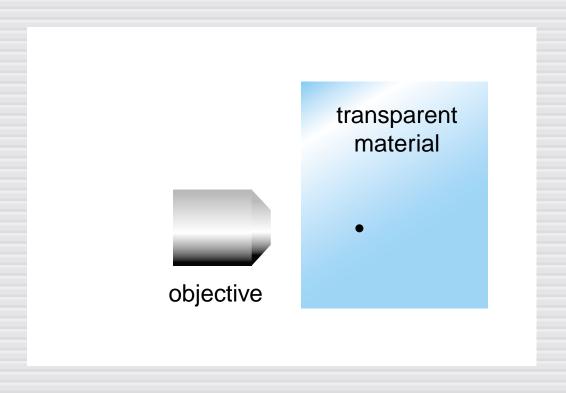


... causes nonlinear ionization...

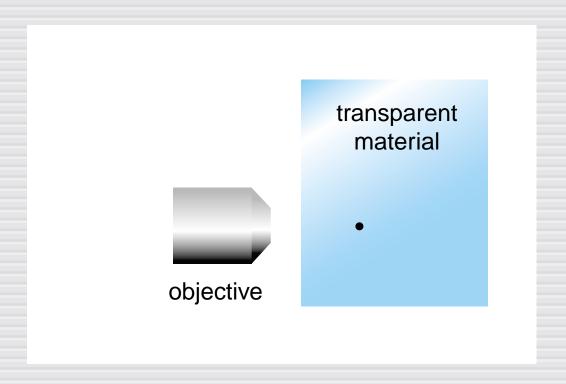


and 'microexplosion' causes microscopic damage

What are the conditions at focus?



What are the conditions at focus?



laser deposits energy in ~1 μm³

What temperature?

What temperature?

$$\Delta E = C_V \rho V \Delta T$$

What temperature?

$$\Delta E = C_V \rho V \Delta T$$

$$C_V = 0.75 \times 10^3 \,\mathrm{J \, kg^{-1} \, K^{-1}}$$

$$\rho = 2.2 \times 10^3 \,\mathrm{kg/m^3}$$

What temperature?

$$\Delta E = C_V \rho V \Delta T$$

$$C_V = 0.75 \times 10^3 \,\mathrm{J \, kg^{-1} \, K^{-1}}$$

$$\rho = 2.2 \times 10^3 \,\mathrm{kg/m^3}$$

So, 1 µJ in 1 µm³ gives

~1,000,000 K!

What pressure?

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Gives

$$p = 10 \text{ MBar!}$$

So:

microexplosionT $\approx 1 \text{ MK}$ p $\approx 10 \text{ MBar}$ ρ $2.2 \times 10^3 \text{ kg/m}^3$

So:

	microexplosion	sun
T	≈1 MK	2-5 MK
p	≈10 MBar	
ρ	$2.2\times10^3\mathrm{kg/m^3}$	$0.15 - 150 \times 10^3 \mathrm{kg/m^3}$

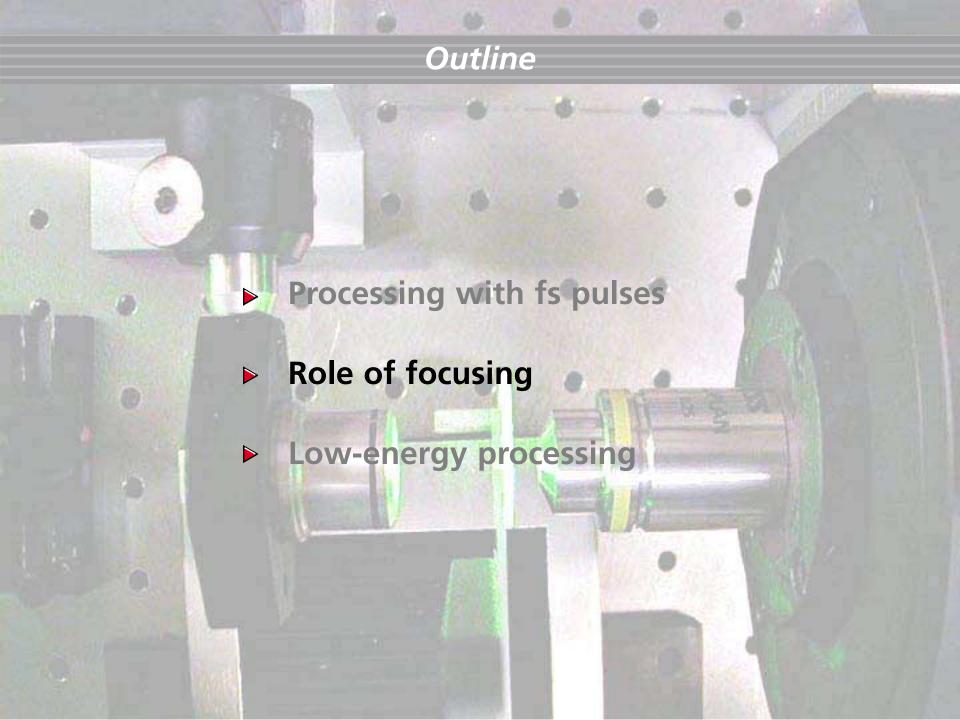
So:

	microexplosion	sun
T	≈1 MK	2-5 MK
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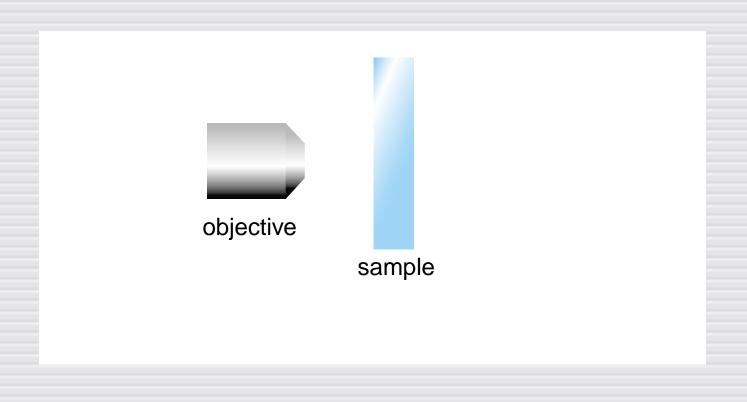
creating stellar conditions in lab!

Points to keep in mind:

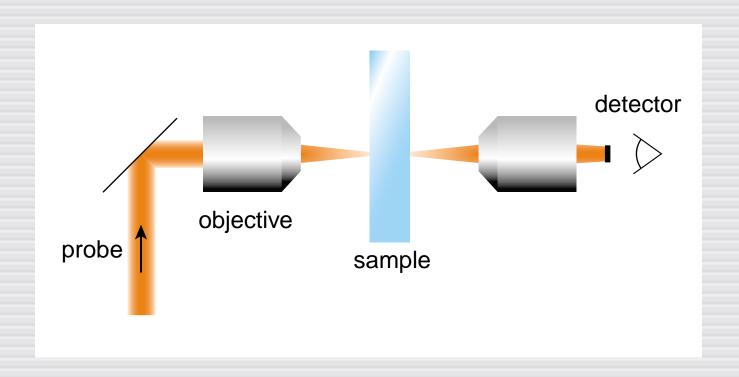
- fs laser processing works
- focusing very important
- no collateral damage



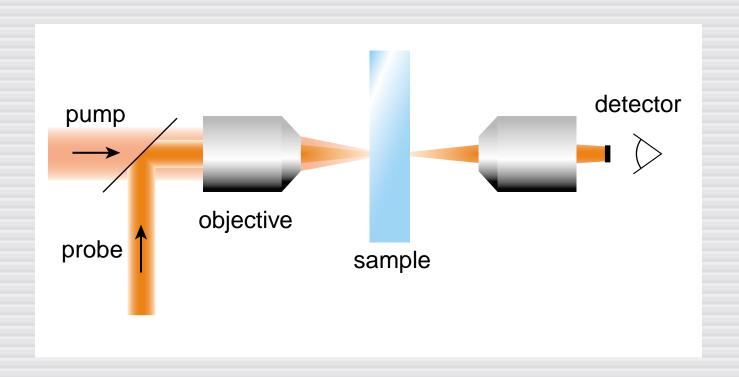
Dark-field scattering



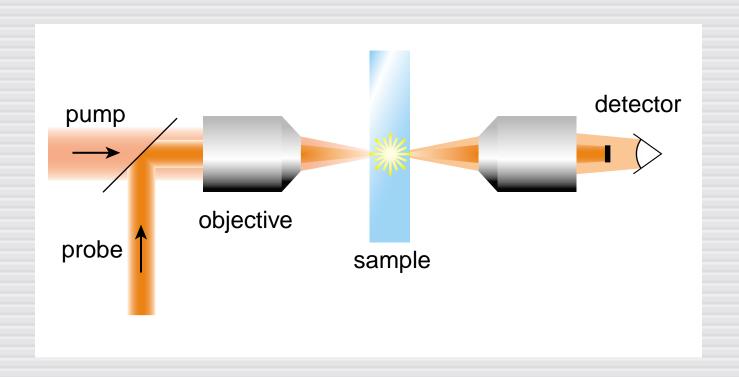
block probe beam...

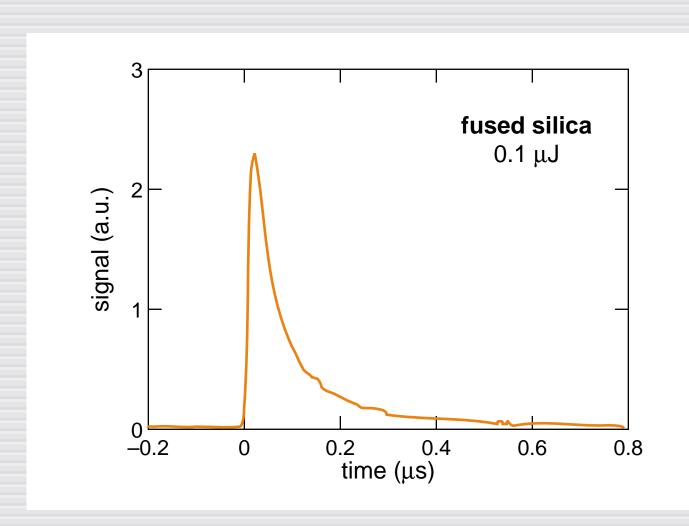


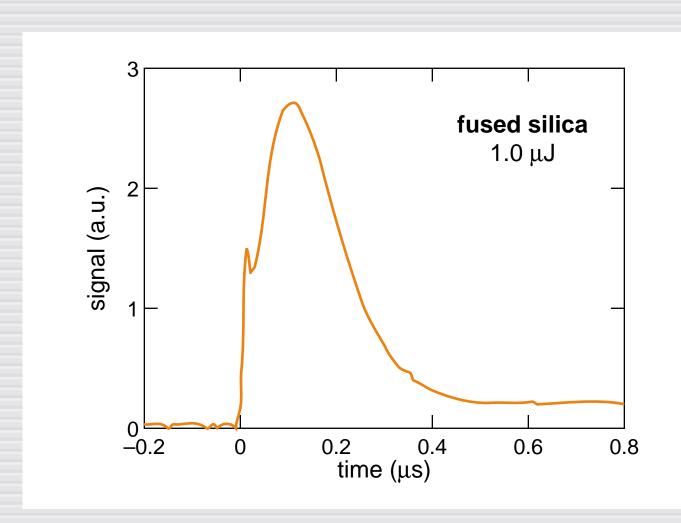
... bring in pump beam...

