Dispersive optics: limits and challenges

V. Pervak

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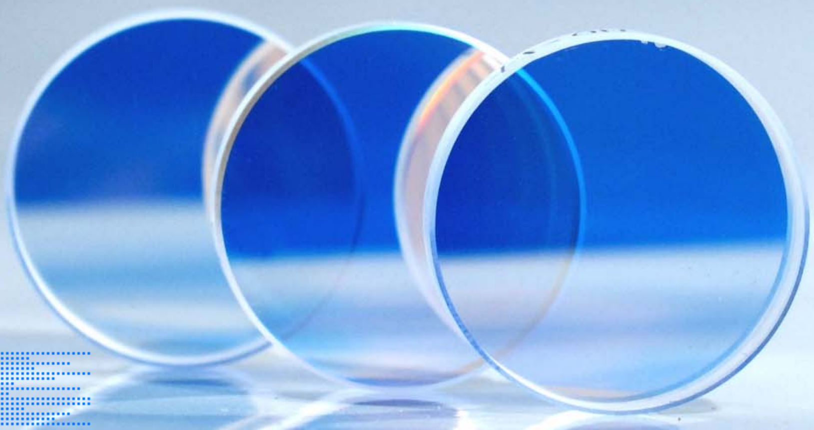
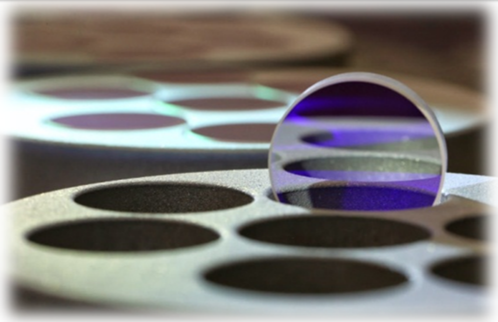
Ultrafast Innovations GmbH,



09.06.2015 - Buchs, Switzerland

Outline

- *Motivation*
- *Introduction – group delay makes a pulse longer*
- *How does DM work?*
- *Pulse compression*
- *Femtosecond Yb:YAG disk oscillator*
- *Robust design synthesis*
- *Damage threshold at kHz and MHz rep. rate*
- *Non-linear behaviour of dispersive mirrors*
- *The highest absolute GDD value realized*
- *Summary*



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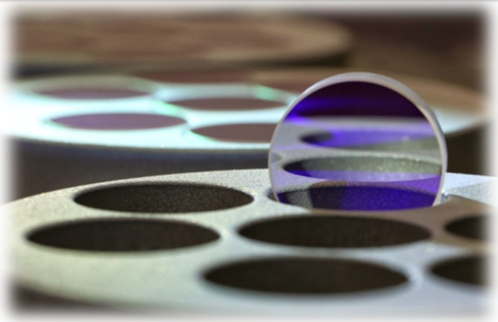
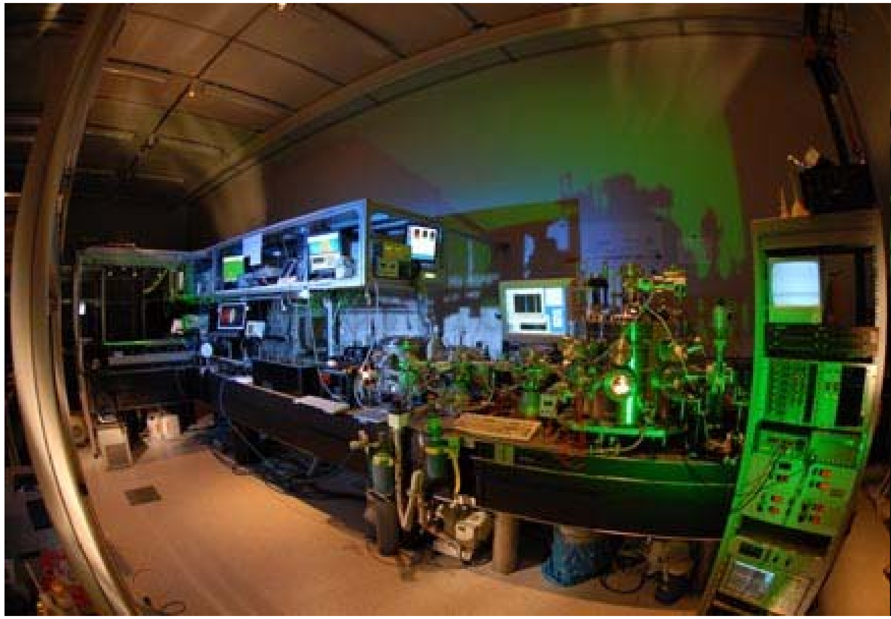
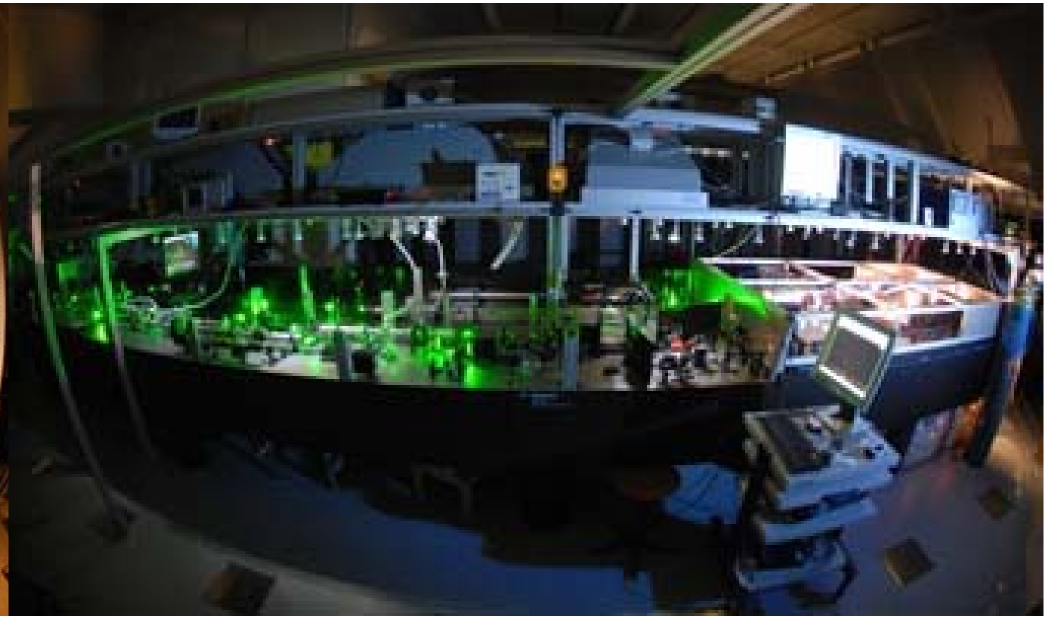



Motivation



The attosecond measurement system (AS). A commercial Ti:sapphire laser delivers 5-fs (@750-nm) laser pulses at a repetition rate of 4 kHz. The laser pulses produce isolated 80-as extreme ultraviolet pulses in the first vacuum chamber. AS allowed the first real-time observation of electron tunneling out of atoms.

E. Gouliemakis et al., Science 320, 1614 (2008)



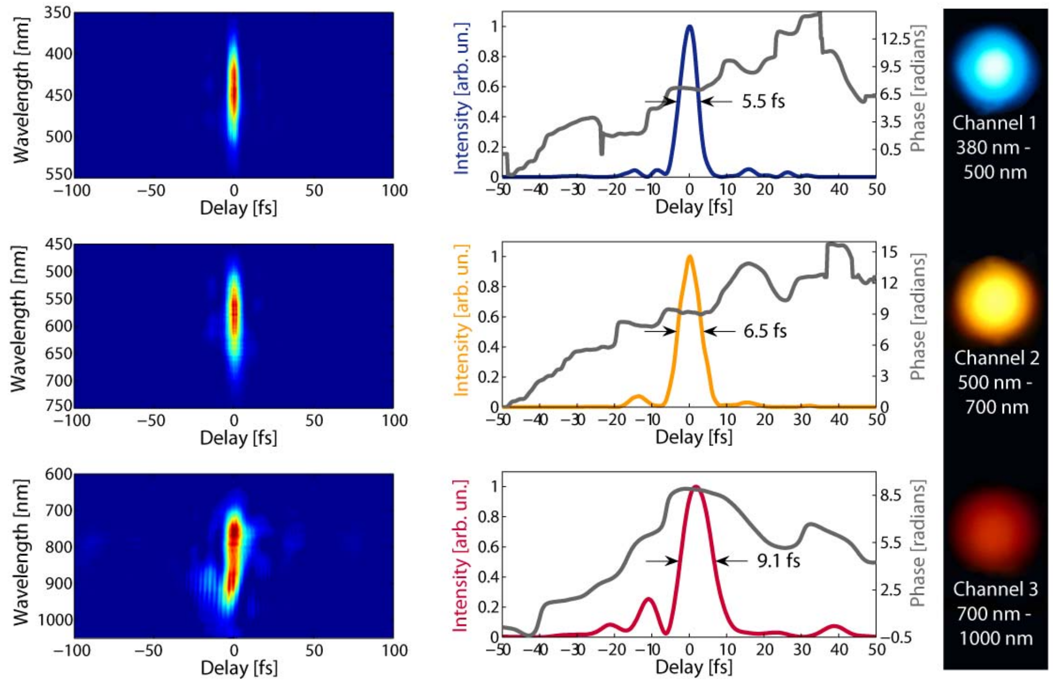
Light wave sythesizer is a 10 TW sub-10-fs light source based on the novel optical parametric chirped pulse amplification (OPCPA) technique. The amplified seed is compressed temporally to 8 fs.

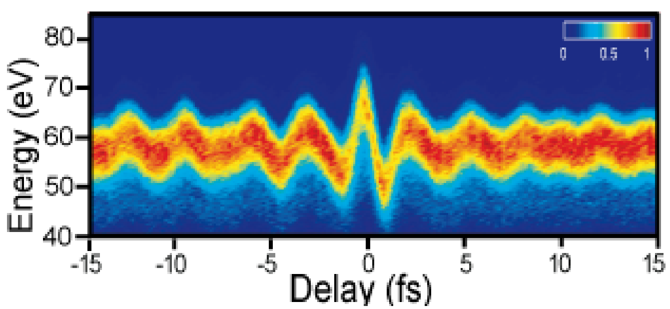
D. Hermann et al., Optics Express 18, 18752 (2010);

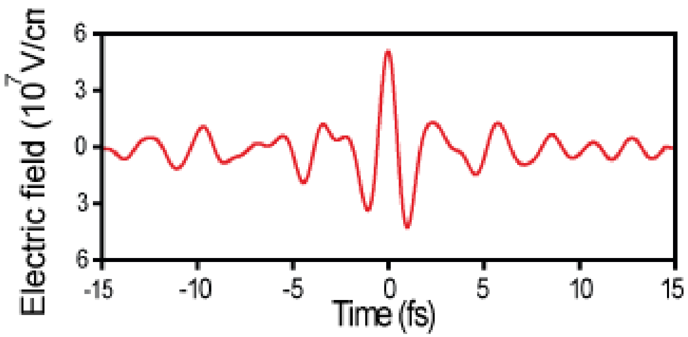
Motivation

Intense 2.1 fs sub-optical-cycle light waveforms

A. Wirth et al., Science 334, 195–200 (2011).







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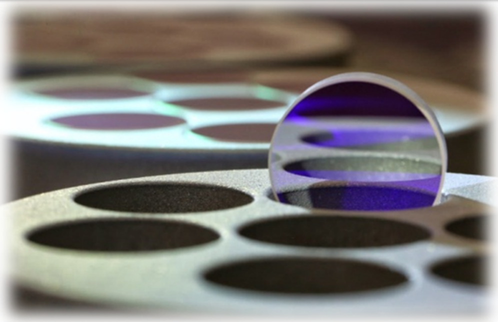
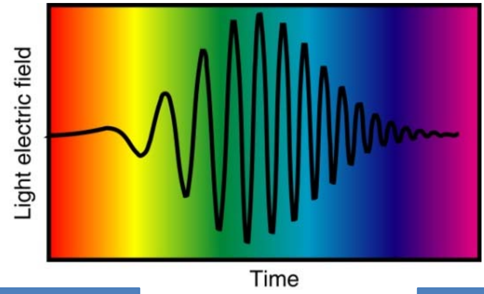
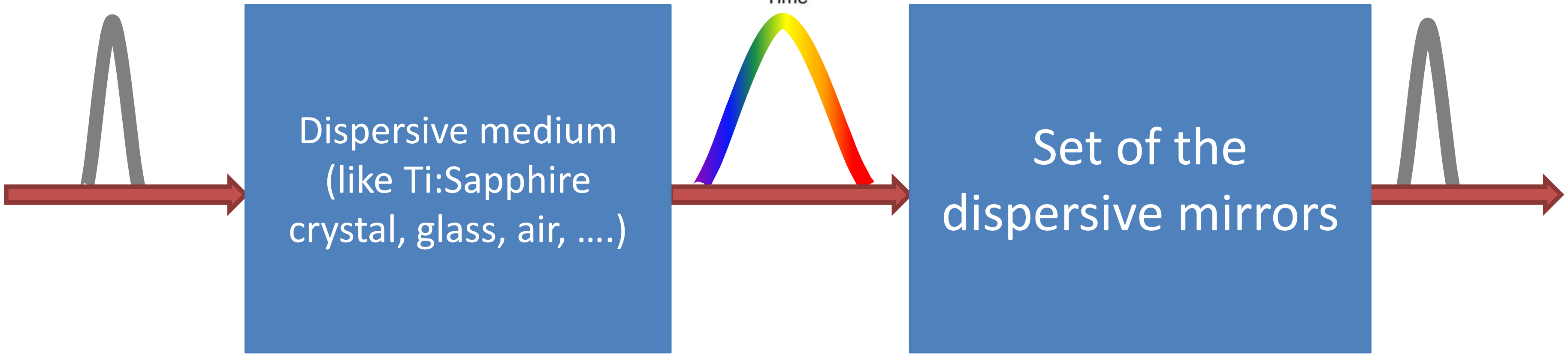
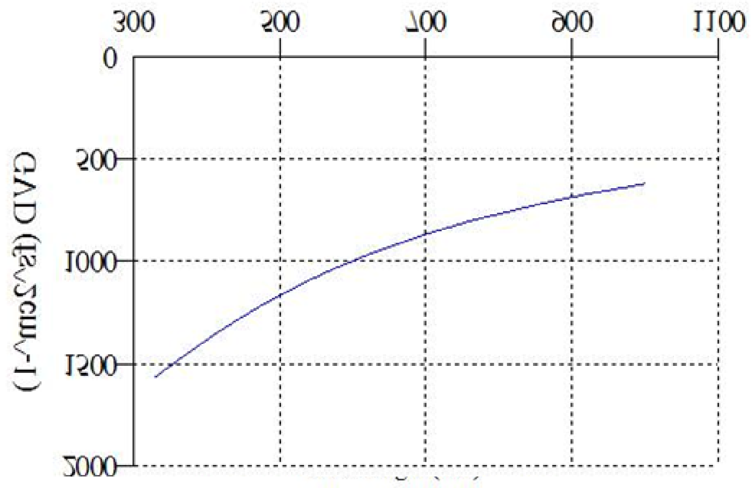


Group delay makes a pulse longer







Pulse duration

$$\tau(z) = \tau_0 \left(1 + \zeta \frac{\phi''}{{\tau_0}^2}\right)^{1/2}$$

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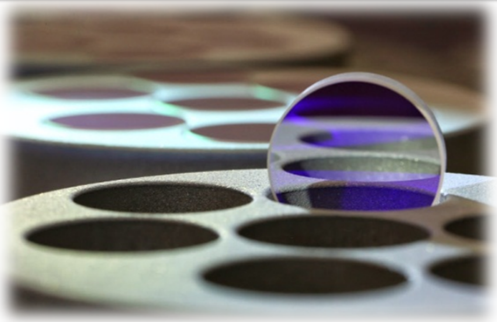

How does DM work?

