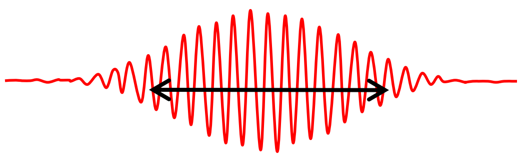
Stress dynamics of femtosecond laser-induced bulk machining inside single crystals

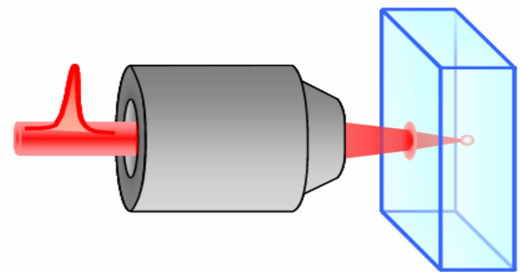
○Masaaki Sakakura
Kyoto University, Kyoto, JAPAN 615-8520
msakakura@saci.kyoto-u.ac.jp

Femtosecond laser processing inside transparent materials

Strong electromagnetic field
in a short time



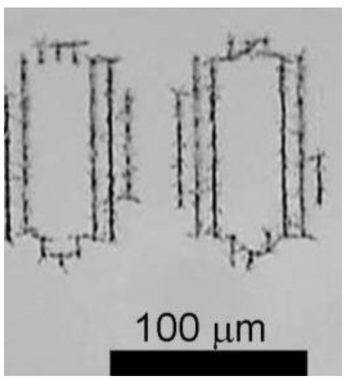
$<10^{-12}$ second



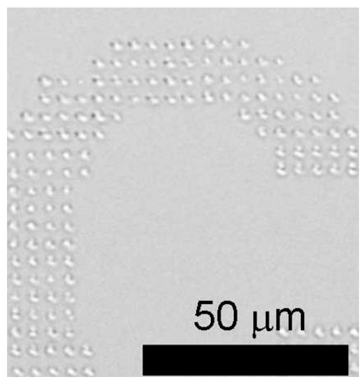
Nonlinear light absorption

Low energy threshold

Smooth refractive index distribution
Inside transparent materials

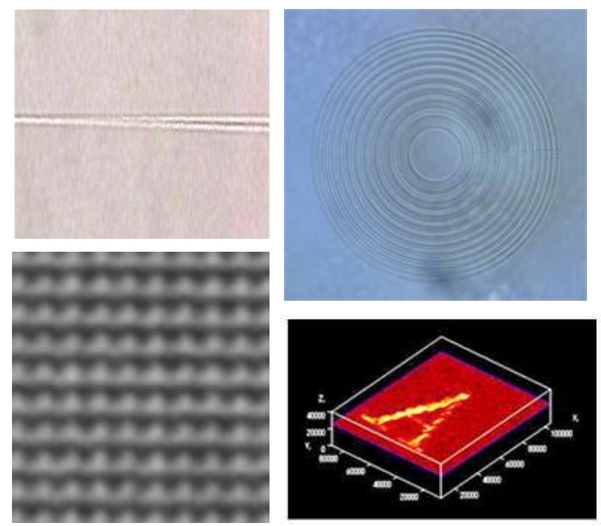


with a ns laser



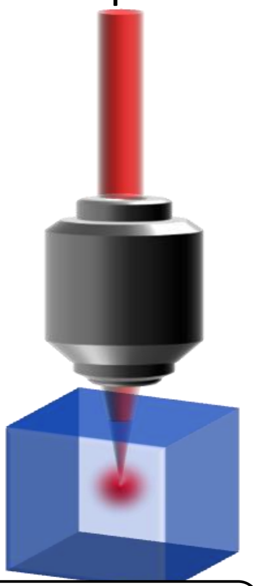
with a fs laser

Various optical devices



Modification inside Transparent Materials with a fs laser

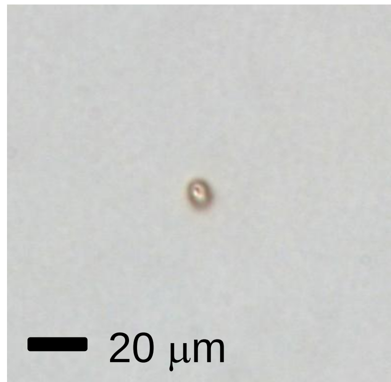
<1 μJ
<1 ps



Nonlinear light absorption

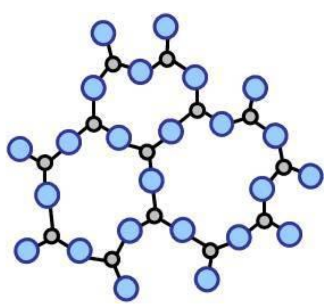
Modification only around the focal region

Glasses



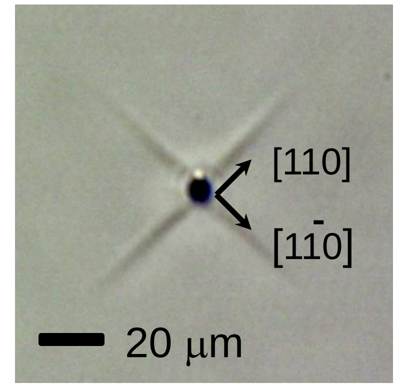
E. N. Glezer *et al*.,
Opt. Lett. **21**, 2023 (1996)

Isotropic or random modification



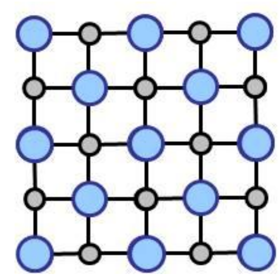
Crystals

MgO



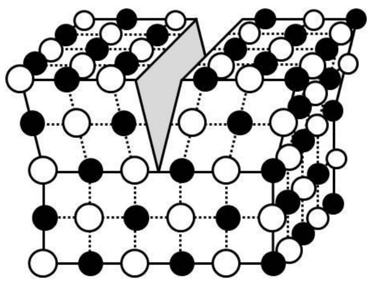
Kanehira *et al*.,
Appl. Phys. Lett. **90**, 163110 (2007)

Modification in the specific directions in long range

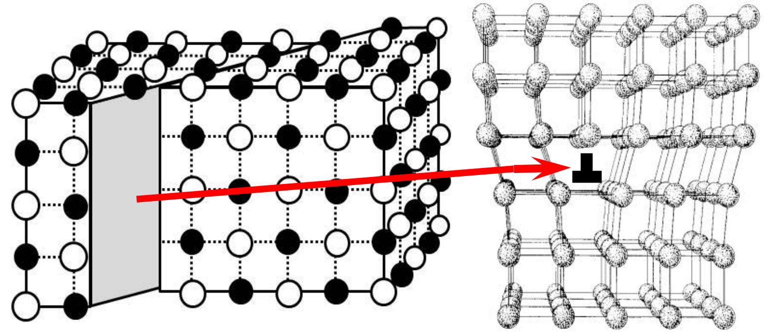


Two important fractures inside crystals

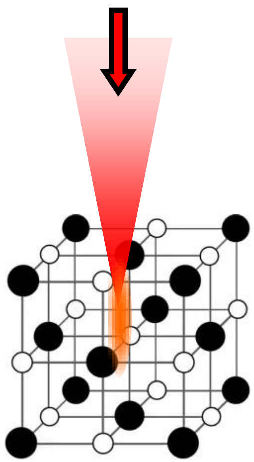
Cleavage

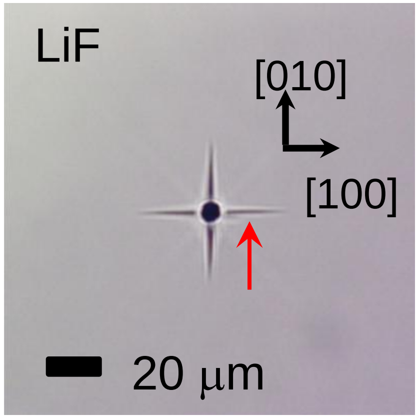


Slip and Dislocation (Line defect)

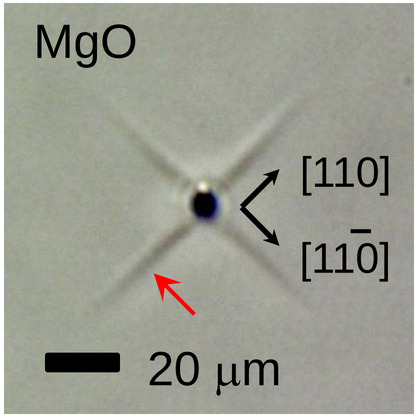


Ex: Inside rock-salt crystals





Cleavages
<100>



Dislocation bands
<110>

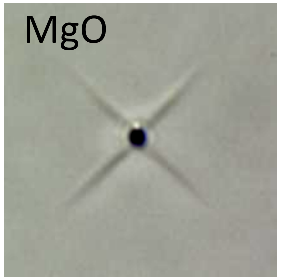
Object of this study

●Why is the deformation direction always same in single crystals?

✓ Crystals have the cleavage planes and slip planes. (According to Crystallography)

But, **the stress which induces the deformation** has not been elucidated.

