Optimized components for high-power ultrafast thin-disk lasers

Andreas Diebold

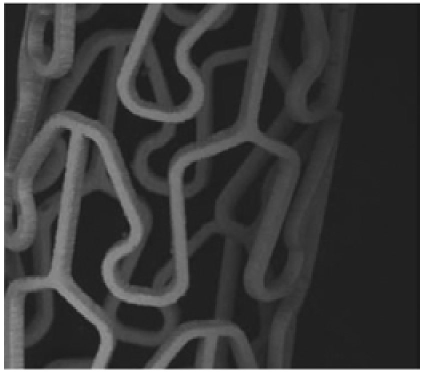
Group of Professor **Ursula Keller**

Ultrafast Laser Physics, ETH Zurich, Switzerland

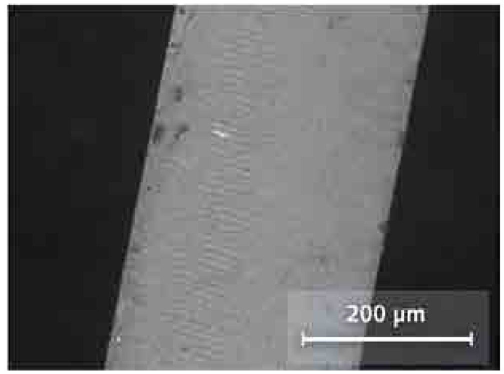
Ultrafast high-power applications

Industry: high-precision micro-machining

Processing of metals, semiconductors, polymers, and glasses



medical stents



smartphone glass

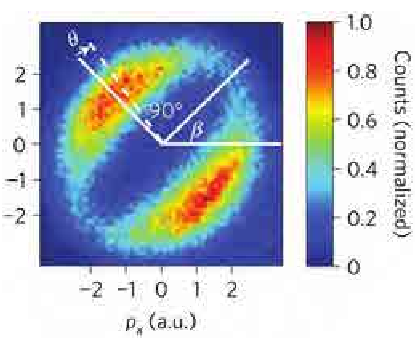
S. Weiler, *Laser Focus World*, 2011

required
E_P > 10 µJ
τ_p < 10 ps
P_{pk} > 10 MW

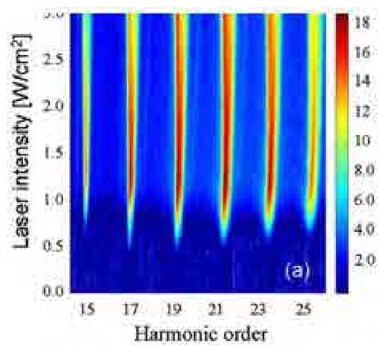
desired
f_{rep} ≈ MHz
P_{av} > 100 W

Science

Driving sources of strong-field physics experiments



attosecond science



HHG

A. Pfeiffer et al., *Nat. Phys.* **8** (2012)

T. Auguste, et al., *PRA* **80** (2009)

required
τ_p < 100 fs
P_{pk} > 30 MW

desired
f_{rep} ≈ MHz
P_{av} > 100 W

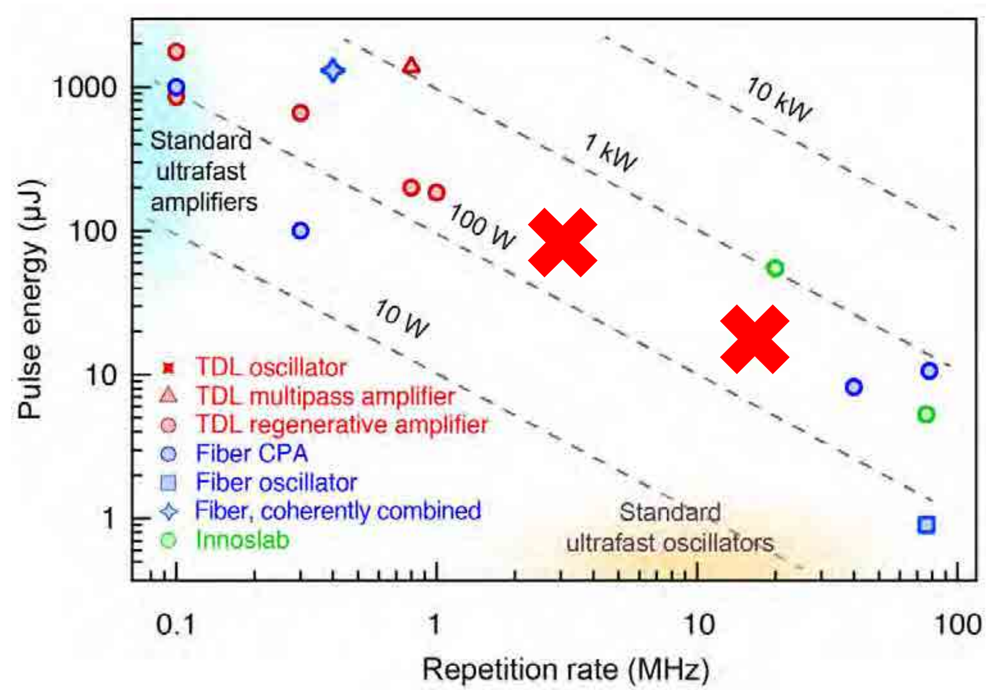
Reaching high power at MHz rep. rate

- Geometry suited for efficient cooling
- Operation at reduced peak intensity
- Maximization of surface/volume ratio

[#1] Fiber amplifiers

[#2] Innoslab

[#3] Thin-disk amplifiers



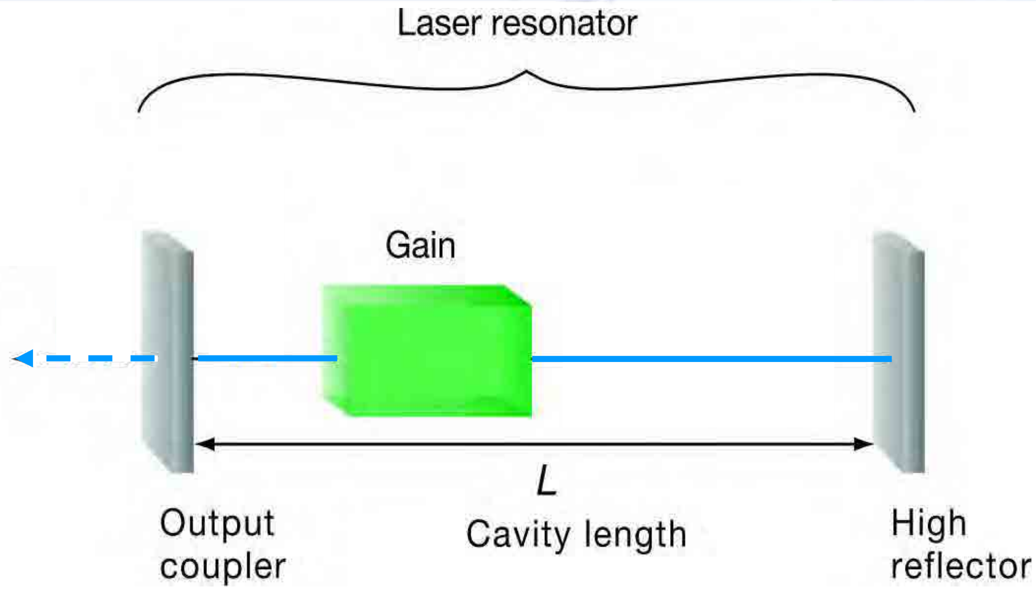
✖ Modelocked thin-disk oscillators:
High average power and pulse energy directly from a multi-MHz oscillator

[#1] T. Eidam, et al., *Opt. Lett.* **35** (2010) [#2] P. Russbueldt, et al., *Opt. Lett.* **35** (2010) [#3] J. P. Negel, et al., *Opt. Exp.* ***23*** (2015)

Outline

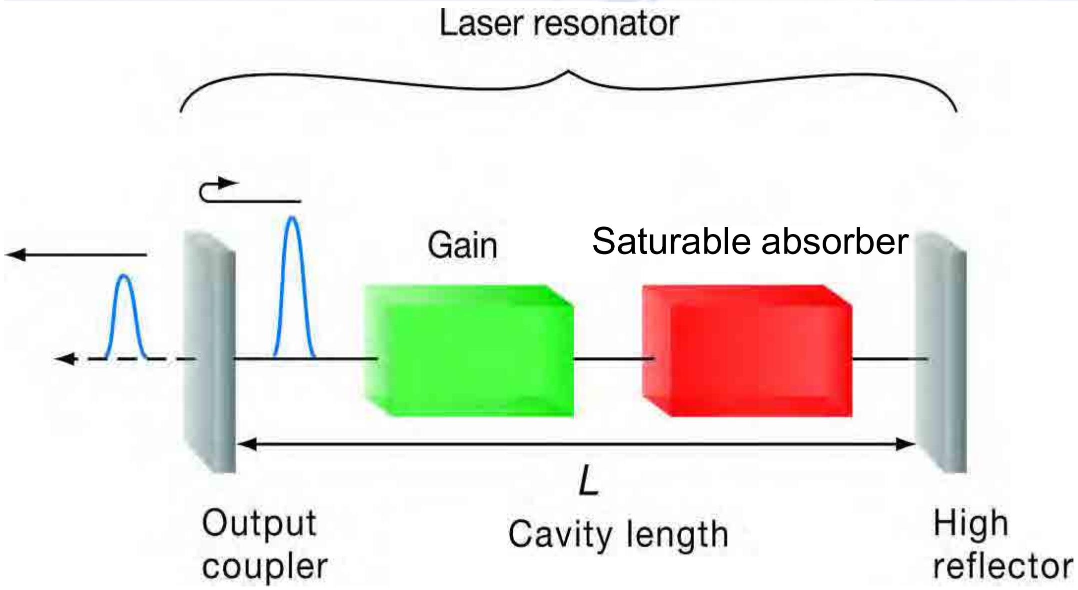
- SESAM-modelocked thin-disk lasers (TDL)
- Scientific application of TDLs:
  High-harmonic generation
- Pushing TDLs to the kW regime:
  novel SESAM designs
- Conclusion and outlook

