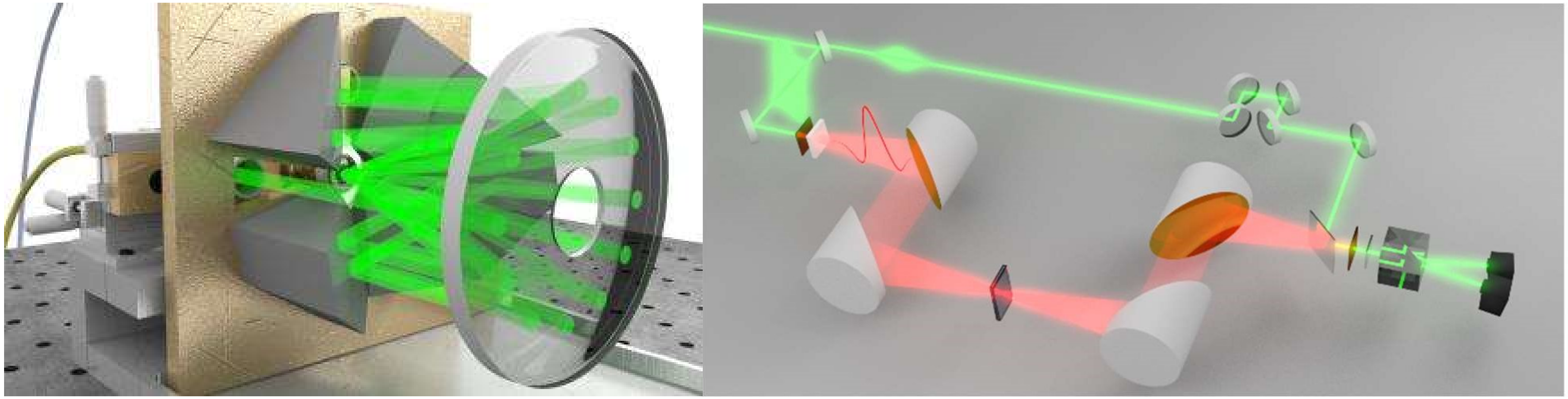

Ultrafast lasers for THz generation using nonlinear optical techniques

Part 1: ultrafast laser technology

Clara J. Saraceno

ICTP Winter School on Terahertz Optics and Photonics - February 2023

What you need to follow this lecture

- Be interested in latest advances in ultrafast laser technology and Terahertz technology
- A running understanding of electromagnetics and Fourier transformations
- A QR-code reader for interactive questions
- A pen and piece of paper
- Don’t be shy: ask questions during and after…

https://arsnova.rub.de/mobile/#id/87676337

About me

2002 - 2007
Studies in Lyon and Paris, France
'Classe Preparatoire' and 'Grande Ecole' specialized in optics

INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech

2008
Experience in Industry
Santa Clara, California, USA
Topic: R&D in ultrafast oscillators

COHERENT.

2009 - 2012
PhD degree
Physics
Topic:
High-power ultrafast thin-disk lasers

ETH zürich

2013 - 2016
Postdoc
Topic: High power ultrafast oscillators for compact XUV sources

unine
UNIVERSITÉ DE NEUCHÂTEL

ETH zürich

2016 - 2019
Associate Prof. (Tenure Track)
Research:
High-power ultrafast lasers, THz sources, time-domain spectroscopy

RUHR UNIVERSITÄT BOCHUM
RUB

2020
Full Prof.

"Photonics and Ultrafast Laser Science" …

puls
Photonics and Ultrafast Laser Science

Acknowledgments

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Tim Vogel
Mohsen Khalili

"Ultrafast Lasers" sub-team:
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Simulations
Dr. Martin Saraceno

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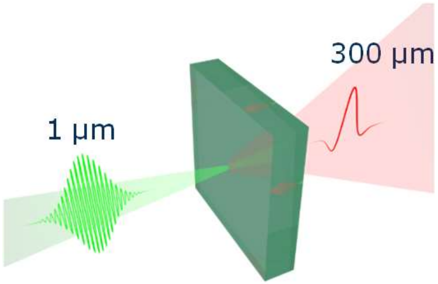
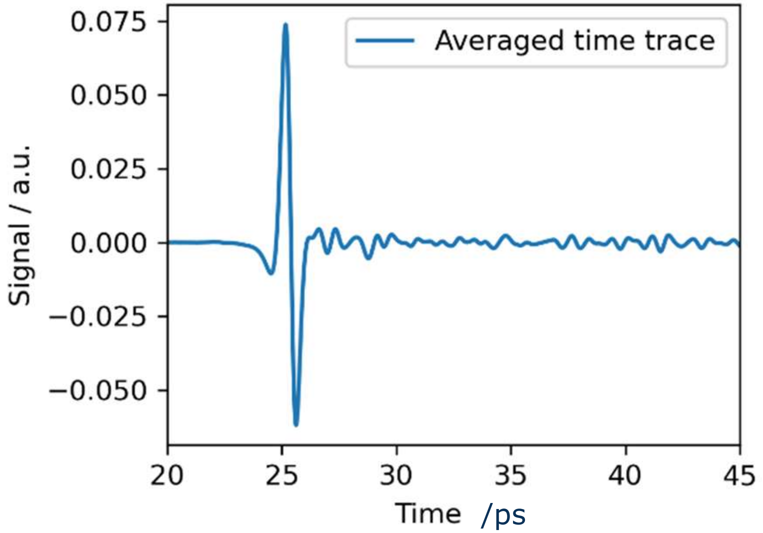
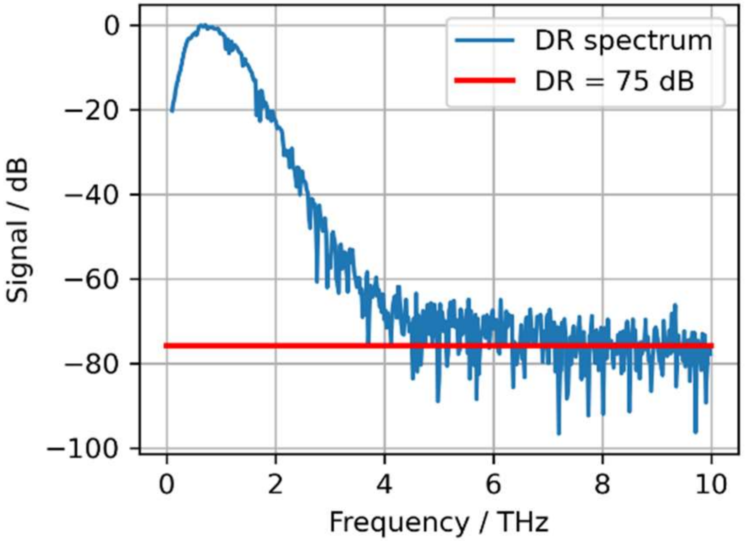
Prof. Globisch, Dr. Kohlhaas, Fraunhofer HHI
Prof. Havenith, RUB
Prof. Keller, ETH Zürich
… etc

Ultrafast laser driven Terahertz pulses



0.1 THz-10 THz
1 THz ≙ 300 µm

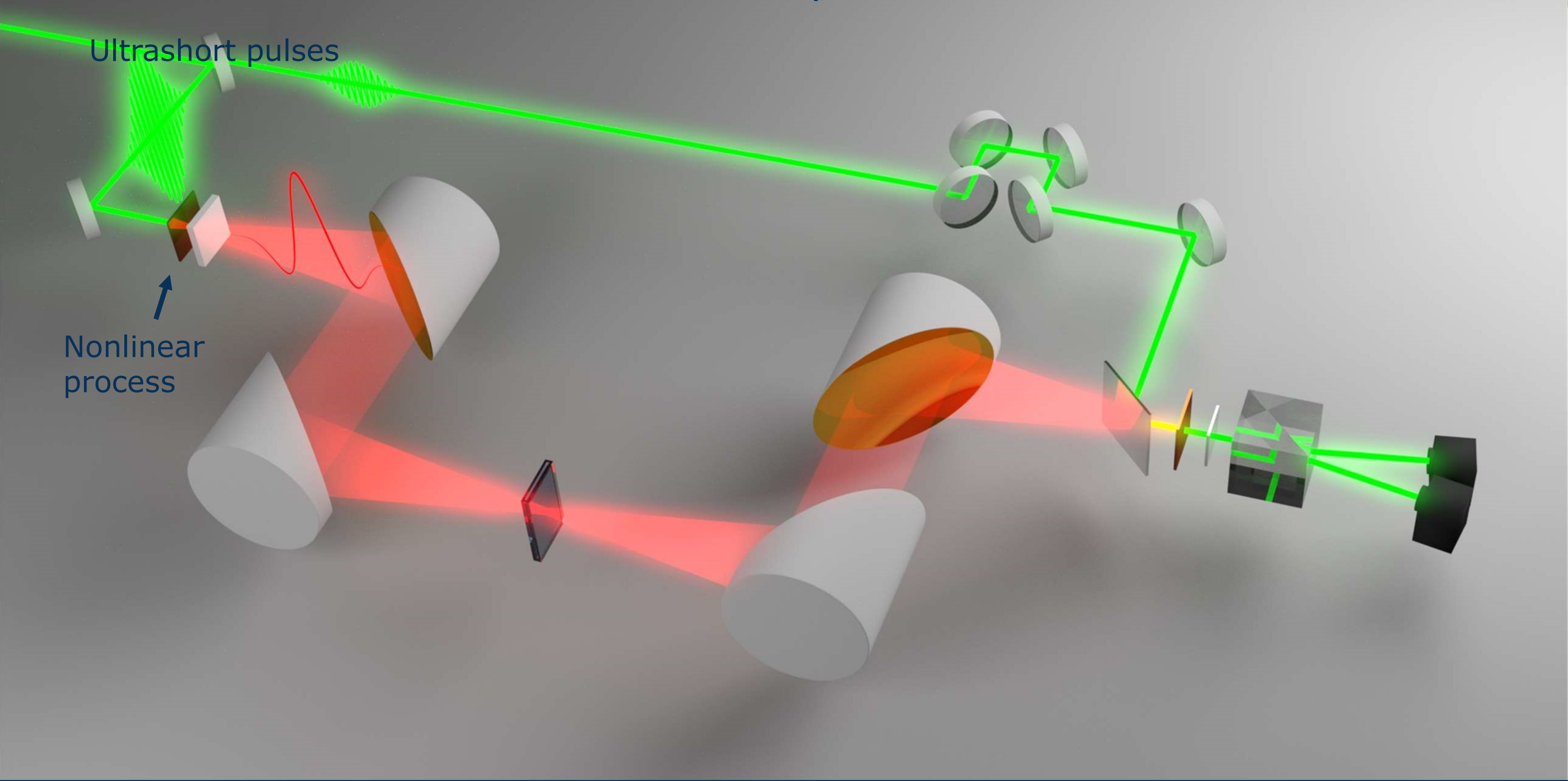




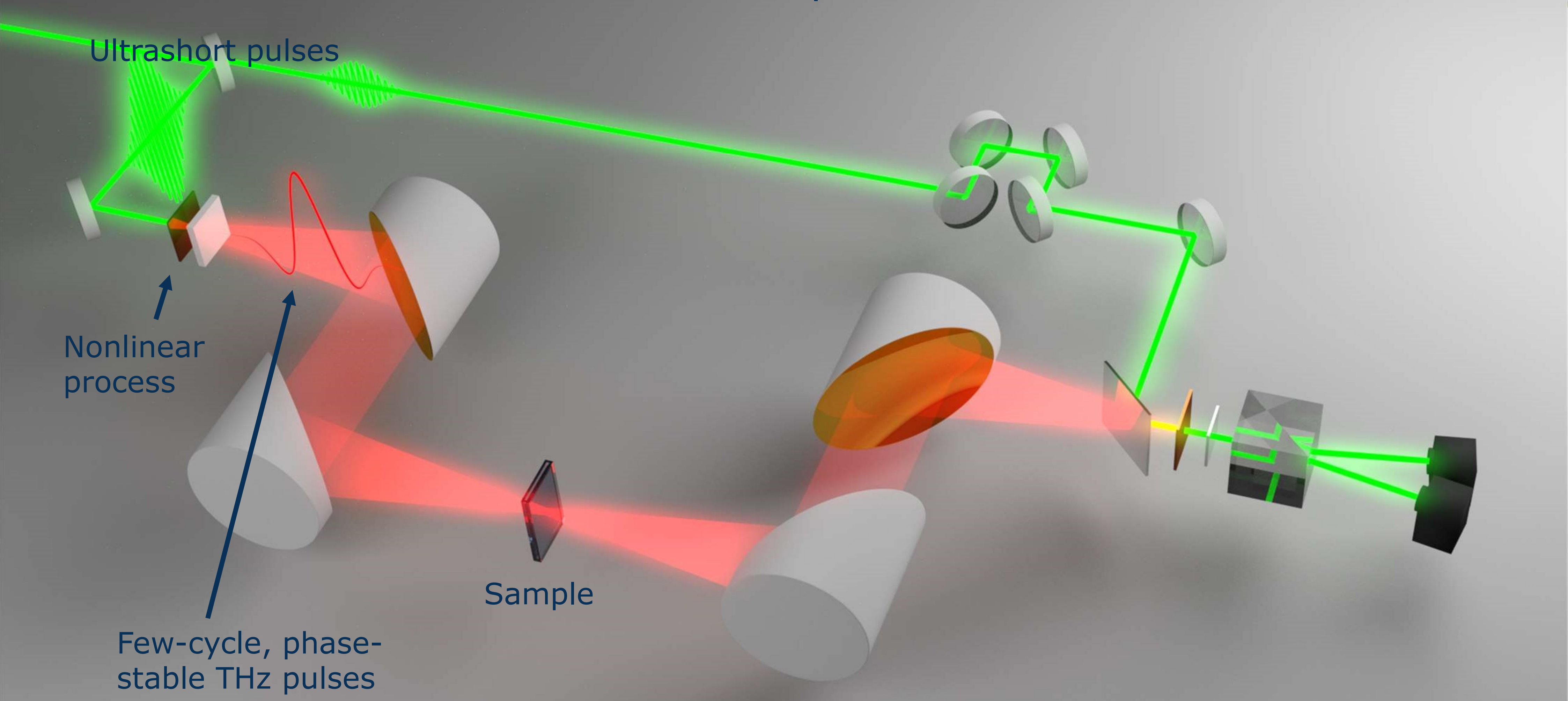
few-cycle THz pulses

- **phase-stable, field-resolved**
- **time-resolved**
- **ultra broadband**
- **commonly accepted: low average power**

Time-domain spectrometer



Time-domain spectrometer



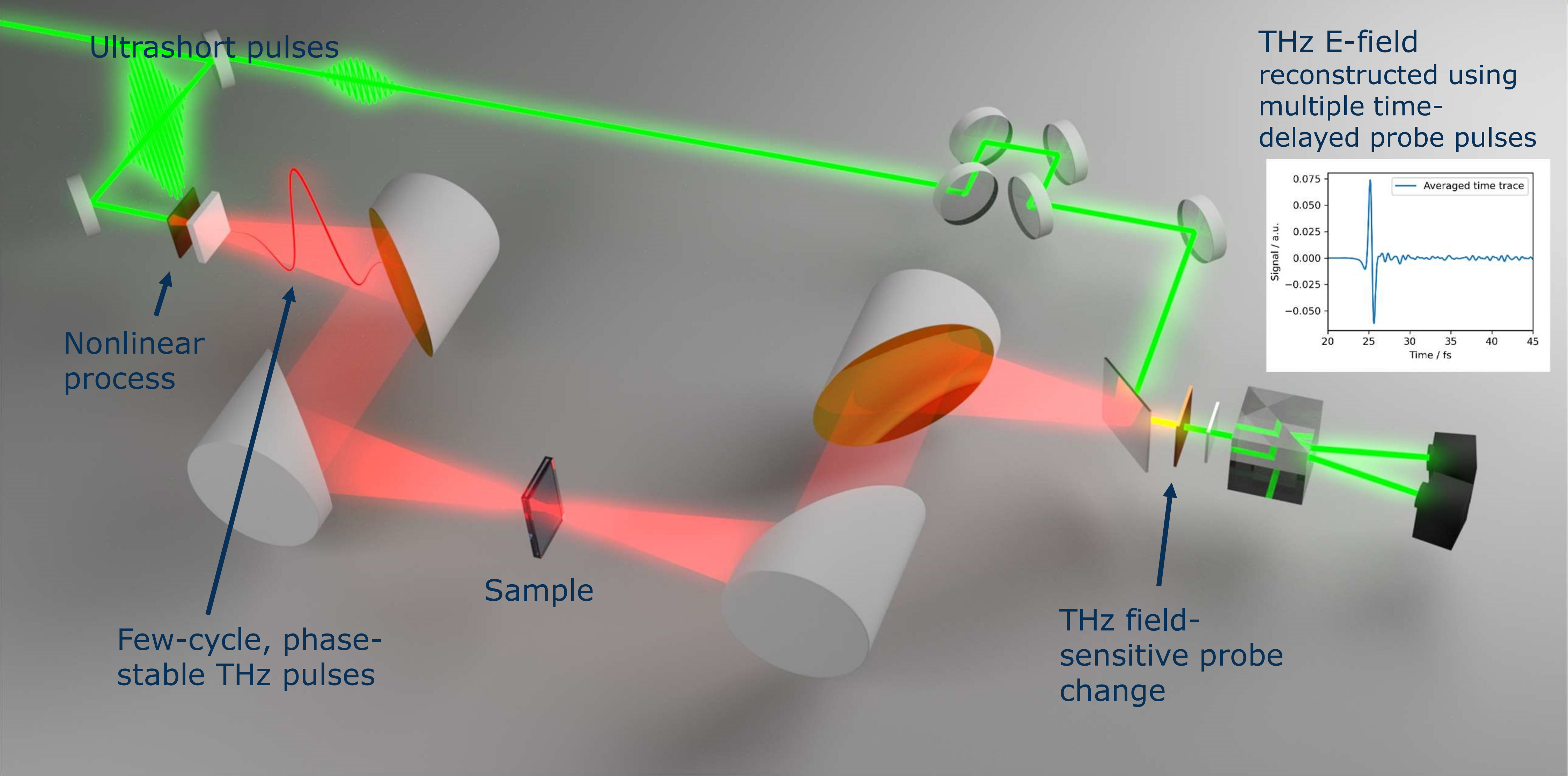
Ultrashort pulses

Nonlinear process

Few-cycle, phase-stable THz pulses

Sample

Time-domain spectrometer



Ultrashort pulses

Nonlinear process

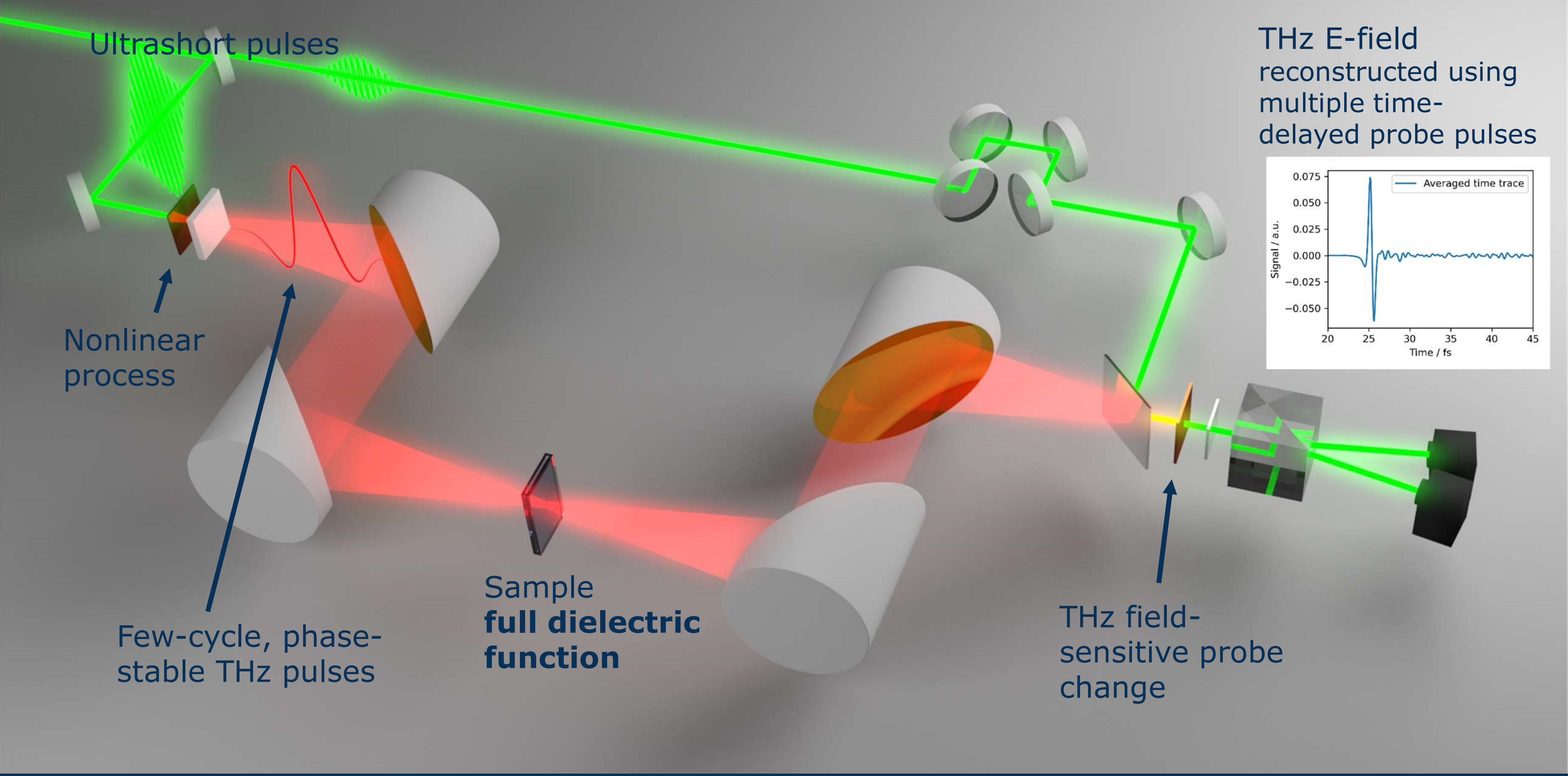
Few-cycle, phase-stable THz pulses

Sample

THz field-sensitive probe change

THz E-field
reconstructed using multiple time-delayed probe pulses

Time-domain spectrometer



Ultrashort pulses

THz E-field reconstructed using multiple time-delayed probe pulses

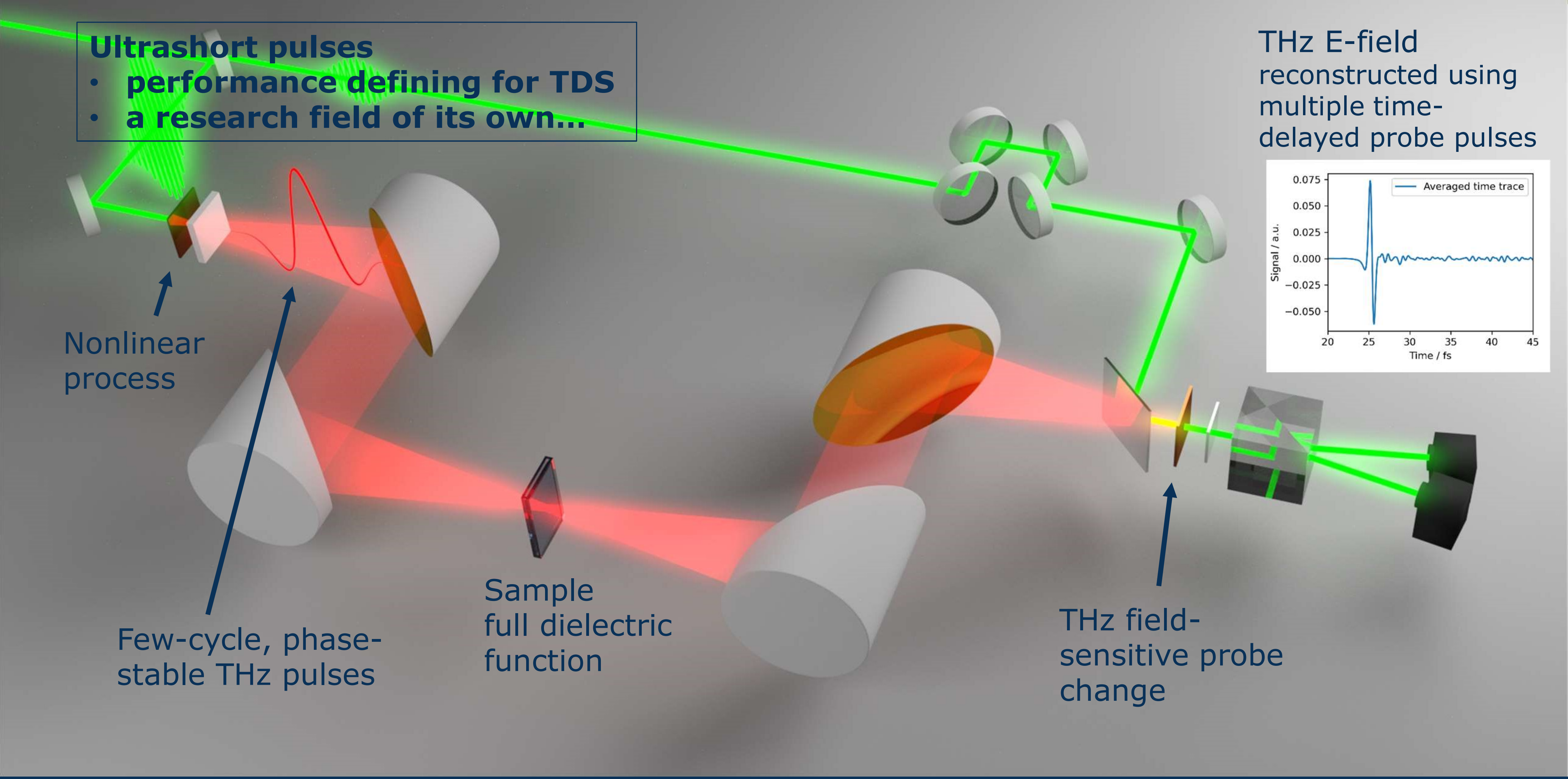
Nonlinear process

Few-cycle, phase-stable THz pulses

Sample
full dielectric function

THz field-sensitive probe change

Time-domain spectrometer



Ultrashort pulses

- **performance defining for TDS**
- **a research field of its own…**

THz E-field reconstructed using multiple time-delayed probe pulses

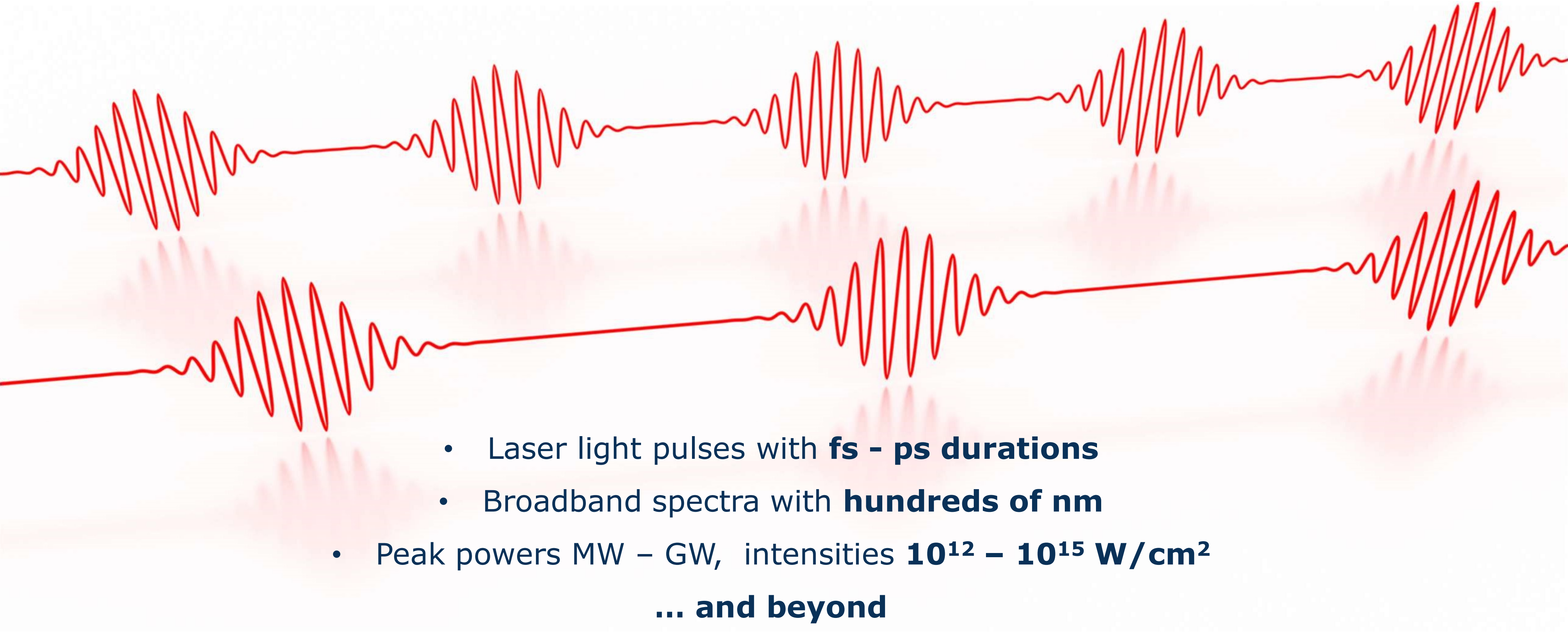
Nonlinear process

Few-cycle, phase-stable THz pulses

Sample full dielectric function

THz field-sensitive probe change

ultrafast lasers

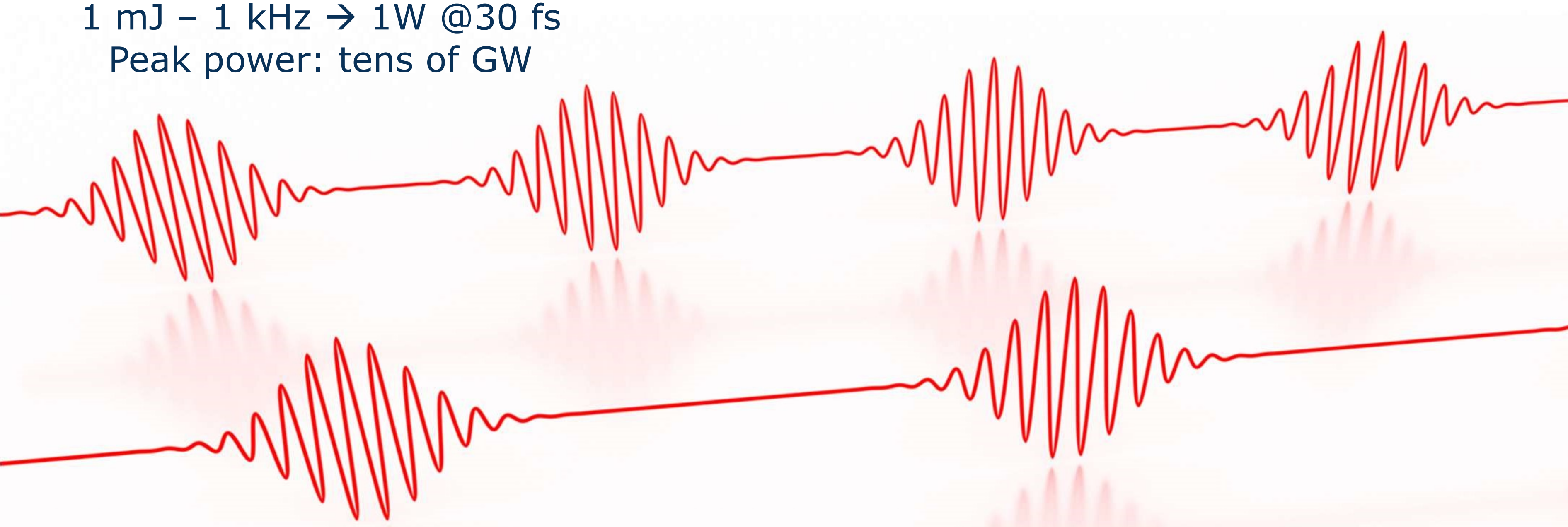


- Laser light pulses with **fs - ps durations**
- Broadband spectra with **hundreds of nm**
- Peak powers MW – GW, intensities **10^{12} – 10^{15} W/cm^2**

… and beyond

ultrafast lasers

Example: commercial Ti:Sa amplifier
1 mJ – 1 kHz → 1W @30 fs
Peak power: tens of GW



- Laser light pulses with **fs - ps durations – down to attoseconds**
- Broadband spectra with **hundreds of nm – up to several octaves**
- Peak powers MW – GW, intensities **10^{12} – 10^{15} W/cm^2 – above 10^{18} W/cm^2**

… and beyond

Physics 2018
Mourou, Strickland

“for their method of generating high-intensity, ultra-short optical pulses”

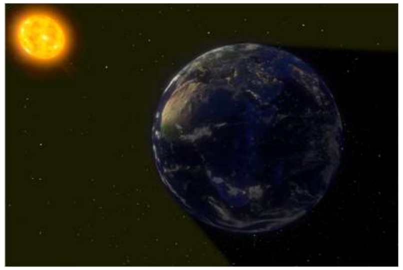
some scaling

1 Gigawatt
1 000 000 000 W

For a very short time, ultrafast lasers generate **peak powers** similar to the **power of a nuclear power plant (some laser systems generate TeraWatts)**

1 femtosecond
= 0. 000 000 000 000 001 s

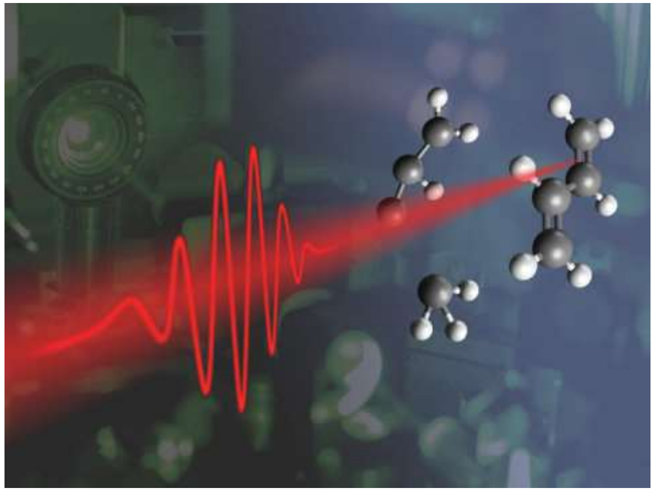
human hair thickness ≈ 10^{-4} m



distance earth sun ≈ 10^{11} m

Measuring **1 second** with **femtosecond precision** is like measuring the **distance between the earth and the sun** with the precision of a **hair thickness**!