●Why are the deformations different in crystals of the same crystal system?

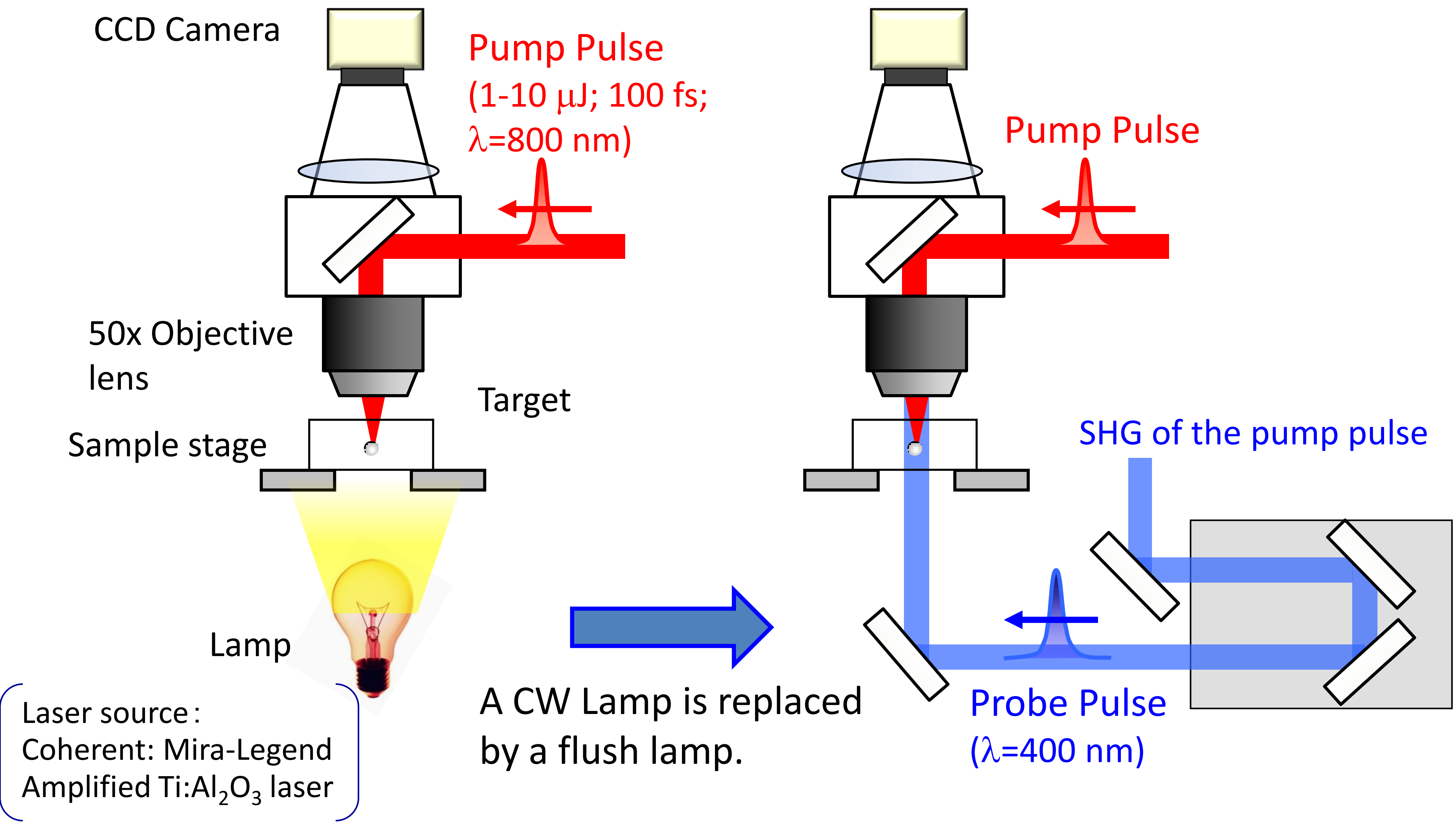


They belong to the same crystal system,
but the deformations are different…

1. Observation of the dynamics of the deformation.
2. Observation of the transient stress.
3. Elucidation of the relation between the transient stress distribution and the directional modification inside single crystals.

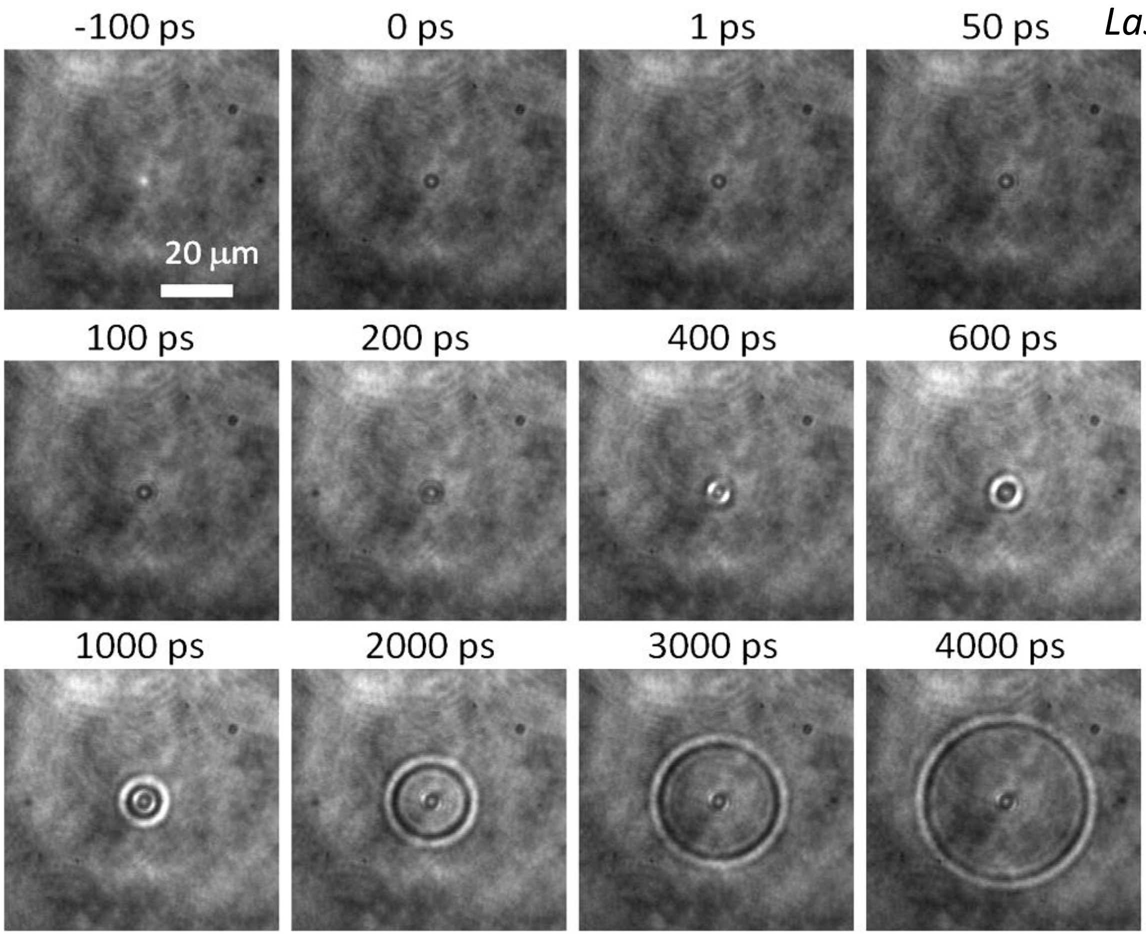
Observation of dynamics in laser induced damage

Normal laser machining system **With time-resolved observation**



Dynamics after the photoexcitation inside a glass

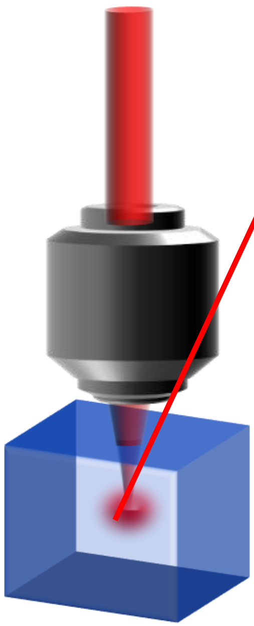
Laser Chemistry, (2010) 2010, 1-15.



The generation and propagation of a pressure wave (stress wave).

Fast heating and thermal expansion occurred in the photoexcited region.
(much faster than the elastic relaxation.)