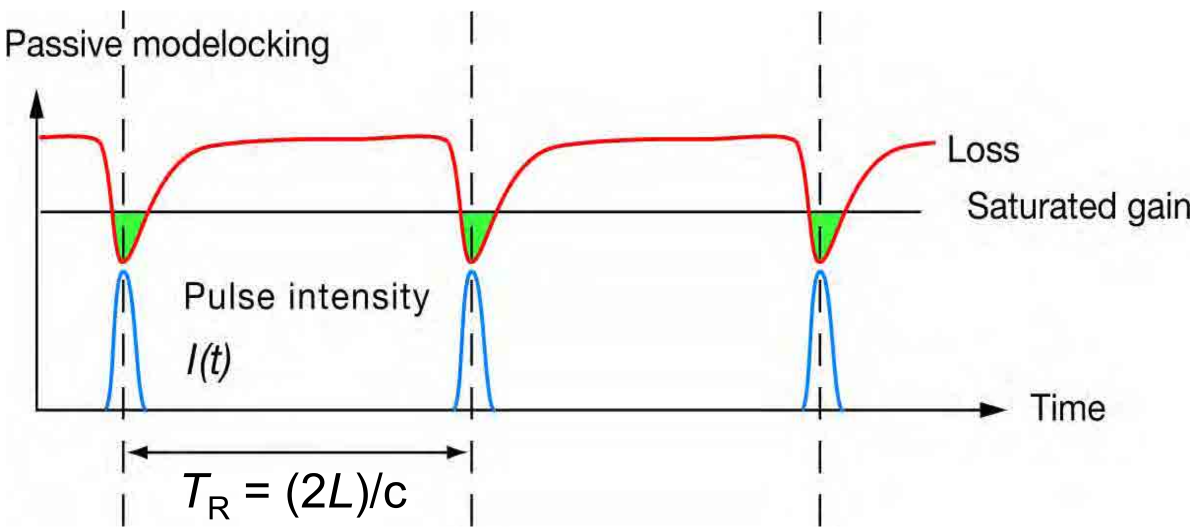
Continuous-wave laser



- Light circulates in resonator
- Losses compensated by saturated gain in laser medium (which is externally pumped)
- Light emission typically **continuous**

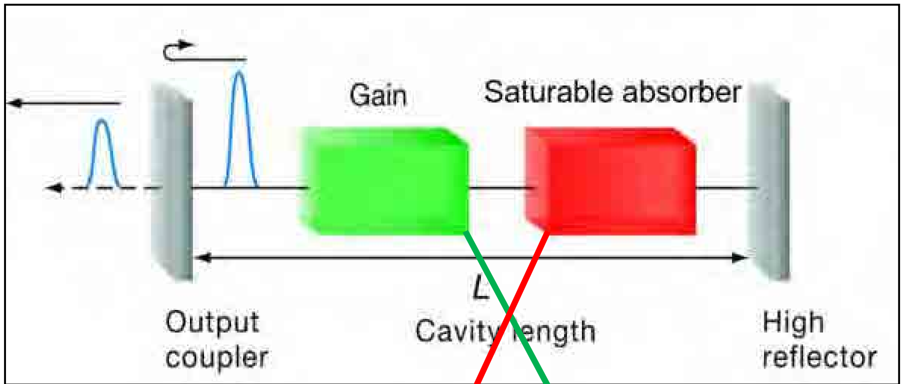
Passively modelocked laser

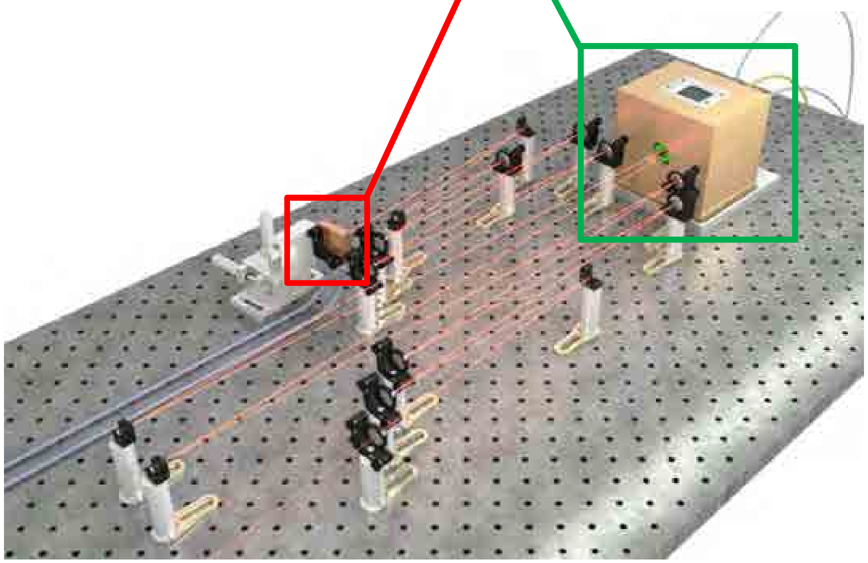




- **Saturable absorber (loss)** initiates and stabilizes the pulse formation process
- High repetition rate pulse train at the output (MHz)
- Steady-state soliton pulse parameters:
  governed by interplay of **gain, (saturable) loss, dispersion, Kerr nonlinearity**, …

SESAM-modelocked thin-disk lasers





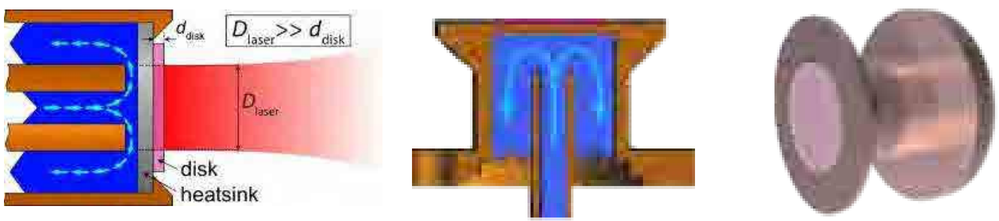
Graphic by Martin Hoffmann

Gain: **Thin-disk crystal**

Saturable absorber: **SESAM**

(SEmiconductor Saturable Absorber Mirror)

SESAM-modelocked thin-disk lasers

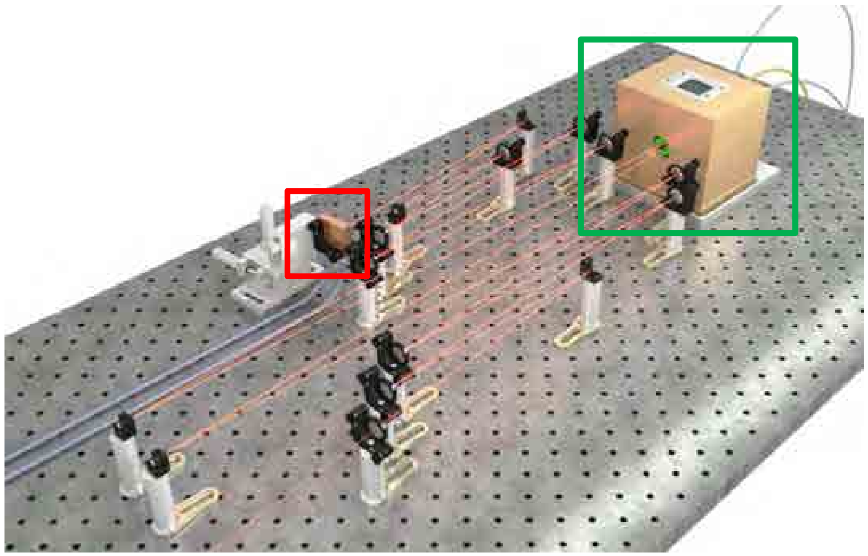


A. Giesen, et al., *Appl. Phys. B* **58** (1994)

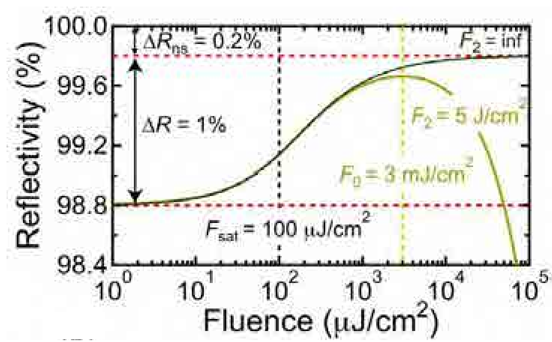
Gain: **Thin-disk crystal**

→ **Power Scalability**

Graphic by Martin Hoffmann



Saturable absorber: **SESAM**



U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2** (1996)