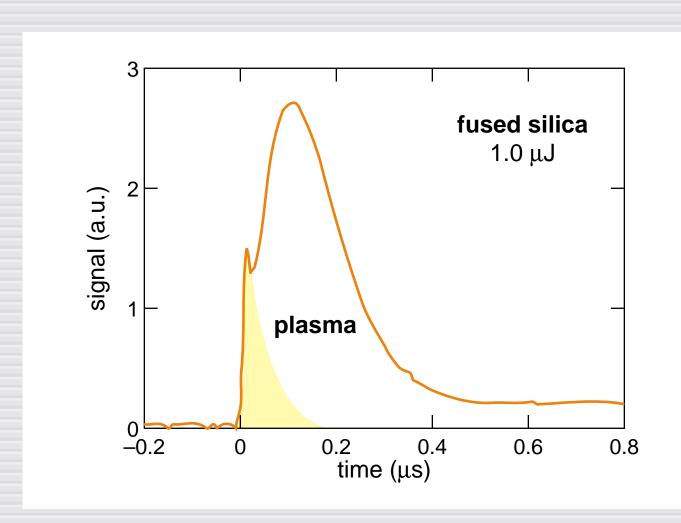


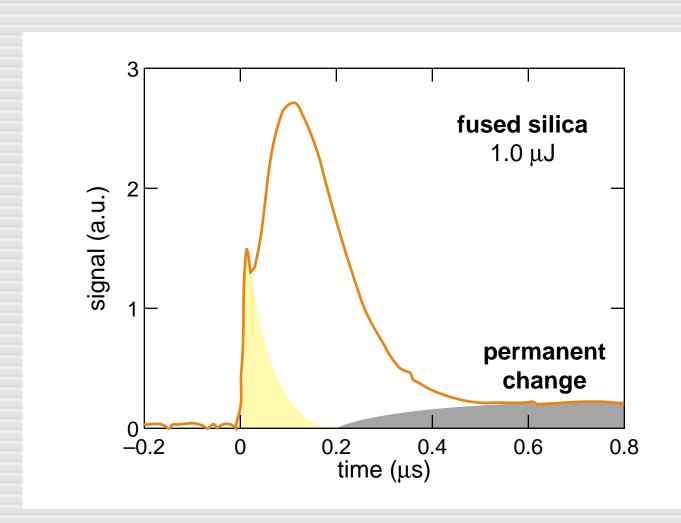
... damage scatters probe beam

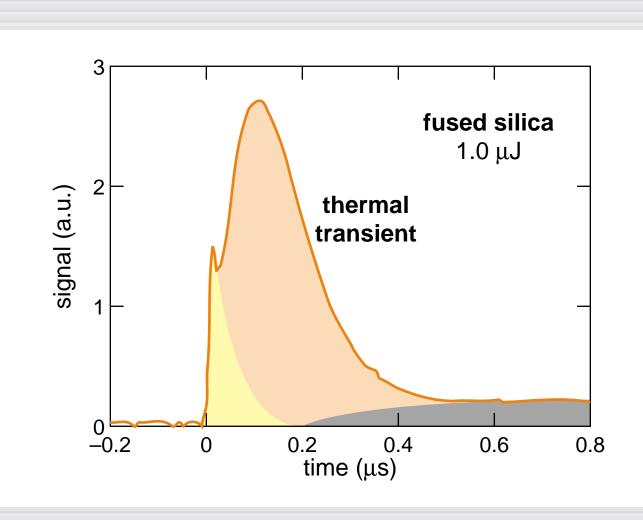




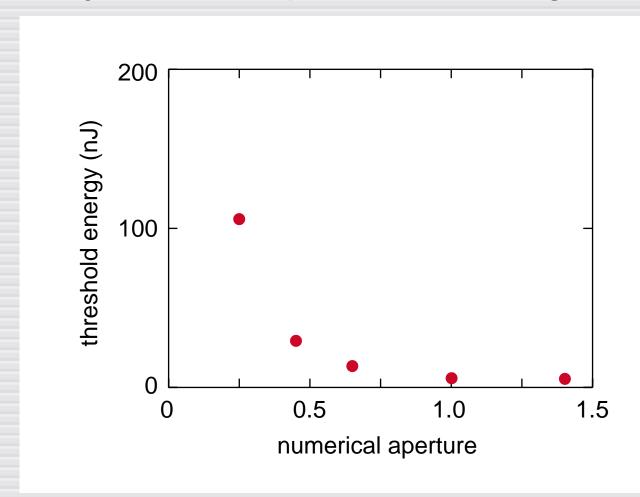


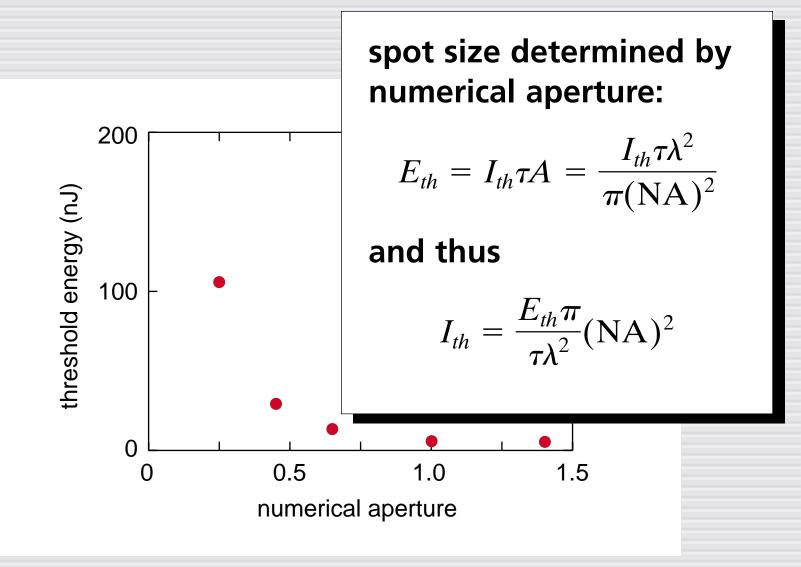




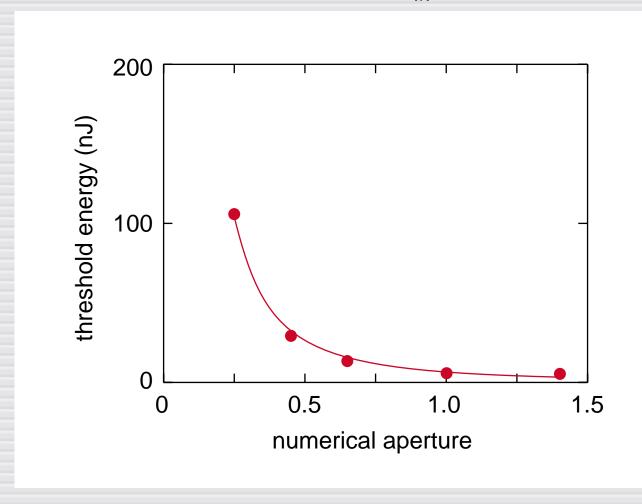


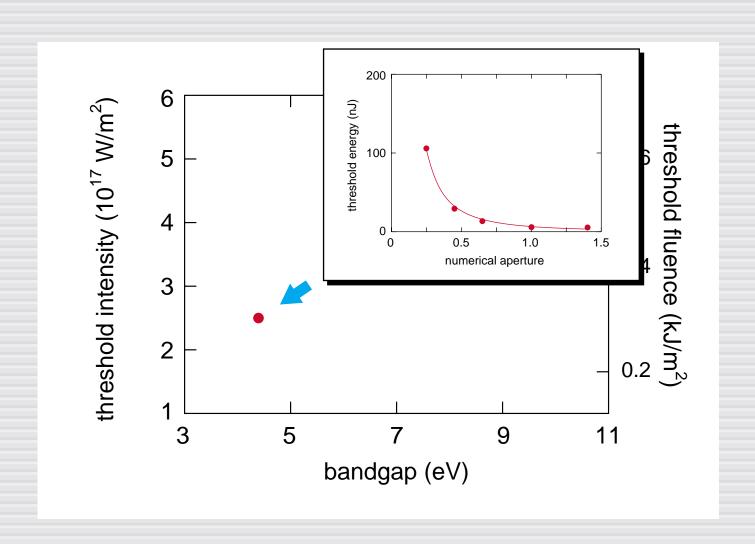
vary numerical aperture in Corning 0211



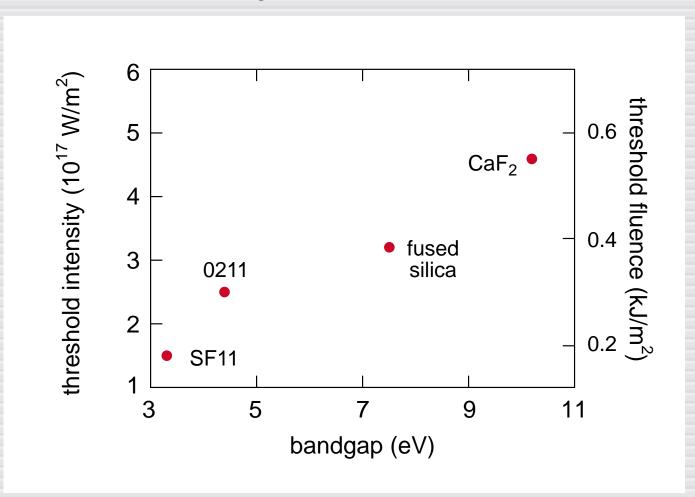


fit gives threshold intensity: $I_{th} = 2.5 \times 10^{17} \text{ W/m}^2$

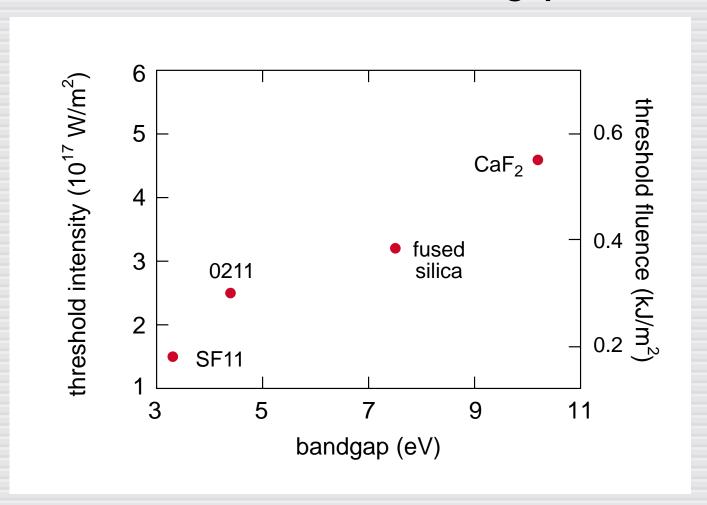




vary material...

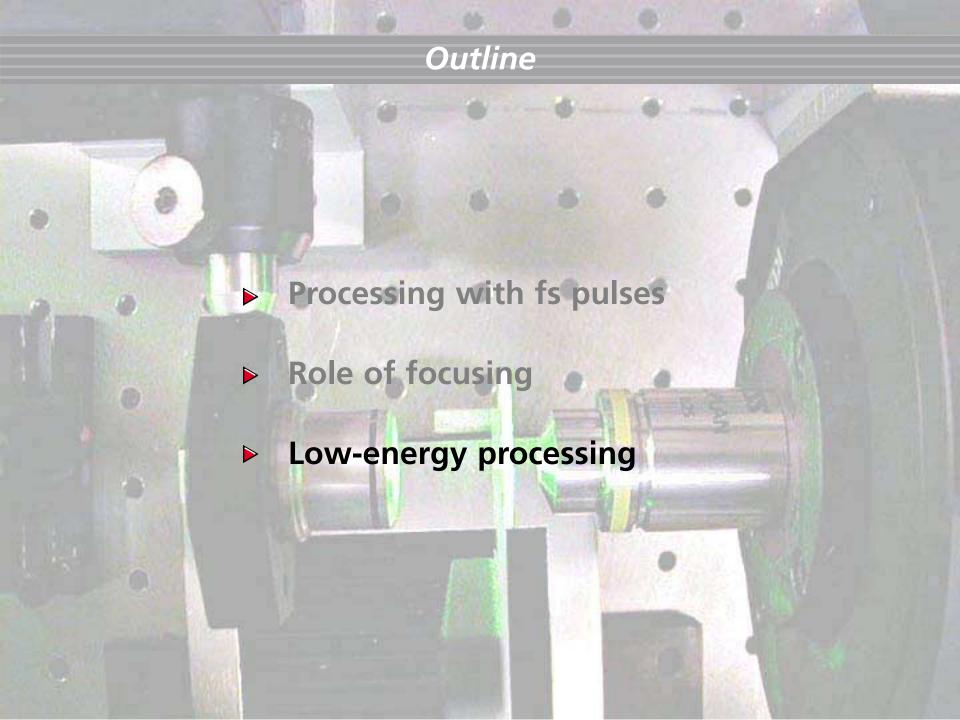


threshold varies with bandgap

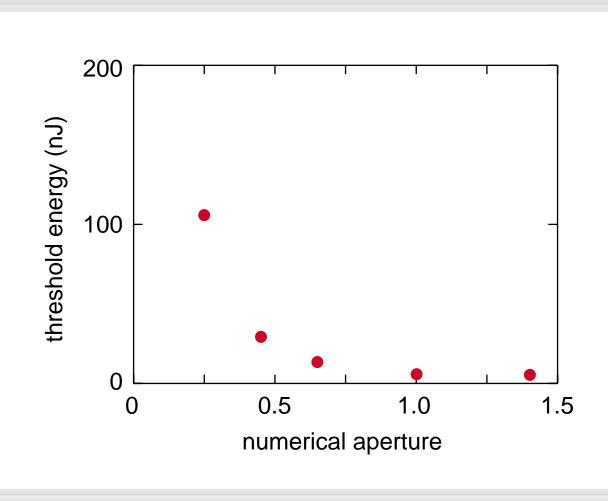


Points to keep in mind:

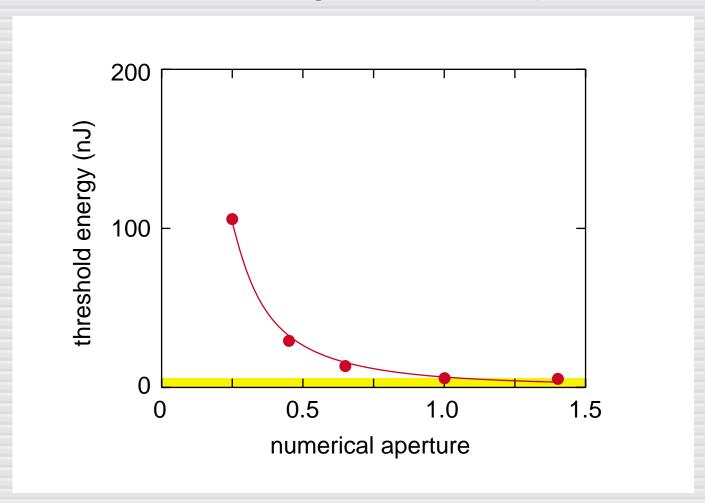
- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important



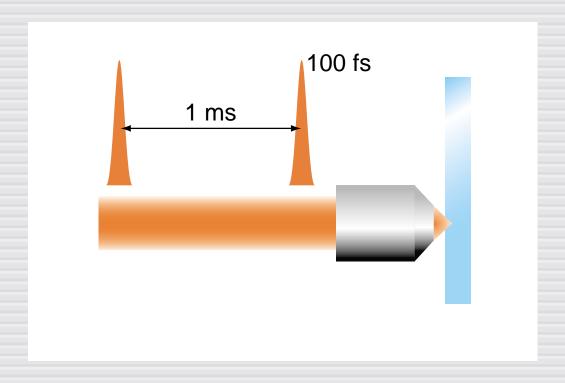
threshold decreases with increasing numerical aperture



less than 10 nJ at high numerical aperture!