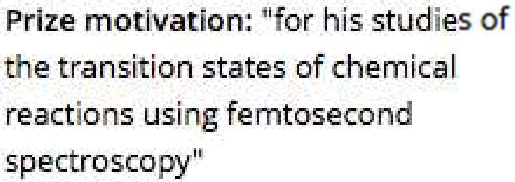
ultrashort timescales



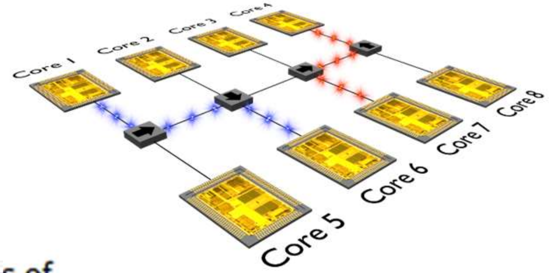
access to ultrafast time-scales:
observe and use ultrafast dynamics

- understand atomic and molecular dynamics
- fast data communication
- …

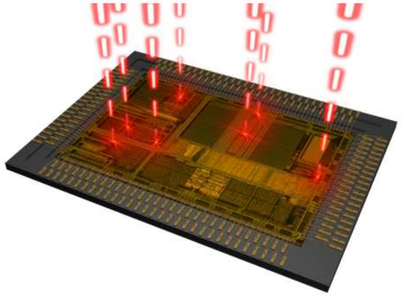
A. H. Zewail in 1994:
understand transition states
in chemical reactions



Prize motivation: "for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

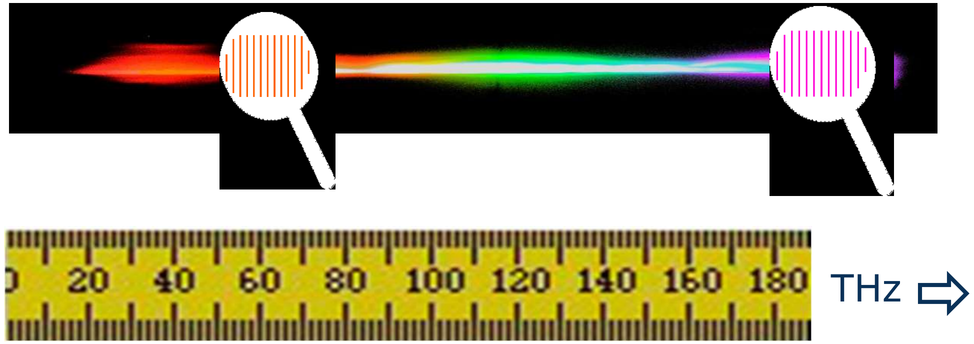


interconnects



optical clocking

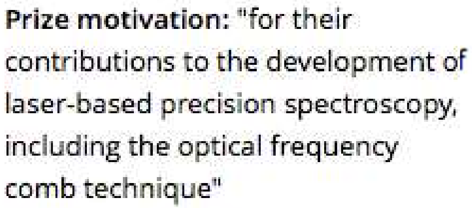
broad frequency combs



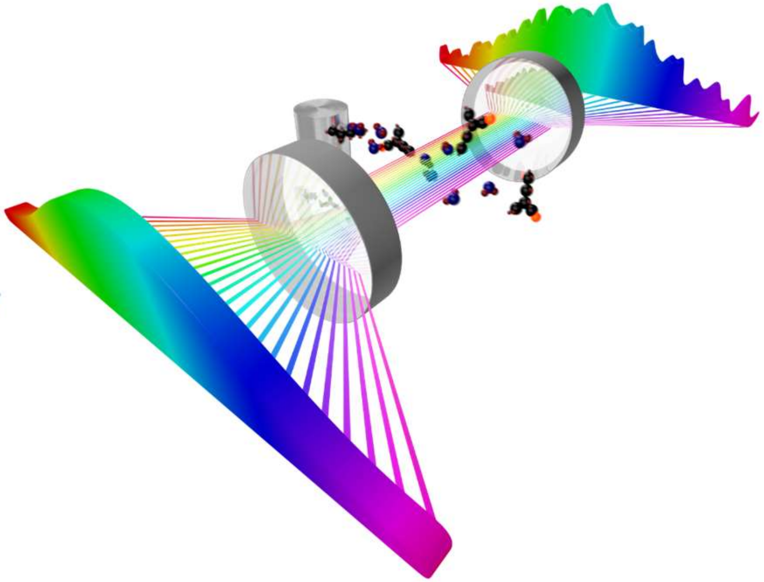
frequency comb:
ruler for unknown frequencies

- optical clocks
- high-precision spectroscopy
- …

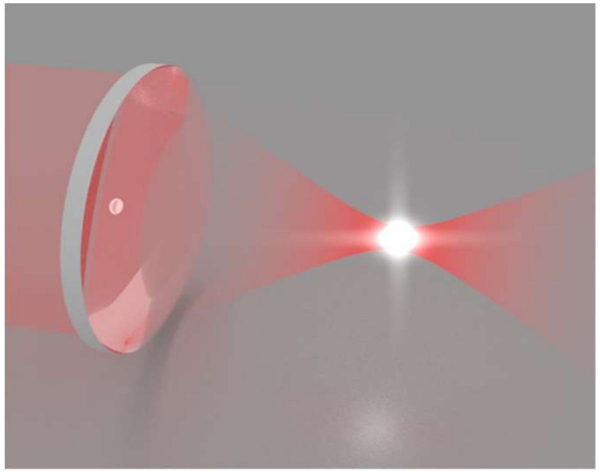
Roy J. Glauber,
John L. Hall,
Theodor W. Hänsch, in 2005:



Prize motivation: "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"



access to high intensities



⇨

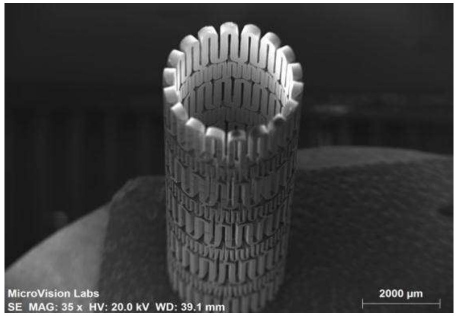
achieve extremely high intensities:

nonlinear optics and material modification

- material processing: cold ablation
- multi-photon biomedical imaging
- nonlinear optics
- ...

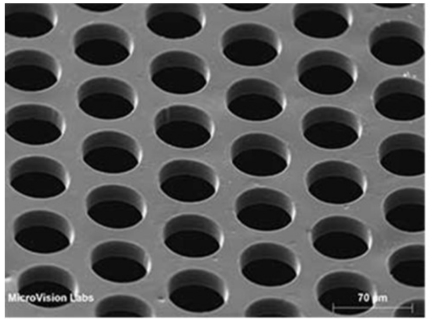
“almost perfect micromachining of almost any material”

Bioresorbable polymer



Courtesy of Resonetics

Polyimide Hole array drilling



Courtesy of Resonetics

Ceramics

Courtesy of Lightmotif

Courtesy of Dr. Kurt Weingarten, Lumentum

“... and create functional surfaces”

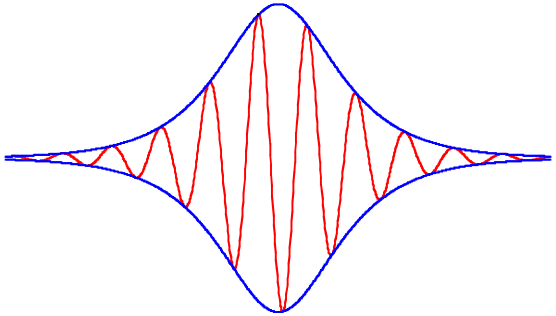
Important Parameters

Notation	Everyday parameters	How are they linked together?	Subtleties
E_p	Pulse energy (J)		
τ_p	Pulse duration (fs)		• Definition often FWHM – can be misleading • RMS pulse duration better suited but rarely used
P_{pk}	Peak power (W)	*Can be calculated from* E_p and τ_p	• Requires knowledge about pulse amplitude shape • Simple for well-known pulse shapes (Gaussian,…) • Usually fixed (wanted) for a given experiment
I_{pk}	Peak intensity (W/m^2)	*Can be calculated from* P_p and *beam area A*	Requires knowledge on transverse beam profile

Light Pulse Electric Field: superposition of monochromatic waves

$$\boxed{E(t) = \frac{1}{2\pi}\int \tilde{E}(\omega)e^{j\omega t}d\omega}$$

$$E(t) = A(t)e^{j\omega_0 t} \quad \text{where} \quad A(t) = \frac{1}{2\pi}\int \tilde{A}(\Delta\omega)e^{j\Delta\omega t}d\Delta\omega$$



Pulse envelope *A*(t): sufficient to describe pulse entirely

Important Parameters

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$\Delta\lambda_p, \Delta\nu_p$	Spectral bandwidth (nm, Hz)		• Often defined by width of spectral intensity in nm. • Only relative bandwidths are the same in wavelength and frequency

Spectral domain: **spectral amplitude** and **spectral phase**

$$\tilde{E}(\omega) = \left|\tilde{E}(\omega)\right| \exp\left(i\varphi(\omega)\right)$$

→ Spectral amplitude continuous function for one pulse

→ "short pulse – broad amplitude spectrum"

Important Parameters

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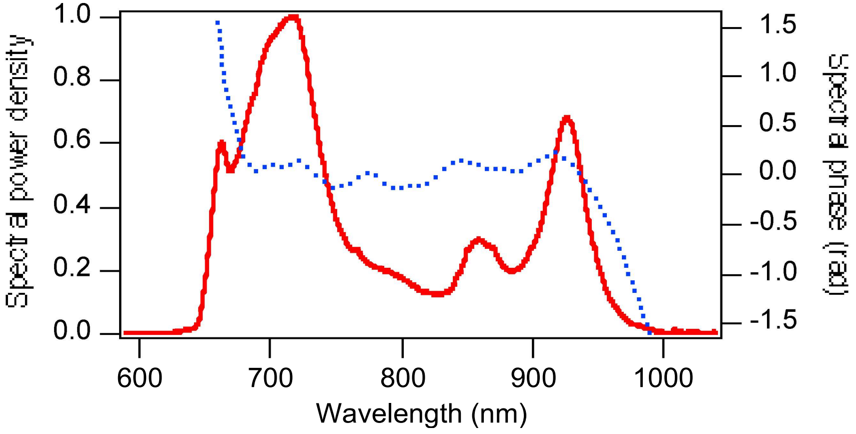
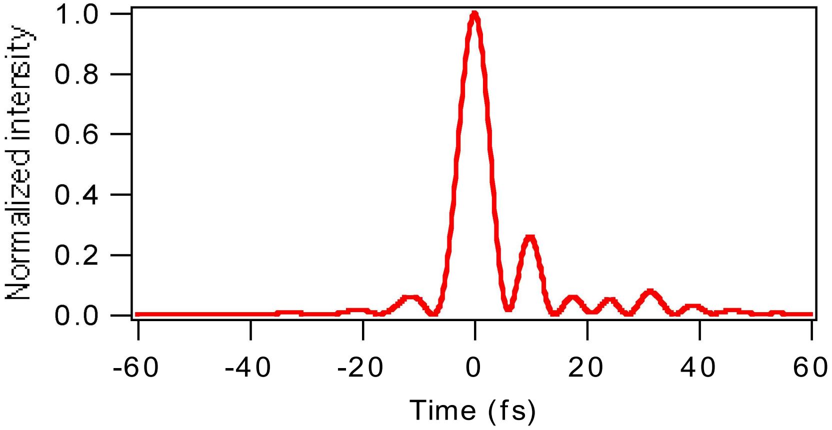
TBP	Time-bandwidth product (no unit)	$TBP = \tau_p\Delta\nu_p$	• Defined with intensity FWHM • Reaches a minimum that gives us information about the shortest pulses reachable with a given spectral width • Can be flawed for complex, very short pulses

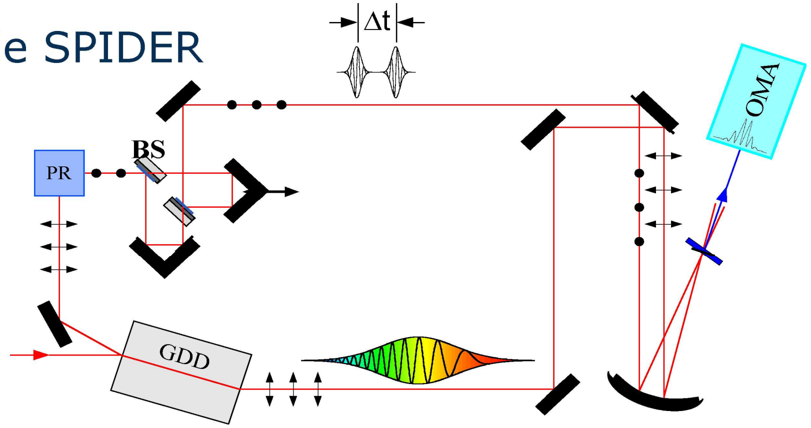
Full pulse information

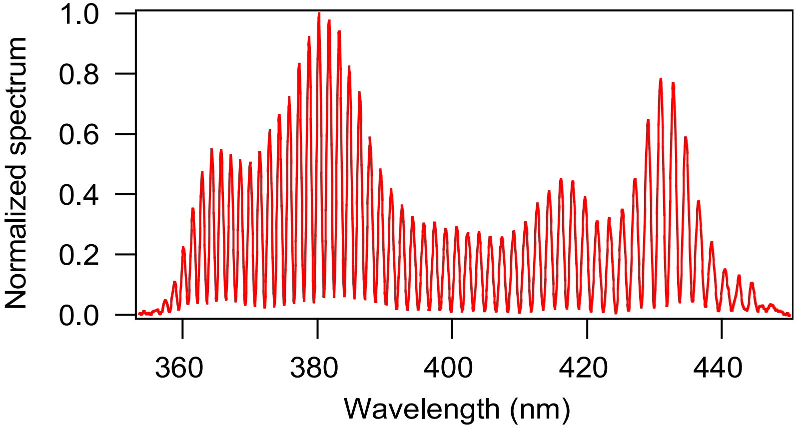




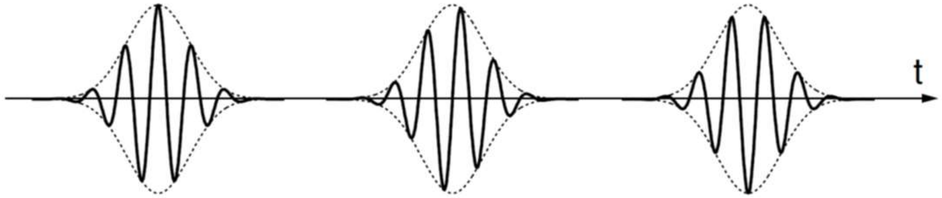
- Full pulse characterization needs **amplitude** and **phase**
- Requires sophisticated measurement techniques (FROG, SPIDER...)

Example SPIDER





ultrafast lasers = train of pulses = frequency comb

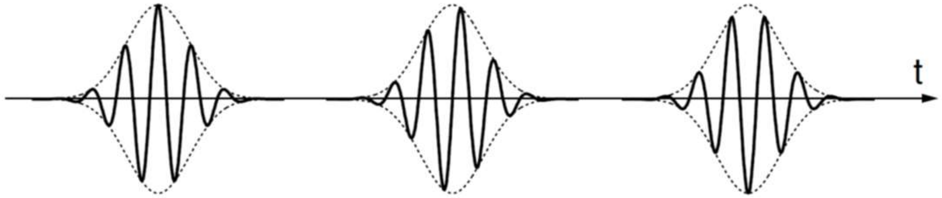


$$E_{train}(t) = \boxed{A(t)\exp\left(i\omega_c t + i\varphi_0(t)\right)} \otimes \boxed{\sum_{m=-\infty}^{+\infty} \delta\left(t - mT_R\right)}$$

One pulse + linearly time varying carrier-envelope phase

Dirac comb

ultrafast lasers = train of pulses = frequency comb

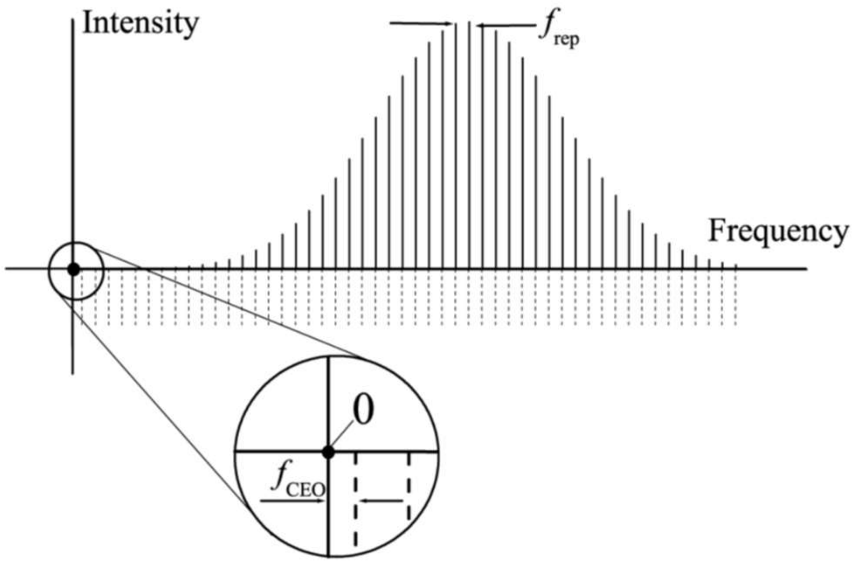


$$E_{train}(t) = \boxed{A(t)\exp\left(i\omega_c t + i\varphi_0(t)\right)} \otimes \boxed{\sum_{m=-\infty}^{+\infty} \delta\left(t - mT_R\right)}$$

One pulse + linearly time varying carrier-envelope phase

Dirac comb

$$f_m = mf_{rep} + f_{CEO}$$



$$\tilde{E}_{train}(f) = \tilde{A}(f - f_c) \cdot \sum_{m=-\infty}^{+\infty} \delta\left(f - mf_{rep} - f_{CEO}\right)$$

Frequency comb with offset

Important Parameters

Notation	Everyday parameters	How are they linked together?	Subtleties
E_p	Pulse energy (J)		
τ_p	Pulse duration (fs)		• Definition often FWHM – can be misleading • RMS pulse duration better suited but rarely used
f_{CEO}	Carrier envelope frequency		• Difficult to measure
P_{pk}	Peak power (W)	*Can be calculated from* E_p and τ_p	• Requires knowledge about pulse amplitude shape • Simple for well-known pulse shapes (Gaussian,…) • Usually fixed (wanted) for a given experiment
I_{pk}	Peak intensity (W/m^2)	*Can be calculated from* P_p and *beam area A*	Requires knowledge on transverse beam profile
λ_0, ν_0	Central Wavelength (nm), frequency (Hz)		For complex spectra the central frequency might become different to the center of mass of the spectrum
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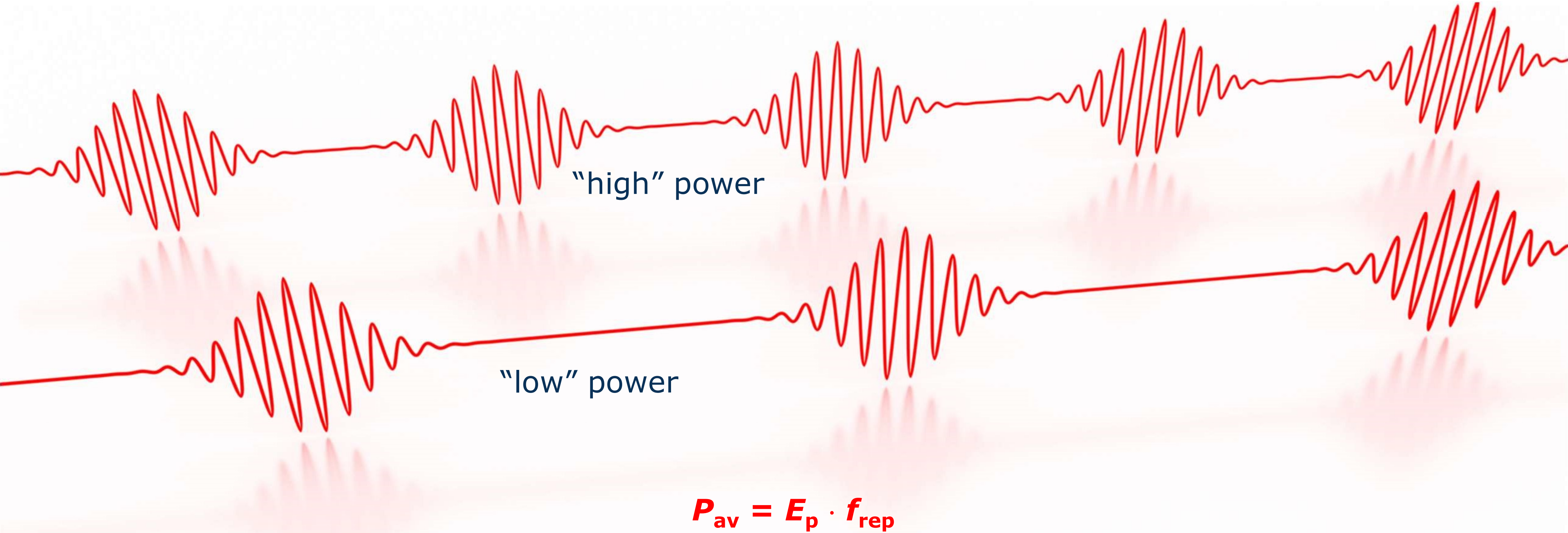
All applies to THz but definitions become flawed because single-cycle pulse

Focus here: higher average power



"high" power

"low" power

$$P_{av} = E_p \cdot f_{rep}$$

Higher average power at a given pulse energy = **more pulses / s**

⇨ Higher signal to noise ratio, shorter measurement times, higher speed, …

⇨ Challenges: thermal and other accumulation effects, …

Important Parameters

Notation	**Everyday parameters**	**How are they linked together?**	**Subtleties**
E_p	Pulse energy (J)		
τ_p	Pulse duration (fs)		- Definition often FWHM – can be misleading - RMS pulse duration better suited but rarely used
f_{CEO}	Carrier envelope frequency		- Difficult to measure
f_{rep}	Repetition rate (Hz)		
P_{av}	Average power (W)	$P_{av} = f_{rep}E_p$	- **Usually technology limited**
P_{pk}	Peak power (W)	*Can be calculated from* E_p and τ_p	- Requires knowledge about pulse amplitude shape - Simple for well-known pulse shapes (Gaussian,…) - Usually fixed (wanted) for a given experiment
I_{pk}	Peak intensity (W/m^2)	*Can be calculated from* P_p and *beam area A*	Requires knowledge on transverse beam profile
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Question 1

https://arsnova.rub.de/mobile/#id/87676337

A fs-pulse has an intensity FWHM duration of 100 fs an average power of 1 W and a repetition rate of 1 kHz.

What is the peak power of the pulse?

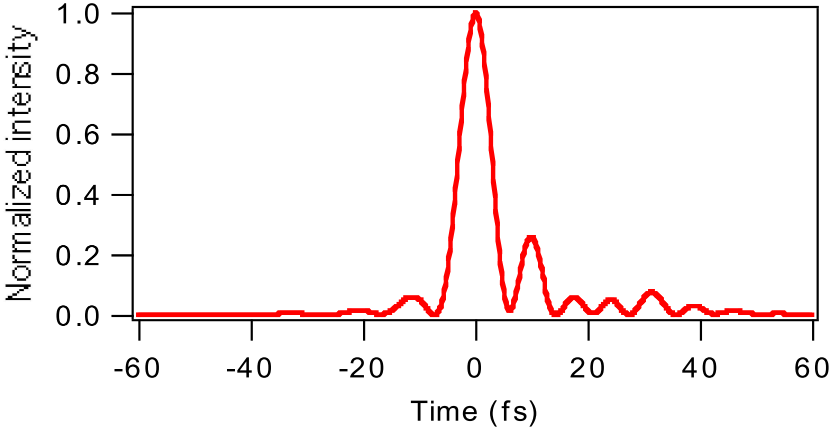
Question 1

https://arsnova.rub.de/mobile/#id/87676337

A fs-pulse has an intensity FWHM duration of 100 fs an average power of 1 W and a repetition rate of 1 kHz.

What is the peak power of the pulse?

Knowledge and control of your lasers has influence on nonlinear conversion!



Question 2

https://arsnova.rub.de/mobile/#id/87676337

A fs-pulse centered at 1000 nm has a spectral intensity full-width half maximum bandwidth of 100 nm, what bandwidth can we potentially reach in the THz domain with optical rectification (approximations are allowed)?

Optical rectification can be seen as frequency mixing of spectral components inside your bandwidth: but short pulses are needed!

Traditional front-end femtosecond laser for THz-TDS

Ti:Sapphire amplifiers/oscillators at 800 nm

(typical amp)
$P_{av}=1$ W
$\tau_p=30$ fs
$f_{rep}=1$ kHz
$E_p = 1$ mJ

- large
- expensive
- scientific system
- high pulse energy

user community: mostly scientific

Erbium fiber laser at 1550 nm

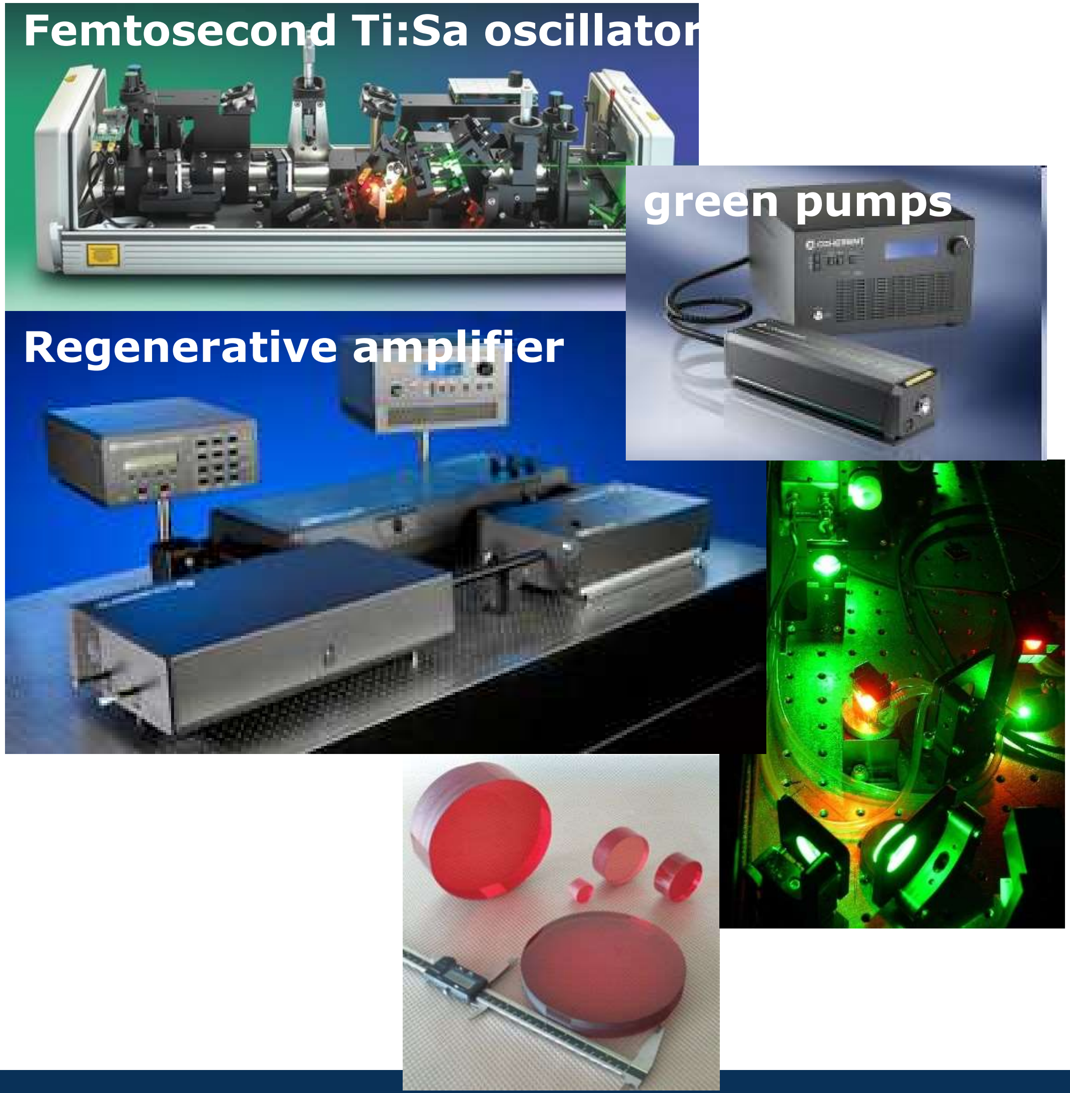
(typical)
$P_{av}=100$ mW
$\tau_p=100$ fs
$f_{rep}=100$ MHz
$E_p = 1$ nJ

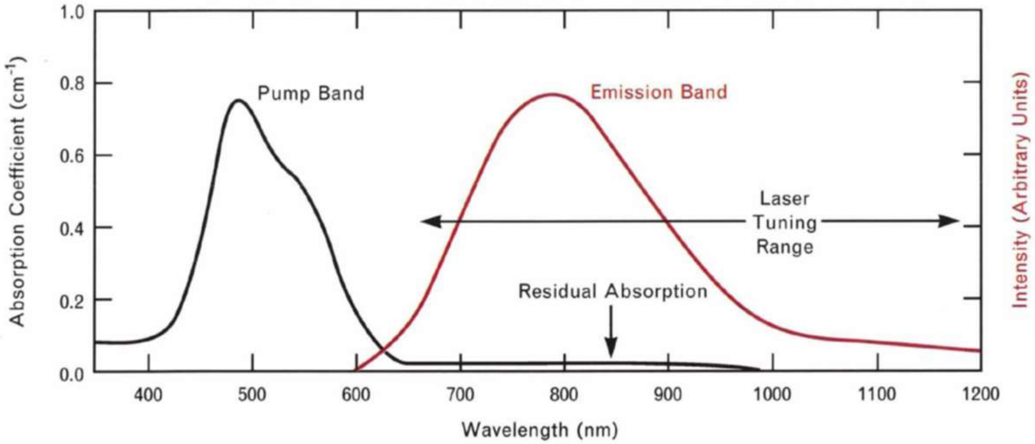
- compact
- cheap
- fiber-based robust
- low pulse energy

user community: scientific and industrial

Low average power limited to few-watts

the workhorse of ultrafast science





Typical amplifiers:

- **Pulse duration** ~30 fs
- **Pulse energy** ~mJ
- **Rep Rate** ~few kHz
- **Peak power** ~ GW

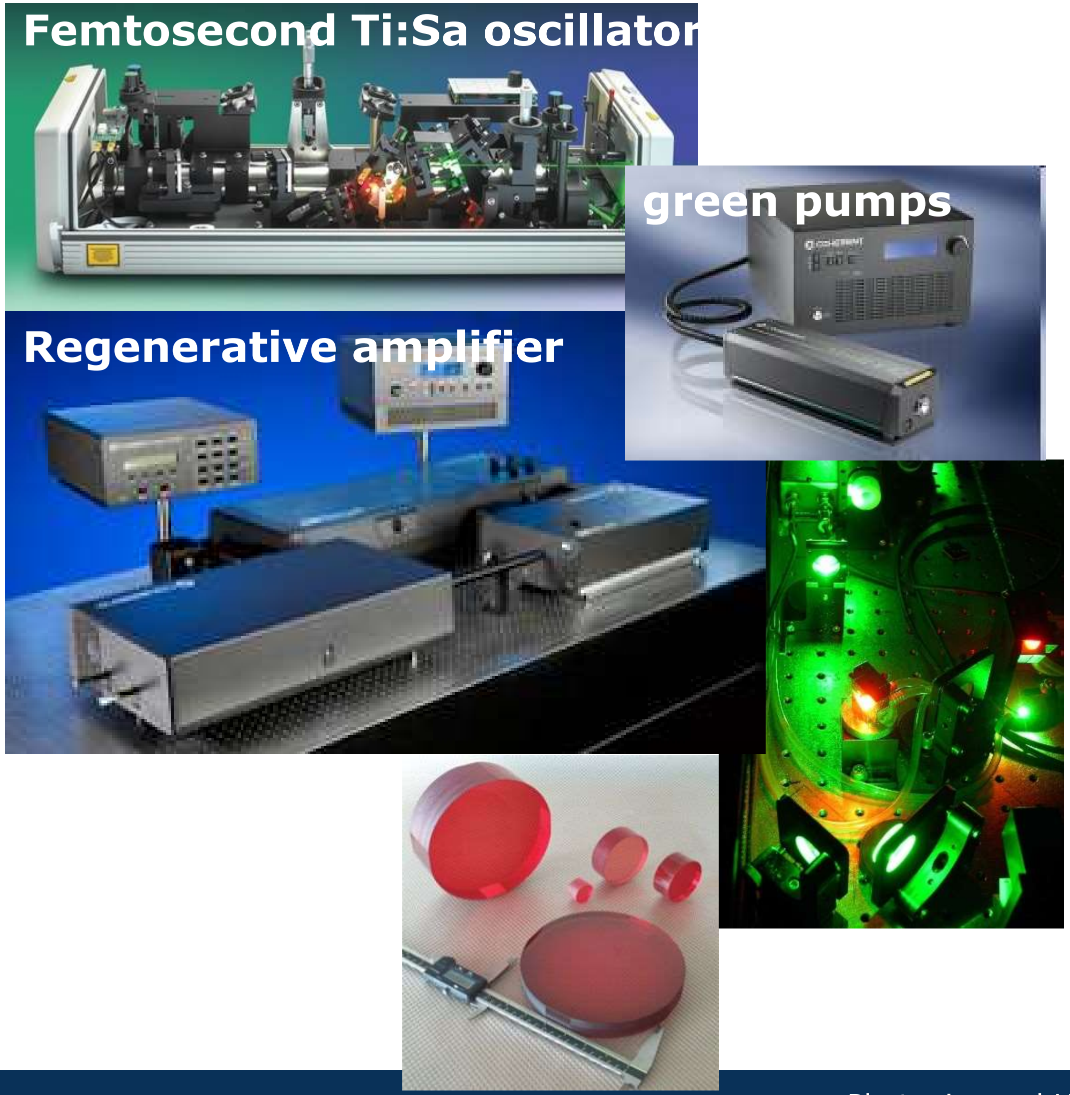
Typical oscillators:

- **Pulse duration** ~20 fs
- **Pulse energy** ~nJ
- **Rep Rate** ~ tens of MHz
- **Peak power** ~ 10s kW

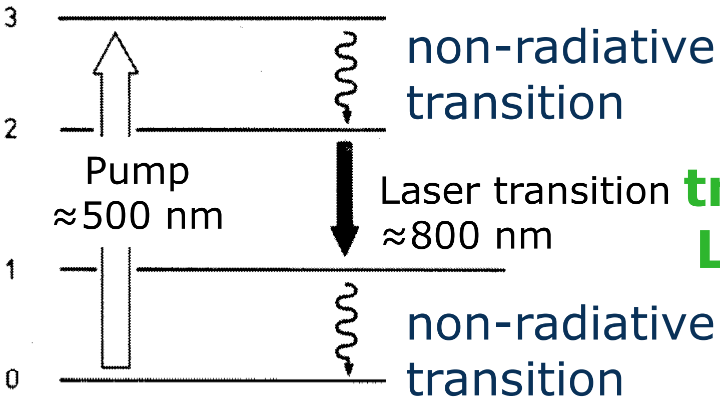
→ Average power limited to few watts

$$P_{av} = E_p \cdot f_{rep}$$

the workhorse of ultrafast science



Ti:sapphire laser:



non-radiative transition

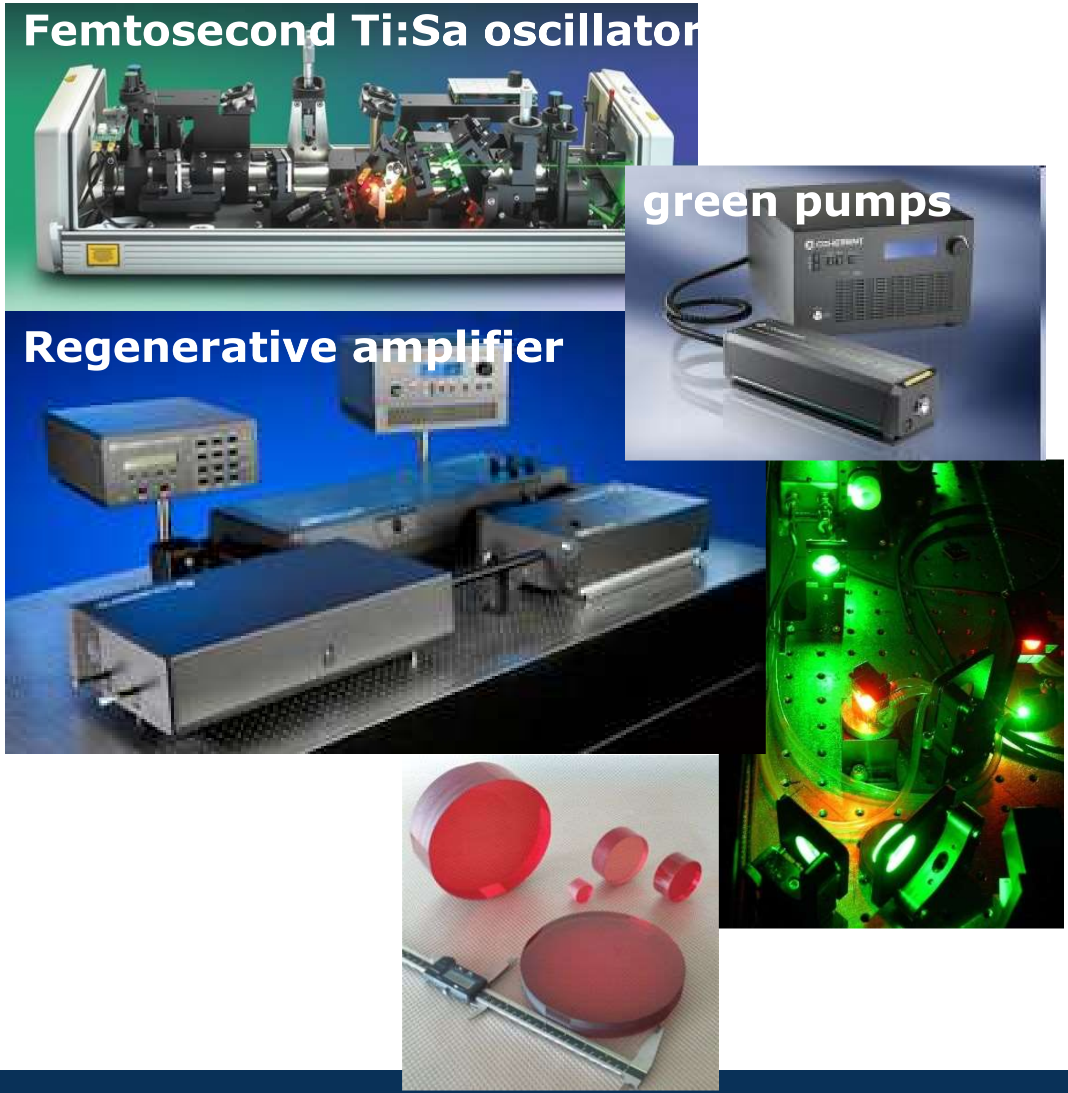
Pump ≈500 nm

Laser transition ≈800 nm

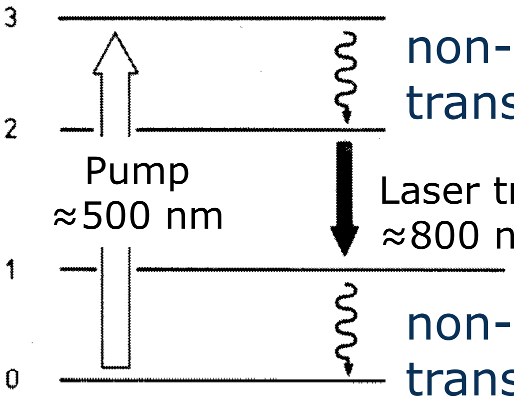
non-radiative transition

Non-radiative transitions: Large heat load

the workhorse of ultrafast science



Ti:sapphire laser:



non-radiative transition

Pump ≈500 nm

Laser transition ≈800 nm

non-radiative transition

Non-radiative transitions: Large heat load

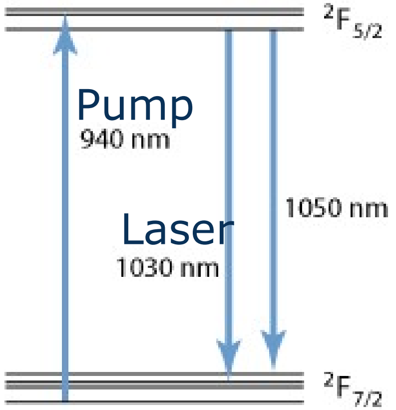
+ other problems:

- small upper-state lifetime (few µs) → high pump intensities needed to saturate
- degradation of crystal quality when increasing doping

Bulk geometry with large thermal load → thermal aberrations

CW power: material properties + advanced cooling geometries

Yb:YAG laser:



- **Small heat load < 10%**
- **Long lifetime (ms)**
- **High doping**

+

1090 OPTICS LETTERS / Vol. 16, No. 14 / July 15, 1991

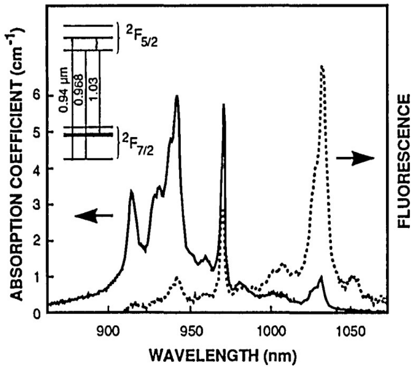
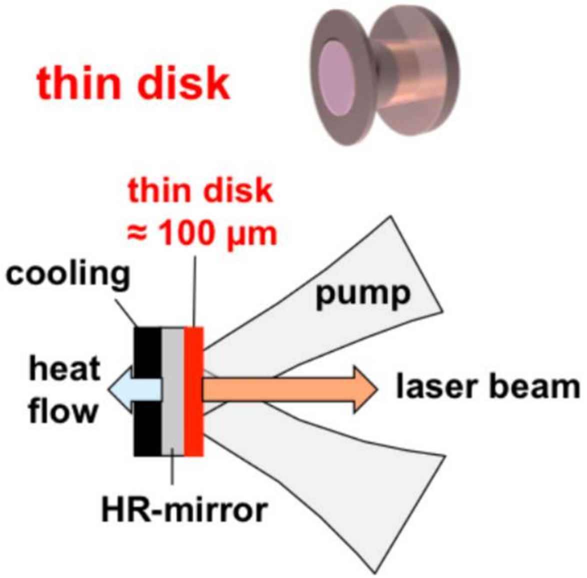
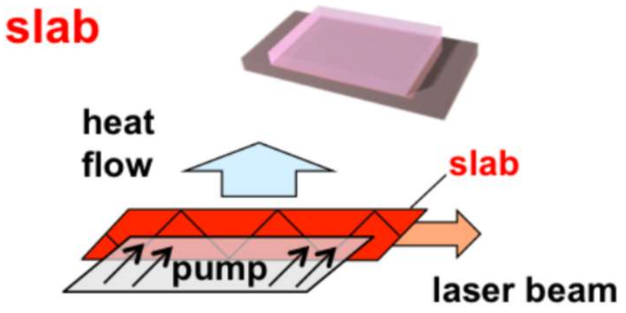
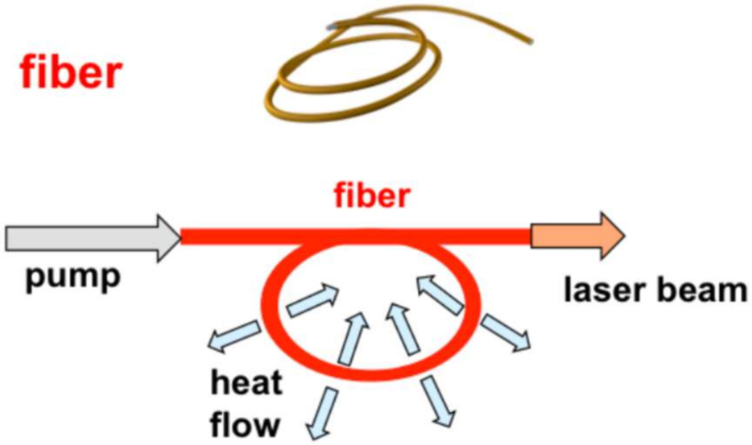


Fig. 1. Absorption and fluorescence spectra of 6.5 at.% Yb:YAG. The energy levels are from Ref. 13.



