Optical and laser properties of $Yb^{3+}:CaF_2$ for laser applications

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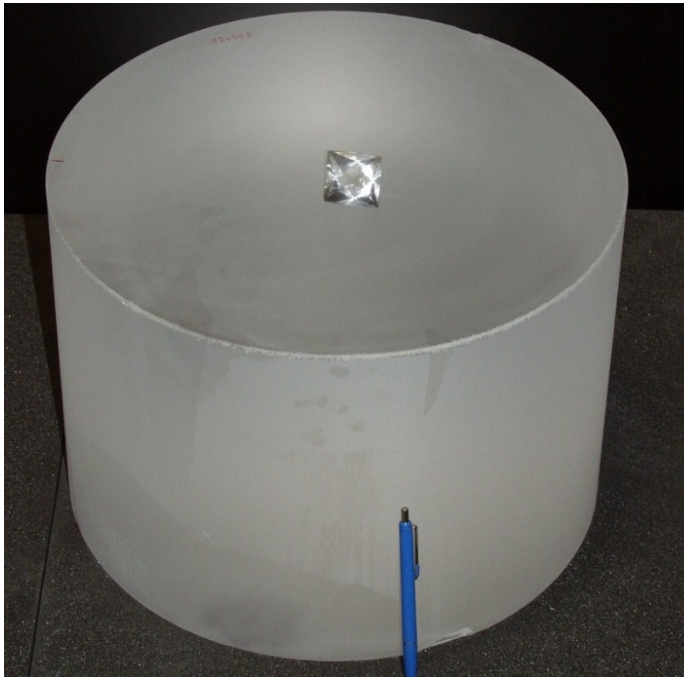
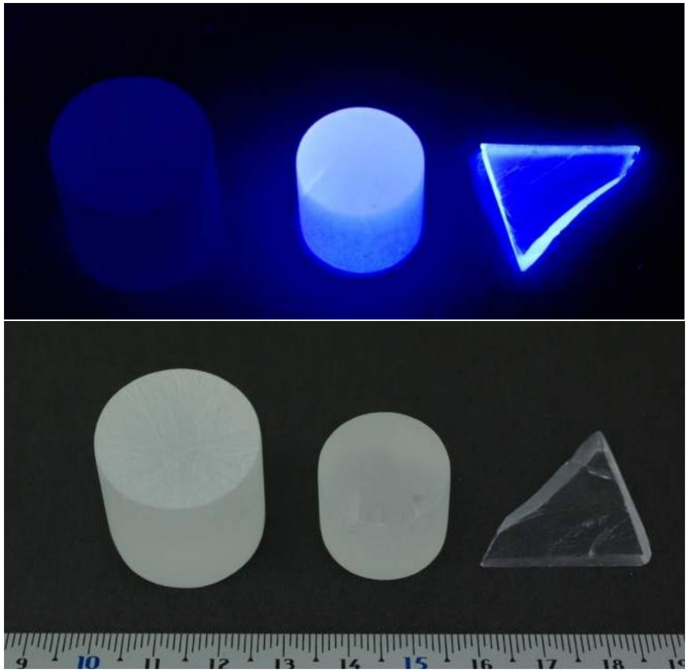
1.1 Who we are

- **Incorporated:** 2010
- **Employees:** 60
- **Revenue 2013:** EUR 10 Mill.
- **Capacity:** 76 furnaces
- **Located:** Jena, Germany

1.2 What we do

Optical crystals	Scintillation crystals
CaF_2, BaF_2, Yb^{3+}:CaF_2	$CeBr_3$, SrI_2:Eu, CaF_2:Eu





Size: 440mm x 300 mm	Size 3” x 3”

2.1. Crystal properties

$Yb^{3+}:CaF_2$		required	achieved
Refractive index homogeneity	ppm	1 .. 5	
Stress birefringence	nm/cm PV	1 .. 3	
Dopant concentration Yb^{3+}	at%	1 .. 3 .. (5)	
dopant gradiant		none	
Crystal defects	Small angle grain bound.	weak	
	slip planes	weak	
	Scatter class	<2	
Size	mm	D=100 .. 150	
Damage (2..3ns)	J/cm^2	>10	

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For pure CaF_2 in DUV imaging optics refractive index variation is specified to be extremely low. Annealing processes are in place to deliver blanks with Δn down to 0.5ppm over a diameter of 250mm.

Sample:

Melting Nr.:	038029
Part Nr.:	S111
Anneal.Nr.:	0,0,0,0
X-Size:	272.60 mm
Y-Size:	272.60 mm
Thickness:	41.50 mm

Zernike results: n(ppm)

x marks subtracted Zernike term

x	C 1 =	0.0005
x	C 2 =	0.0083
	C 3 =	0.1368
	C 4 =	0.0278
	C 5 =	-0.0300
	C 6 =	0.0179
	C 7 =	-0.0173
	C 8 =	-0.0081
	C 9 =	0.0031
	C10 =	-0.0040

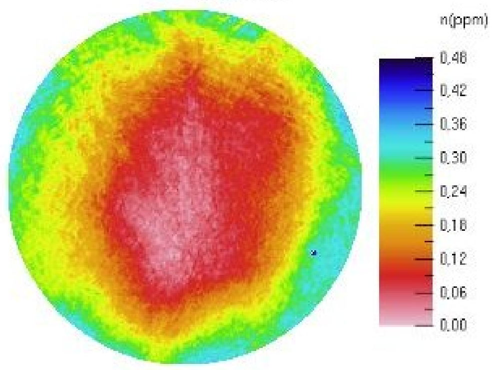
Evaluation:

Date:	28.02.08
Tmp. before:	21.54 °C
Tmp. after:	21.54 °C
Diameter:	208.50 mm

Spec test:

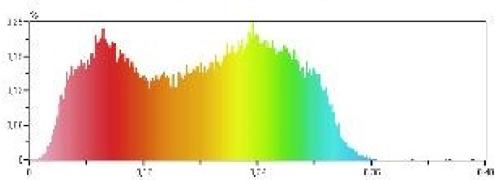
Customer:	
ID:	99999
pass?:	O.K.

Wavefront



PV:	0.4791 n(ppm)
RMS:	0.0847 n(ppm)

Histogram Homogeneity



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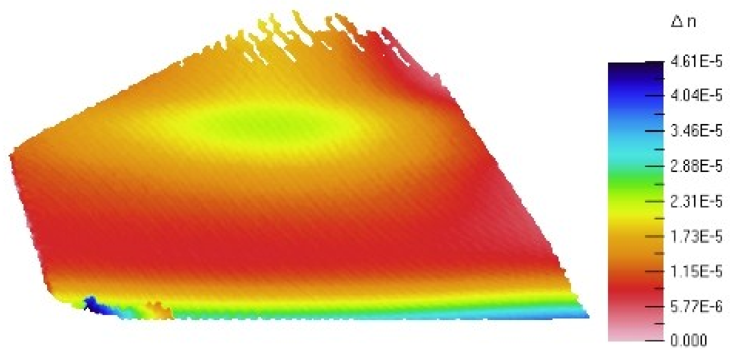
Refractive index homogeneity of today´s products is < 10ppm for D up to 3”

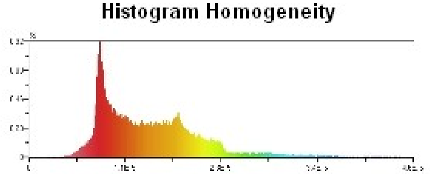
Glass-Type:	CaF2	
Batch No.:	32032	
Part No.:	YB-XX	**Order No.:**
Diameter Ø:	120.0 mm	
Thickness:	47.3 mm	