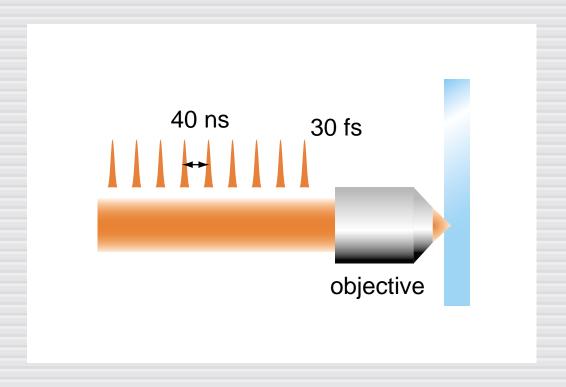


amplified laser

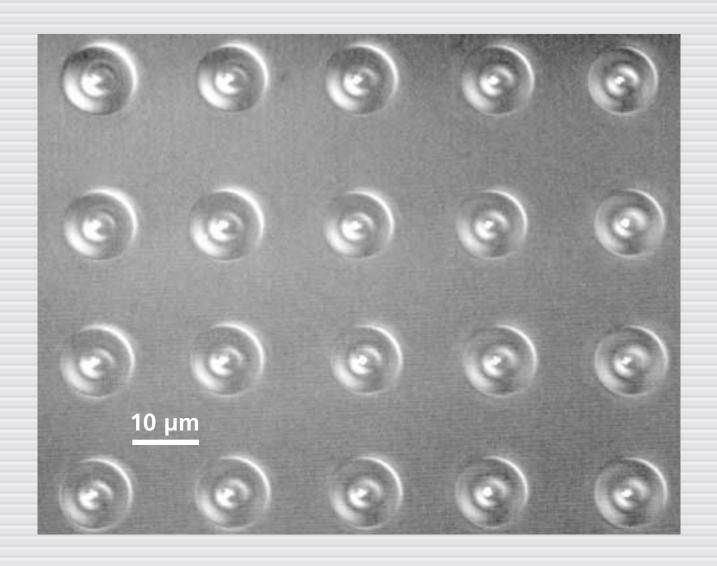


heat-diffusion time: $\tau_{diff} \approx 1 \ \mu s$

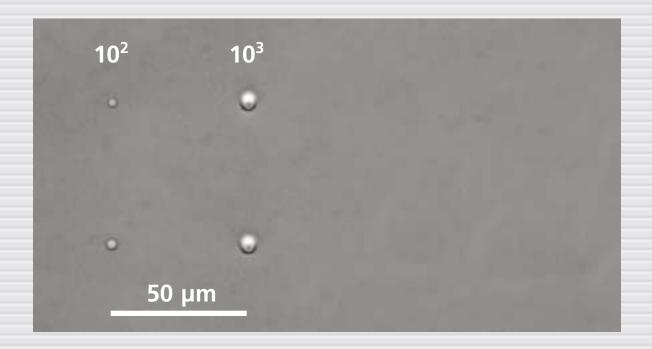
long-cavity Ti:sapphire oscillator

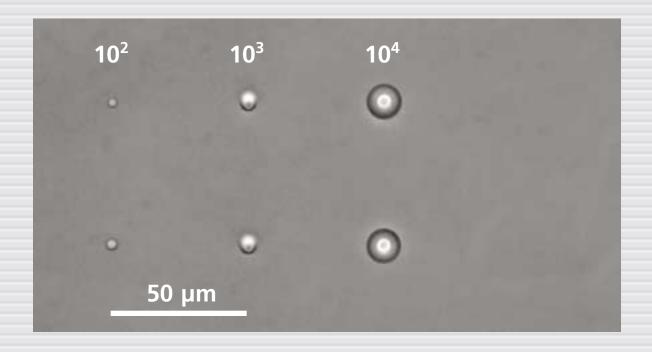


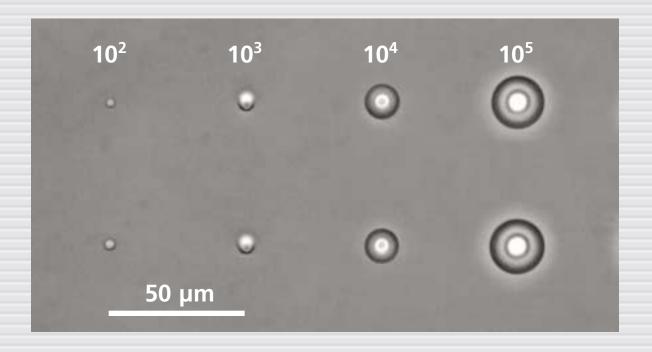
heat-diffusion time: $\tau_{diff} \approx 1 \ \mu s$

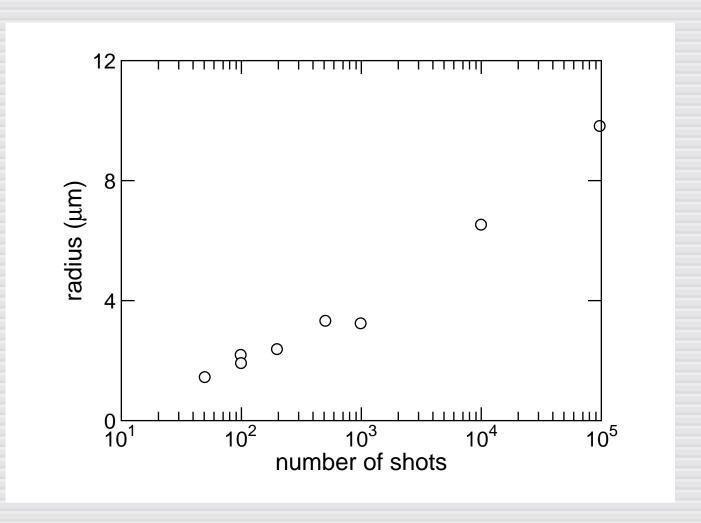




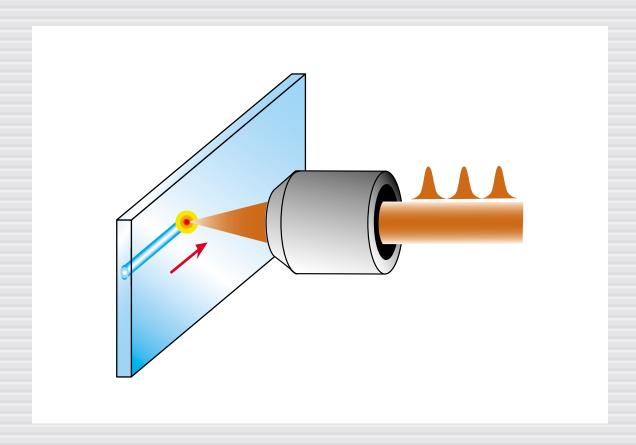




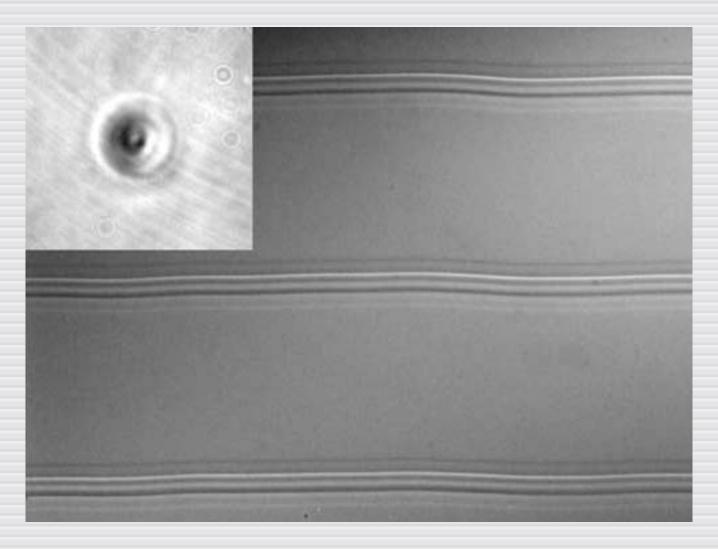




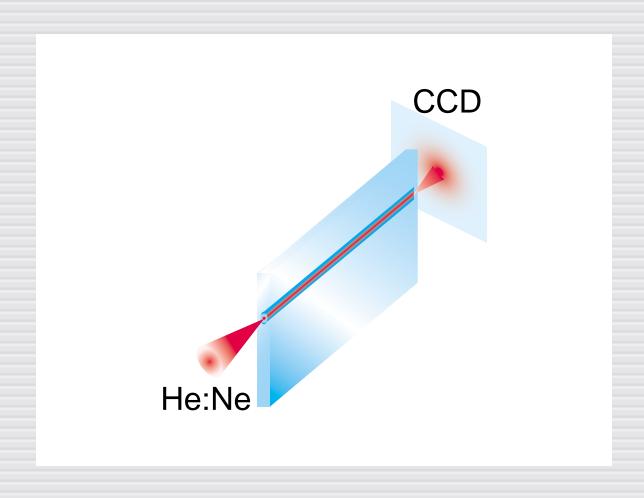
waveguide machining



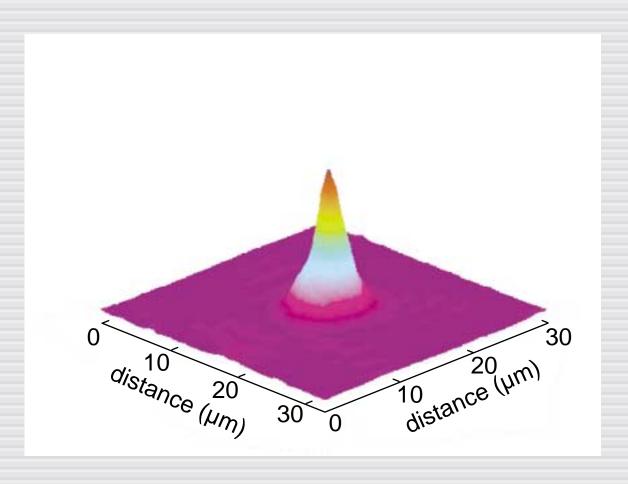
waveguide machining



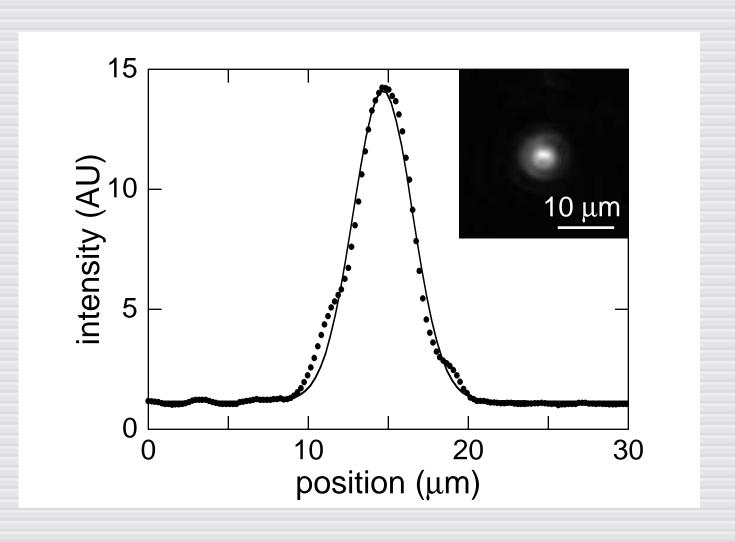
waveguide mode analysis



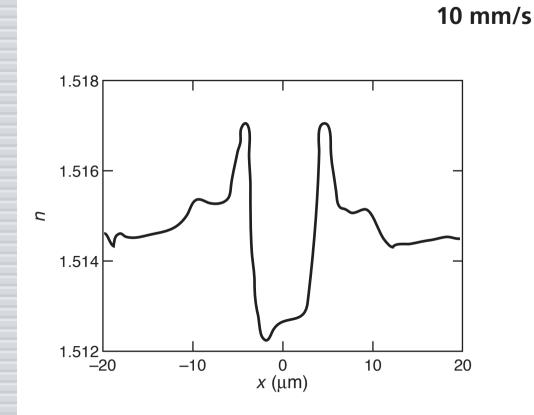
near field mode

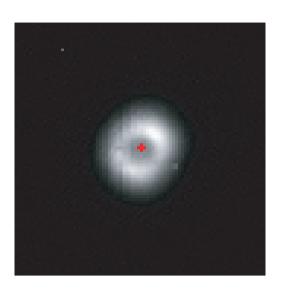


near field mode



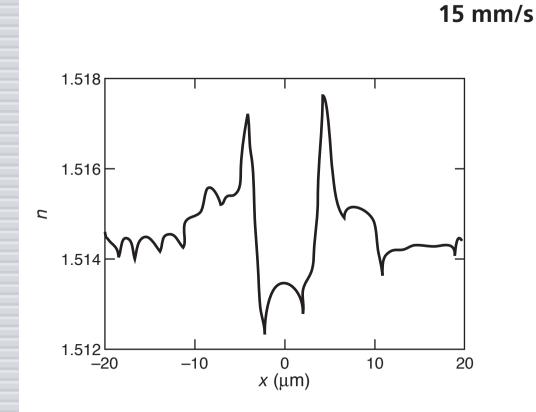
refractive index profiles and near field mode at 1550 nm

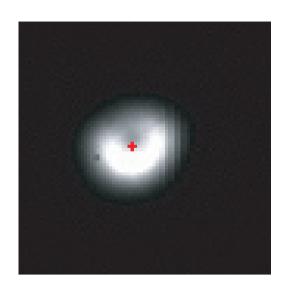




Sagitta, Inc.

