Lecture Series Buenos Aires

18-3-2024 until 22-3-2024

Lecture F6 – Optical Parametric Chirped Pulse Amplification

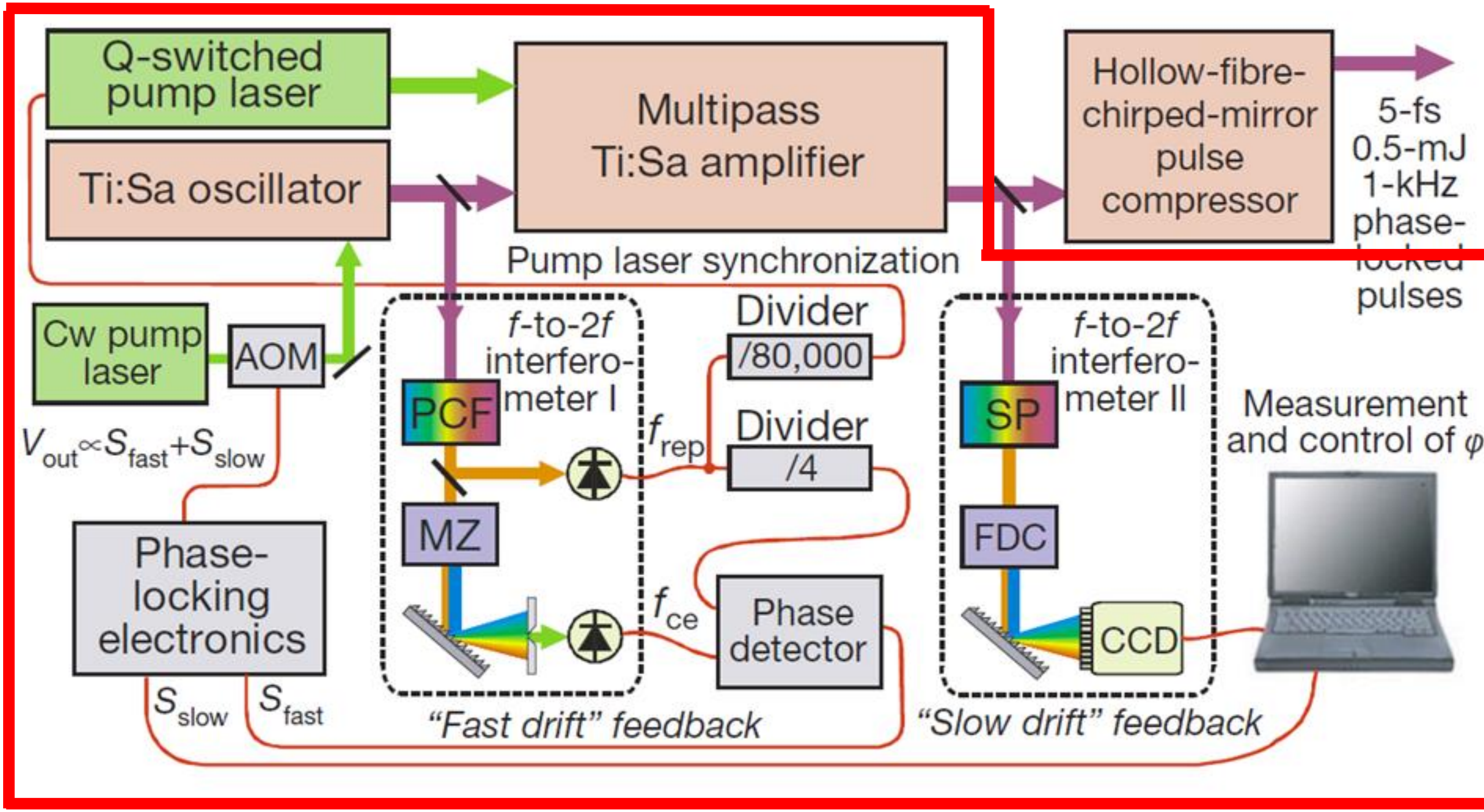
Federico Furch

furch@mbi-berlin.de

Max-Born-Institut

Optical Parametric Chirped Pulse Amplification (OPCPA)

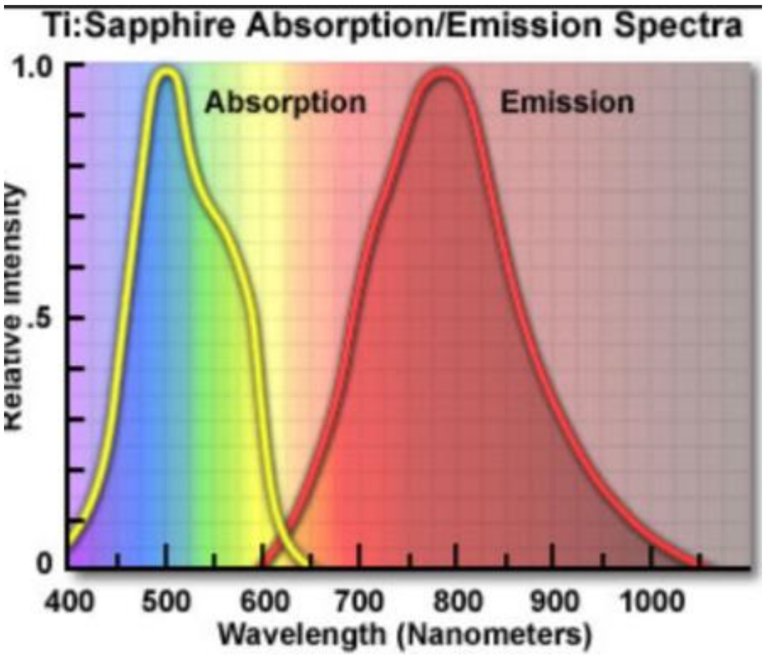
A state-of-the-art laser system for attosecond science: an alternative



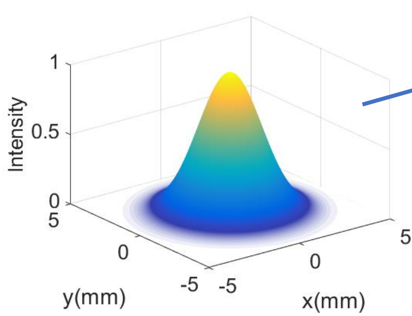
A. Baltuska et al., Nature 421, 611 (2003)

Limitations of Ti:Sapphire CPAs

Limitations to spectral range



$P_{pump}(x,y) \propto e^{-2(x^2+y^2)/w^2}$



Limitations to pulse duration

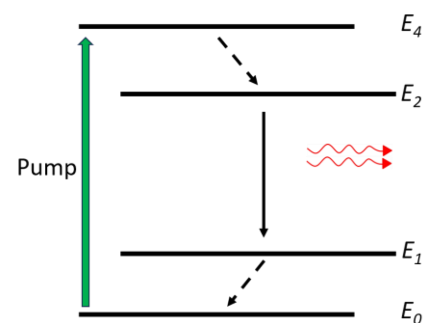
gain $\sim e^{g(\omega)L}$

gain narrowing $\Delta\omega_{out} \ll \Delta\omega_{g(\omega)}$

Limitations to power scaling

$P_{avg} = Energy_{pulse} * f_{rep.rate}$

Fraction of pump that turns into heat $1 - \frac{\hbar\omega_{laser}}{\hbar\omega_{pump}}$

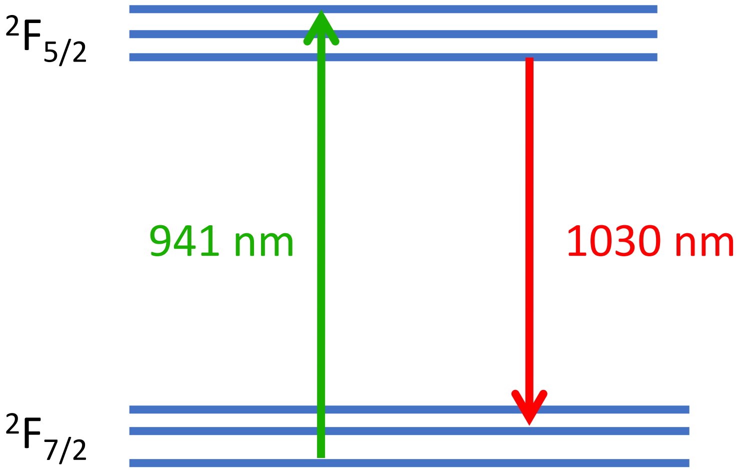


Heat source profile: may originate

- Thermal lensing (dn/dT)
- Thermal induced birefringence
- Damage of material

A laser material for high average power

Yb-doped Yttrium
Aluminum Garnet
Yb:YAG



- Absorption band at InGaAs wavelengths
  - High power laser diodes are commercially available
- Low quantum defect ($1 - \frac{\hbar\omega_{laser}}{\hbar\omega_{pump}} < 0.1$)
  - Potential for high average power operation
- Long upper level lifetime (~1 msec)
  - Efficiently store energy from low peak power pump
- High quality (large) crystals
  - Crystalline or ceramic form
- BUT narrow gain bandwidth: post-compression, OPCPAs

Alternatives using Yb systems

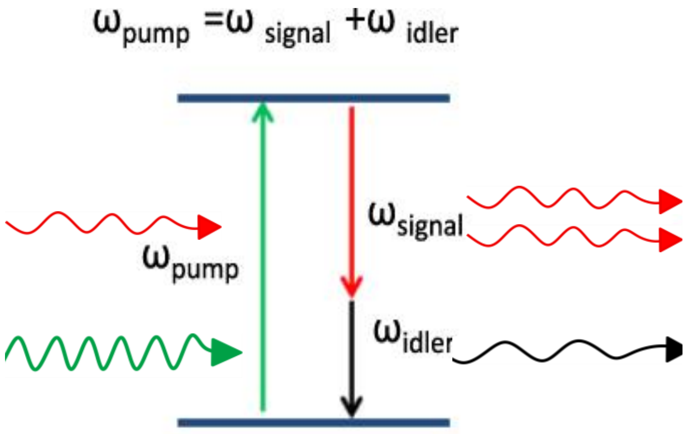
Ti:Sapphire → ultrashort pulses
Yb-doped → high energy, high average power

Energy transfer in Optical Parametric Amplifier

Yb-doped → high energy, high average power
Nonlinear pulse compression with large compression factors to reach sub-50 fs and even sub-10 fs pulses