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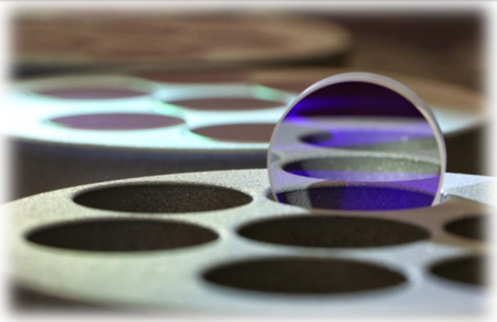
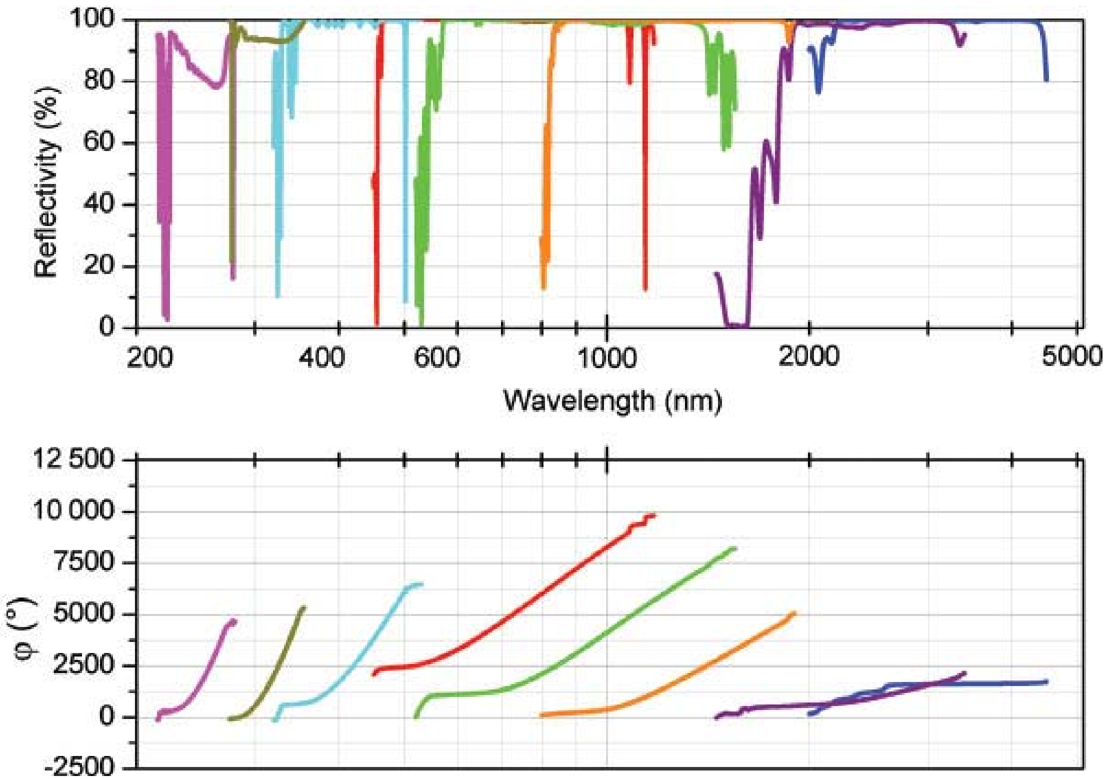



Pulse compression in range 220 – 4500 nm

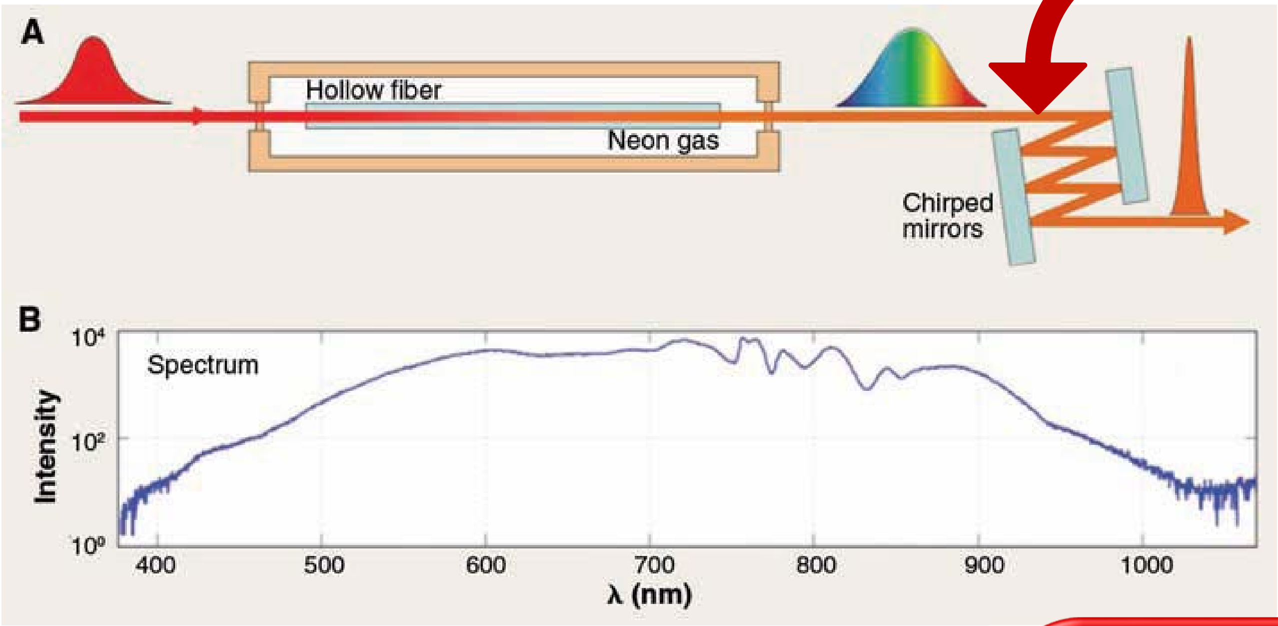


Spectral region covered by designed and produced dispersive mirrors. Reflectivity (upper box) and phase (lower box) are shown.

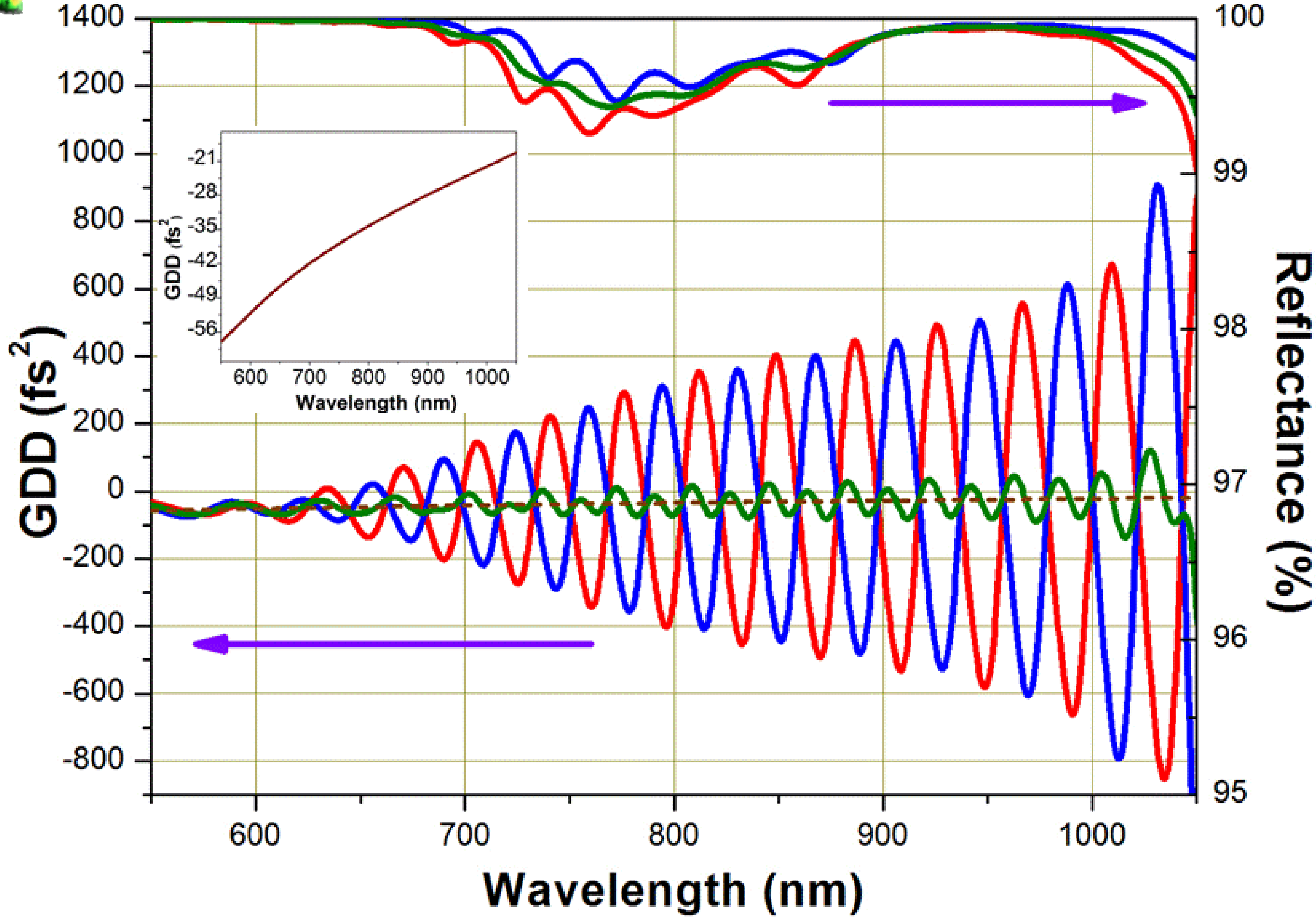
- Magenta curves correspond to DMs with a working range of 220−290 nm.
- Dark yellow curves correspond to DM [1].
- Cyan – DM with a working range of 350−500 nm [2].
- Red – DM with a working range of 500−1050 nm [3 - 4].
- Green – DM with a working range of 700−1350 nm [5].
- Orange – DM with a working range of 1000−1800 nm [http://www.ultrafast-innovations.de].
- Violet – DM with a working range of 1900−3200 nm [1].
- Blue – DM with a working range of 2500−4200 nm [6].

[1] V. Pervak et al, Advanced Optical Technologies. 3, pp. 55–63, (2013)
[2] A. Wirth et al., Science 334, 195–200 (2011).
[3] V. Pervak et al., Opt. Express 17, 7943–7951 (2009).
[4] A. L. Cavalieri et al., New J. Phys. 9, 242–242 (2007).
[5] V. Pervak, in “Frontiers of Optical Coatings”,’ (Hangzhou, P.R. China, 15–18 October 2012) paper WA-2.
[6] A. Marandi et al, Opt. Express 20, 7255 (2012).

Ultra-Broadband Dispersive mirrors



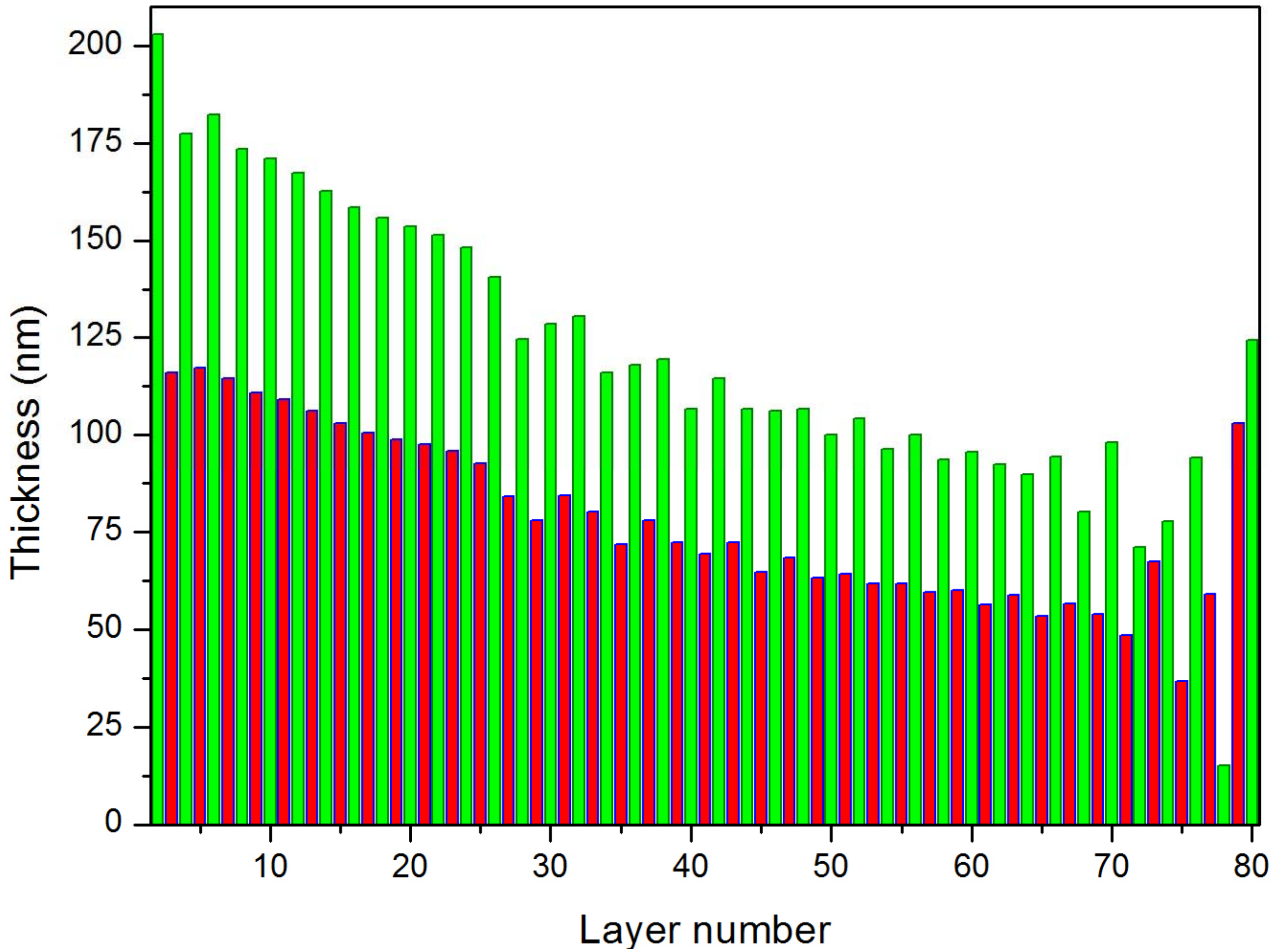
Ultra-Broadband Dispersive mirrors



The realized design of DADMs. The Red and blue curves show the dispersion at 5 and 20 degrees of incidence. The green curve shows the average curve of the dispersion, demonstrating an effect of compensation reached by using DADMs.

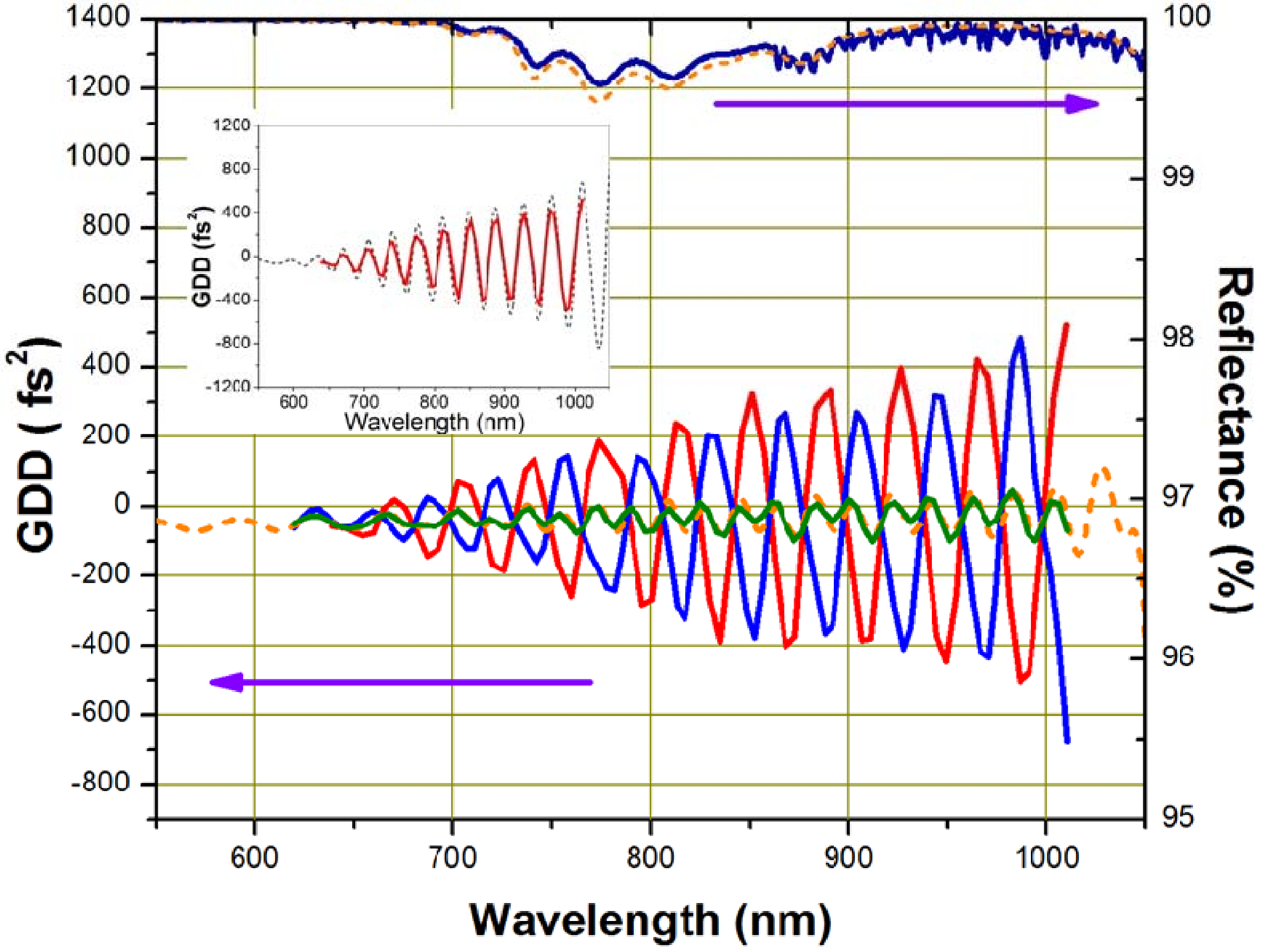
V. Pervak et al Opt. Exp. 17 , 7943 (2009)

Ultra-Broadband Dispersive mirrors



Physical thicknesses of layers in our prototypical double-angle DM design. Layers are numbered starting from the substrate. Green and red bars correspond to low and high refractive index materials, SiO_2 and Nb_2O_5, respectively.