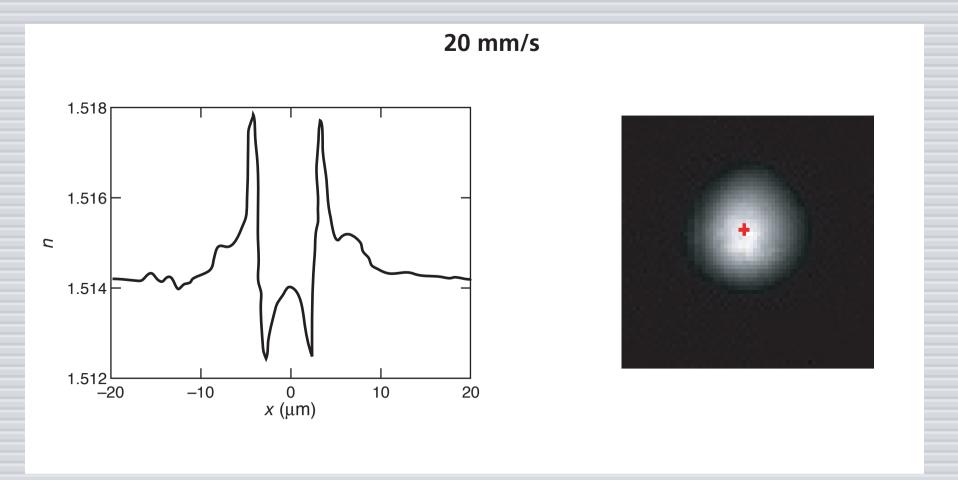
refractive index profiles and near field mode at 1550 nm





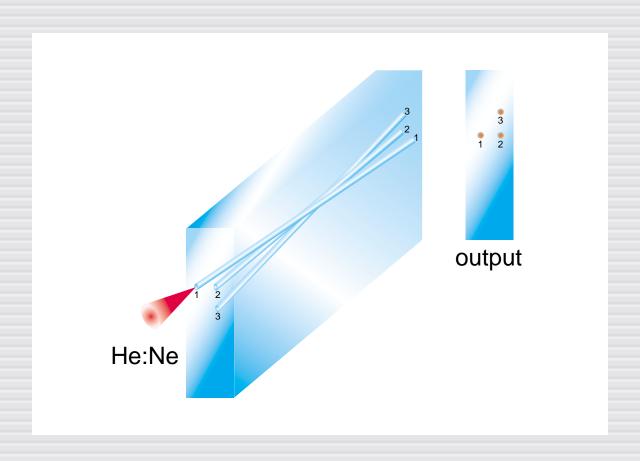
Sagitta, Inc.

refractive index profiles and near field mode at 1550 nm

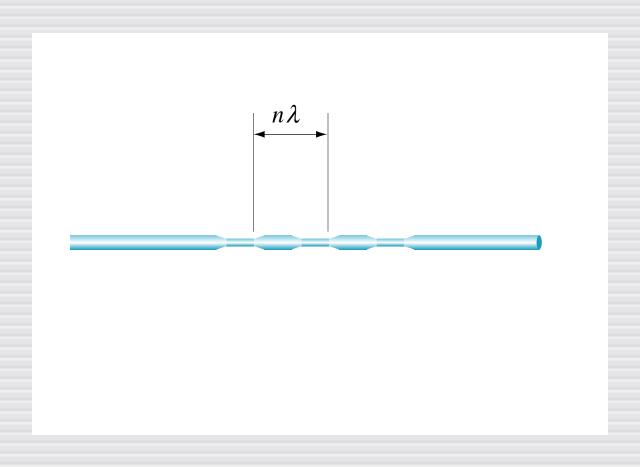


Sagitta, Inc.

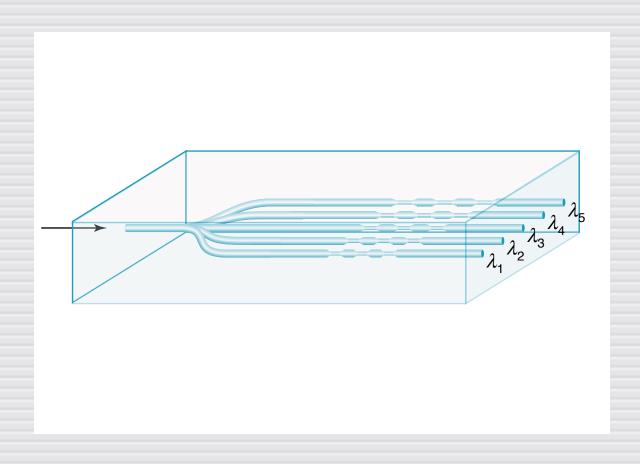
3D wave splitter



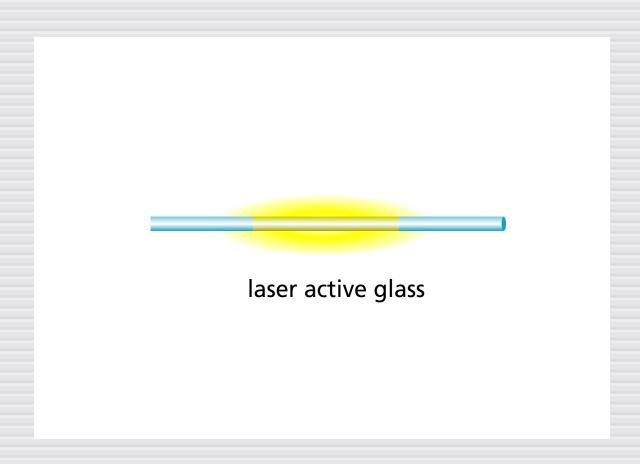
Bragg grating



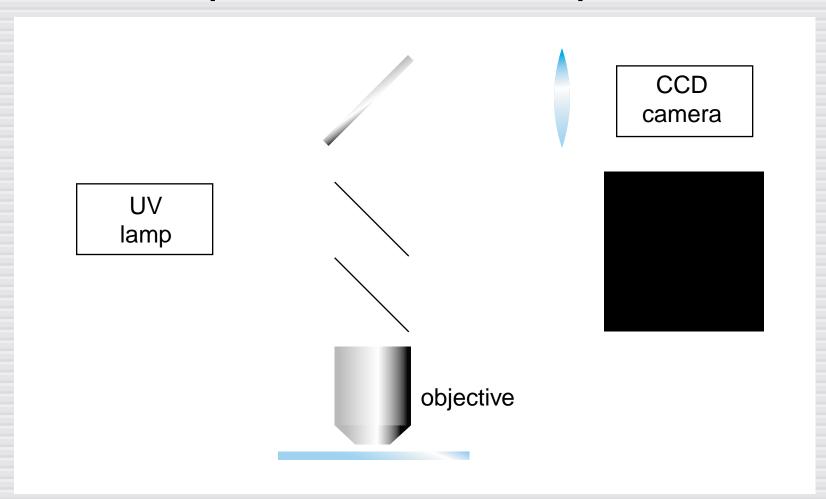
Bragg grating



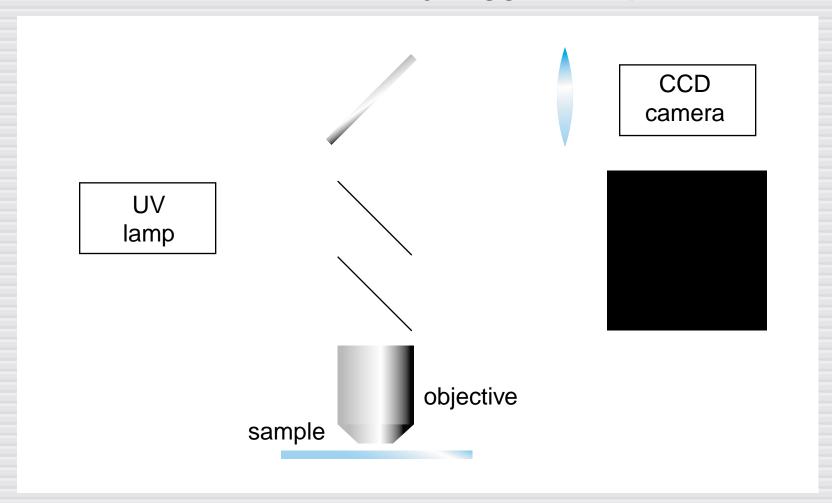
monolithic amplifier



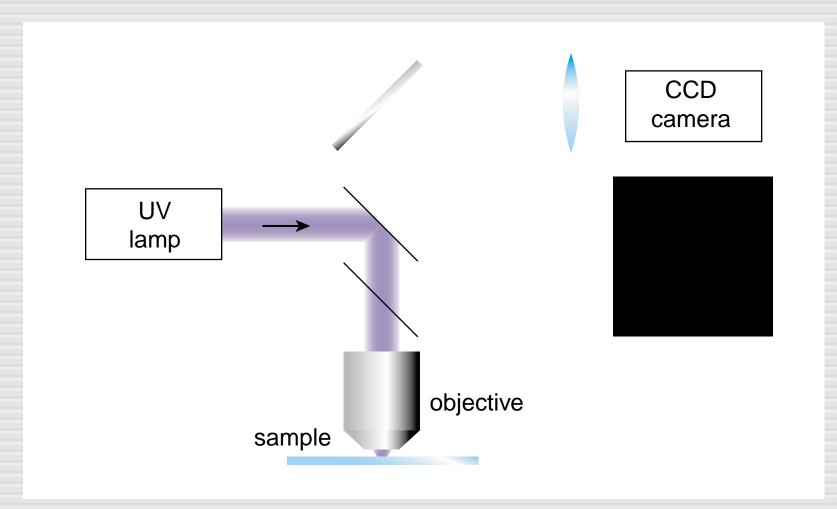
epi-fluorescence microscope



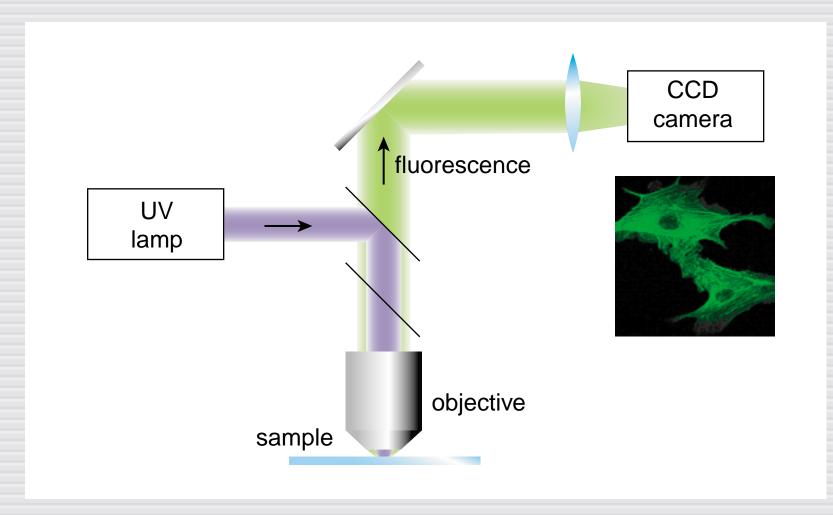
mount fluorescently tagged sample



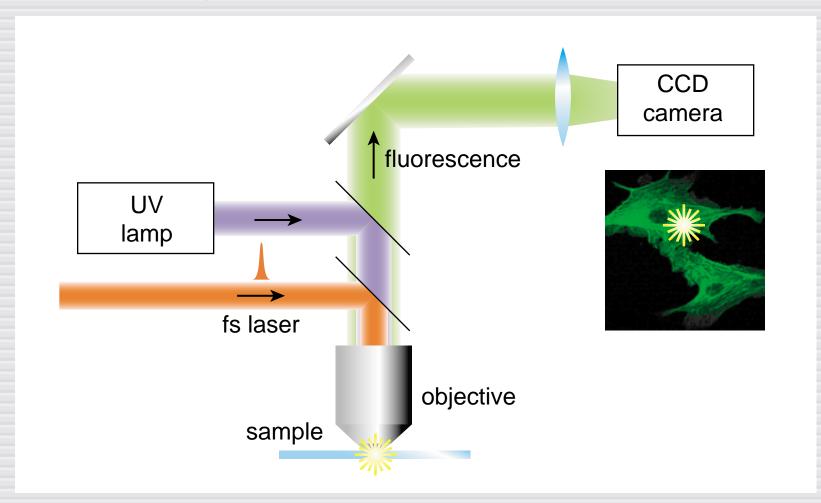
UV illumination...