Evaluation:

Test Size:	178.1 x 94.8 mm	
PV:	46.13 E-6	
Delta n:	± 23.07 E-6	(H0)
RMS:	5.73 E-6	

Histogram Homogeneity

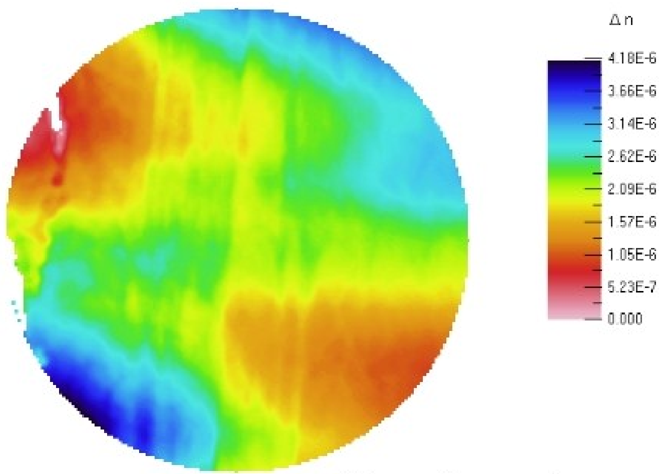


3.1.2 Index homogeneity

Refractive index homogeneity of today´s products is < 10ppm for D up to 3”

Glass-Type:	CaF2
Batch No.:	032031
Part No.:	Q401
Size:	159.4 x 117.8 mm
Thickness:	67.6 mm

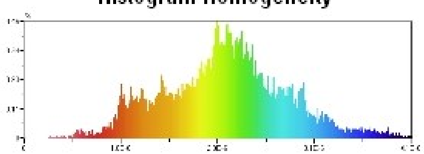
Order No.:
999999999



Evaluation:

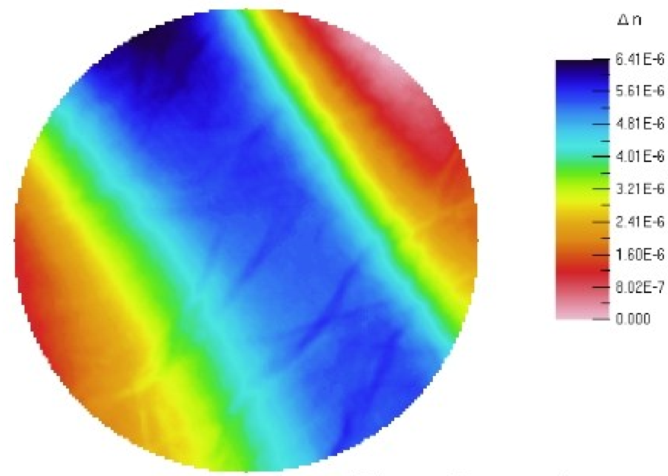
Test Diameter Ø:	50.0 mm	
PV:	4.18 E-6	
Delta n:	± 2.09 E-6	(H2)
RMS:	0.64 E-6	

Histogram Homogeneity



Glass-Type:	CaF2
Batch No.:	032032
Part No.:	Q405
Size:	220.5 x 148.2 mm
Thickness:	61.7 mm

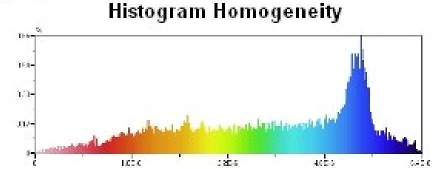
Order No.:
999999999



Evaluation:

Test Diameter Ø:	50.0 mm	
PV:	6.41 E-6	
Delta n:	± 3.21 E-6	(H2)
RMS:	1.51 E-6	

Histogram Homogeneity



3.1.3 Index homogeneity

Sometime things go wrong ….

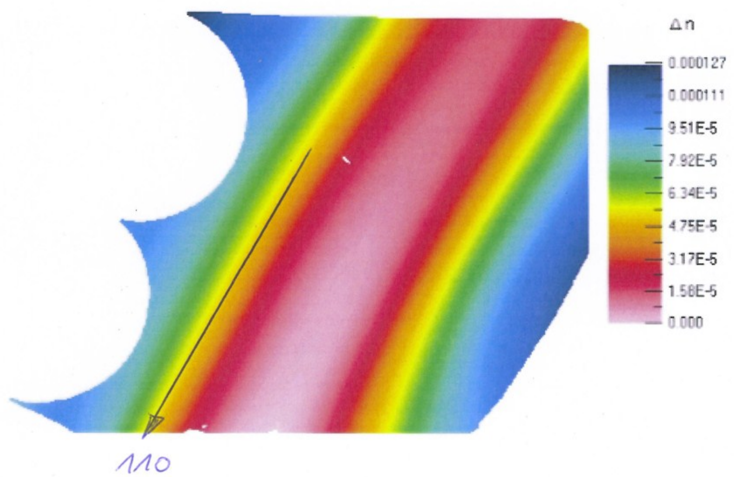
Sample:

Glass-Type:	CaF2
Batch No.:	032032
Part No.:	Q403
Size:	262.4 x 149.8 mm
Thickness:	36.4 mm

Customer:

Order No.: 999999999

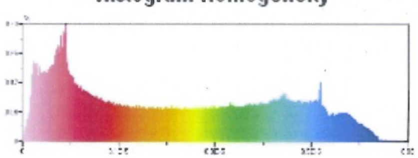
Date: 20. Mrz. 2014



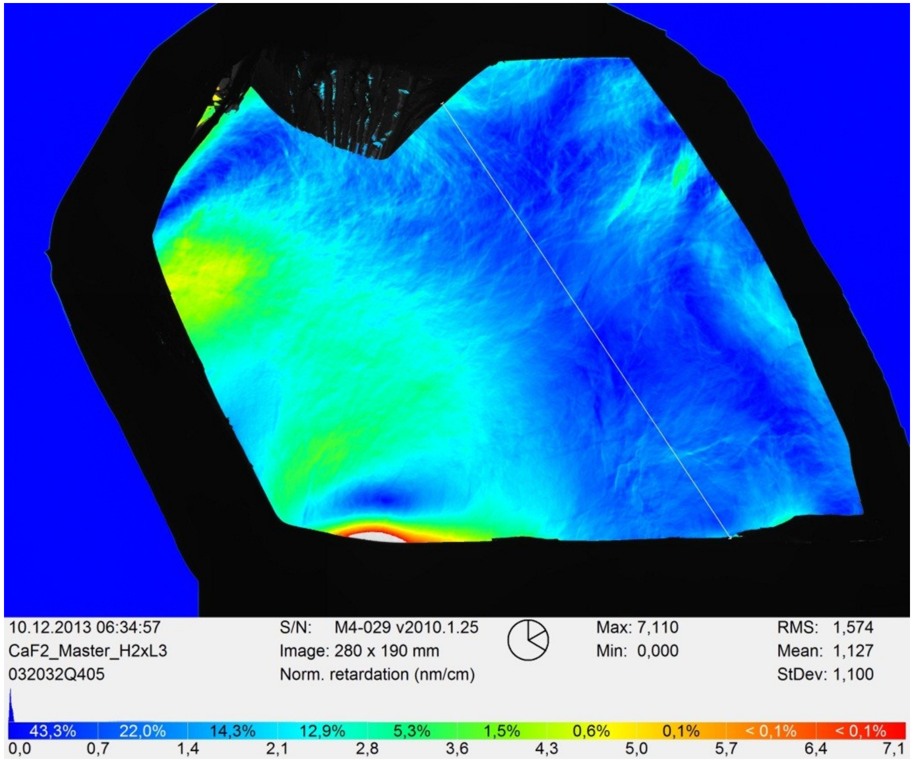
Evaluation:

Test Size:	200.6 x 145.8 mm	
PV:	126.76 E-6	
Delta n:	± 63.38 E-6	(HO)
RMS:	33.65 E-6	

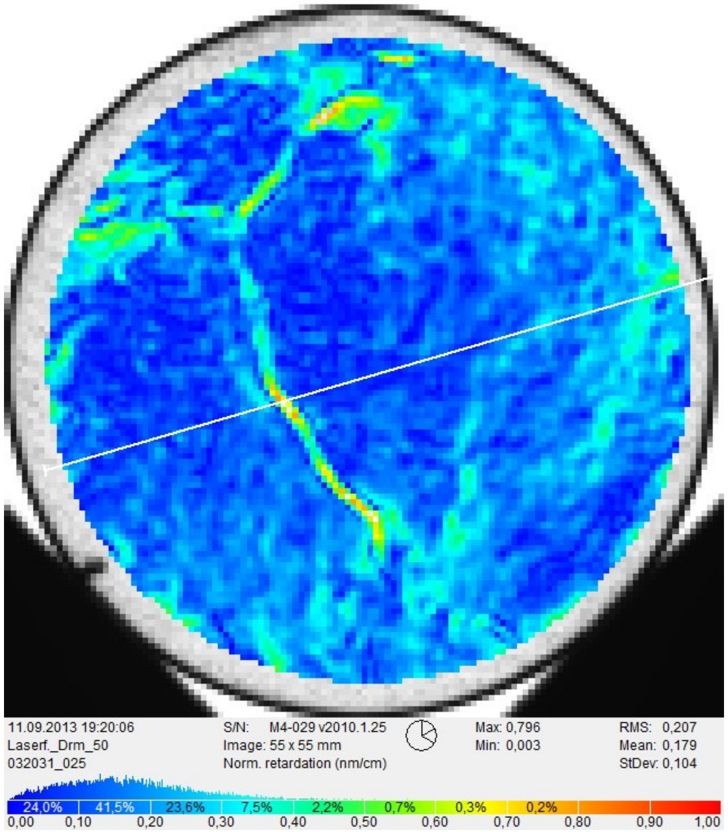
Histogram Homogeneity

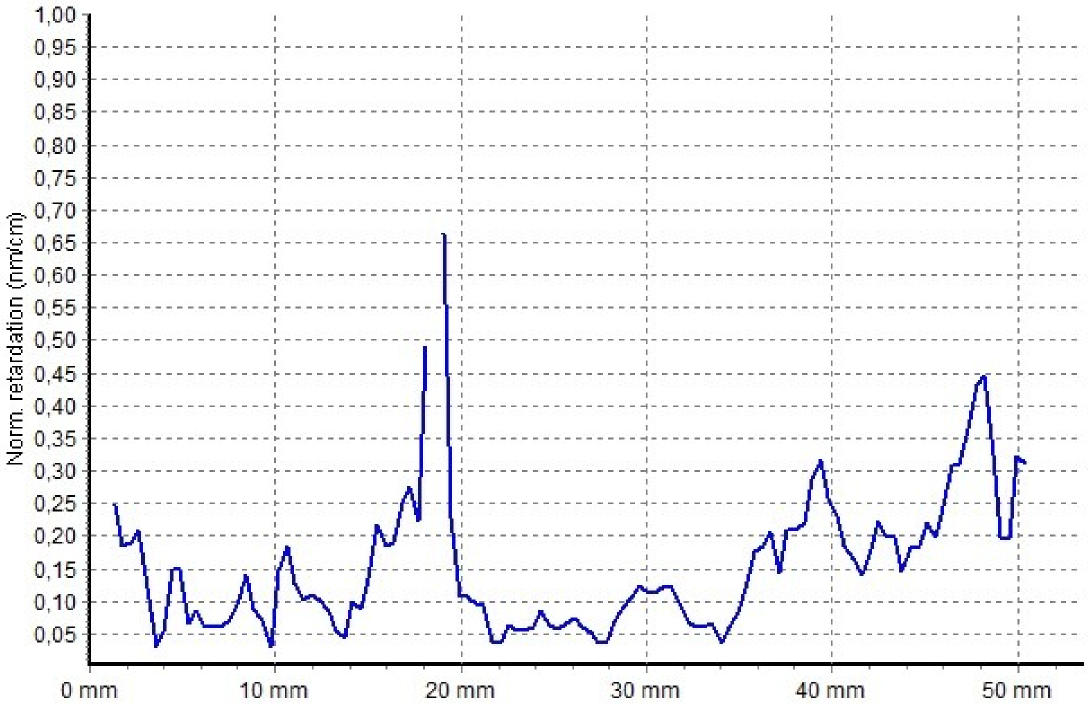


Stress birefringence can be smaller than 1.0nm/cm PV



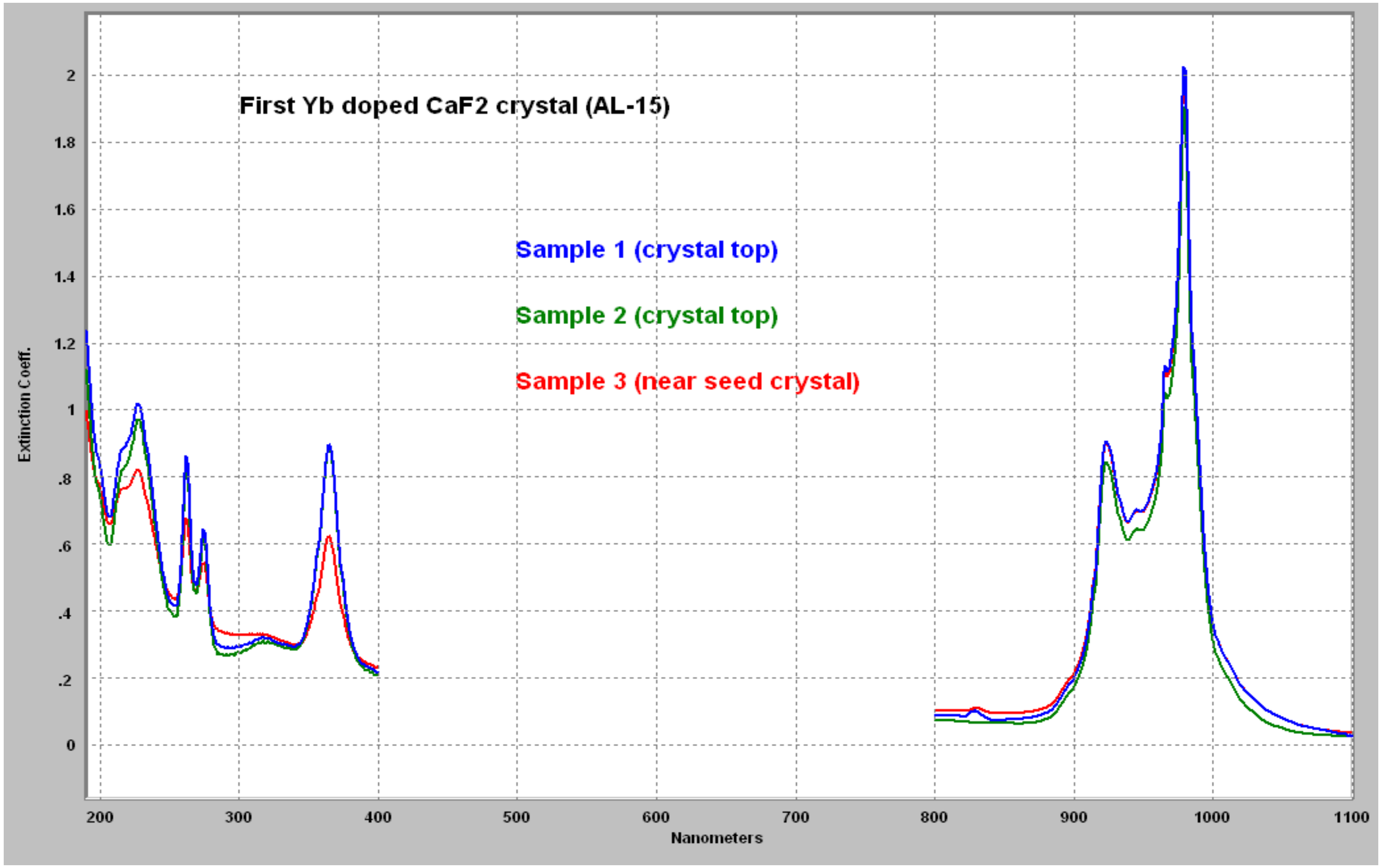
Stress birefringence can be reduced below 1nm/cm by annealing