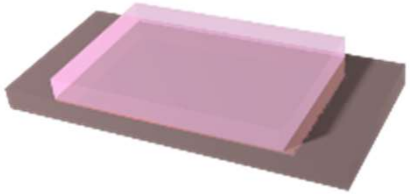
Advanced laser concepts for high average power





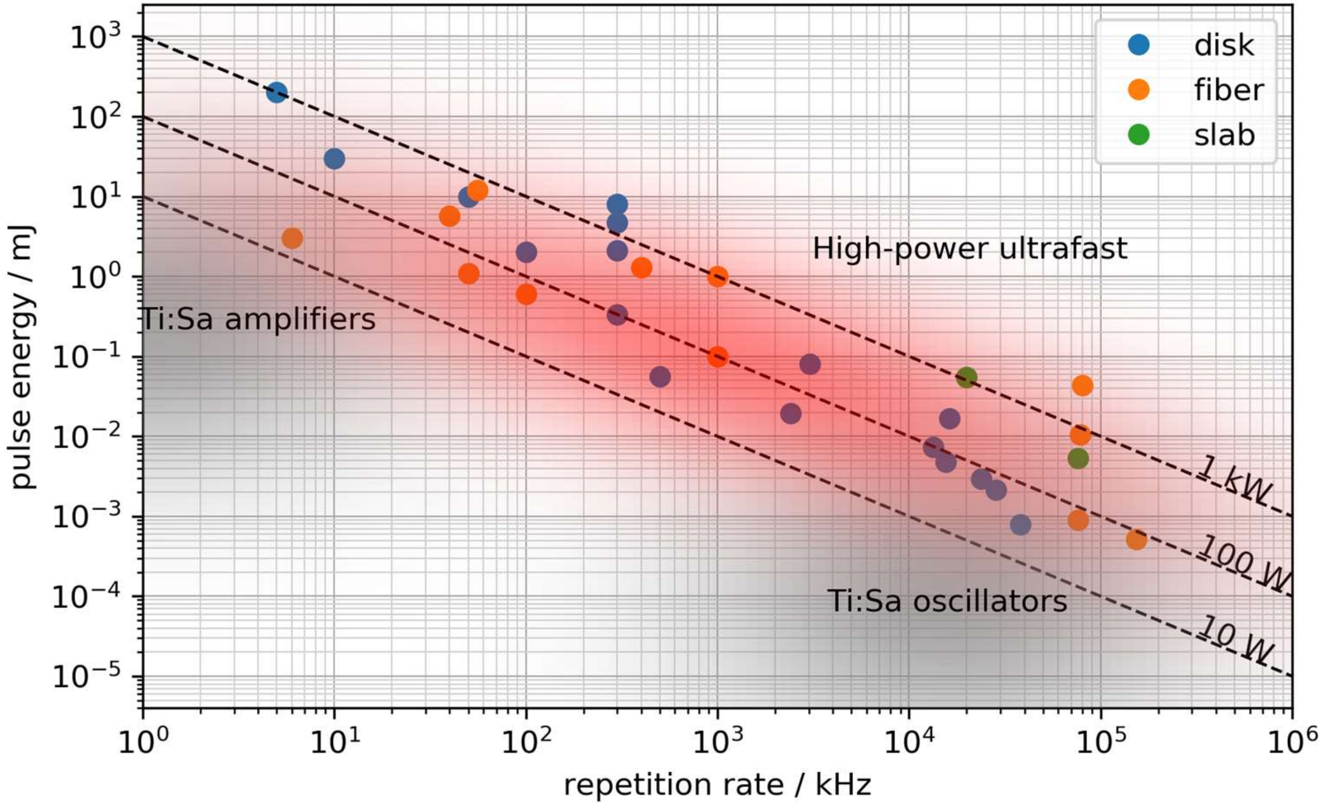
ultrafast high-power lasers based on Yb-doped technology

✓ Fiber



✓ Slab

✓ Thin disk



Additional difficulty for ultrafast operation: nonlinearities need to be kept small

Self-phase modulation (SPM)

Self-phase modulation

$$n(I) = n + n_2 I$$

$I(t)$ → self-phase modulation
$I(x,y)$ → self-focusing

$$\phi(t) = -kn(I)L_K = -k\left[n + \boxed{n_2 I(t)]L_K}\right.$$

Nonlinear phase [mrad]
Nonlinear refractive index [cm^{2}/W]

Self-phase modulation (SPM)

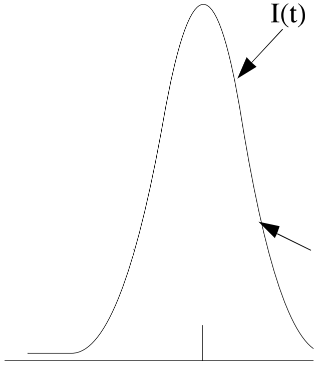
Self-phase modulation

$$n(I) = n + n_2 I$$

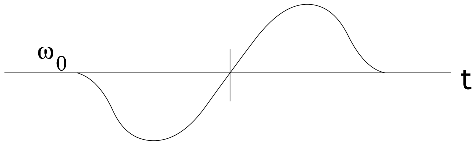
$I(t)$ → self-phase modulation
$I(x,y)$ → self-focusing

$$\phi(t) = -kn(I)L_K = -k[n+\boxed{n_2 I(t)]L_K}$$

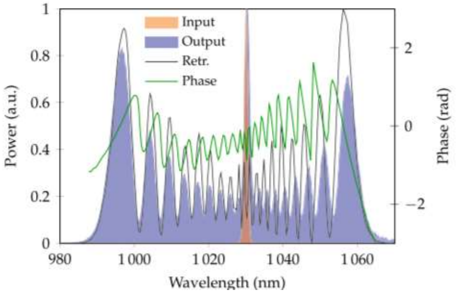
Nonlinear phase



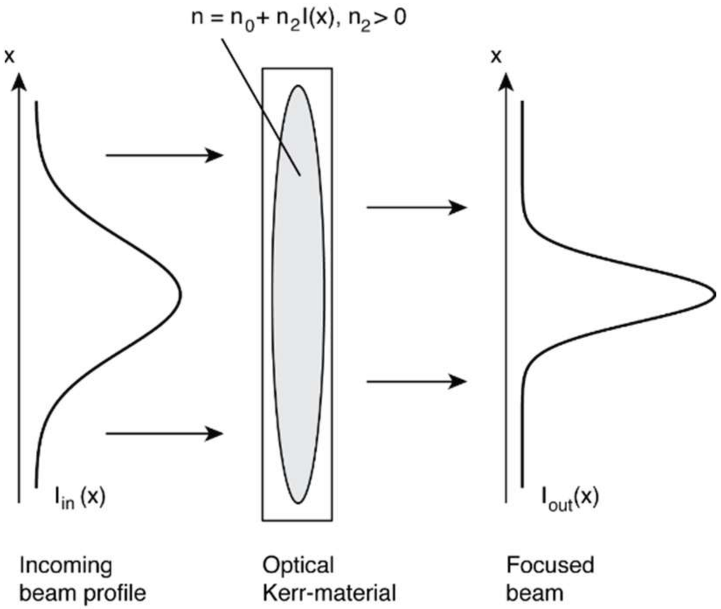
Refractive index modulation follows pulse intensity envelope



→ Creates new frequency components



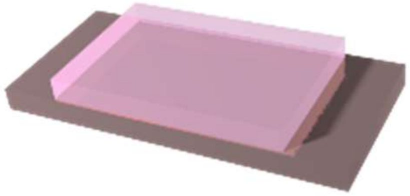
Self-focusing



→ Leads to beam degradation, spatio-temporal couplings, catastrophic damage if nonlinear phase is too large

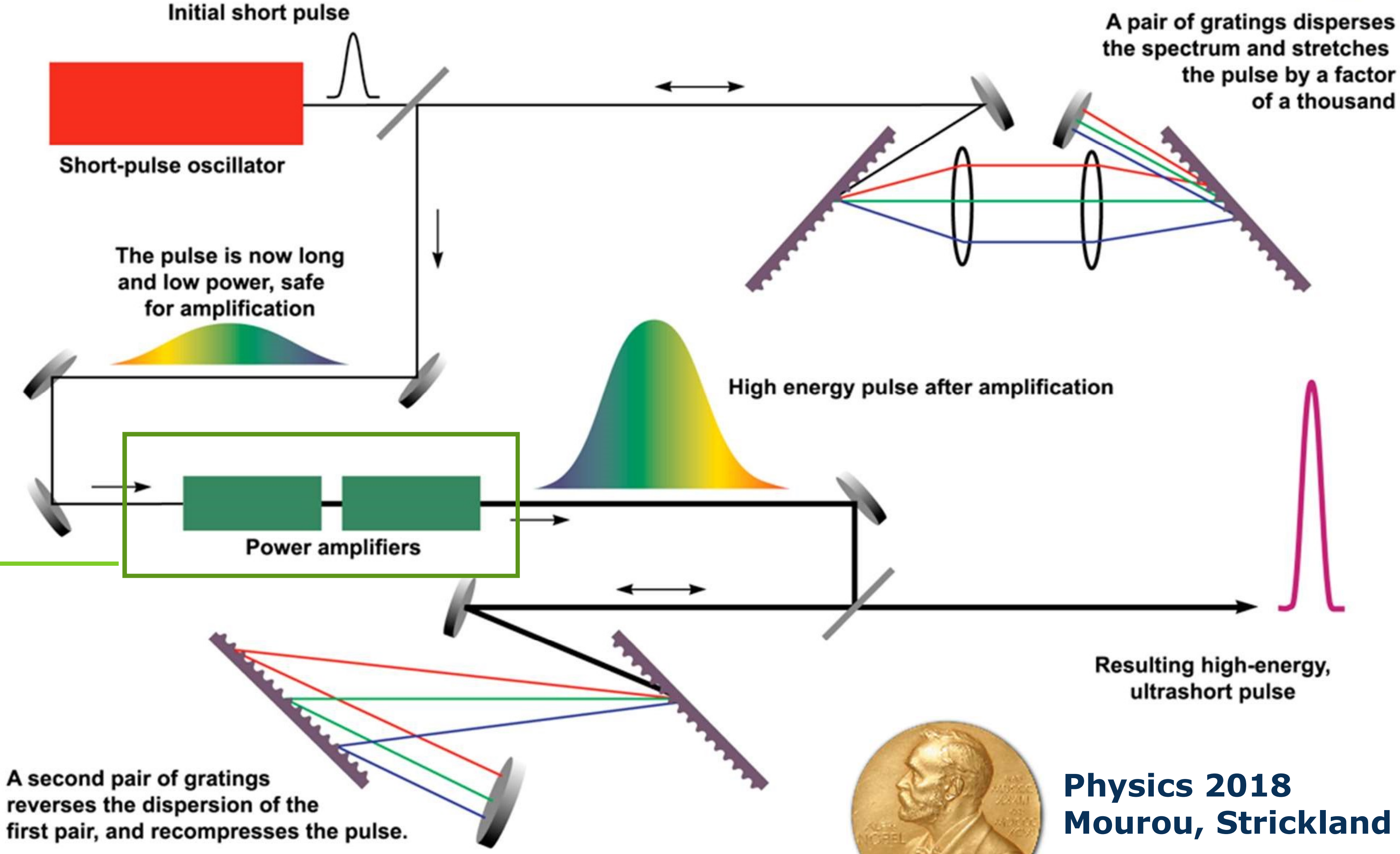
most commonly: chirped-pulse amplification

- ✓ Fiber



- ✓ Slab

- ✓ Thin disk



Initial short pulse

Short-pulse oscillator

A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand

The pulse is now long and low power, safe for amplification

High energy pulse after amplification

Power amplifiers

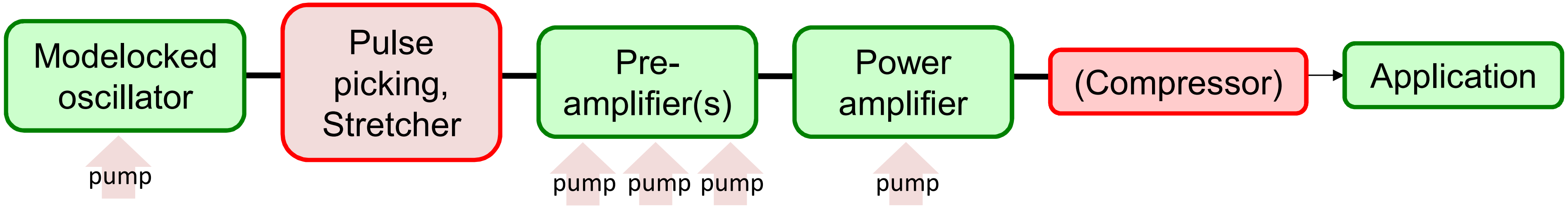
Resulting high-energy, ultrashort pulse

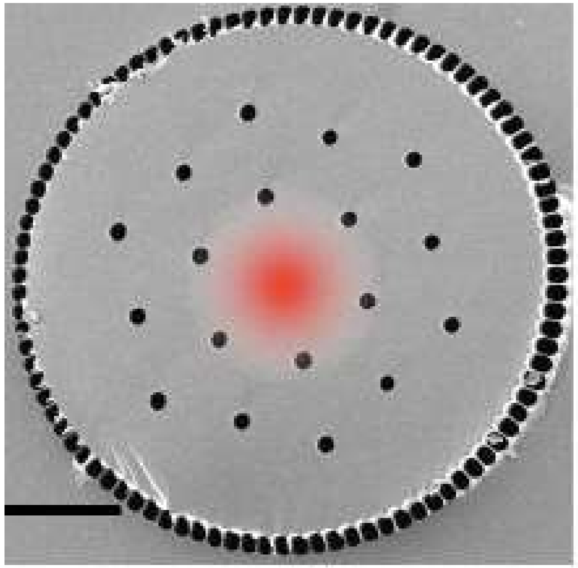
A second pair of gratings reverses the dispersion of the first pair, and recompresses the pulse.

Physics 2018
Mourou, Strickland

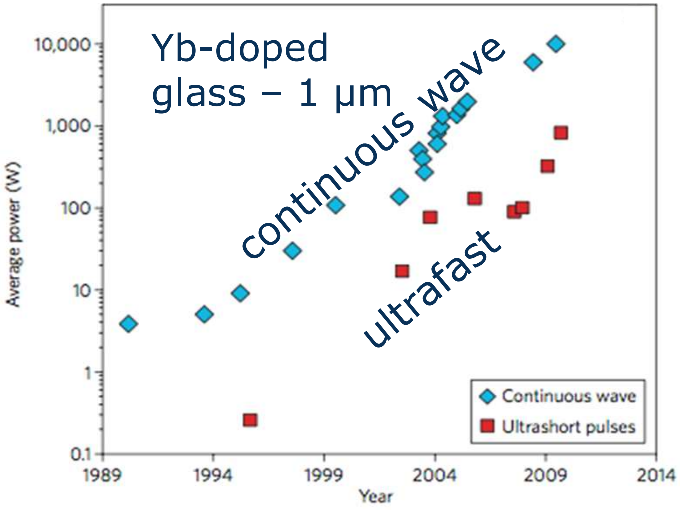
high power fiber CPA

Most commonly used: chirped pulse amplification (CPA)





large –mode-area photonic crystal fiber



Single-stage ultrafast fiber amplifier @1µm
830 W, 640 fs,
78 MHz, 11 µJ

T. Eidam, … J. Limpert,
A. Tünnermann,
Opt. Lett. 35, 94-96 (2010)

→ Limit: high-order mode instabilities

Group of J. Limpert, Uni Jena

further scaling: coherent combination

Performance:

- 10.4 kW
- 254 fs pulses
- 80 MHz
- 130 µJ

Letter Vol. 45, No. 11 / 1 June 2020 / *Optics Letters* 3083

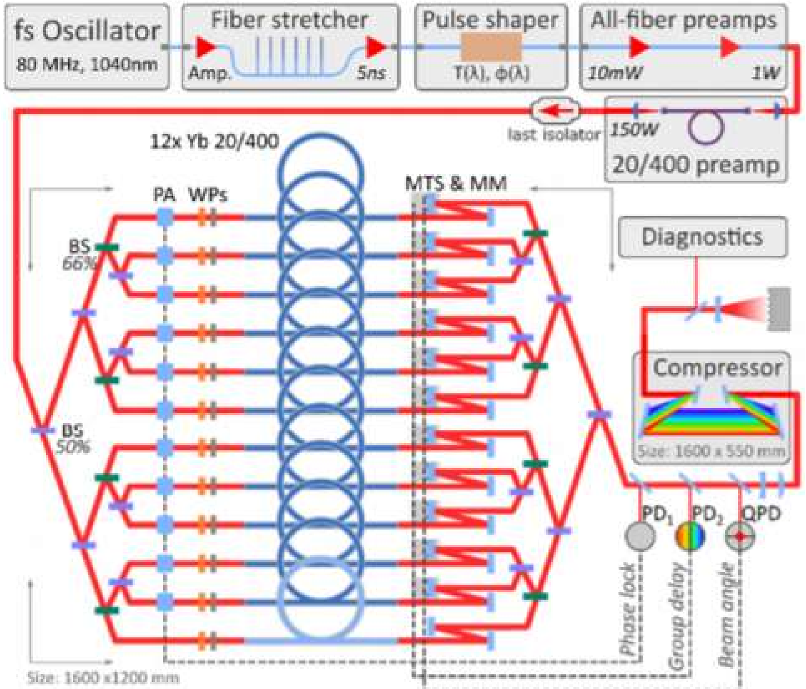
Optics Letters

10.4 kW coherently combined ultrafast fiber laser

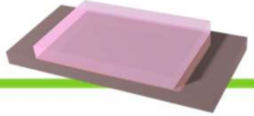
Michael Müller,[1,*] Christopher Aleshire,[1] Arno Klenke,[1,2] Elissa Haddad,[3] François Légaré,[3] Andreas Tünnermann,[1,2,4] and Jens Limpert[1,2,4]

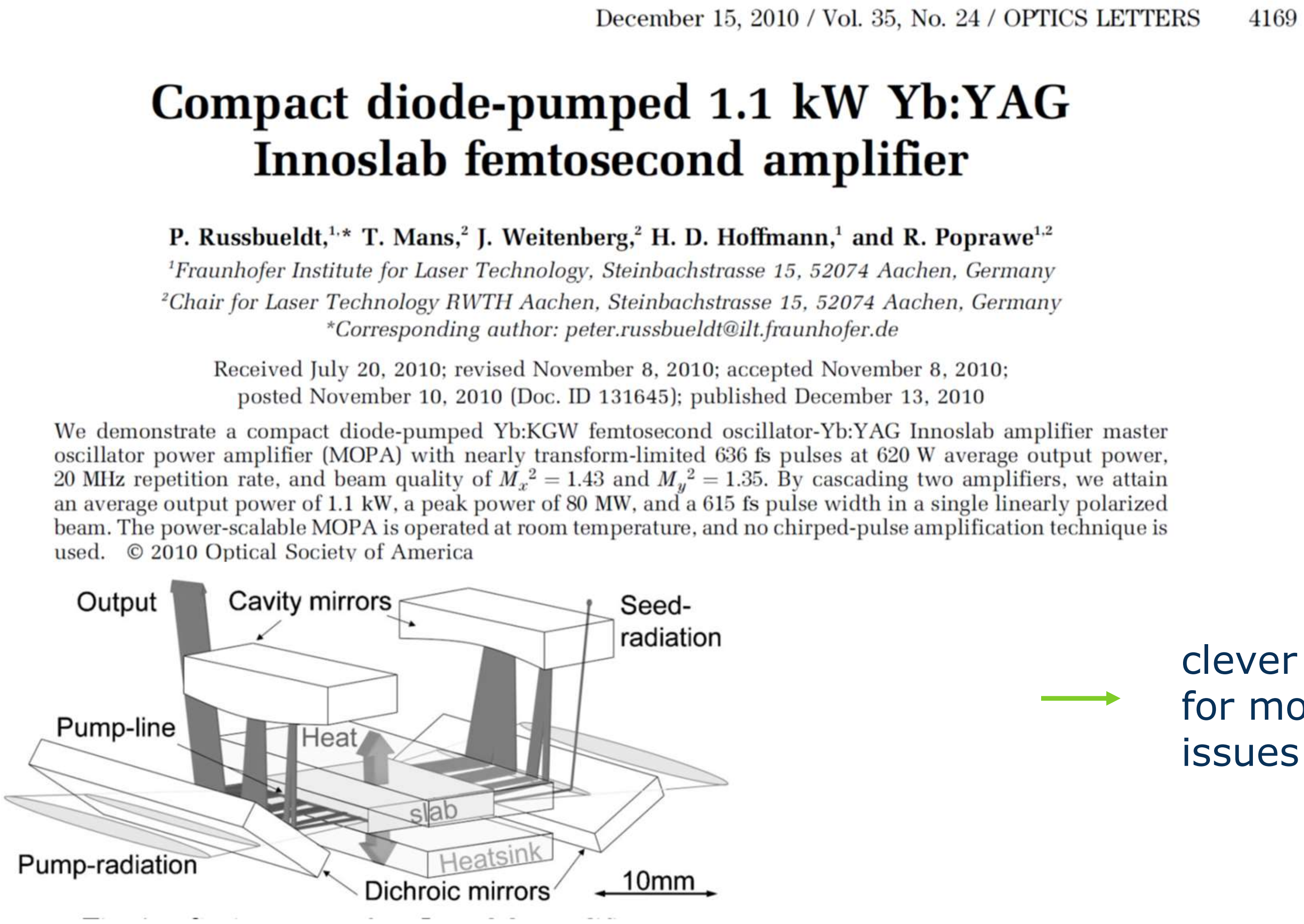
[1] *Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Straße 15, 07745 Jena, Germany*
[2] *Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany*
[3] *INRS, Centre Énergie Matériaux et Télécommunications, 1650 Blvd. Lionel-Boulet, Varennes, J3X1S2, Canada*
[4] *Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Straße 7, 07745 Jena, Germany*
*Corresponding author: michael.mm.mueller@uni-jena.de

Received 17 March 2020; revised 24 April 2020; accepted 30 April 2020; posted 1 May 2020 (Doc. ID 392843); published 28 May 2020



slab amplifiers





December 15, 2010 / Vol. 35, No. 24 / OPTICS LETTERS 4169

Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier

P. Russbueldt,[1,*] T. Mans,[2] J. Weitenberg,[2] H. D. Hoffmann,[1] and R. Poprawe[1,2]
[1]*Fraunhofer Institute for Laser Technology, Steinbachstrasse 15, 52074 Aachen, Germany*
[2]*Chair for Laser Technology RWTH Aachen, Steinbachstrasse 15, 52074 Aachen, Germany*
**Corresponding author: peter.russbueldt@ilt.fraunhofer.de*

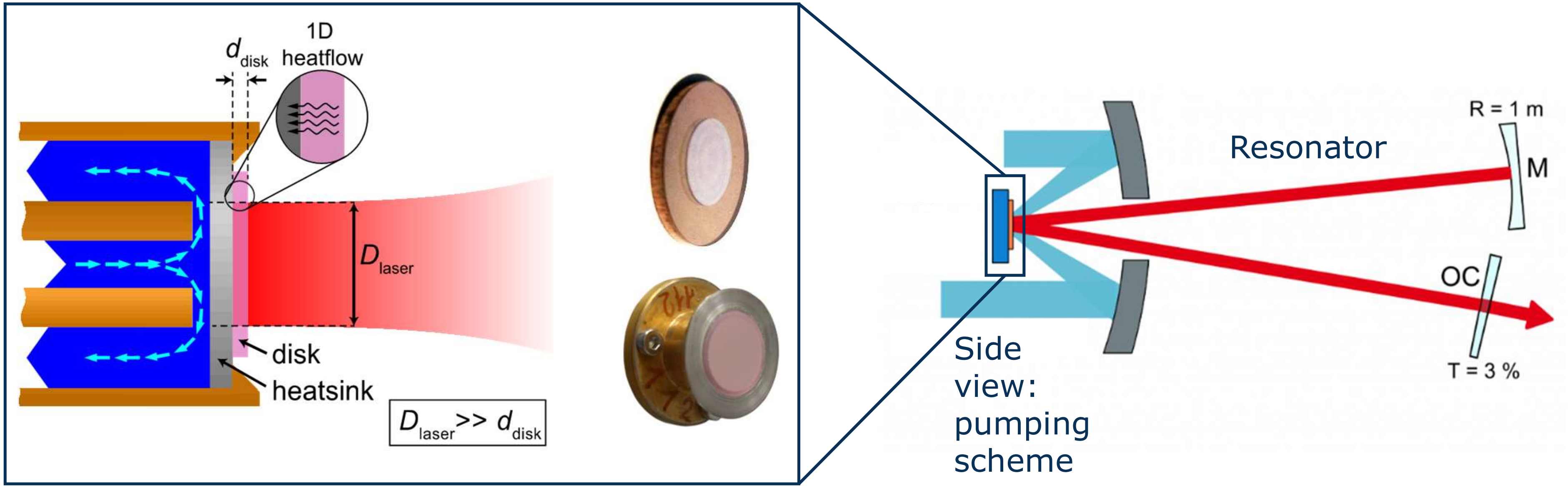
Received July 20, 2010; revised November 8, 2010; accepted November 8, 2010;
posted November 10, 2010 (Doc. ID 131645); published December 13, 2010

We demonstrate a compact diode-pumped Yb:KGW femtosecond oscillator-Yb:YAG Innoslab amplifier master oscillator power amplifier (MOPA) with nearly transform-limited 636 fs pulses at 620 W average output power, 20 MHz repetition rate, and beam quality of $M_x^2 = 1.43$ and $M_y^2 = 1.35$. By cascading two amplifiers, we attain an average output power of 1.1 kW, a peak power of 80 MW, and a 615 fs pulse width in a single linearly polarized beam. The power-scalable MOPA is operated at room temperature, and no chirped-pulse amplification technique is used.

- 1.1 kW,
- 615 fs
  20 MHz
- 55 µJ

→ clever geometry: CPA avoided
for moderate pulse energies
issues: pointing, beam quality

thin-disk concept



Side view: pumping scheme

- → outstanding heat removal, extremely small thermal aberrations
- → Yb^{3+}-doped gain: diode pumped, accessible high-power diodes
- → good pump absorption: many passes through gain required
- → very small accumulated nonlinearities

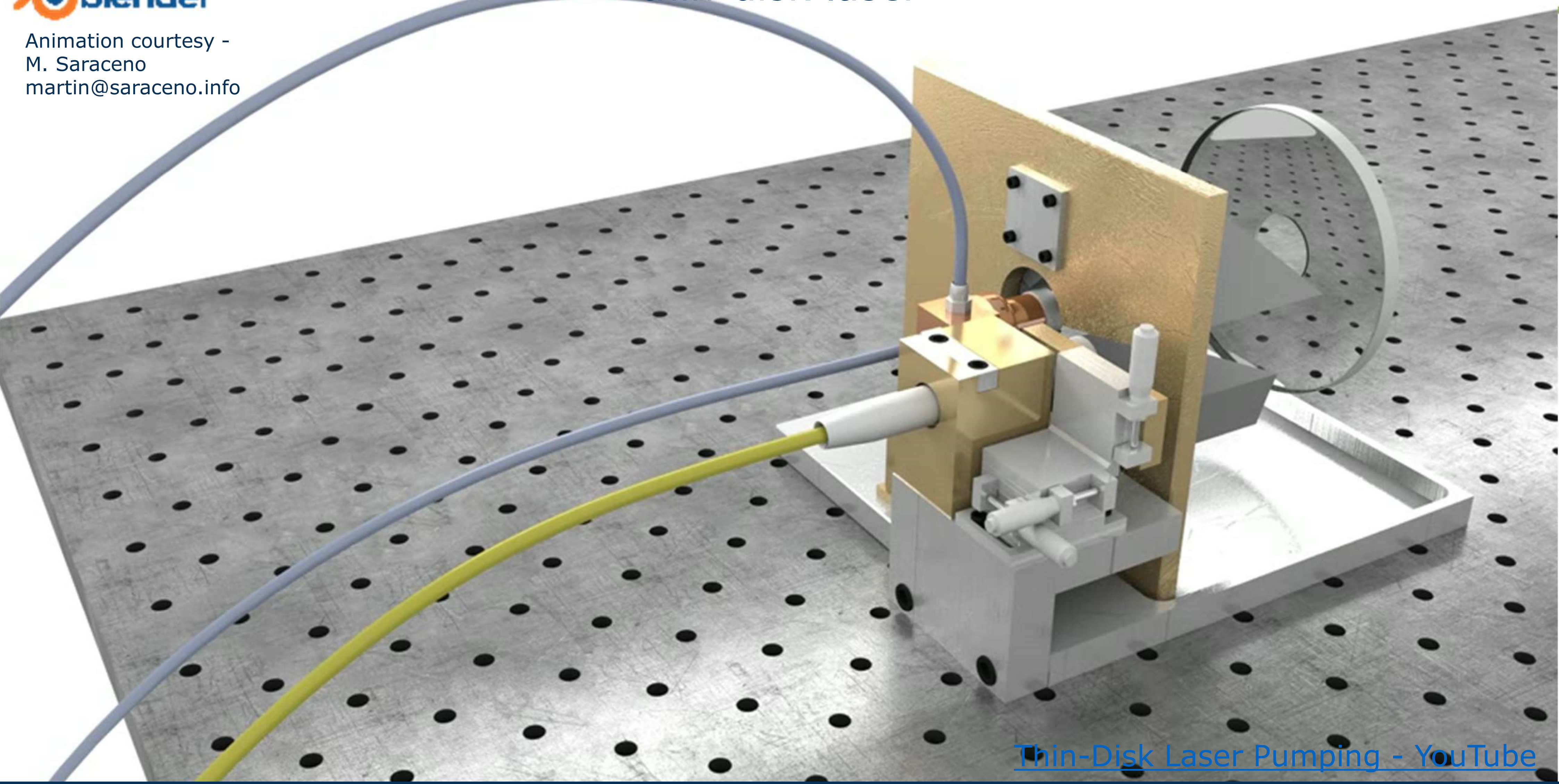
→ ideal for ultrafast + high power

A. Giesen, et al., *Appl. Phys. B* **58**, 365 (1994)

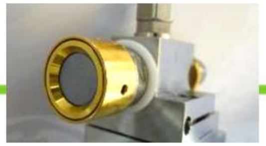
thin-disk laser

blender

Animation courtesy -
M. Saraceno
martin@saraceno.info



[Thin-Disk Laser Pumping - YouTube]



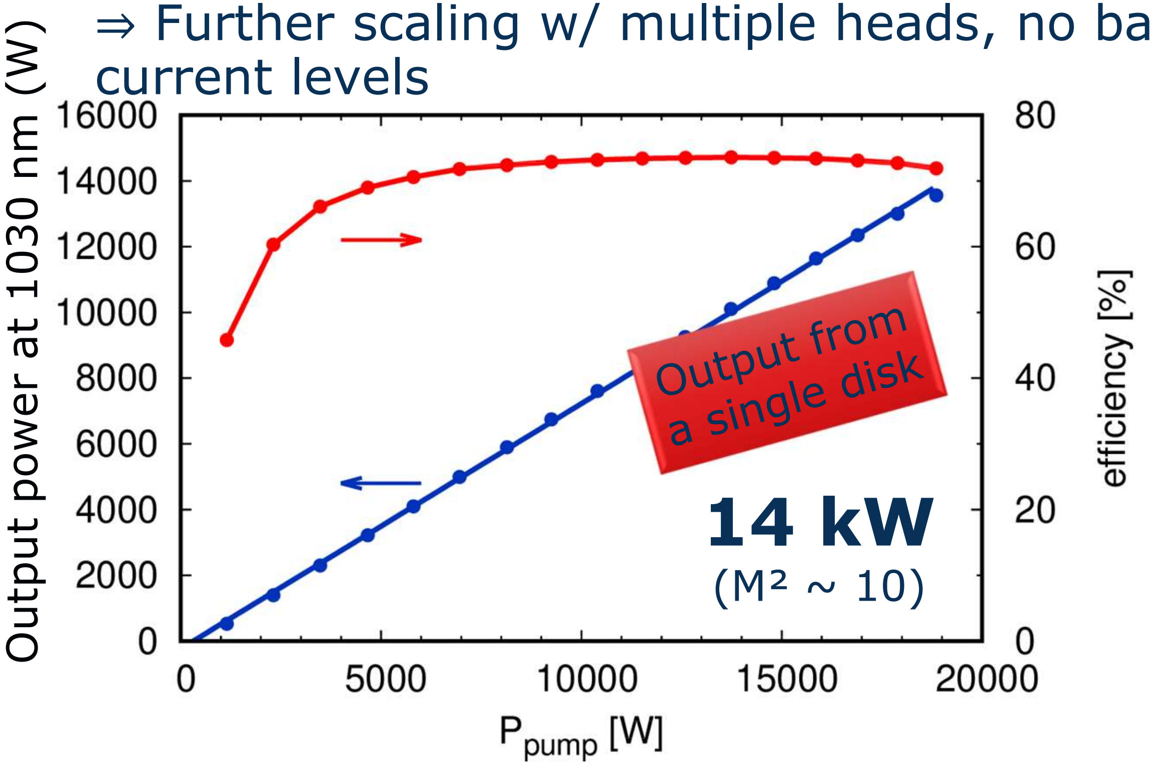
Single-disk high-power CW operation

Courtesy of Dirk Sutter

14 kW with $\eta_{opt.}$>70%

4 kW TEM_{00} (2013)