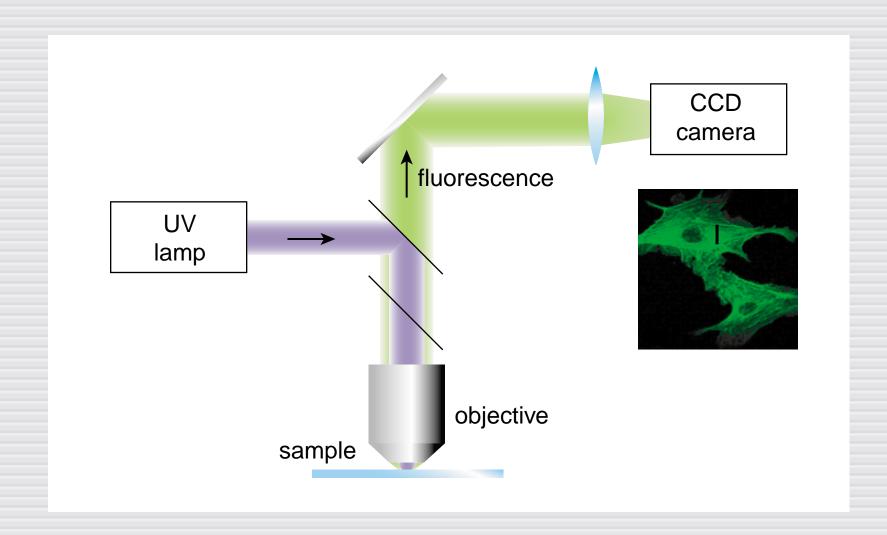


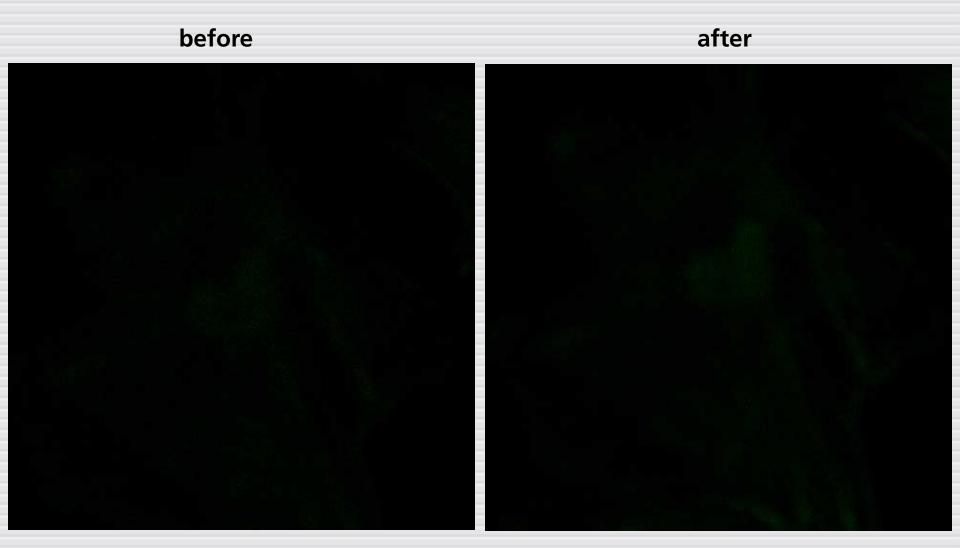
... causes fluorescence



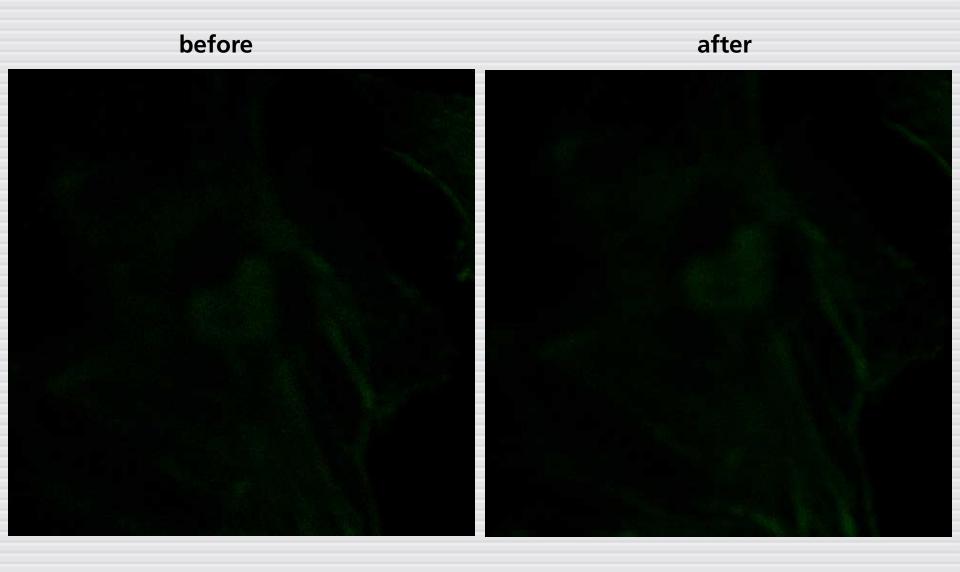
process with fs laser beam

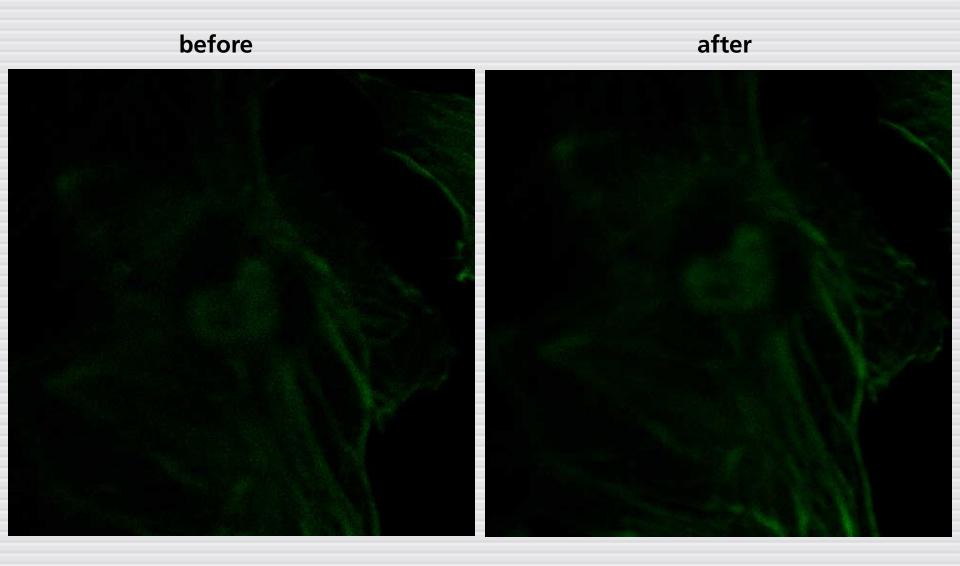


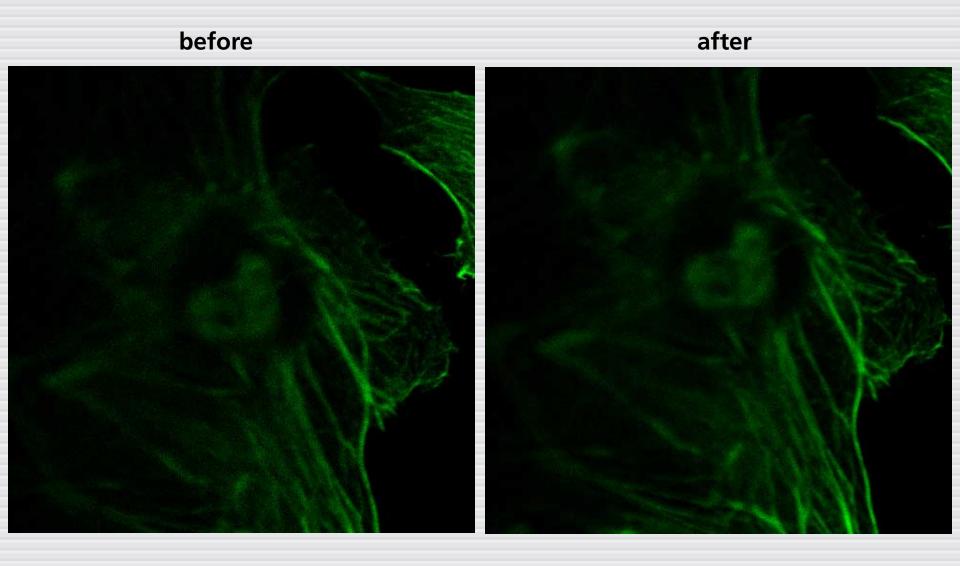


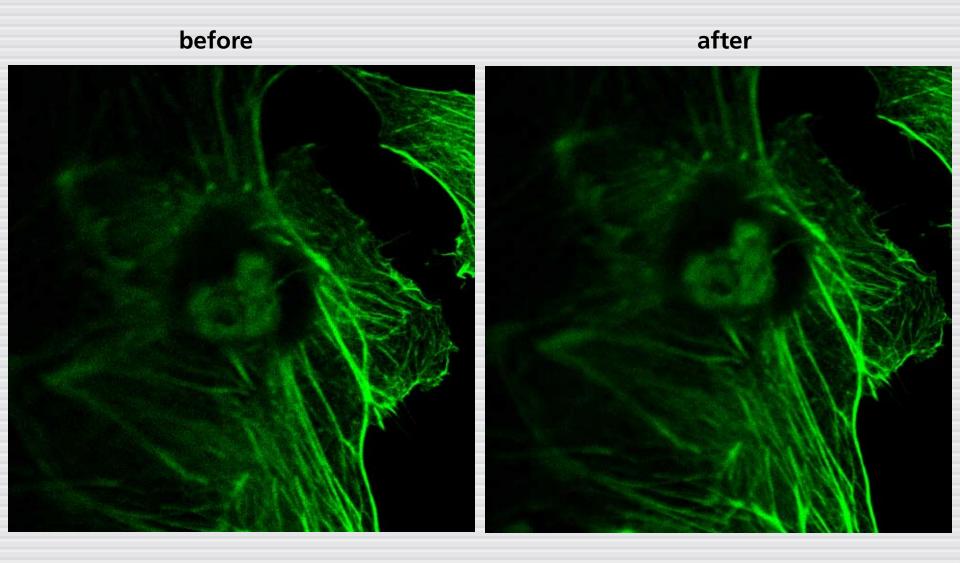


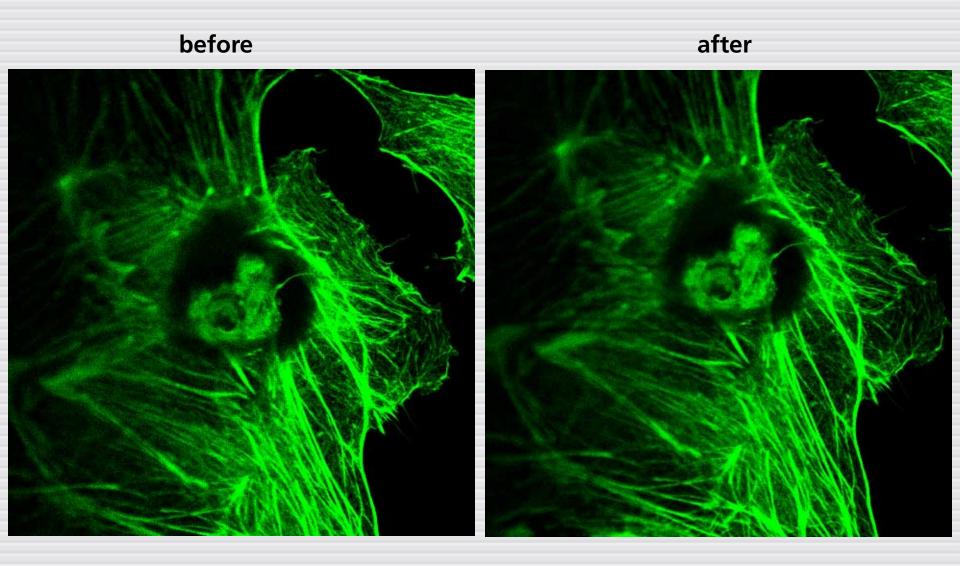
examine in confocal microscope

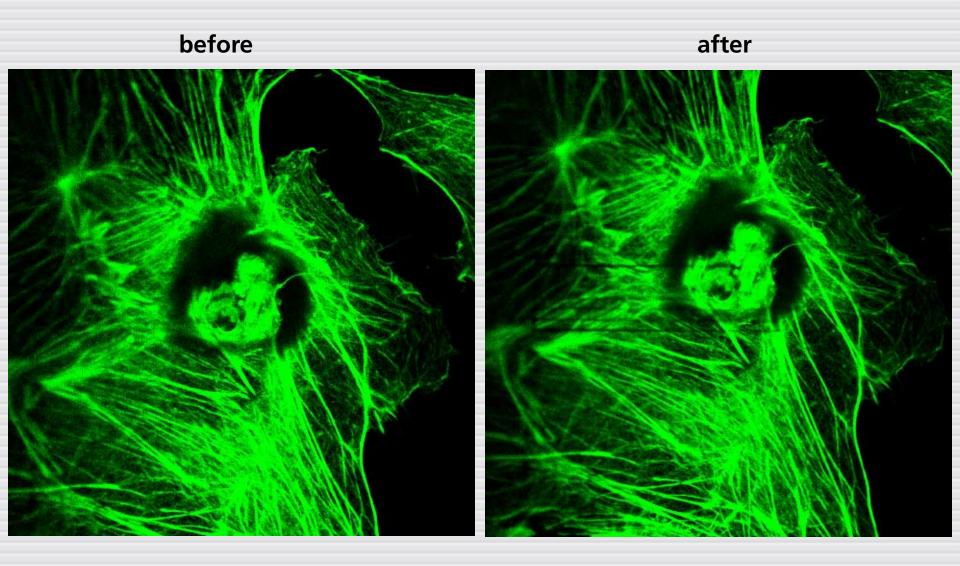


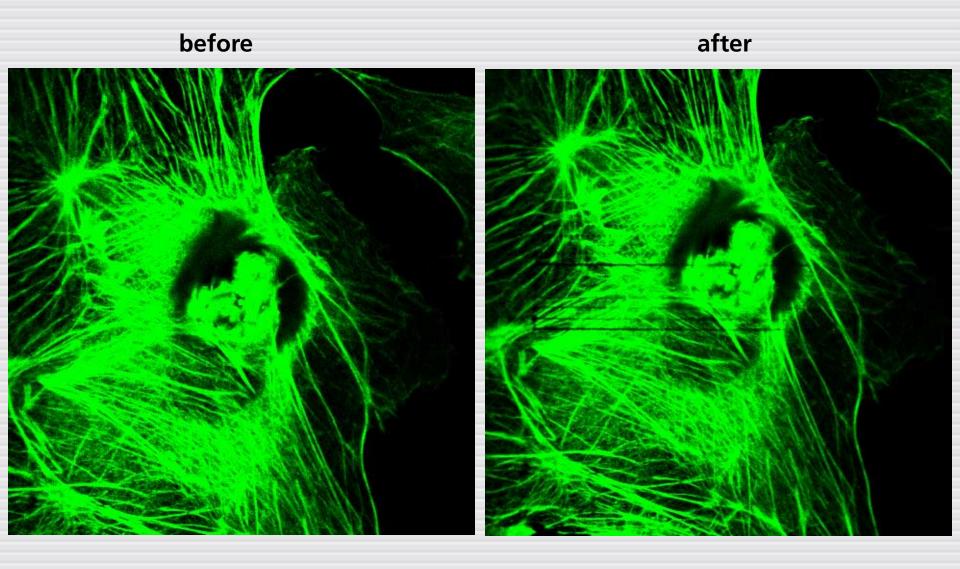


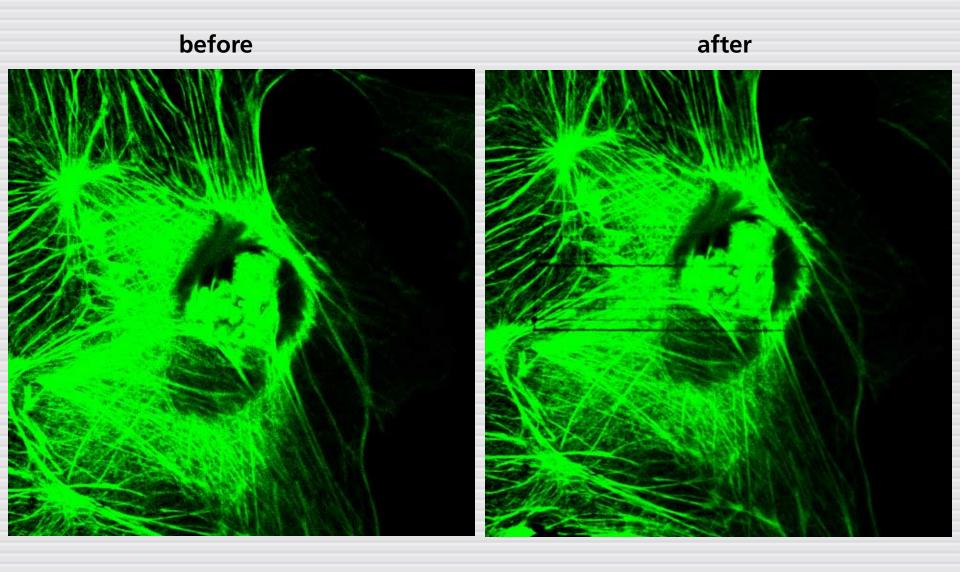


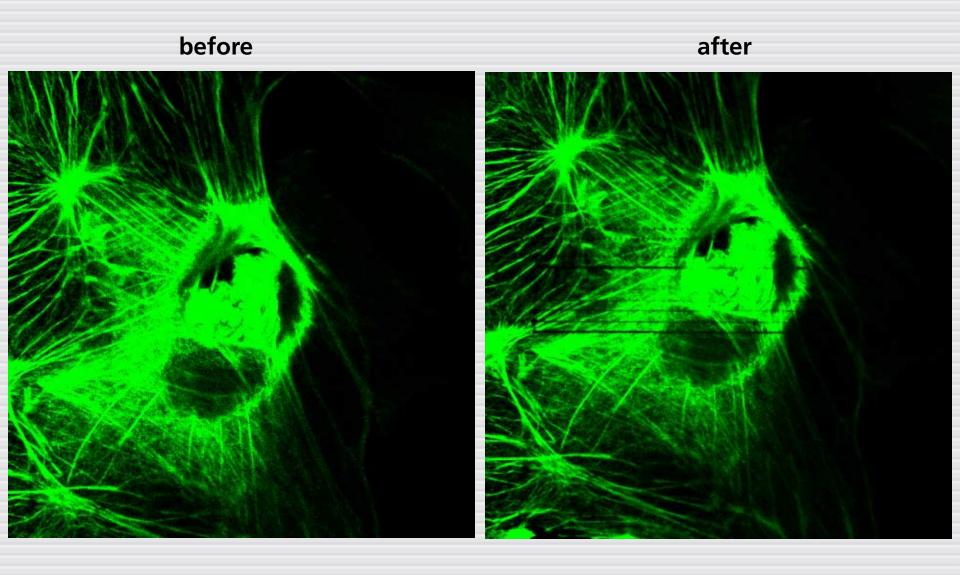