Dynamics after photoexcitation



Photoexcitation

~1 ps

Temperature is elevated

~1 ps

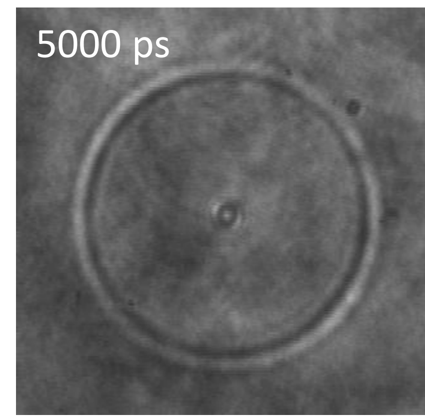
Thermal stress is generated

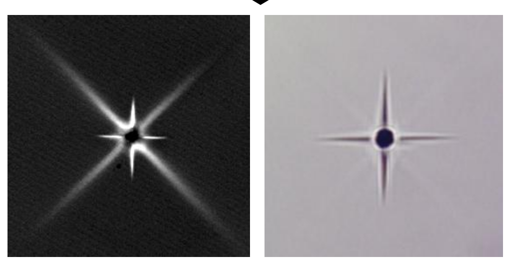
~100 ps

Stress relaxation starts

Stress wave

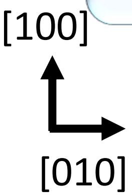
Stress wave inside a glass





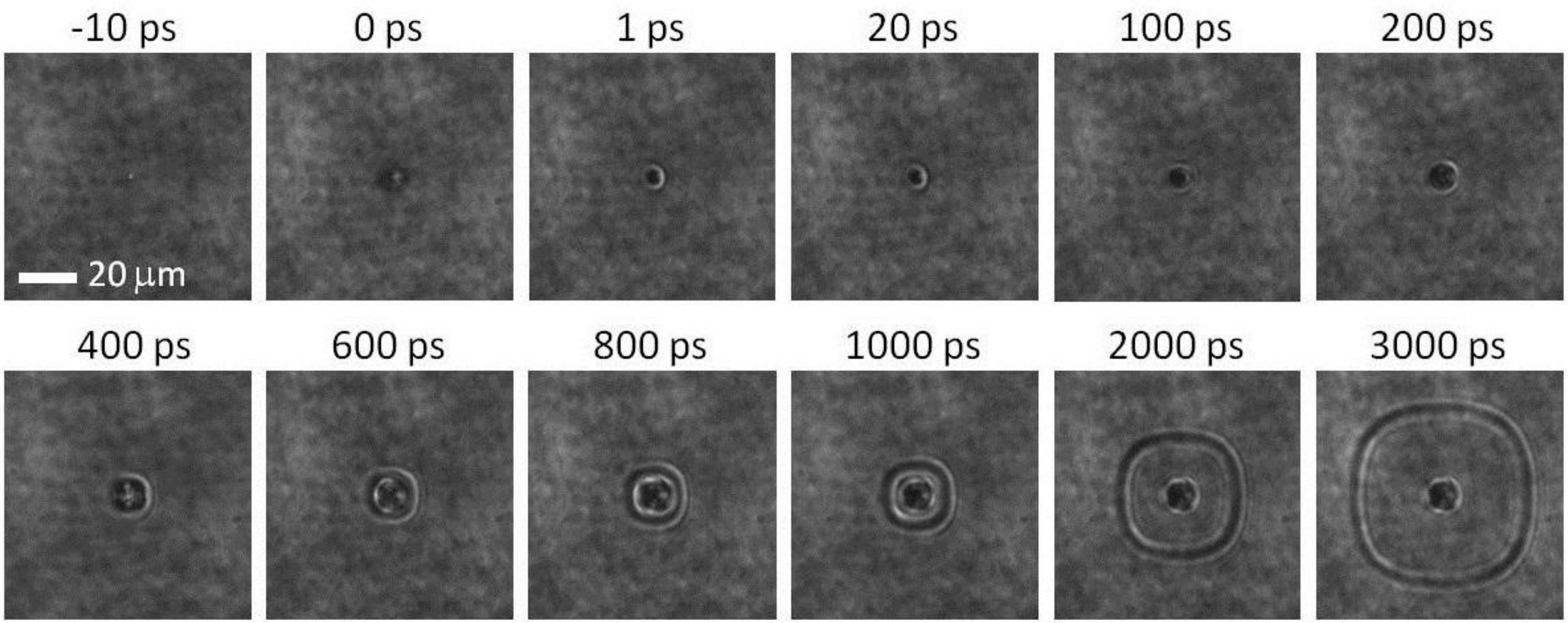
Permanent structural change

Dynamics inside crystals



inside MgO(001) (10 μJ/pulse)

Sakakura et al., Opt. Express, (2011) 19, 17780.



✓A rounded-square-shaped stress wave

Sound Velocities (Theory)
- <100> : 9.11km/s
- <110> : 9.92km/s

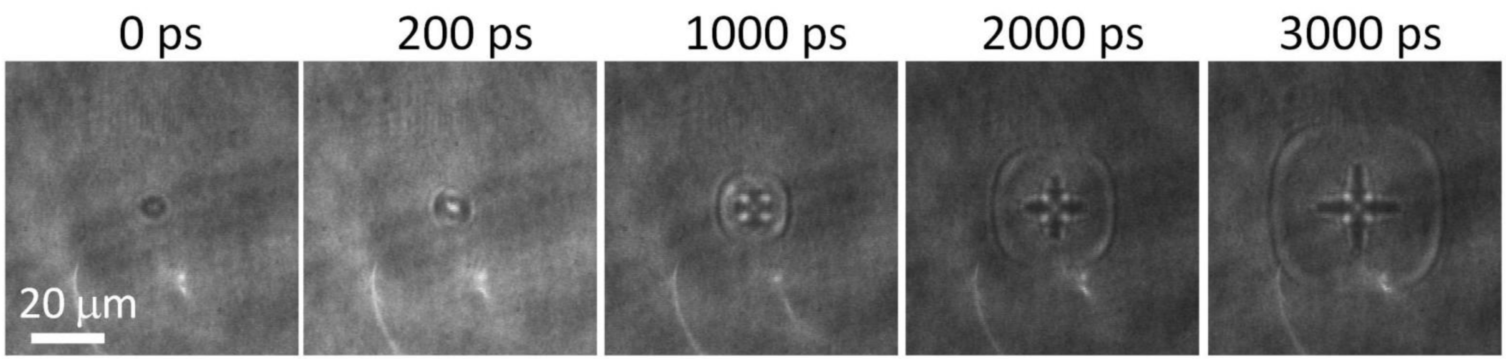
Dynamics inside crystals

Sakakura et al., Opt. Express, (2011) 19, 17780.

[100]

[010]

inside LiF(001) (10 μJ/pulse)



✓A rounded-square-shaped stress wave.

✓Cleavages propagate in <100>.

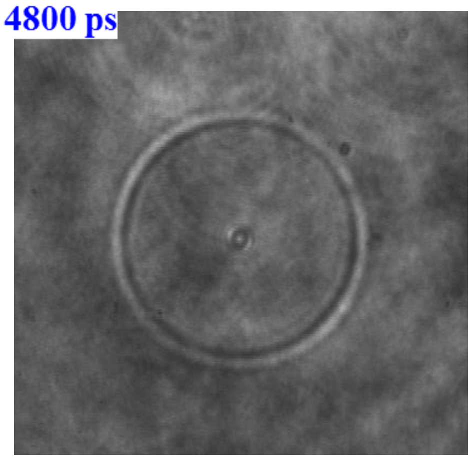
Sound Velocities (Theory)

- <100> : 6.48 km/s
- <110> : 7.08 km/s

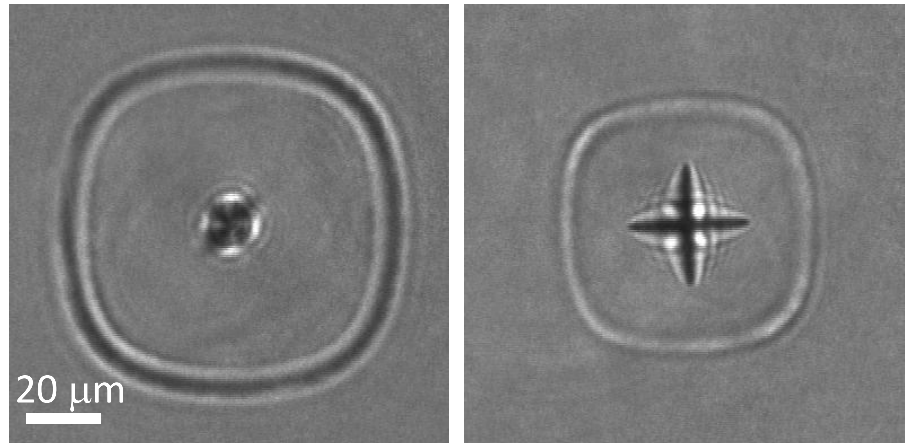
The characteristic shape of the stress wave is due to the anisotropic elastic property of the crystal.

Difference between glass and crystal

Glass



Crystal



✓The **shape of the stress wave** depends on material.

Inside a glass	**Inside a crystal**
Both amplitude and direction of the stress are isotropic.	Both amplitude and direction of the stress depend on the direction from the photoexcited region.

The transient stress distributions may induce the structural changes in the specific directions inside crystals.