⇒ Further scaling w/ multiple heads, no barriers for power scaling beyond current levels

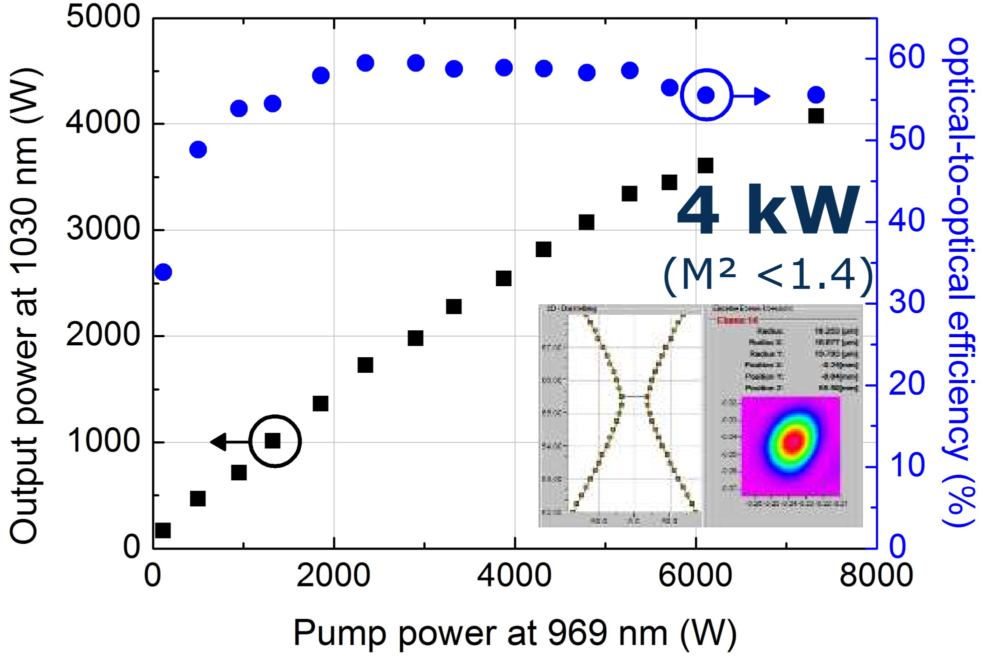


Output from a single disk

14 kW

(M² ~ 10)

B. Metzger et al. (TRUMPF, 2019)



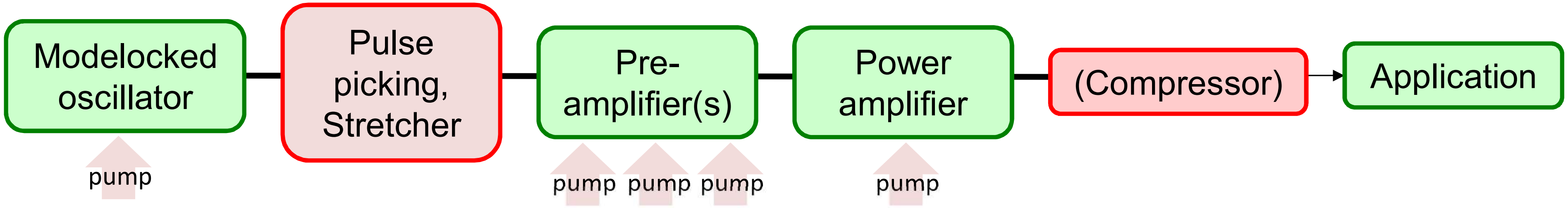
4 kW

(M² <1.4)

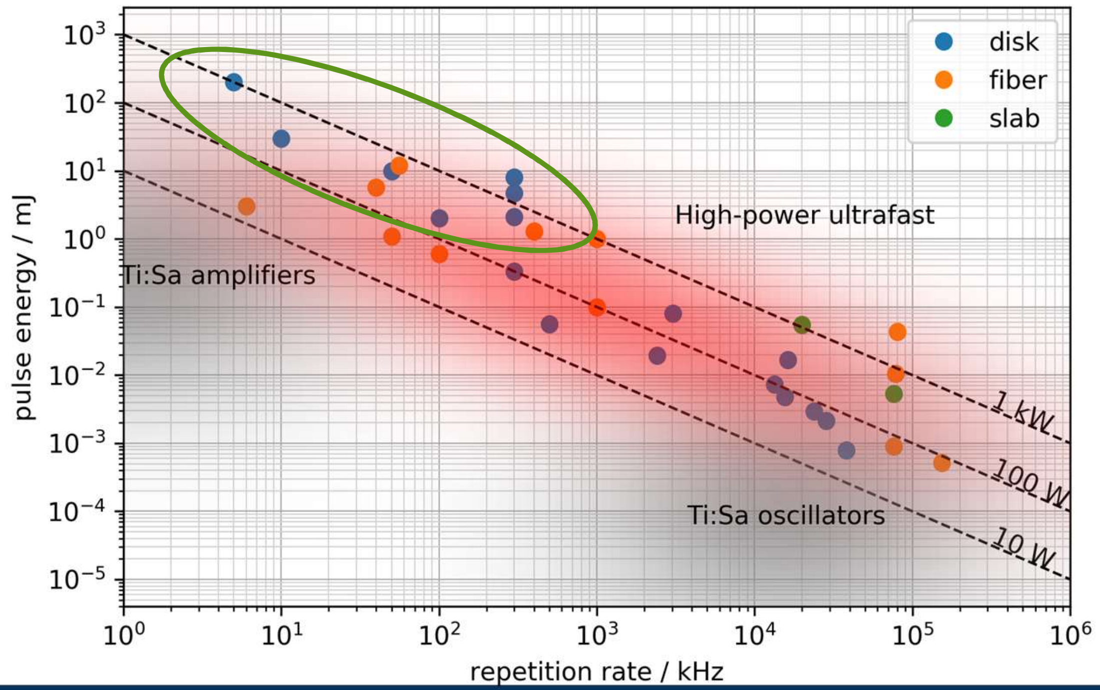
Gottwald et al., Security and Defense 2013

thin-disk ultrafast *amplifiers*

Most commonly used: chirped pulse amplification (CPA)



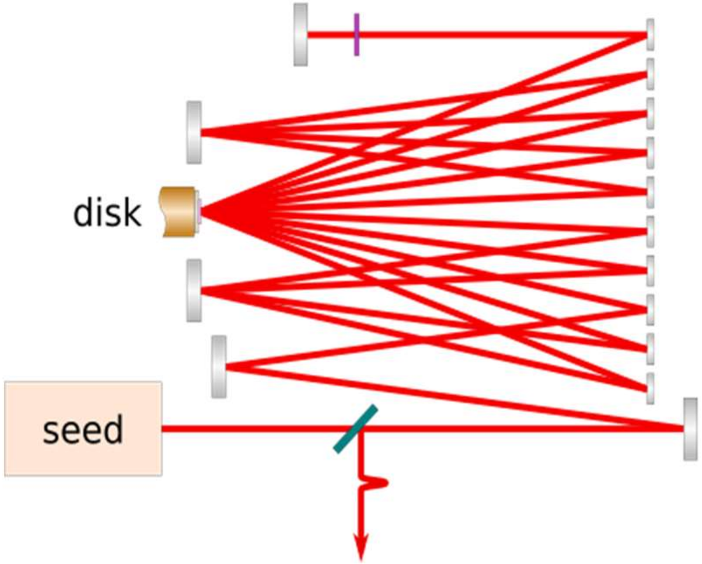
unique combination of high energy and high average power:
kilowatt powers
100s mJ
1-10s kHz



thin-disk *amplifier* geometries

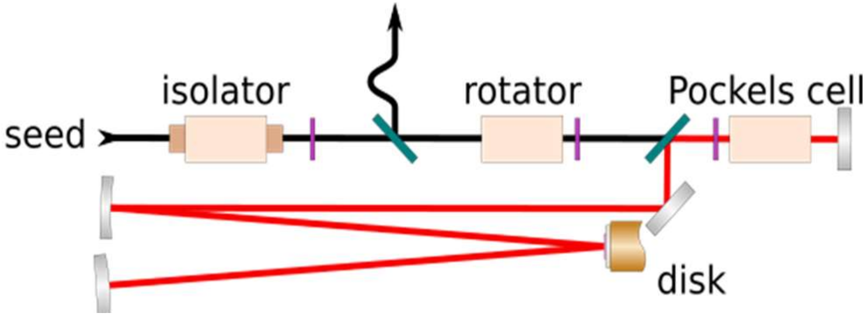
→ Thin-disk: low gain per pass (typical 10%)

Multi-pass amplifier



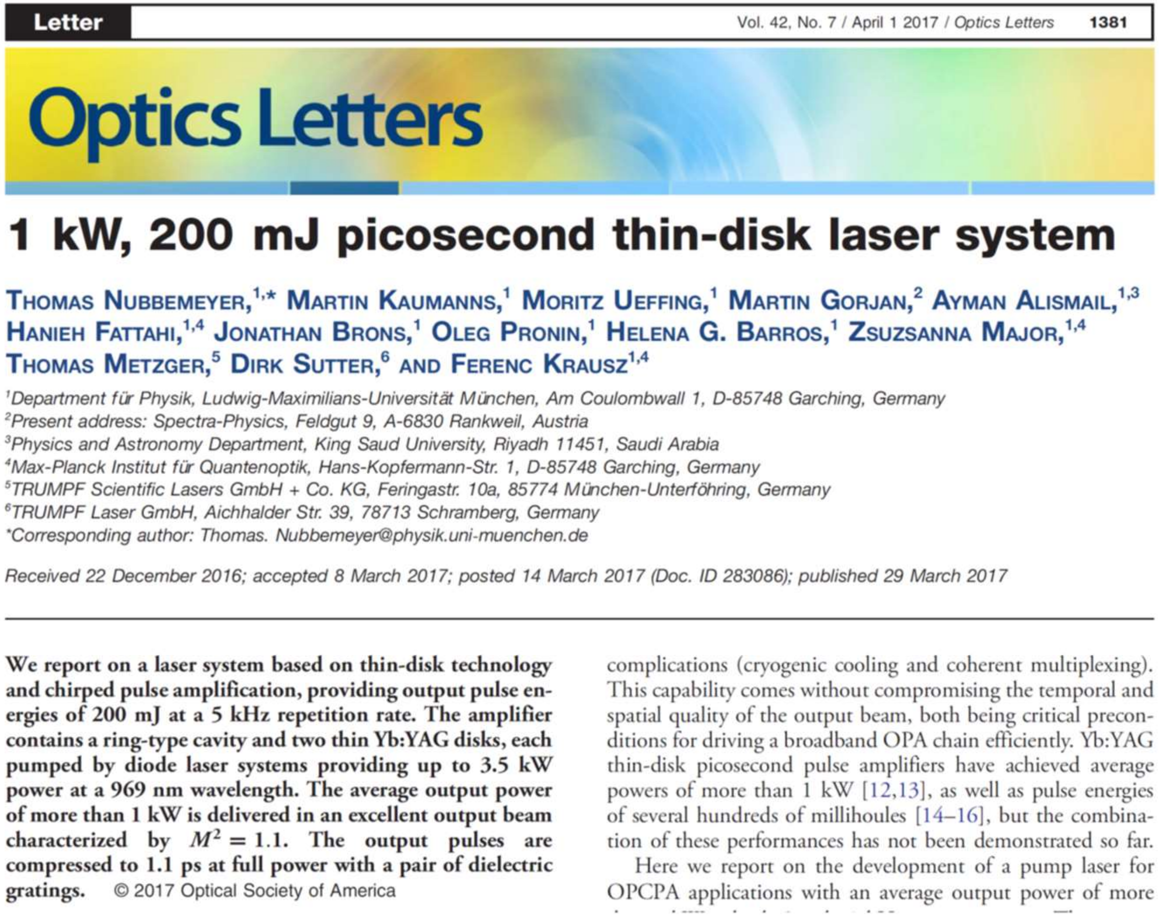
→ moderate amplification, high extraction (booster)

Regenerative amplifier



→ large amplification (main)

state-of-the-art *thin-disk* regenerative amplifiers



Letter Vol. 42, No. 7 / April 1 2017 / *Optics Letters* **1381**

Optics Letters

1 kW, 200 mJ picosecond thin-disk laser system

THOMAS NUBBEMEYER,[1,*] MARTIN KAUMANNS,[1] MORITZ UEFFING,[1] MARTIN GORJAN,[2] AYMAN ALISMAIL,[1,3] HANIEH FATTAHI,[1,4] JONATHAN BRONS,[1] OLEG PRONIN,[1] HELENA G. BARROS,[1] ZSUZSANNA MAJOR,[1,4] THOMAS METZGER,[5] DIRK SUTTER,[6] AND FERENC KRAUSZ[1,4]

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[2] *Present address: Spectra-Physics, Feldgut 9, A-6830 Rankweil, Austria*
[3] *Physics and Astronomy Department, King Saud University, Riyadh 11451, Saudi Arabia*
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[5] *TRUMPF Scientific Lasers GmbH + Co. KG, Feringastr. 10a, 85774 München-Unterföhring, Germany*
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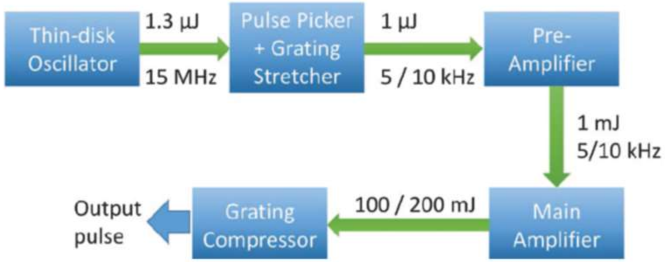
Received 22 December 2016; accepted 8 March 2017; posted 14 March 2017 (Doc. ID 283086); published 29 March 2017

We report on a laser system based on thin-disk technology and chirped pulse amplification, providing output pulse energies of 200 mJ at a 5 kHz repetition rate. The amplifier contains a ring-type cavity and two thin Yb:YAG disks, each pumped by diode laser systems providing up to 3.5 kW power at a 969 nm wavelength. The average output power of more than 1 kW is delivered in an excellent output beam characterized by $M^2 = 1.1$. The output pulses are compressed to 1.1 ps at full power with a pair of dielectric gratings.

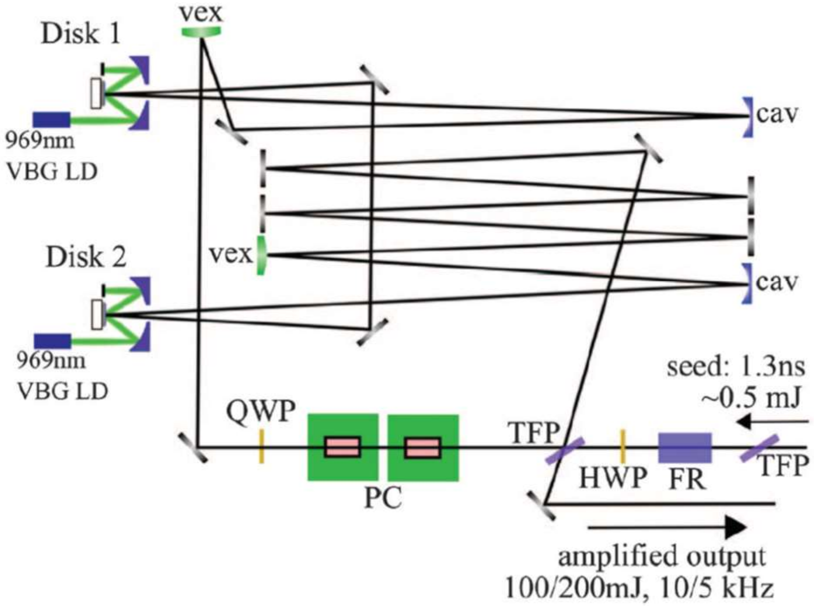
complications (cryogenic cooling and coherent multiplexing). This capability comes without compromising the temporal and spatial quality of the output beam, both being critical preconditions for driving a broadband OPA chain efficiently. Yb:YAG thin-disk picosecond pulse amplifiers have achieved average powers of more than 1 kW [12,13], as well as pulse energies of several hundreds of millihoules [14–16], but the combination of these performances has not been demonstrated so far.

Here we report on the development of a pump laser for OPCPA applications with an average output power of more

- 1 kW
- 200 mJ
- 5 kHz
- 1.1 ps



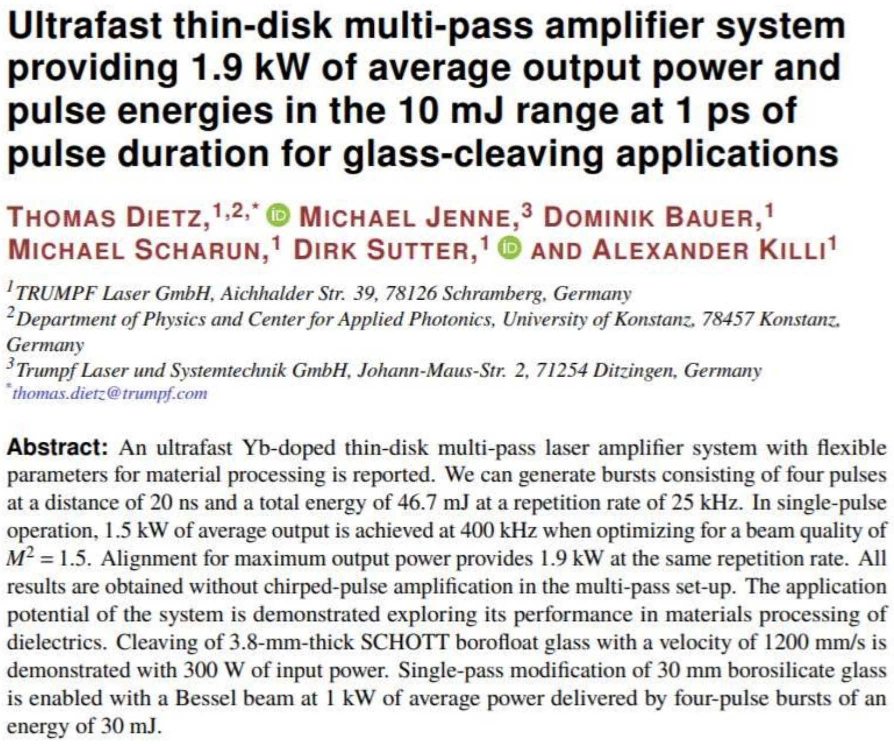
Thin-disk Oscillator → 1.3 µJ, 15 MHz → Pulse Picker + Grating Stretcher → 1 µJ, 5 / 10 kHz → Pre-Amplifier → 1 mJ, 5/10 kHz → Main Amplifier → 100 / 200 mJ → Grating Compressor → Output pulse



state-of-the-art thin-disk *multi-pass* amplifiers

- 1.9 kW
- 400 kHz
- 1.1 ps
- ! No CPA

(now up to 2.3 kW)



Ultrafast thin-disk multi-pass amplifier system providing 1.9 kW of average output power and pulse energies in the 10 mJ range at 1 ps of pulse duration for glass-cleaving applications

THOMAS DIETZ,[1,2,*] **MICHAEL JENNE,**[3] **DOMINIK BAUER,**[1] **MICHAEL SCHARUN,**[1] **DIRK SUTTER,**[1] **AND ALEXANDER KILLI**[1]

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[2] *Department of Physics and Center for Applied Photonics, University of Konstanz, 78457 Konstanz, Germany*
[3] *Trumpf Laser und Systemtechnik GmbH, Johann-Maus-Str. 2, 71254 Ditzingen, Germany*
[*] *thomas.dietz@trumpf.com*

Abstract: An ultrafast Yb-doped thin-disk multi-pass laser amplifier system with flexible parameters for material processing is reported. We can generate bursts consisting of four pulses at a distance of 20 ns and a total energy of 46.7 mJ at a repetition rate of 25 kHz. In single-pulse operation, 1.5 kW of average output is achieved at 400 kHz when optimizing for a beam quality of $M^2 = 1.5$. Alignment for maximum output power provides 1.9 kW at the same repetition rate. All results are obtained without chirped-pulse amplification in the multi-pass set-up. The application potential of the system is demonstrated exploring its performance in materials processing of dielectrics. Cleaving of 3.8-mm-thick SCHOTT borofloat glass with a velocity of 1200 mm/s is demonstrated with 300 W of input power. Single-pass modification of 30 mm borosilicate glass is enabled with a Bessel beam at 1 kW of average power delivered by four-pulse bursts of an energy of 30 mJ.

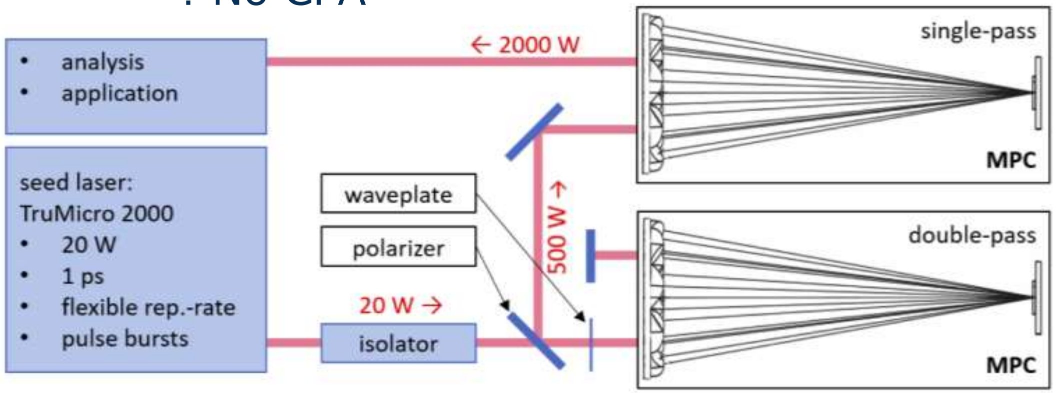
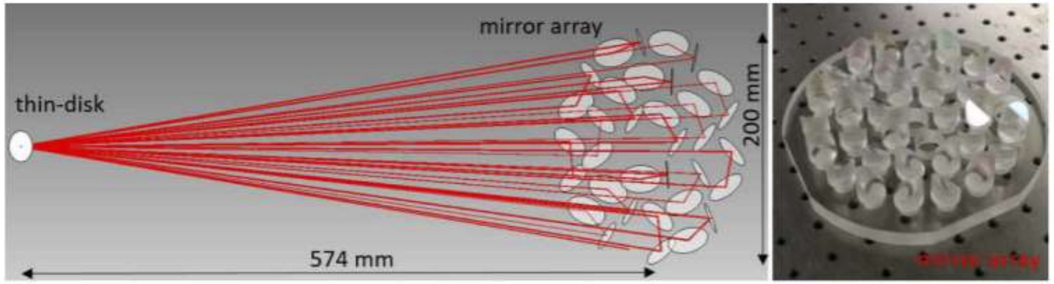
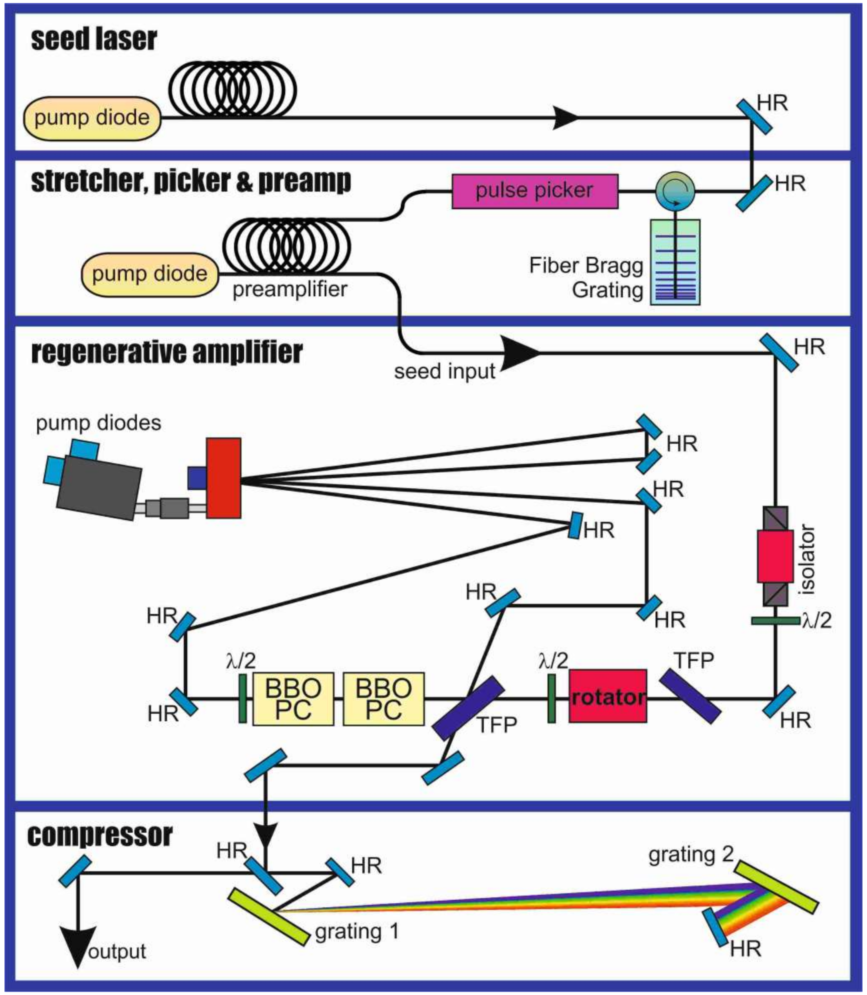


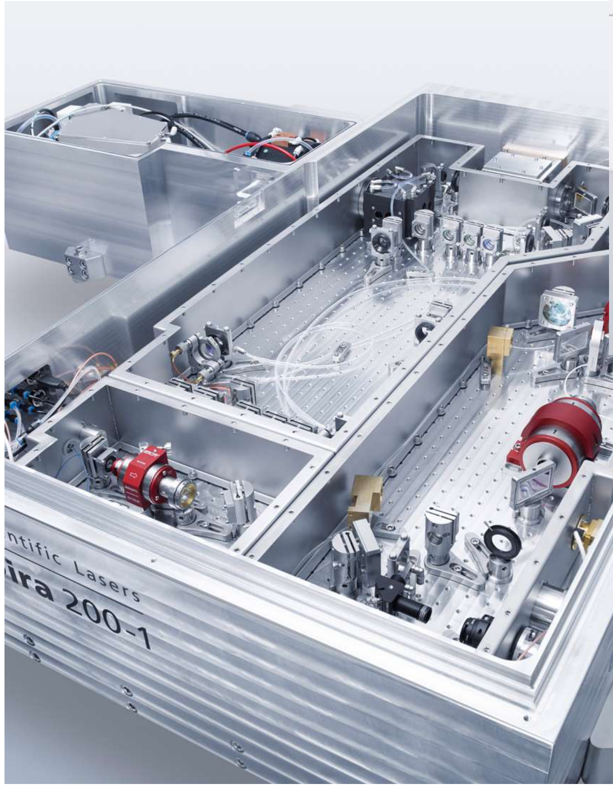
Fig. 1. Schematic set-up of the amplifier system. The seed laser is a commercial TruMicro 2000, followed by two amplifier stages. Red lines indicate the laser beam. MPC: Multi-pass cell.



thin-disk regenerative amplifiers: state-of-the-art

Courtesy of Thomas Metzger





"Flagship" Laser

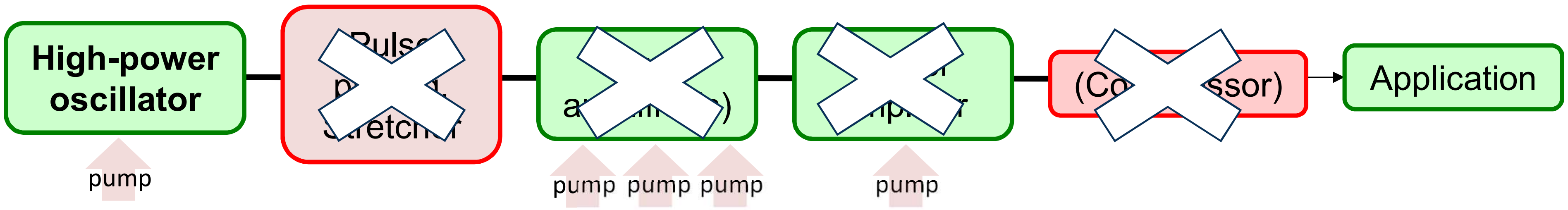
Energy: 200 mJ
Power: >1.0 kW
Duration: 500 fs
Peak Power: 0.4 TW

T. Nubbemeyer et al. OL 42, 7 (2017)

New developments: 2 kW – 20 kHz – ps, etc…

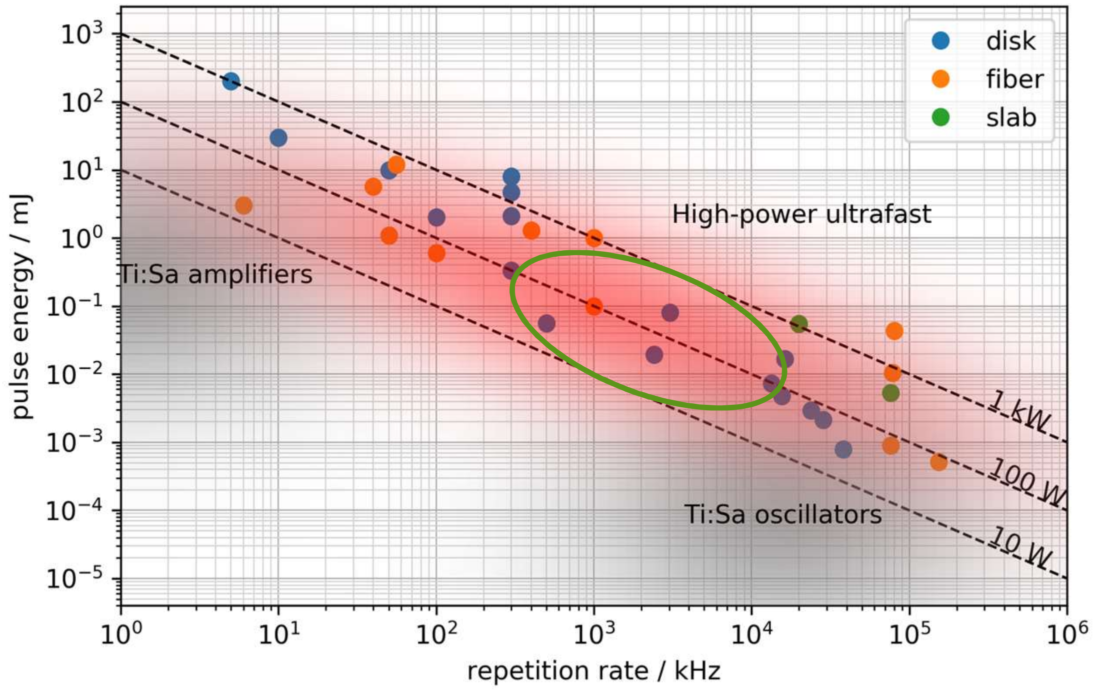
thin-disk ultrafast *oscillators*

High-power oscillators: one-box, MHz repetition rate

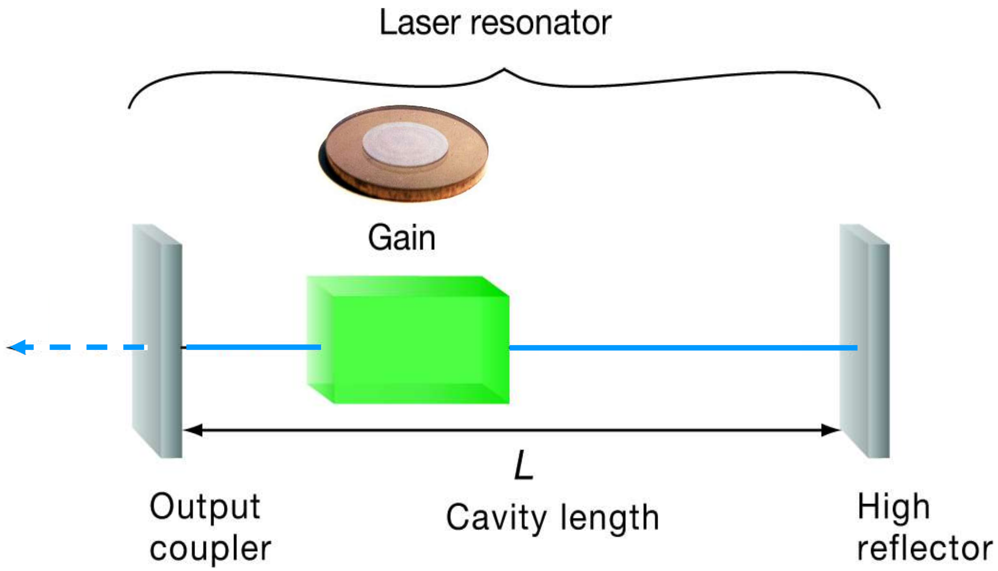


Amplifier-free, one-box modelocked oscillators:
hundreds of watts
3 - 100 MHz
10 - 100 µJ

…. the 'future' ?