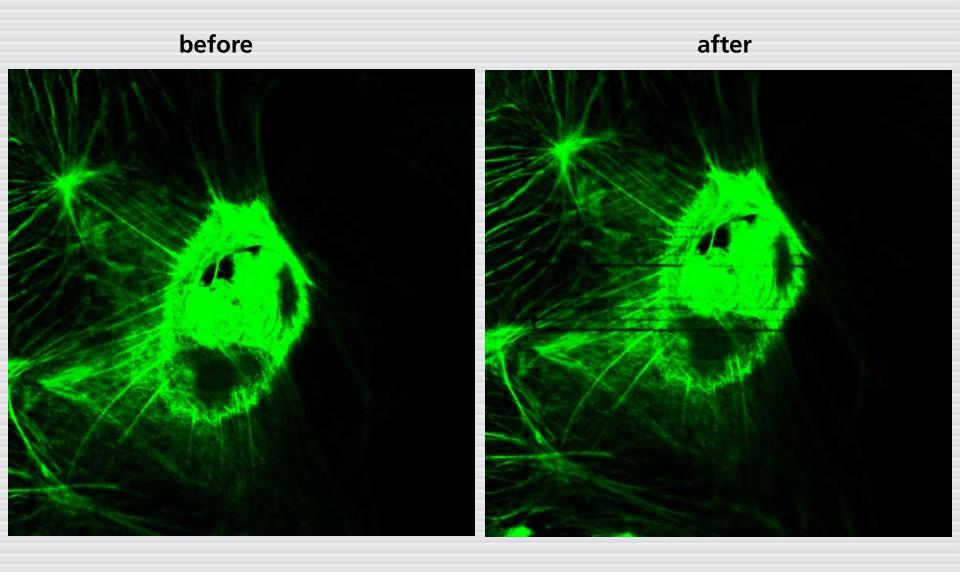


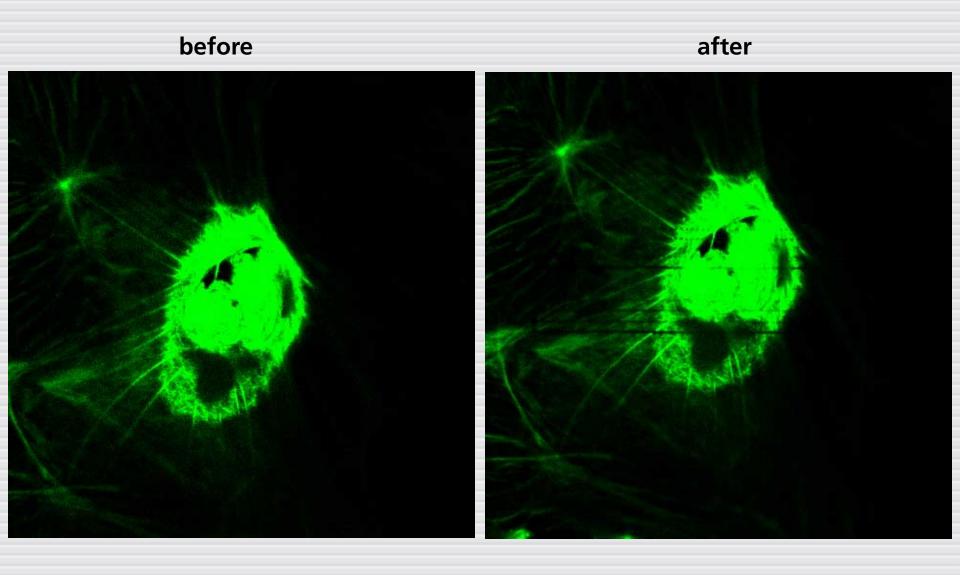


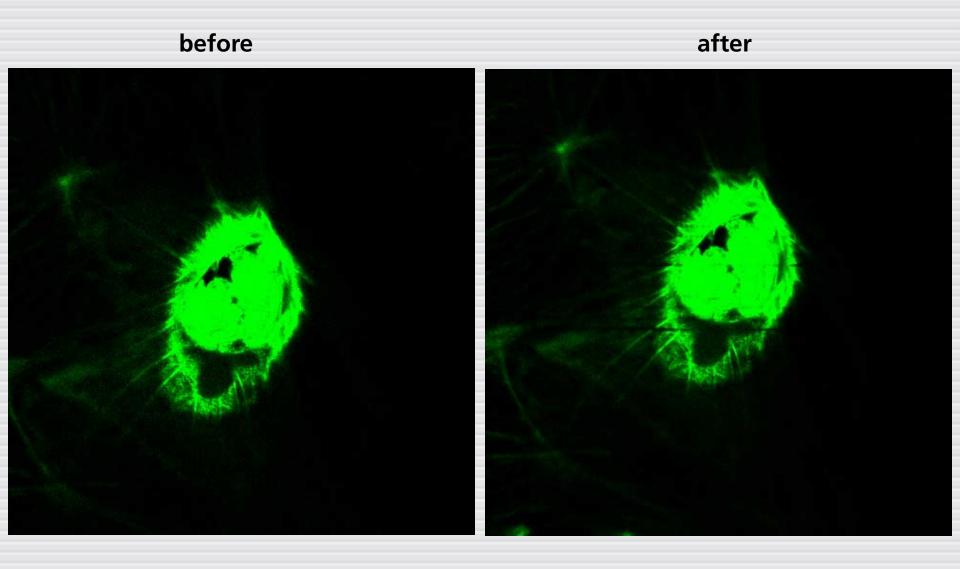


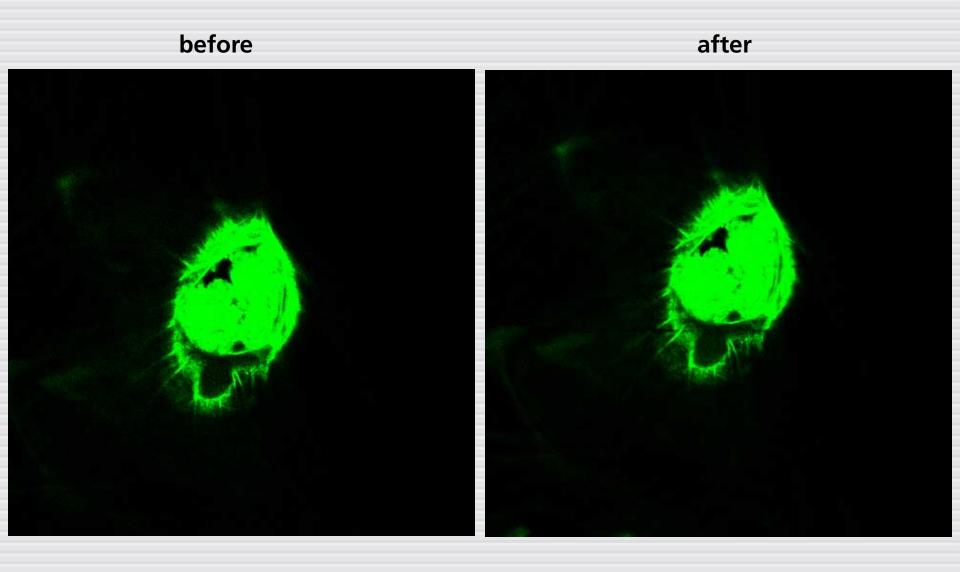


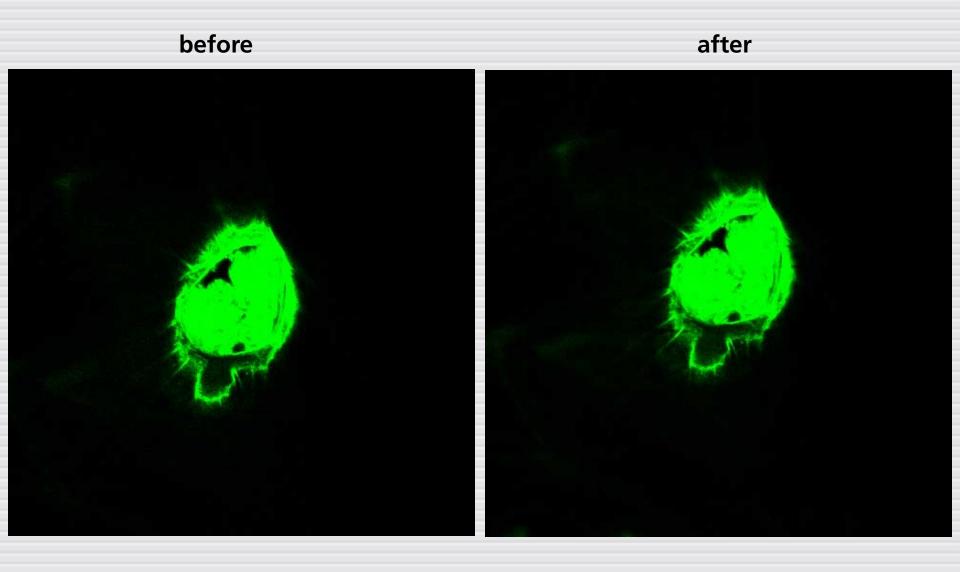


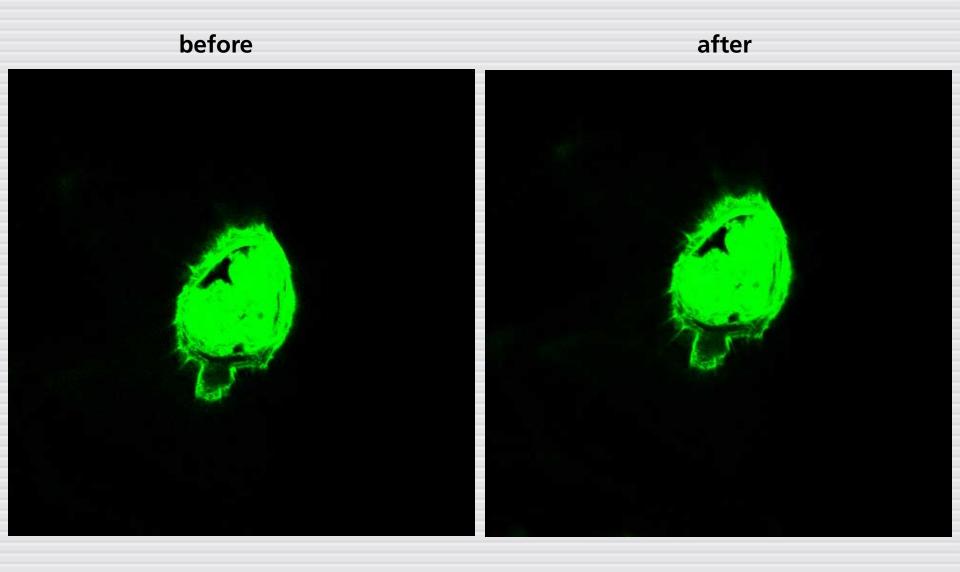


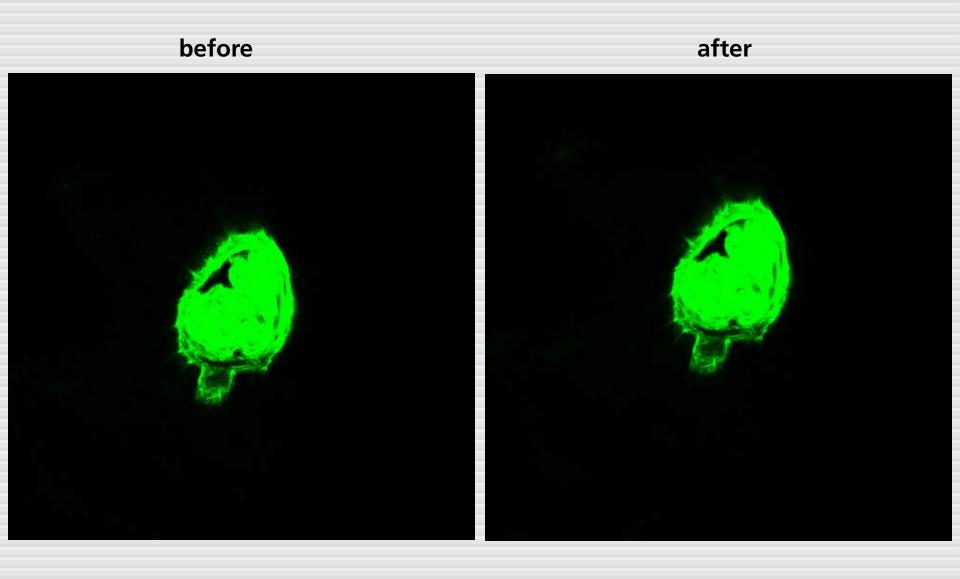


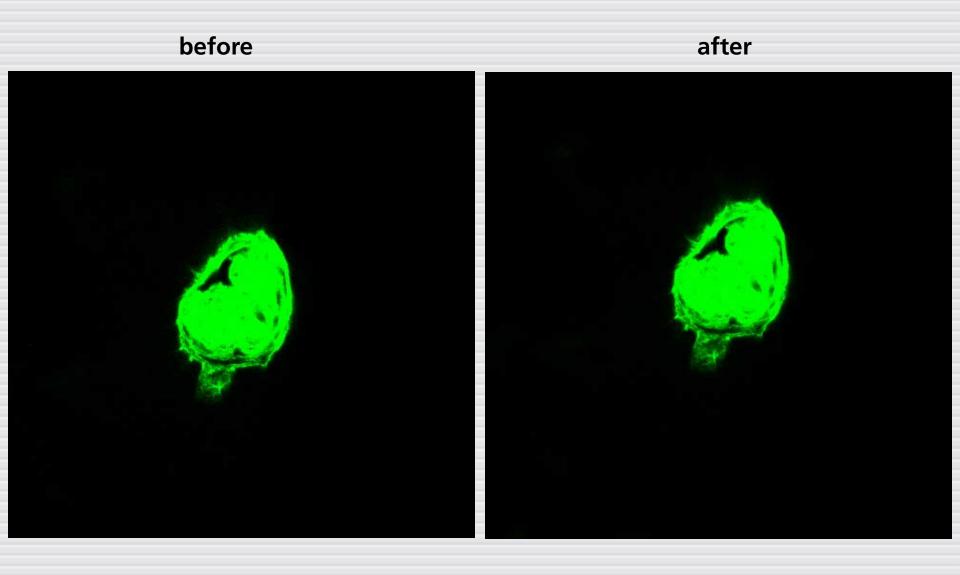


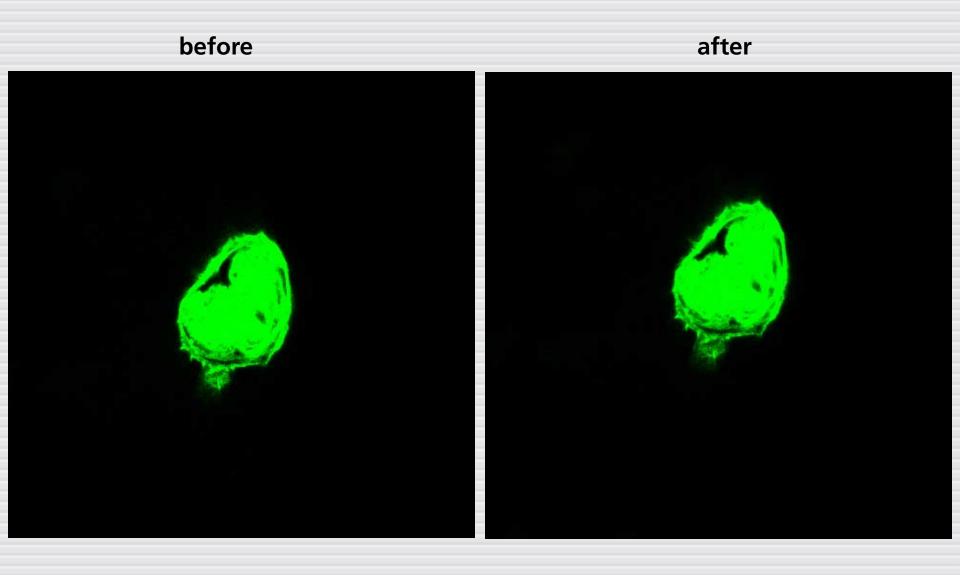


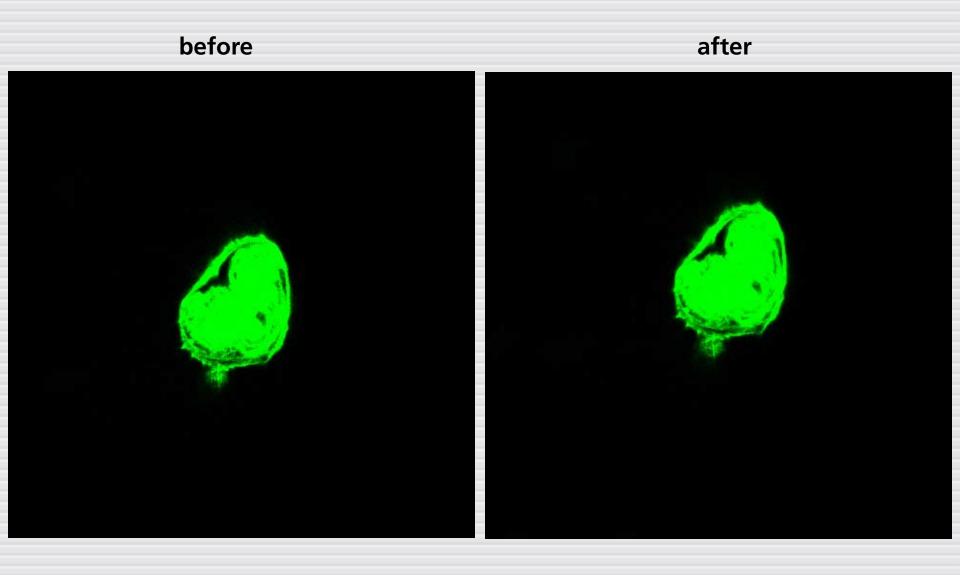


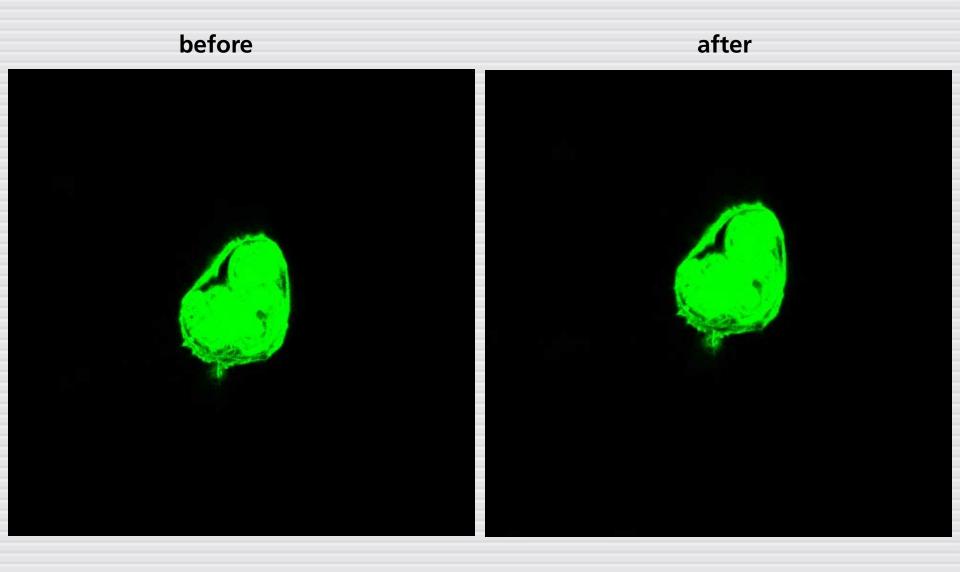


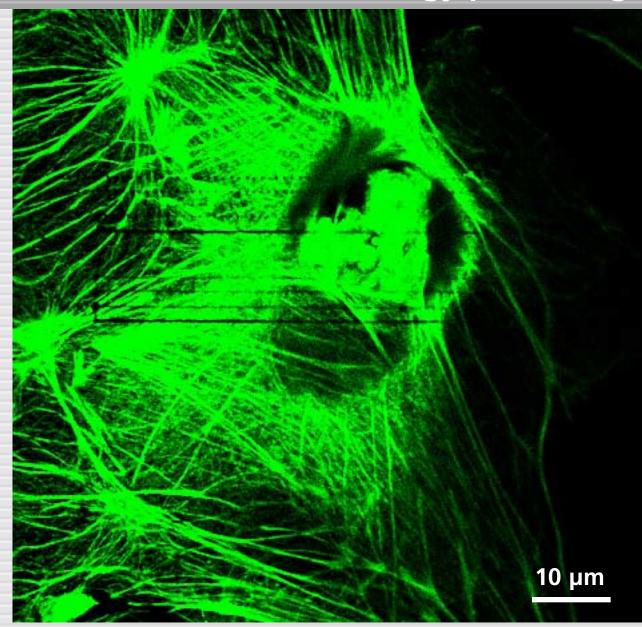