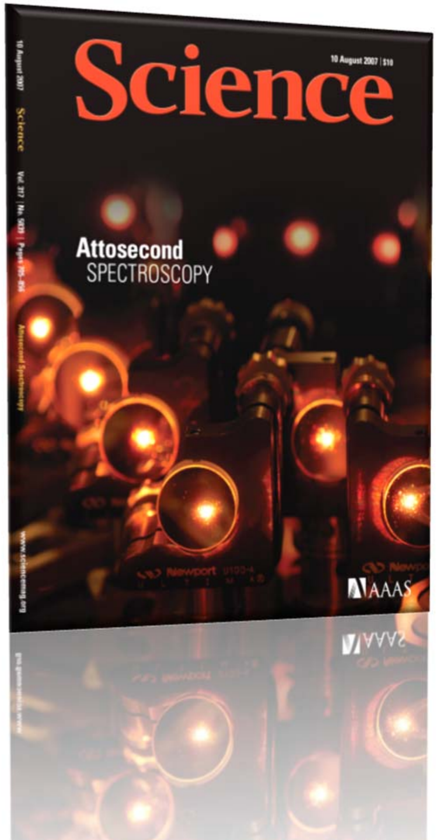
Ultra-Broadband Dispersive mirrors

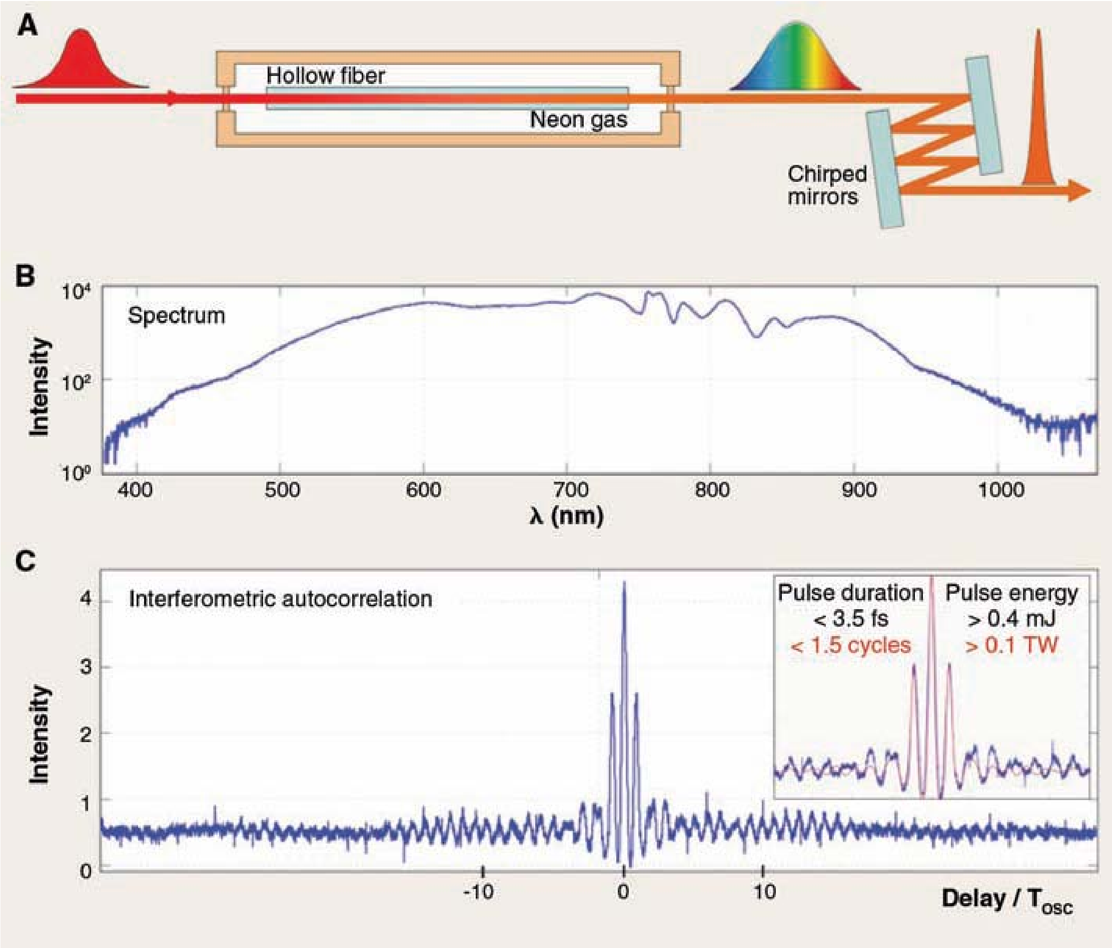


Measured GDD and reflectance of our prototypical double-angle DM for an angle of incidence of 5 and 20 degrees (full lines). GDD and reflectance of the theoretical design are shown by dashed lines. Red and blue curves correspond to angles of incidence of 5 and 20 degrees, respectively. Dark green and dark blue curves show the effective measured GDD and reflectance

Ultra-Broadband Dispersive mirrors

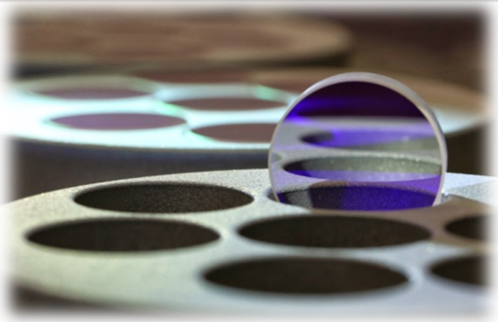
Measured interferometric autocorrelation function of the pulses compressed with double-angle DM compressor, indicating sub-4 fs pulse duration.





E. Goulielmakis et al. Science 317, 769 (2007)
A. L. Cavalieri et al. New J. Phys. **9**, 242 (2007)

Outline



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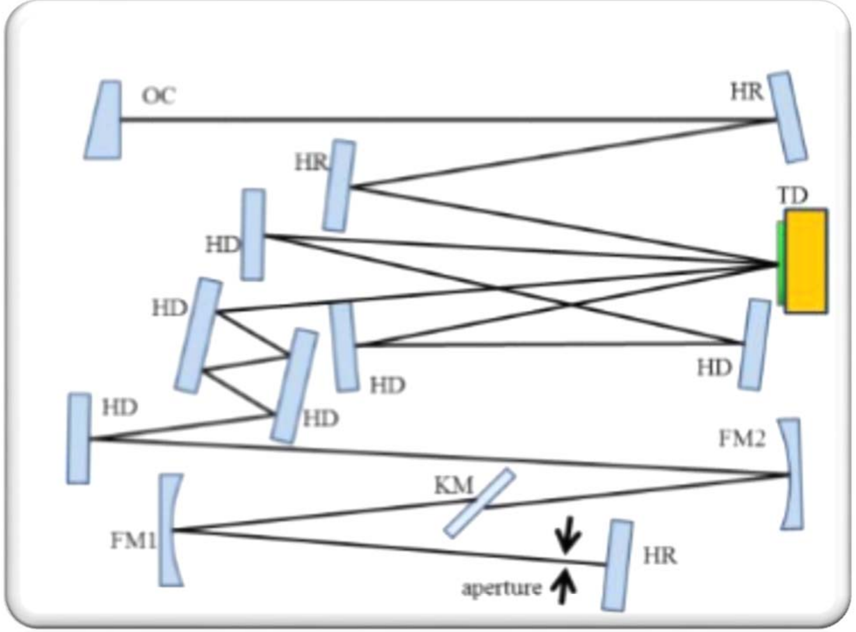
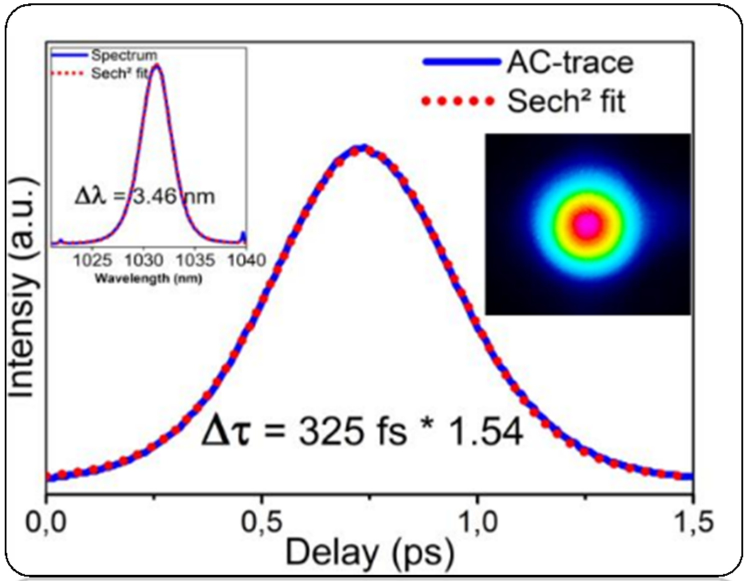
Femtosecond Yb:YAG disk oscillator

- The higher the pulse energy, the higher the GDD should be because of soliton pulse regime.

-Required high dispersive mirrors -5000 fs² in the wavelength range 1025-1035 nm.

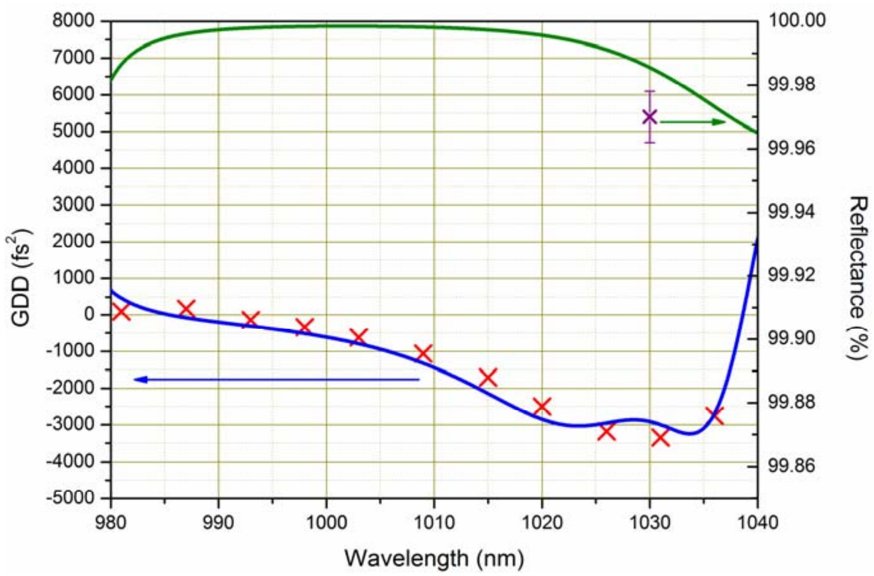


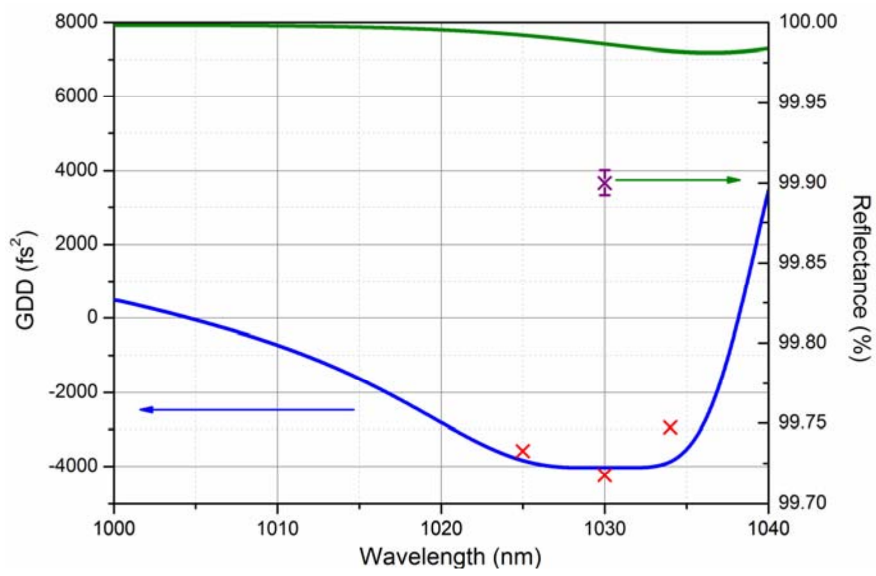


Kerr-lens mode- locked Yb:YAG thin-disk oscillator delivering 230 W, 11.5 μJ, 330 fs (30 MW)

J. Brons et al., talk SM4F, CLEO 2014

High dispersive mirrors @ 1030 nm





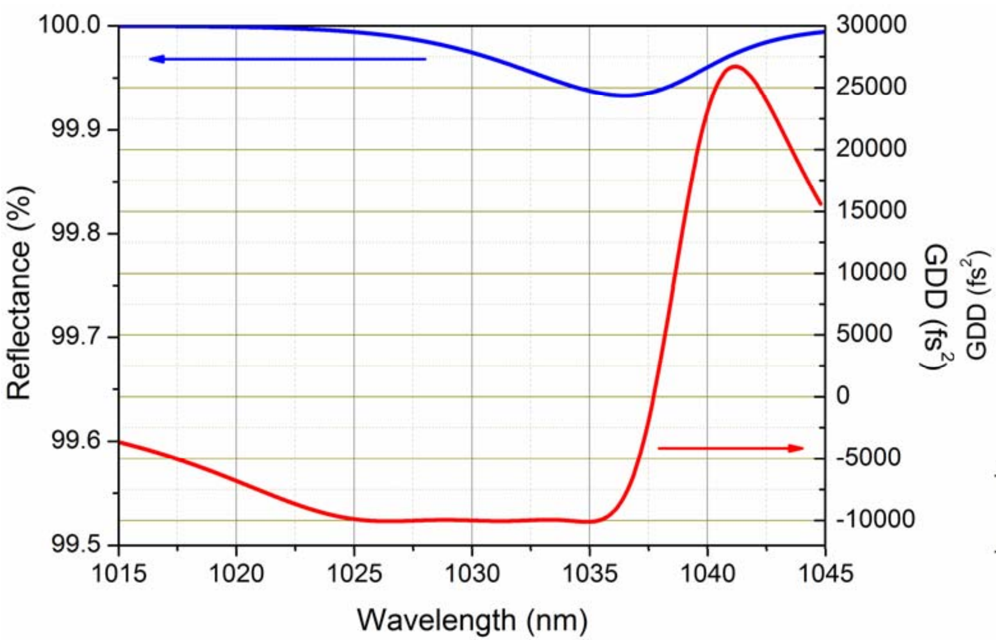
HDMs assist in pushing frontiers in both ultrafast high power oscillators as well as in modern enhancement cavity, enable them to reach tens of kW level with high reflectivity optics. By using HDMs, one can compress pulse with duration of a few nanoseconds down to femtosecond range. The HDM were successfully implemented in an Yb:YAG disk oscillator with over 1 kW of intracavity circulated power

V. Pervak et al., Optics Express 20, 4503 (2012);

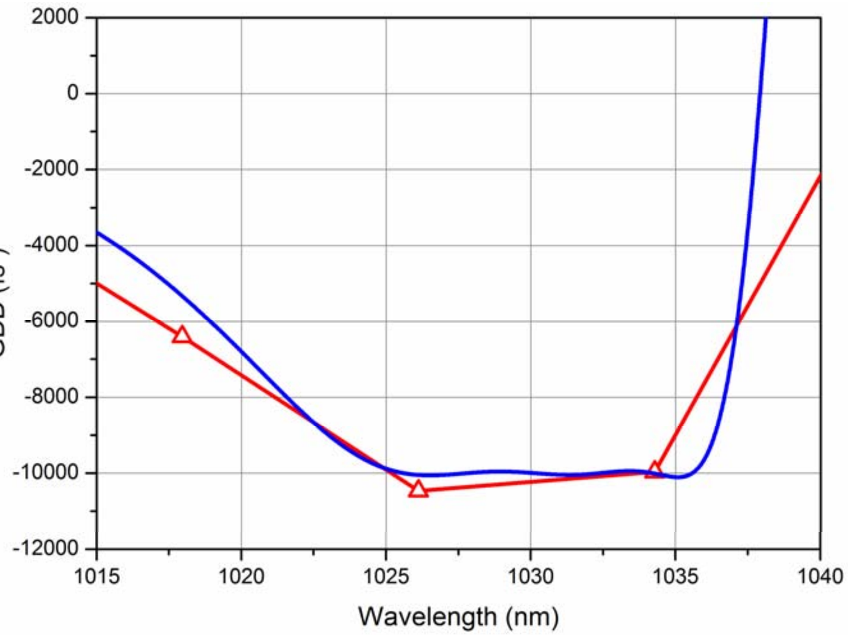
HDM with -10000 fs²

High dispersive mirrors with -10000 fs² in the wavelength range 1025-1035 nm.

