Diffraction gratings for high power lasers

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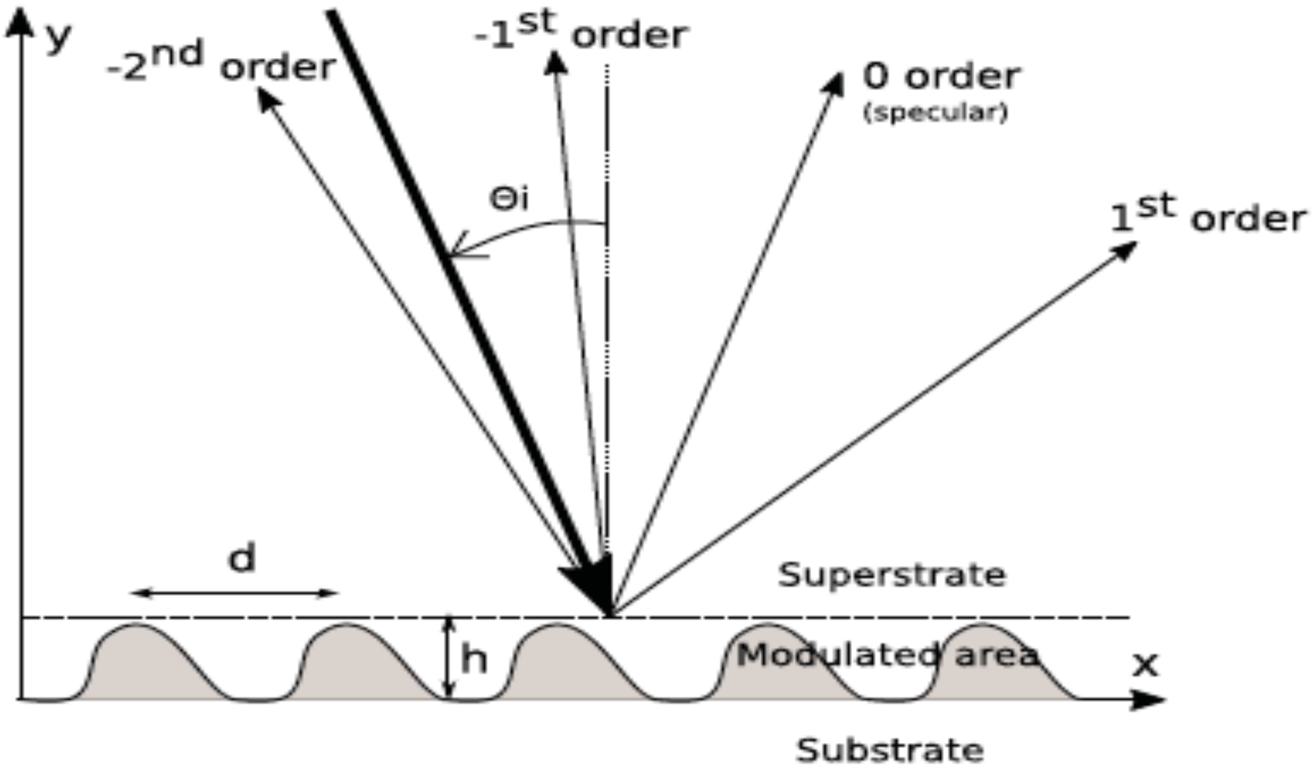
Diffraction gratings: basics



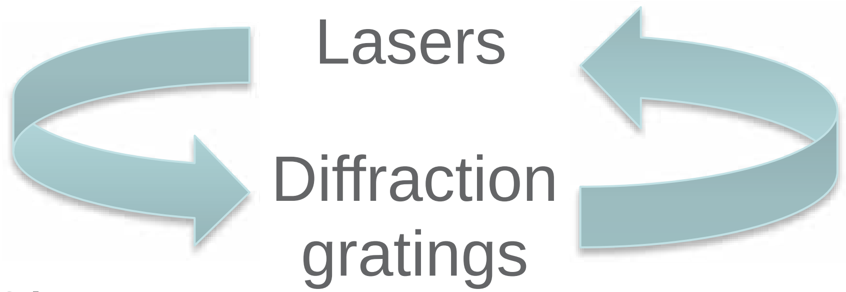
The periodic pattern yields multiple diffraction orders

Dispersion: $\sin\theta_m = \sin\theta_i + m\lambda/d$ - angle of propagation depends on λ

N. Bonod, J. Néauport, Adv. Opt. Photonics **8**, 156-199 (2016)

Diffraction gratings & lasers : a long history

- **1673:** James Gregory reports a dispersive effet with a feather
- **1785**: F. Hopkinson reports dispersion by a silk handkerchief. D. Rittenhouse probably conceived the first diffraction grating using 50 hairs between two finely threaded screws



- **1960s**: discovery of lasers
- **1960s-70s**: discovery of optical lithography thanks to lasers. Major breakthrough for fabricating gratings with a well controled pitch.
- **1980s**: CPA (Chirped Pulse Amplification) and Diffraction gratings: breakthrough in high power lasers
- **Today**-High power laser facilities for high energy physics&laser fusion ignition push diffraction gratings towards their extreme limits

N. Bonod, J. Néauport, Adv. Opt. Photonics **8**, 156-199 (2016)

High power laser facilities: need of high performances optical components

LMJ: high energy laser (ns)

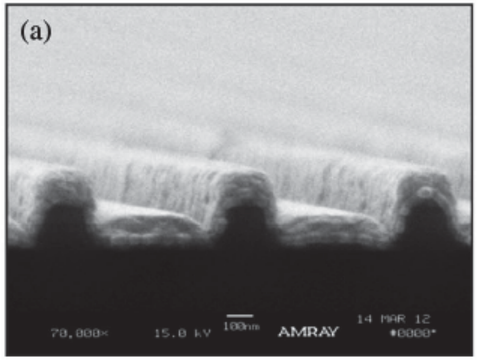
PETAL: high power laser (fs)

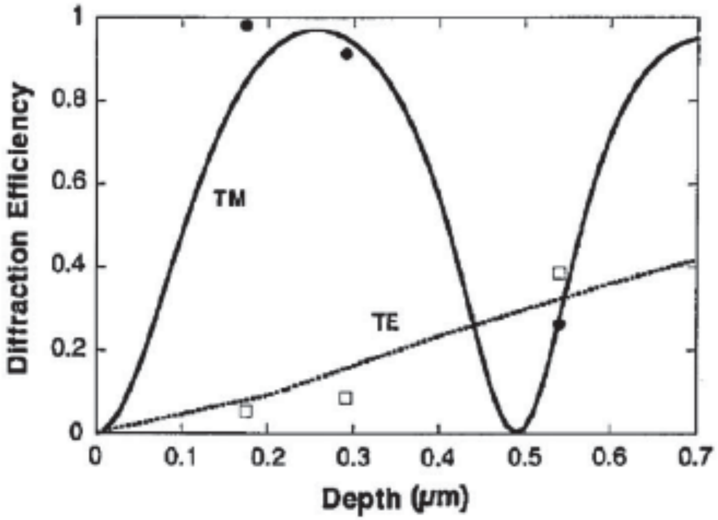
High performance optical components:

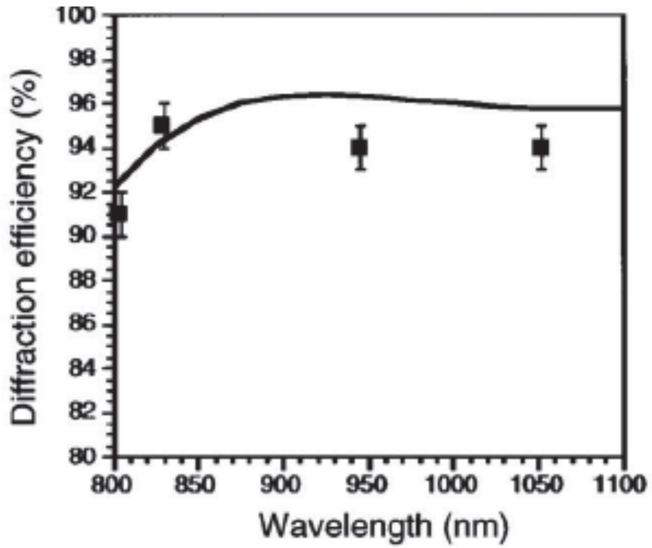
- ❖ High diffraction efficiency
- ❖ Large size
- ❖ High LIDT
- ❖ Wide spectral tolerance
- ❖ Wavefront quality

…

Metallic gratings







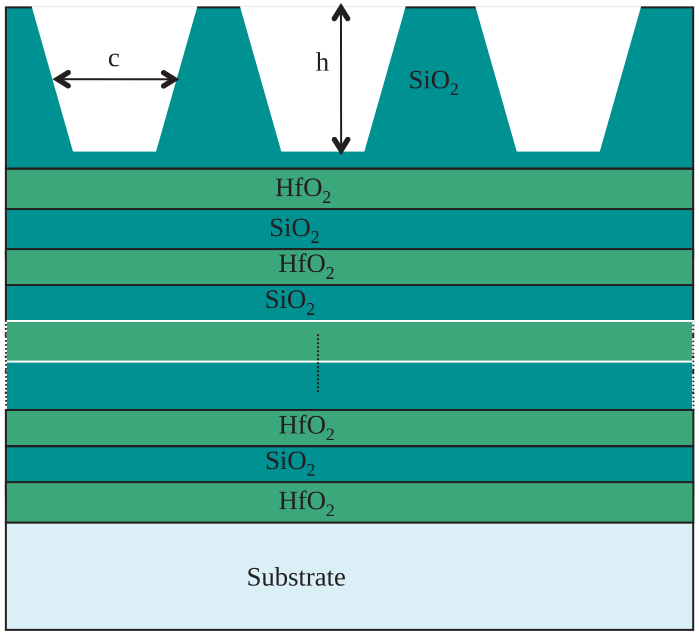
Operate in TM polarization
Wide spectral tolerance: well adapted for compressing ultrashort pulses.
Intrinsic losses of metals :Limited efficiency and laser resistance