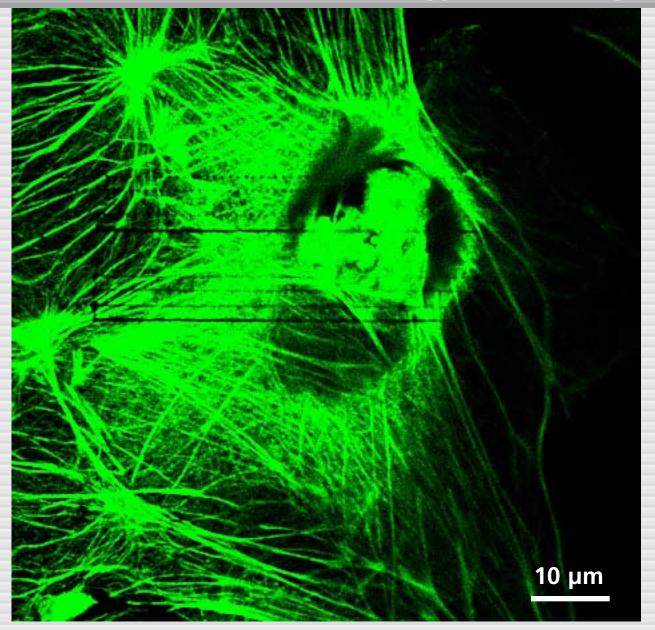


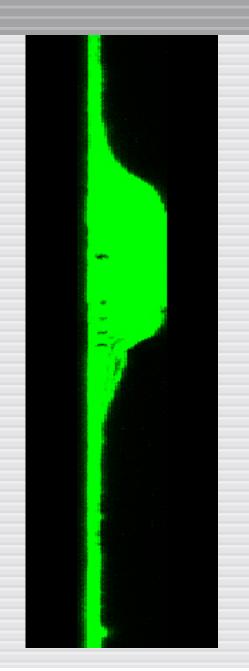


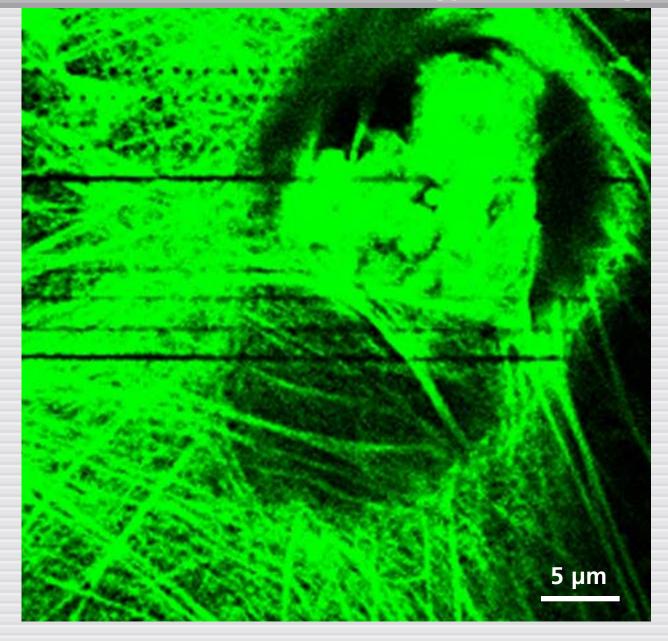


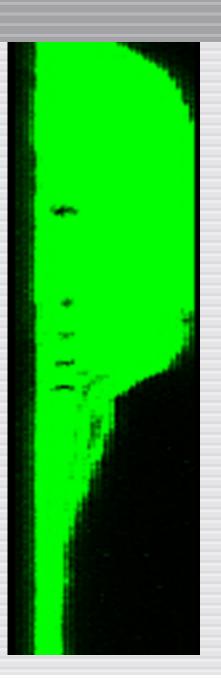


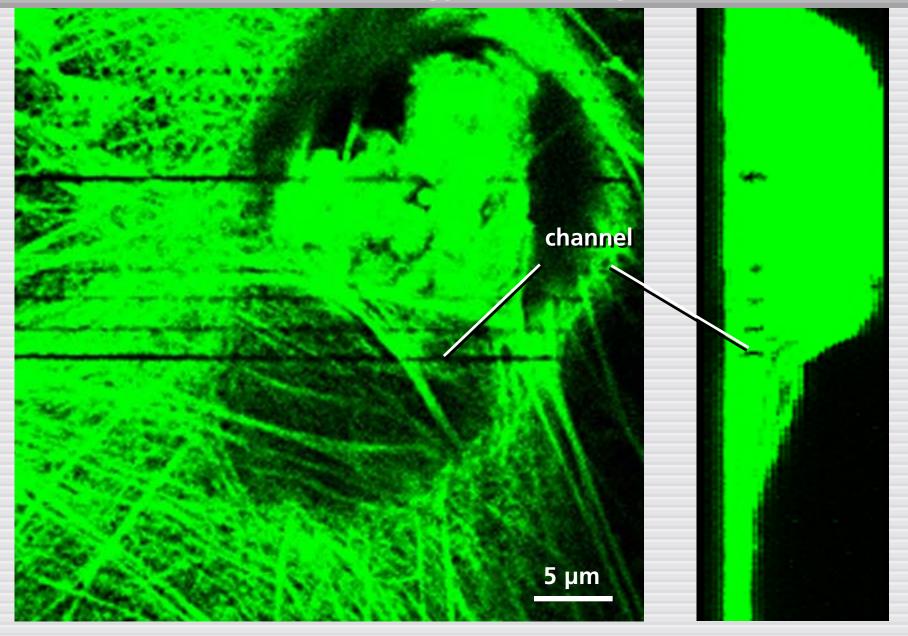


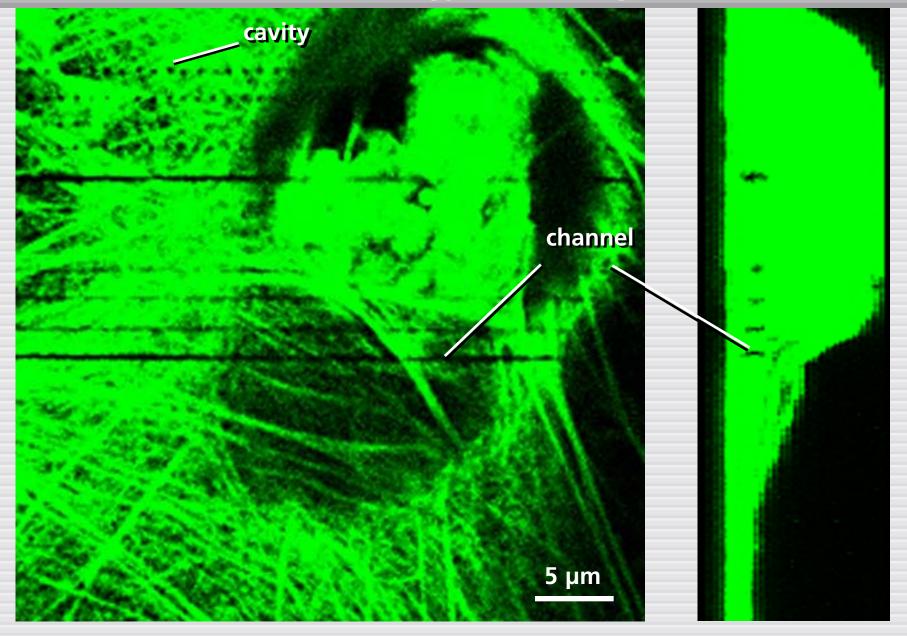


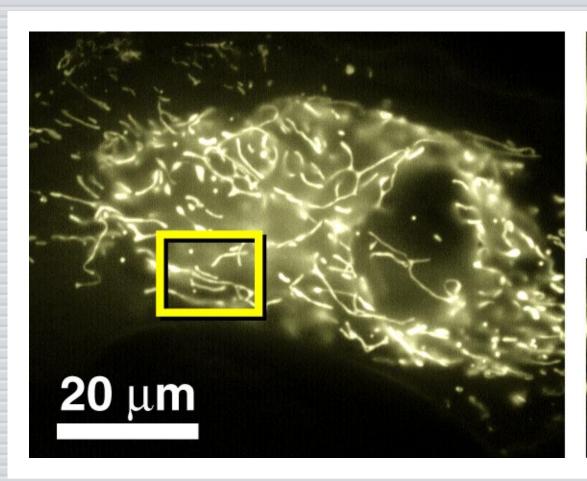


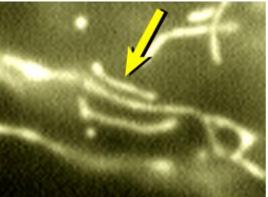


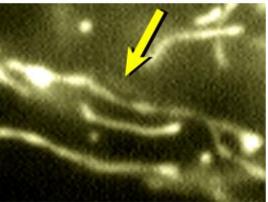


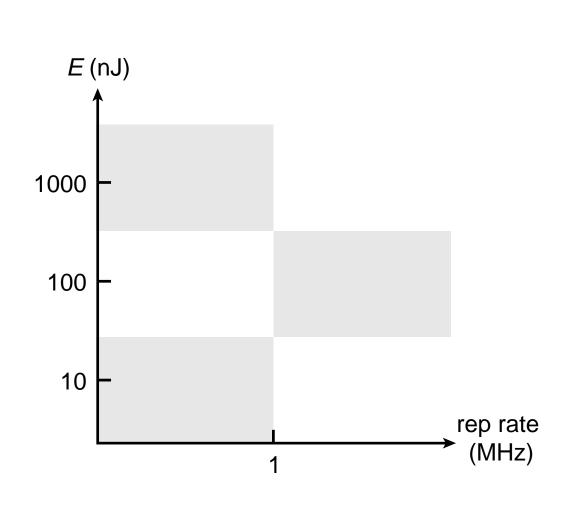


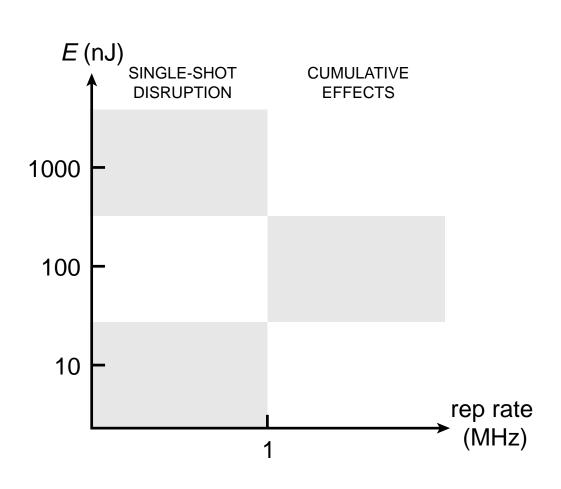


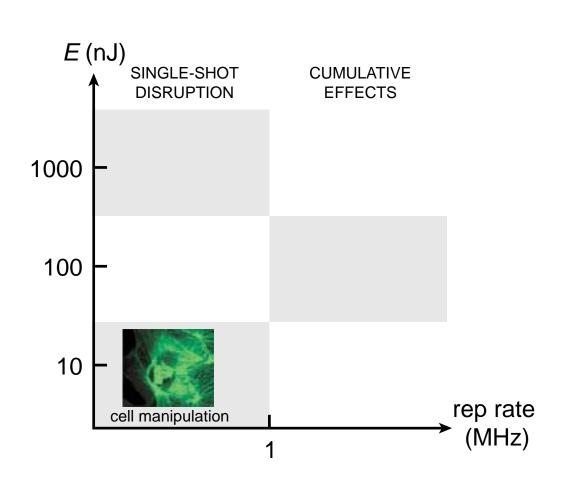