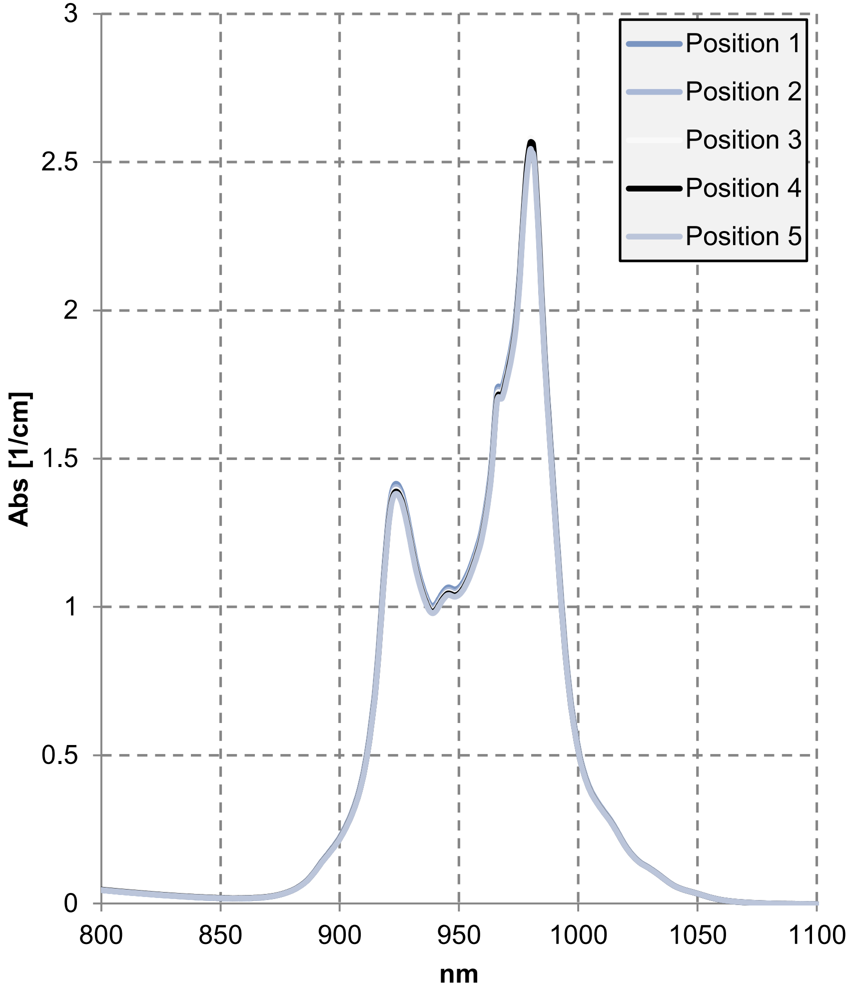
3.3.1 Results - homogeneity of Yb^{3+} distribution

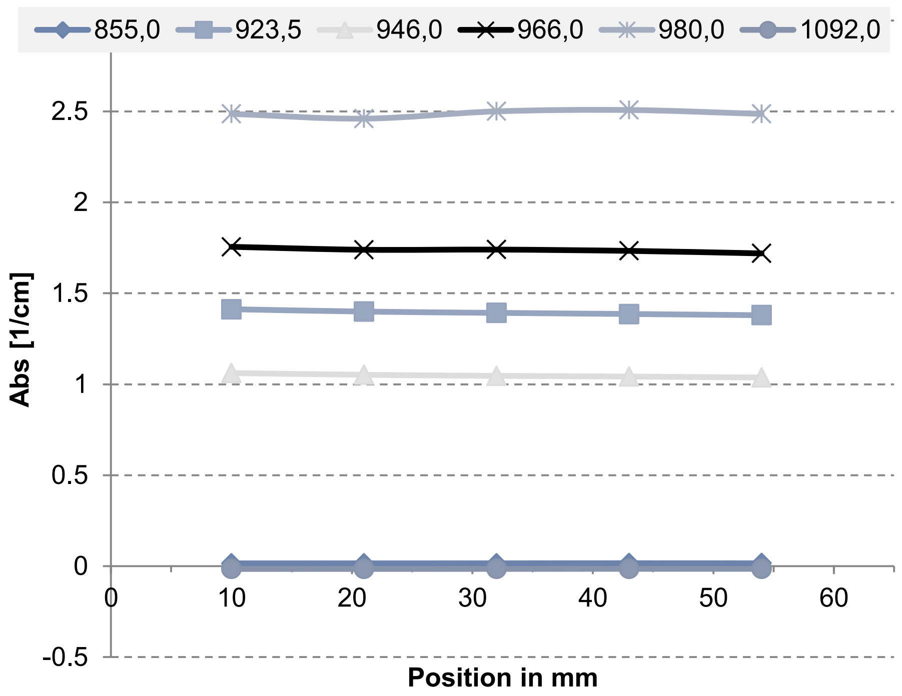
There is no difference for Yb^{3+} between bottom an top of the crystal, but for Yb^{2+} there is a lower absorption at the bottom (near seed crystal)