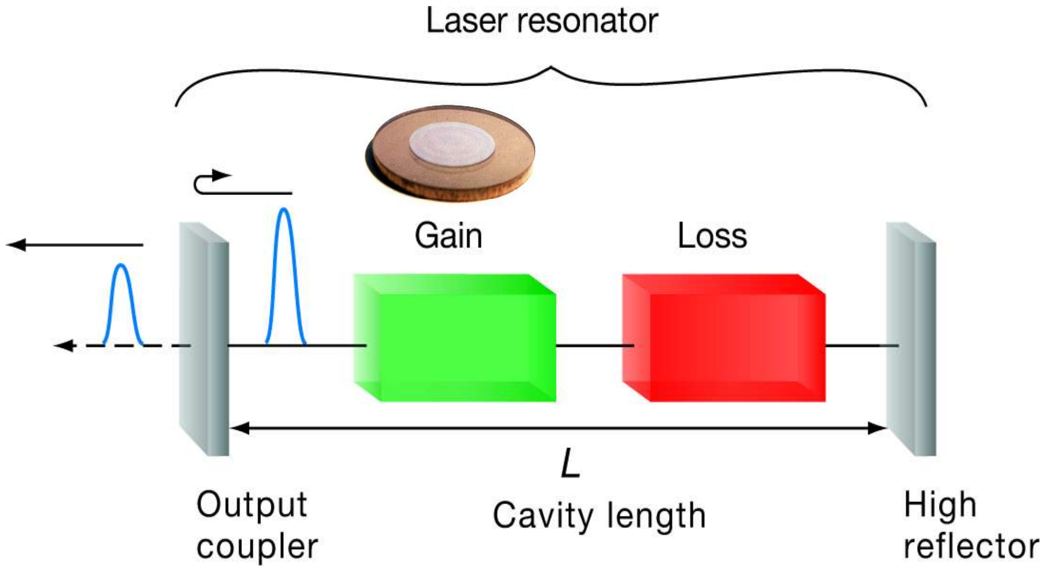


modelocked lasers



- Light circulates in resonator
- Losses compensated by gain in laser medium (which is externally pumped)
- Gain saturates to a level that it compensates the losses
- Light emission typically continuous
- Power: limited by thermal aberrations and pump power

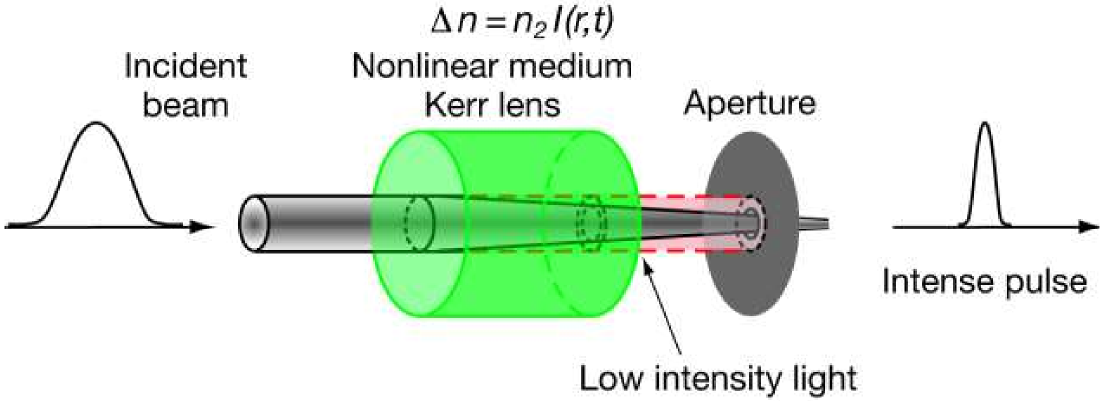
modelocked lasers



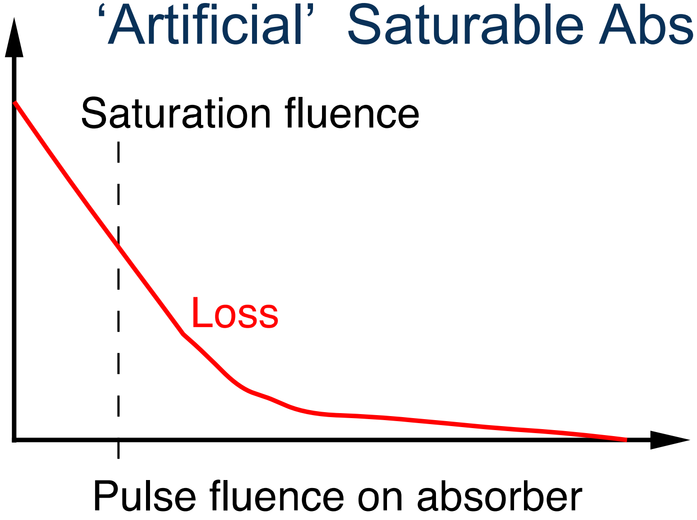
- Short pulse circulates in cavity (fs-ps)
- High repetition rate pulse train at the output (MHz)
- Pulse starting
  - Semiconductor saturable absorbers
  - Kerr lensing
- Pulse formation
  - Soliton modelocking
  - Kerr lens modelocking
- Steady-state pulse parameters: interplay of gain, (saturable) loss, dispersion, Kerr nonlinearity, etc.

saturable absorbers

Example: Kerr lens modelocking



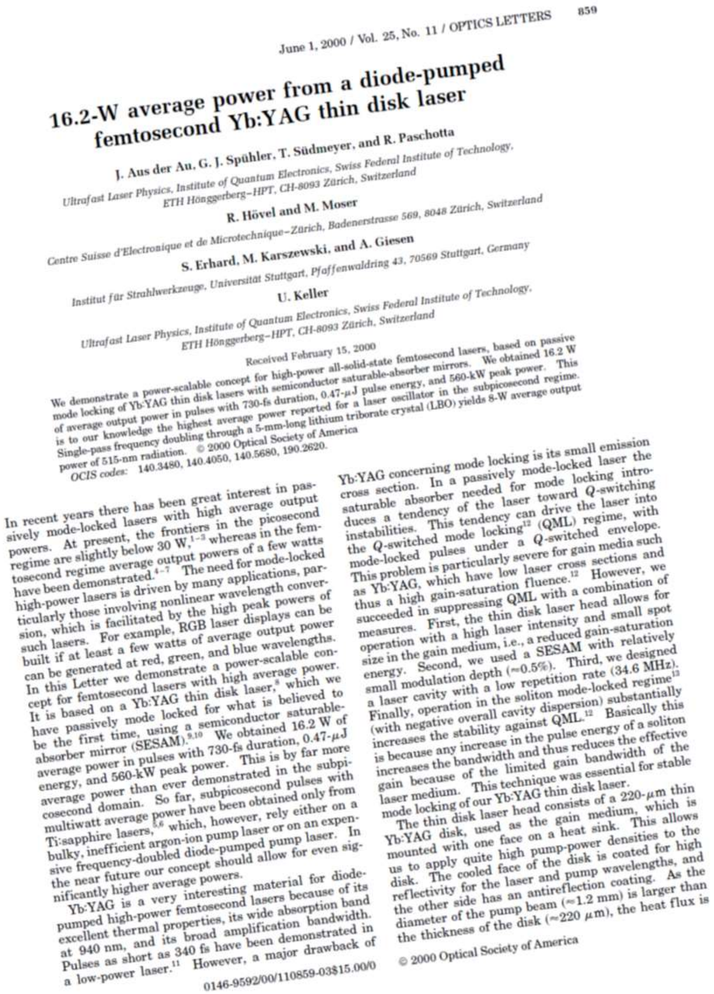
'Artificial' Saturable Absorber



+ others
- Semiconductor saturable absorber mirrors
- Nonlinear polarization rotation

....

first modelocked thin-disk oscillator: nearly 20 years ago



June 1, 2000 / Vol. 25, No. 11 / OPTICS LETTERS 859

16.2-W average power from a diode-pumped femtosecond Yb:YAG thin disk laser

J. Aus der Au, G. J. Spühler, T. Südmeyer, and R. Paschotta
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ETH Hönggerberg–HPT, CH-8093 Zürich, Switzerland
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Received February 15, 2000

We demonstrate a power-scalable concept for high-power all-solid-state femtosecond lasers, based on passive mode locking of Yb:YAG thin disk lasers with semiconductor saturable-absorber mirrors. We obtained 16.2 W of average output power in pulses with 730-fs duration, 0.47-μJ pulse energy, and 560-kW peak power. This is to our knowledge the highest average power reported for a laser oscillator in the subpicosecond regime. Single-pass frequency doubling through a 5-mm-long lithium triborate crystal (LBO) yields 8-W average output power of 515-nm radiation. © 2000 Optical Society of America

OCIS codes: 140.3480, 140.4050, 140.5680, 190.2620.

In recent years there has been great interest in passively mode-locked lasers with high average output powers. At present, the frontiers in the picosecond regime are slightly below 30 W,[1–3] whereas in the femtosecond regime average output powers of a few watts have been demonstrated.[4–7] The need for mode-locked high-power lasers is driven by many applications, particularly those involving nonlinear wavelength conversion, which is facilitated by the high peak powers of such lasers. For example, RGB laser displays can be built if at least a few watts of average output power can be generated at red, green, and blue wavelengths. In this Letter we demonstrate a power-scalable concept for femtosecond lasers with high average power. It is based on a Yb:YAG thin disk laser,[8] which we have passively mode locked for what is believed to be the first time, using a semiconductor saturable-absorber mirror (SESAM).[9,10] We obtained 16.2 W of average power in pulses with 730-fs duration, 0.47-μJ energy, and 560-kW peak power. This is by far more average power than ever demonstrated in the subpicosecond domain. So far, subpicosecond pulses with multiwatt average power have been obtained only from Ti:sapphire lasers,[5,6] which, however, rely either on a bulky, inefficient argon-ion pump laser or on an expensive frequency-doubled diode-pumped pump laser. In the near future our concept should allow for even significantly higher average powers.

Yb:YAG is a very interesting material for diode-pumped high-power femtosecond lasers because of its excellent thermal properties, its wide absorption band at 940 nm, and its broad amplification bandwidth. Pulses as short as 340 fs have been demonstrated in a low-power laser.[11] However, a major drawback of Yb:YAG concerning mode locking is its small emission cross section. In a passively mode-locked laser the saturable absorber needed for mode locking introduces a tendency of the laser toward Q-switching instabilities. This tendency can drive the laser into the Q-switched mode locking[12] (QML) regime, with mode-locked pulses under a Q-switched envelope. This problem is particularly severe for gain media such as Yb:YAG, which have low laser cross sections and thus a high gain-saturation fluence.[12] However, we succeeded in suppressing QML with a combination of measures. First, the thin disk laser head allows for operation with a high laser intensity and small spot size in the gain medium, i.e., a reduced gain-saturation energy. Second, we used a SESAM with relatively small modulation depth (≈0.5%). Third, we designed a laser cavity with a low repetition rate (34.6 MHz). Finally, operation in the soliton mode-locked regime[13] (with negative overall cavity dispersion) substantially increases the stability against QML.[12] Basically this is because any increase in the pulse energy of a soliton increases the bandwidth and thus reduces the effective gain because of the limited gain bandwidth of the laser medium. This technique was essential for stable mode locking of our Yb:YAG thin disk laser.

The thin disk laser head consists of a 220-μm thin Yb:YAG disk, used as the gain medium, which is mounted with one face on a heat sink. This allows us to apply quite high pump-power densities to the disk. The cooled face of the disk is coated for high reflectivity for the laser and pump wavelengths, and the other side has an antireflection coating. As the diameter of the pump beam (≈1.2 mm) is larger than the thickness of the disk (≈220 μm), the heat flux is

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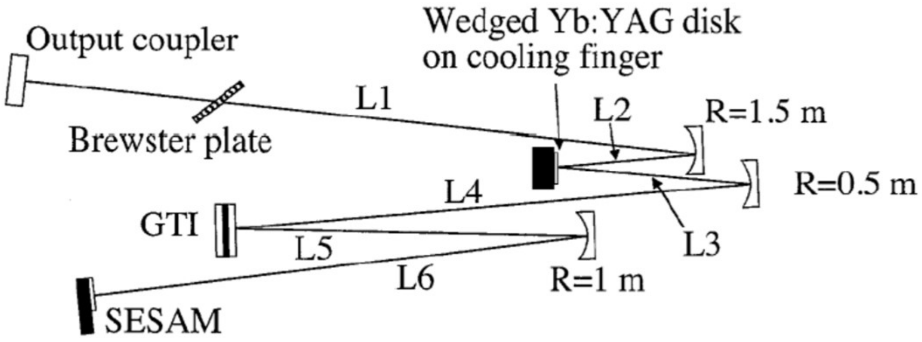
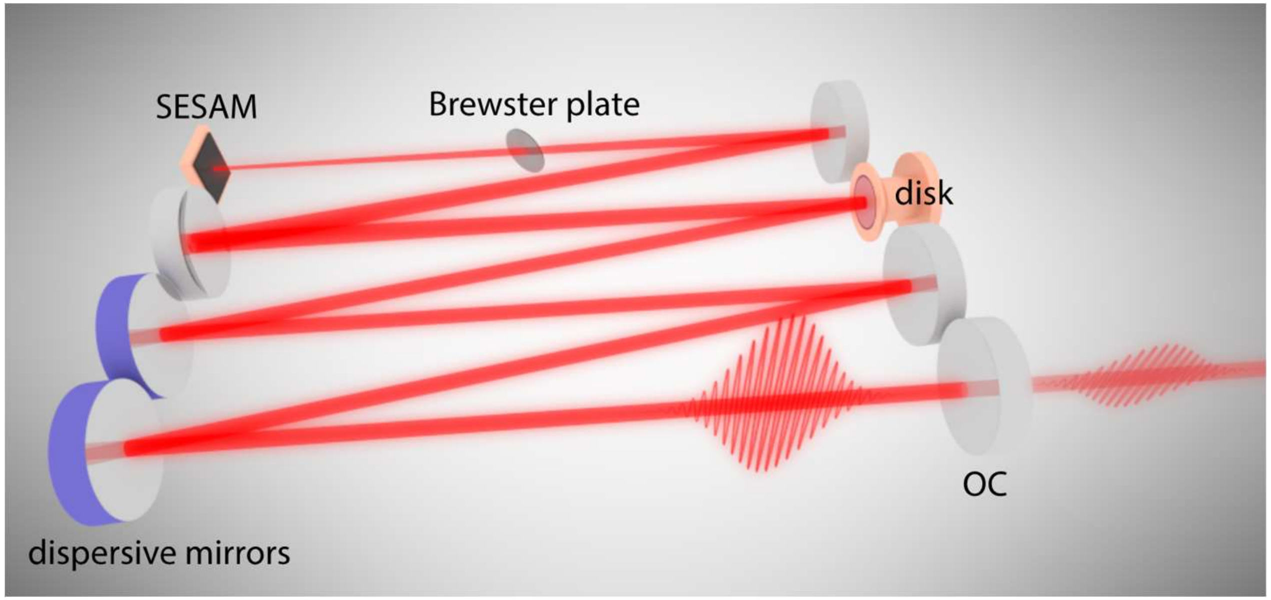
Group of Prof. U. Keller



16.2 W, 730 fs, 34.6 MHz, 0.5 µJ
Aus der Au et al. Opt. Lett. 25, 11 (2000)

the technology has come very far



- ‘One-box’ oscillator
- femtosecond soliton pulses

Specifications:

- Emission wavelength around 1 μm (typical 1030 nm)
- Average power: up to 350 W [1]
- Pulse energy: up to 80 μJ [2]
- Repetition rate: 3-70 MHz
- Pulse duration: 30-1000 fs

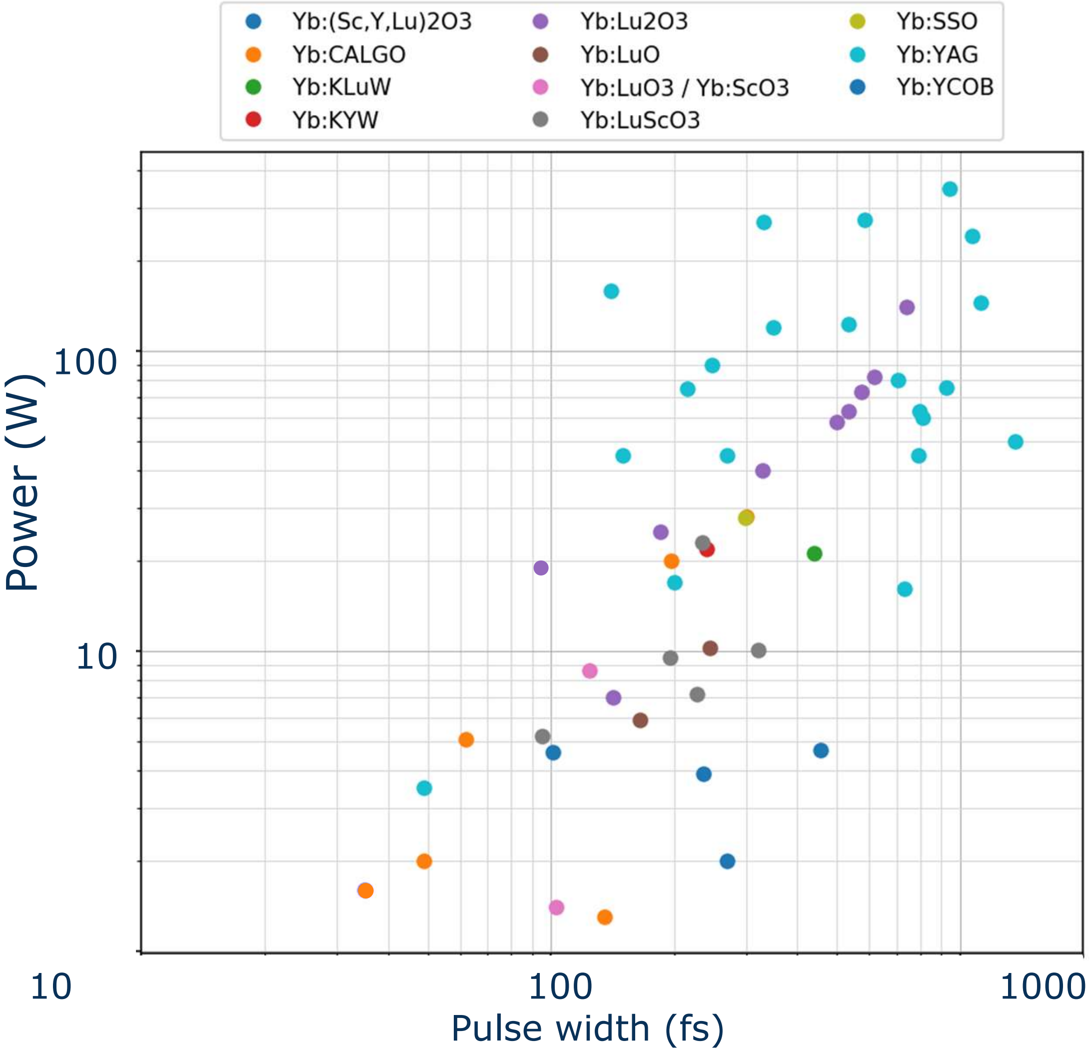
1. F. Saltarelli et al., Opt. Express 27, 31465-31474 (2019)
2. C. J. Saraceno et al., Opt. Lett. 39, 9 (2014).

→ **orders of magnitude higher levels than other oscillator laser technologies**

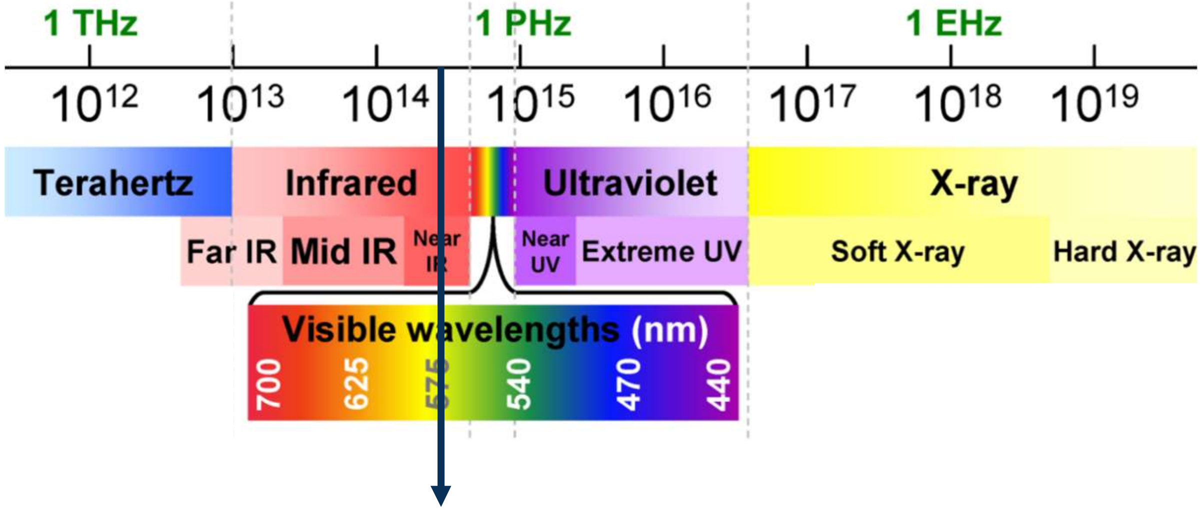
why have these (and other) Yb systems taken long to be adopted?

Yb:YAG: narrow emission bandwidth
$\Delta\lambda \sim 7$ nm

Strong compromise between pulse duration and average power/pulse energy



challenge: long pulses



high-power laser technology:
- limited spectral coverage
Yb:YAG - 1030 nm
- narrow bandwidths: long pulses

SPM

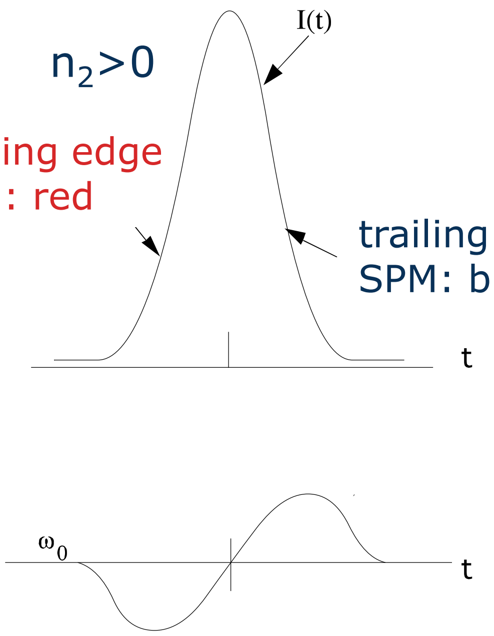
Self-phase modulation

$$n(I) = n + n_2 I$$

$I(t)$ → self-phase modulation
$I(x,y)$ → self-focusing

$$\phi(t) = -kn(I)L_K = -k\left[n + \boxed{n_2 I(t)\,\big]\,L_K}\right.$$

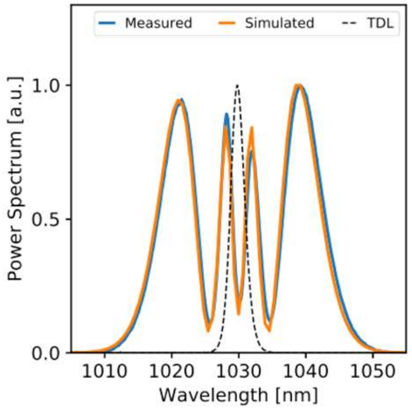
nonlinear phase



$n_2>0$

leading edge
SPM: red

trailing edge
SPM: blue



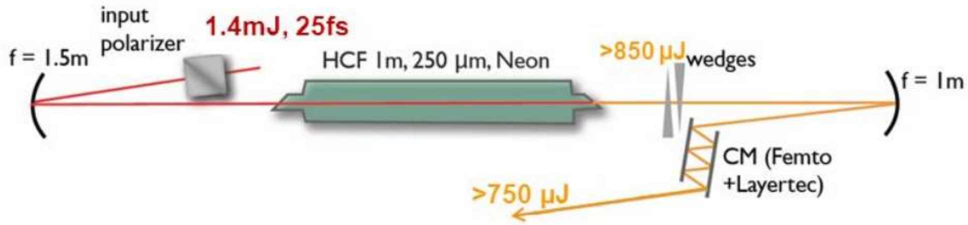
→ Creates new frequency components

- → **Spectral components not in phase, transform-limited input pulse: "*red before blue*"**
- → **Needs *negative dispersion (blue before red)* to reach short pulses**

pulse compression using SPM

C. V. Shank *et al.*, “Compression of femtosecond optical pulses”, Appl. Phys. Lett. 40, 761 (1982)

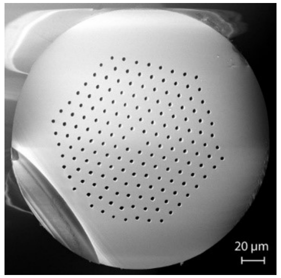
- Hollow capillaries

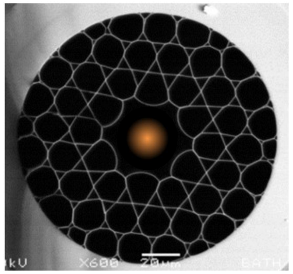


Nisoli et al, Appl. Phys. Lett. 68, 2793 (1996)

- Grazing incidence reflections
- Losses increase at moderate to small core sizes, typical 70% transmission
- Suited only for very high energies (mJ and above)

- Fibers
  - Solid-core fibers
  - Hollow-core fibers



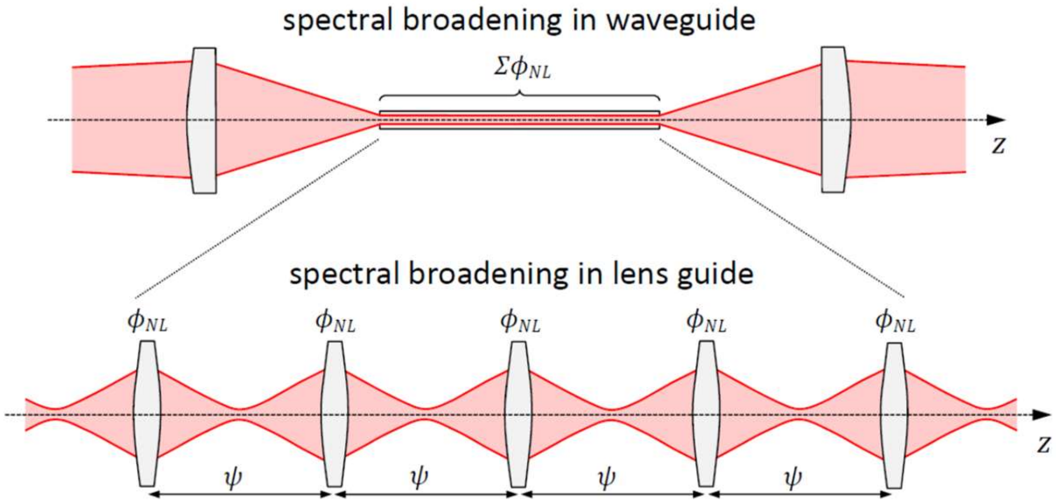


- Real guiding
- Solid-core: limited by self-focusing (4 MW for linear polarization and glass), damage threshold and bending loss at large mode areas
- Hollow-core: limited by difficulties in bending and damage

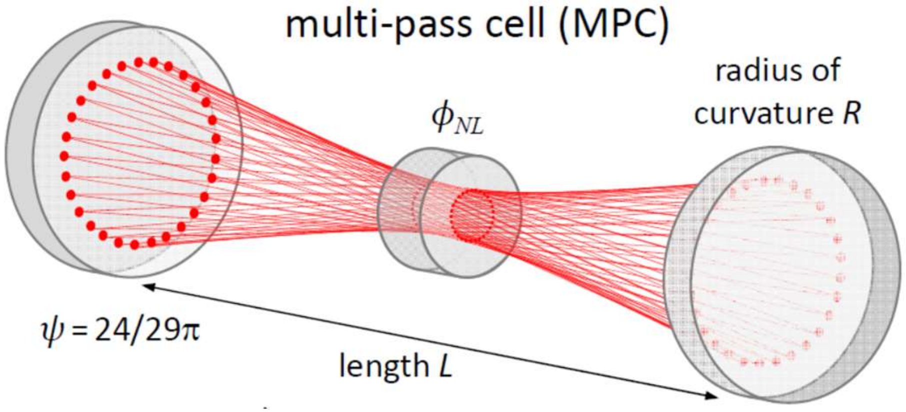
T. Südmeyer *et al.*, “Nonlinear femtosecond pulse compression at high average power levels by use of a large-mode-area holey fiber”, Opt. Lett. 28 (20), 1951 (2003)

K. F. Mak *et al.*, “Two techniques for temporal pulse compression in gas-filled hollow-core kagomé photonic crystal fiber”, Opt. Lett. 38 (18), 3592 (2013)

Compression in multi-pass cell



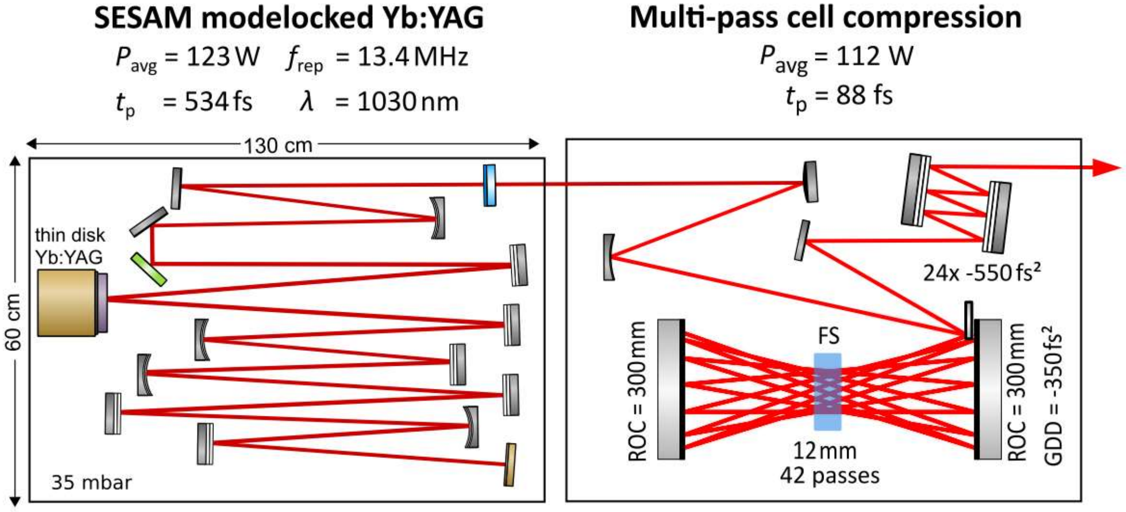
Idea: can one have the advantage of free-space propagation (for average power handling), and the large SPM provided by fibers - free of self-focusing?



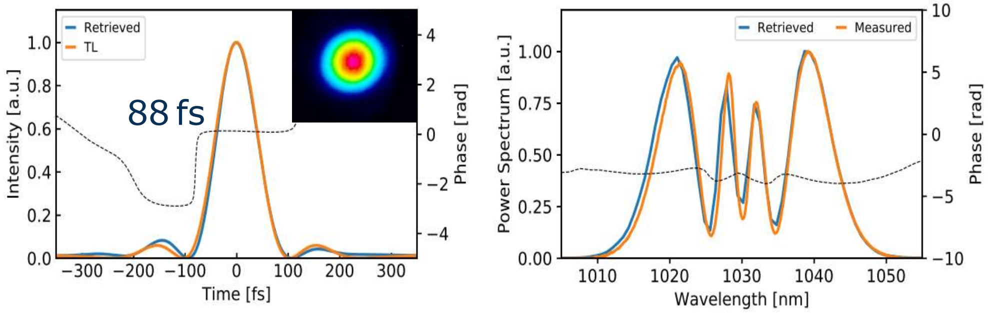
Figures courtesy J. Weitenberg Fraunhofer ILT Aachen

First realization (ILT Aachen): Schulte et al. "Nonlinear pulse compression in a multi-pass cell," Opt. Lett. 41, 4511-4514 (2016)

Example



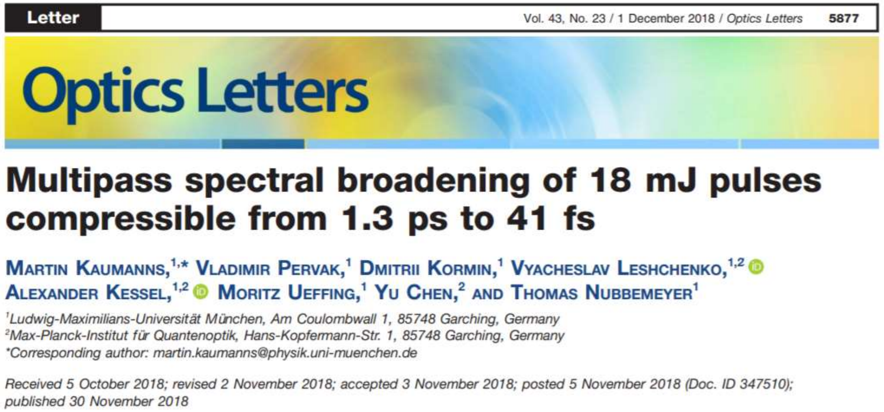
P_{avg} = 112 W f_{rep} = 13.4 MHz **E_p = 8.4 μJ**
t_p = 88 fs P_{peak} = 80 MW λ = 1030 nm



- Herriott type multi-pass cell[1] + fused silica + negative dispersive mirror pair
- Generated spectrum agrees well with 3D pulse propagation model
- $M^2 < 1.15$
- Excellent efficiency: 91%

Tsai et al. "Efficient nonlinear compression of a mode-locked thin-disk oscillator to 27 fs at 98 W average power," Opt. Lett. 44, 4115-4118 (2019)

Works for an extremely large variety of parameters


Letter Vol. 43, No. 23 / 1 December 2018 / *Optics Letters* **5877**

Optics Letters

Multipass spectral broadening of 18 mJ pulses compressible from 1.3 ps to 41 fs

Martin Kaumanns,[1,*] Vladimir Pervak,[1] Dmitrii Kormin,[1] Vyacheslav Leshchenko,[1,2] Alexander Kessel,[1,2] Moritz Ueffing,[1] Yu Chen,[2] and Thomas Nubbemeyer[1]

[1]Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching, Germany
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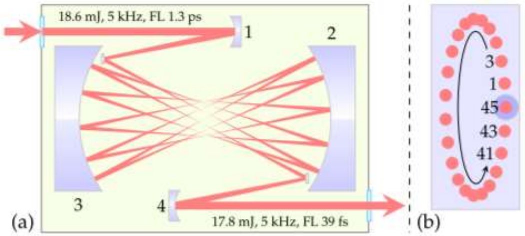
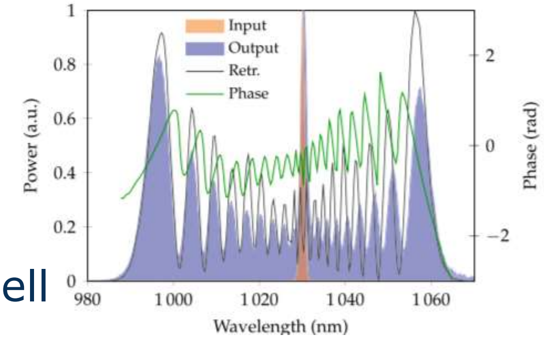
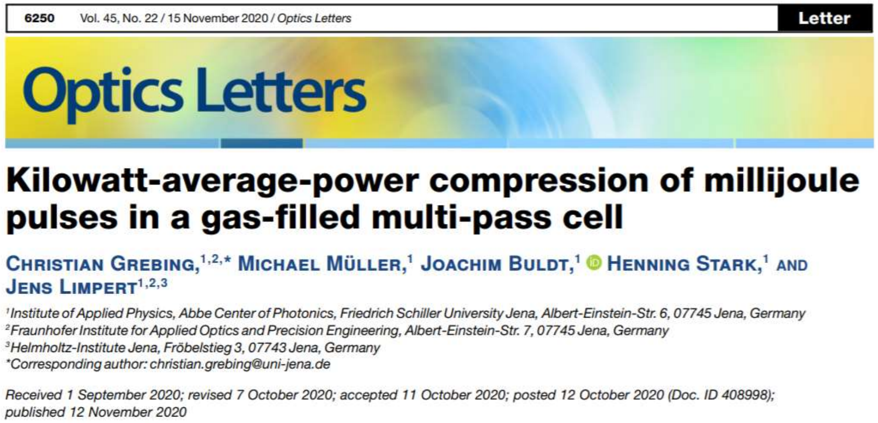
**Corresponding author: martin.kaumanns@physik.uni-muenchen.de*

Received 5 October 2018; revised 2 November 2018; accepted 3 November 2018; posted 5 November 2018 (Doc. ID 347510); published 30 November 2018





High energies – gas filled cell


6250 Vol. 45, No. 22 / 15 November 2020 / *Optics Letters* **Letter**

Optics Letters

Kilowatt-average-power compression of millijoule pulses in a gas-filled multi-pass cell

Christian Grebing,[1,2,*] Michael Müller,[1] Joachim Buldt,[1] Henning Stark,[1] and Jens Limpert[1,2,3]

[1]Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Str. 6, 07745 Jena, Germany
[2]Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany
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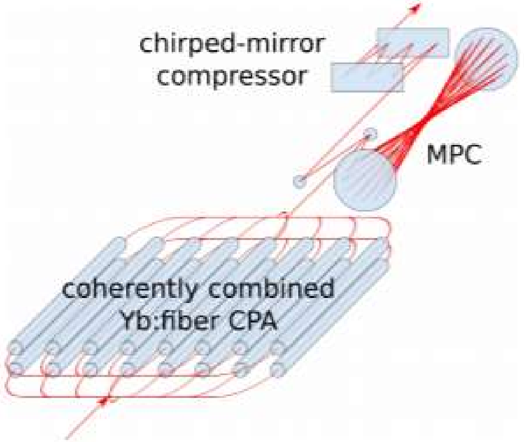
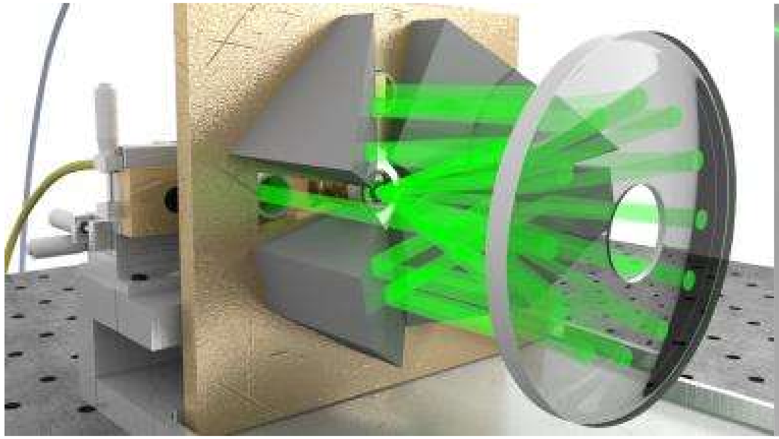
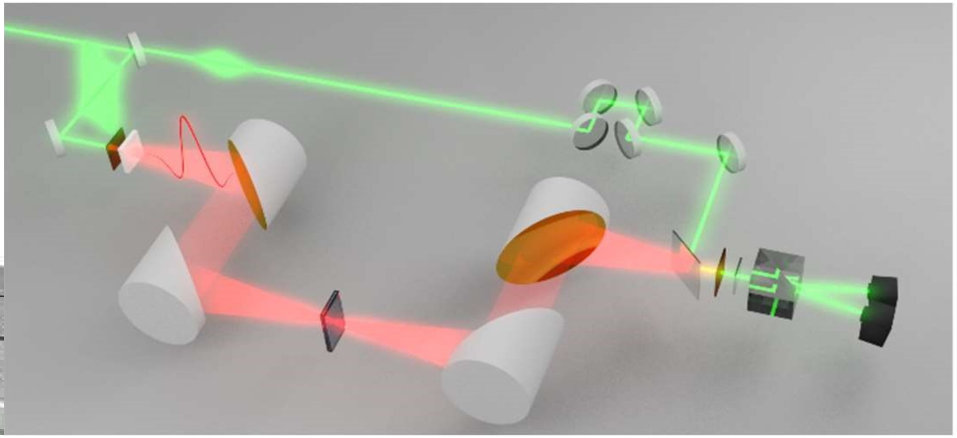
**Corresponding author: christian.grebing@uni-jena.de*

Received 1 September 2020; revised 7 October 2020; accepted 11 October 2020; posted 12 October 2020 (Doc. ID 408998); published 12 November 2020

1 mJ, 31 fs pulses







Ultrafast lasers for THz generation using nonlinear optical techniques

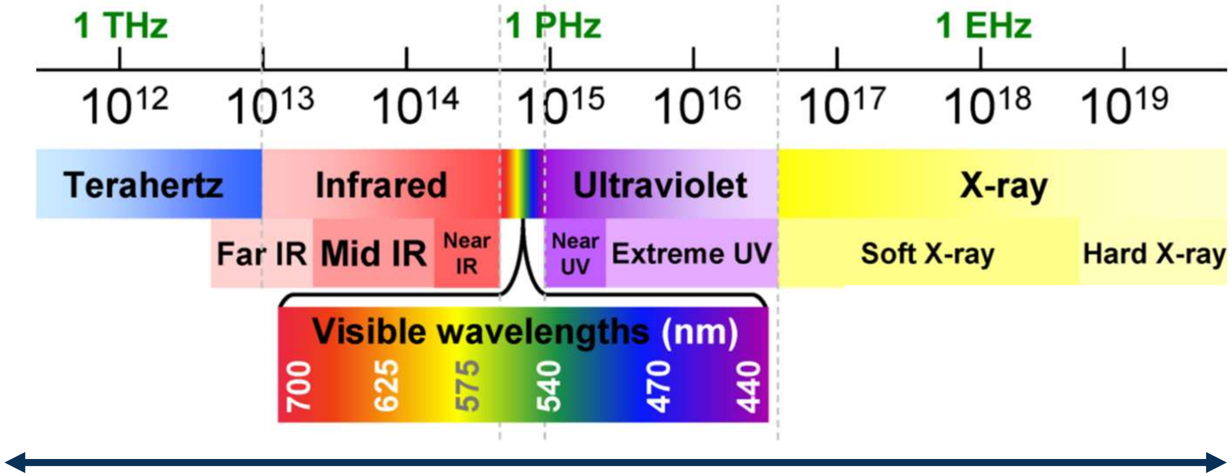
Part 2: Terahertz generation at high-power

Clara J. Saraceno

ICTP Winter School on Terahertz Optics and Photonics - February 2023

spectral coverage

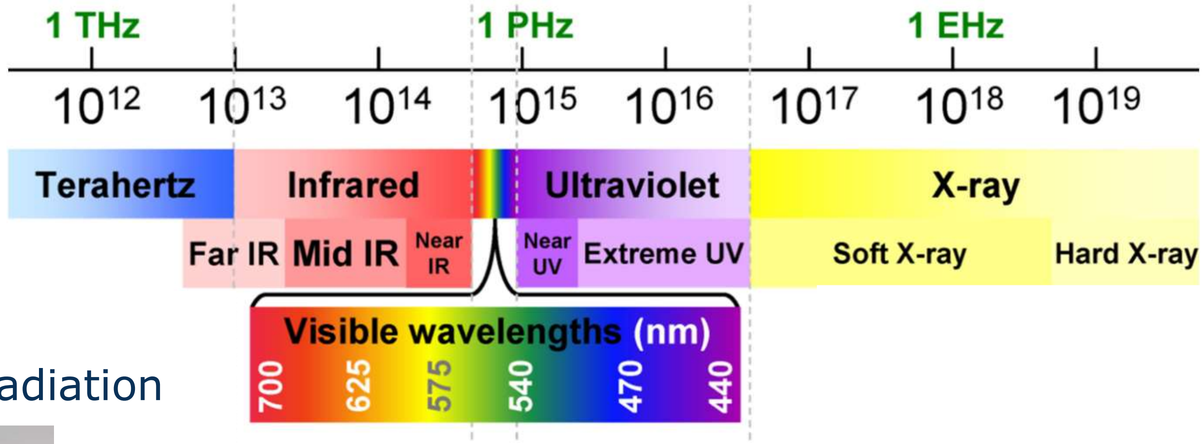
We have kilowatt, fs lasers, so now what?