Parametric Amplification

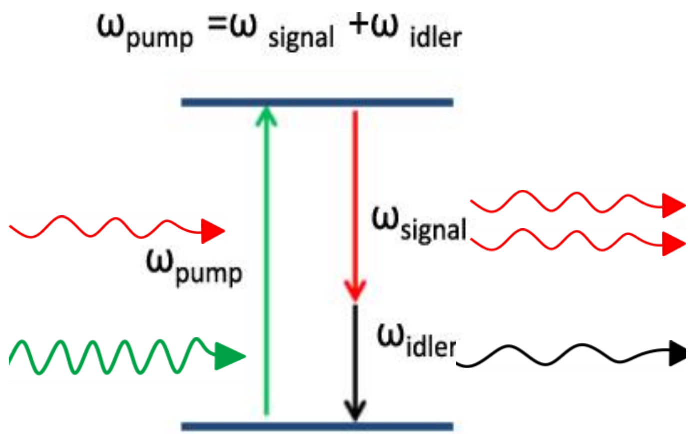
- No absorption



Instantaneous nonlinear process of second order in the E-field

Parametric Amplification

- No absorption



Instantaneous nonlinear process of second order in the E-field

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \right)$$

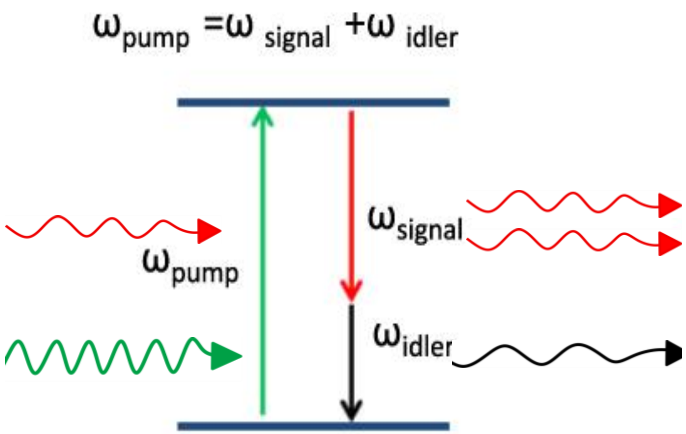
$$\hat{\mathbf{D}}(\mathbf{r}, \omega, z) = \epsilon_0 \epsilon(\omega) \hat{\mathbf{E}}(\mathbf{r}, \omega, z) + \hat{\mathbf{P}}(\mathbf{r}, \omega, z),$$

$$\boldsymbol{P} = \boldsymbol{P}^{(1)} + \boldsymbol{P}^{(NL)}, \qquad \boldsymbol{P}^{(NL)} \propto \chi^{(2)} \boldsymbol{E}^2$$

Parametric Amplification

- No absorption

- Gain bandwidth determined by phase-matching

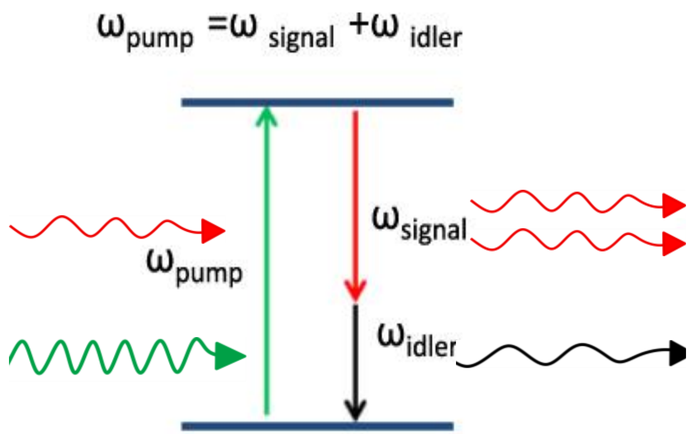


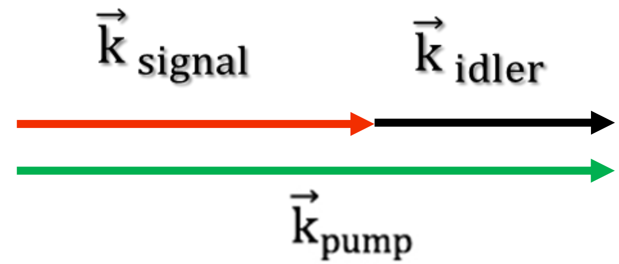
Phase-matching

$$\Delta \mathbf{k} = \mathbf{k}_{\mathbf{signal}} + \mathbf{k}_{\mathbf{idler}} - \mathbf{k}_{\mathbf{pump}} = \mathbf{0}$$

Parametric Amplification

- No absorption





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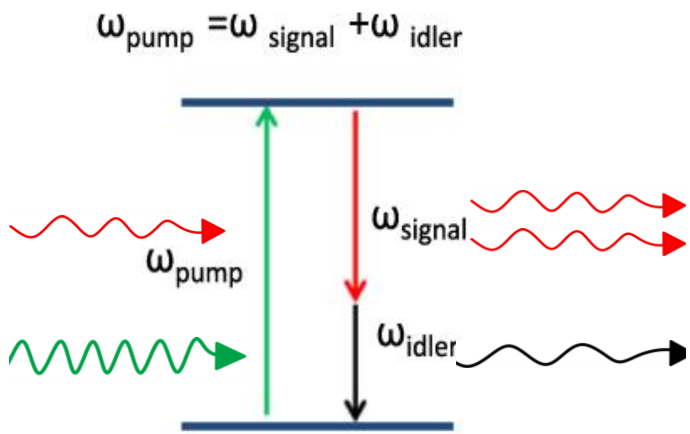
$$\Delta \mathbf{k} = \mathbf{k}_{\mathbf{signal}} + \mathbf{k}_{\mathbf{idler}} - \mathbf{k}_{\mathbf{pump}} = \mathbf{0}$$

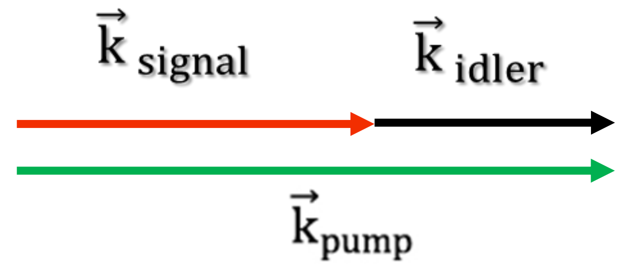
$$k(\omega) = \frac{\omega n(\omega)}{c}$$

Use bi-refringent material

Parametric Amplification

- No absorption
- Gain bandwidth determined by phase-matching





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Use bi-refringent material

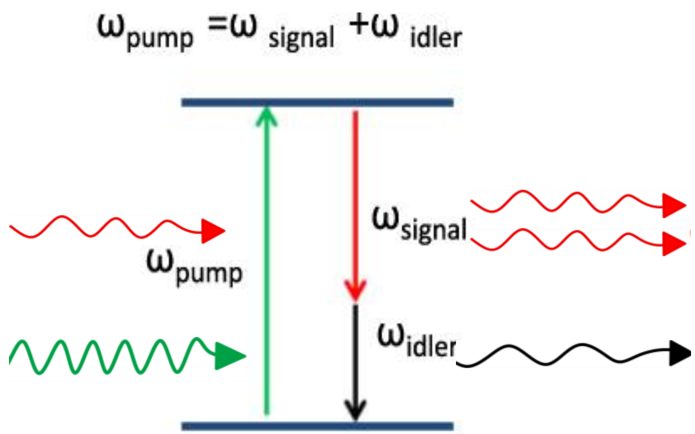
Type-I phase matching: $k_{pump}(\omega) = \frac{\omega n(\omega,\theta)}{c}$

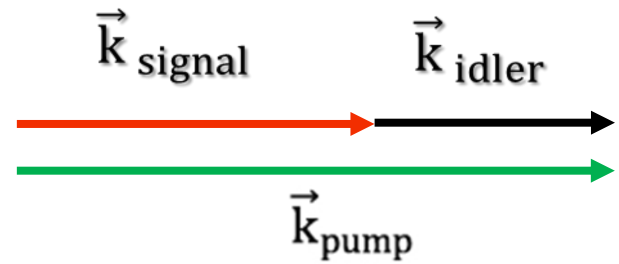
θ: Angle between k-vector and crystal axis

$$\frac{1}{n_e(\theta)^2} = \frac{sin^2\theta}{n_{e,90^0}{}^2} + \frac{cos^2\theta}{n_0{}^2}$$

Parametric Amplification

- No absorption
- Gain bandwidth determined by phase-matching





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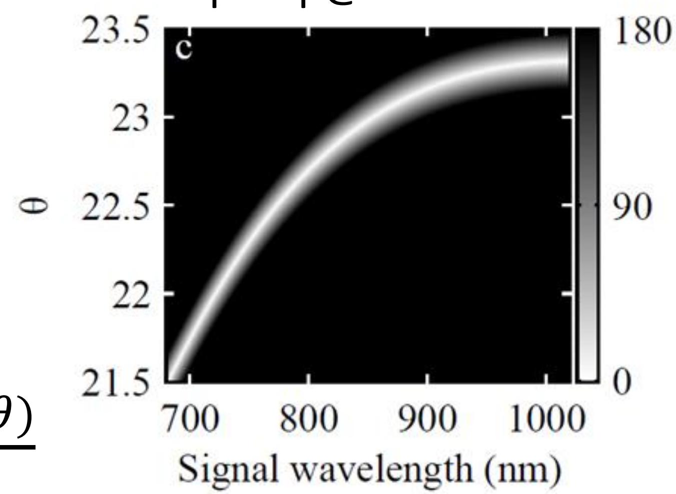
BBO 1 mm
pump@ 515 nm



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- No absorption
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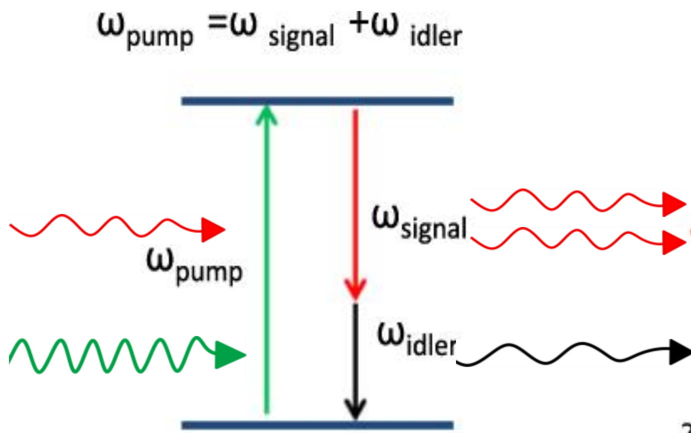

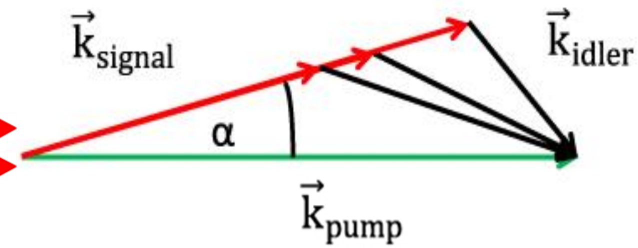

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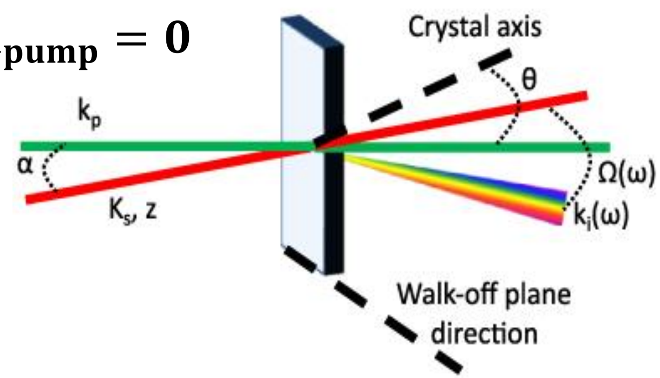
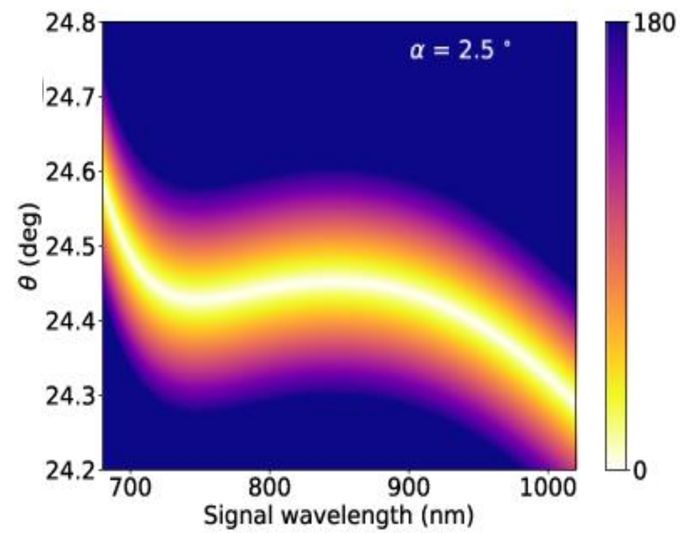