Highest average power (275 W[#1]) and highest pulse energy (80 µJ[#2])
of any ultrafast oscillator technology

[#1]C. J. Saraceno, et al., *Opt. Express* **20** (2012)

[#2]C. J. Saraceno, et al., *Opt. Lett.* **39** (2014)

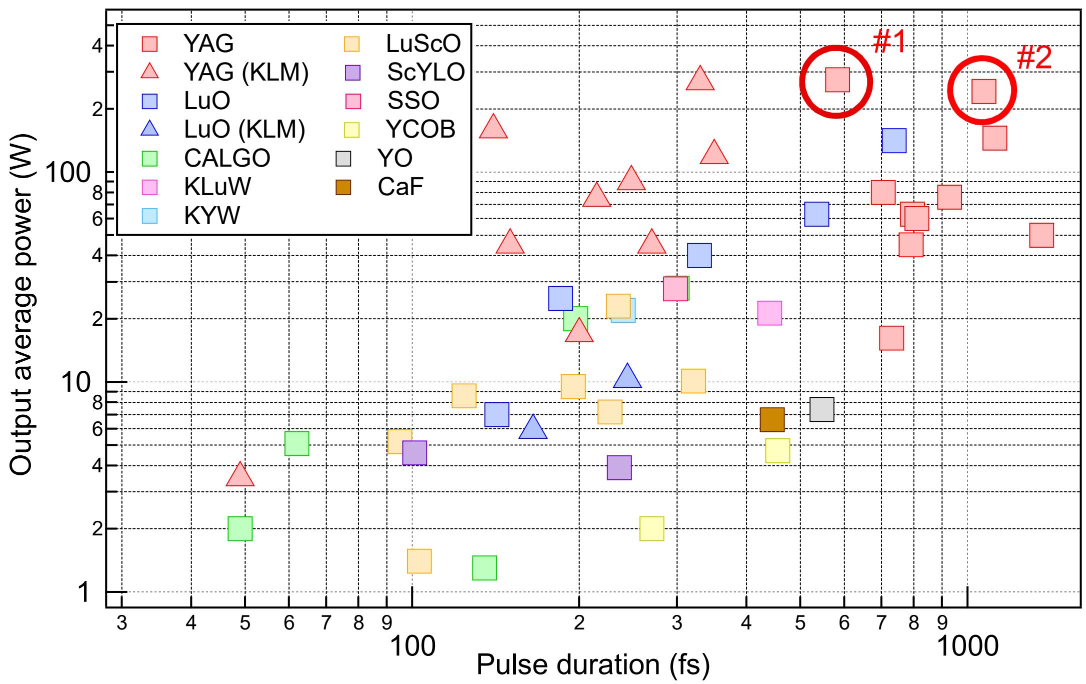
Cutting-edge ultrafast thin-disk lasers (TDLs)

Power and energy scaling (Yb:YAG)

$\lambda \approx 1030$ nm

- **SESAM-**modelocked TDLs:
  P_{av} up to 275 W[#1]
  E_p up to 80 µJ[#2]
  P_{pk} up to 66 MW[#2]
  τ_p > 500 fs

[#1] C.J. Saraceno, et al., *Opt. Exp.* ***20*** (2012)
[#2] C.J. Saraceno et al., *Opt. Lett.* ***39*** (2014)



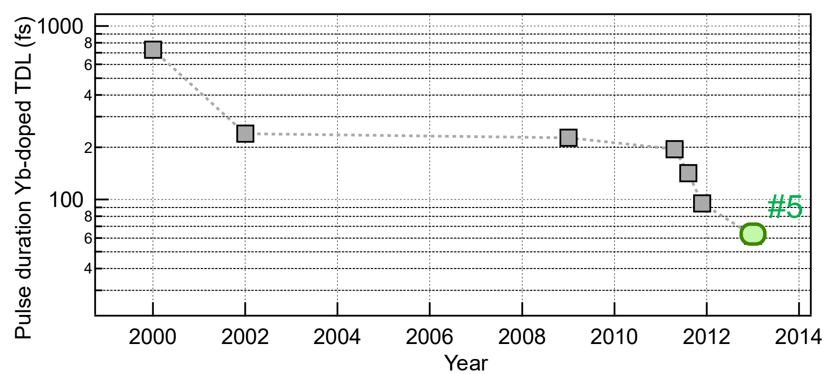
- **Kerr-lens-**modelocked TDLs:
  P_{av} up to 270 W[#3]
  τ_p > 140 fs

[#3] J. Brons, et al., *Opt. Lett.* ***39*** (2014)

Shortest pulse durations (Yb:CALGO)

- Novel **broadband** gain materials (only SESAM-modelocked):
  τ_p down to 49 fs[#5]
  P_{av} < 5 W

[#5] A. Diebold, et al., *Opt. Lett.* ***38*** (2013)



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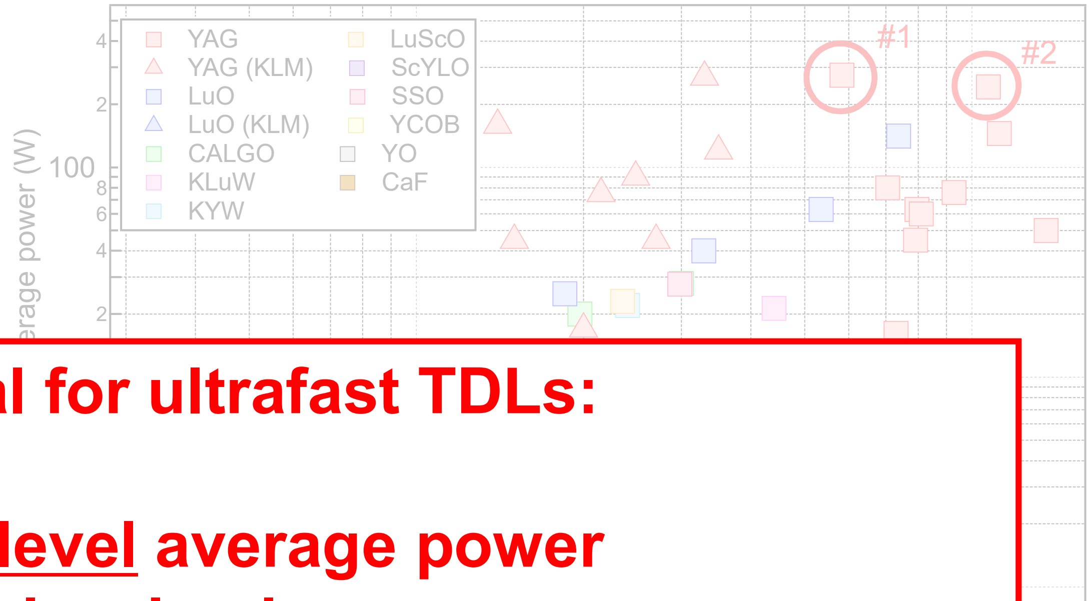

- **Kerr-**
  P_{av} u
  τ_p >

[#3] J. Brons,

Goal for ultrafast TDLs:

<u>kW-level</u> average power
<u>mJ-level</u> pulse energy

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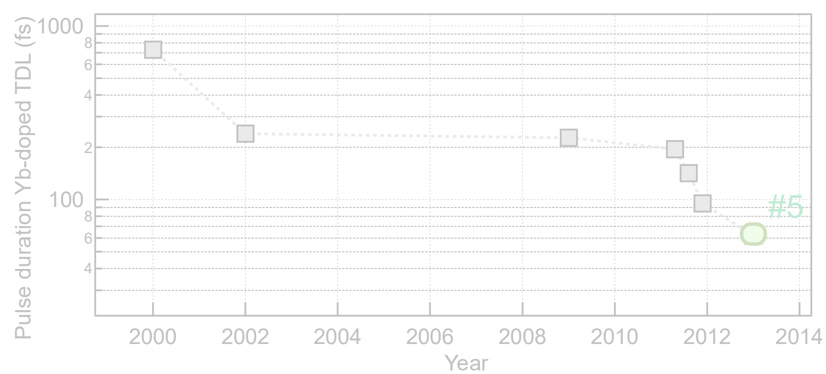