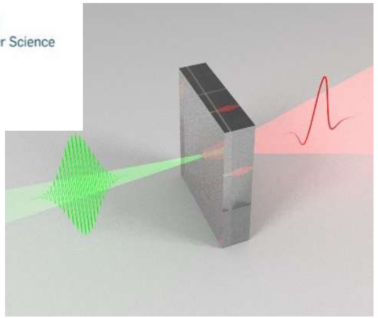
Trend: high-power from THz to XUV

spectral coverage

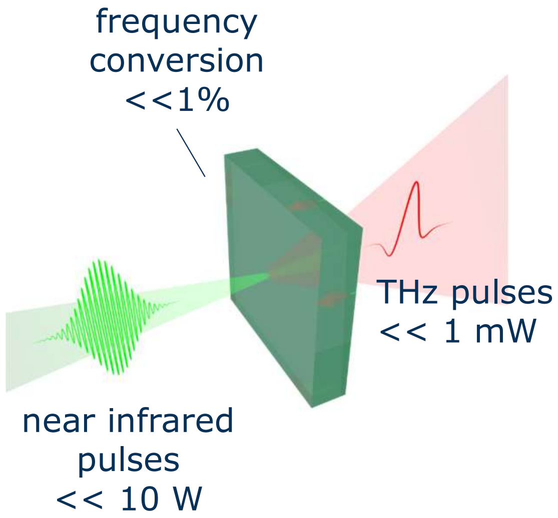
We have kilowatt, fs lasers, so now what?

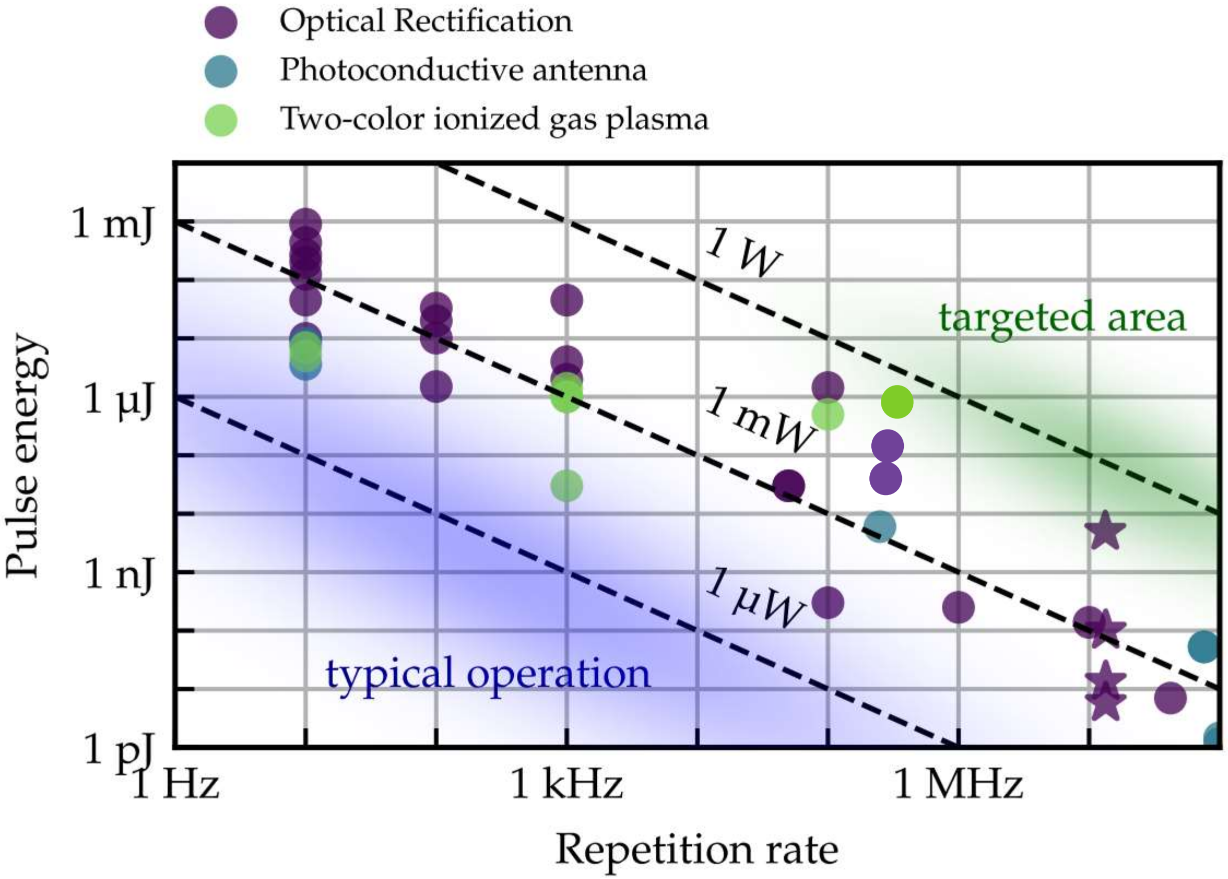


High power THz radiation



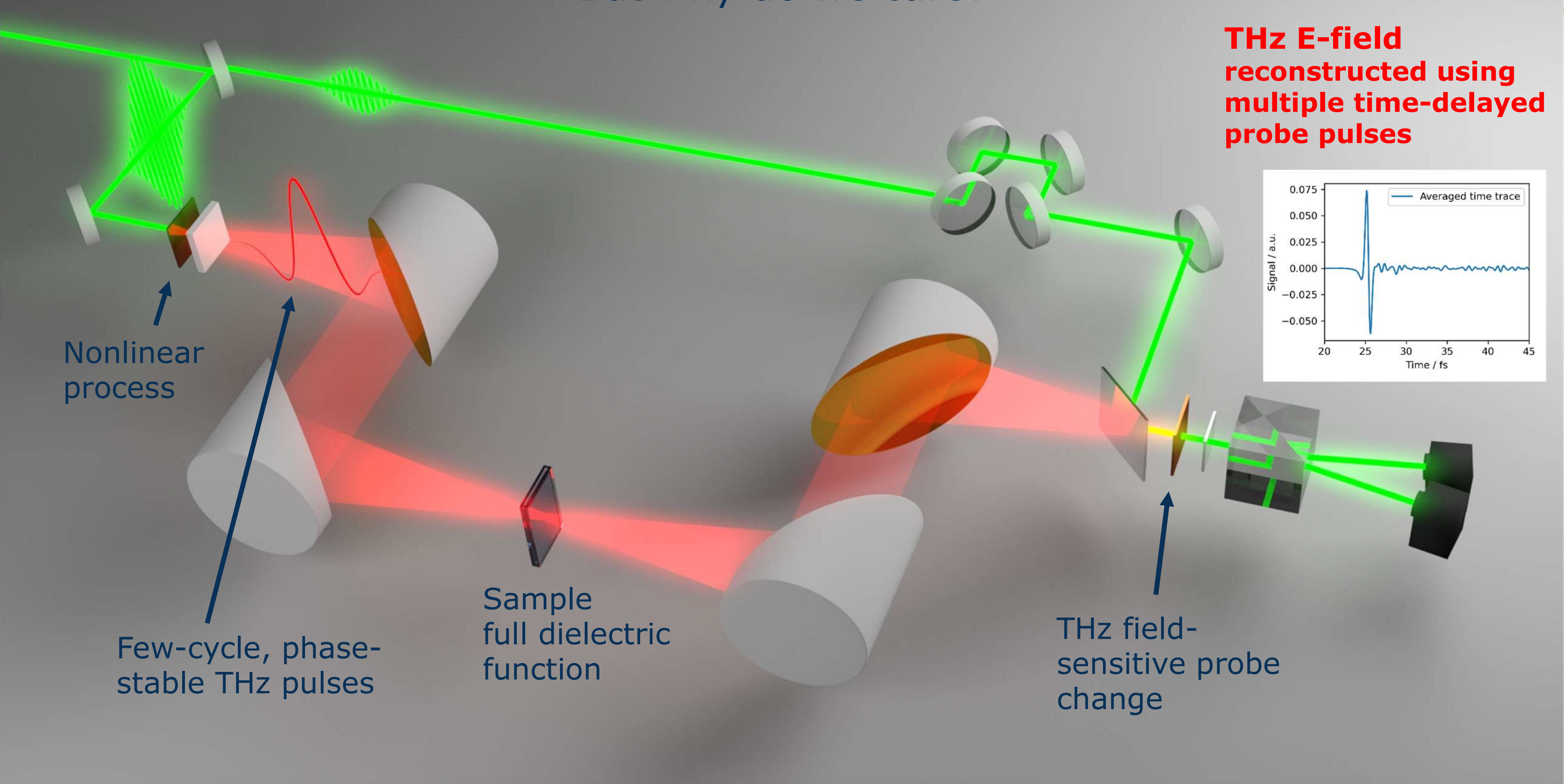
THz lab-sources: low average power





- state-of-the-art THz power: mW level
- repetition rate or pulse strength: compromise necessary
- origin of limitations: low driving power and efficiency
- power-hungry applications: traditionally accelerators

But why do we care?



THz E-field reconstructed using multiple time-delayed probe pulses

Nonlinear process

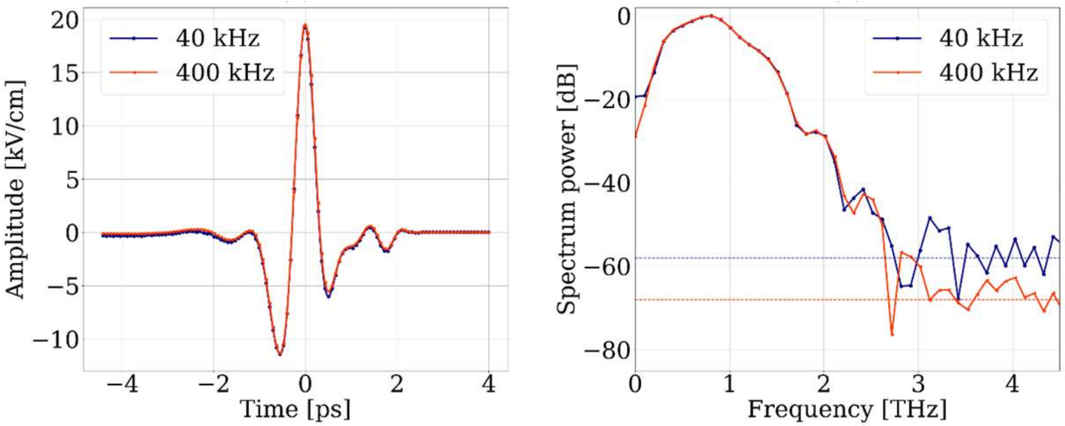
Few-cycle, phase-stable THz pulses

Sample
full dielectric function

THz field-sensitive probe change

why do we care?

Same measurement time (approx 1 min)



- Same measurement time -- more samples per second, higher dynamic range (and bandwidth!)

OR

- same dynamic range at 10 times shorter measurement time

Performance of a TDS?

$$\mathrm{SNR} = \frac{\text{mean magnitude of amplitude}}{\text{standard deviation of amplitude}}$$

→ Stability **from trace to trace**

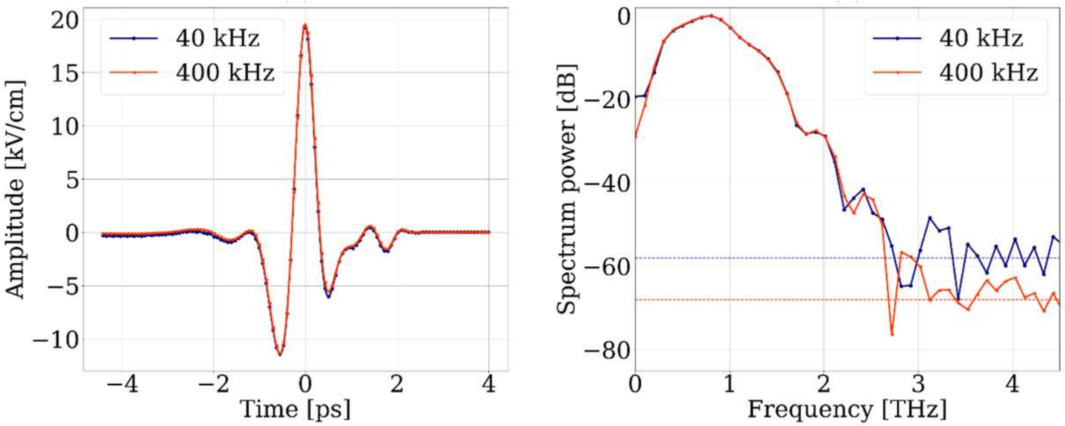
$$\mathrm{DR} = \frac{\text{maximum magnitude of amplitude}}{\text{rms of noise floor}}$$

→ Fluctuations **within one EOS trace**

M. Naftaly and R. Dudley, “Methodologies for determining the dynamic ranges and signal-to noise ratios of terahertz time-domain spectrometers,” Optics Letters, vol. 34, p. 1213, Apr. 2009.

why do we care?

Same measurement time (approx 1 min)



- Same measurement time -- more samples per second, higher DR (and bandwidth!)

OR

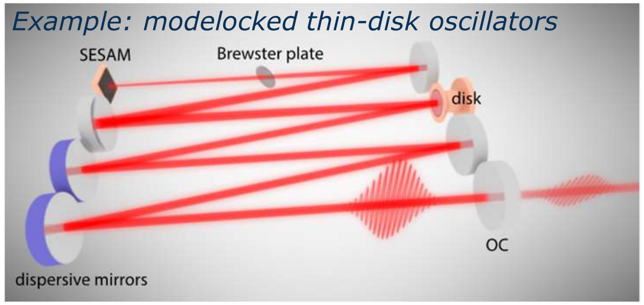
- same DR at 10 times shorter measurement time

Average power advantage strongly depends on the experiments specifics and detection setup

our THz research in a nutshell

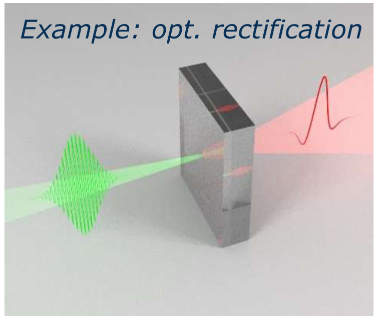
High average power ultrafast lasers

Example: modelocked thin-disk oscillators



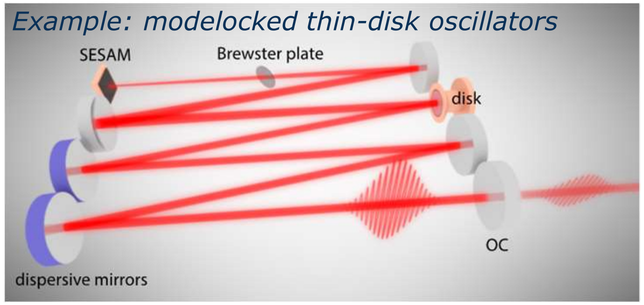
High average power THz-TDS

Example: opt. rectification

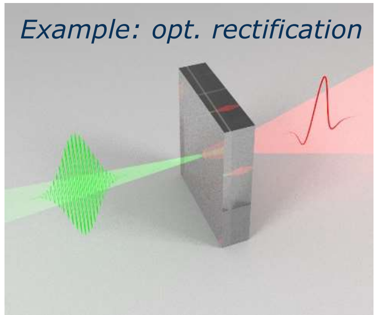


our THz research in a nutshell

High average power ultrafast lasers


Example: modelocked thin-disk oscillators

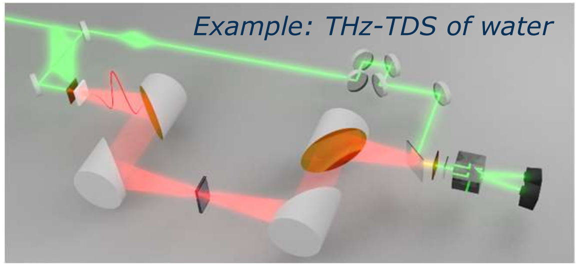
High average power THz-TDS

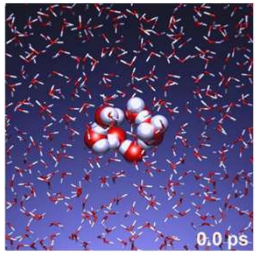

Example: opt. rectification

Power-hungry applications

RESOLV
RUHR EXPLORES SOLVATION
CLUSTER OF EXCELLENCE - EXC 2033

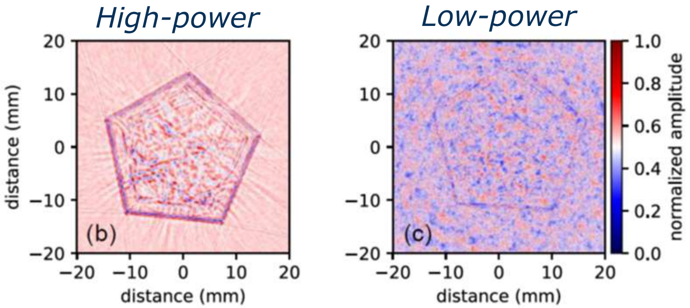
Spectroscopy


Example: THz-TDS of water



"understand solvents at a molecular level…"

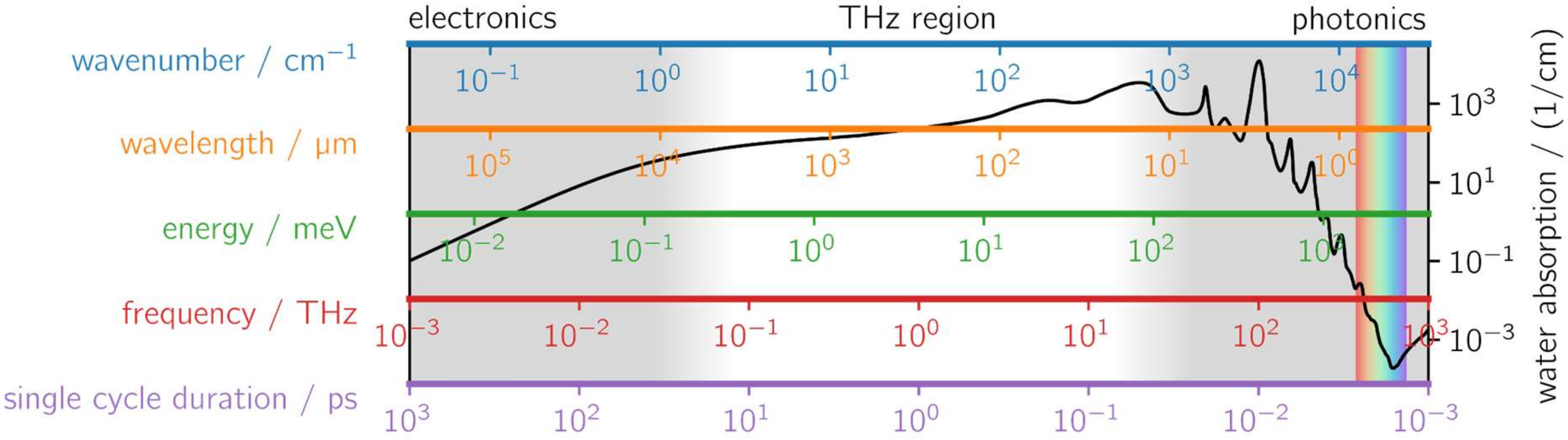
Imaging & sensing

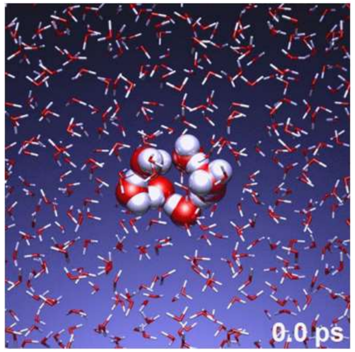


Marie
SFB / TRR 196

"mobile material characterization and identification in the THz range…"

how we started looking into this





M. Heyden, J. Sun, S. Funkner, H. Forbert, G. Mathias, M. Havenith and D. Marx, Proc. Natl. Acad. Sci. USA 107, 2010

source “dream”:

- short, phase-stable THz pulses covering [1-10 THz] or more
- high repetition rate (MHz): high signal-to-noise ratio, short measurement times
- high energy (µJ): nonlinear spectroscopies

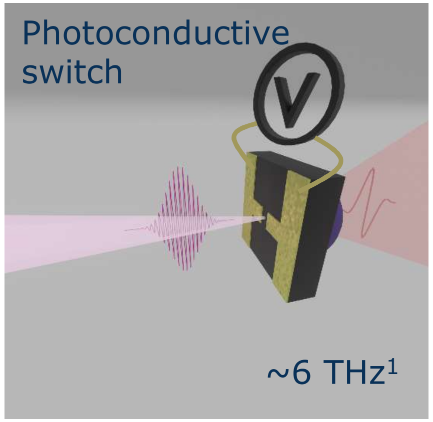
➡ **high average power (watts)**

RESOLV
RUHR EXPLORES SOLVATION
CLUSTER OF EXCELLENCE - EXC 2033

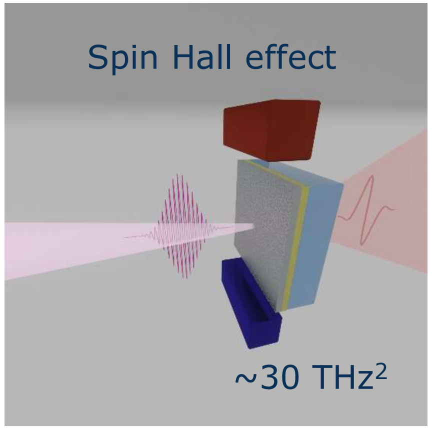
- *200 scientists in the Ruhr area*
- *solvent molecular details in the focus*

selection of THz generation methods

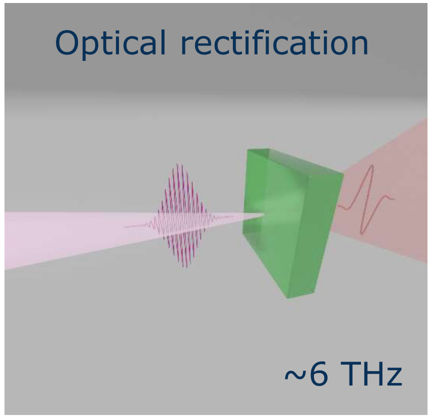
photocurrent in semiconductor

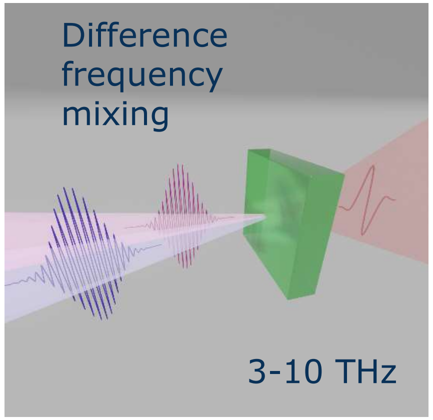


spintronic emitters

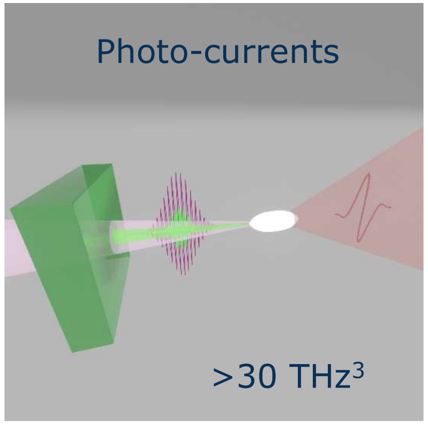


$\chi^{(2)}$ in non-centrosymmetric crystals





two-color ionized gas plasma



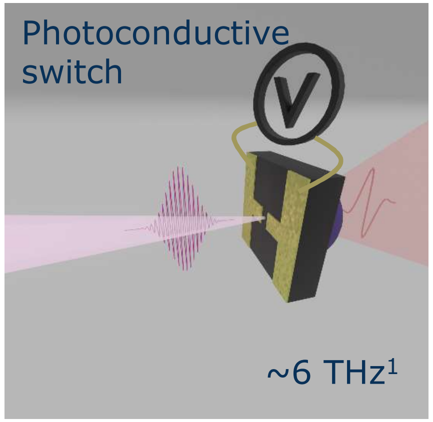
Typically min. required driving pulse energy for efficient conversion

nJ → mJ

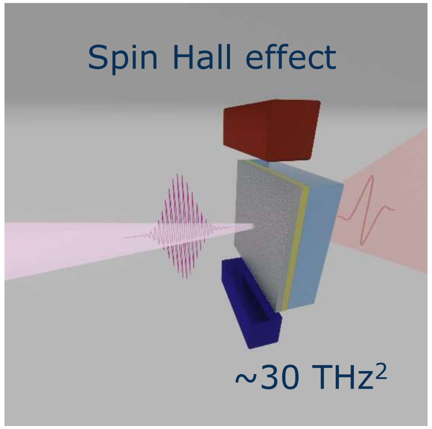
1. Burford, N. M. & El-Shenawee, M. O. *Opt. Eng.* **56**, 010901 (2017).
2. Seifert, T., Jaiswal, S., Martens, U. *et al. Nature Photon* **10,** 483–488 (2016).
3. Matsubara, E., Nagai, M. & Ashida, M. *Appl. Phys. Lett.* **101**, (2012).

selection of THz generation methods

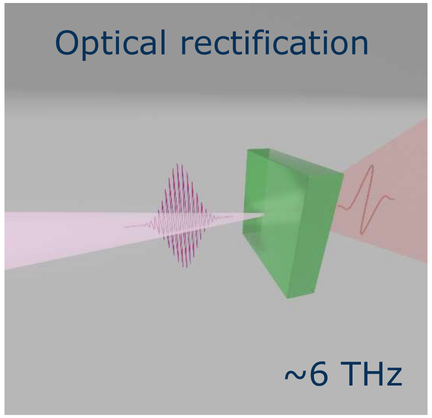
photocurrent in semiconductor

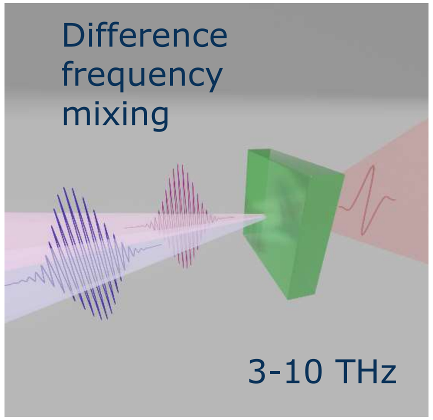


spintronic emitters

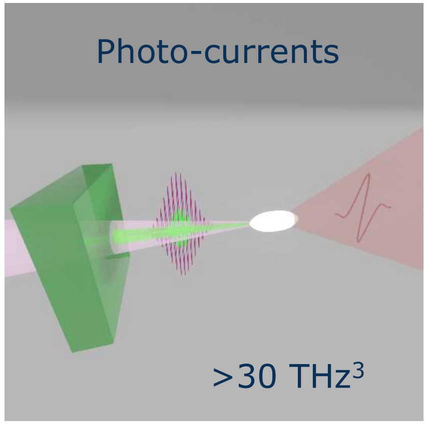


$\chi^{(2)}$ in non-centrosymmetric crystals





Two-color ionized gas plasma



Typically min. required driving pulse energy for efficient conversion

nJ → mJ

All generation methods have interesting and unexplored high average power regimes of operation!

1. Burford, N. M. & El-Shenawee, M. O. *Opt. Eng.* **56**, 010901 (2017).
2. Seifert, T., Jaiswal, S., Martens, U. *et al. Nature Photon* **10,** 483–488 (2016).
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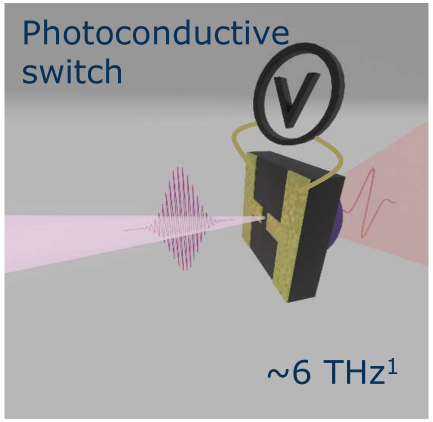
selection of THz generation methods

MHz repetition rates
thin-disk oscillators

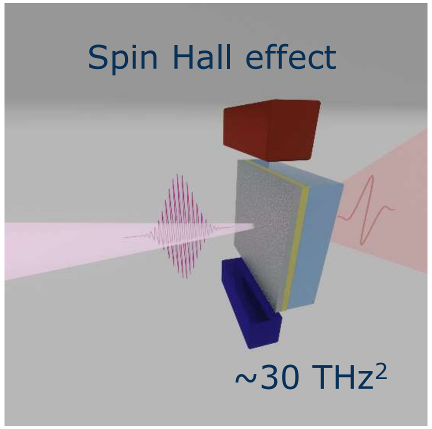
photocurrent in semiconductor



Photoconductive switch

~6 THz[1]

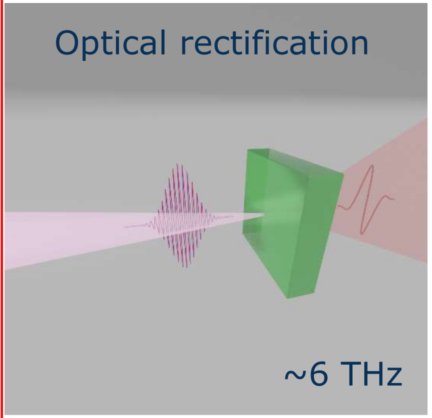
spintronic emitters



Spin Hall effect

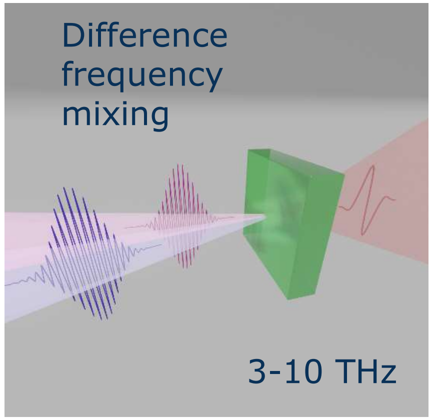
~30 THz[2]

$\chi^{(2)}$ in non-centrosymmetric crystals



Optical rectification

~6 THz



Difference frequency mixing

3-10 THz

Two-color ionized gas plasma

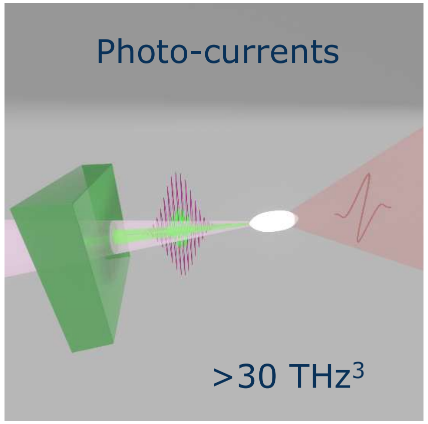


Photo-currents

>30 THz[3]

Typically min. required driving pulse energy for efficient conversion

nJ → mJ

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2. Seifert, T., Jaiswal, S., Martens, U. *et al. Nature Photon* **10,** 483–488 (2016).
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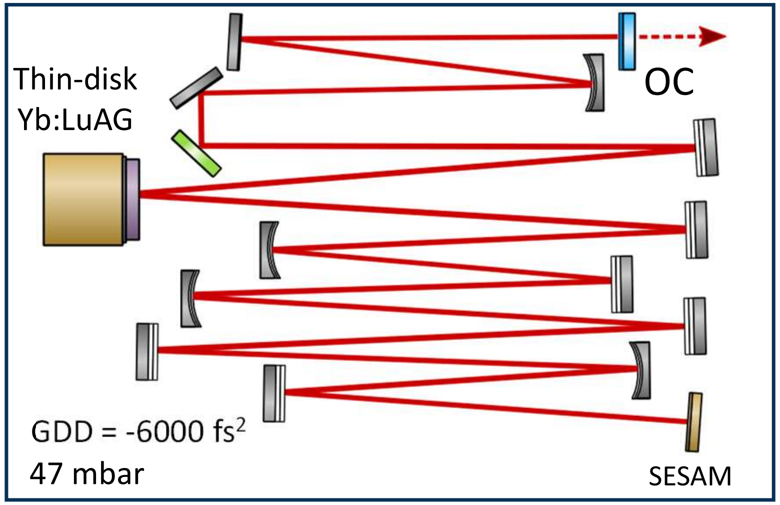
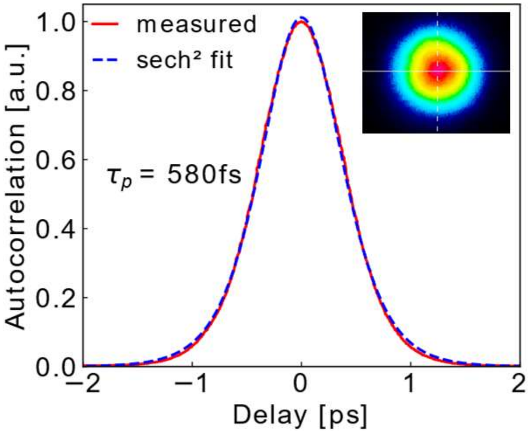
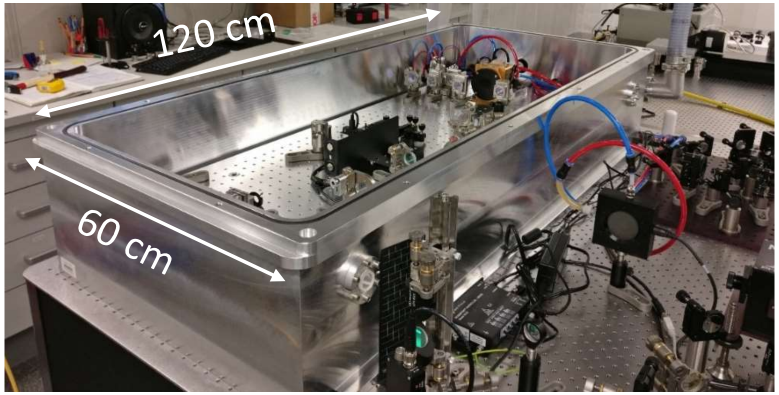
Workhorse thin-disk oscillator