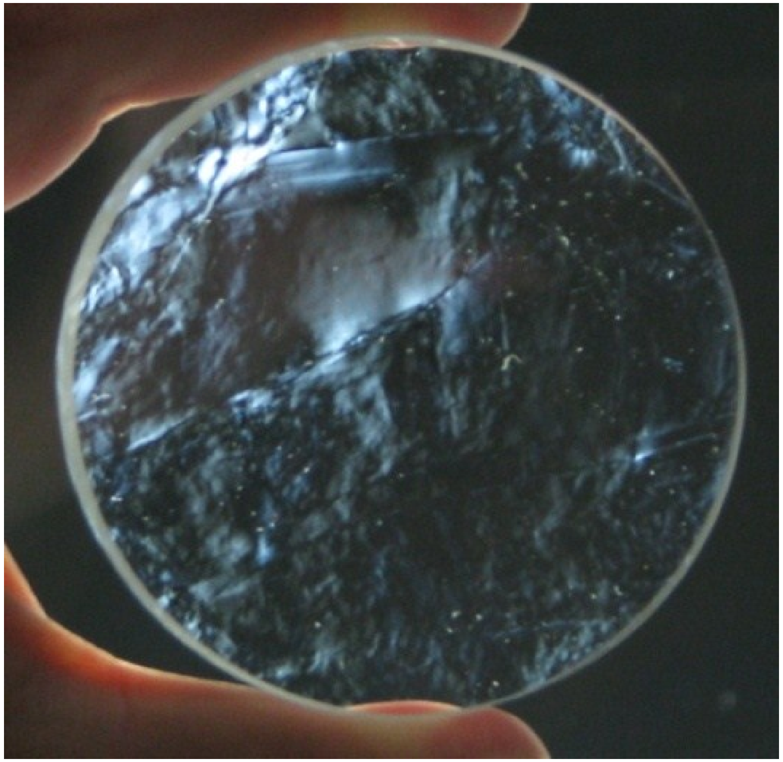
3.3.2 Results - homogeneity of Yb3+ distribution

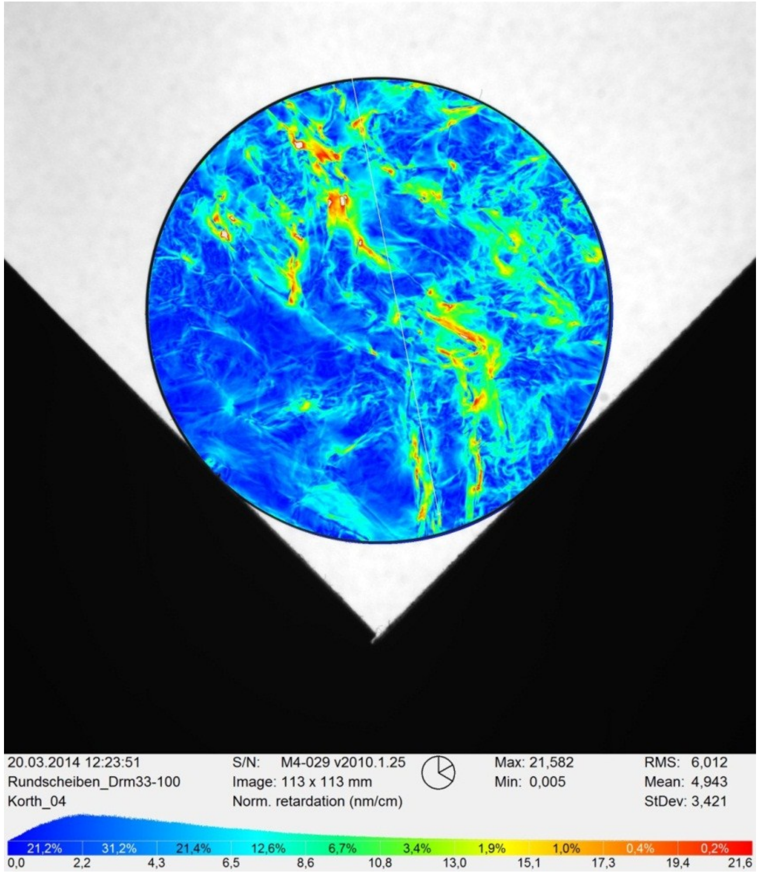
Absorption fluctuation is smaller than 2%





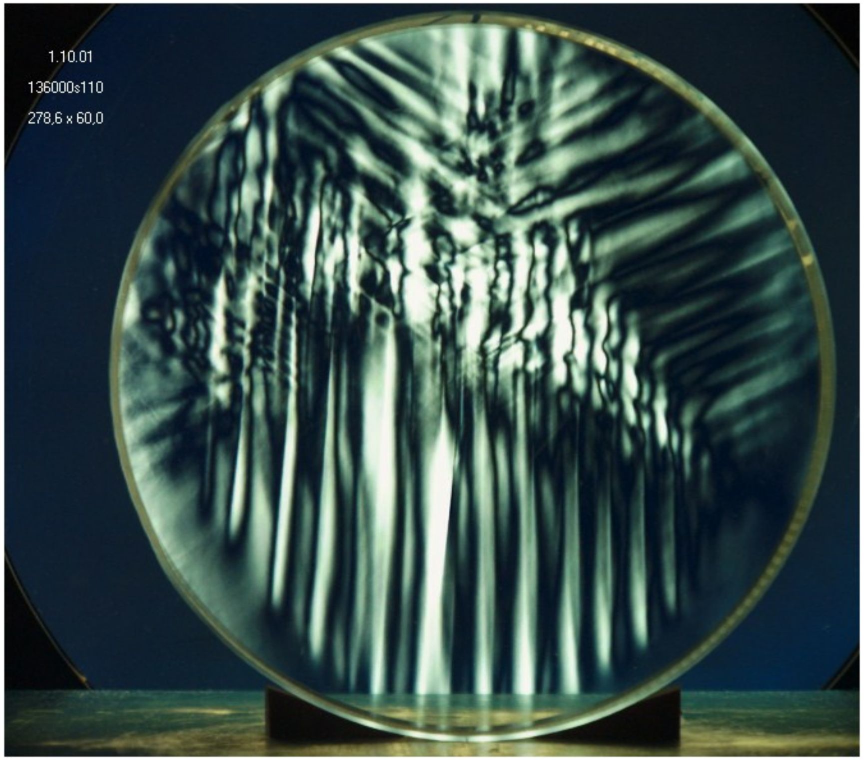
Small angle grain boundaries cannot be removed with annealing
Classification weak, middle, strong





3.4 Crystal defects – Slip planes

Slip planes defects can be reduced by annealing
Classification: weak, middle, strong



3.4 Crystal defects - Scattering

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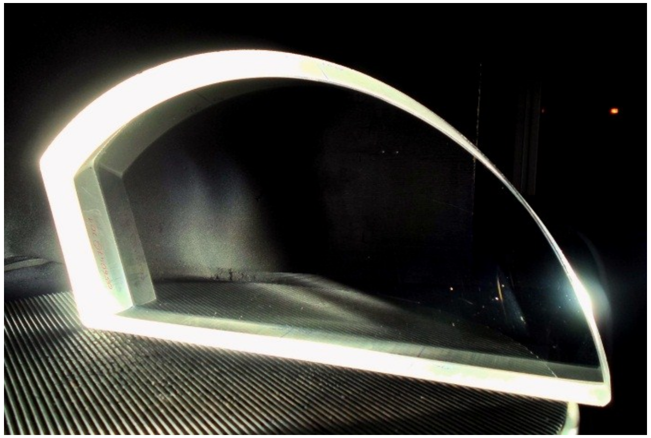
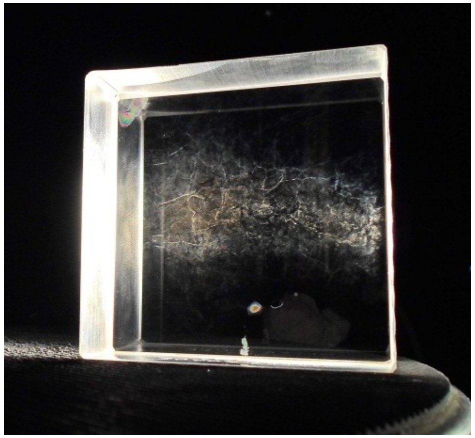
Scattering is determined by bright light source – classification 0, 0-1, 1, 1-2, … 3