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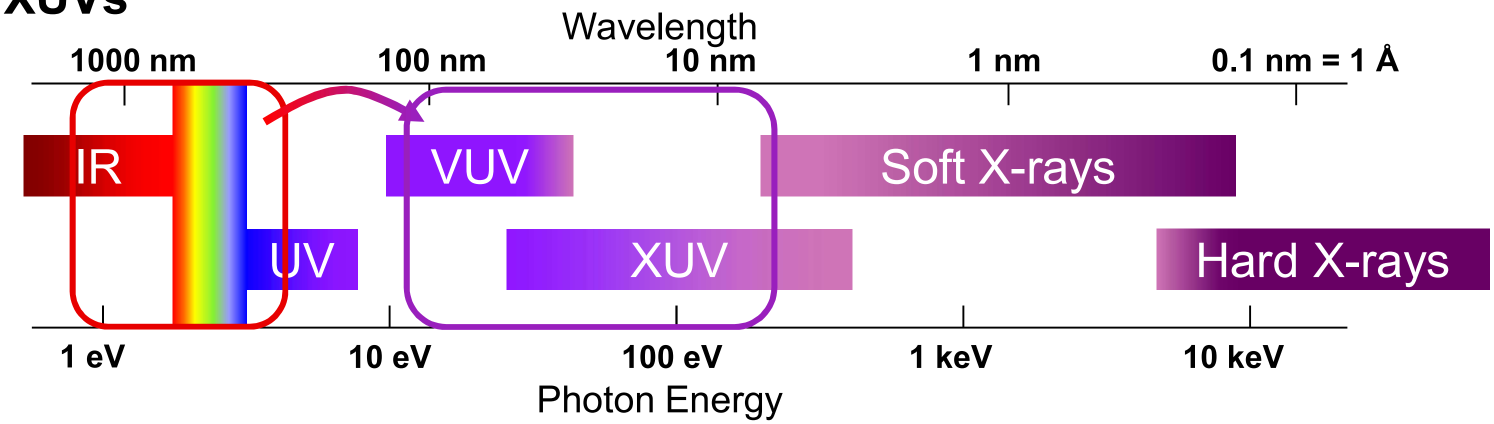
Motivation for HHG

Going to XUVs

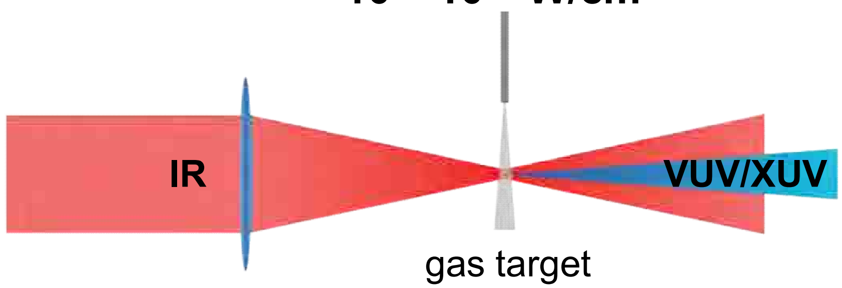


HHG: high harmonic generation[#1,2]

Ultrafast laser source

- E_p > 10 μJ
- $\lambda \approx$ 1000 nm
- τ_p < 100 fs
- Focus w < 20 μm
- $f_{rep} \approx$ MHz

focused laser peak intensity
10^{13}-10^{15} W/cm²



- Odd harmonics of order 3, 5, 7…

λ = 10 - 100 nm

$P = 10^{-4} - 10^{2}$ μW

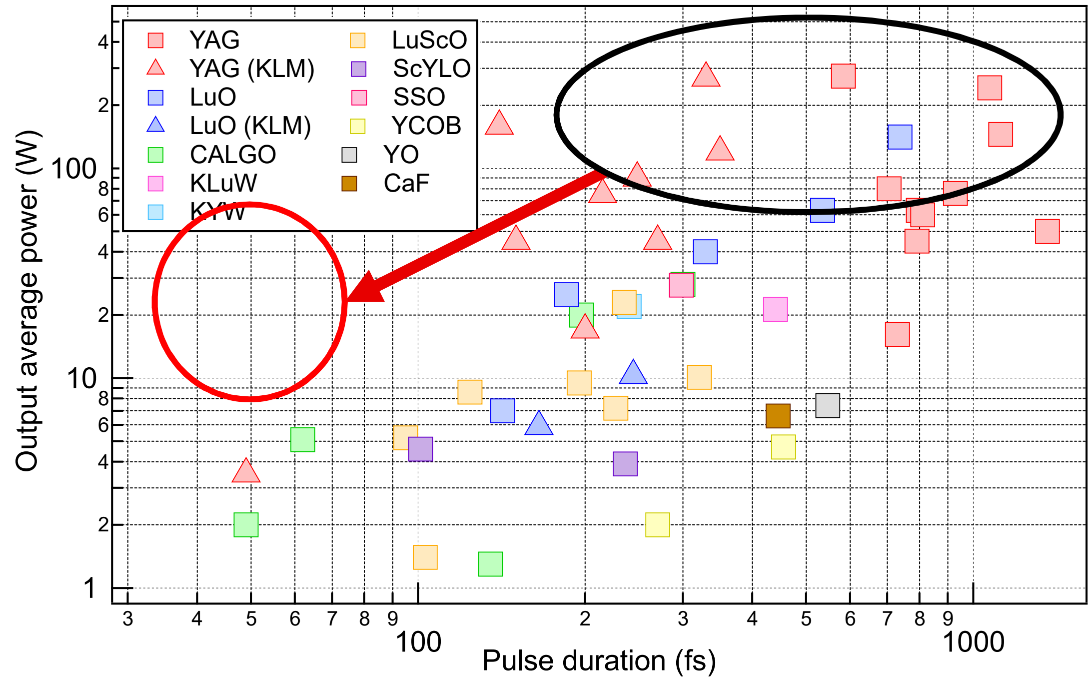
τ_p < 100 as
(1 as = 10^{-18} s = 10^{-3} fs)

[#1] A. McPherson, et al., *JOSA B*, **4** (1987)

[#2] M. Ferray, A. L'Huillier, et al., *J. Phys. B: At. Mol. Opt. Phys.* **21** (1988)

Extra-cavity pulse compression

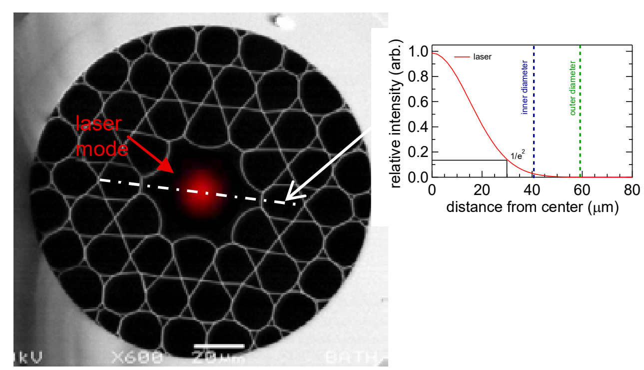
Multi-100-W TDL results based on Yb:YAG, pulse durations >500 fs



Many applications and scientific experiments require sub-100 fs

Pulse compression in Kagome-type photonic crystal fiber[#2]

- low mode overlap with the structure (< 0.05%)
- low losses (< 200 dB/km)
- Compression of **800 fs → 100 fs** with **>100 W** with a power efficiency of **>88%** demonstrated[#3]



[#2] F. Benabid, et al., *Science* **298**, 399 (2002)

[#3] F. Emaury, C. J. Saraceno, … , A. Diebold, … , U. Keller, *Opt. Lett.* **39** (2014)