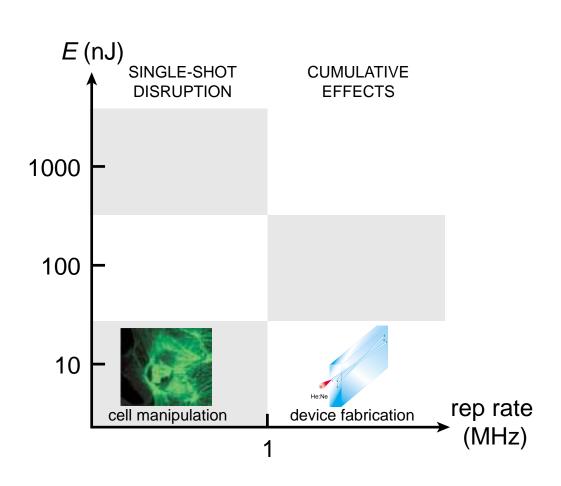


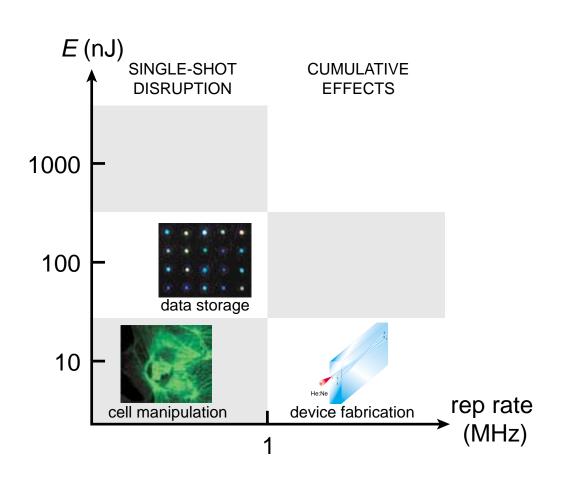


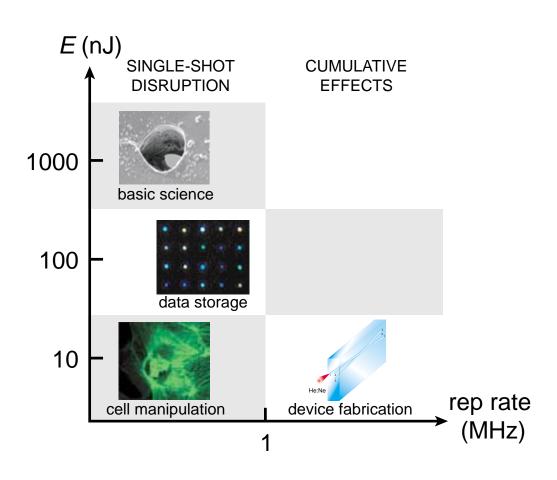












Conclusions

- stellar conditions
- precision micromachining
- exciting new applications



Funding: National Science Foundation Harvard Office of Technology and Trademark Licensing

Acknowledgments:
Prof. Nico Bloembergen (Harvard University)
Willie Leight (Yale University)
Yossi Chai (Sagitta, Inc.)

For a copy of this talk and additional information, see:

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