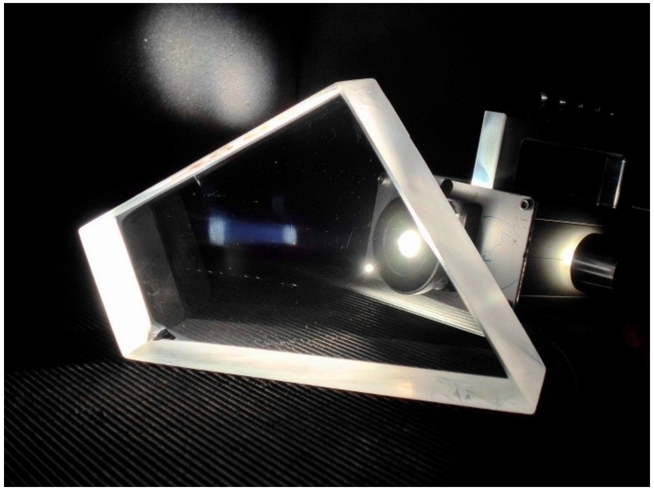
0-1



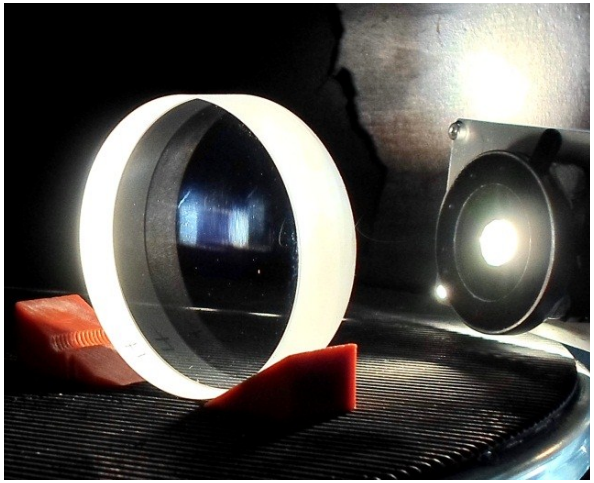
2-3



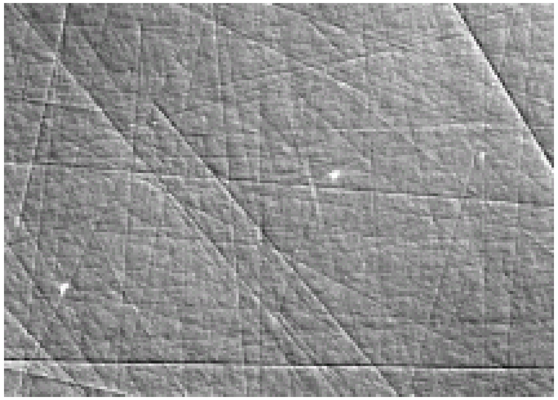
1



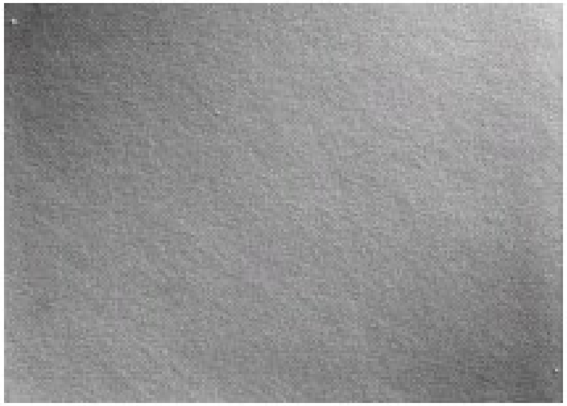
1-2



Polishing technology to reduce sub-surface damage and increase lifetime



Rq = 1,6 nm



Rq = 0,2 nm

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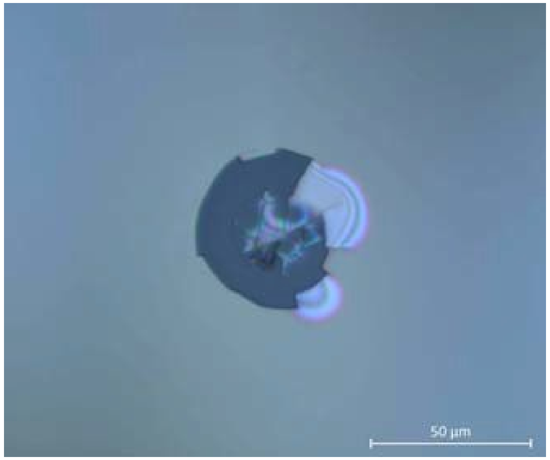
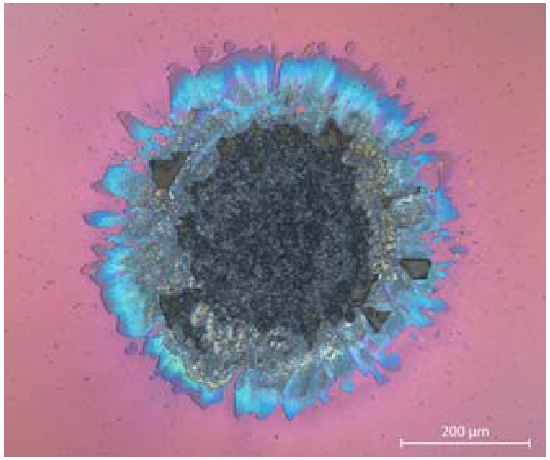
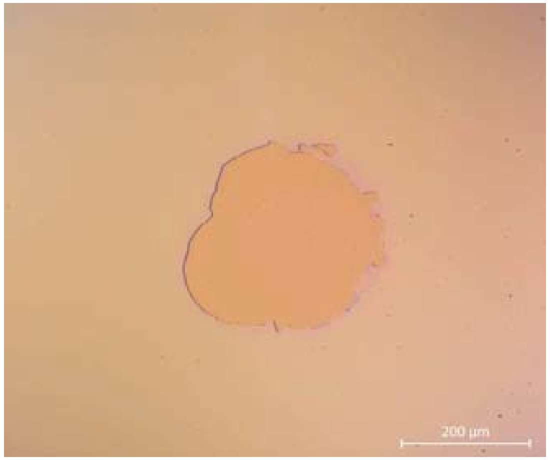
Different damage mechanisms



Inclusion dominated breakdown defects„ Damaged coating at position 84 of sample #3 (energy density **33 J/cm²**, damage after 1 pulse)



Melting due to absorption/ Recrystallization damaged coating at position 138 of sample #1 (energy density **70,0 J/cm²**)damage after 1244 pulses)



Coating ablation damage at position 64 of sample #1 (energy density **120,0 J/cm²**, damage after 2 pulses)