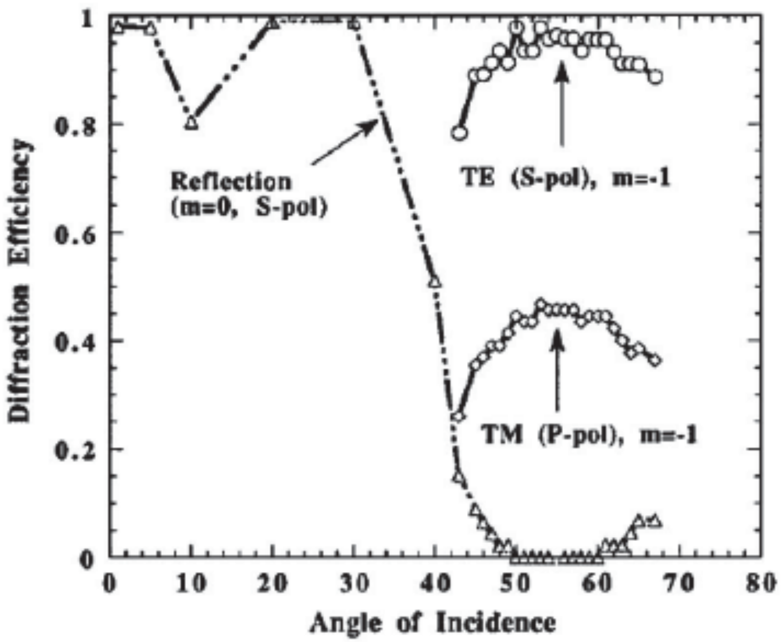
J. Britten et al., Opt. Lett. **21**, 540-542 (1996)
R. Boyd et al., Appl. Opt. **34**, 1697-1706 (1995)

Multilayer dielectric gratings

MLD grating= MLD mirror + grating on top

Developed to overcome damage limitation of gold compression gratings





-Operate in TE polarization (but can also operate in TM)

-Very high efficiency

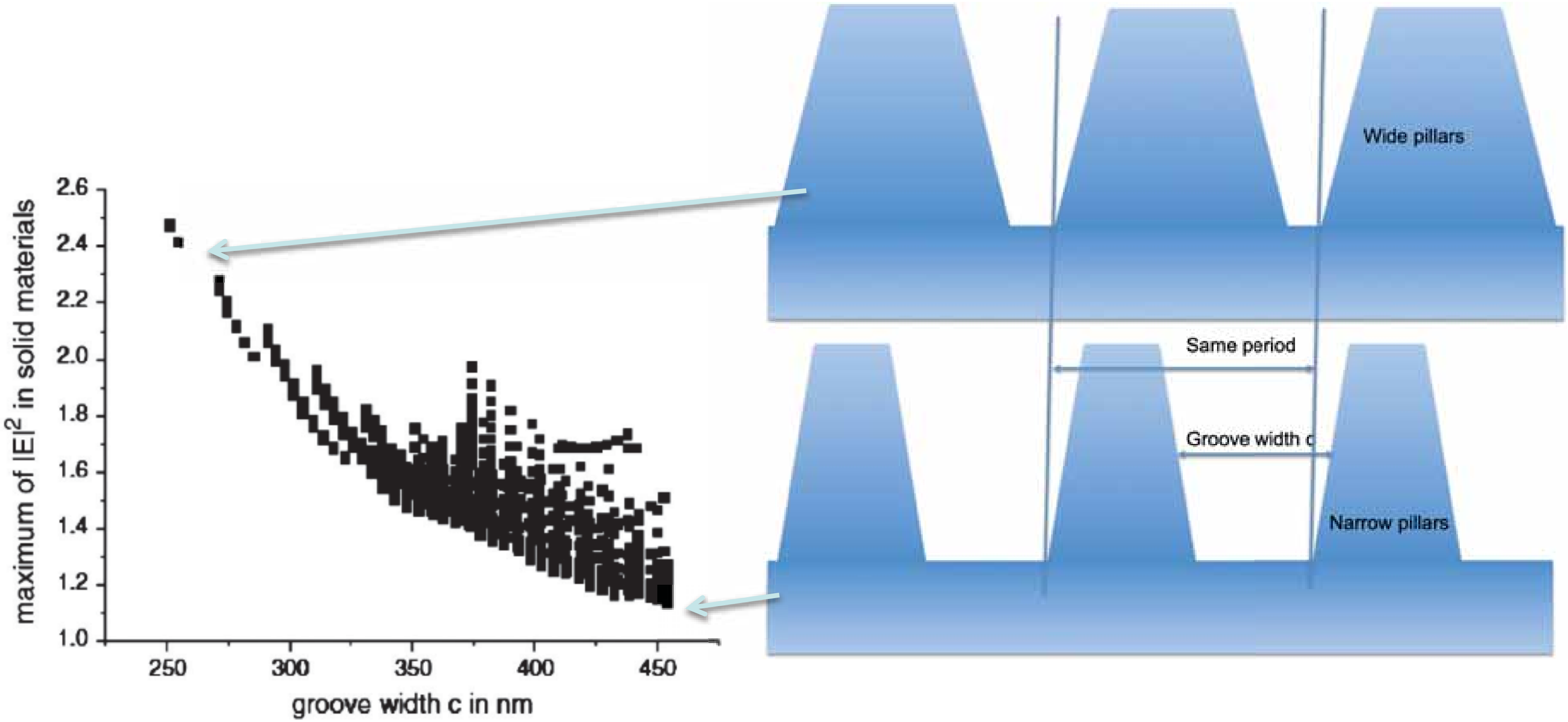
-Bandwidth: much narrower than metallic gratings

M. D. Perry et al., "High-efficiency multilayer dielectric diffraction gratings," Opt. Lett. **20**, 940-942 (1995)

Gratings for pulse compression at 1053 nm, 500fs

PETAL: high power laser (fs)

Influence of the grating profile on LIDT



Narrow pillars: smaller field enhancement inside the grating

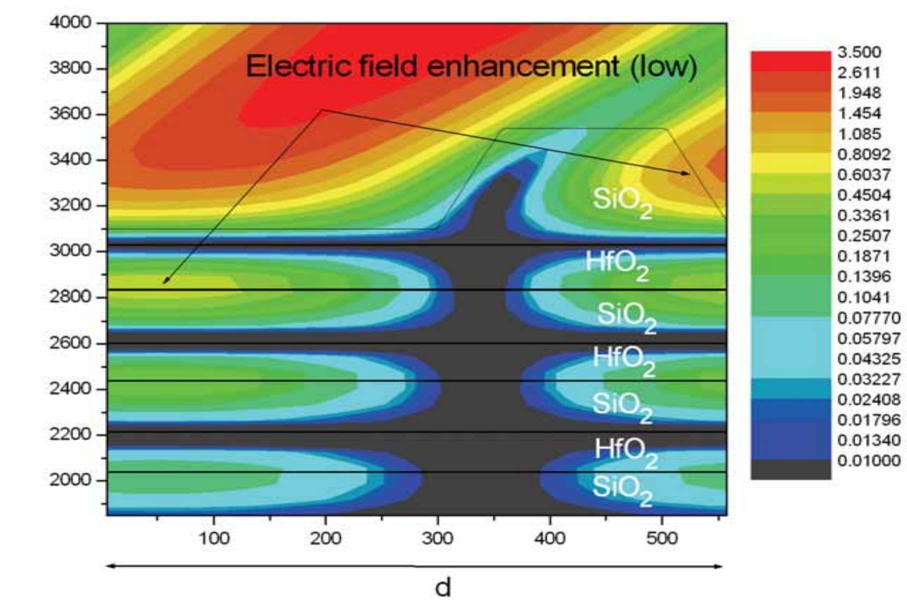
N. Bonod et al., Opt. Commun. **260**, 649-655 (2006)

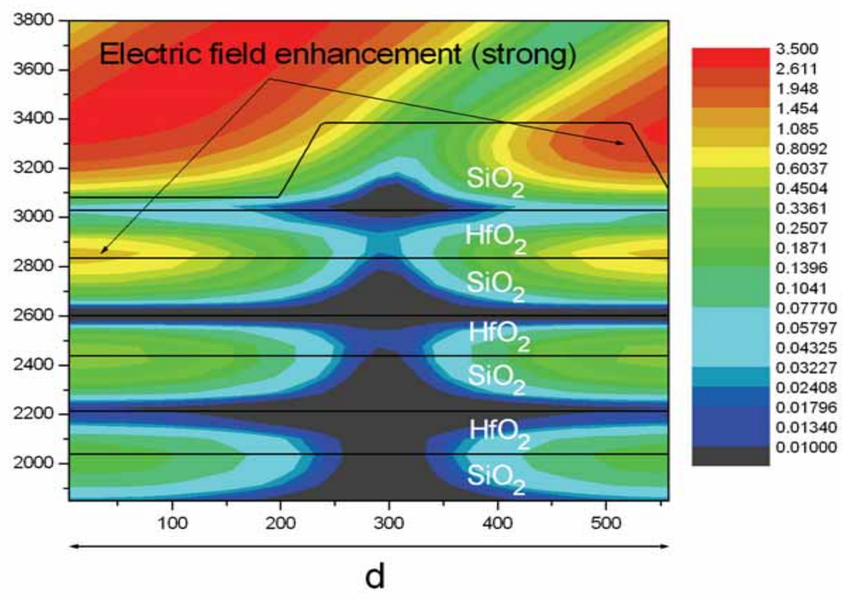
Influence of the grating's profile on the near field distribution

Experiment on two diffraction gratings:

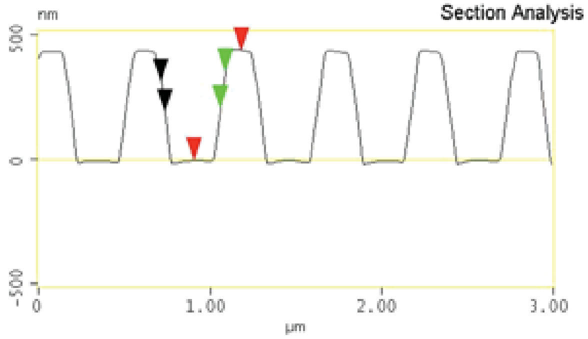
= period but ≠ groove widths

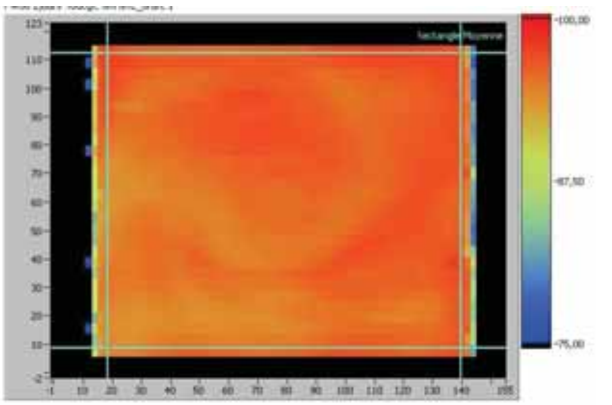
Similar diffraction efficiency but different near field distributions





Fabrication of 4 samples: same period but different groove widths

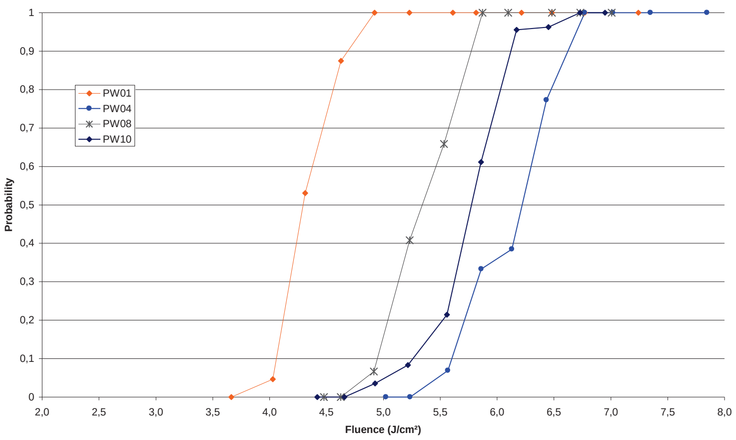




R=96%

Fabrication of different profiles

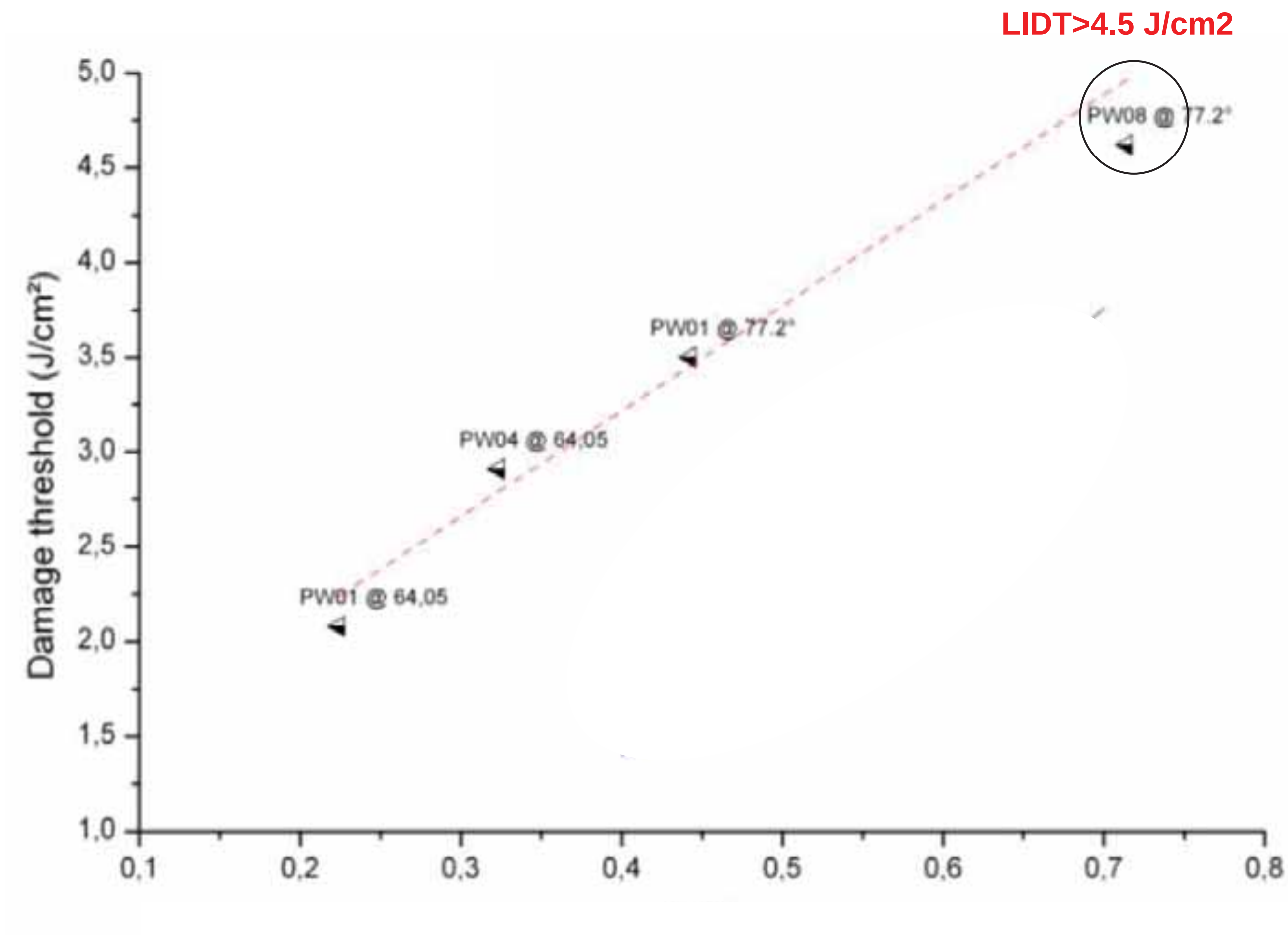
Diffraction efficiencies: ~96% for all profiles



The grating profile strongly influences the LIDT !

J. Neauport et al., Opt. Express **15**, 12508-12522 (2007).

LIDT *vs* max |E|^2



S/1 mode

1.057µm

Gaussian beam 200µm @ 1/e²

~ 200 sites, 100 shots per site

10 Hz, **500 fs**

RH<10% (dry Argon)

Fluence given in beam normal

MLD

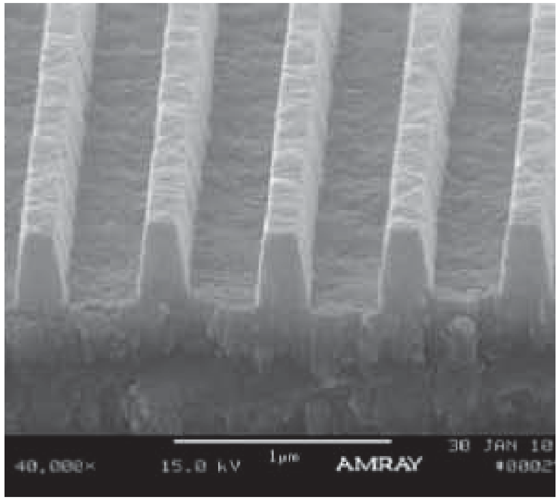
EBPVD coating : SAGEM

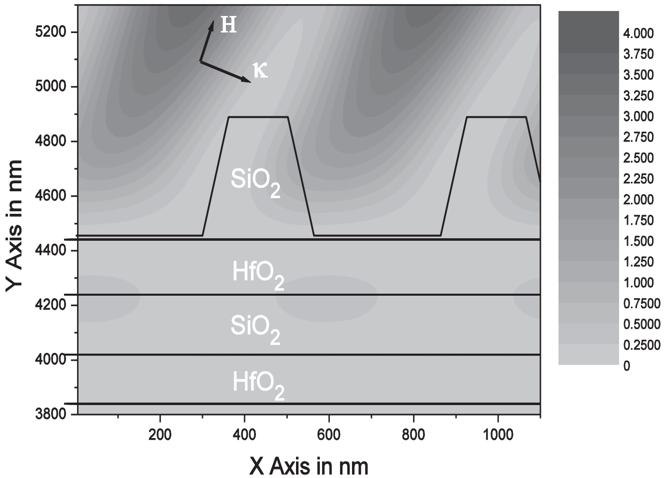
Grating : HORIBA JOBIN YVON

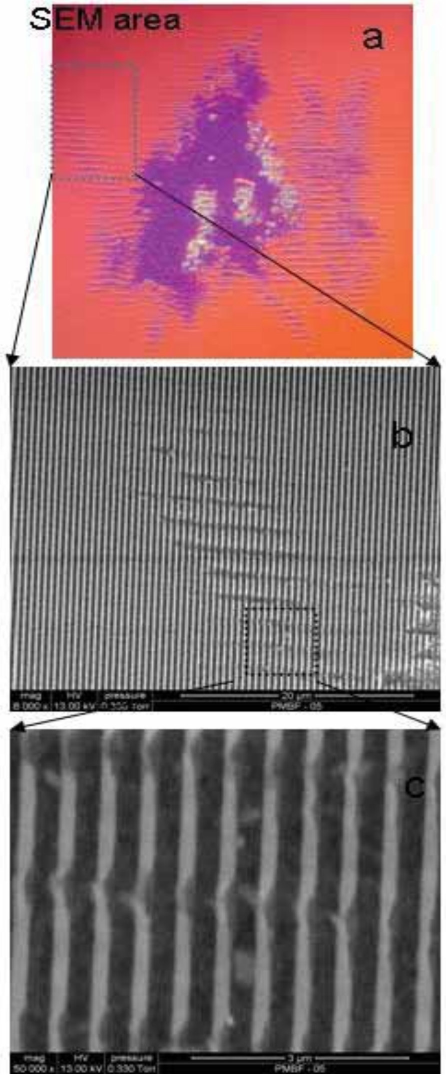
Linear relation between LIDT *and 1*/max |E|^2

J. Neauport et al., Opt. Express **15**, 12508-12522 (2007).

Localisation of the damage at a sub-micrometer scale







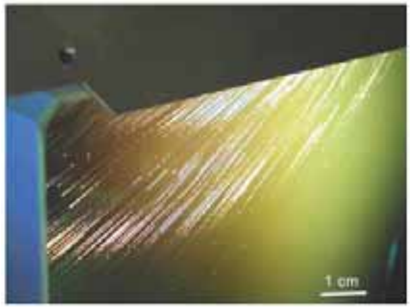
Damages initiate at the opposite to incoming wave with good concordance with E field computations.
SEM measurements show that ripples reduce damage threshold of MLD gratings.