Phase-mismatch ($\Delta \mathbf{k}$):
1mm BBO Crystal

- Noncollinear geometry allows broadband amplification

Type-I phase matching:

$$k_{pump}(\omega) = \frac{\omega n(\omega,\theta)}{c}$$

Optical Parametric Amplification

OBSERVATION OF PARAMETRIC AMPLIFICATION IN THE OPTICAL RANGE

S. A. Akhmanov, A. I. Kovrigin, A. S. Piskarskas, V. V. Fadeev, and R. V. Khokhlov
Physics Faculty, Moscow State University
Submitted 23 July 1965

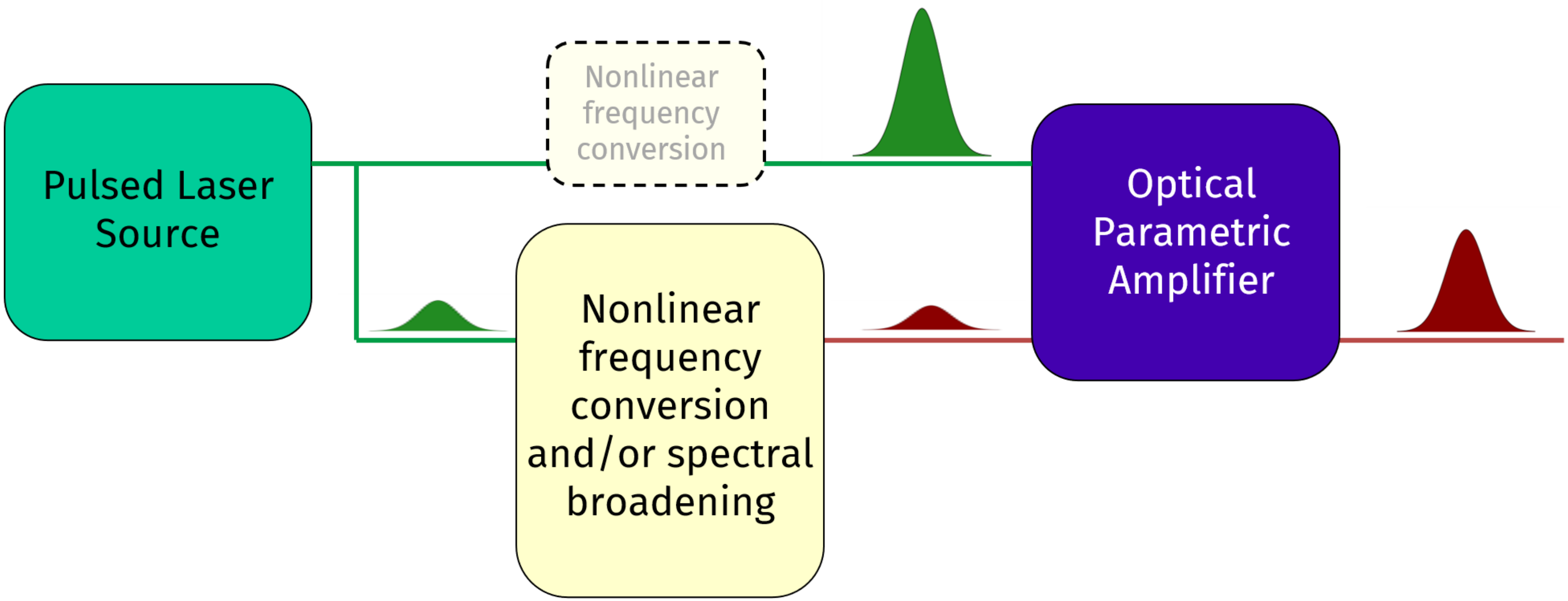
We report here the results of an experiment in which we observed directly parametric amplification of an optical signal with wavelength $\lambda_s = 1.06\ \mu$ in a KDP crystal excited by an intense pump wave with $\lambda_p = 0.53\ \mu$. The feasibility of such an effect in the optical band and its theory were detailed in [1-3]; results of experiments in which parametric amplification at wavelength $\lambda_s = 0.63\ \mu$ has been indirectly registered are described in [4].

In a nonlinear medium with a polarization that depends quadratically on the magnetic field intensity, the energy of an intense pump wave (frequency ω_p) can be transferred to waves with frequencies ω_1 and ω_2 satisfying the relation $\omega_p = \omega_1 + \omega_2$. The energy transfer is most effective if the following relation is satisfied between the wave vectors of the interacting waves (the so-called synchronism condition):

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_p. \qquad (1)$$

Optical Parametric Amplification

OPA: Great way to go to a different part of the spectrum
(if I already have short pulses with high energy)



Optical Parametric Amplification

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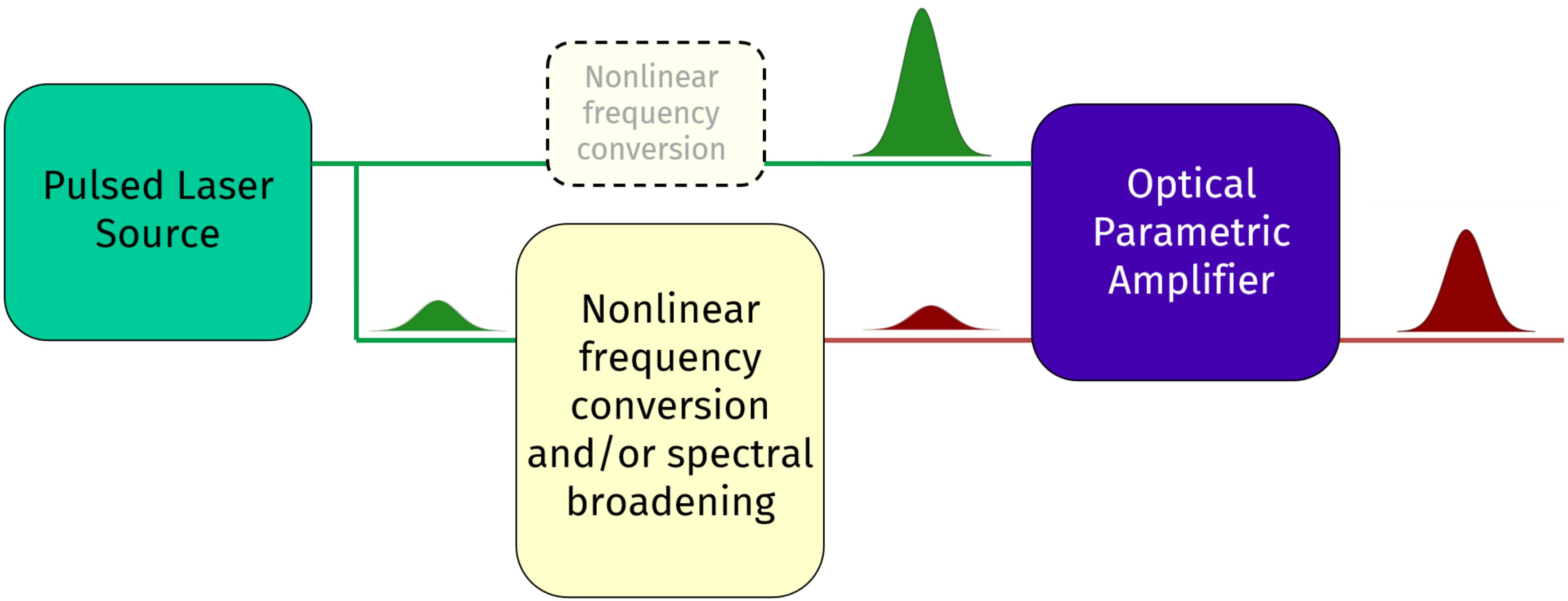


Example: start from 800 nm and go to 1300 nm to generate higher frequencies during HHG, or IAP combining HHG with 800 nm + 1300 nm

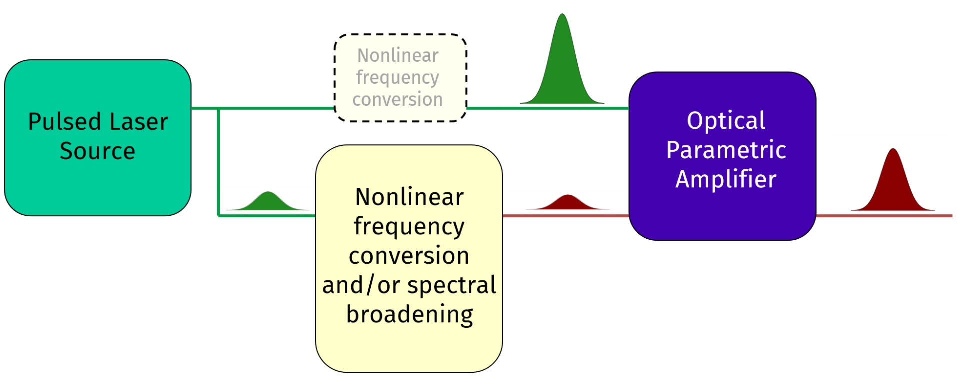
Optical Parametric Amplification

1494 OPTICS LETTERS / Vol. 22, No. 19 / October 1, 1997

Sub-20-fs pulses tunable across the visible from a blue-pumped single-pass noncollinear parametric converter

T. Wilhelm, J. Piel, and E. Riedle

Institut für Medizinische Optik, Ludwig-Maximilians-Universität München, Barbarastrasse 16, D-80797 München, Germany