⇨ **The stress must be visualized.**

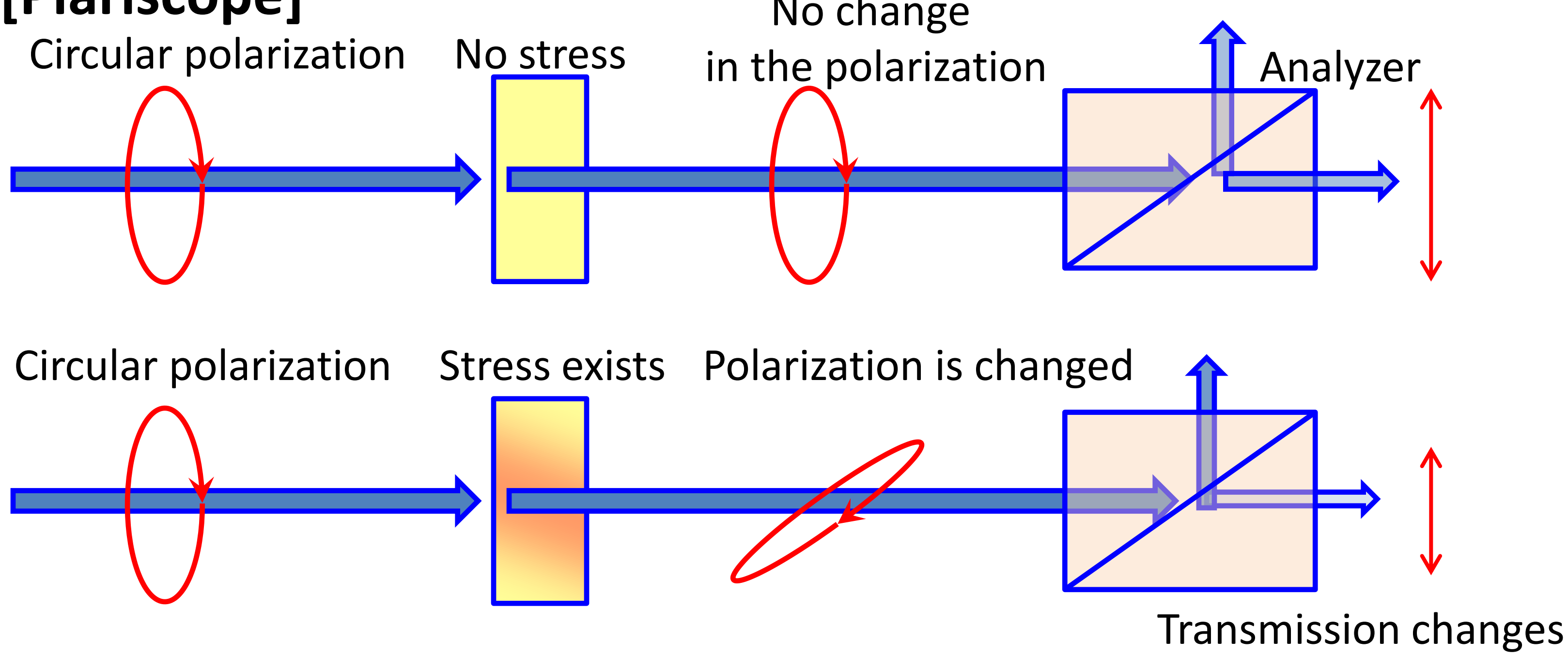
Visualization of stress

Normal transmission imaging is not sensitive to stress inside materials.

Stress imaging by polariscope

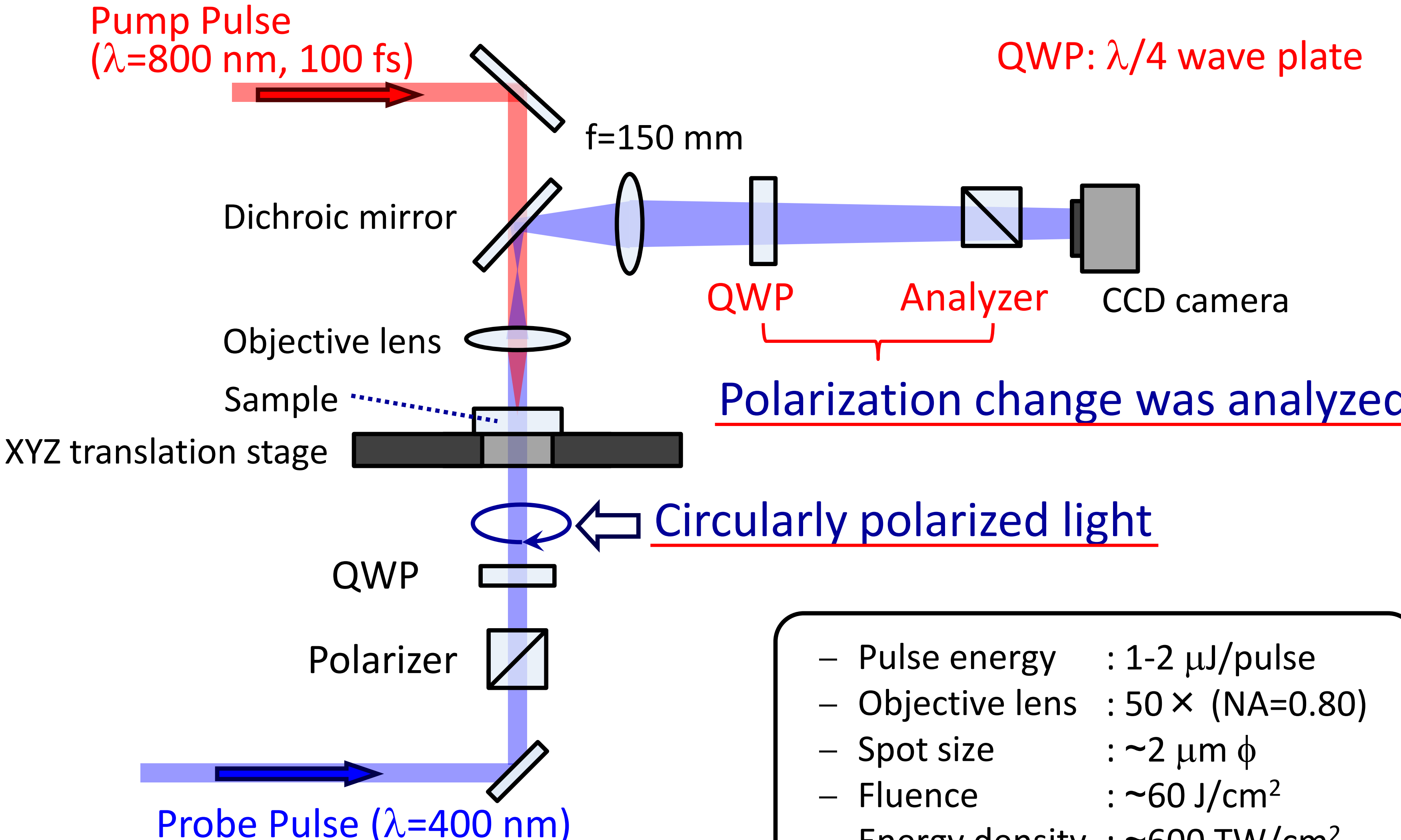
Stress → Strain → Birefringence

[Plariscope]



The amplitude and direction of the stress can be obtained by analyzing the polarization change.

Transient birefringence imaging system



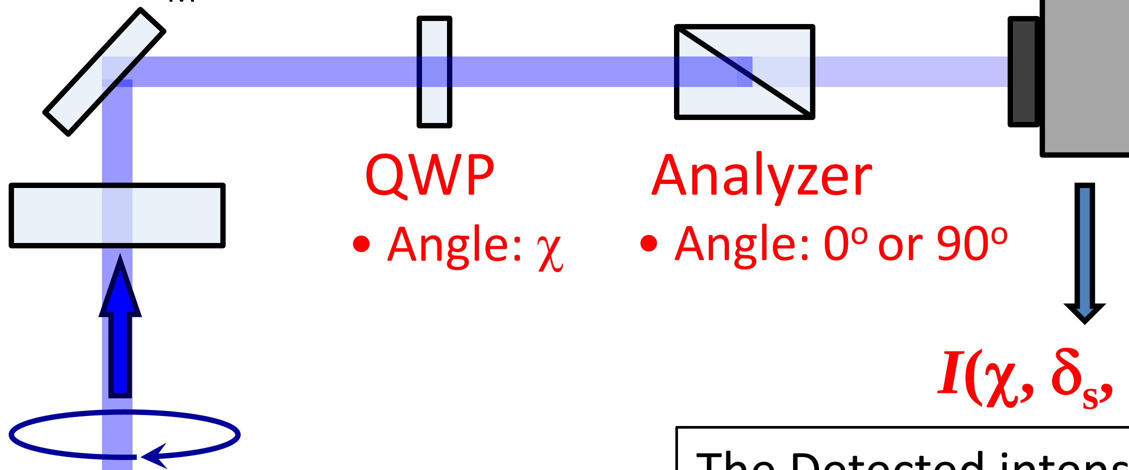
– Pulse energy	: 1-2 μJ/pulse
– Objective lens	: 50× (NA=0.80)
– Spot size	: ~2 μm ϕ
– Fluence	: ~60 J/cm^2
– Energy density	: ~600 TW/cm^2

Analysis of birefringence

(QWP=λ/4 waveplate)

Retardance after the mirror :δ_M (known value)

Birefringence
- Retardance : δ_s
- Azimuth: θ_s



$$\boldsymbol{I(\chi, \delta_s, \theta_s)}$$

Circular polarized light
(Intensity=$\boldsymbol{I_0}$) $\sqrt{\frac{I_0}{2}}\begin{pmatrix}1\\ i\end{pmatrix}$

The Detected intensity is the function of χ, δ_s, θ_s.