P_{avg} = 125 W

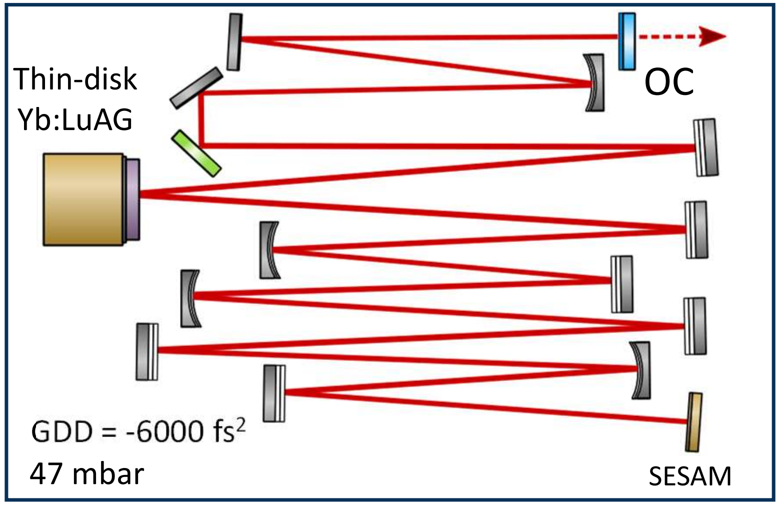
f_{rep} = 13.4 MHz

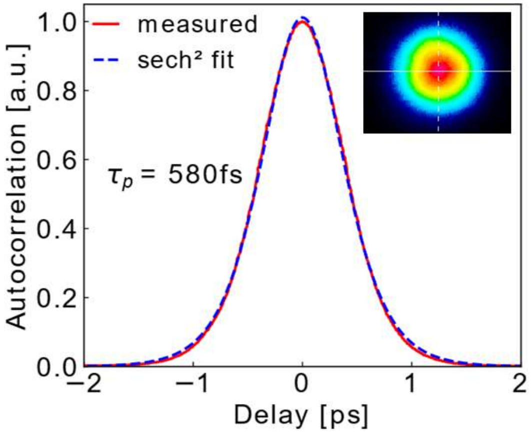
E_{p} = 9.3 μJ

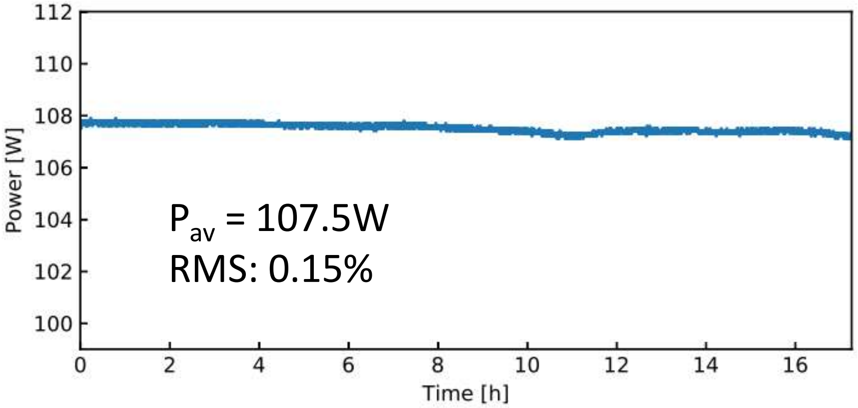
τ_{p} = 580 fs

λ = 1030 nm

Workhorse thin-disk oscillator







P_{av} = 107.5W
RMS: 0.15%

P_{avg} = 125 W
f_{rep} = 13.4 MHz
E_p = 9.3 μJ
τ_p = 580 fs
λ = 1030 nm

Flexible pulse compression

SESAM modelocked Yb:LuAG

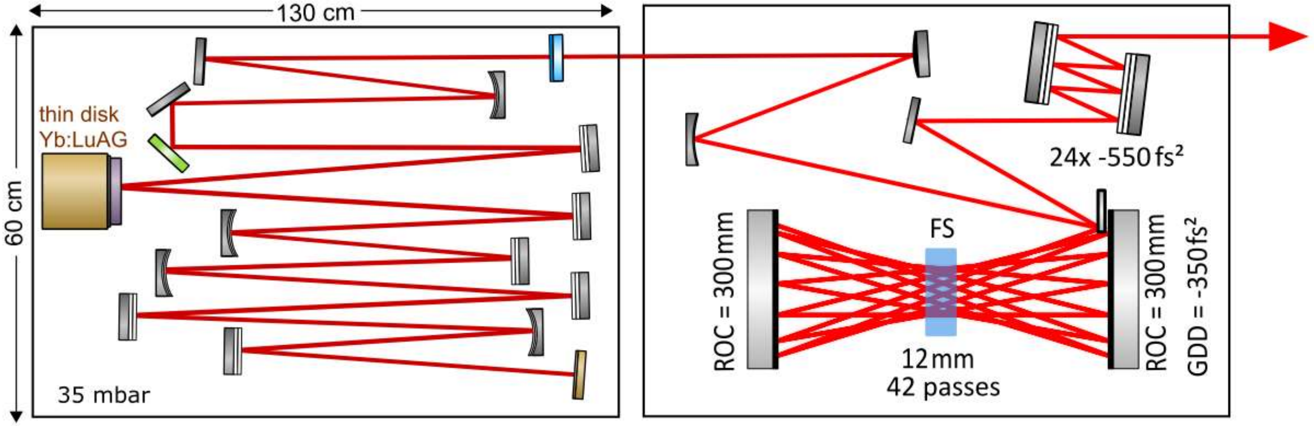
P_{avg} = 123 W f_{rep} = 13.4 MHz

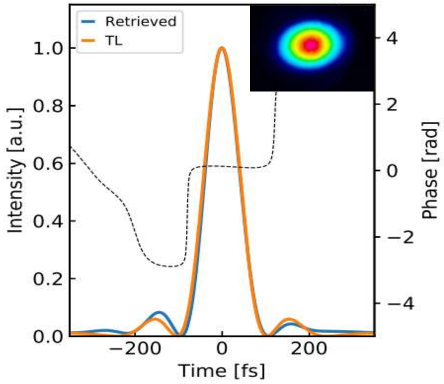
t_p = 534 fs λ = 1030 nm

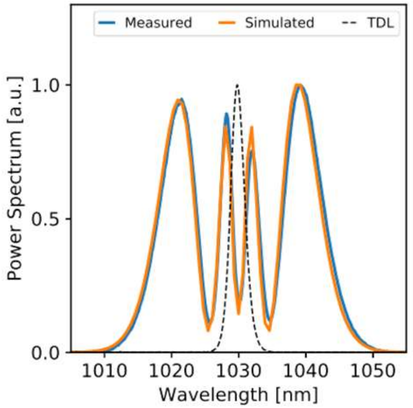
Multi-pass cell compression

P_{avg} = 112 W

t_p = 88 fs







- Herriott type multi-pass cell[#] + fused silica + dispersive mirror pair
- Generated spectrum agrees well with 3D pulse propagation model
- M² < 1.15
- Excellent efficiency: 91%

P_{avg} = 112 W f_{rep} = 13.4 MHz **E_P = 8.4 µJ** t_p = 88 fs P_{peak} = 80 MW λ = 1030 nm

1. J. Schulte et al., "Nonlinear pulse compression in a multi-pass cell," Opt. Lett. **41**, 4511-4514 (2016)

Collinear optical rectification

SESAM modelocked Yb:LuAG

P_{avg} = 123 W f_{rep} = 13.4 MHz

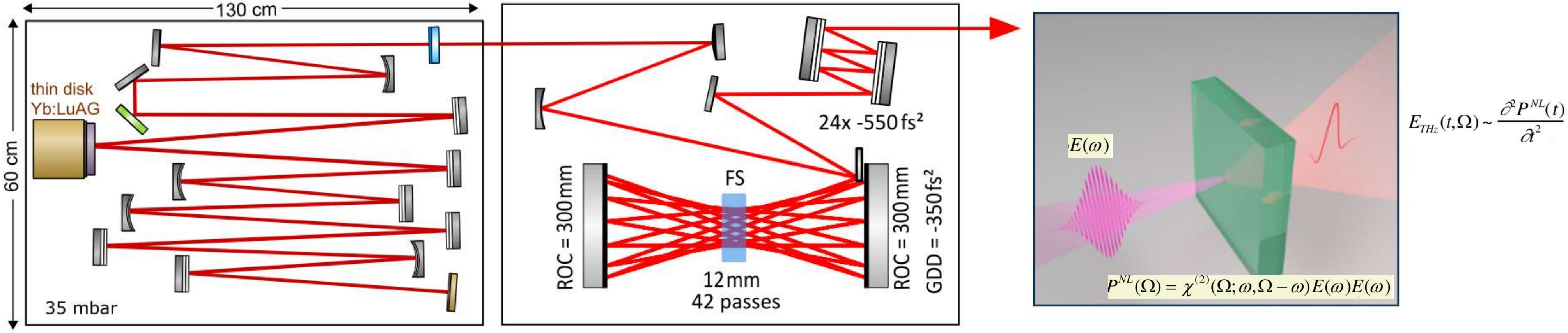
t_p = 534 fs λ = 1030 nm

Multi-pass cell compression

P_{avg} = 112 W

t_p = 88 fs

Optical rectification



$$E_{THz}(t,\Omega) \sim \frac{\partial^2 P^{NL}(t)}{\partial t^2}$$

$$P^{NL}(\Omega) = \chi^{(2)}(\Omega;\omega,\Omega-\omega)E(\omega)E(\omega)$$

- Herriott type multi-pass cell# + fused silica + dispersive mirror pair
- Generated spectrum agrees well with 3D pulse propagation model
- M² < 1.15
- Excellent efficiency: 91%

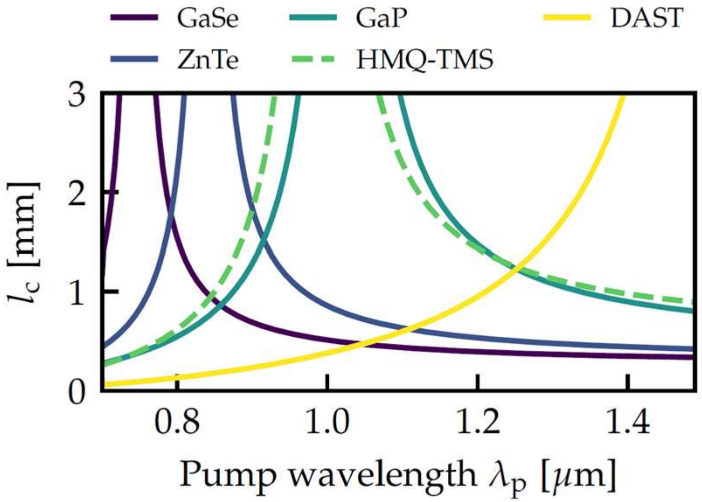
P_{avg} = 112 W f_{rep} = 13.4 MHz **E_p = 8.4 µJ** t_p = 88 fs P_{peak} = 80 MW λ = 1030 nm

Choice of nonlinear crystal?

- **velocity matching**

Coherence length = measure of walk-off between pump pulses and the generated THz pulses

$$l_\mathrm{c} = \frac{1}{2 f_\mathrm{T} \left| \frac{1}{v_\mathrm{p}^\mathrm{gr}} - \frac{1}{v_\mathrm{T}^\mathrm{ph}} \right|}$$



- **strength of nonlinear coefficient**

improves conversion efficiency

- **THz absorption**

strongly affects bandwidth, typically phonon absorption lines

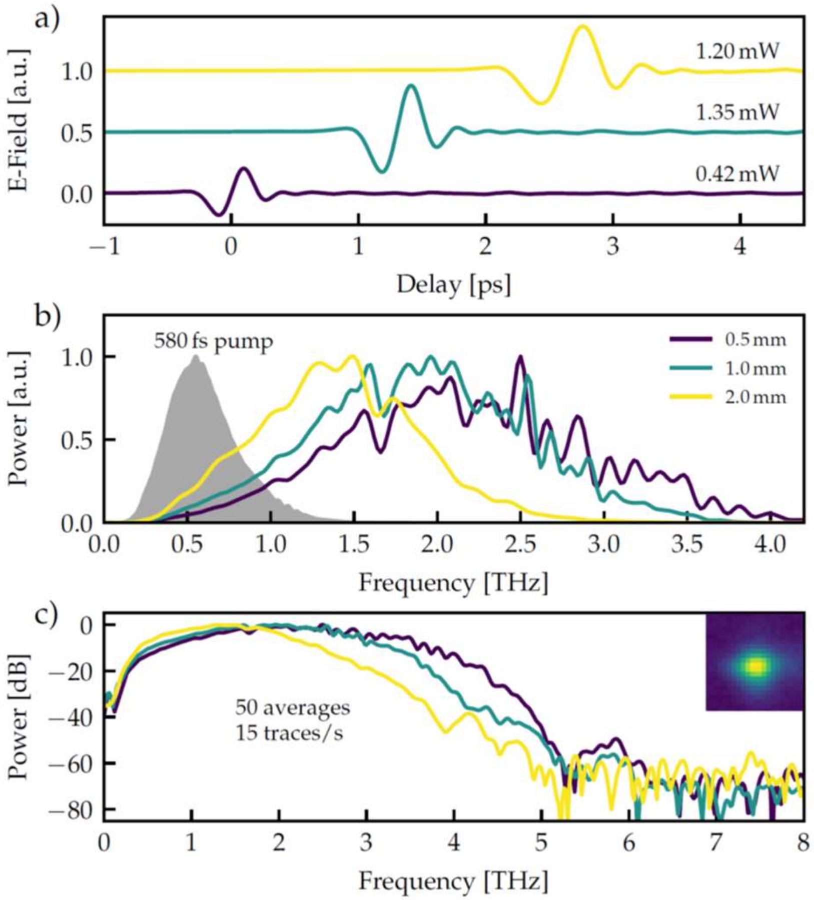
- **damage threshold**

nonlinear process scales with intensity, limited by detrimental processes (multi-photon absorption, free-carrier absorption, damage, etc.)

Material	E_g [eV]	d_eff [pm/V]	$n_g^{1030\,\mathrm{nm}}$	n_T	α_T [1/cm]	FOM [pm²cm²/V²]
GaSe	2.02	28.0	2.96 [105]	3.27	0.5	1.1
GaP	2.48	24.8	3.33 [106]	3.34	0.2	0.8
ZnTe	2.26	68.5	2.98 [107]	3.17	1.3	4.5
LN	3.8	168.0	2.22 [108]	4.96	17.0	16.9
LN 100 K		168.0	2.22 [108]	4.96	4.8	48.8
DAST		615.0	2.59 [109]	~2.25 [101]	~30.0 [101]	151.6
HMQ-TMS		>190.0 [110]	2.14 [111]	~2.17 [111]	~50.0 [111]	>5.8

etc……

Broadband THz generation in GaP

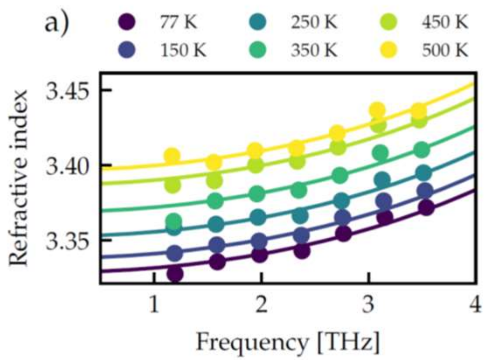


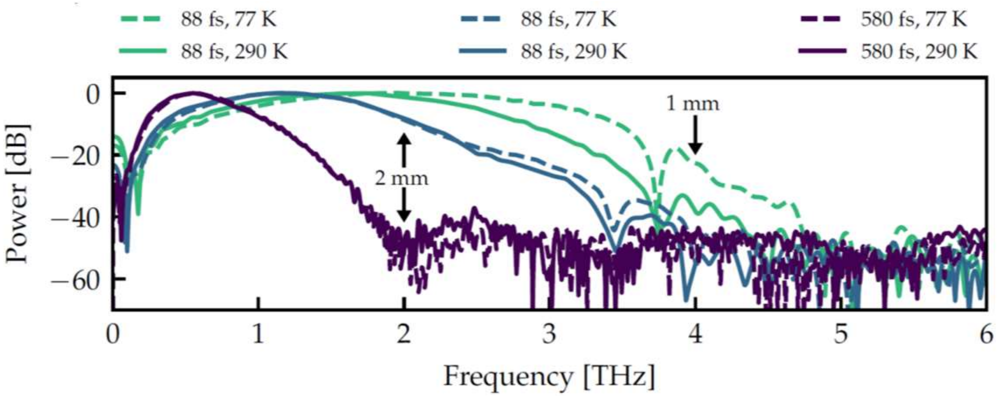
- 1.35 mW for OR in GaP and broadband THz spectra (up to 6 THz)
- Limitations at high power level remained unknown
- Resistance to high-average power and broad bandwidth prompted further study

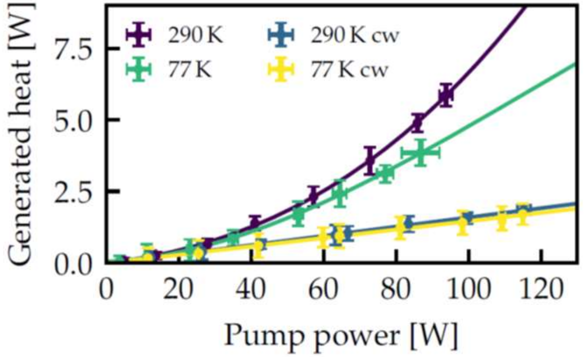
THz	$\mathbf{P_{THz}}$	1.35 mW
	$\mathbf{E_{peak}}$	~ 7.5 kV/cm
	$\mathbf{P_{peak}}$	~ 300 W
	$\boldsymbol{\eta}$	$1.2\cdot10^{-5}$
	$\mathbf{f_{rep}}$	13.3 MHz

F. Meyer et al., "Milliwatt-class broadband THz source driven by a 112 W, sub-100 fs thin-disk laser," Opt. Express **27**, 30340-30349 (2019)
N. Hekmat, et al. “Cryogenically cooled GaP for optical rectification at high excitation average powers,” Opt. Mat. Express, vol. 10, (2020)

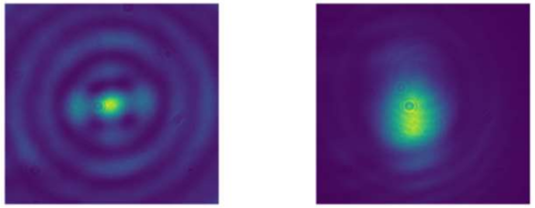
GaP at Cryogenic Temperatures







- Only small decrease of refractive index and velocity matching conditions, minor increase in conversion efficiency, broader bandwidth
- Multi-photon absorption (MPA) still the main limiting factor for efficiency in our excitation regime



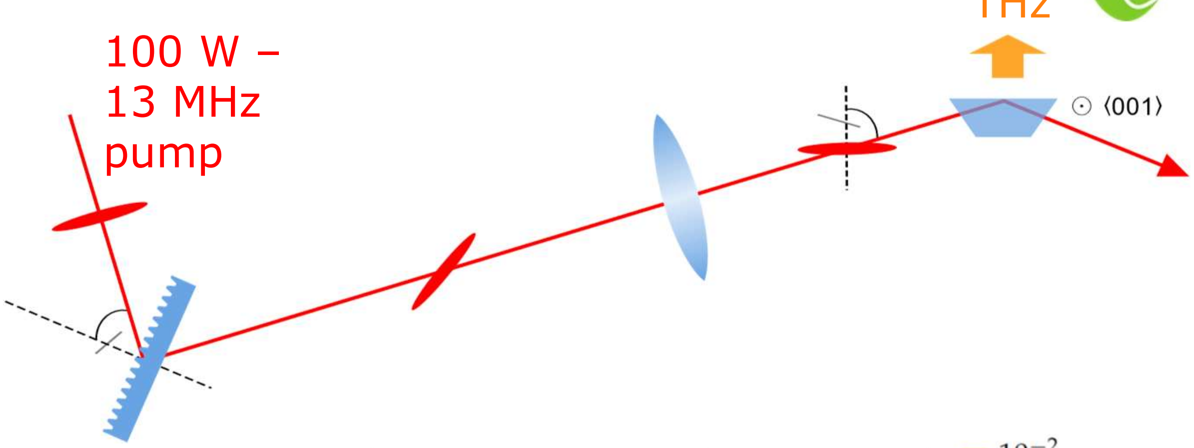
b) 112 W 290 K

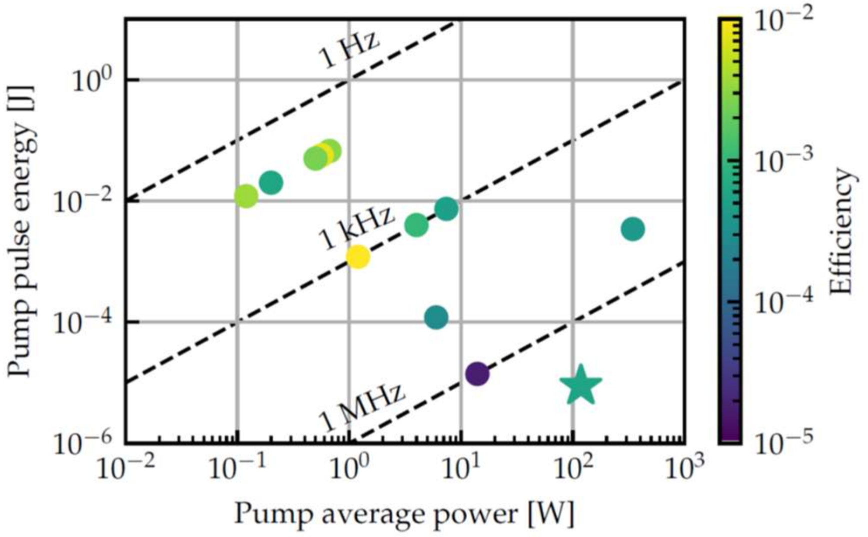
c) 112 W 77 K

N. Hekmat, et al. “Cryogenically cooled GaP for optical rectification at high excitation average powers,” Opt. Mat. Express, vol. 10, (2020)

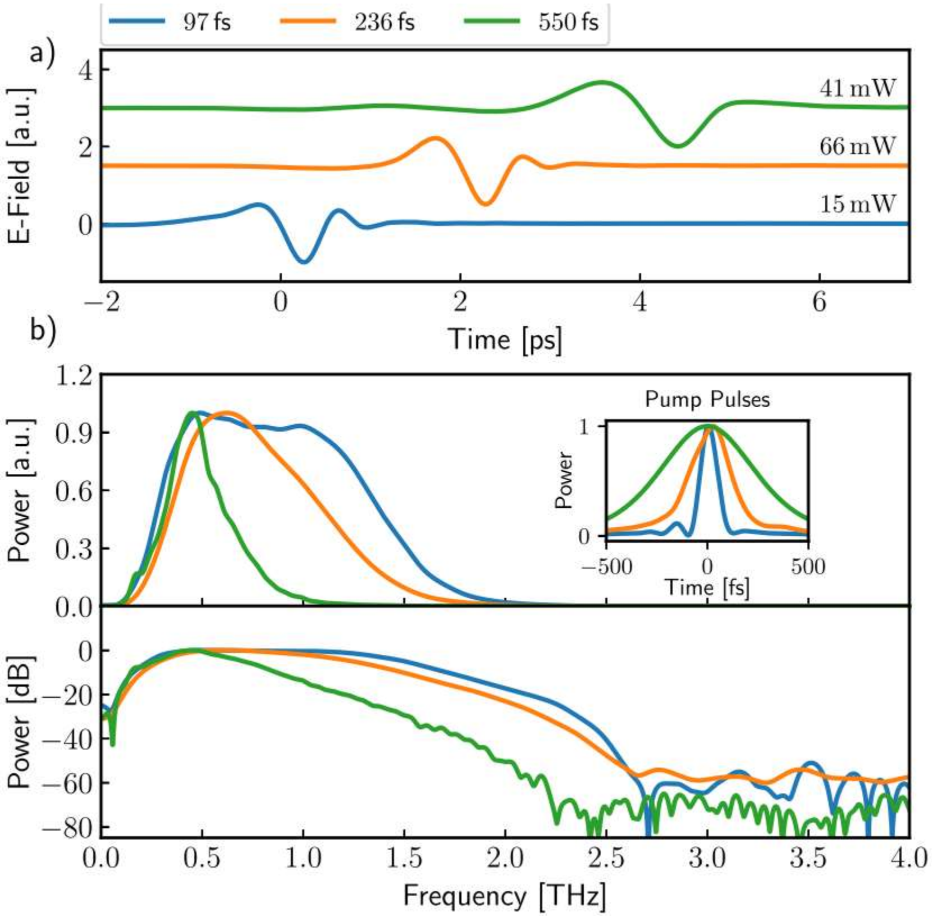
tilted pulse front in Lithium Niobate

- Lithium Niobate (LN): high nonlinearity and little multi-photon absorption
- <u>But:</u> phase matching requires tilting the pulse $v_{NIR}^{gr} \cos\gamma = v_{THz}$
  ($n_{gr,\,NIR} \simeq 2.2$) ($n_{THz} \simeq 5$)
- Increased experimental complexity, more complex generation process due to spatio-temporal couplings and less bandwidth
- **Conversion efficiencies on the 1% level demonstrated (at lower repetition rate)**


100 W –
13 MHz
pump



tilted pulse front in Lithium Niobate



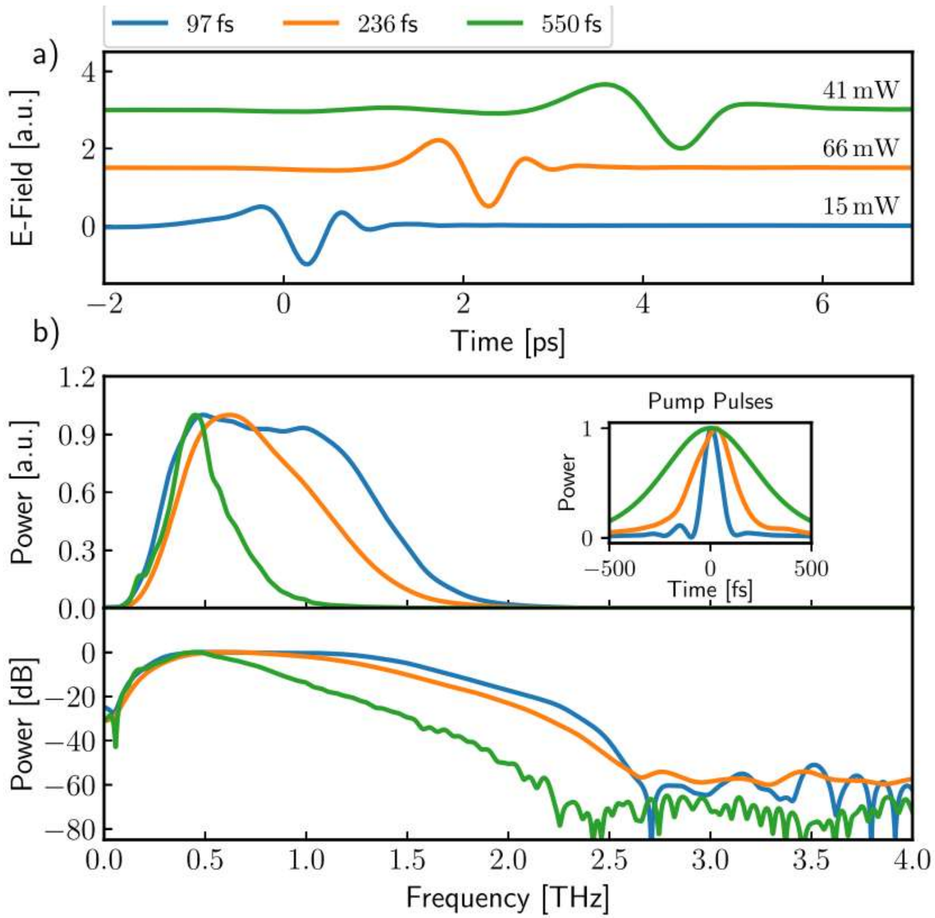
- Higher conversion efficiency at the expense of bandwidth
- Record-high average powers
- Limitations identified: combination of thermal effects and walk-off/depletion due to small spot sizes
- Scaling to watt-level: technically possible

THz	**P_{THz}**	66 mW
	E_{peak}	~16.7 kV/cm
	P_{peak}	~18 kW
	η	$6\cdot10^{-4}$
	f_{rep}	13.3 MHz

F. Meyer et al., "Single-cycle, MHz repetition rate THz source with 66 mW of average power," Opt. Lett. **45**, 2494-2497 (2020)

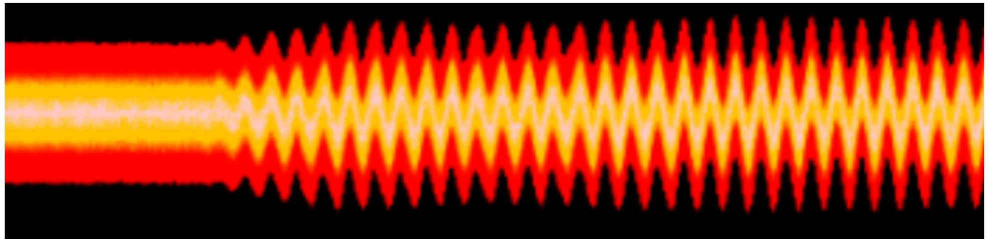
F. Wulf, et al., "Analysis of THz generation using the tilted pulse front geometry in the limit of small pulse energies and beam sizes" Opt. Express 29(12), 18889-18904 (2021)

Benchmarking



A “mini-accelerator”

***High-Field High-Repetition-Rate Terahertz facility @ ELBE** (TELBE)*



TELBE: single-cycle @100 kHz, 0.25 µJ → 25 mW
TELBE (target): single-cycle @ 1 MHz → 0.2 mW
Our oscillator-driven source @13 MHz → 66 mW

THz	**P_{THz}**	66 mW
	E_{peak}	~16.7 kV/cm
	P_{peak}	~18 kW
	η	$6 \cdot 10^{-4}$
	f_{rep}	13.3 MHz

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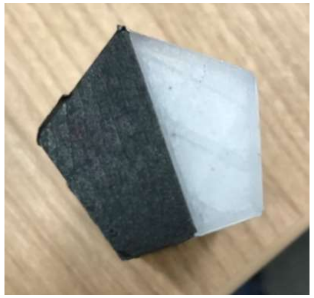
THz imaging

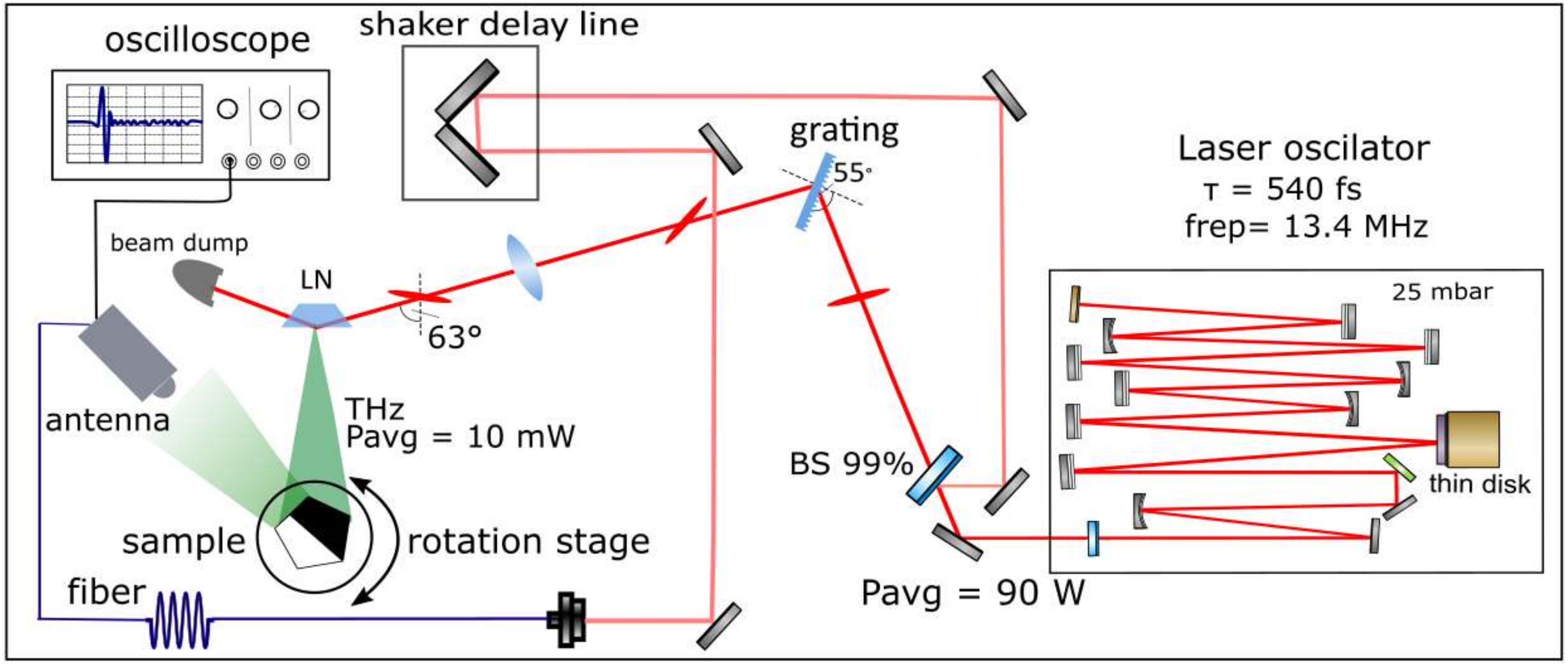
Marie
SFB / TRR 196

"mobile material characterization and identification in the THz range…"

In collaboration with Prof. Jan Balzer, University of Duisburg Essen
Lensless THz imaging of 3D printed sample

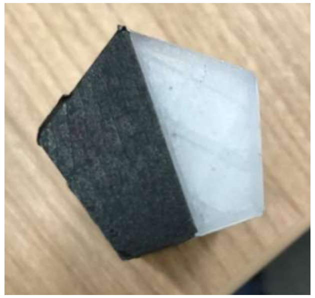
Sample

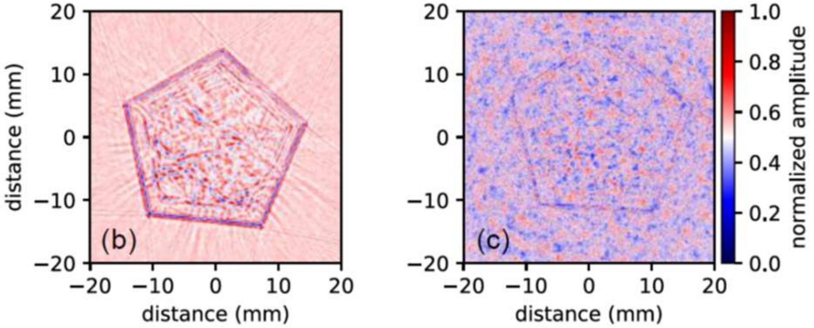




S. Mansourzadeh, D. Damyanov, T. Vogel, F. Wulf, R. Kohlhaas, B. Globisch, T. Schultze, M. Hoffmann, J. C. Balzer, and C. J. Saraceno "High-power Lensless THz Imaging of Hidden Objects," in IEEE Access, doi: 10.1109/ACCESS.2020.3048781 (2021)

THz imaging with LN source





	Commercial system (TeraK15)	**High-power TDL**
Power	200 µW	20 mW
Pulse duration	100 fs	580 fs
Wavelength Laser	1550 nm (receiver optimized for this λ)	1030 nm
Repetition rate	100 MHz	13.4 MHz

- Same detector and acquisition time
- Contrast enhancement
- Difference in material recognizable

Potential for improvement very large:

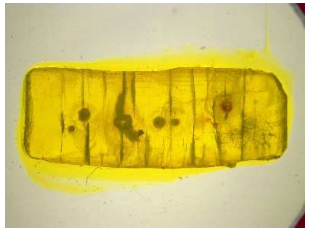
- **Measurement acceleration**
- **3D images**
- **Concealed objects**
- **…**