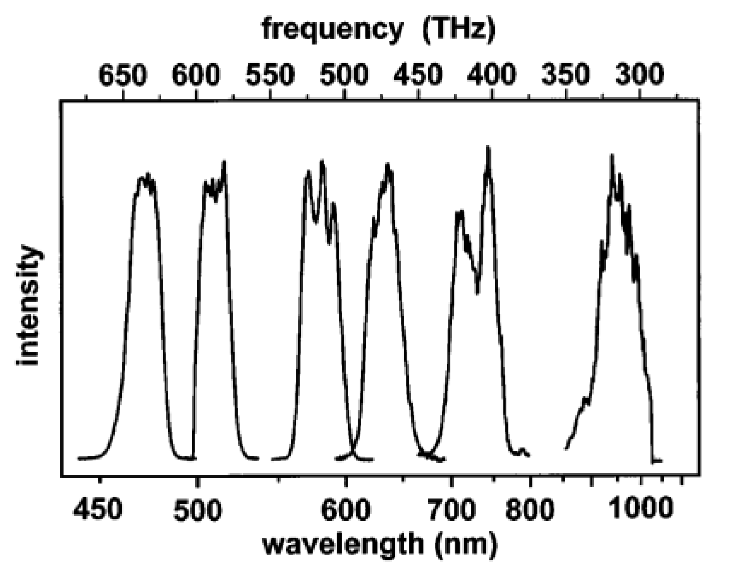
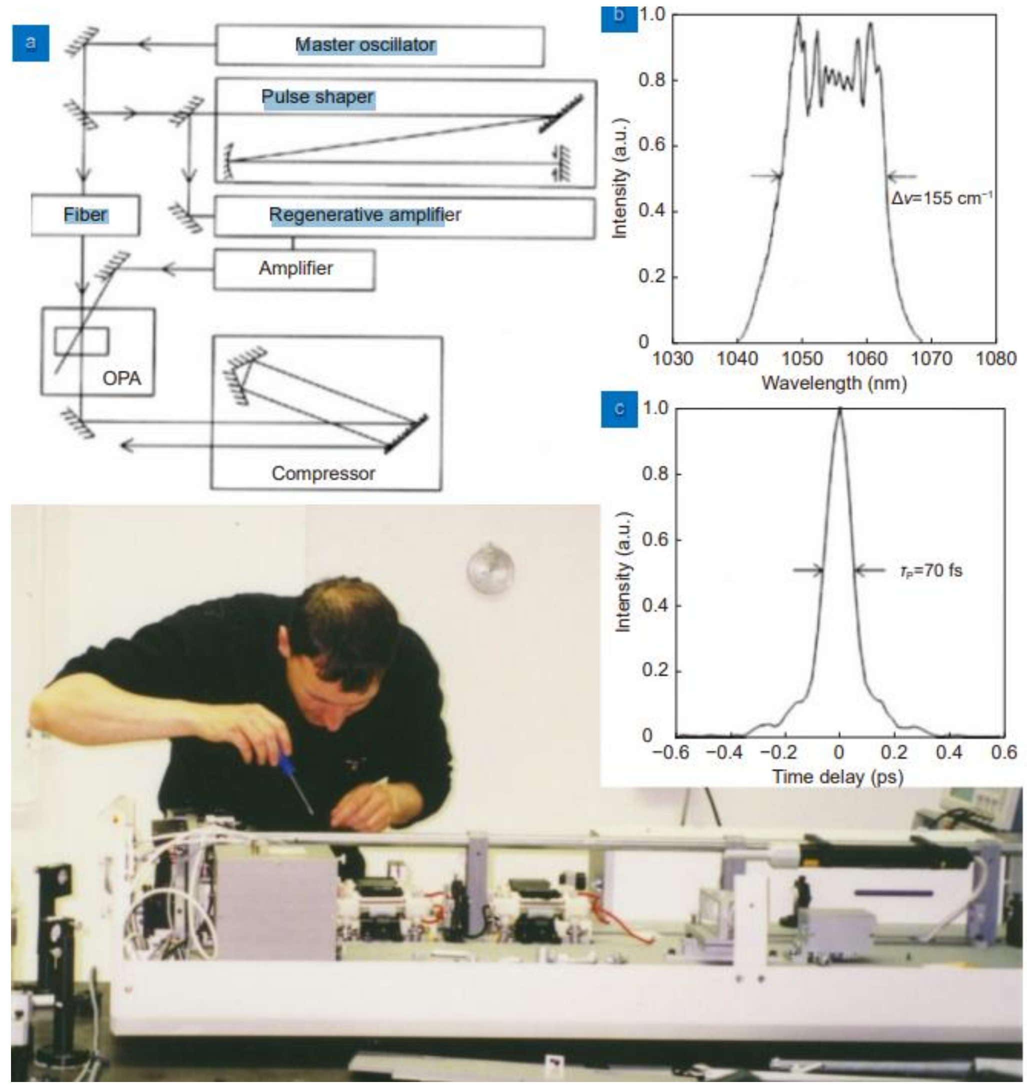


Fig. 2. Spectra of femtosecond pulses generated by non-collinear parametric amplification in a 2-mm BBO crystal.

Optical Parametric Chirped Pulse Amplification (OPCPA)

First demonstration of OPCPA: A. Dubietis,G. Jonušauskas, A. Piskarskas. *Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal*. Opt Commun **88**, 437–440 (1992)

- 1.7ps, 1055nm pulses from a Nd:glass oscillator, spectrally broadened (and stretched) in a fiber
- Amplified in BBO crystal
- Compressed with grating pair: 70fs, 65μJ



Optical Parametric Chirped Pulse Amplification (OPCPA)

ELSEVIER

1 December 1997

Optics Communications 144 (1997) 125–133

OPTICS COMMUNICATIONS

Full length article

The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers

I.N. Ross *, P. Matousek, M. Towrie, A.J. Langley, J.L. Collier

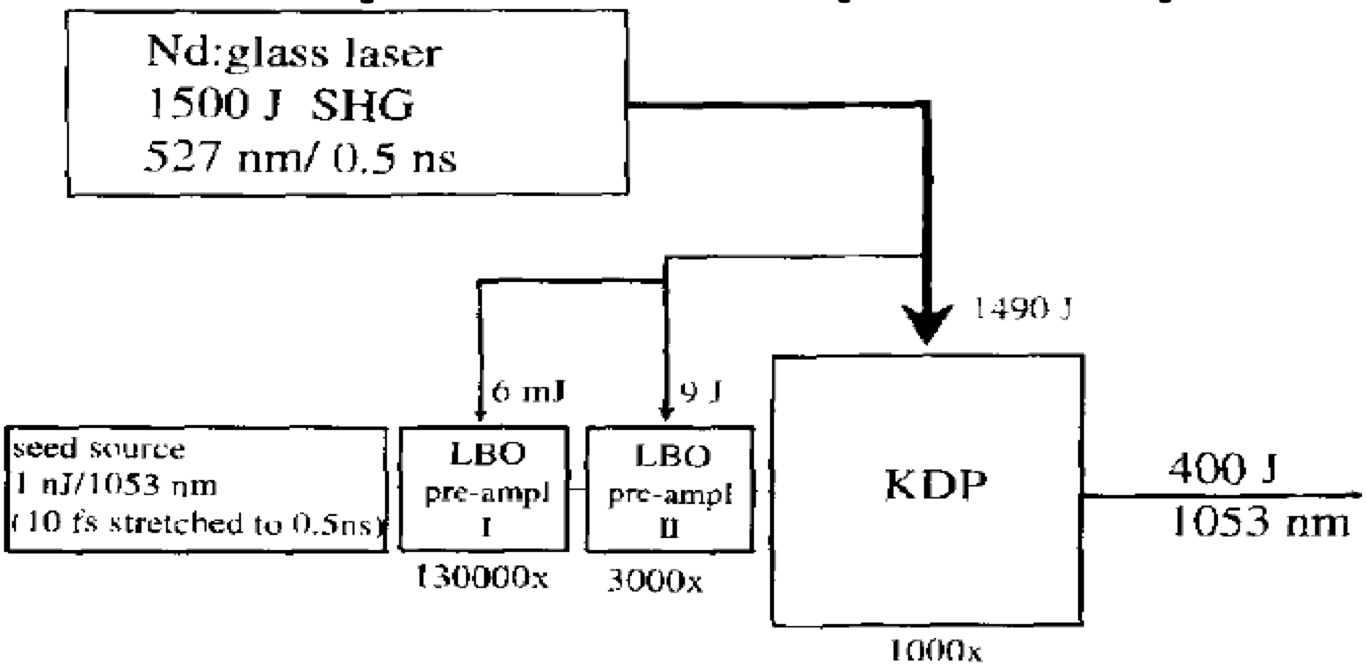
Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

Received 27 May 1997; accepted 8 July 1997

Abstract

The properties of optical parametric amplifiers are presented to show that, in addition to their use in providing tuneable pulses, they can form the critical component in systems generating shorter pulse duration with higher power and intensity than is possible with existing systems. Practical designs are evaluated leading to anticipated powers exceeding 10 PW and focused intensities greater than 10^{23} W cm^{-2}.

Optical Parametric Chirped Pulse Amplification (OPCPA)

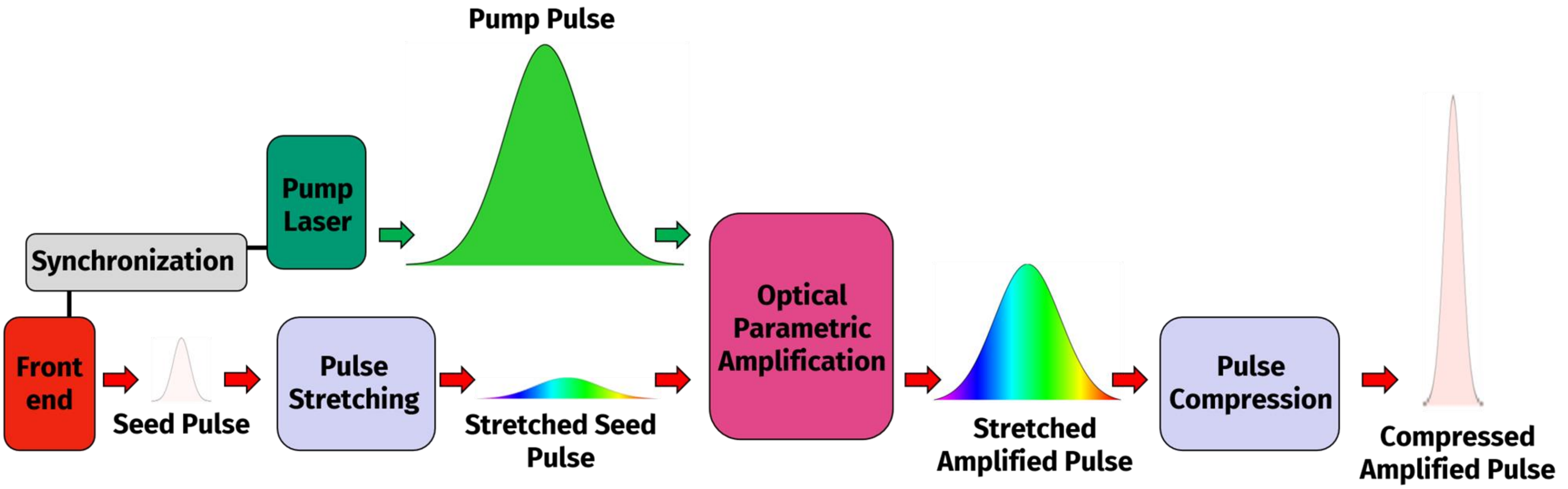


	beam diameter (mm)	crystal length (mm)	pump fluence (J/cm^2)
LBO / pre-amplifier I	0.6	11.5	2
LBO / pre-amplifier II	20	6.8	2.9
KDP	305	28.6	2

Fig. 6. PW OPCPA design for a high power Nd:glass laser.