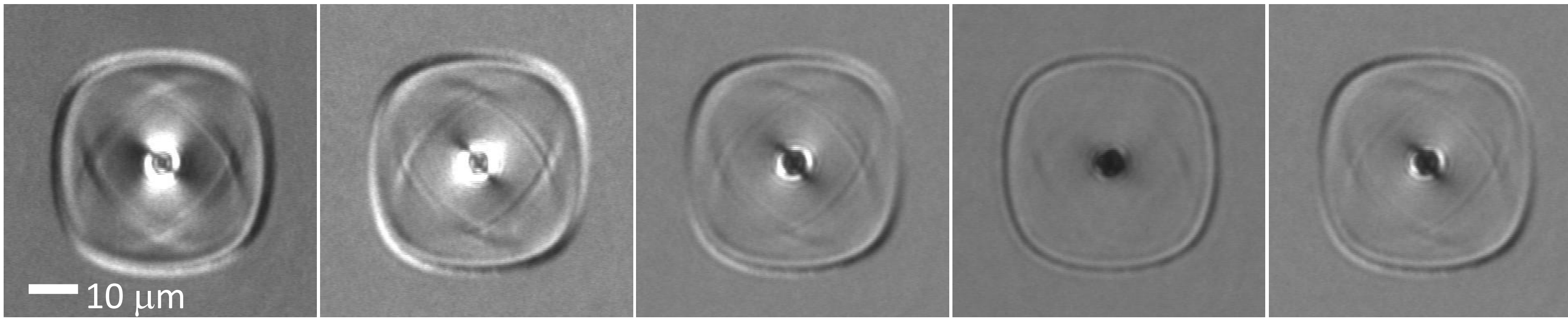
(M(δ,θ): Jones matrix)

$$I(\chi,\delta_s,\theta_s)=\frac{1}{2}I_0\left|\underbrace{\begin{pmatrix}1 & 0\end{pmatrix}}_{\text{Analyzer}}\cdot\underbrace{\mathbf{M}(\pi/2,\chi)}_{\text{QWP}}\cdot\underbrace{\mathbf{M}(\delta_M,0°)}_{\text{Mirror}}\cdot\underbrace{\mathbf{M}(\delta_s,\theta_s)}_{\text{Sample}}\cdot\begin{pmatrix}1\\ i\end{pmatrix}\right|^2$$

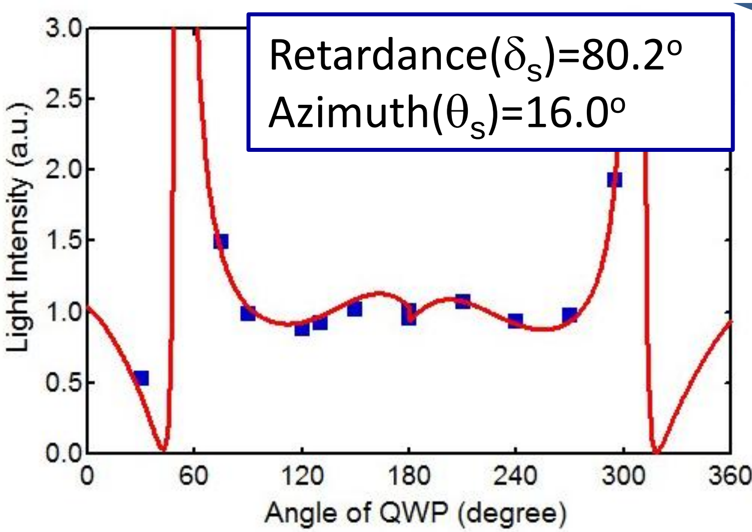
Analysis to obtain the birefringence distribution

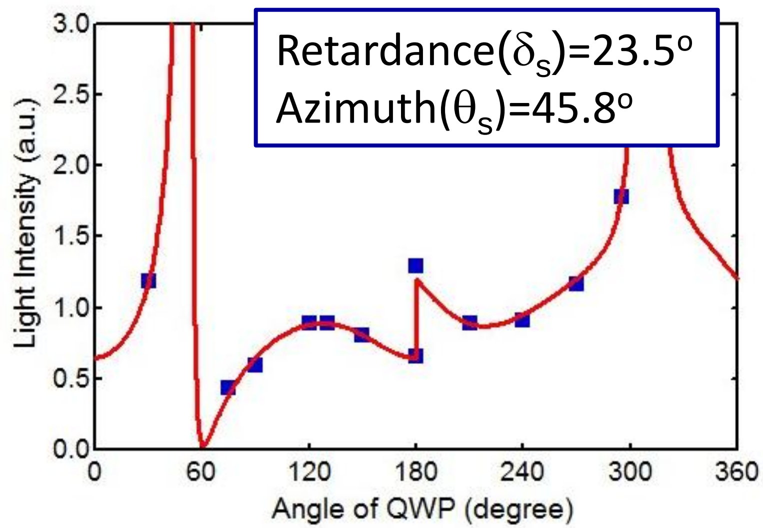
Transmitted light images as a function of χ (Angle of the QWP).

$\chi=30^{O}$ $\chi=75^{O}$ $\chi=90^{O}$ $\chi=120^{O}$ $\chi=180^{O}$



Fitted by $I(\chi, \delta_s, \theta_s)$ (Fitting parameters: δ_s, θ_s)

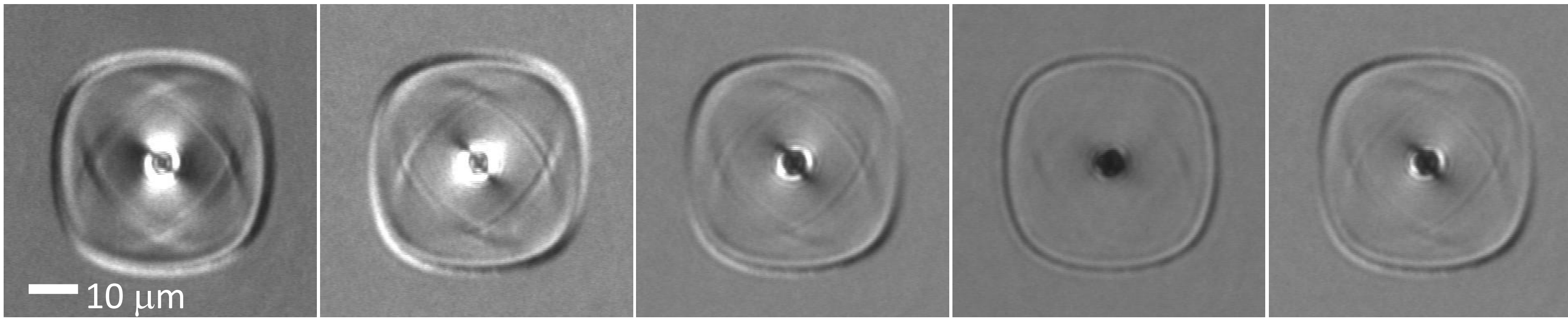




Analysis to obtain the birefringence distribution

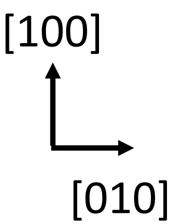
Transmitted light images obtained as a function of χ (Angle of the QWP).

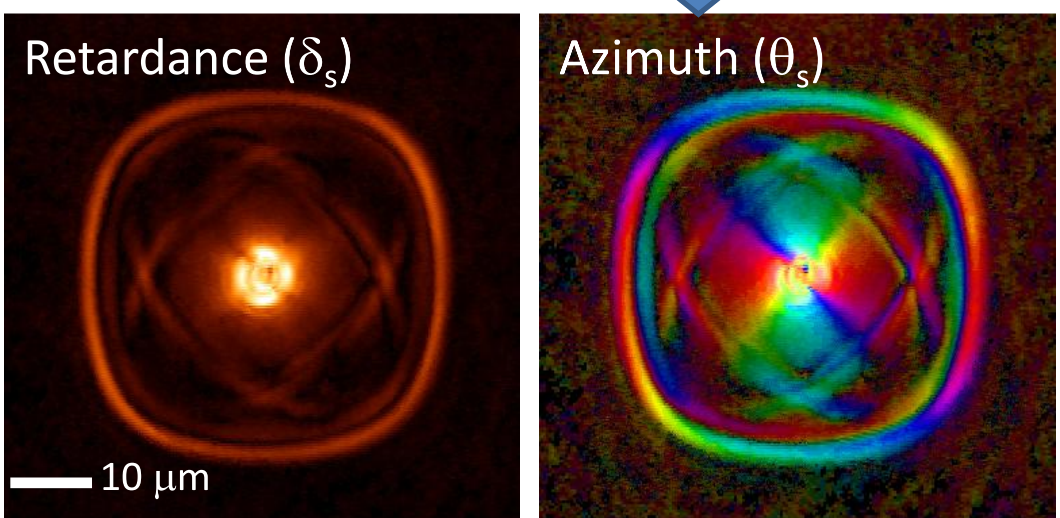
$\chi=30^{\circ}$ $\chi=75^{\circ}$ $\chi=90^{\circ}$ $\chi=120^{\circ}$ $\chi=180^{\circ}$