Theory



Measurement



- For further progress with the high energy laser oscillators and kHz Ti:Sa amplifiers (shorter pulses) we need high-dispersion mirrors.

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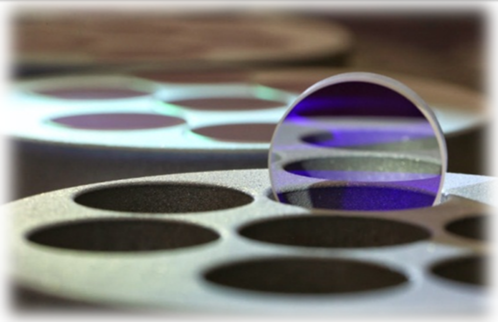
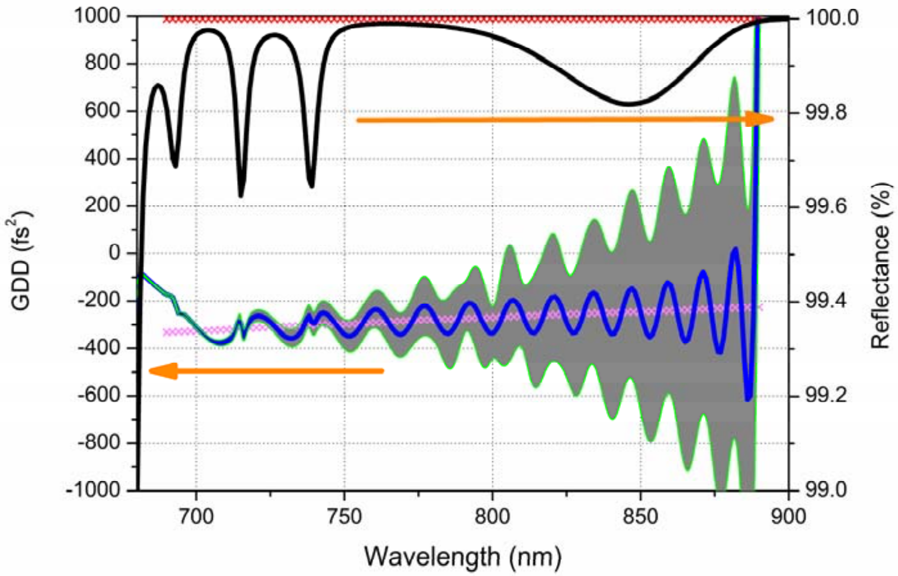
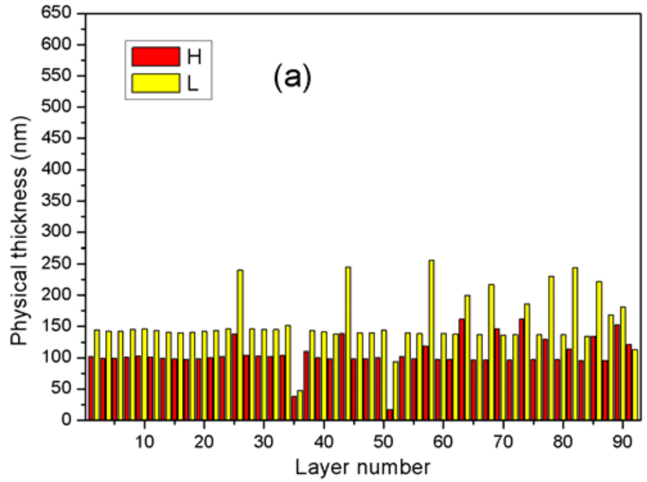


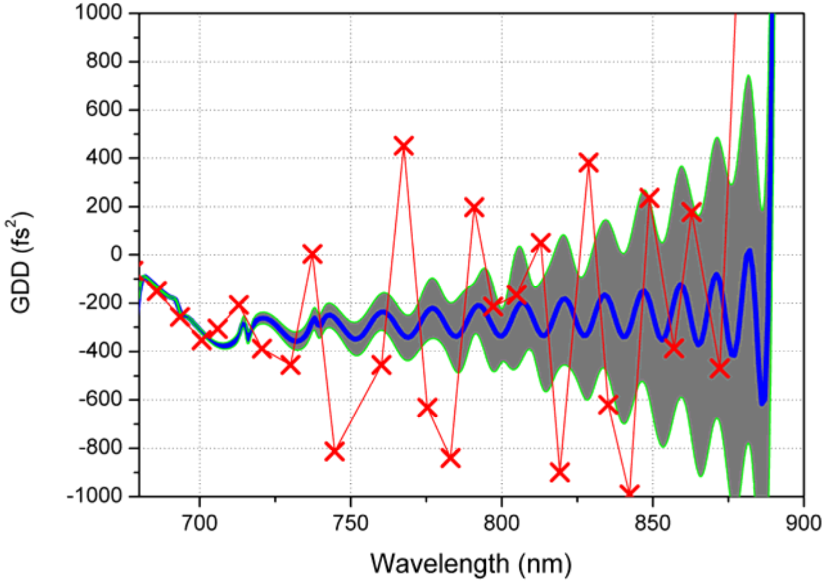

Robust design - Motivation

Standart design



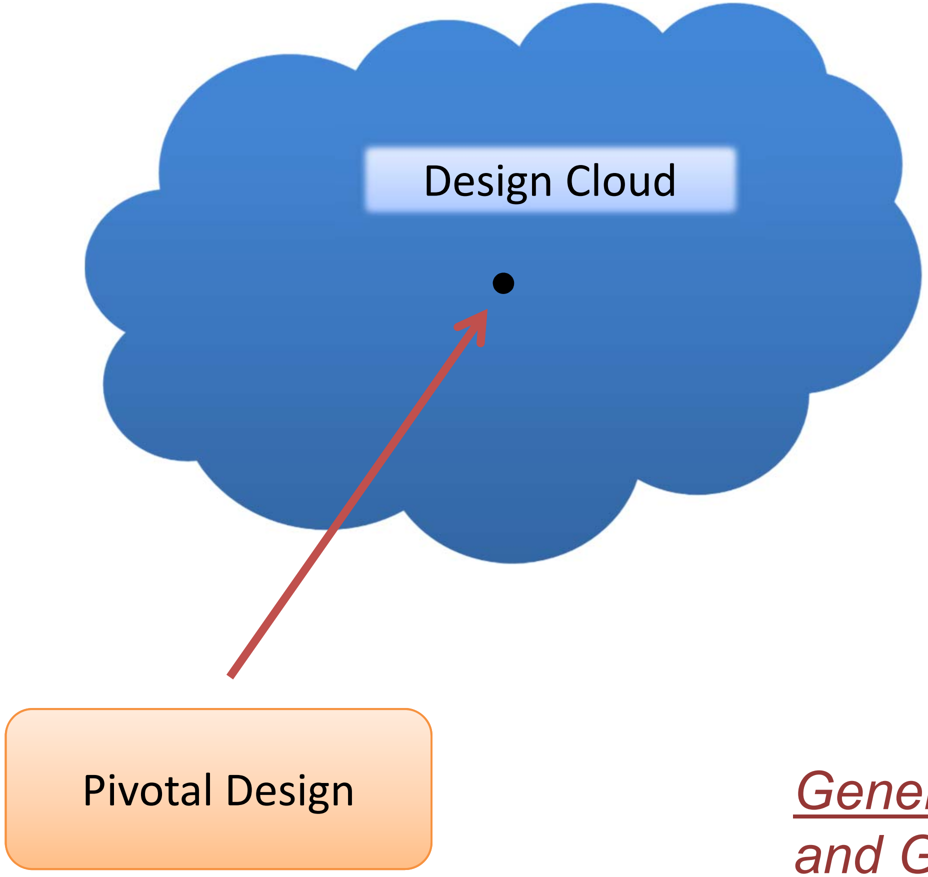


DM is extreme sensetive to deposition errors!



Error during coating process <0.5 nm!

Robust design



Layer thicknesses $d_i, \quad i = 1,\ldots,N$
N – the number of design layers

Layer thicknesses of the *j*-th design in the design cloud are

$$d_i^{(j)} = d_i + \delta_{ij}, \quad i = 1,\ldots,N, \quad j = 1,\ldots,M$$

$$\delta_{ij} = N(0, \sigma^2)$$

σ – cloud size

Merit function of a design cloud:

$$\Phi = \left\{ \frac{\Phi_0^2 + \sum_{j=1}^{M} \Phi_j^2}{M+1} \right\}^{1/2}$$

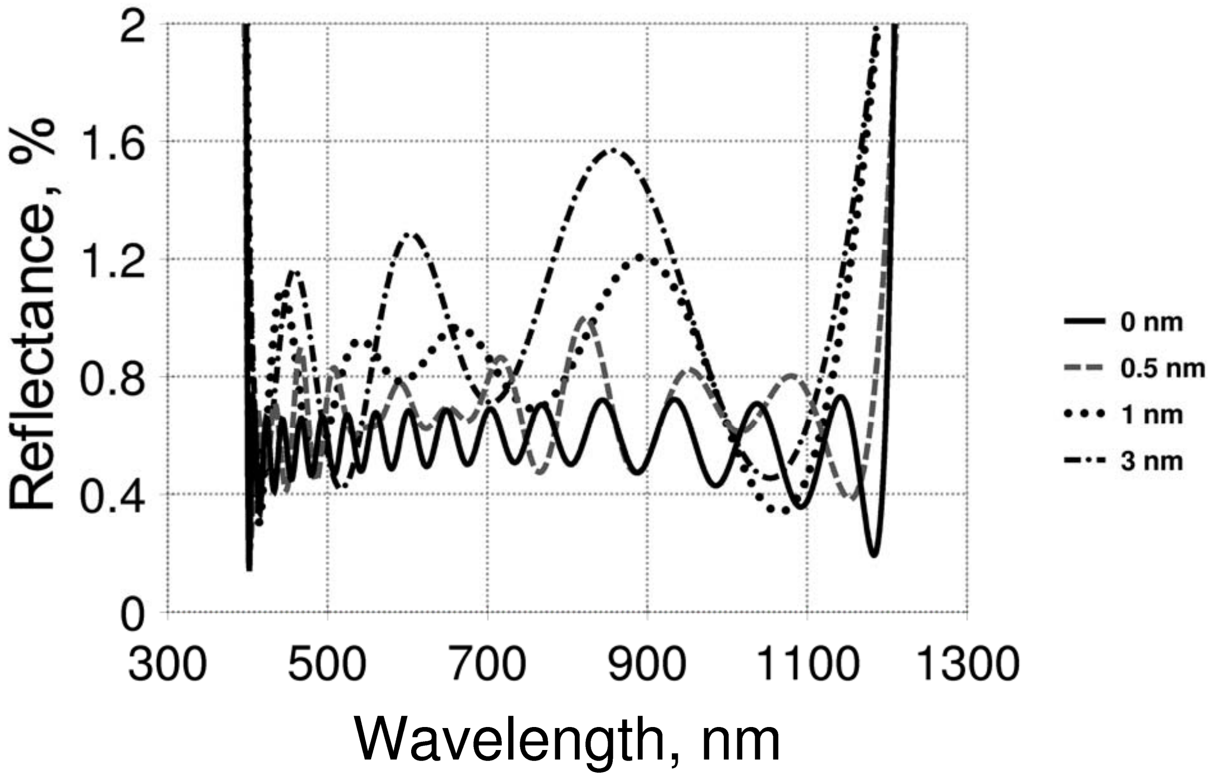
Generalization of the Needle Optimization and Gradual Evolution techniques was obtained

M. K. Trubetskov et al , in Optical Interference Coatings 2010, paper TuA4.

Robust design – AR

AR designs obtained by the robust synthesis

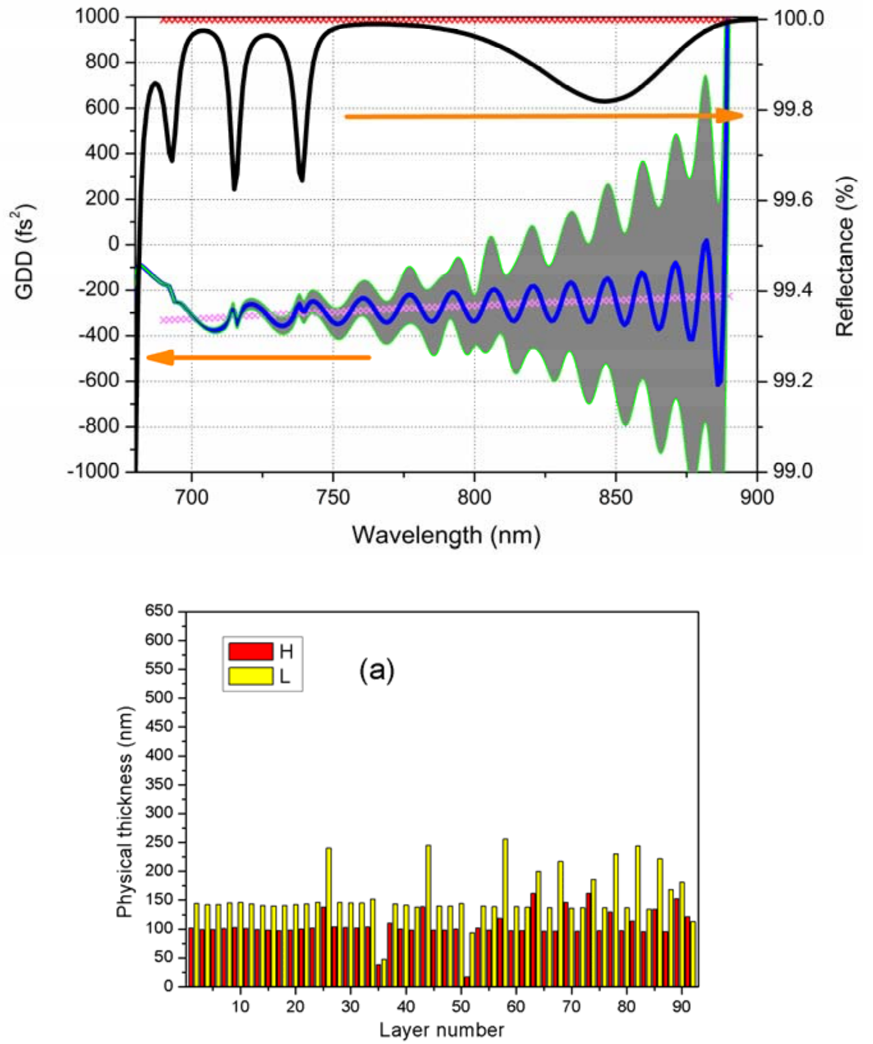
σ, nm	N	Φ_0	$\Delta\Phi$
0	38	0.5825	0.1714
0.1	36	0.5950	0.1373
0.25	32	0.6245	0.1023
0.5	19	0.6948	0.0588
1.0	9	0.9145	0.0235
3.0	8	1.0558	0.0160



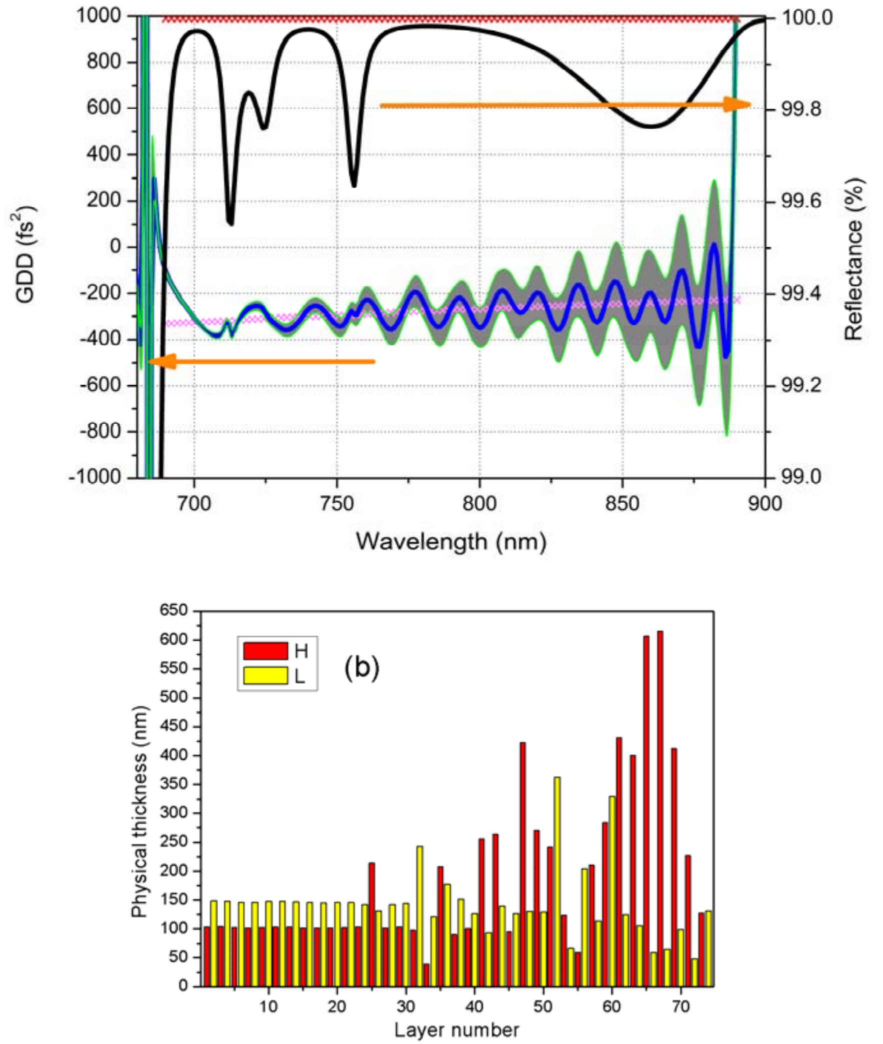
Reflectances of four AR coatings obtained with different values of design cloud size σ