Optical Parametric Chirped Pulse Amplification (OPCPA)

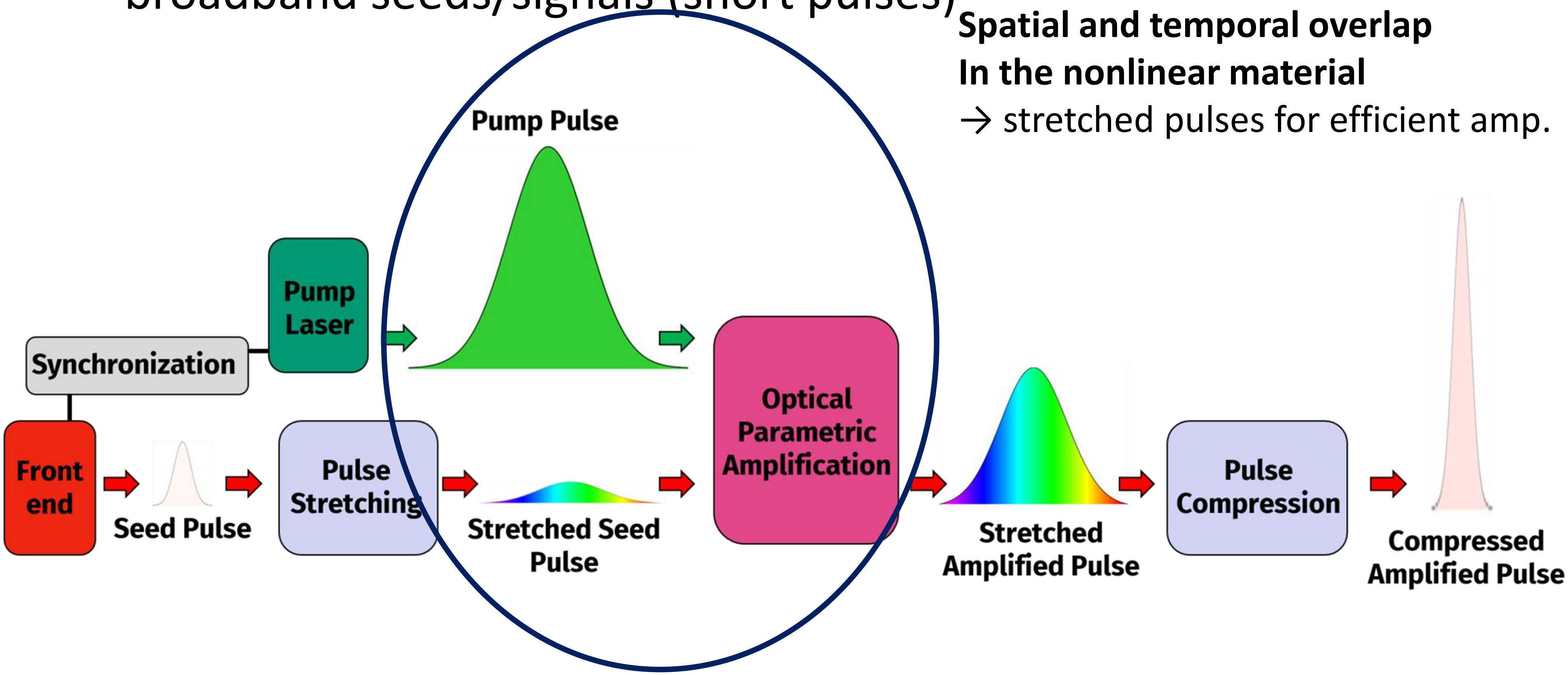
- Amplification of short pulses avoiding unwanted nonlinear effects



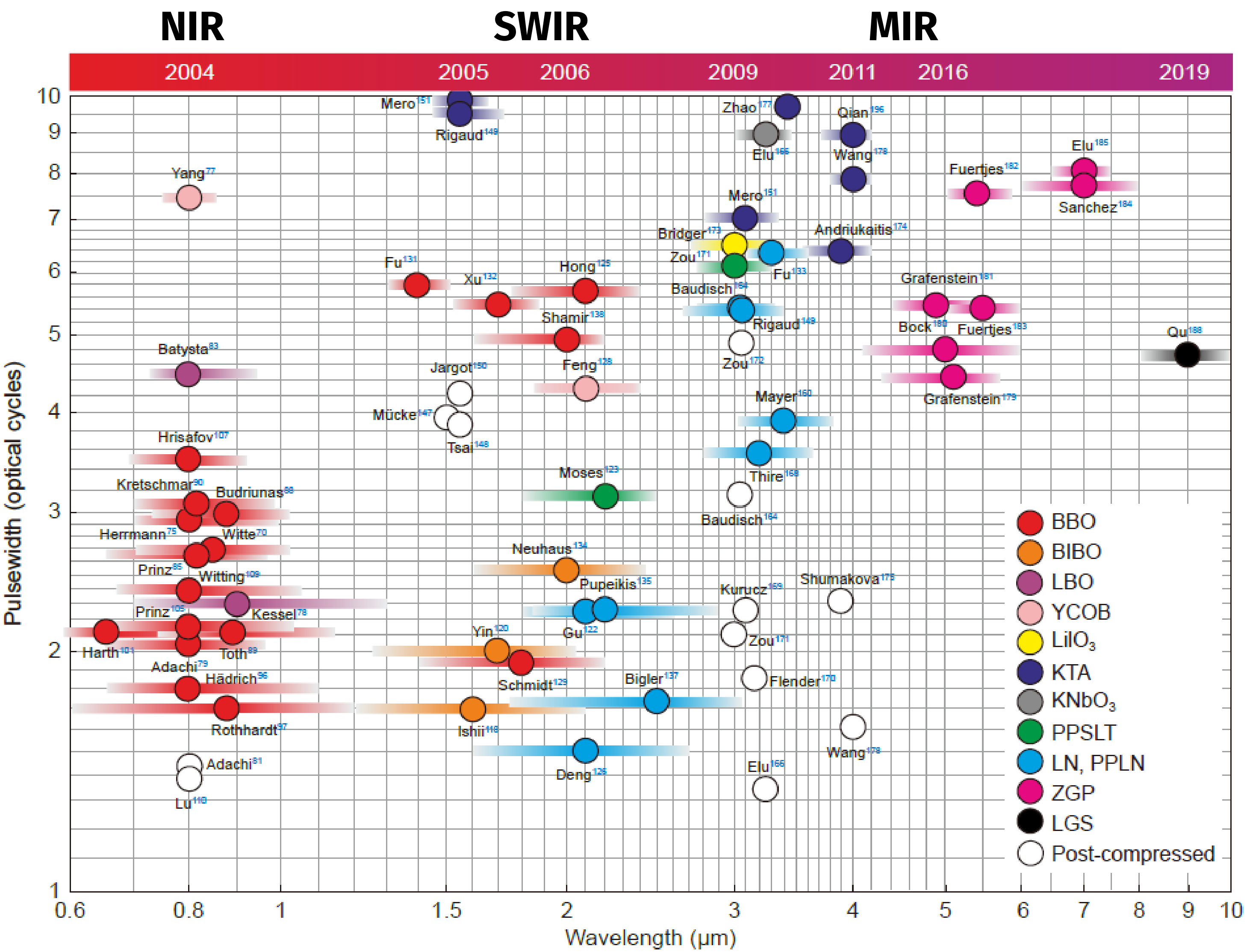
Optical Parametric Chirped Pulse Amplification (OPCPA)

- Amplification of short pulses avoiding unwanted nonlinear effects
- Using narrowband pumps (long pulses) to amplify broadband seeds/signals (short pulses)

Spatial and temporal overlap
In the nonlinear material
→ stretched pulses for efficient amp.



Few-cycle OPCPAs from VIS to MIR



Dubietis and Matijošius, Opto-Electronic Advances 6, 220046 (2023)

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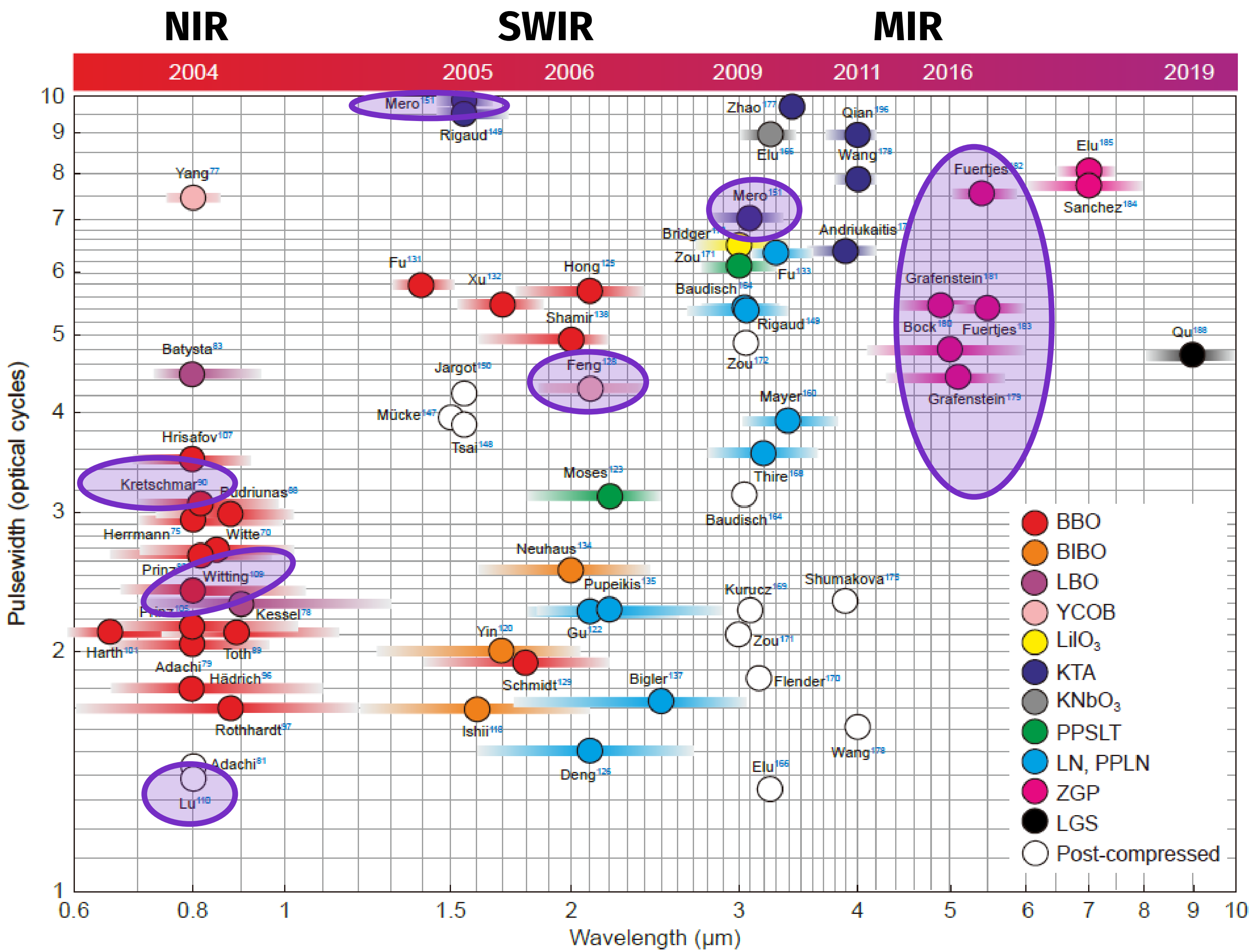
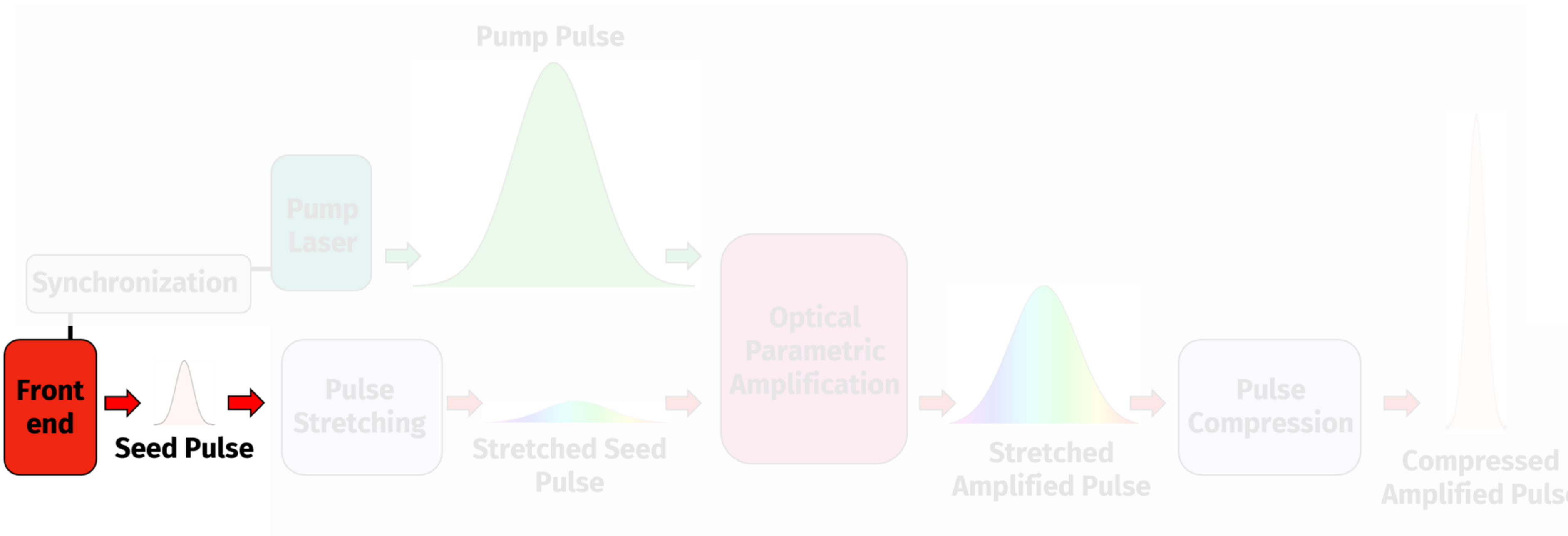