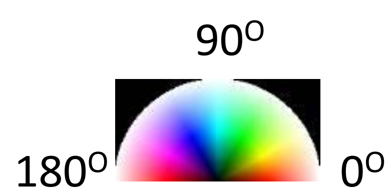
Sakakura et al., SPIE Laser Damage (2012)

Fitting in all the region





Relation between Color and Azimuth

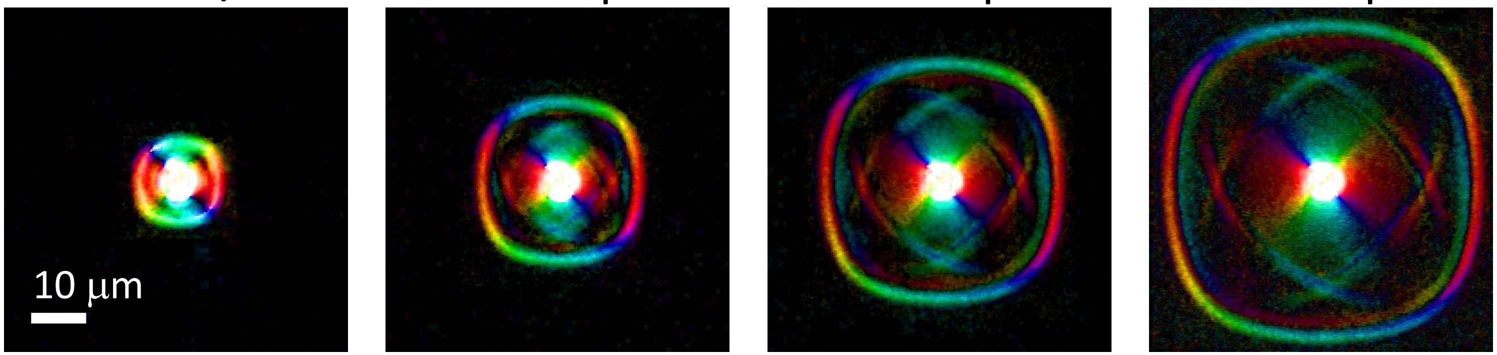


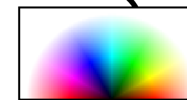
Dynamics of birefringence

Tochio et al., Jpn. J. Appl. Phys., 51(2012)126602.

MgO (100); 2 μJ/pulse

1000 ps 2000 ps 3000 ps 4000 ps

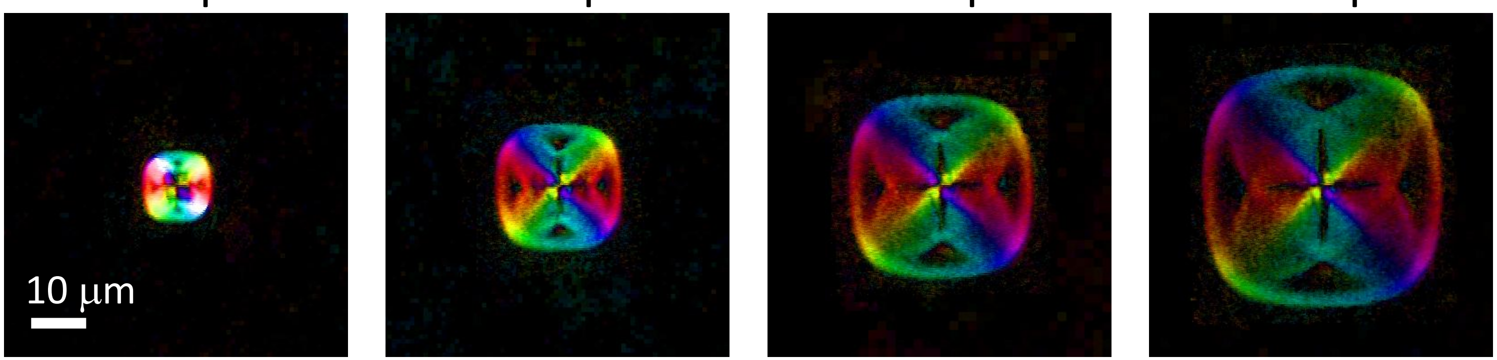




Color=Azimuth
Brightness
=Retardance

LiF (100); 2 μJ/pulse

1000 ps 2000 ps 3000 ps 4000 ps



- Another slow stress wave was observed inside a main stress wave.

Primary stress wave→Longitudinal Secondary stress wave→Transverse

Birefringence to Strain

Relationship between dielectric constant change and strain

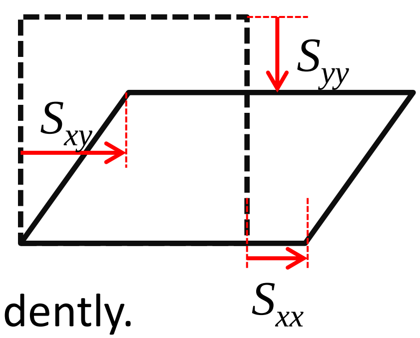
of Cubic crystals

$$\begin{bmatrix} (\Delta\varepsilon^{-1})_{xx} \\ (\Delta\varepsilon^{-1})_{yy} \\ (\Delta\varepsilon^{-1})_{zz} \\ (\Delta\varepsilon^{-1})_{yz} \\ (\Delta\varepsilon^{-1})_{zx} \\ (\Delta\varepsilon^{-1})_{xy} \end{bmatrix} = \begin{pmatrix} p_{11} & p_{12} & p_{12} & & & \\ p_{12} & p_{11} & p_{12} & & 0 & \\ p_{12} & p_{12} & p_{11} & & & \\ & & & p_{44} & & \\ & 0 & & & p_{44} & \\ & & & & & p_{44} \end{pmatrix} \begin{pmatrix} S_{xx} \\ S_{yy} \\ S_{zz} \\ 2S_{yz} \\ 2S_{zx} \\ 2S_{xy} \end{pmatrix}$$

ε : dielectric constant　　　$\{S_{ij}\}$: strain

$\{p_{\mathrm{ij}}\}$: Photoelastic constant (tensor)

$$\left|S_{xx} - S_{yy}\right| = \frac{\lambda\delta_S}{\pi d n_0^3}\left|\frac{\cos 2\theta_S}{p_{11} - p_{12}}\right| \qquad \left|S_{xy}\right| = \frac{\lambda\delta_S}{\pi d n_0^3}\left|\frac{\sin 2\theta_S}{2 p_{44}}\right|$$



Unfortunately S_{xx} and S_{yy} cannot be determined independently.

	p_{11}-p_{12}	p_{44}
MgO	-0.25*	-0.10*
LiF	-0.13**	-0.045**

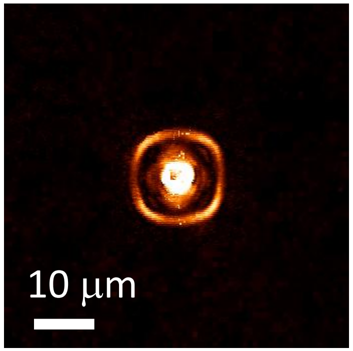
There are a lot of reports on p_{11} and p_{12}, but they depend on reports.

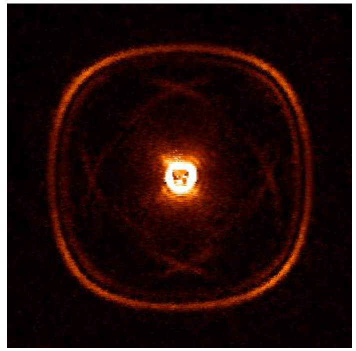
*A. A. Giardini and E. Poindexter, J. Opt. Soc. Am., 48 (1958) 556.
** K. S. Iyengar, Nature, 176 (1955) 1119.

Transient strain distributions and stress

1000 ps | 3000 ps

MgO



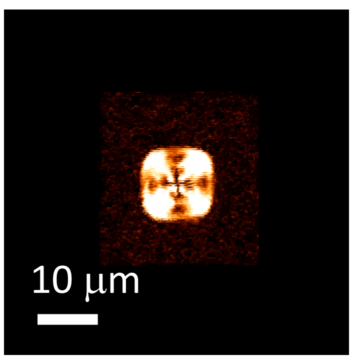


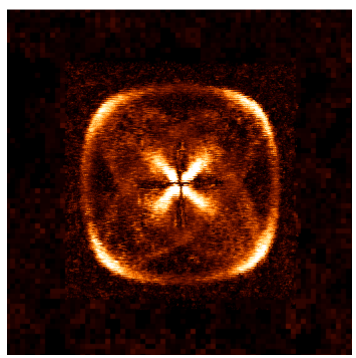
	1000 ps	3000 ps
@[110]	0.8 GPa	0.4 GPa
@[100]	0.8 GPa	0.6 GPa
@Sec. Wave	1.4 GPa	0.4 GPa

(Rough estimation)

✓Principal strain difference is largest along the <110> lines.
✓Strain of dislocation in the <110> direction was not clear.