Robust design - HDM

Standart design

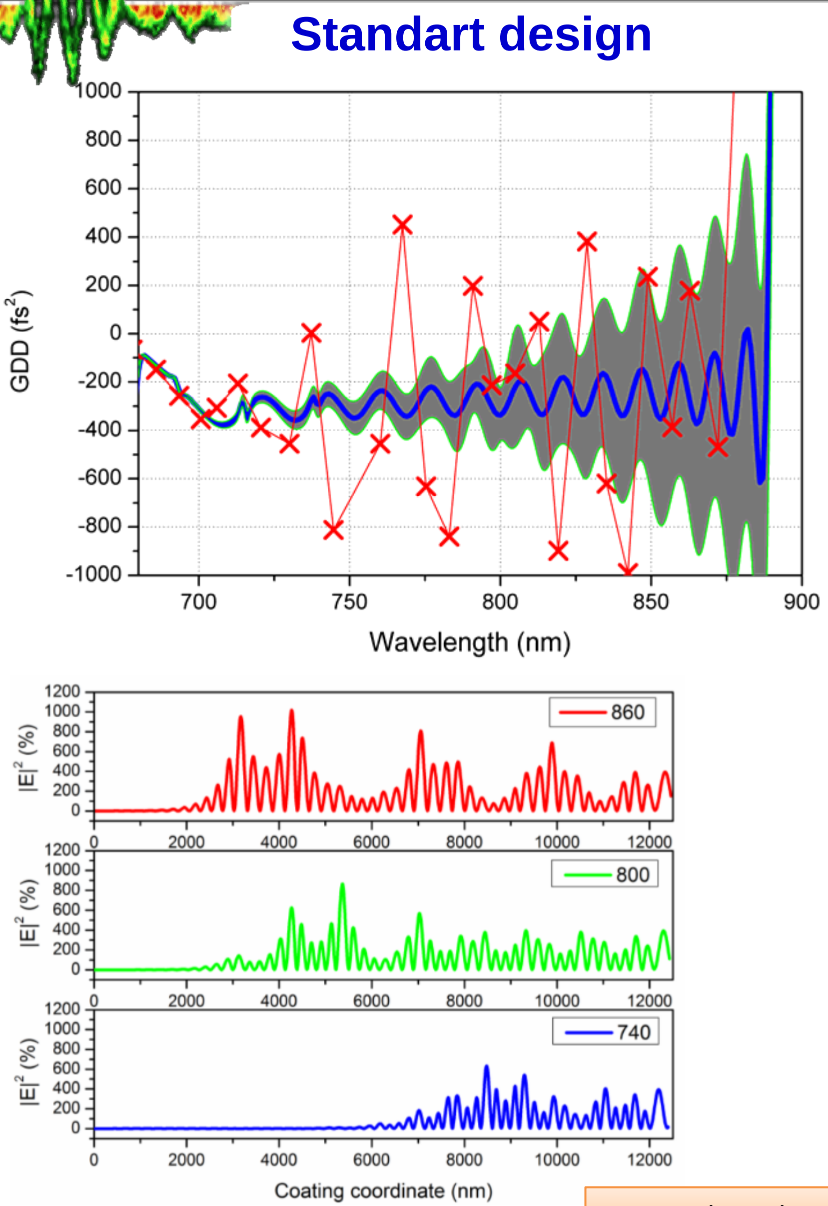


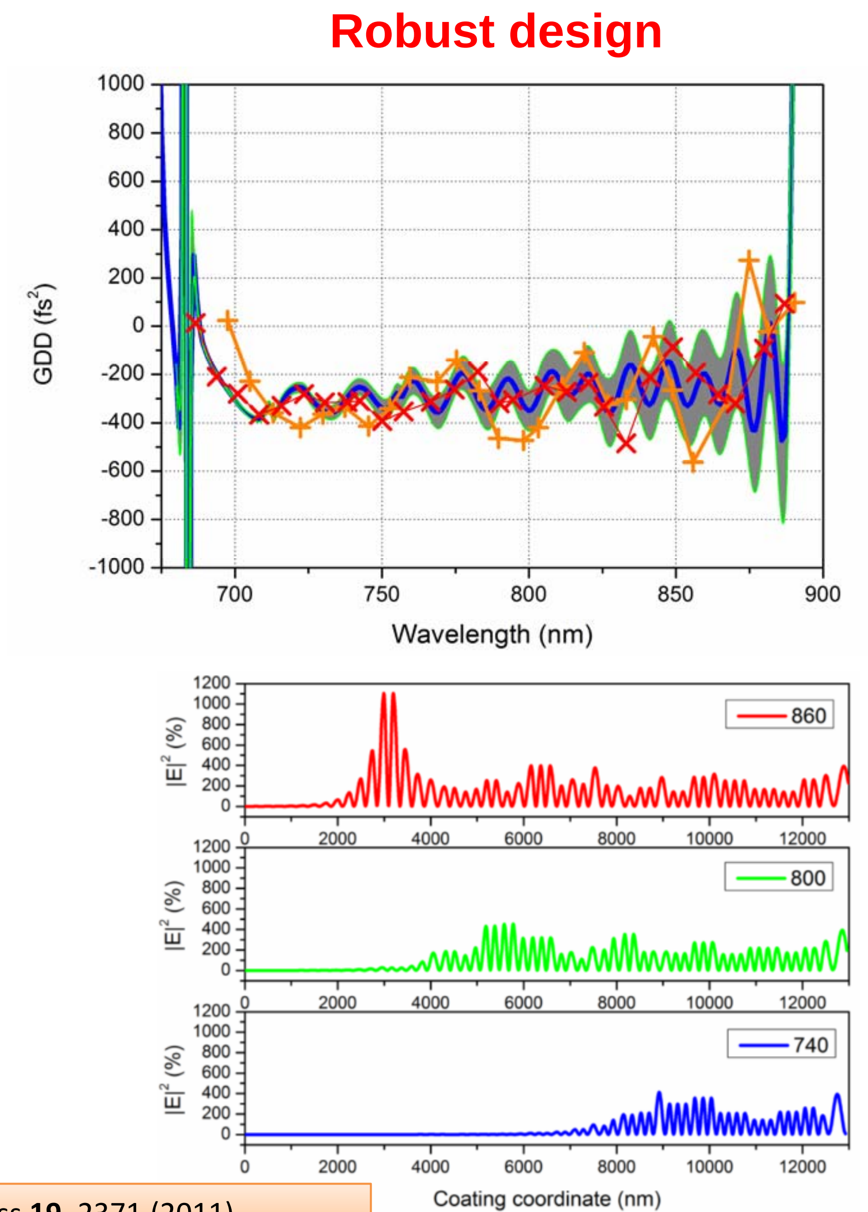
Robust design



V. Pervak et al Opt. Express **19**, 2371 (2011)

Robust design – HDM realization





V. Pervak et al Opt. Express **19**, 2371 (2011)

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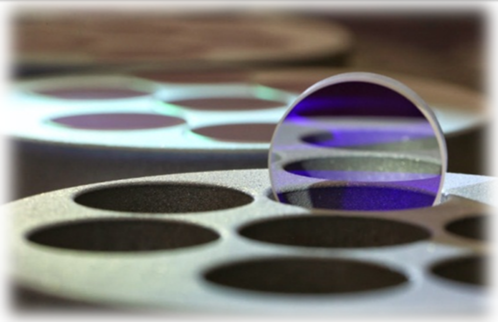
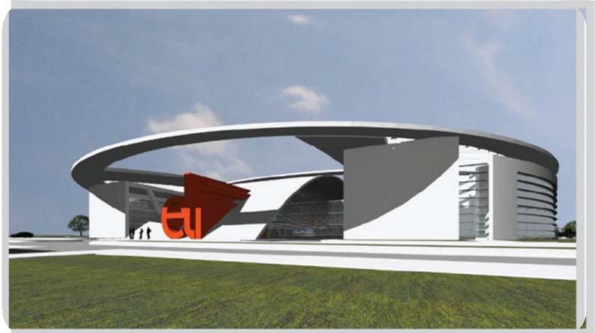


Motivation

➤ **Low-repetition rate systems (up to kHz):**

Extreme Light Infrastructure

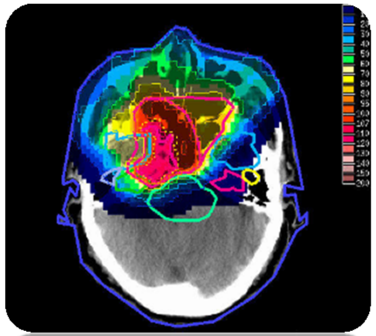


Centre for Advanced Laser Applications

Biomedical applications of lasers,

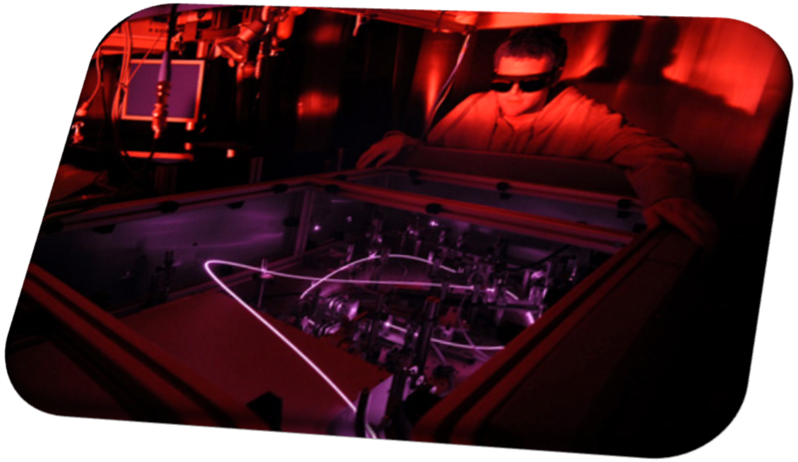
e.g. early diagnosis and

treatment of cancer

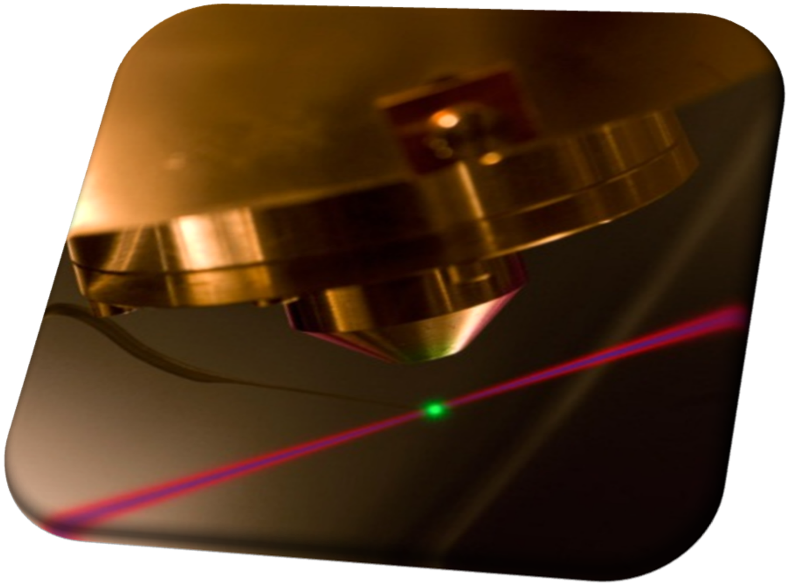


Motivation

➢ **High-repetition rate systems MHz:**



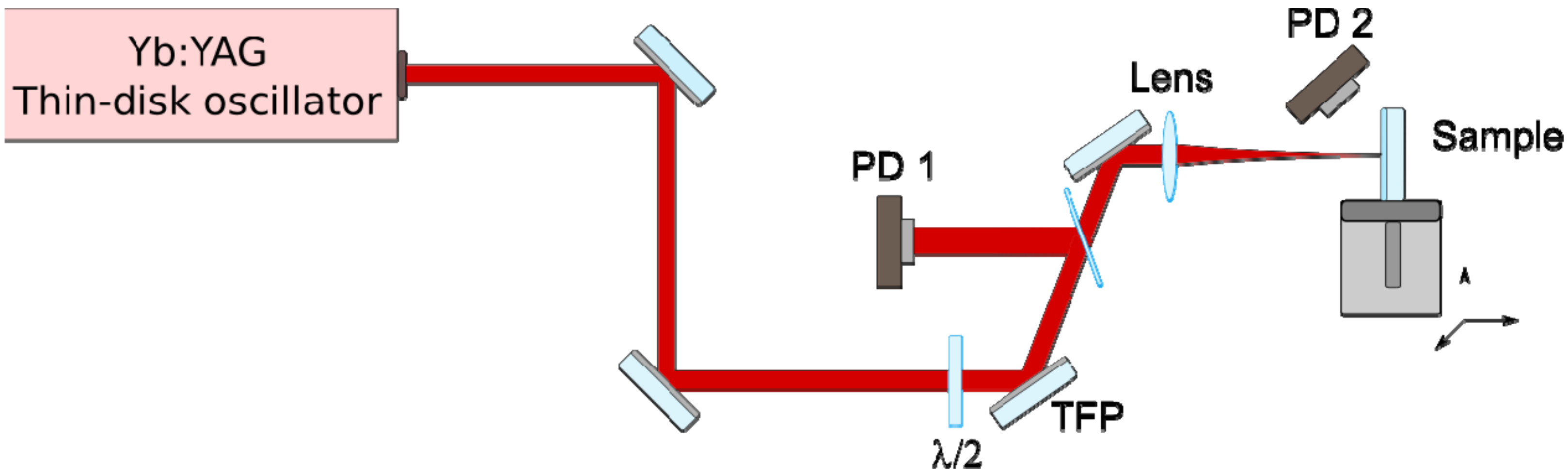
- Enhancement cavities
- Thin-disk oscillators



To be used for generation of

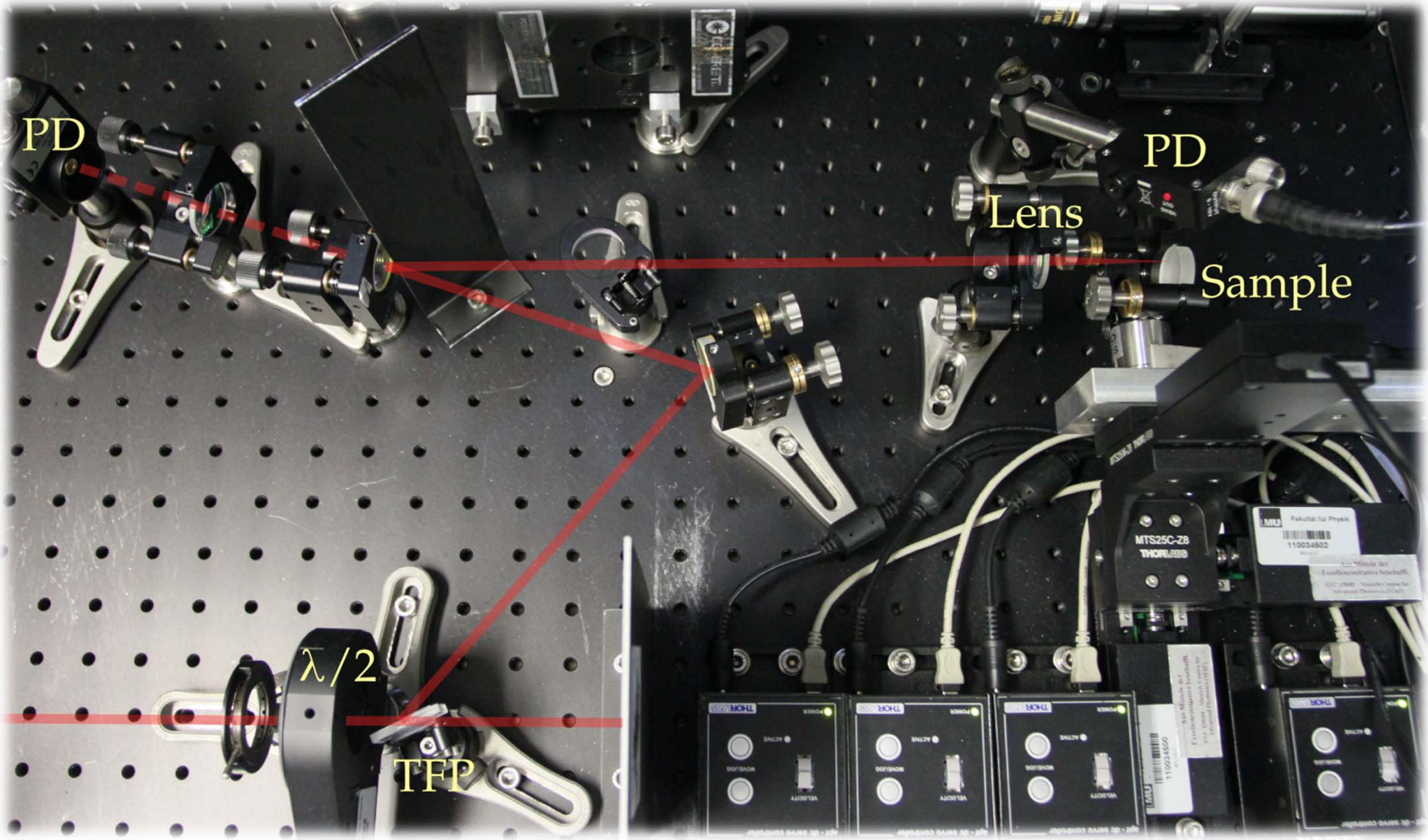
high-harmonics and attosecond pulses.