Systems at the MBI

Dubietis and Matijošius, Opto-Electronic Advances 6, 220046 (2023)

Building blocks



Front end

March 15, 2001 / Vol. 26, No. 6 / OPTICS LETTERS 373

Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser

R. Ell, U. Morgner, and F. X. Kärtner

High Frequency and Quantum Electronics Laboratory, University of Karlsruhe, D-76128 Karlsruhe, Germany

J. G. Fujimoto and E. P. Ippen

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

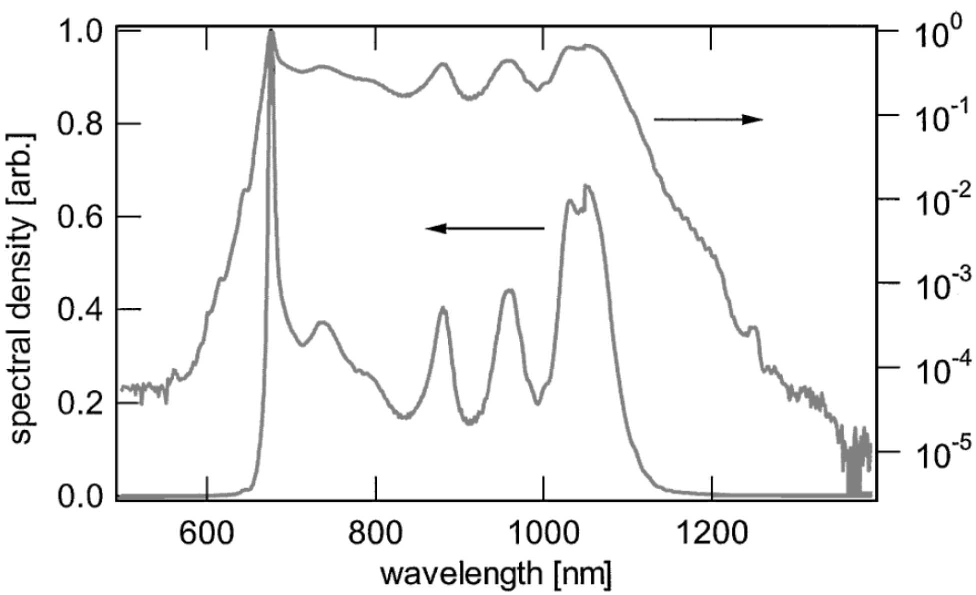
V. Scheuer, G. Angelow, and T. Tschudi

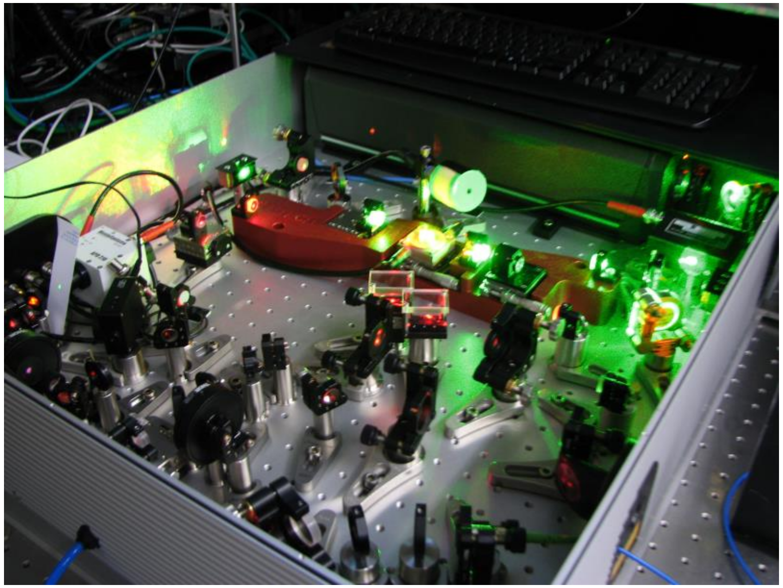
Institute for Applied Physics, TU Darmstadt, Germany

M. J. Lederer, A. Boiko, and B. Luther-Davies

Ultra-broadband Ti:Sapphire oscillators:

- Support ultrashort, down to few-cycle pulses
- Optical Synchronization
- CEP stability

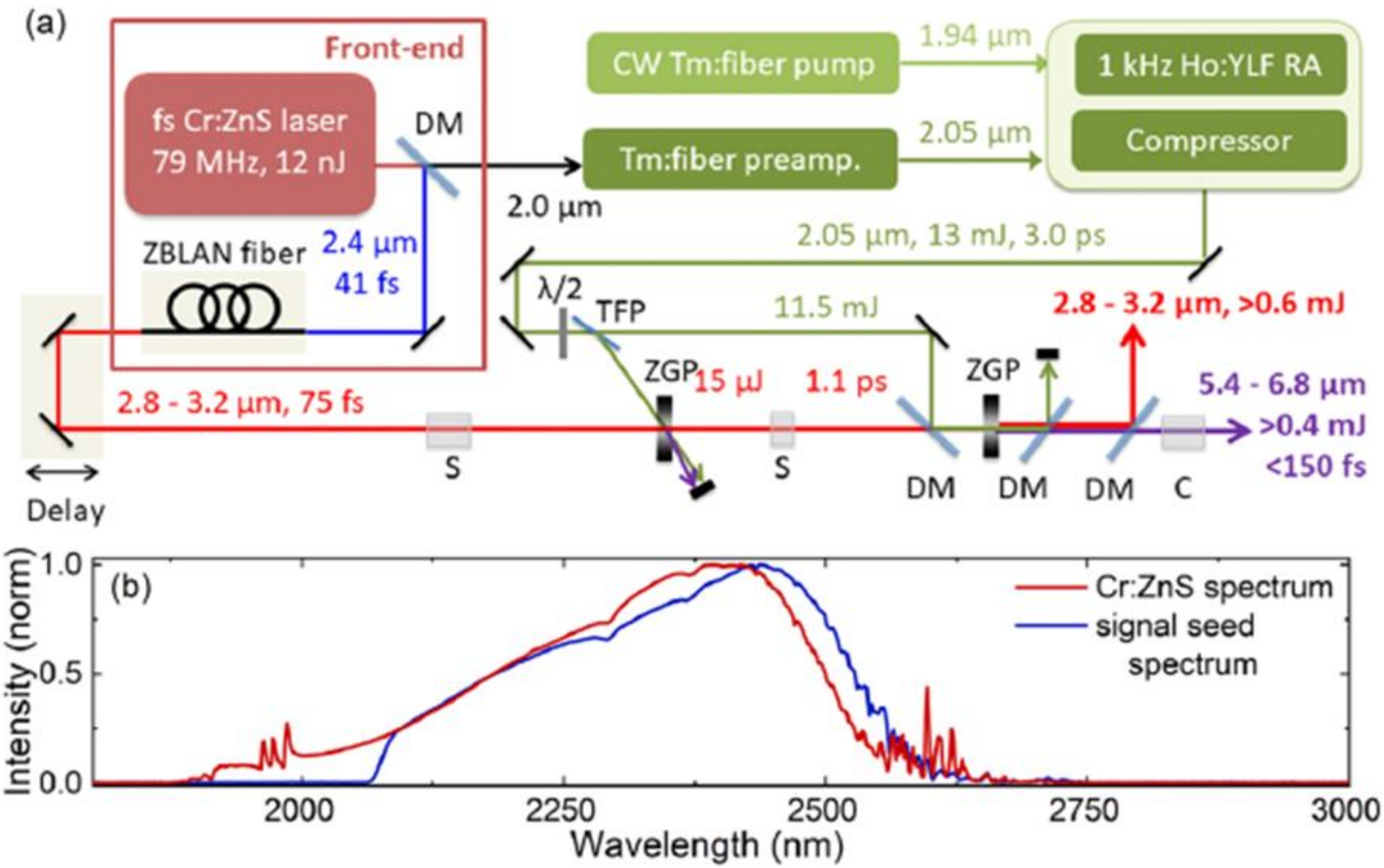




Photograph of the Venteon Ti:Sapphire oscillator at MBI

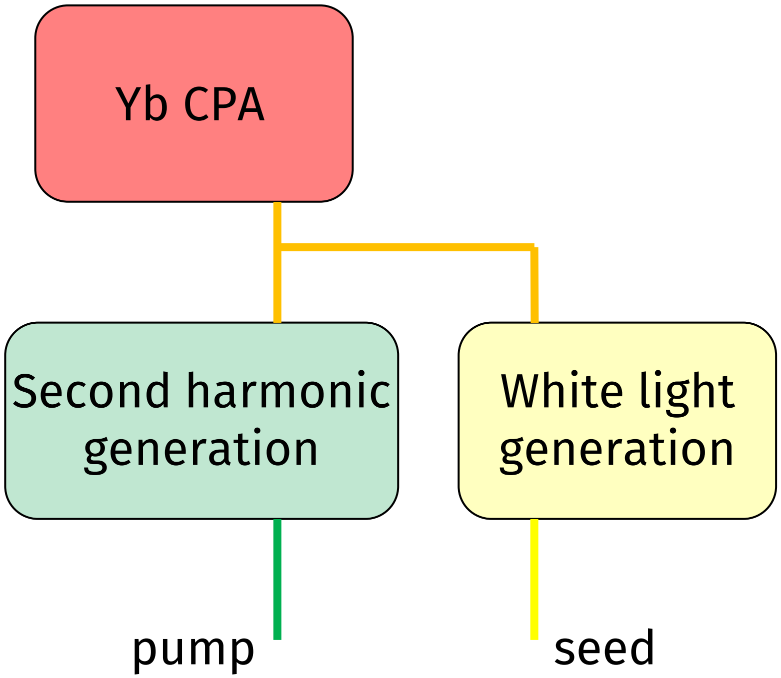
Front end

Broadband Cr:ZnS or Cr:ZnSe oscillators:
- Ultrashort pulses in the MWIR
- Optical Synchronization



Fuertjes et al., Opt. Lett. 46, 1704 (2021)

Front end



Yb-based system+different nonlinear processes

- Access to different parts of the spectrum
- Seed for OPCPA pump (optical synchronization)
- Passive CEP stabilization