LiF

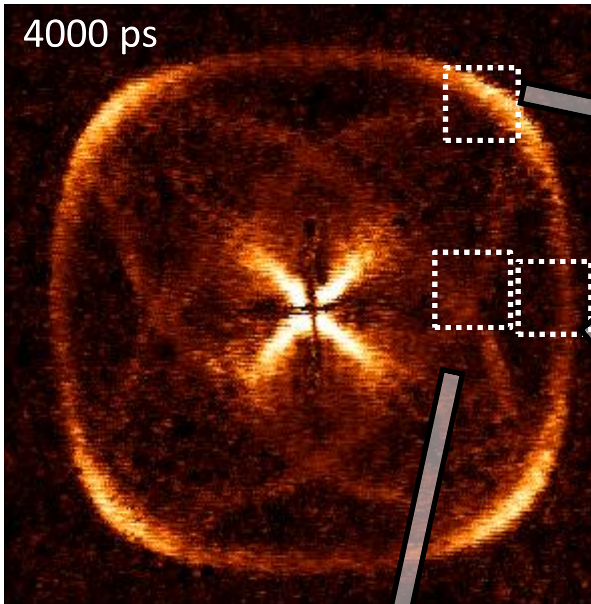


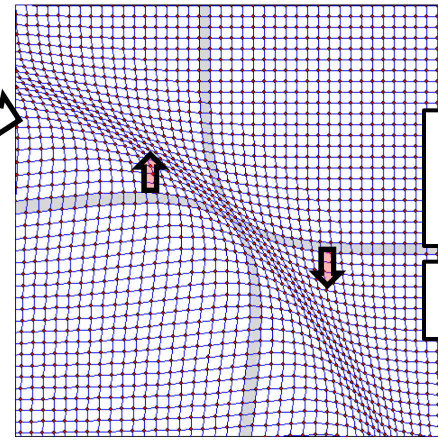


	1000 ps	3000 ps
@[110]	0.6 GPa	0.3 Gpa
@[100]	0.9 GPa	0.4 Gpa
@Sec. Wave	1.5 GPa	0.4 GPa

✓Strain is larger than that of MgO.
✓Strain of dislocation in the <110> direction was clearly observed.
✓Strain in the secondary stress wave was in the cleavage propagation direction.
✓Stress at the secondary stress wave was enough large to induce cleavage.

Lattice deformations based on the observation

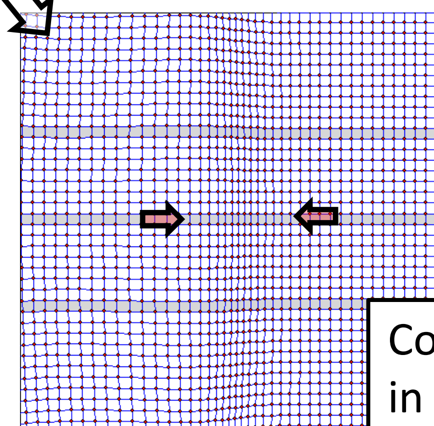


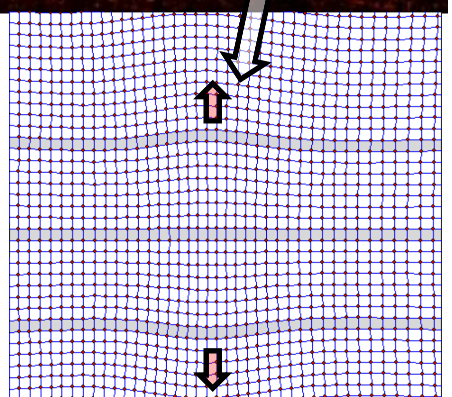


Spatial change of stress direction is largest

Compression is largest

Slip and dislocation





Compressive stress mainly in the <100> direction.

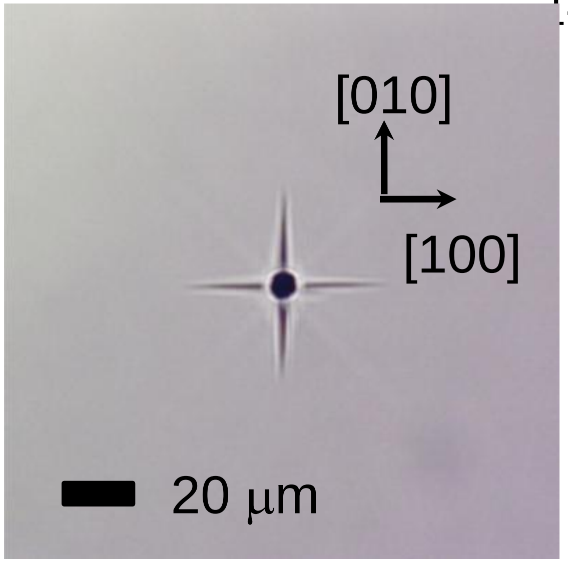
Tensile stress perpendicular to the cleavage.

Cleavage

Difference between structural changes in LiF and MgO

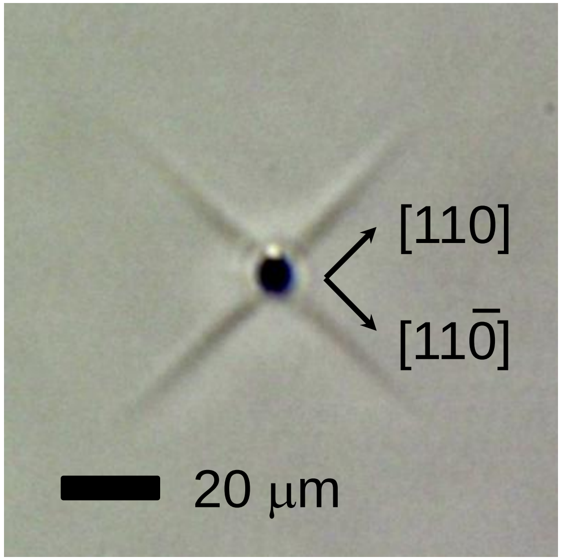
In a LiF crystal, cleavages are generated much more easily.

LiF



[100]
[010]

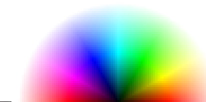
MgO



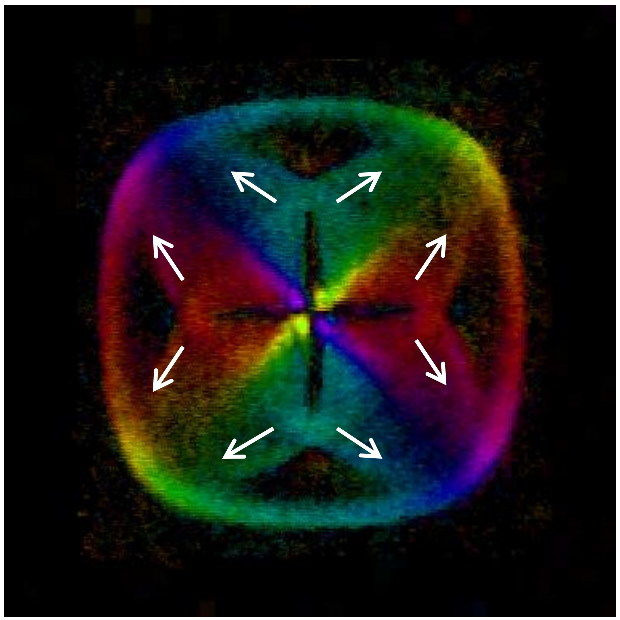
	Mohs hardness	Knoop hardness (kg/mm^2)	Young's modulus (GPa)
MgO	5.5	692.0	249
LiF	4	102	64.97

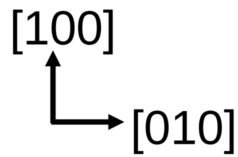
Difference between stress distributions in LiF and MgO

The stress distribution in the secondary stress wave is different.