Damage threshold setup (MHz)

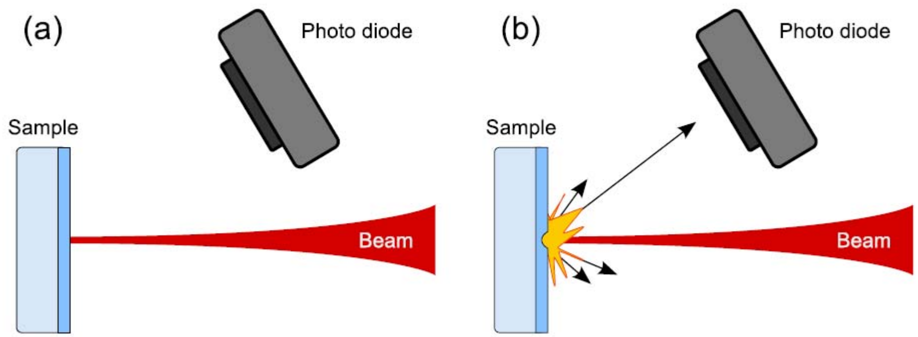


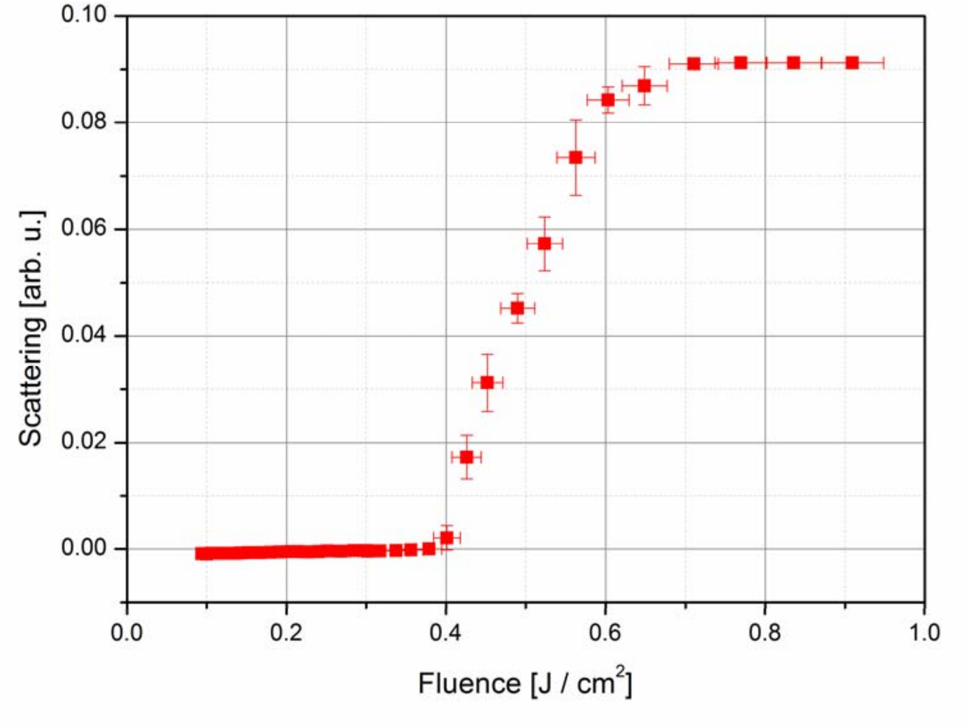
Pulse duration:	~1 ps @ 1030 nm
Max. avg. power:	55 W
Repetition rate:	11 MHz
Max. pulse energy:	5 µJ
Beam radius on the sample:	~15 µm [$1/e^2$]
Achievable fluence:	~1,4 J/cm^2

Damage threshold - setup (MHz)



Damage threshold observation

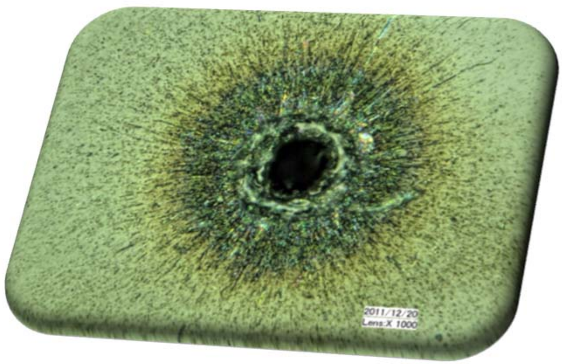


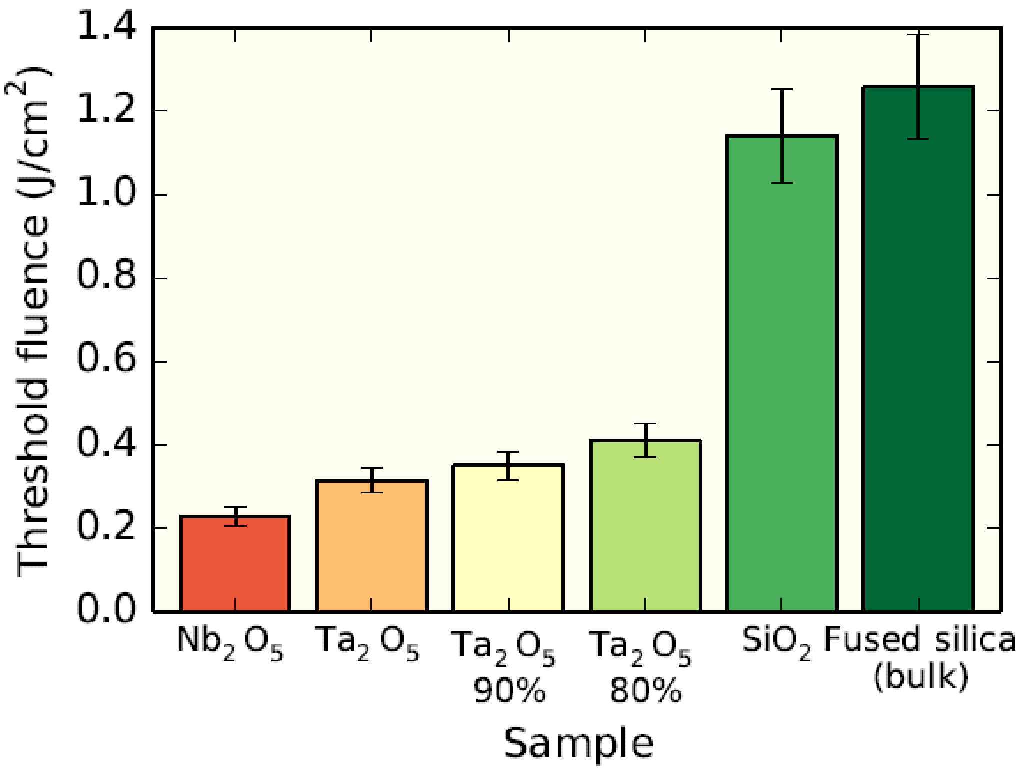


Band gap dependence

Comparison of quarter wave optical thickness stacks (QWOT) employing different high-refractive index materials

Material	Band gap (eV)
Nb_2O_5	3.0
Ta_2O_5	4.0
HfO_2	5.5
SiO_2	8

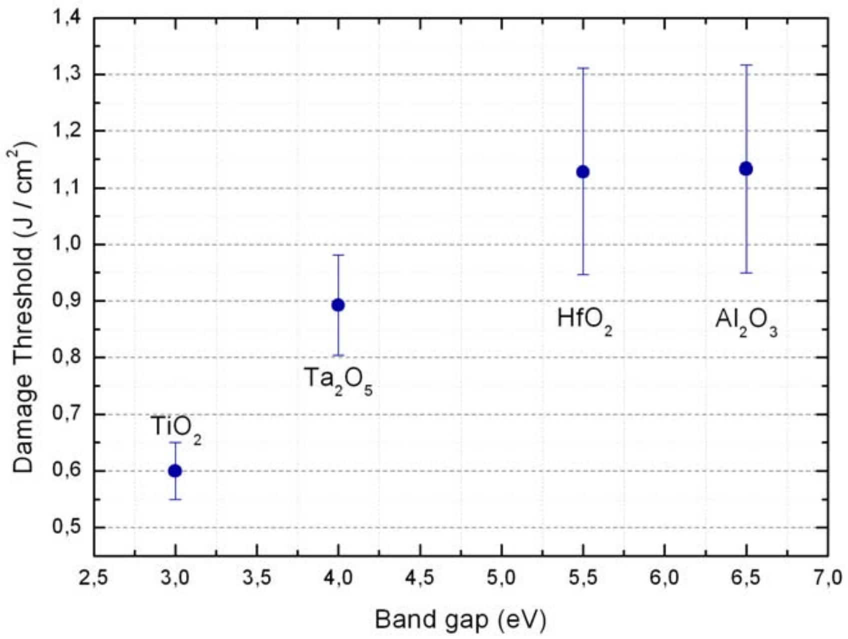


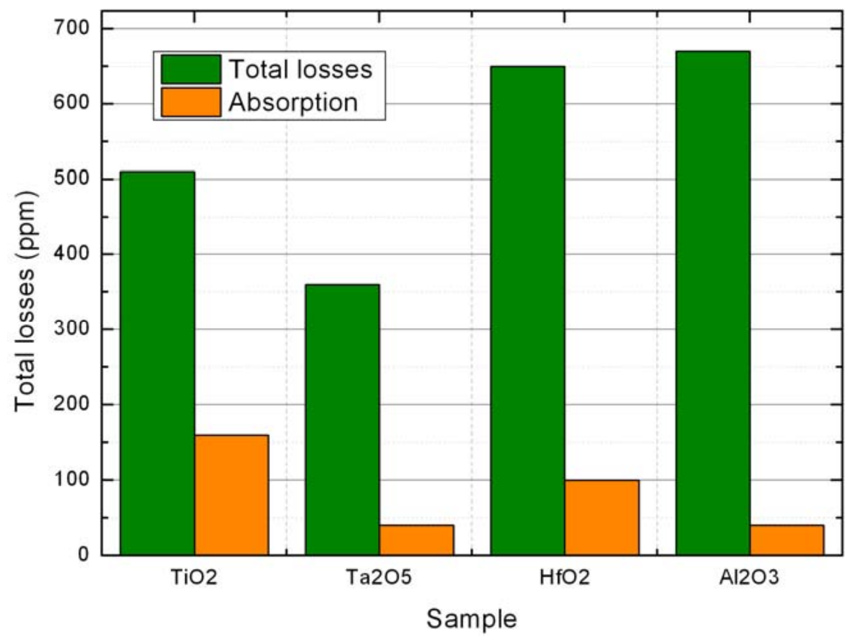


Clear band gap dependence of the laser-induced damage threshold

I. Angelov, et al Opt. Express 21, 31453-31461 (2013)

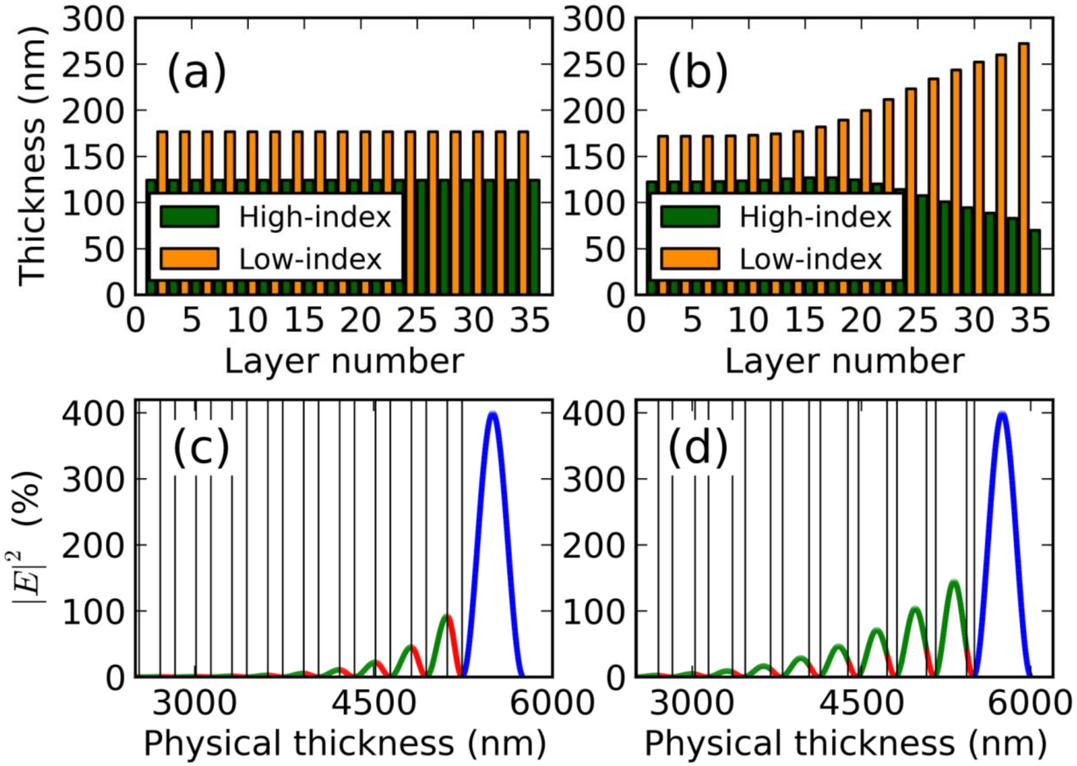
Band gap dependence





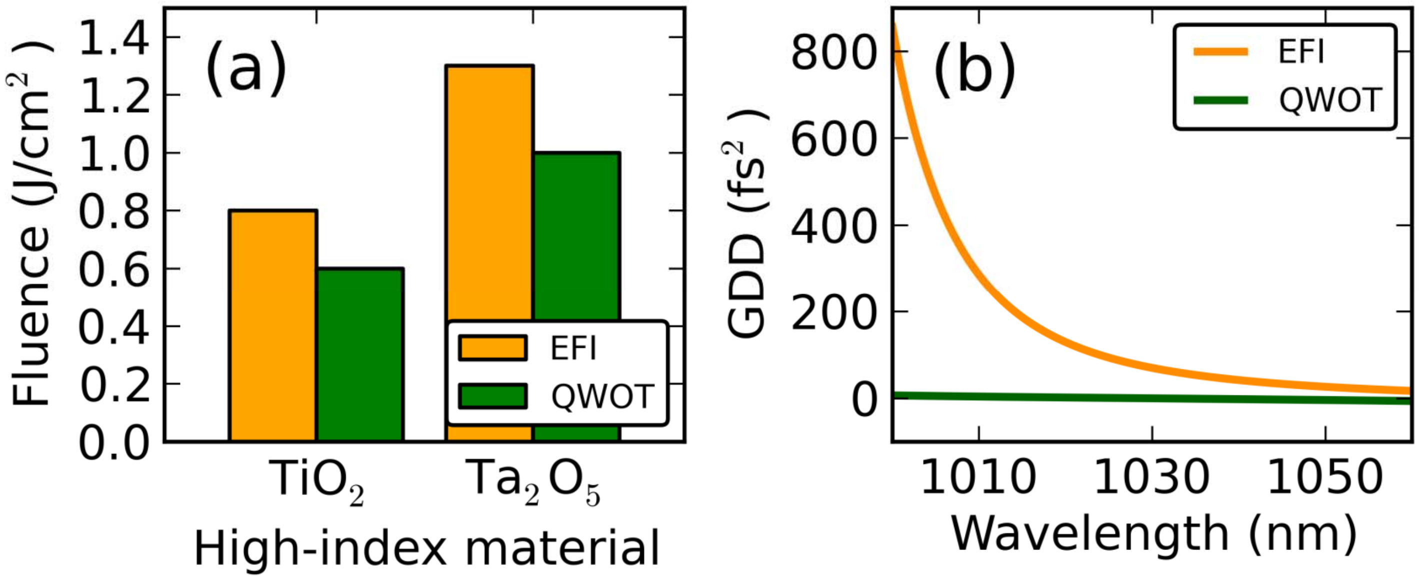
- Clearly visible damage threshold dependence on the band gap of the high-refractive index material
- No correlation between total losses/absorption and damage threshold