First HHG from a TDL

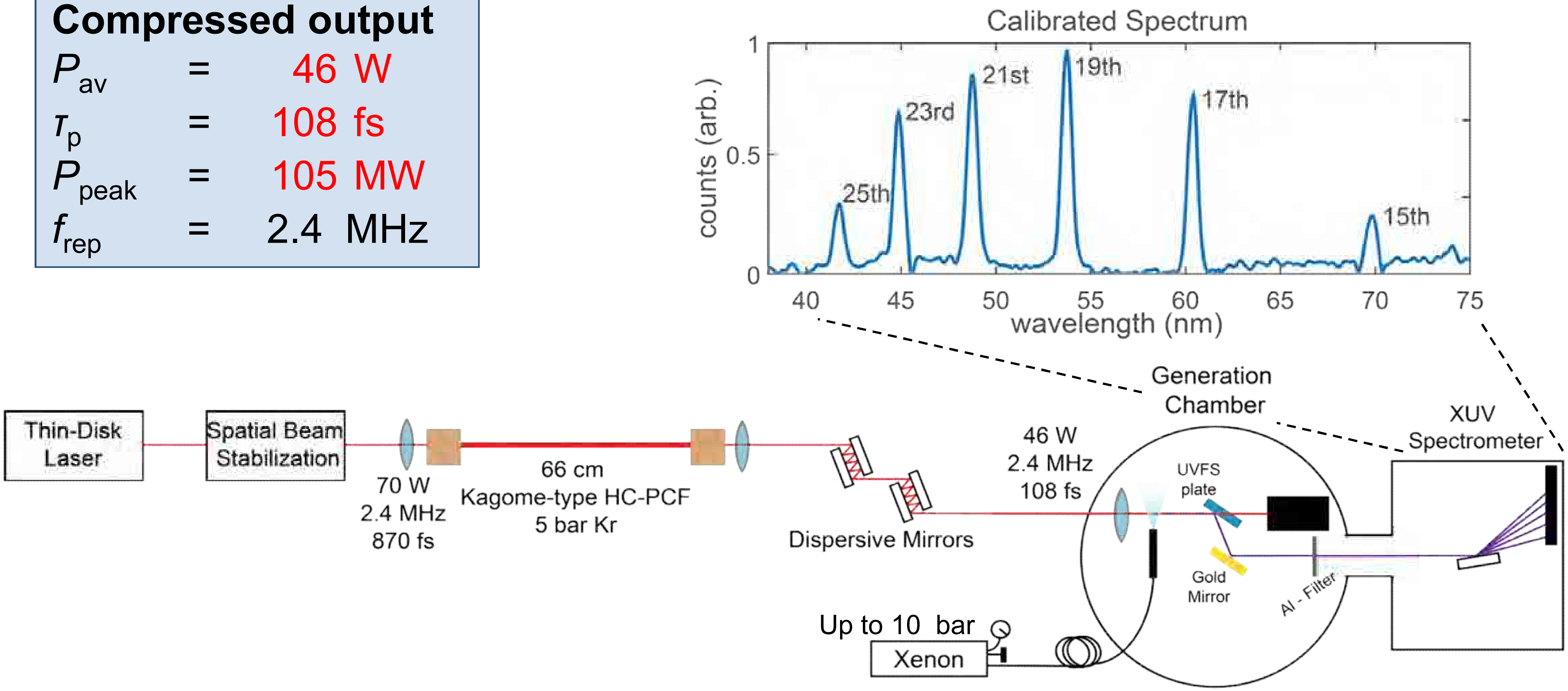
Compressed output

P_{av} = 46 W

τ_p = 108 fs

P_{peak} = 105 MW

f_{rep} = 2.4 MHz



- Oscillator-driven high harmonic generation at MHz repetition rate#
- **Compact and simple set-up for HHG** with up to **5x10^7 photons/s on the 19th harmonic**
- Harmonics created **down to 41 nm**

F. Emaury, A. Diebold, C. J. Saraceno, U. Keller, *Optica* **2** (2015)

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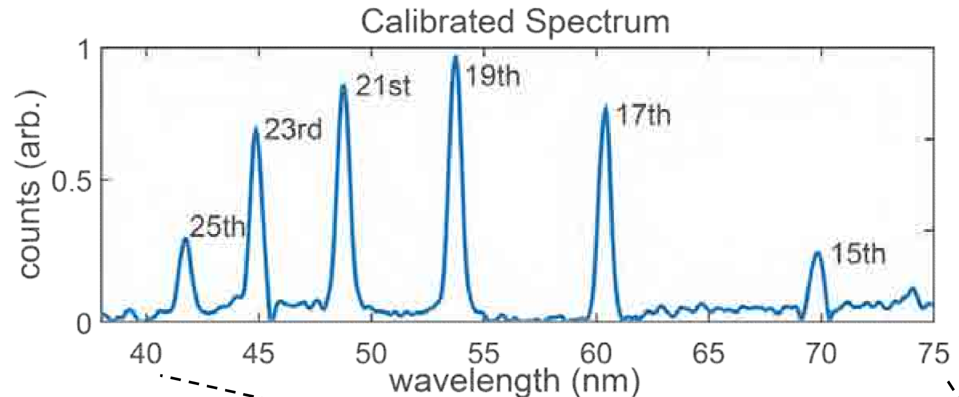

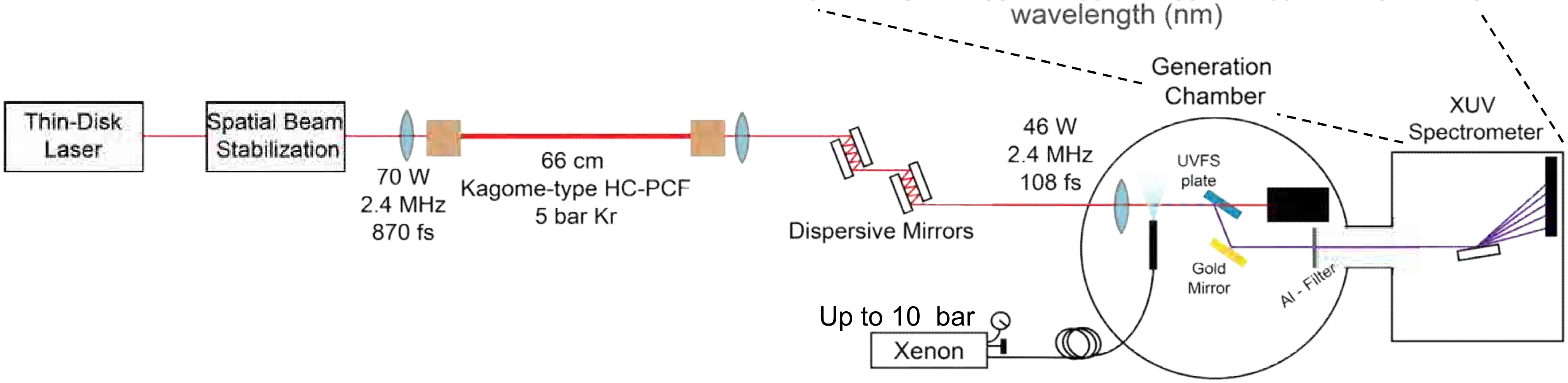

- Oscillator-Driven High Harmonic Generation at MHz Repetition Rate[#]
- Harmonics created **down to 41 nm**

Increase XUV flux by increasing efficiency or <u>input average power</u>

[#] F. Emaury, A. Diebold, C. J. Saraceno, U. Keller, *Optica* **2** (2015)

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- Pushing TDLs to the kW regime: novel SESAM designs
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Challenges towards kW powers from TDLs

✓ **Challenge 1: TEM(00) cw operation at kW-level**

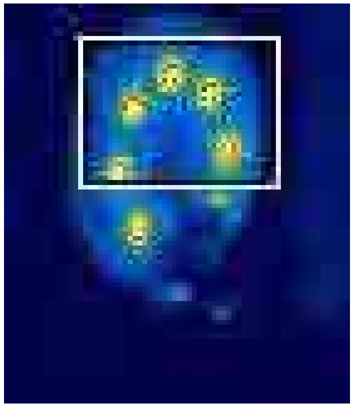
→ 4 kW fundamental transverse mode demonstrated [#1]

✓ **Challenge 2: Pulse formation at high intracavity peak power**

→ operation in vacuum and multipass geometries allow to sufficiently reduce nonlinearities to support kW operation [#2,3]

○ **Challenge 3: Intracavity components at extremely high intracavity powers**

- dispersive mirrors
- **SESAM**



thermal camera picture of dispersive mirror in Multi-pass cell at 2 kW intracavity cw power

[#1] T. Gottwald, et al., *Proc SPIE* **8898**, (2014) [#2] D. Bauer, et al., *Opt. Expr.* ***20*** (2012) [#3] C.J. Saraceno, et al., *Opt. Expr.* ***20*** (2012)

Optimizing the SESAM

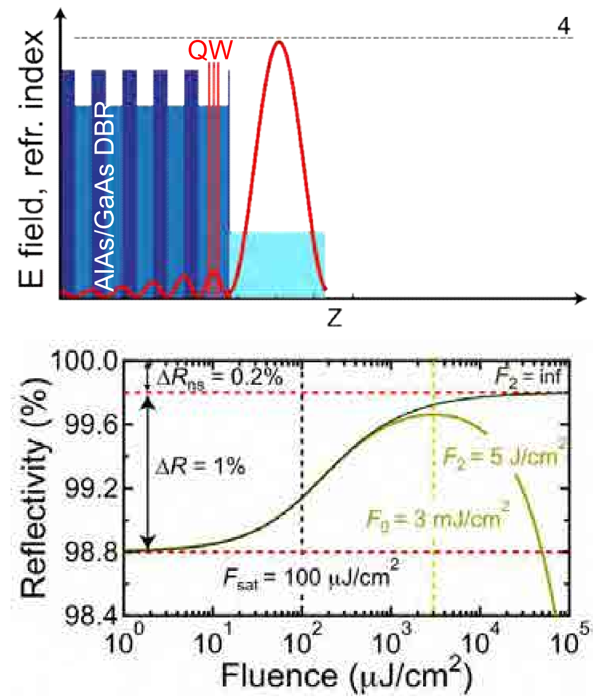
Center for Micro- and Nanoscience

SESAM#

- Semiconductor structure grown by molecular beam epitaxy (MBE) or metallo-organic vapour-phase epitaxy (MOVPE)

- AlAs/GaAs Distributed Bragg reflector (DBR) followed by InGaAs quantum-well (QW) absorber layers

- Idea:
  low reflectivity for low fluences, high reflectivity for high fluences
  → **pulsed regime energetically favored**



U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2** (1996)

Optimizing the SESAM

○ **Challenge: Adapt SESAMs for high intracavity powers**

- Minimize losses, optimize designs for high damage thresholds
- Shift all nonlinear parameters to higher fluences
- Optimize thermal properties and flatness