S. Hocquet, J. Néauport, N. Bonod, Appl. Phys. Lett. **99**, 061101 (2011)

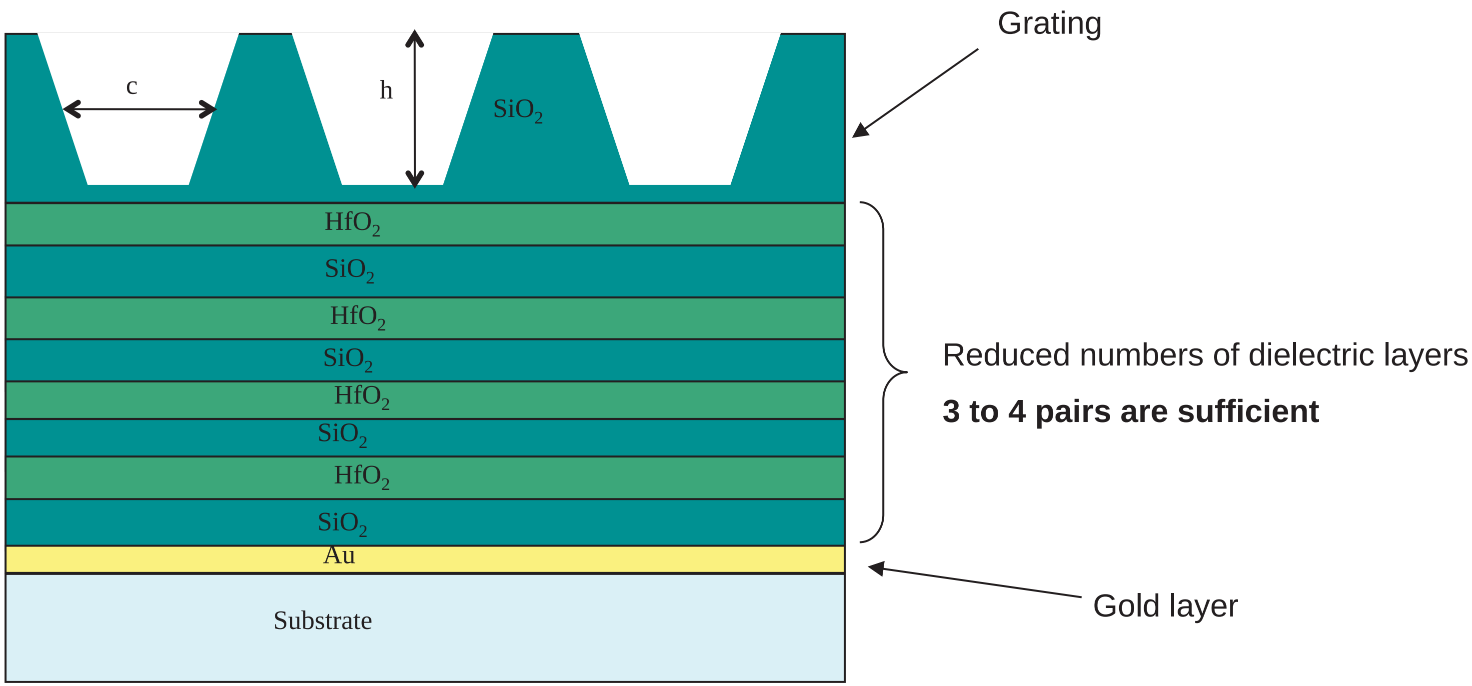
Metal-MultiLayer Dielectric gratings

Hybrid metal-dielectric grating

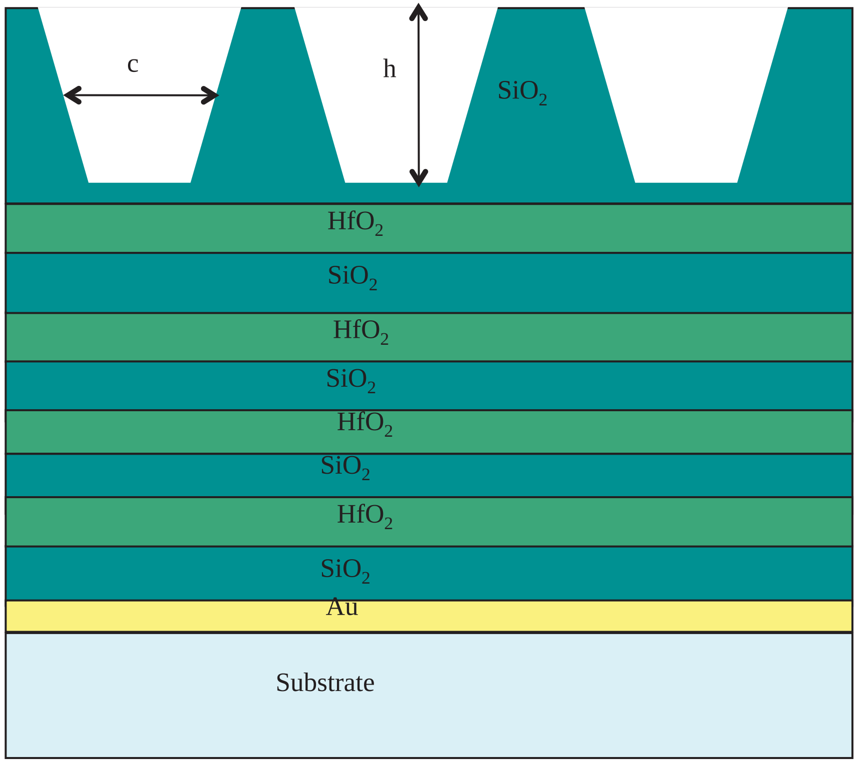
First proposed to decrease the number of dielectric layers for decresing the stress indside the stack

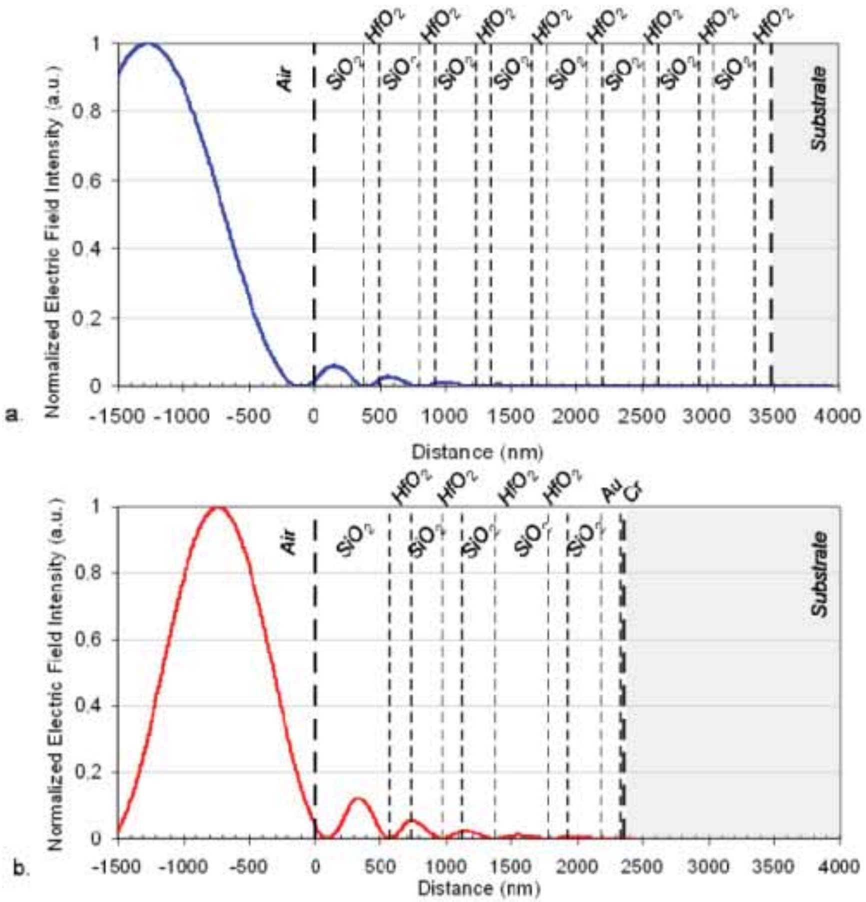


'A metal layer is inserted between the substrate and the dielectric stack to reduce the number of dielectric bilayers and thus the mechanical stress within the stack' N. Bonod et al., Opt. Commun. 260, 649-655 (2006)



Low bandwidth Hybrid metal-dielectric grating





Sensitivity to crazings: Two samples of MLD and MMLD stacks (EBPVD) 120×140 mm^2 have been exposed to a few air/vacuum cycles. Samples were observed using an intense fiber lamp: a few fractures were observed on the MLD stack only.