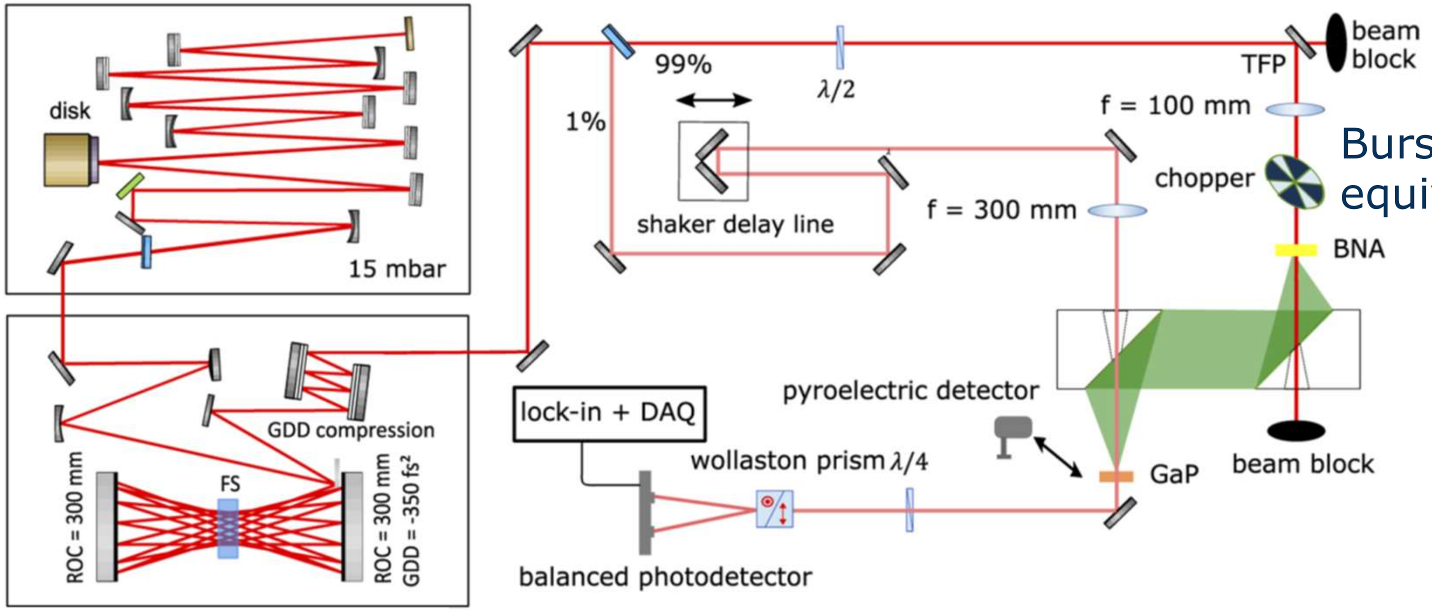
S. Mansourzadeh, D. Damyanov, T. Vogel, F. Wulf, R. Kohlhaas, B. Globisch, T. Schultze, M. Hoffmann, J. C. Balzer, and C. J. Saraceno "High-power Lensless THz Imaging of Hidden Objects," in IEEE Access, doi: 10.1109/ACCESS.2020.3048781 (2021)

broader bandwidths: organic crystals

Organic crystals:

- Combine high conversion efficiency and broad THz bandwidth in collinear scheme
- Most results limited to low repetition rate due to poor thermal properties
- BNA (N-benzyl-2-methyl-4-nitroaniline): collinear phase-matching for 1030 nm





Burst-mode equivalent

S. Mansourzadeh, T. Vogel, M. Shalaby, F. Wulf, and C. J. Saraceno “Milliwatt average power, MHz-repetition rate, broadband THz generation in organic crystal BNA with diamond substrate” Optics Express Vol. 29, Issue 24, pp. 38946-38957 (2021)

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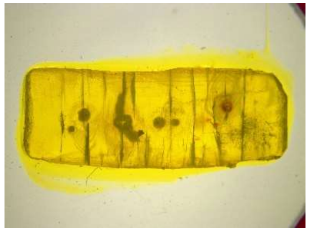
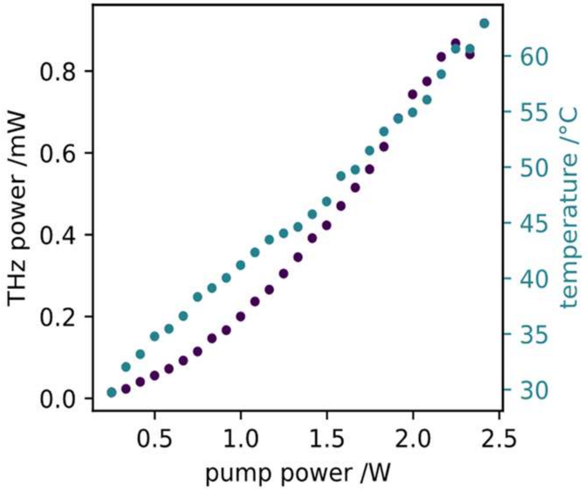
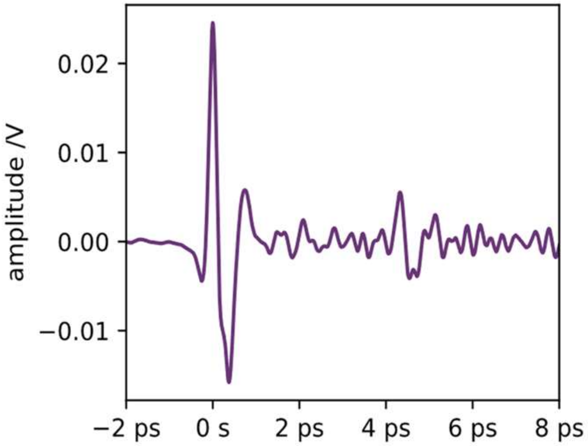
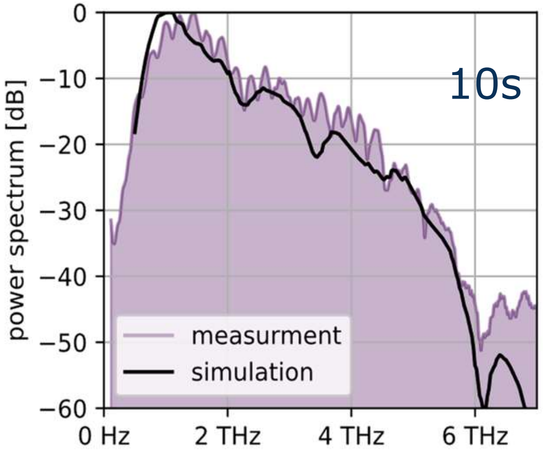




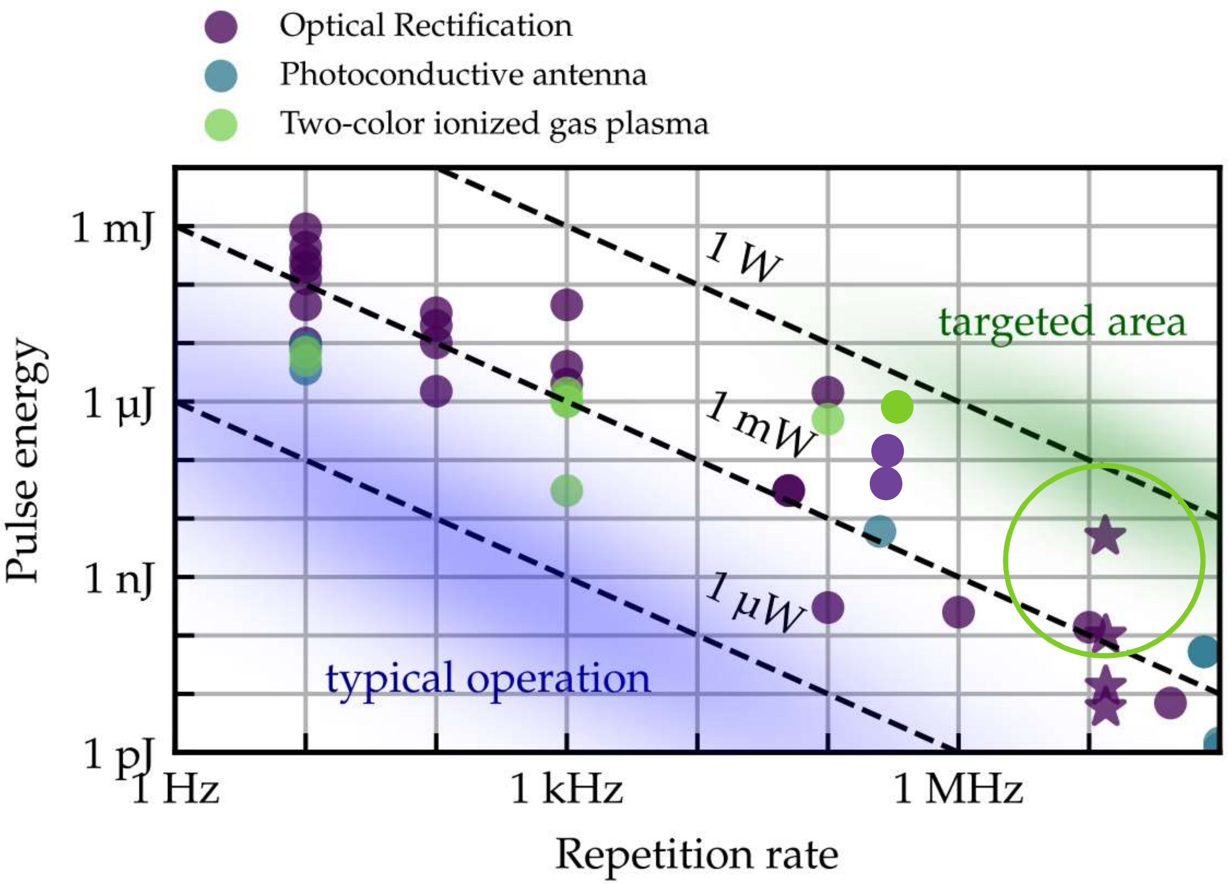




- Laser power 24 W (**10% duty cycle** – 2.4 W on crystal)
- **0.95 mW THz power** using **diamond-heatsinked BNA**
- Broad flat spectrum – limited by detection in 0.2 mm GaP

S. Mansourzadeh, T. Vogel, M. Shalaby, F. Wulf, and C. J. Saraceno "Milliwatt average power, MHz-repetition rate, broadband THz generation in organic crystal BNA with diamond substrate" Optics Express Vol. 29, Issue 24, pp. 38946-38957 (2021)

Back to the state-of-the-art

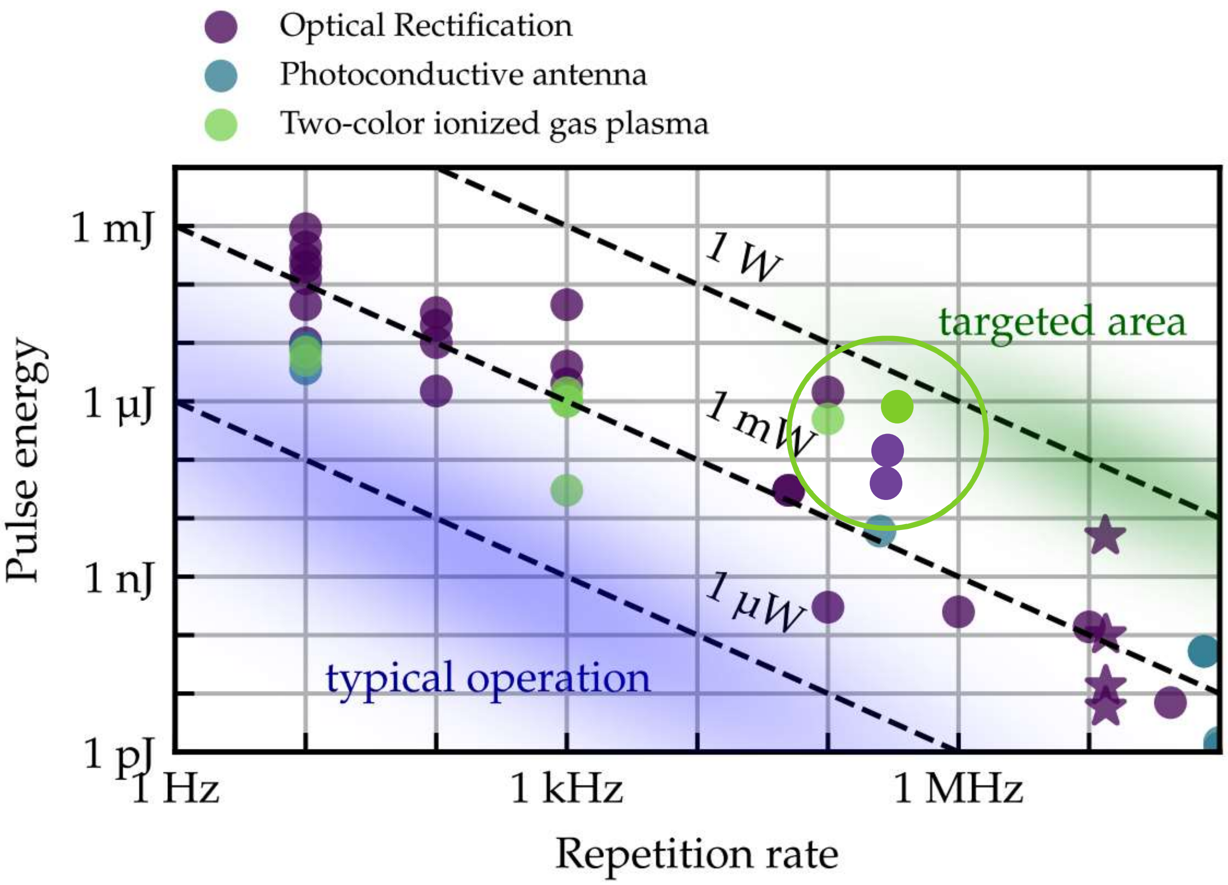


10 MHz – 100 MHz

Moderate pulse energies (10s nJ)

Promising for linear spectroscopy, imaging, etc.

Back to the state-of-the-art

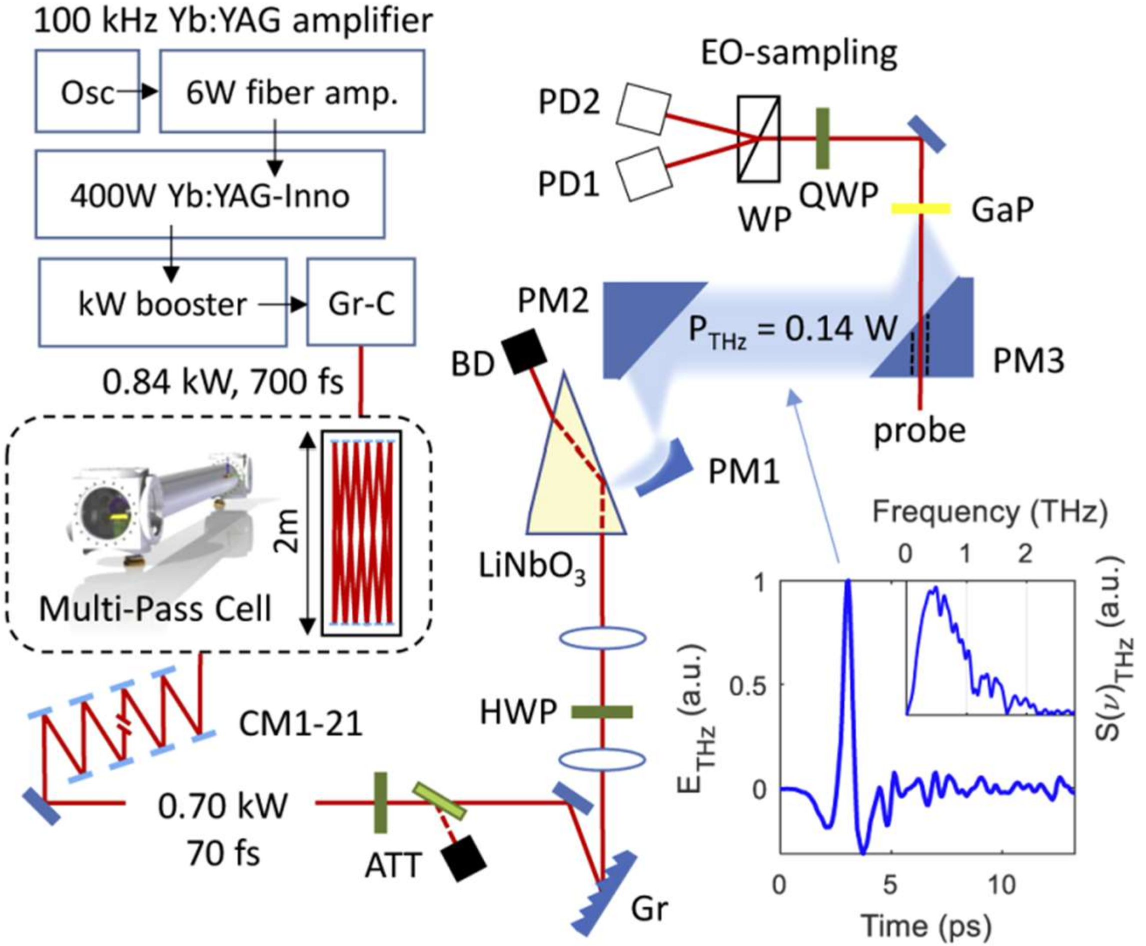


100 kHz – 1 MHz

High pulse energies (µJ THz energies)

Promising for nonlinear spectroscopy

Lithium niobate - slab amplifier

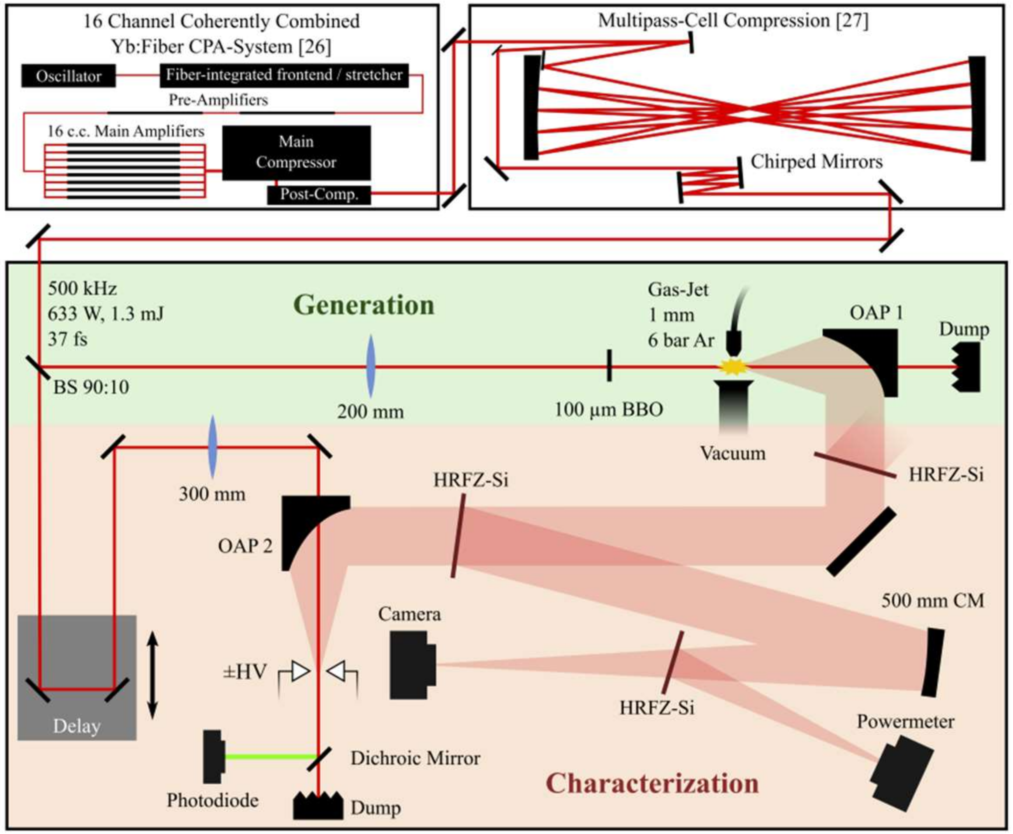


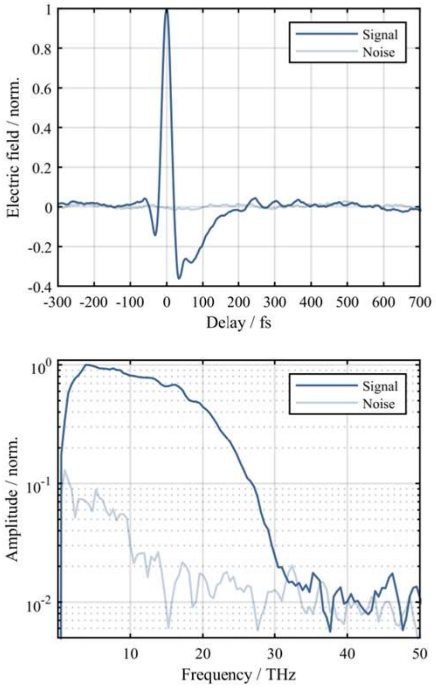
- 144 mW (344 W input)
- 100 kHz repetition rate
- Lithium Niobate: up to 2 THz
- 150 kV/cm estimated peak E-field

P. Kramer, M. Windeler, K. Mecseki, E. G. Champenois, M. C. Hoffmann, and F. Tavella, "Enabling high repetition rate nonlinear THz science with a kilowatt-class sub-100 fs laser source," Opt. Express 28, 16951-16967 (2020)

Plasma source – multi-channel rod amplifier

IAP, University of Jena, Germany

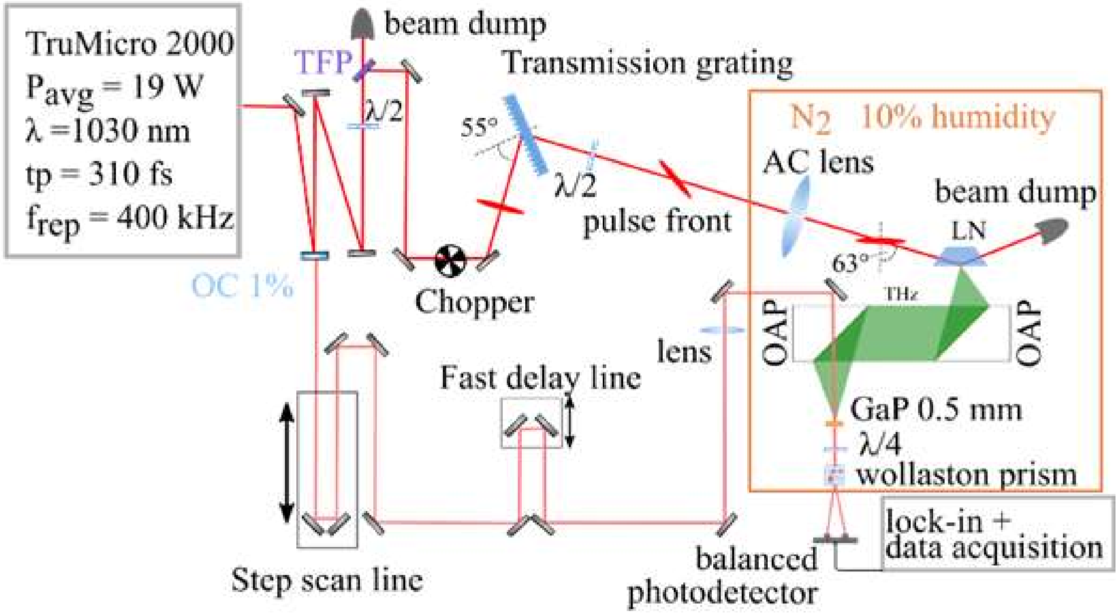


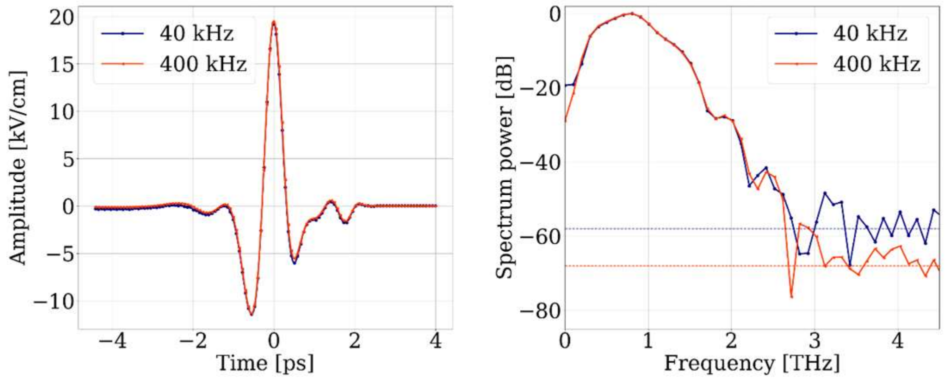


- **640 mW** (633 W input)
- **500 kHz** repetition rate
- Very broadband up to 30 THz – performance limited by detection
- Estimated peak E-field 1 MV/cm

Joachim Buldt, Henning Stark, Michael Müller, Christian Grebing, César Jauregui, and Jens Limpert, "Gas-plasma-based generation of broadband terahertz radiation with 640 mW average power," Opt. Lett. 46, 5256-5259 (2021)

Lithium niobate – commercial Yb laser

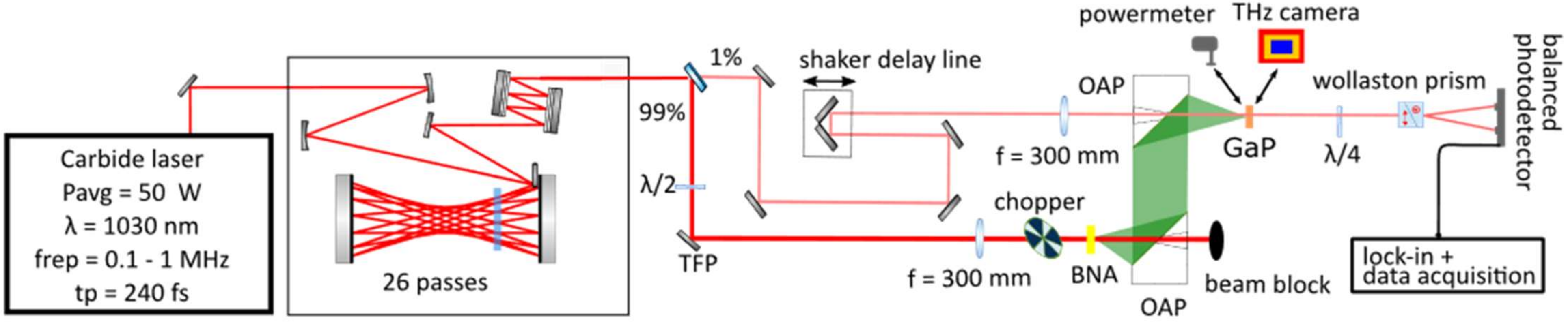


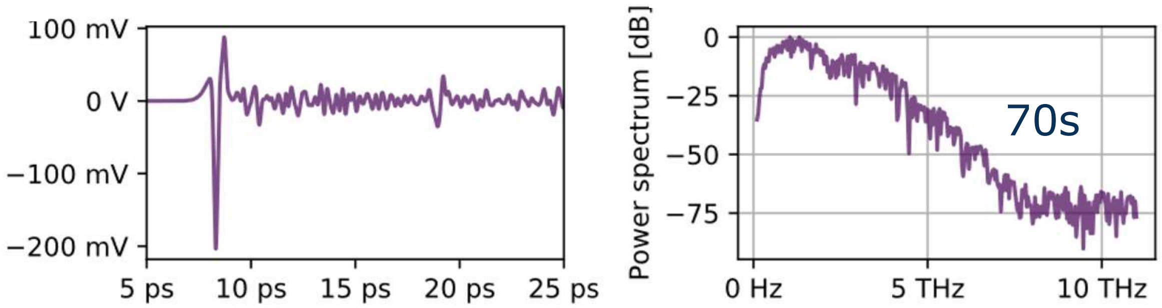


- **400 kHz**
- **25 mW** of average power **(19 W input)**
- Simple turn-key commercial laser
- Repetition rate variable, allows to study accumulation effects
- Estimated peak E-field 60 kV/cm

C. Millon, et al. Optics Express, accepted for publication (2023)

Organic crystals – commercial Yb laser

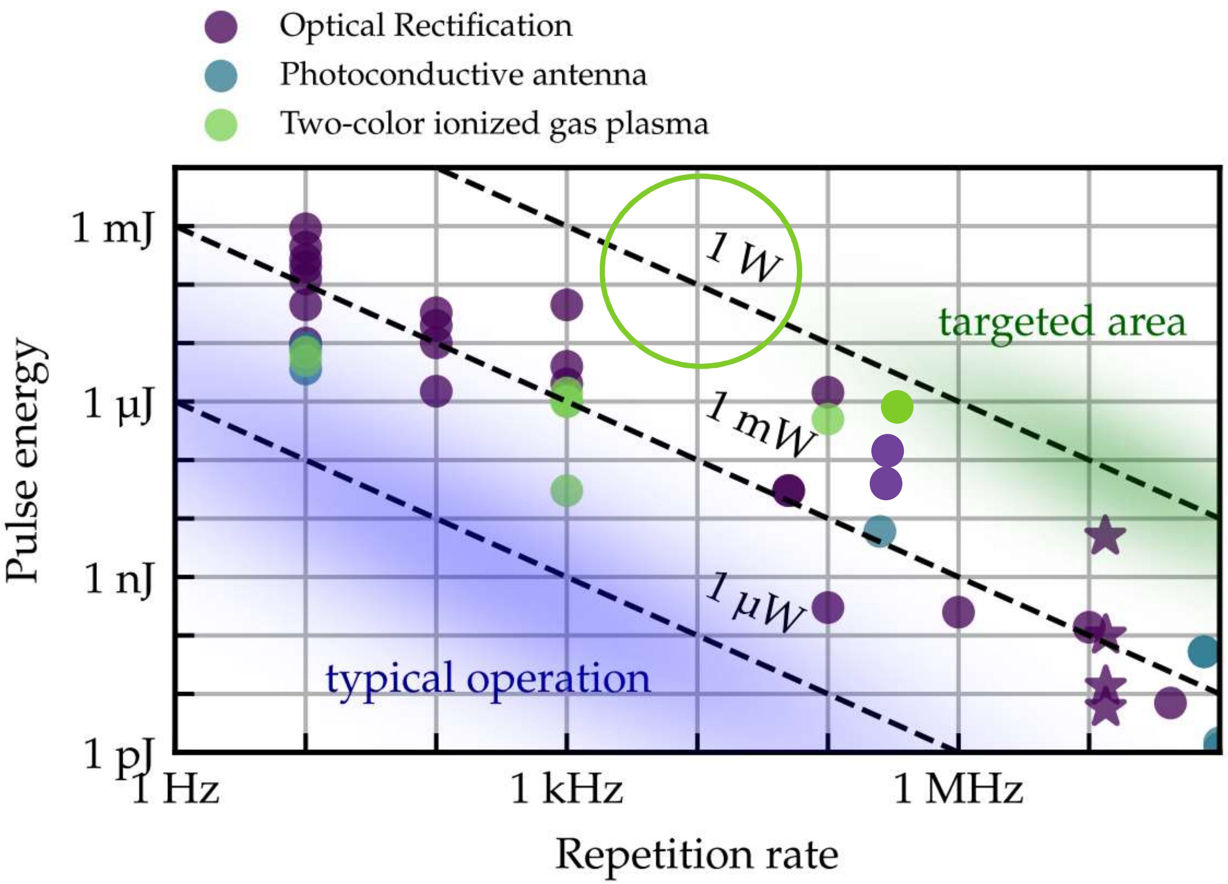




- **540 kHz rep rate**
- **5.6 mW THz power (6 W input)**
- **Very broad bandwidth up to 7.8 THz**
- Conversion efficiency similar to low repetition rate
- Estimated peak E-field 29 kV/cm

S. Mansourzadeh et al, APL Photonics, accepted (2023)

Back to the state-of-the-art



100 kHz – 1 MHz

Very high pulse energies

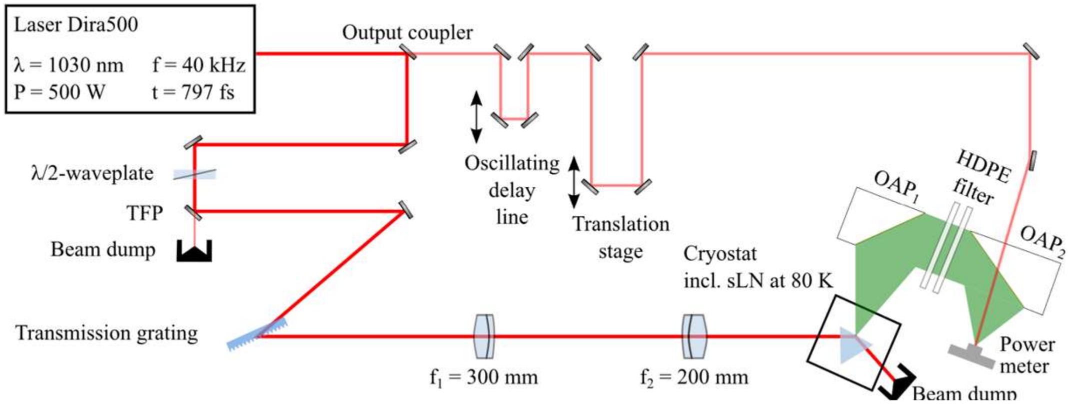
(mJ THz energies)

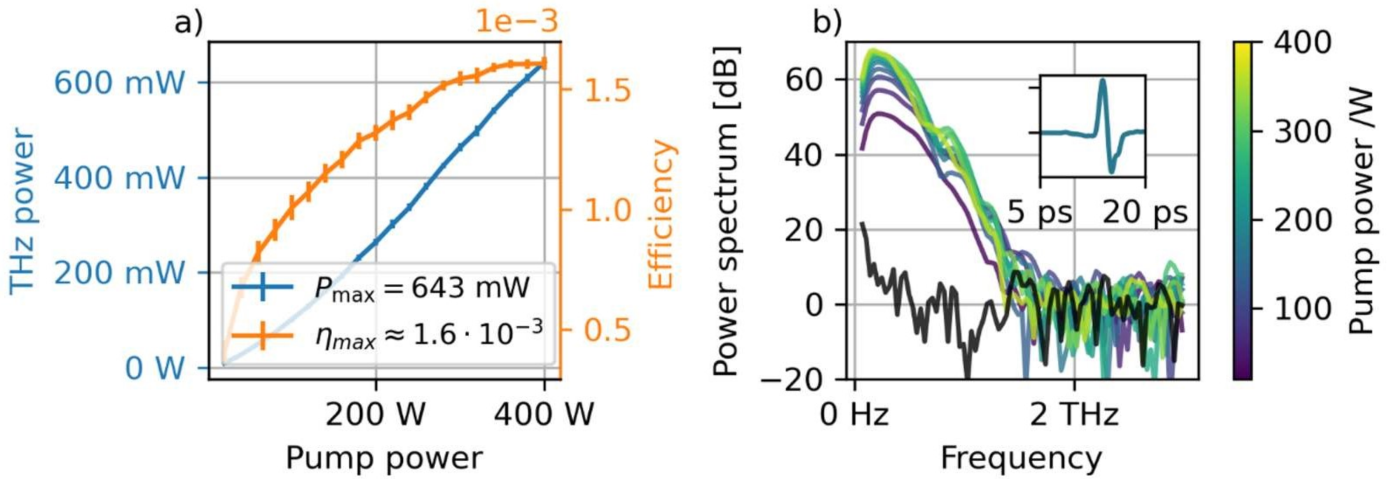
Promising for nonlinear spectroscopy

Higher THz energies

Next step: Thin-disk amplifier

500 W @ 10 kHz → 50 mJ, 700 fs





- **First step: 40 kHz rep rate**
- **643 mW THz power**
- peak E-field --- not measured yet!
  should approach MV/cm

T. Vogel – in preparation

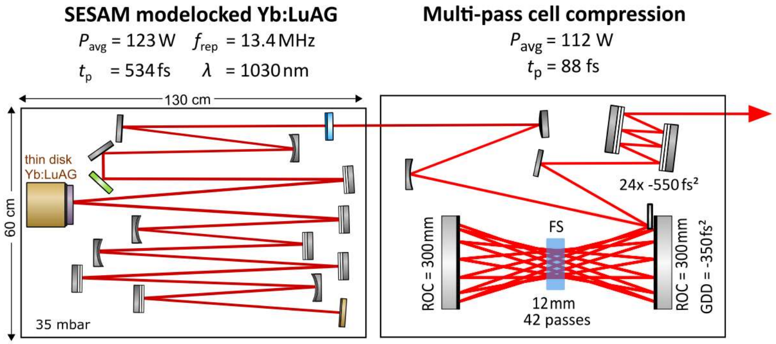
Conclusion

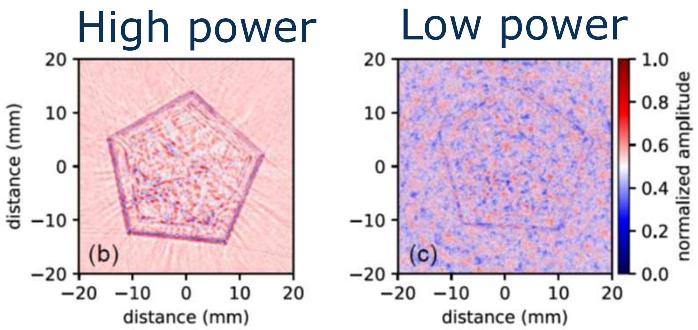
Conclusion:

- Few-cycle THz broadband sources with average powers in the **tens to hundreds of mW** can be generated using new high-power laser technology with **hundreds of watts**
- Watt-level and beyond seems to be near future goals

Outlook:

- Keep improving the sources, both driving lasers and THz generation techniques
- Work on suitable detectors
- Find other areas of application where the sources can shine





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