E-field optimized stack (EFI)



Electric field peaks were shifted to the low-index material (green sections):
The field in the high-index material (red sections) – lower by a factor of 2 in the EFI stack with respect to the QWOT stack

DT of EFI stacks



EFI stacks tend to be optically more resistant by about 30%
However, in the region of interest the EFI stack has large positive GDD, as well as higher dispersion orders

Similar result for 1 kHz:
G. Abromavicius *et al*. Proc. of SPIE **6720**, 67200Y (2007)

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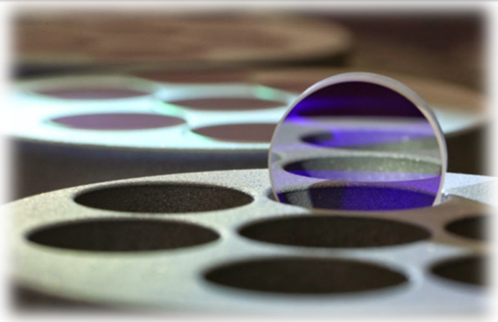
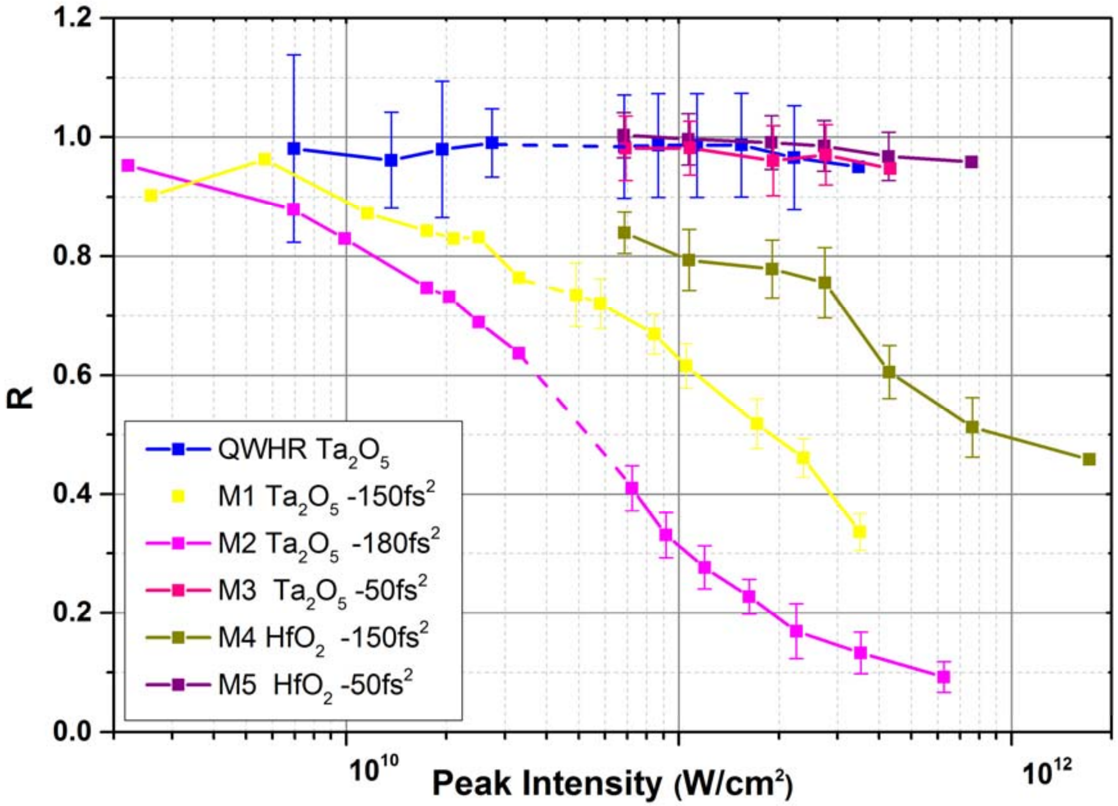
- *The highest absolute GDD value realized*
- *Summary*




Nonlinear response of DM

- Nonlinear response of DM was observed
- Correlations between material/introduced GDD and character of the drop

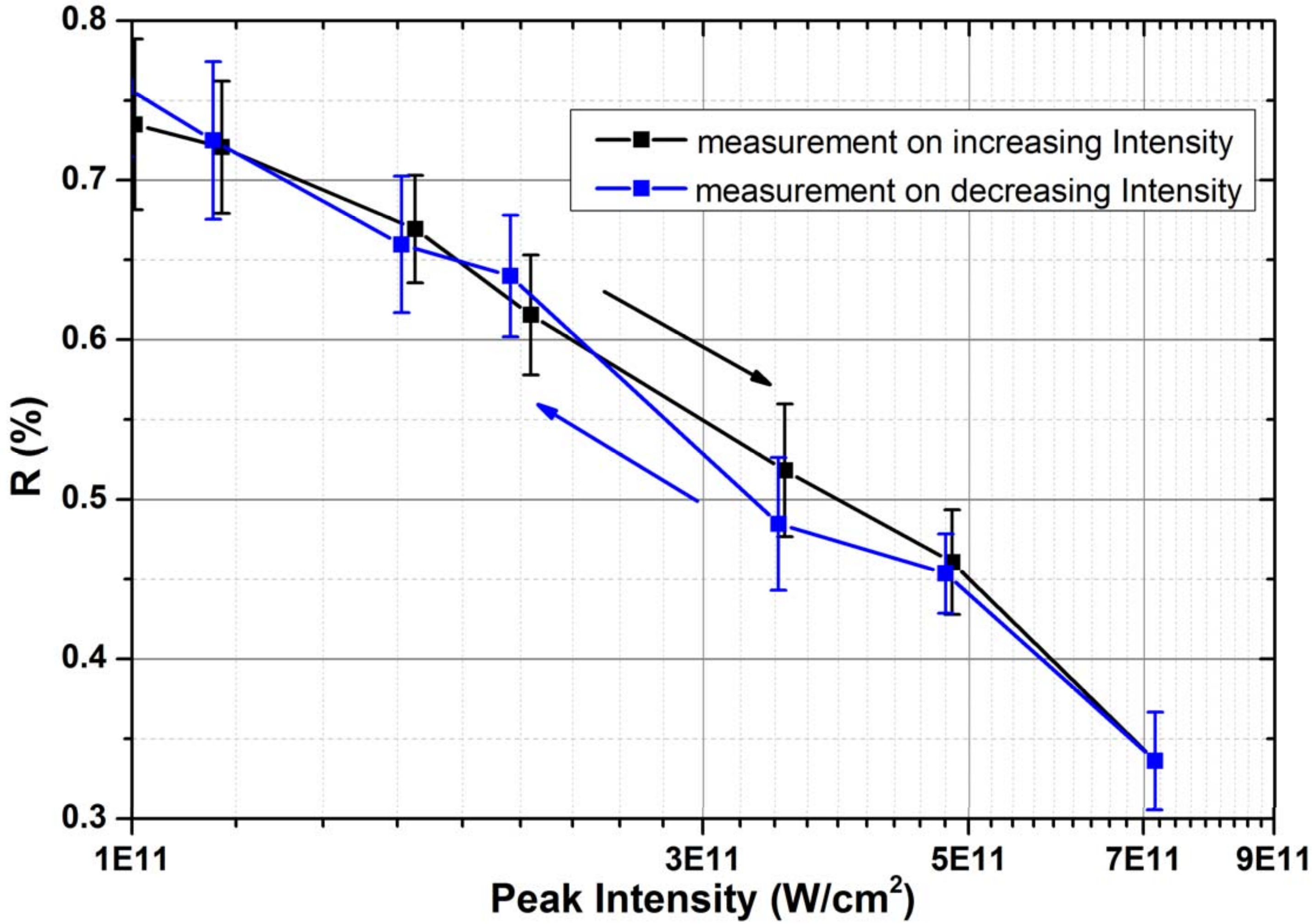


Laser: @400 nm, 40 fs, 3 kHz

DM type	GDD, fs^2	Material
M1	-150	Ta_2O_5/SiO_2
M2	-180	Ta_2O_5/SiO_2
M3	-50	Ta_2O_5/SiO_2
M4	-150	HfO_2/SiO_2
M5	-50	HfO_2/SiO_2

Reversible effect

Measurement of increasing and decreasing of Intensity



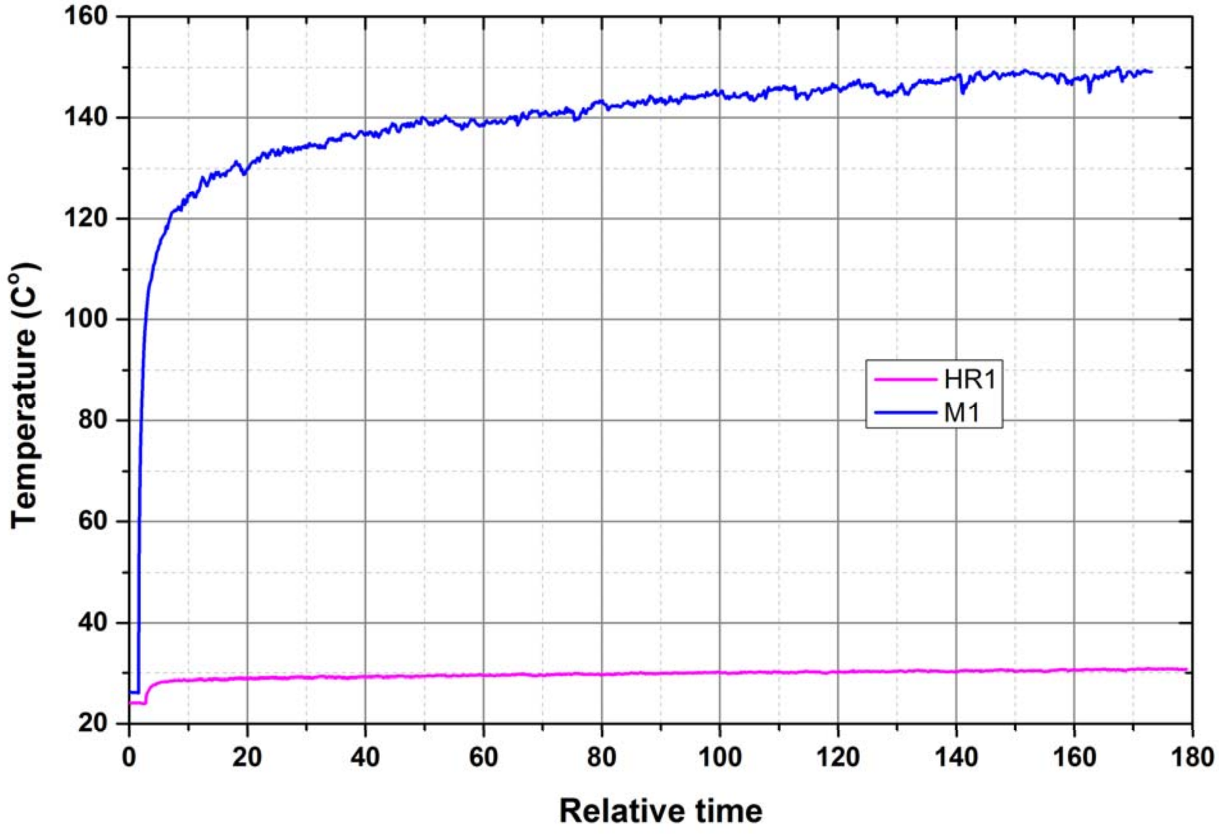
Possible cause

- <u>Two-photon absorption in H/L index materials</u>

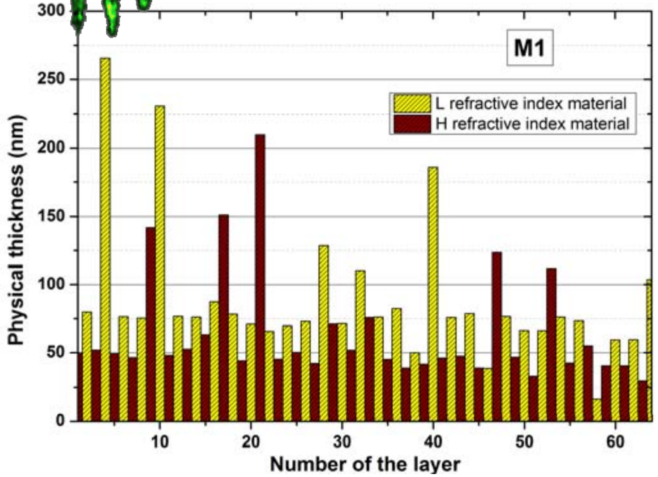
$$I(x) = I_0/(1 + \beta c x I_0),$$

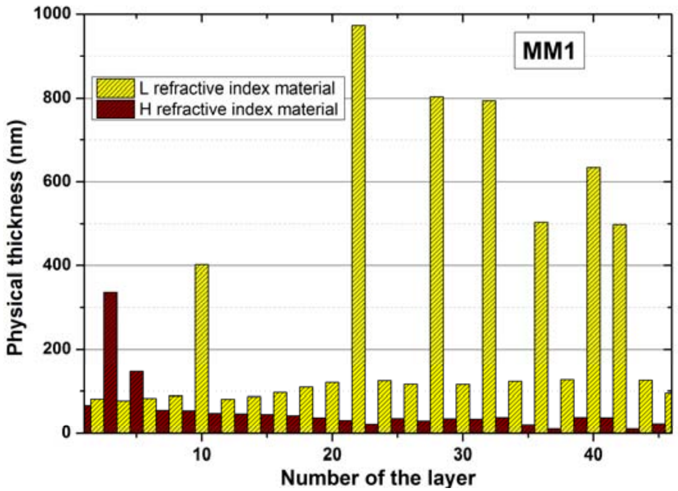
where I – optical intensity, I_0 – incident intensity, ß – two-photon absorption coefficient, c – concentration, x – cross section.

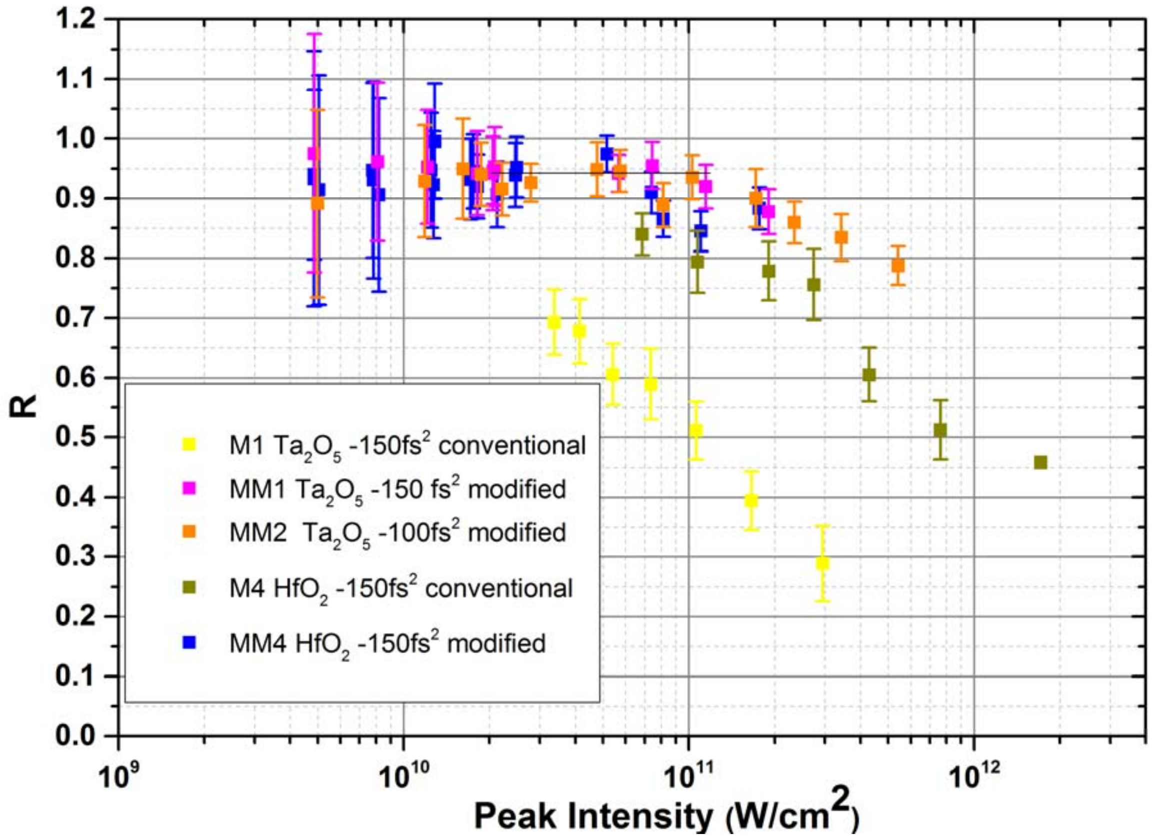
Band gaps: Ta_2O_5 ~ 4eV, HfO_2 ~4.7eV, SiO2 ~7eV > appearance of TPA in H-index materials is possible.