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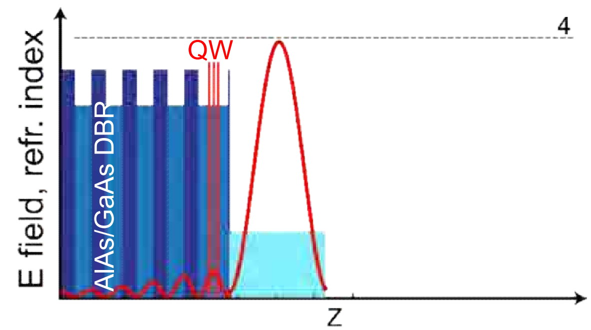

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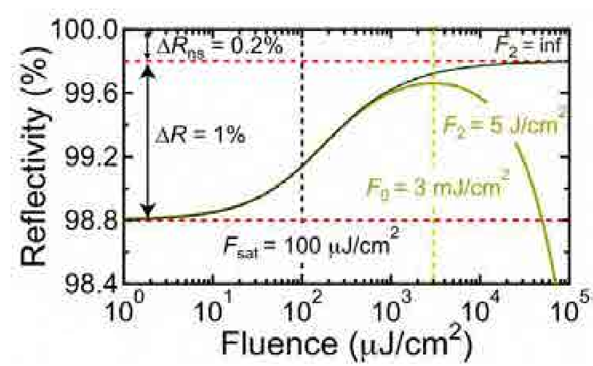


U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2** (1996)

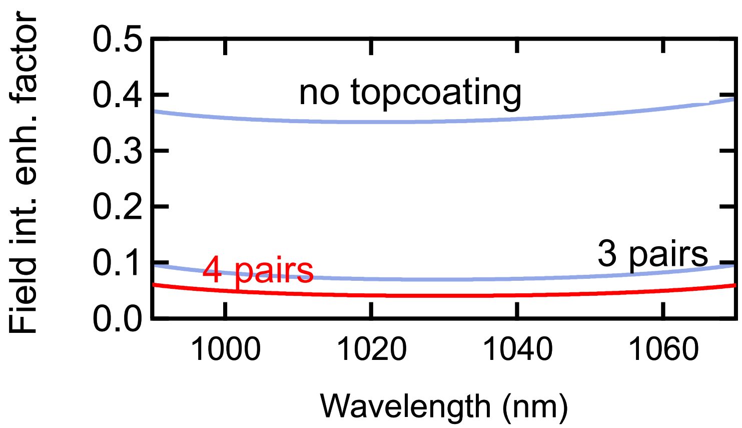
Dielectric topcoatings

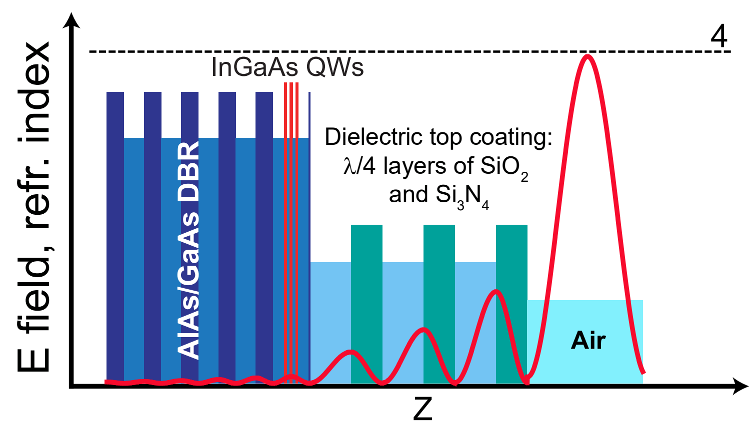
○ **Challenge: Adapt SESAMs for high intracavity powers**

- **Minimize losses, optimize designs for high damage thresholds** ✓
- Shift all nonlinear parameters to higher fluences ☐
- Optimize thermal properties and flatness ☐

Dielectric topcoatings[#]

- Dielectric topcoatings of quarter-wave layers of SiO_x/SiN_y **(PECVD, IBS)** reduce the electric field entering the structure





[#] C. J. Saraceno, et al., *IEEE Sel. Top. Quantum Electron.* **18** (2012)

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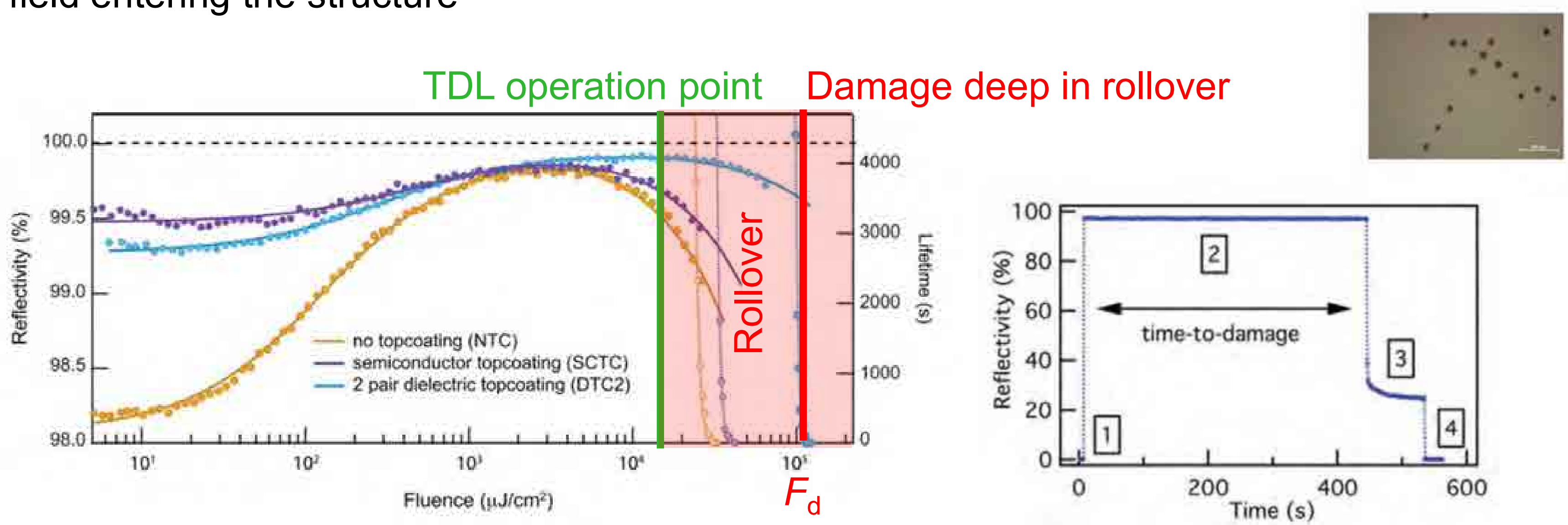

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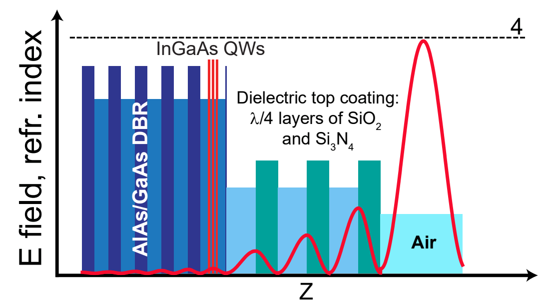


- **SESAM damage mechanism** originates in energy deposited due to the rollover
- Damage fluence F_d depends on two-photon absorption (TPA) in roll-over regime: $F_{\mathrm{d}} \propto \sqrt{F_2}$, with $F_2 = \frac{\tau_{\mathrm{p}}}{0.585 \int \beta_{\mathrm{TPA}}(z) n^2 |E(z)|^4 dz}$

→ High damage thresholds by using low-TPA material in top coating section
→ Problem: modulation depth decreased

	β_{TPA} (1030 nm)
GaAs	20 cm/GW
AlAs	5 cm/GW
SiO_x/SiN_y	~0 cm/GW

[#] C. J. Saraceno, et al., *IEEE Sel. Top. Quantum Electron.* **18** (2012)

Strain compensation

○ **Challenge: Adapt SESAMs for high intracavity powers**

- Minimize losses, optimize designs for high damage thresholds ☑
- **Shift all nonlinear parameters to higher fluences** ☑
- Optimize thermal properties and flatness ☐