J. Neauport et al., “Mixed metal dielectric gratings for pulse compression,” Opt. Express **18**, 23776-23783 (2010)

Hybrid metal-dielectric gratings

20nm Cr 150nm Au (225nm SiO2 157nm HfO2)^4 558nm SiO2

20nm Cr 150nm Au (235nm SiO2 155nm HfO2)^4 580nm SiO2

20nm Cr 150nm Au (235nm SiO2 155nm HfO2)^4 580nm SiO2

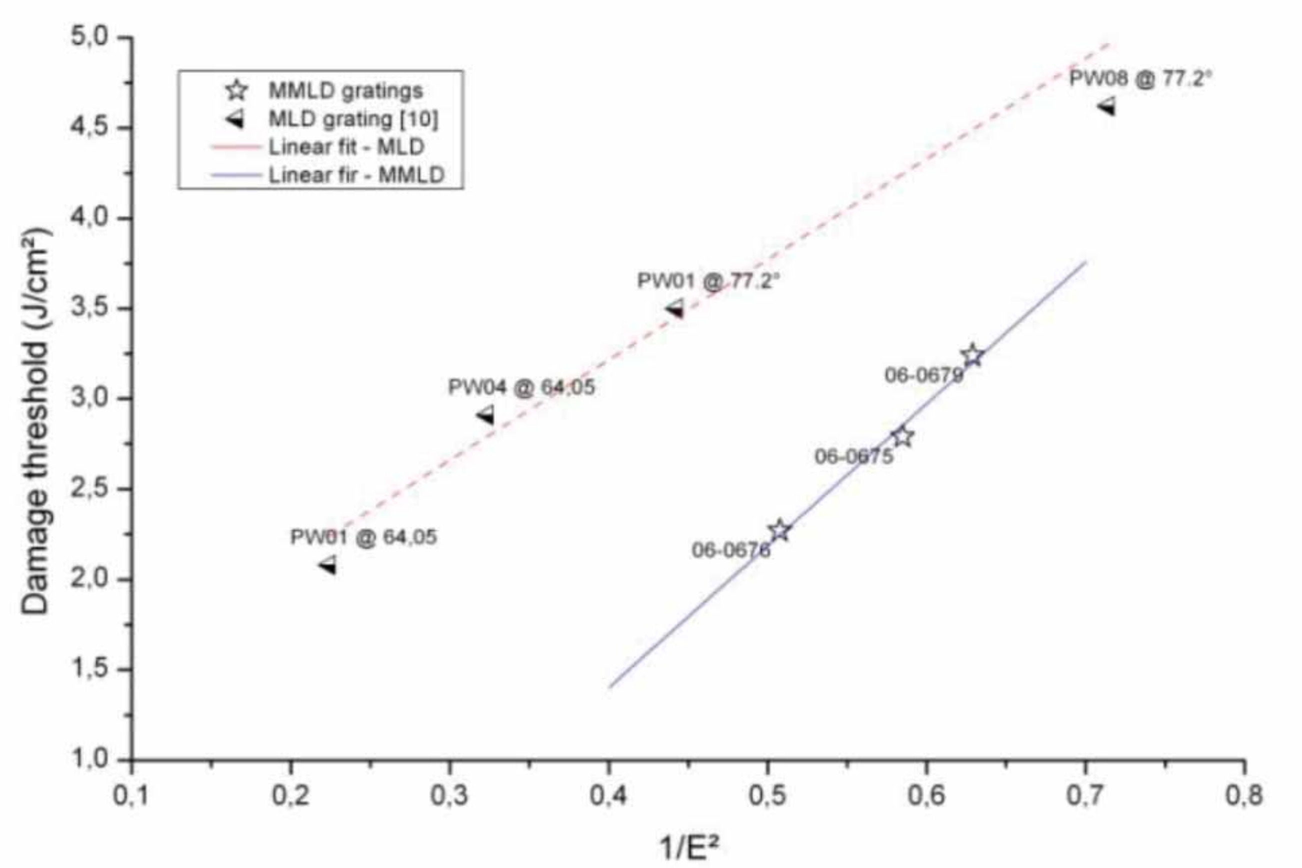
α	e (nm)	h (nm)	DC	(-1) reflected order diffraction efficiency, measured / calculated	$\|E/E_0\|^2$
80°	164	394	0.346	96.7% / 99.2%	1.71
81°	180	400	0.365	96.3% / 95.5%	1.97
78°	124	456	0.357	96.9% / 97.2%	1.59

2mm × 4mm sampling step

Hybrid metal-dielectric grating: **high efficiency**

J. Neauport et al., Opt. Express **18**, 23776-23783 (2010)

Hybrid metallo-dielectric grating: LIDT



Hybrid metal-dielectric grating: LIDT>3 J/cm^2 (500 fs)

J. Neauport et al., Opt. Express **18**, 23776-23783 (2010)

Optimization of the Field distribution in MLD transport mirrors for PW lasers

M. Chorel, CEA CESTA, France

	LIDT under nominal conditions [J/cm^2]	LIDT under cumulative errors [J/cm^2]
Reference QWOT design	1.93	1.71
Design optimized as function of the 2 outer layers	2.54	1.89
Design optimized as function of the 12 outer layers	2.73	1.75
Design optimized as function of the 12 outer layers featuring the highest LIDT with cumulative errors	2.22	2.08

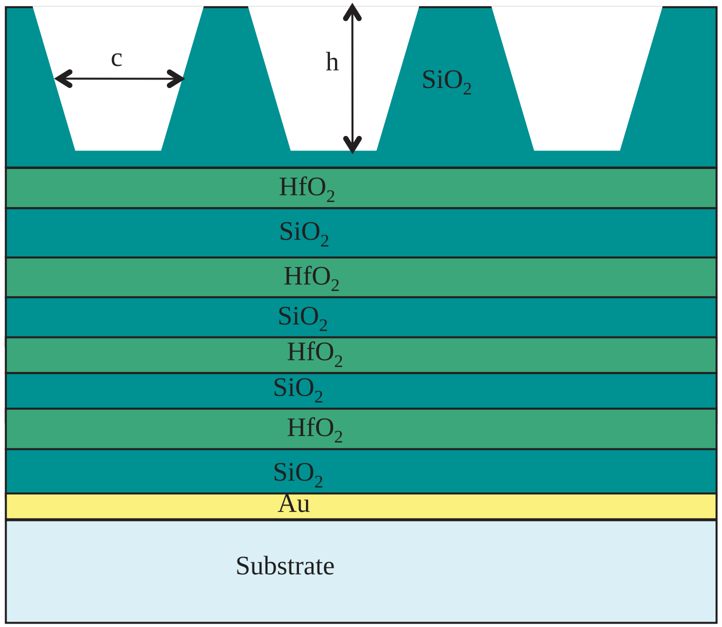
MLD mirrors: importance of the field distribution on the LIDT !

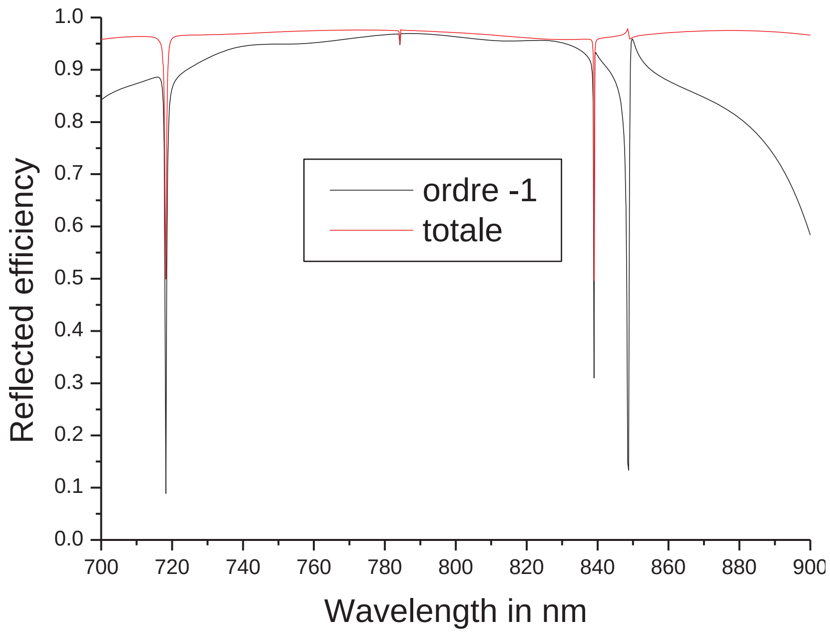
M. Chorel et al., Opt. Express **26**, 11764 (2018)

Application for short laser pulses ~20fs

Wide spectral tolerance required !!!