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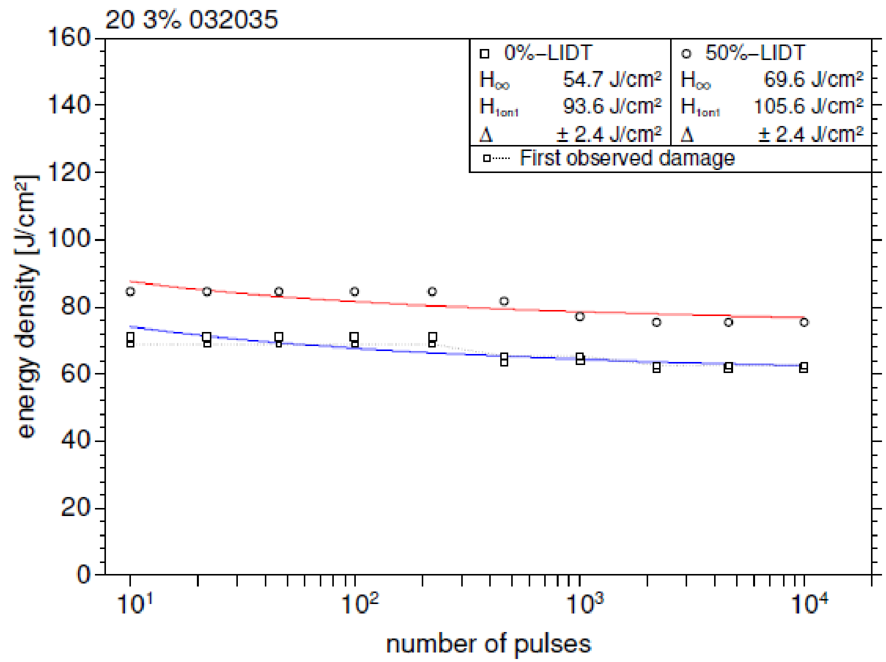
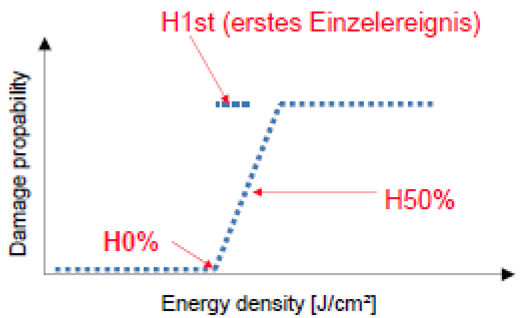
Laser damage for AR coating ~25J/cm² at small beams





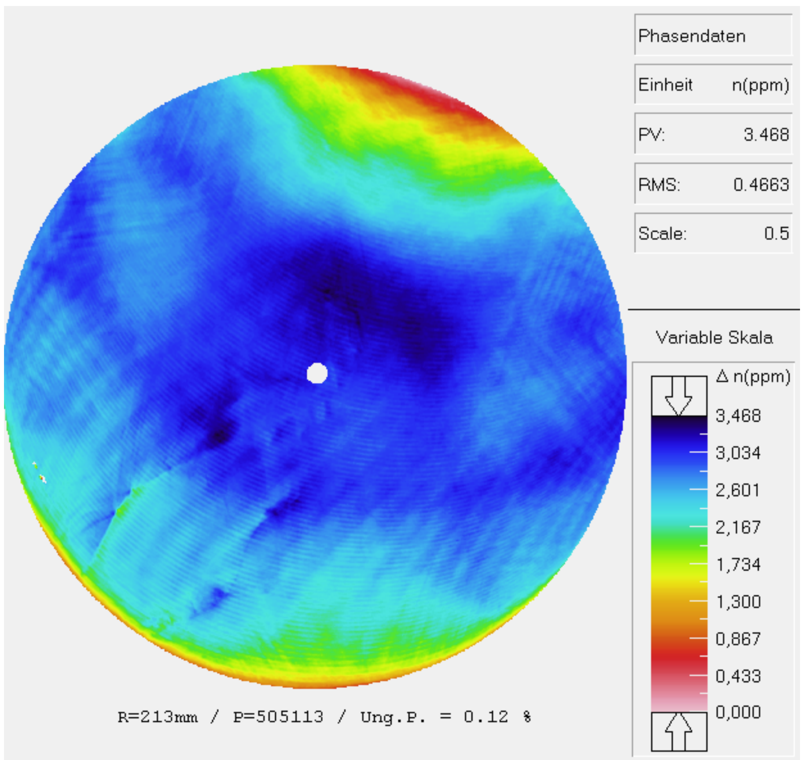
Faktor für kürzere Pulse:

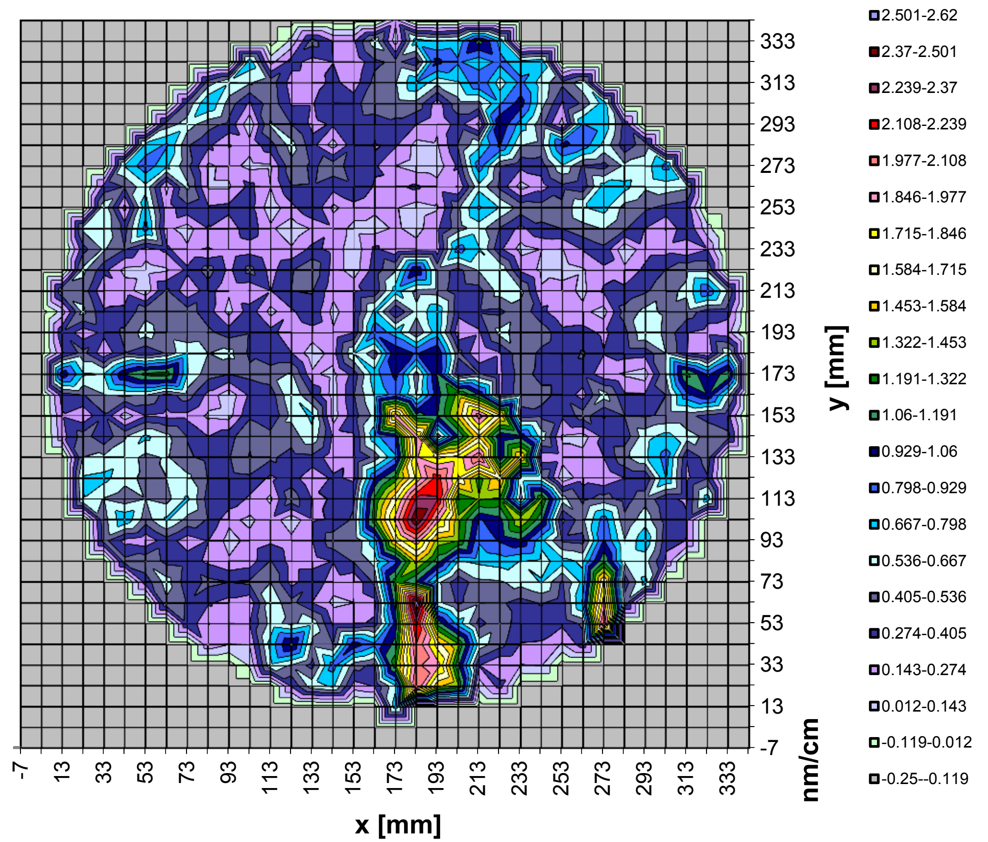
$$H_{3ns} = H_{11ns} * \frac{\sqrt{3ns}}{\sqrt{11ns}} = 0.52$$

Lit.: B.C. Stuart et. al.; Nanosecond-to-femtosecond laser-induced breakdown in dielectrics; Phys. Rev., vol. 53, number 4. pp 1749

4.1 Large aperture, low dispersion and low n_2 windows

D=426 mm, t=52mm
Refractive index homogeneity < 3.5 ppm,
Stress birefringence: <2.7 nm/cm (330mm)