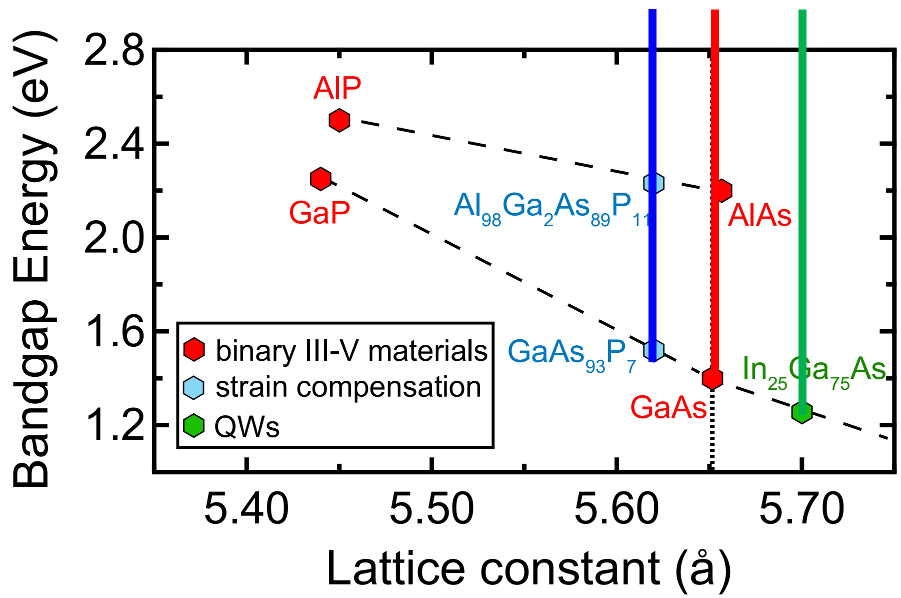
Strain compensation#

- AlAsP strain-compensation layers allow for increasing the number of InGaAs quantum-well absorber layers without surface degradation#
  → Increase of modulation depth

DBR – distributed Bragg reflector

QW – quantum-well absorbers

SC – strain compensation



C. G. E. Alfieri, A. Diebold, et al., *Opt. Exp.* **24** (2016)

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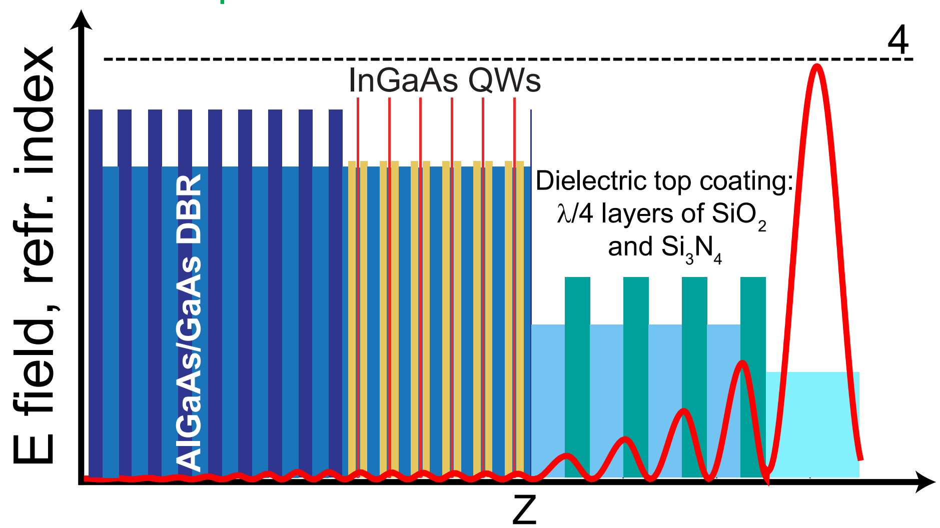

C. G. E. Alfieri, A. Diebold, et al., *Opt. Exp.* **24** (2016)

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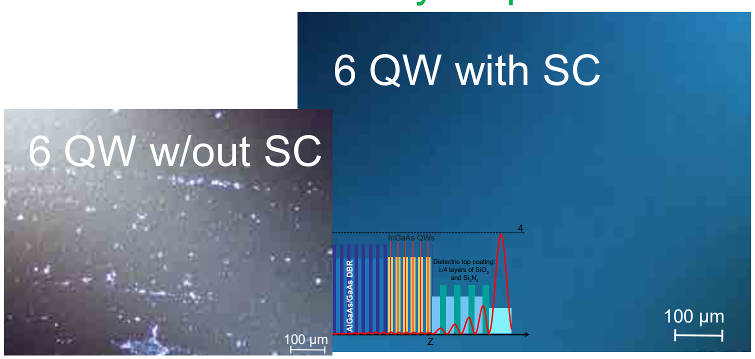
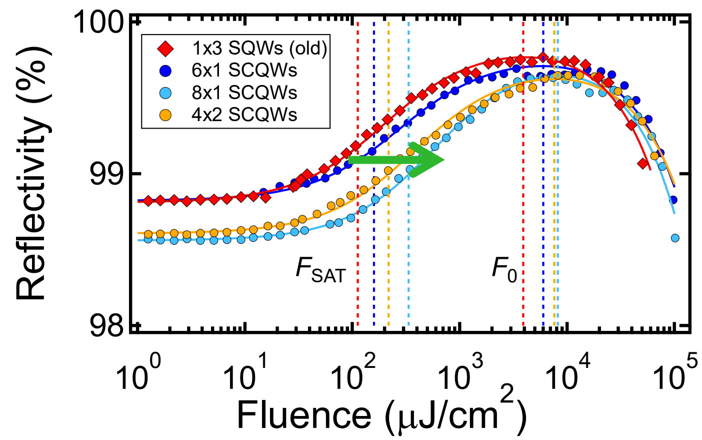
  → Increase of modulation depth
  → >6 QW absorber layers possible





→ Strain compensation shifts nonlinear curve to higher fluences
→ Excellent surface quality

C. G. E. Alfieri, A. Diebold, et al., *Opt. Exp.* **24** (2016)

Bonding techniques

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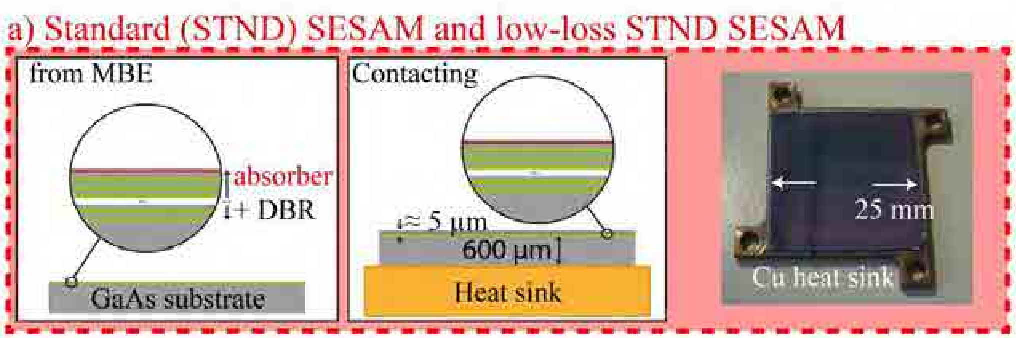
- Minimize losses, optimize designs for high damage thresholds
- Shift all nonlinear parameters to higher fluences
- **Optimize thermal properties and flatness**

Novel bonding techniques#

Standard sample



A. Diebold, et al., *Opt. Exp.* **24** (2016)

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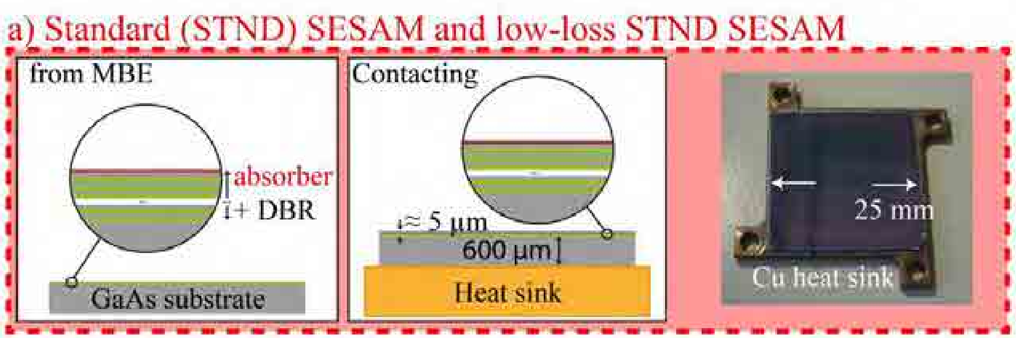
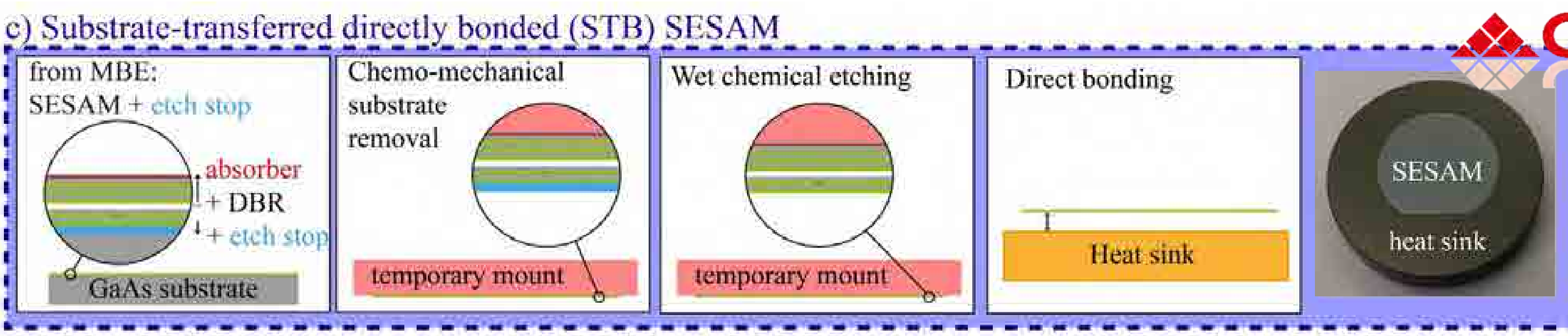