Optimization of the MLD ~800nm



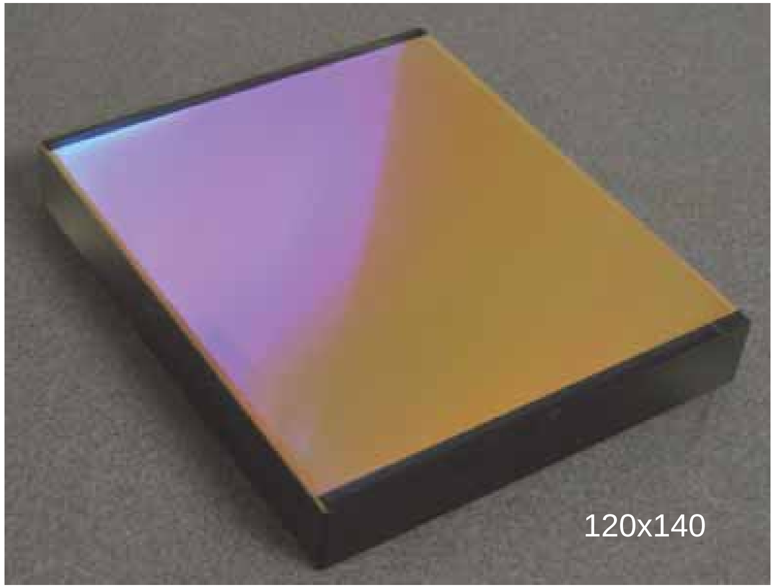


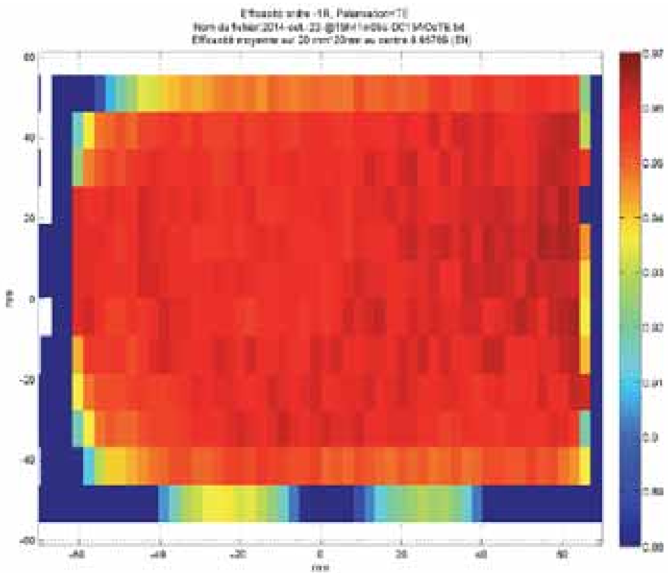
7 dielectric layers (HfO2/SiO2) are needed

The grating is etched in the silica layer, the groove depth= 700 nm

The reflected efficiency averaged over the spectrum is higher than 95%

First wide spectral MMLD manufactured (2014)





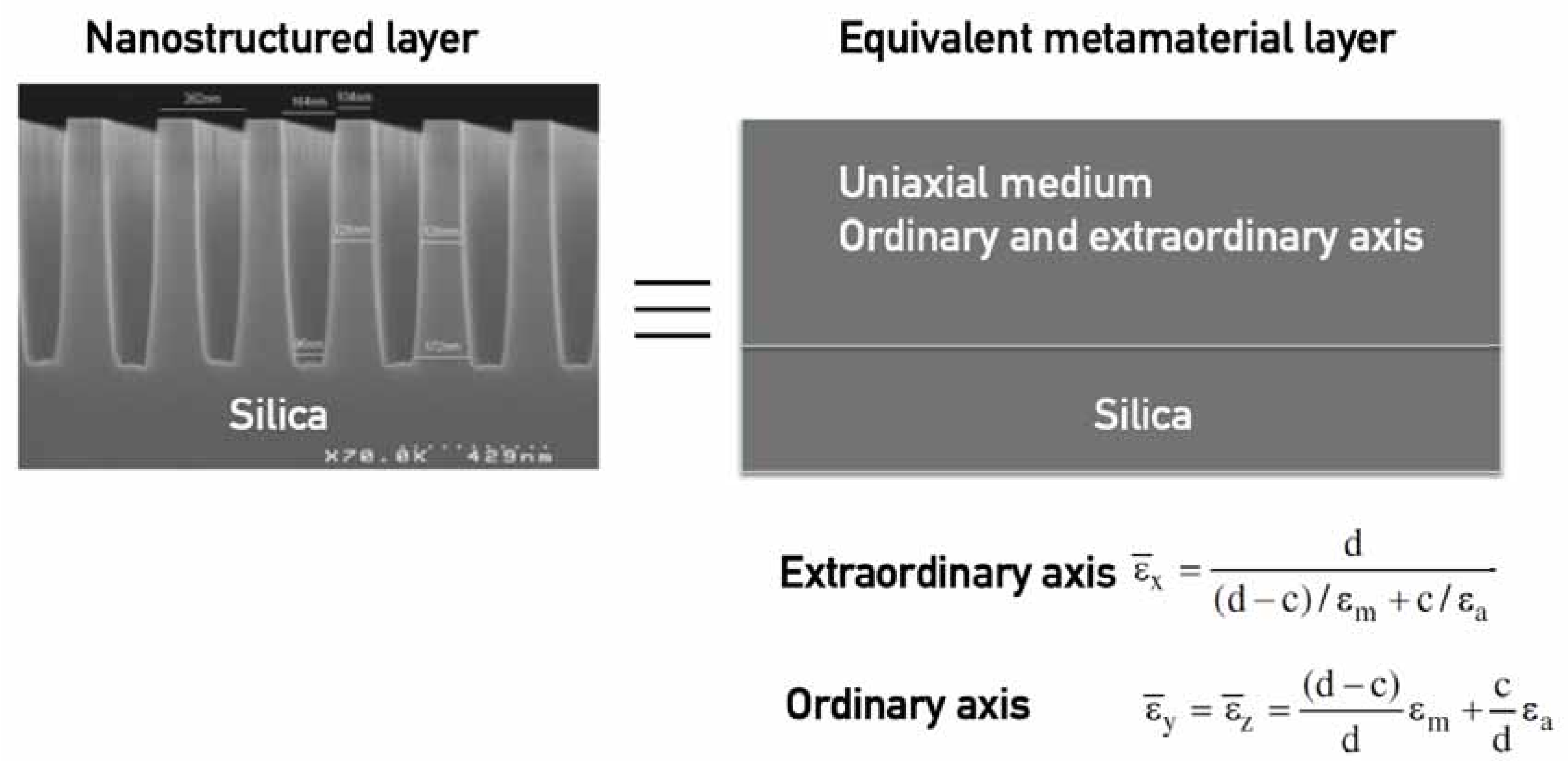
JOBIN YVON Technology

First order Measurement at 785nm, 55.5°: 95%

*HORIBA Jobin Yvon SAS manufactures MMLD gratings under a worldwide exclusive license of the patent, Optimized dielectric reflective diffraction grating - PCT/FR2010/052684 - US 20120300302”.

From diffraction gratings to metasurfaces

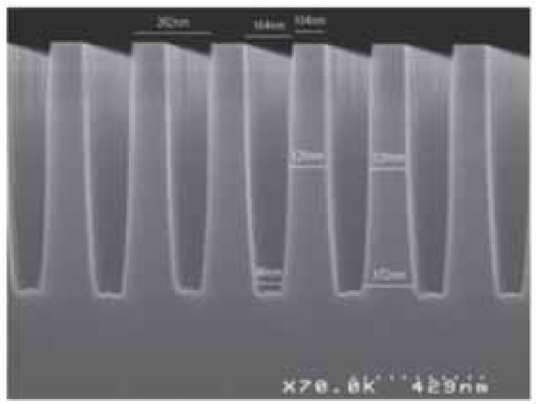
The period is reduced to avoid diffractive orders



Objective: nanostructuring materials to get an equivalent homogeneous metamaterial with novel optical properties.

Full-Silica Quarter Waveplate Metamaterial

- Developping a full-silica quarter wave operating in the UV spectrum (351 nm) for high power beam smoothing



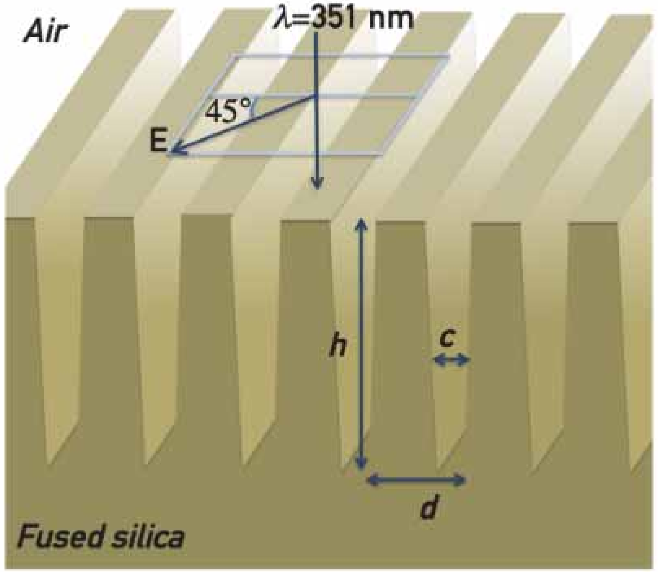
LMJ: high energy laser (ns)

Waveplate characterized by:

❖High transmittance in the UV spectrum

❖High Laser Induced Damaged Threshold

Full-silica quarter waveplate: challenges



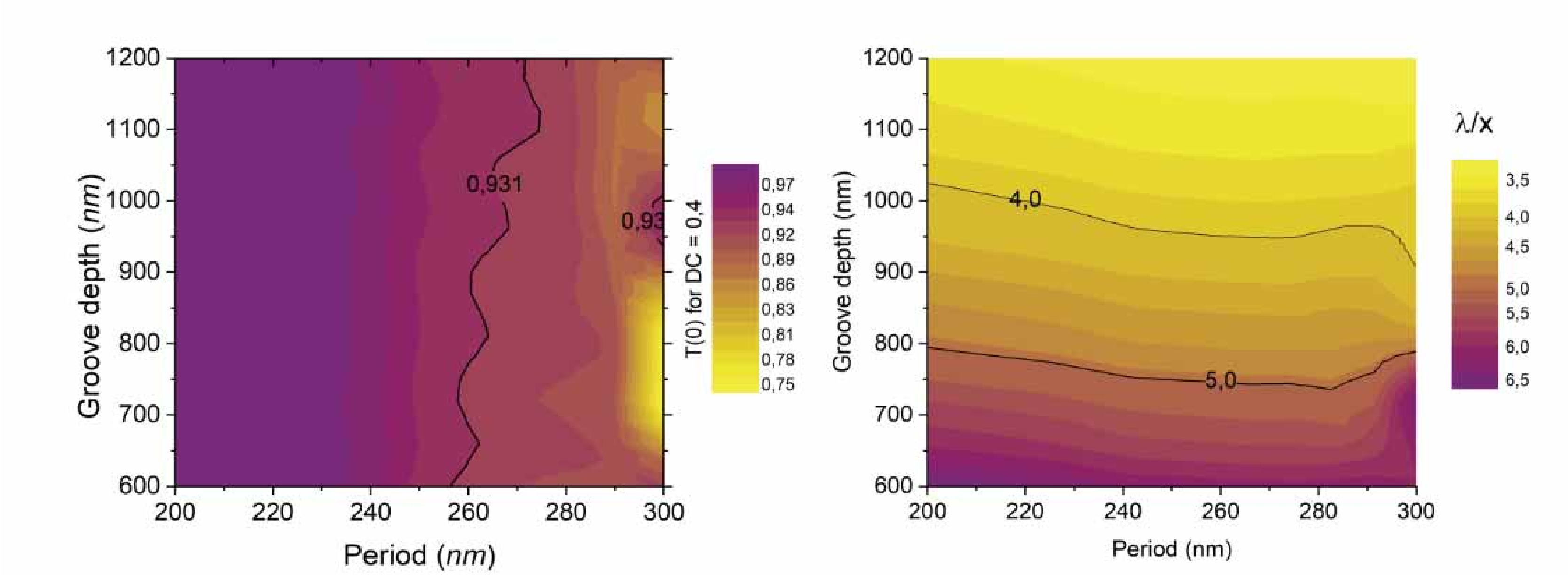
Illumination in normal incidence
Electric field polarized at 45°

Challenges:

- ❖ Short wavelength (351 nm) requires shorter periods
- ❖ Silica must be considered for its high laser resistance
- ❖ Small optical contrast between air and silica (~1.47) requires thick nanostructured layer for getting a $\lambda/4$ linear retardance

Numerical proof of concept

Design & concept



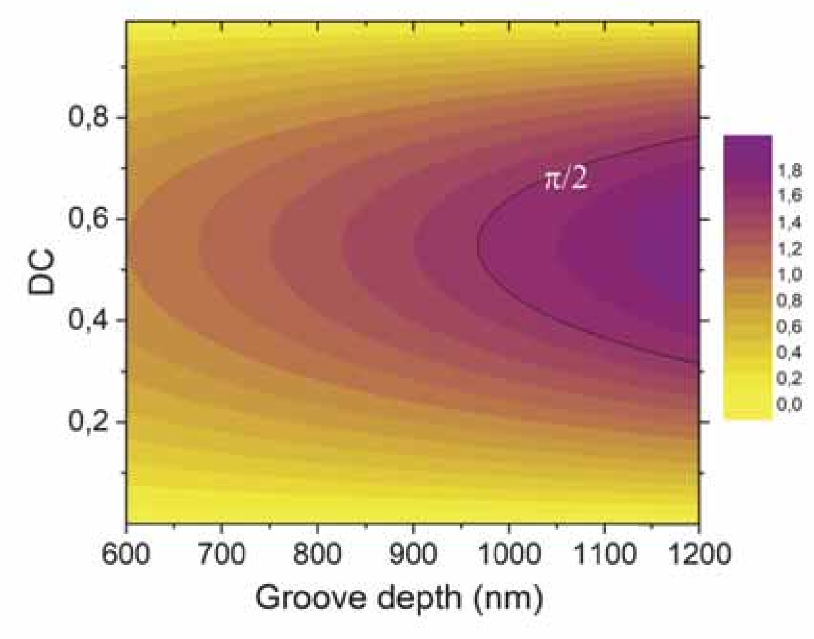
- ❖ Short pitch is required to warrant high transmittance (typically smaller than 260nm)
- ❖ Deep etching is required to get a large effect on polarization (typically deeper than 800 nm)

Homogenization approach

- Period is considered to tend to zero with the same c/d ratio.
- Nanostructured silica behaves as a homogeneous uniaxial material

$$\frac{1}{\overline{\epsilon_e}} = \frac{1}{d}\left(\frac{d-c}{\epsilon_{SiO_2}} + \frac{c}{\epsilon_{air}}\right)$$

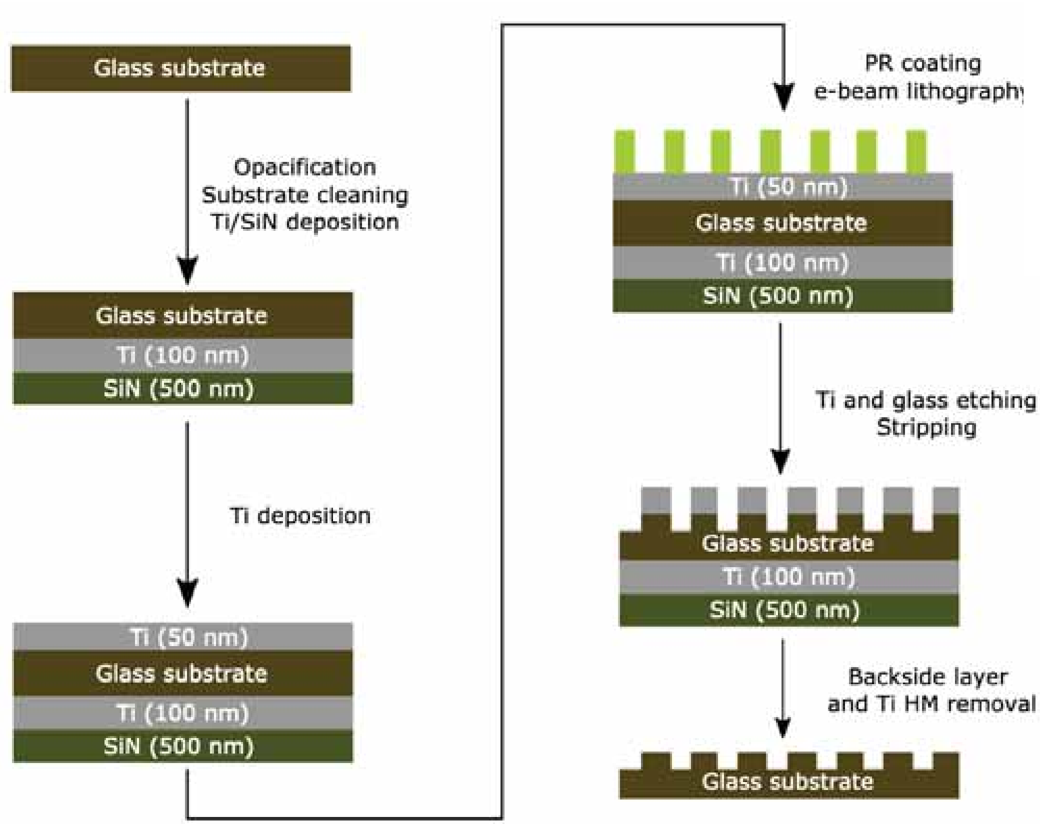
$$\overline{\epsilon_o} = \frac{1}{d}\left((d-c)\epsilon_{SiO_2} + c\epsilon_{air}\right)$$

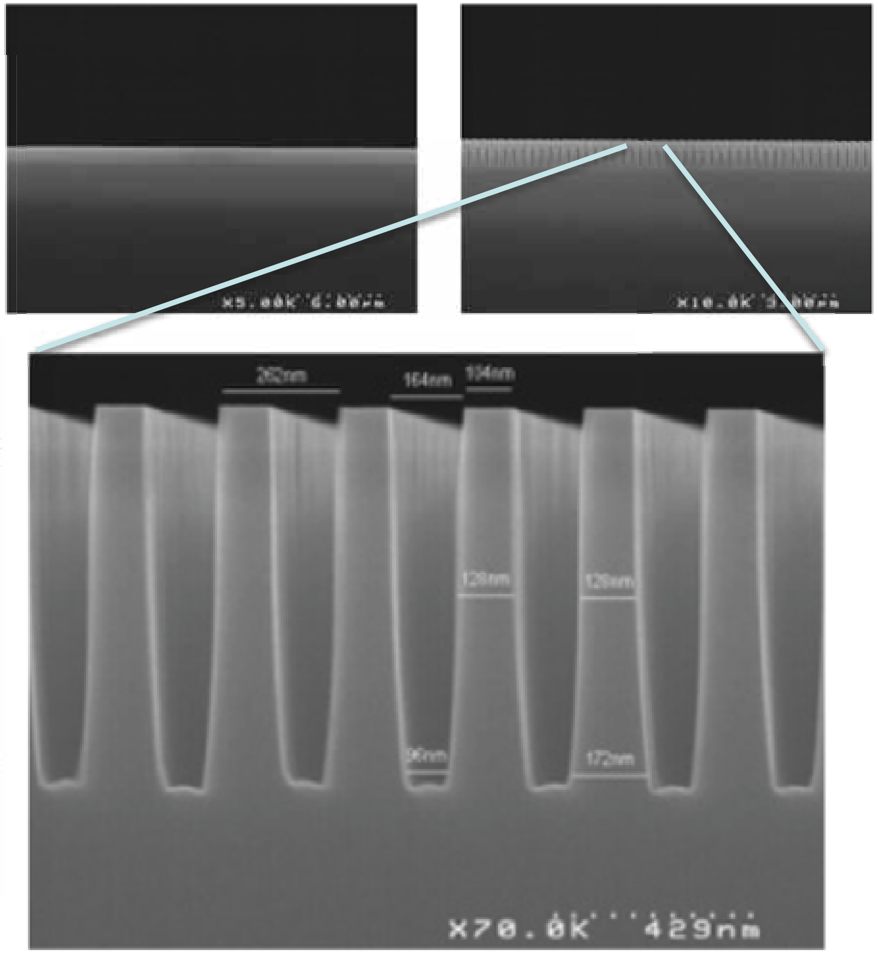


Homogeneous model confirms the ability of nanostructured silica to behave as a l/4 waveplate