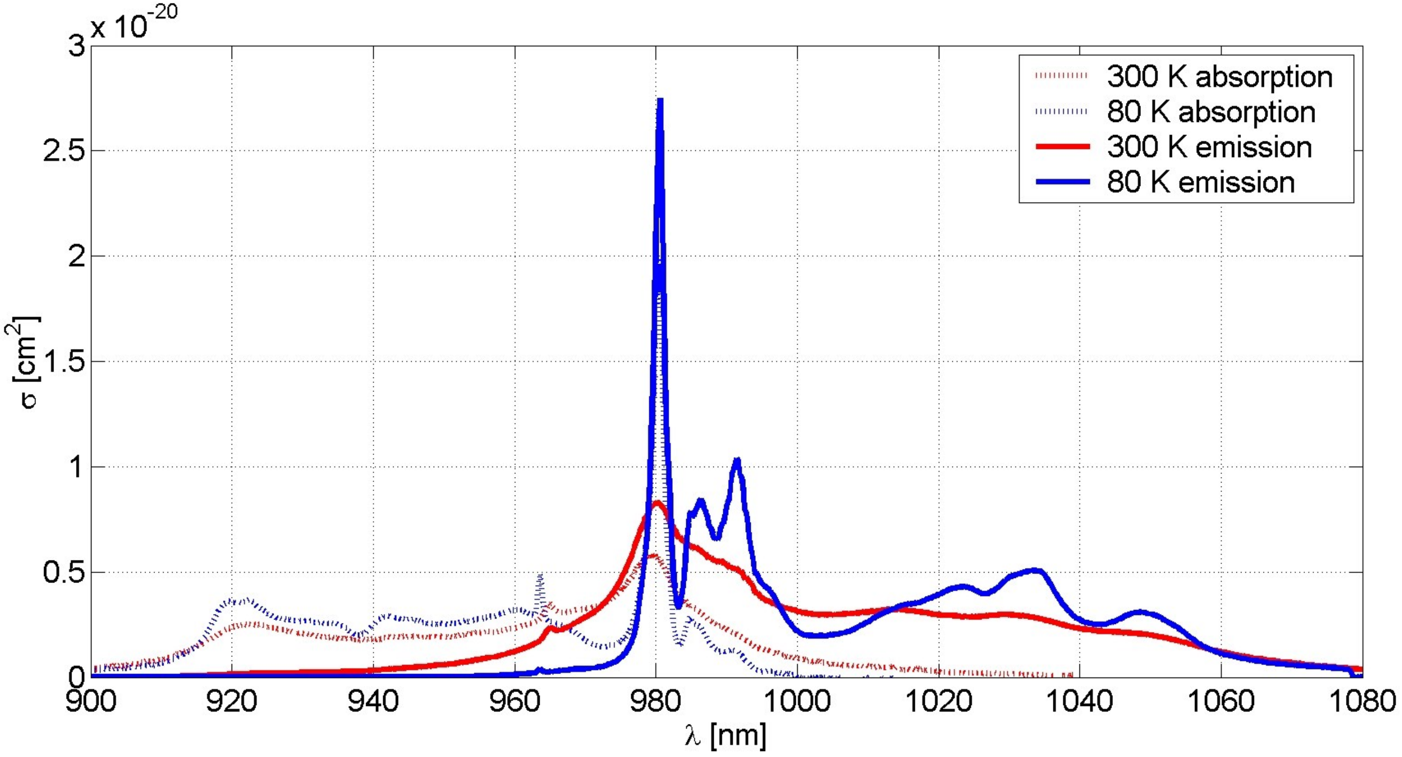


5.1 Summary

$Yb^{3+}:CaF_2$		required	achieved
Refractive index homogeneity	ppm	1 .. 5	<10 (D=75 mm)
Stress birefringence	nm/cm PV	1 .. 3	<1
Dopant concentration Yb^{3+}	at%	1 .. 3 .. (5)	0.9 .. 3
dopant gradiant		none	none
Crystal defects	Small angle grain bound.	weak	partially weak
	slip planes	weak	weak (after annealing)
	Scatter class	<2	1
Size	mm	D=100 .. 150	D>150
Damage (2..3ns)	J/cm^2	>10	>25 (small beam)

When every photon counts.

A1 Absorption and emission cross section



A2 Refractive index and dn/dT of $Yb^{3+}:CaF_2$

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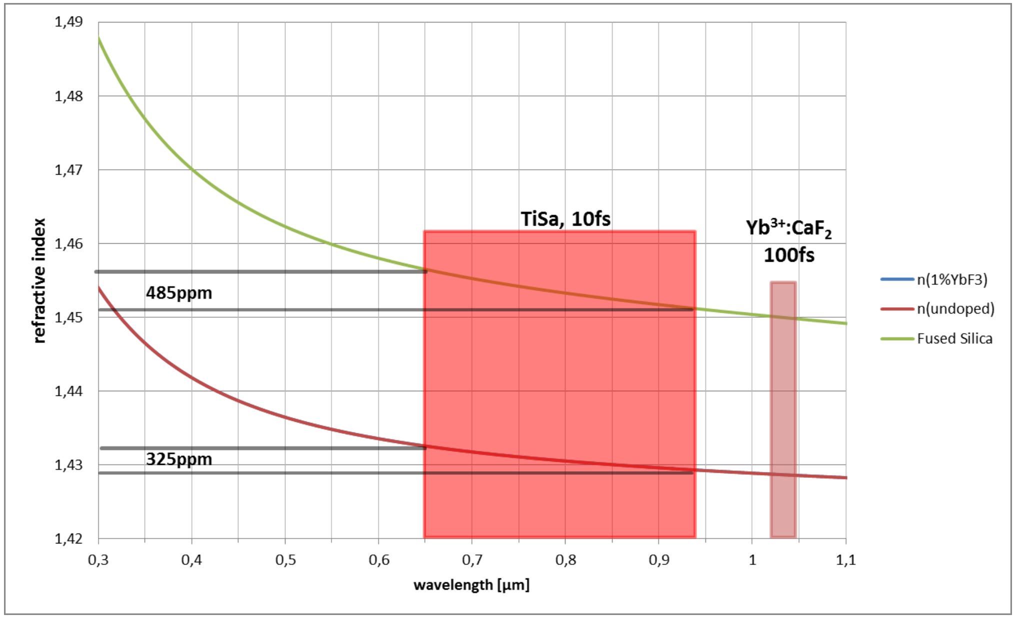
Almost no differences between pure CaF_2 and 1% Yb-doped CaF_2



Spectral Line	Vacuum wavelength [µm]	dn_{rel}/dT [1E-6 / K]			
		Nitrogen, -40--20		Nitrogen, 60-80	
		CaF_2 pure	CaF_2 1%Yb	CaF_2 pure	CaF_2 1%Yb
i	0,365	-7,7	-7,8	-10,3	-10,5
h	0,405	-7,9	-8,0	-10,6	-10,8
g	0,436	-8,1	-8,1	-10,7	-10,9
F'	0,480	-8,2	-8,2	-10,8	-11,0
e	0,546	-8,3	-8,4	-11,0	-11,2
d	0,588	-8,4	-8,4	-11,0	-11,2
(HeNe)	0,633	-8,4	-8,5	-11,1	-11,3
C'	0,644	-8,4	-8,5	-11,1	-11,3
s	0,852	-8,5	-8,6	-11,2	-11,4
t	1,014	-8,6	-8,6	-11,2	-11,5
(Nd)	1,060	-8,6	-8,6	-11,2	-11,5