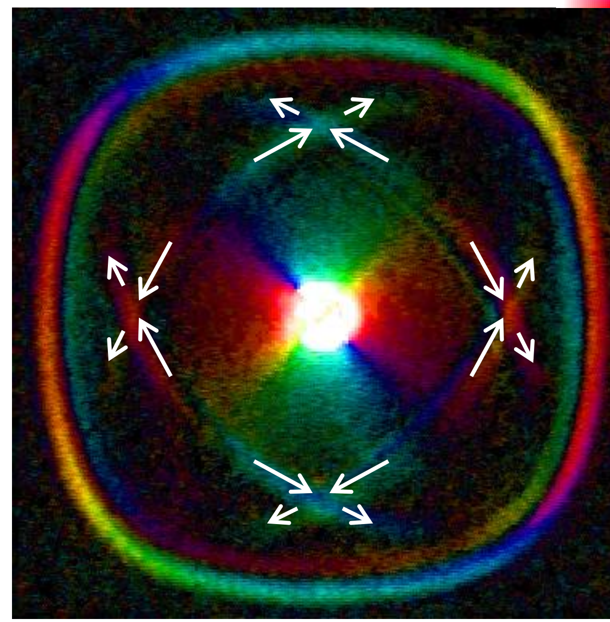


LiF





MgO



	Mohs hardness	**Knoop hardness (kg/mm^2)**	**Young's modulus (GPa)**
MgO	5.5	692.0	249
LiF	4	102	64.97

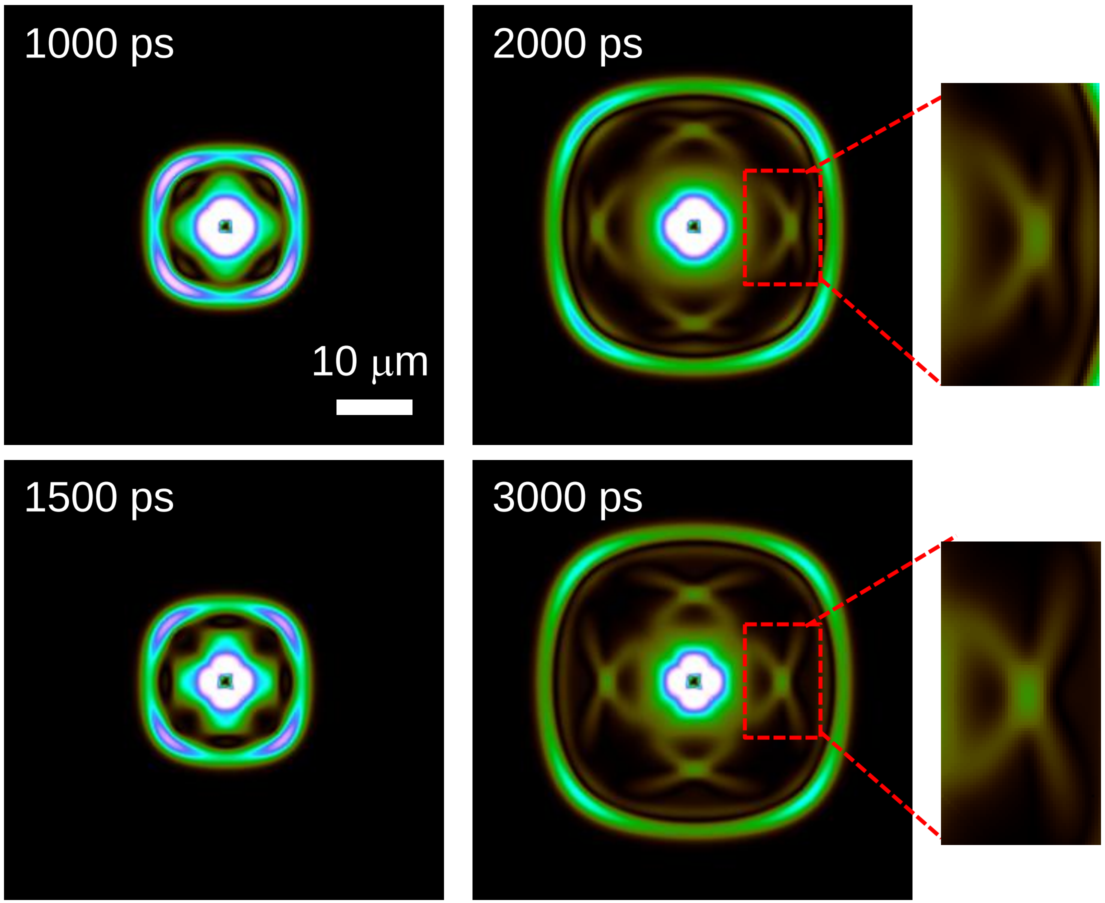
Not only hardness but stress distribution is related to the difference.

Difference in the strain distributions

Distribution of difference of principle strains

MgO

LiF



Elastic constants in the elastic tensor

MgO

k_{11}	k_{23}	k_{44}
297	95	156 (GPa)

$k_{23}<k_{44}$

LiF

k_{11}	k_{23}	k_{44}
111	63	46 (GPa)

$k_{23}>k_{44}$

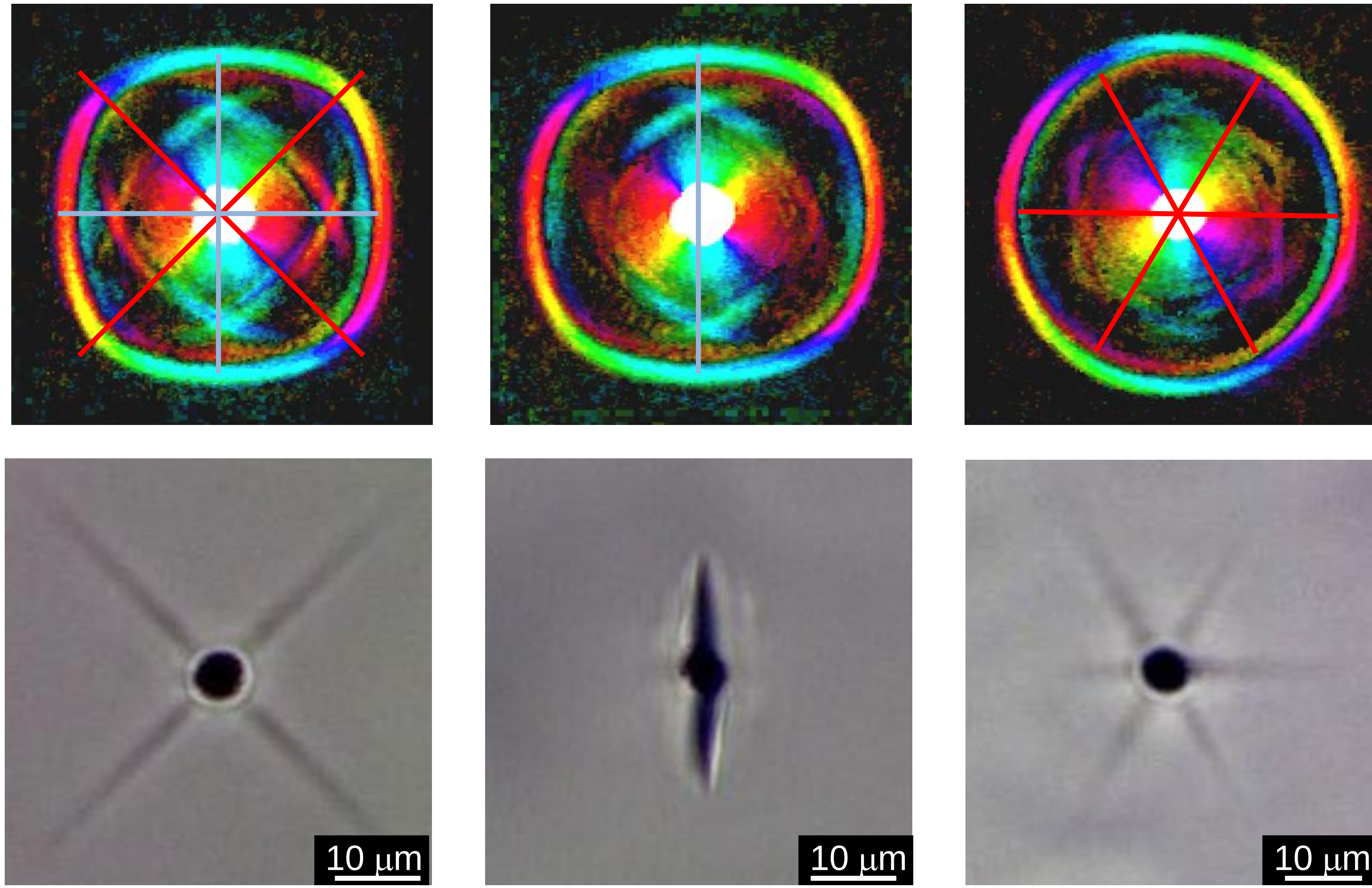
In the LiF, the tips of the cleavages are **pulled into the propagation directions.** Therefore, the cleavages are generated more easily in a LiF crystal.

Difference of modifications and transient stress in each plane

(001) **(101)** **(111)**

Transient Stress

Deformation

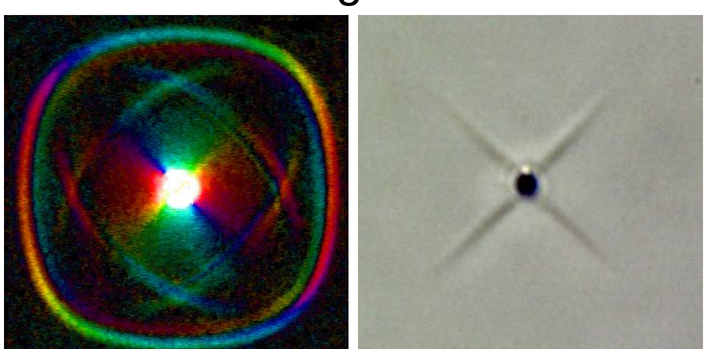


Transient stress distributions can explain the anisotropic modifications.

Summary

- Transient stress distributions after the photoexcitation inside crystals by a focused fs laser pulse were observed by a pump-probe polarization microscope.
- The local compression and large spatial change of the stress direction around <110> line in the primary stress wave could generate the dislocation bands.
- The tensile stress along <100> line in the inner stress wave induced cleavages.
- Stress directions could be controlled by modifying transient stress distributions.

MgO



LiF