N. Bonod, P. Brianceau, J. Néauport, Optica, in press (2021)

Fabrication

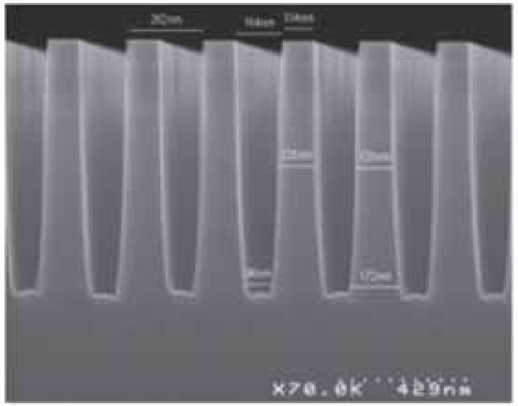




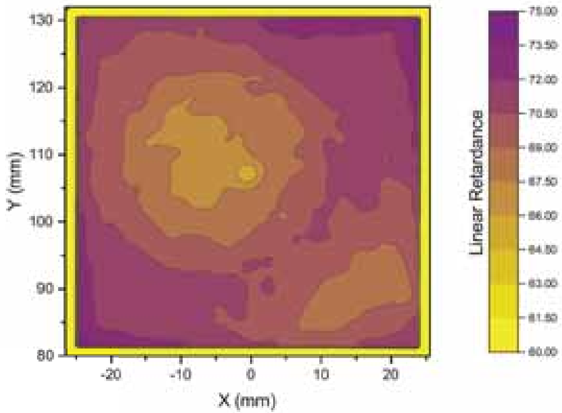
200 mm CMOS compatible fabrication process

P. Brianceau (CEA LETI, grenoble, France)

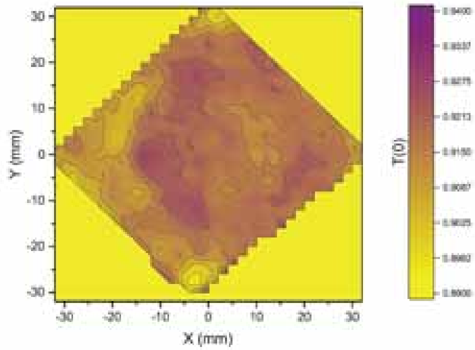
Optical characterization of the meta-waveplate



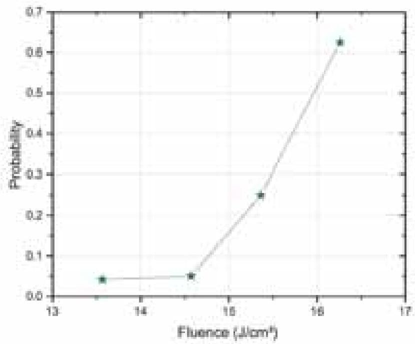
Linear retardance ~λ/5



High transmittance ~95%



High laser damage resistance



LIDT ~ 13J/cm^2
Bulk silica ~ 14J/cm^2

N. Bonod et al., Optica **8**, 1372 (2021)

Ongoing work and Perspectives

Diffraction gratings: engineering of the field distribution in the MLD

Same grating profile on different MLDs: Fabrication and characterization of different samples.

S. Diop’s PhD thesis supervised by L. Lamaignère (CEA CESTA)

Ongoing work and Perspectives

Metasurface quarter waveplate:

- Fabrication of samples at nominal conditions (period of 230 nm) and groove depth at 1µm

- Experimental results: nearly perfect transmittance & exact $\lambda/4$ phase shift

Conclusions

Diffraction gratings & lasers : a long history of mutual development that has not ended Á High power laser facilities have pushed the developement of high performance diffractive optics.

Importance of the E-field minimizing for improving the laser resistance (in mirrors, gratings, Á)

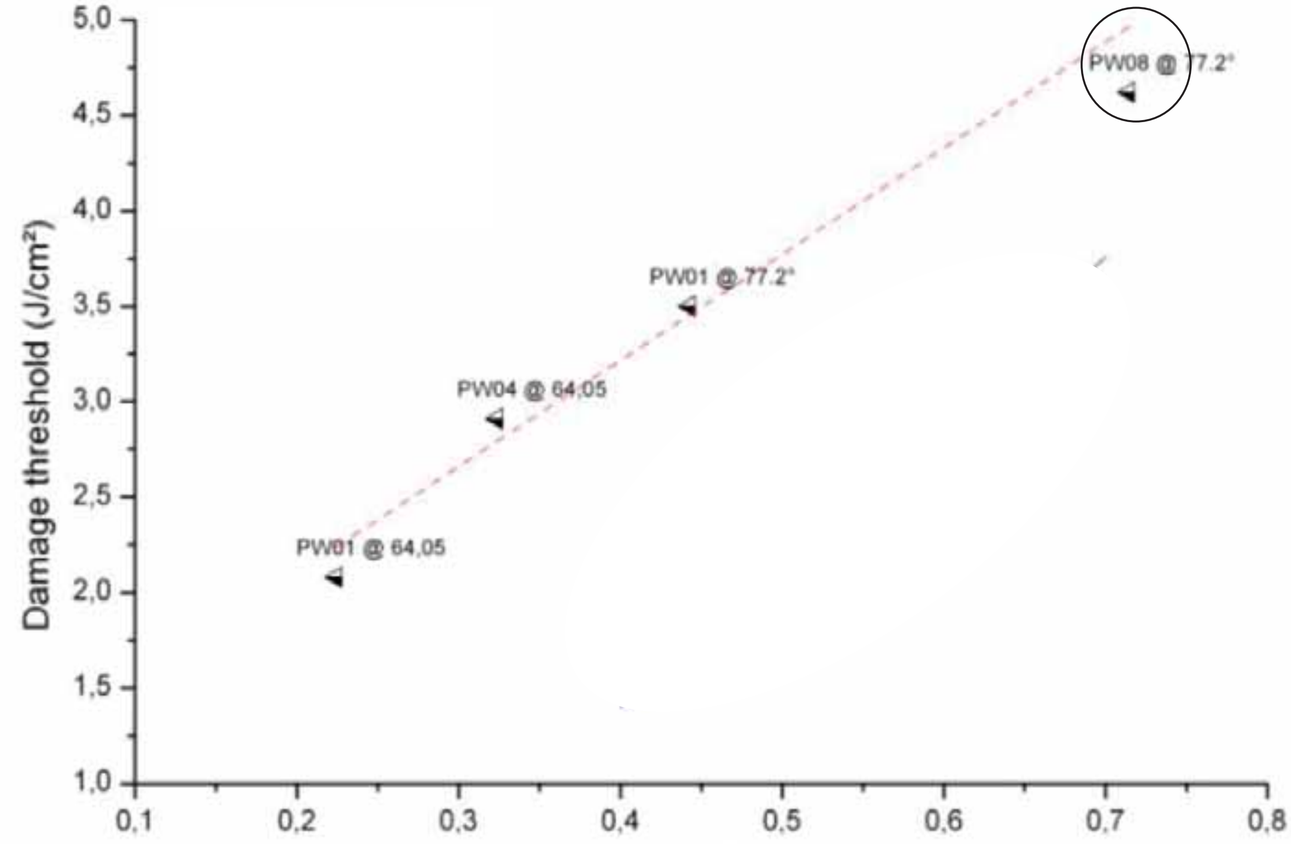
Metamaterials bring novel opportunities to tailor high power laser beams

Fabricating large scale gratings and metamaterials will become a key challenge

Thanks for your attention

LIDT *vs* max $|E|^2$

LIDT>4.5 J/cm2



S/1 mode

1.057µm

Gaussian beam 200µm @ $1/e^2$

~ 200 sites, 100 shots per site

10 Hz, **500 fs**

RH<10% (dry Argon)

Fluence given in beam normal

MLD

EBPVD coating : SAGEM

Grating : HORIBA JOBIN YVON

Linear relation between LIDT *and 1*/max $|E|^2$

J. Neauport et al., Opt. Express **15**, 12508-12522 (2007).

Fabrication#1

- Substrates: Fused silica glass wafers (AQ from AGC Japan). Φ=200mm, thickness: 0.725 mm
- Substrates are polished :surface roughness <2 nm (RMS) for spatial periods smaller than 1 mm
- Patterning over a clear aperture of 55 cm2 centered on the substrate
- Fused silica wafers are transparent in the visible and non-conductive in contrast to silicon wafers. An opacification step is therefore realized to detect wafers with the different equipment sensors
- Opacification step: deposition of two layers - a Ti layer to make wafers opaque and underneath a SiN nitride layer to enable the de-chucking of the wafers

P. Brianceau (CEA LETI, grenoble, France)

Fabrication#2

- Ti layer is deposited on the front glass side. Ti layer is coated by a 360nm PR layer.
- Patterning of the PR layer performed with e-beam lithography (Vistec).
- Ti layer: intentionally increased from 10nm to 50nm to act as an additional
- hard mask to the 360nm thick photo-resist (NEB22) during etching of fused silica.
- This additional hard mask lessens the sidewall roughness and improves the control of the groove width and profile.

Fabrication#3

- SEM measurements of the exposed wafer were performed on 25 areas uniformly distributed over the 55 cm2 grating surface to qualify the uniformity
- Ti hard mask etched (by ICP) due to a two-step recipe. 1: use of BCl_3 to etch the thin TiO_2 oxidized layer at the surface of the Ti. 2: Cl_2=HBr to etch the Ti with a selectivity to SiO_2 and photo-resist of ~3
- Fused silica etching: $C_4F_8/O_2/CO/Ar$ with a selectivity of ~5 to the photo-resist and of ~8 to Ti.