Front end

Yb-based system+different nonlinear processes

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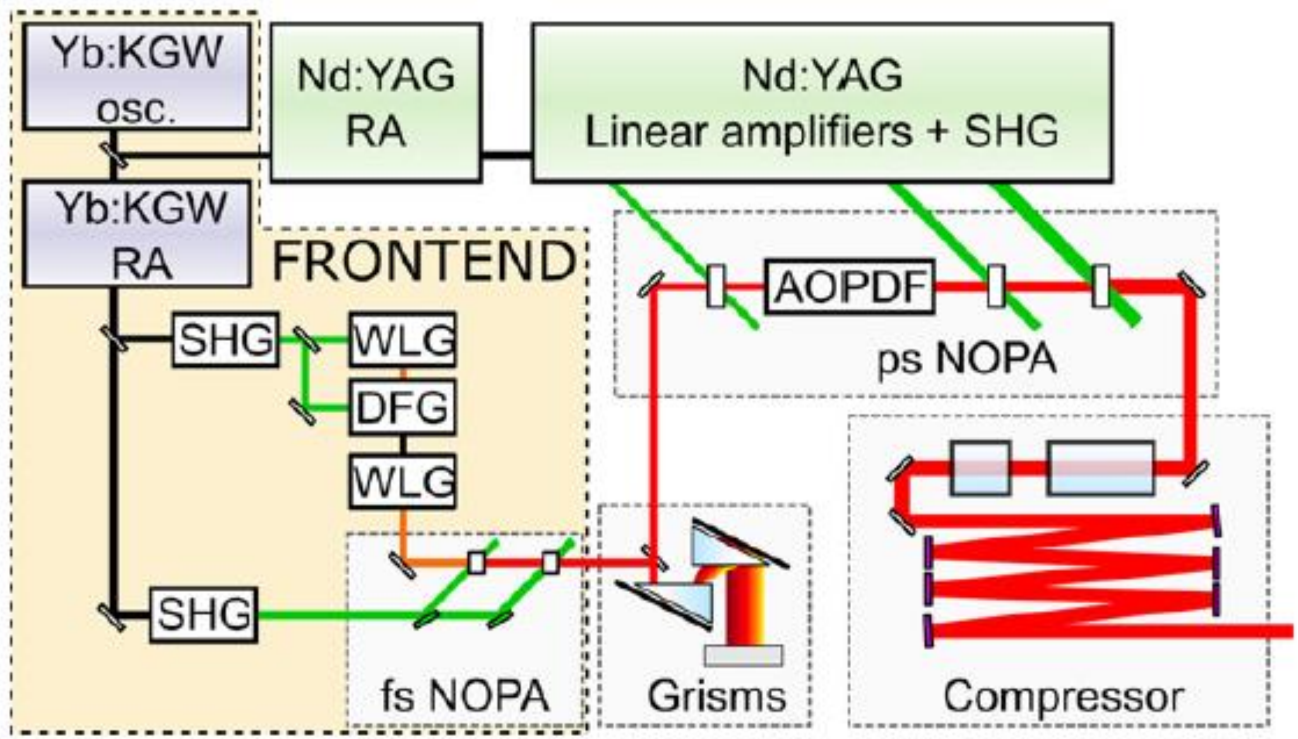
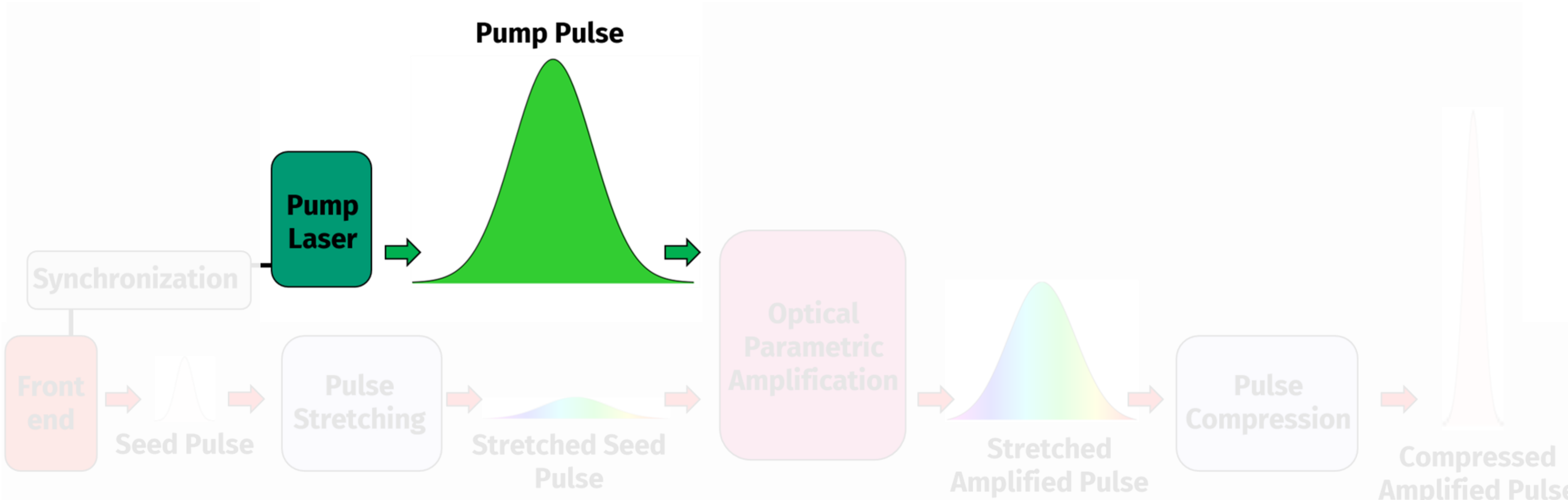


Figure 1. Principal layout of the OPCPA setup.

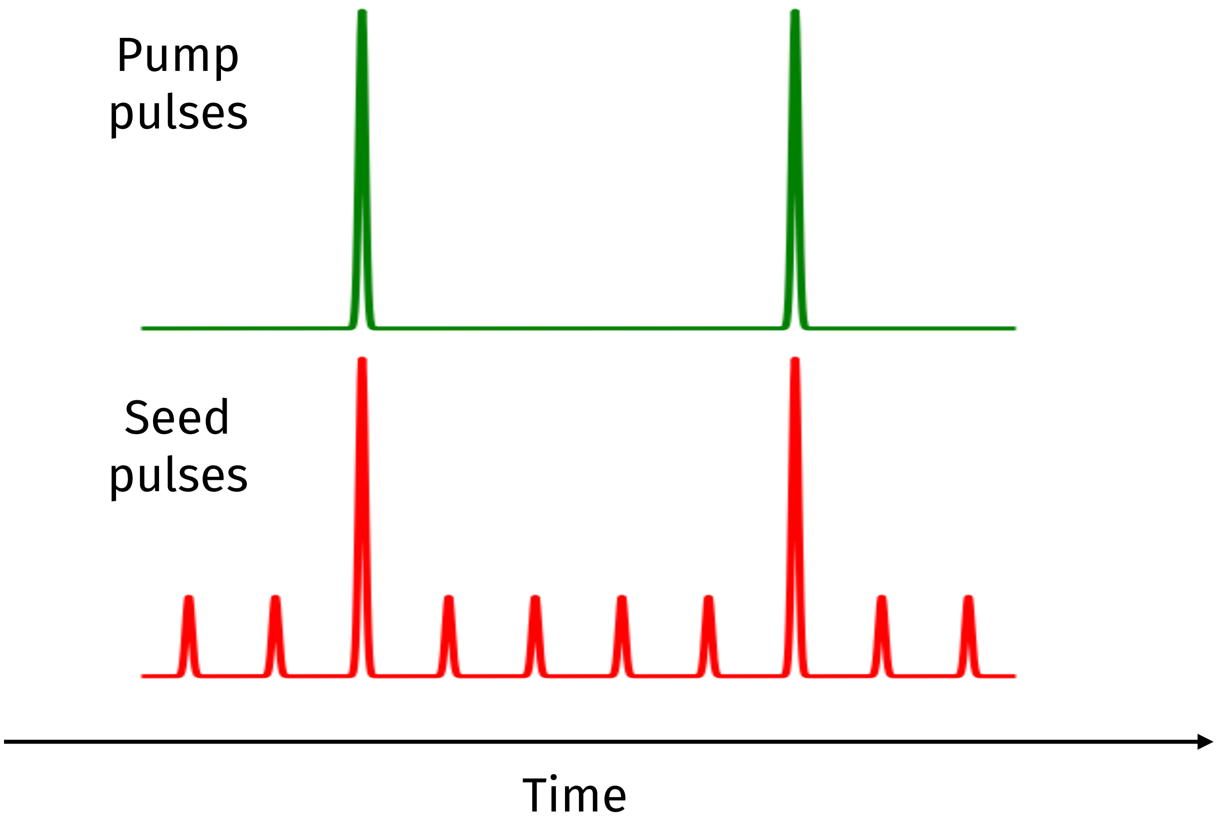
Badriūnas, J. Opt. 17, 094008 (2015)

Building blocks



Pump

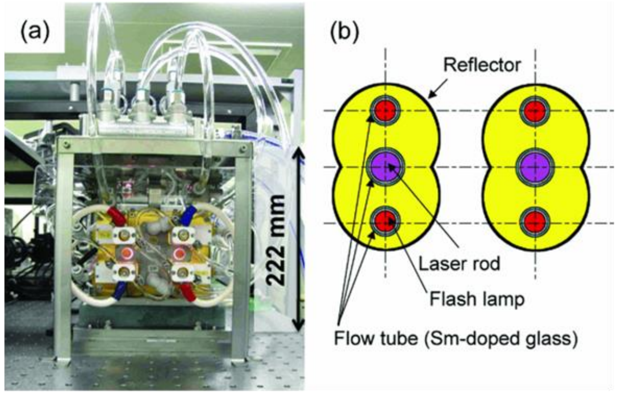
- Determines repetition rate and energy of the system



Pump

- Determines repetition rate and energy of the system
  - Flash lamp pumped systems: high energy at low repetition rates
  - DPSSL and fibers: high repetition rate, high average powers

Multipass thin disk Yb:YAG amplifier part of a DPSSL developed at the MBI



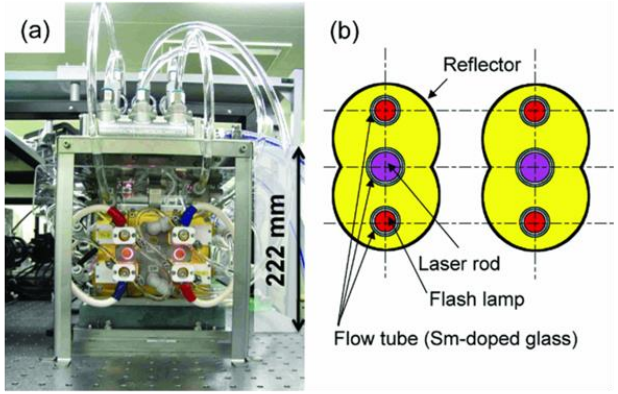
Flashed lamp pumped amplifier. Image from Hatae et al., Rev Sci Instrum **83**, 10E344 (2012)

Pump

- Determines repetition rate and energy of the system
  - ➢Flash lamp pumped systems: high energy at low repetition rates
  - ➢DPSSL and fibers: high repetition rate, high average powers

- Determines the chirp management
  - ➢ns, ~100ps pulses ⇨ grating stretcher / compressor
  - ➢Sub-10ps pulses ⇨ material dispersion / dispersive mirrors / prism pairs