Modification of DM designs

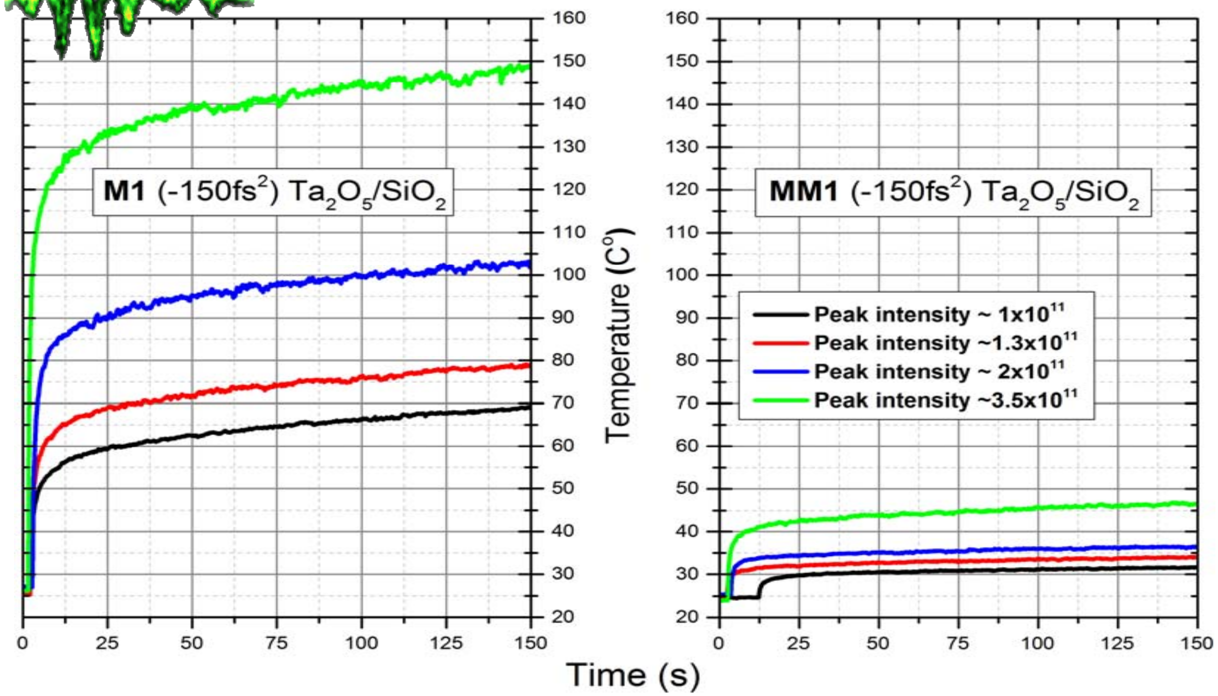


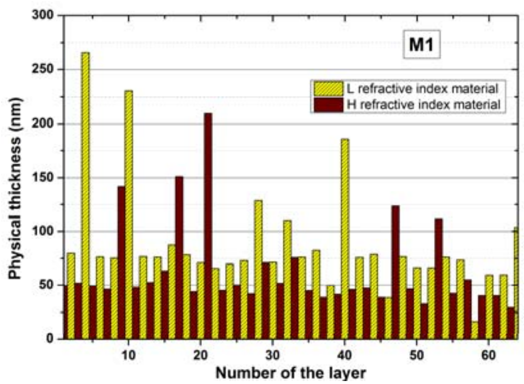


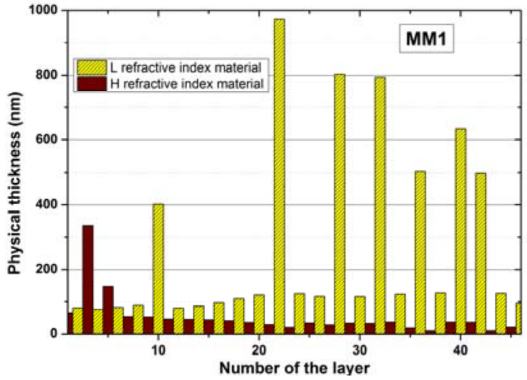


- In order to avoid severe TPA design structure is changed
- Presence of H-index material is decreased in favor to L-index material > minimal thickness is reached and GDD and R characteristics are preserved, while presence of H is decreased

Modification of DM designs







Advances

- Performance of modified designs is improved; reflectivity is increased for higher incident intensities
- Homogeneous reflectivity over broad intensity range

Remained challenges

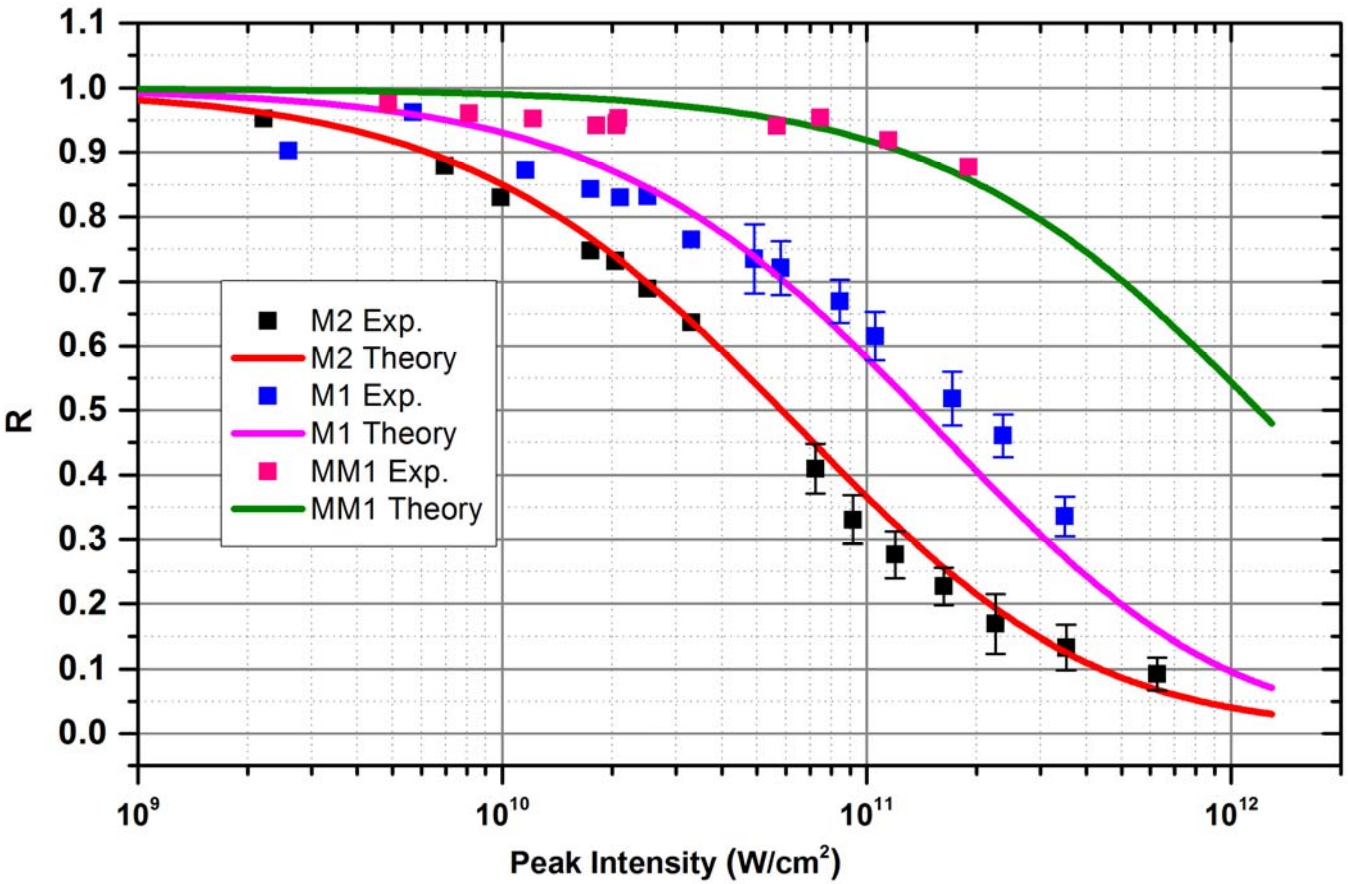
- Effect is not completely erased, but rather postponed to higher intensities
- Reflectivity does not reach ~100% at required incident intensities

Developing mathematical model

2PA is simulated as induced extinction coefficient: $\chi(z)=ß|E(z)|^2$ *, where z – coordinate along mirrors cross-section.*

Approximation of ß being ~4 cm/GW for Ta_2O_5@400nm.

Theory vs. Experiment



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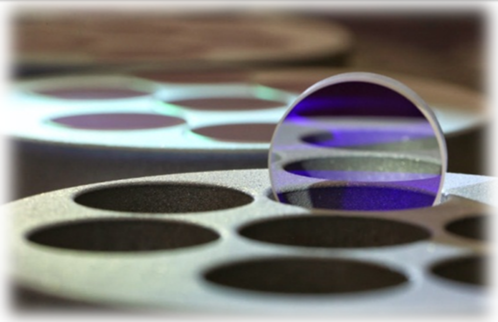
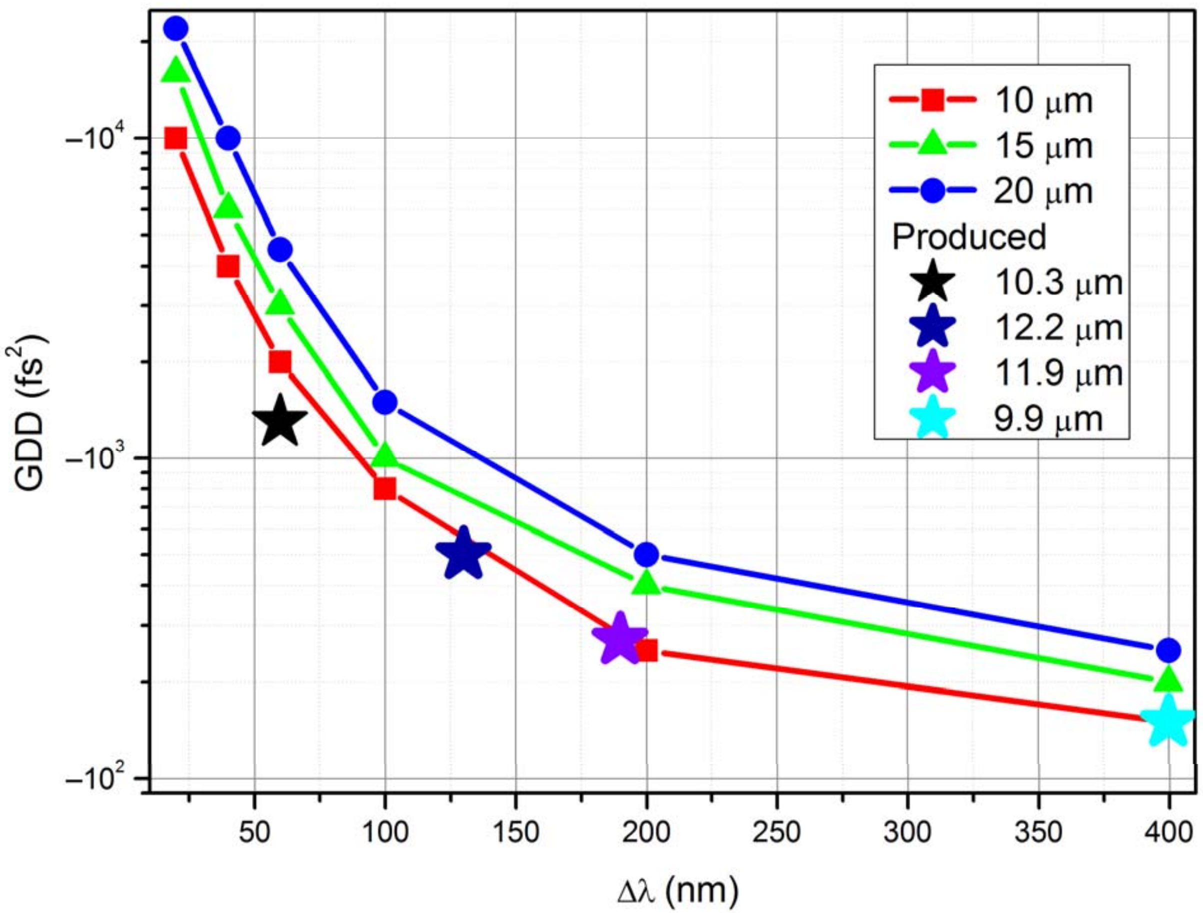


The highest absolute GDD value realized

	Nb_2O_5/SiO_2			
Δλ, nm	Ph. th., nm	Opt. th., nm	GDD, fs^2	N
20	9569.3	17189.2	-10000	87
20	14693.5	26472.9	-16000	125
20	20005.2	36620.0	-22000	167
40	9582.0	17114.4	-4000	91
40	15112.0	26998.7	-6000	133
40	21168.5	37773.3	-10000	181
60	10008.0	17825.6	-2000	84
60	15080.4	26900.0	-3000	120
60	20046.9	35964.2	-4500	167
100	9334.2	16704.9	-600	73
100	15009.3	26564.9	-1000	132
100	17980.0	32508.7	-1500	148
200	10119.8	17913.7	-200	87
200	15145.1	26633.2	-400	101
200	20147.3	36537.3	-500	143
400	11080.0	20054.8	-150	87
400	15836.2	28633.2	-200	102
400	19751.9	35750.5	-250	134



Summarized main parameter of obtained designs with Nb_2O_5/SiO_2 layer materials pair. Red, green and blue curves correspond to designs with the maximum physical thickness of 10 μm, 15 μm and 20 μm, respectively. Asterisks correspond to produced designs [V. Pervak et al Opt. Express **17**, 7943–7951 (2009); V. Pervak, Appl. Opt. **50**, C55–C61 (2010); V. Pervak et al Opt. Express **17**, 2207–2217 (2009)] with physical thicknesses shown in the legend.

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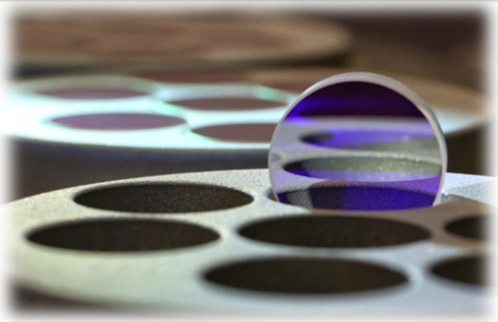
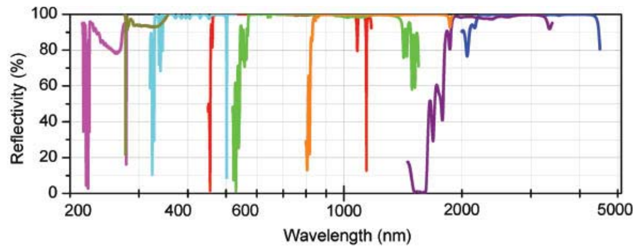
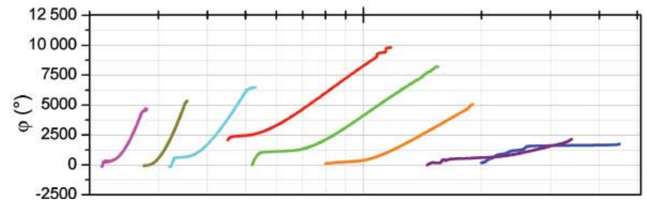
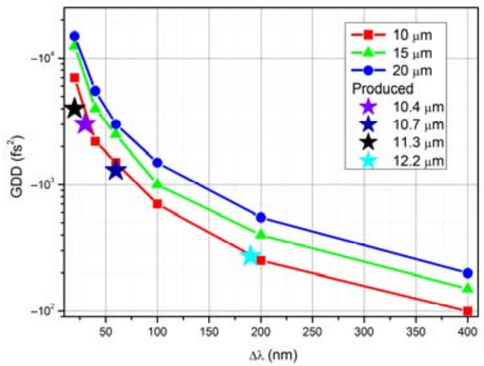



Summary

- *Dispersive optics covers 220 nm –4.5 µm range;*
- *Short pulse compression down to cyrcle optical pulse;*
- *We developed optics for high-energy fs oscillators (with 10 nm, -10000 fs^2);*
- *Dispersive optics with the damage threshold >0.5 J/cm^2 for single fs pulses and for ps pulses at kHz and MHz repetition rates;*
- *For first time non-linear behaviour in dielectric multilayer coatings is observed;*
- *Dispersive optics beyond the empirical curve?*







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Prof. F. Krausz

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ULTRAFAST INNOVATIONS

Thank you for attention!

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