New sample



A. Diebold, et al., *Opt. Exp.* **24** (2016)

G. D. Cole, et al., *Nature Photon.* **7** (2013)

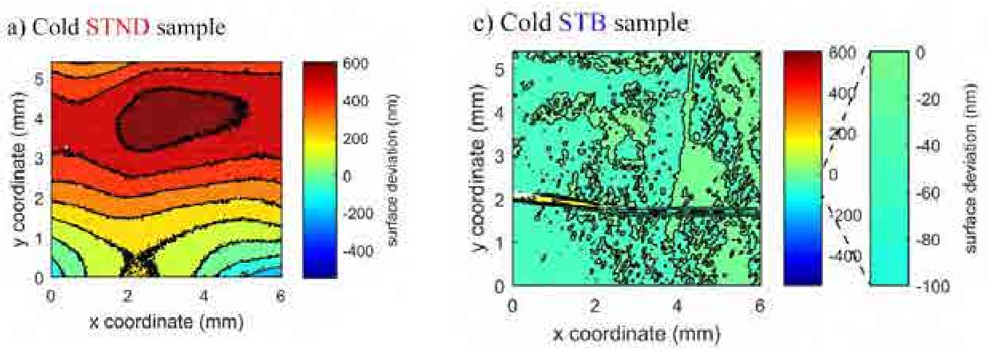
Bonding techniques

○ **Challenge: Adapt SESAMs for high intracavity powers**

- Minimize losses, optimize designs for high damage thresholds
- Shift all nonlinear parameters to higher fluences
- **Optimize thermal properties and flatness**

Novel bonding techniques#

- Cold surface flatness improved by orders-of-magnitude:
  Standard sample: Surface astigmatic, Radius-of-curvature **(ROC) ~10-20 m**
  New sample: Non-astigmatic, **ROC >500 m**



- Thermal behavior drastically improved (spot diameter 800 µm here)

	Standard	New
T/P_{abs} ($K/W_{absorbed}$)	6.6	1.1
F/P_{abs} ($m^{-1}/kW_{absorbed}$)	40	-

A. Diebold, et al., *Opt. Exp.* **24** (2016)

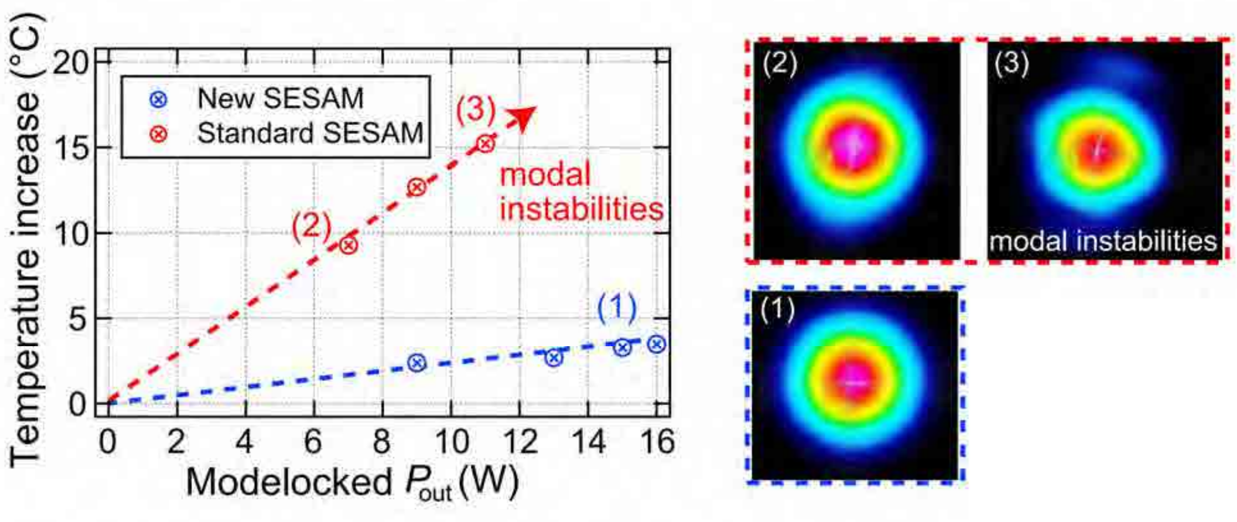
Bonding techniques

○ **Challenge: Adapt SESAMs for high intracavity powers**

- Minimize losses, optimize designs for high damage thresholds
- Shift all nonlinear parameters to higher fluences
- **Optimize thermal properties and flatness**

Novel bonding techniques#

- First test in modelocked TDL shows superior laser mode for new SESAMs



A. Diebold, et al., *Opt. Exp.* **24** (2016)

Optimizing the SESAM

○ **<u>Challenge: Adapt SESAMs for high intracavity powers</u>**

- Minimize losses, optimize designs for high damage thresholds ✓
- Shift all nonlinear parameters to higher fluences ✓
- Optimize thermal properties and flatness ✓

Novel bonding techniques[#]

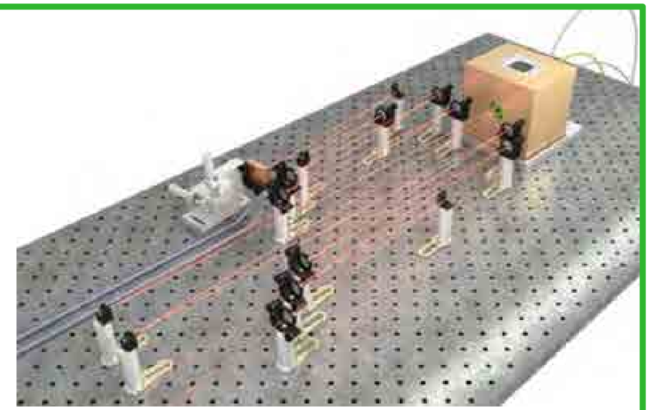
- First test in modelocked TDL shows superior laser mode for new SESAMs

- **All challenges addressed**
- **Optimized SESAMs are ready for the next step in power scaling**

[#] A. Diebold, et al., *Opt. Exp.* **24** (2016)

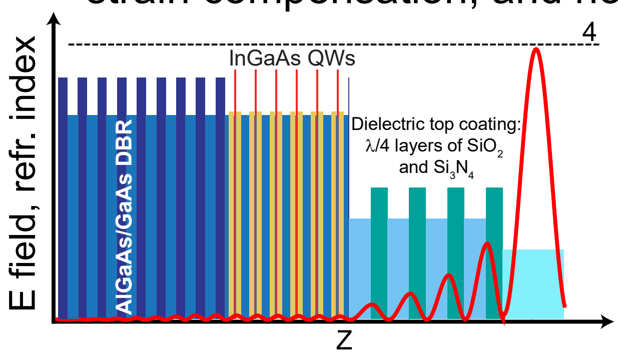
Conclusion and Outlook

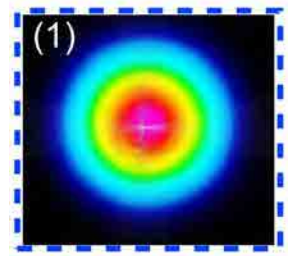
- SESAM-modelocked thin-disk lasers deliver P_{av} **> 200 W** and E_p **> 80 uJ** with **sub-ps pulses** at MHz repetition rate

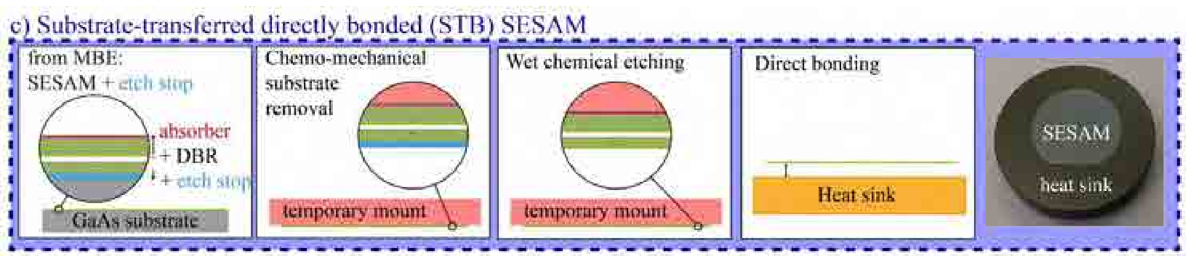


- High-harmonic generation down to 41 nm achieved directly with compressed output

- New SESAM developments deliver ultraflat samples with high damage thresholds thanks to dielectric topcoatings, strain compensation, and novel bonding techniques







kW-class thin-disk lasers are within reach