Multipass thin disk Yb:YAG amplifier part of a DPSSL developed at the MBI



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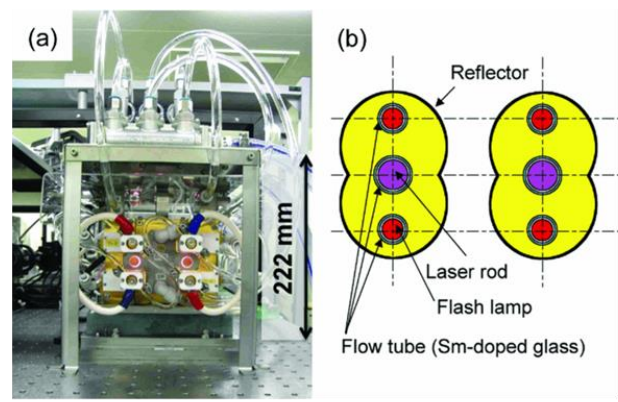
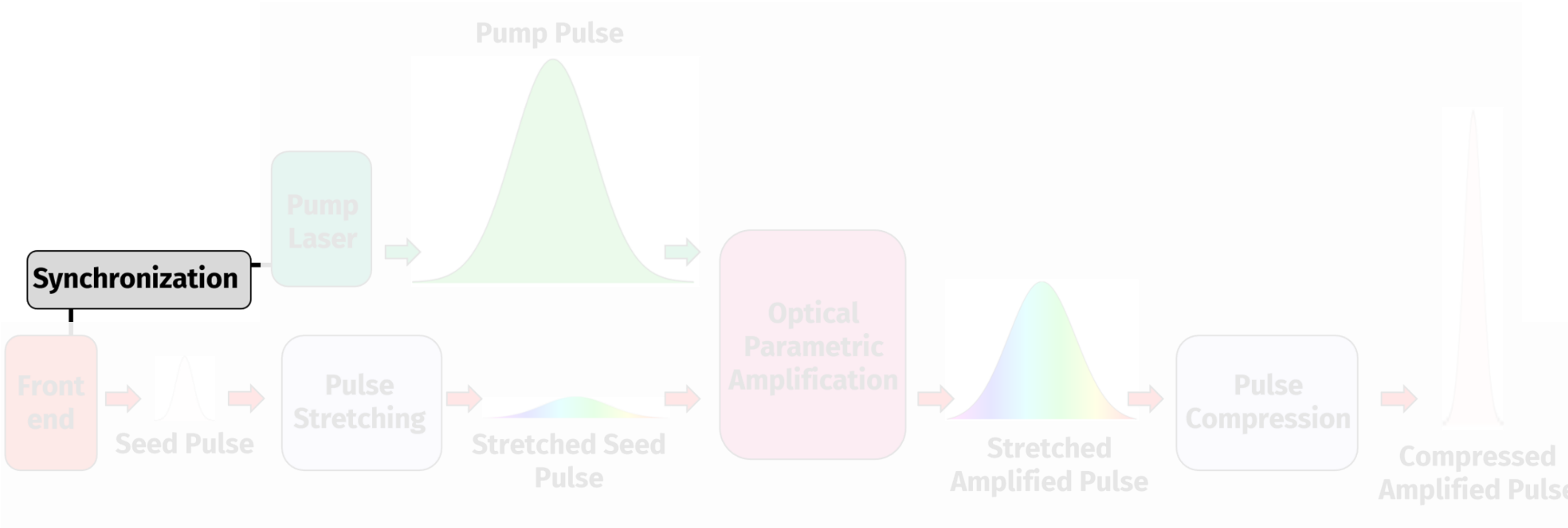
- Different gain materials for pumping OPCPA in different spectral regions
  - 1µm systems for pumping NIR/SWIR: Nd:YAG, Nd:YLF, Nd:YVO4, Yb:YAG, Yb:KGW, Yb-doped fibers
  - 2µm systems for pumping MIR: Ho:YAG, Ho:YLF, Tm:YLF

Multipass thin disk Yb:YAG amplifier part of a DPSSL developed at the MBI



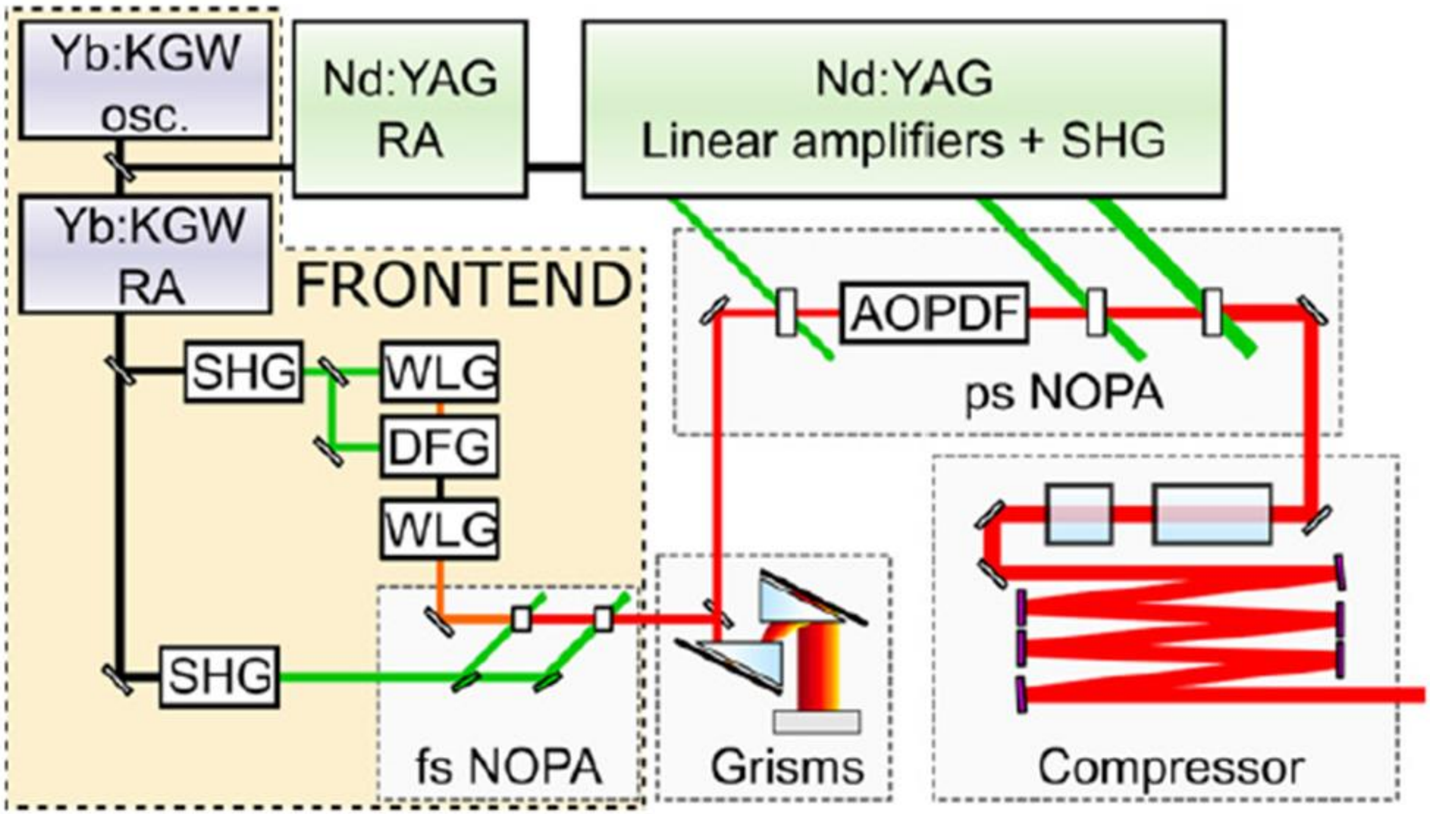
Flashed lamp pumped amplifier. Image from Hatae et al., Rev Sci Instrum **83**, 10E344 (2012)

Building blocks



Synchronization

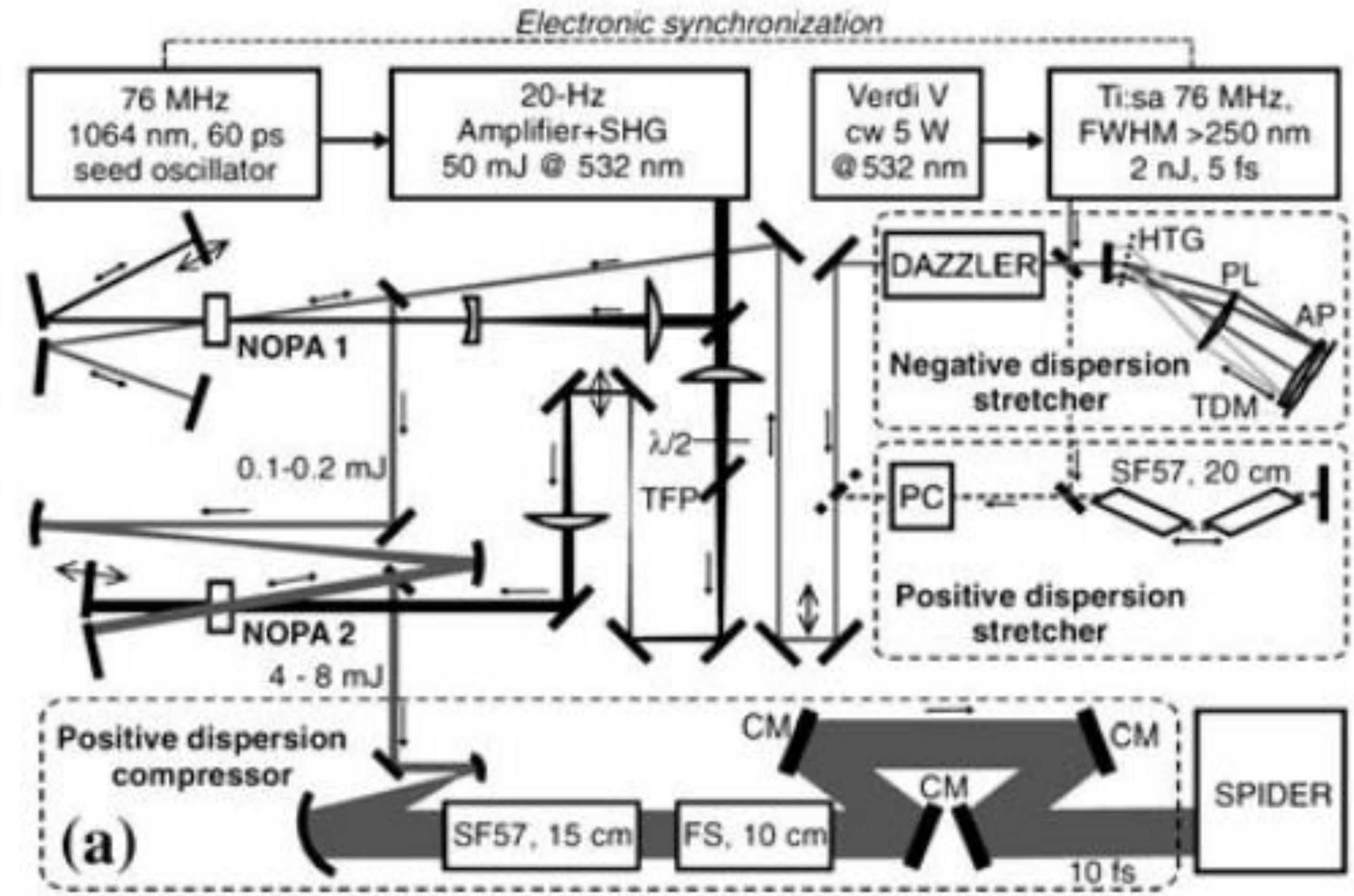
- Optical synchronization
  - ➢Pulses derived from the same front end
  - ➢Residual jitter: effects in amplifier chain



Badriūnas, J. Opt. 17, 094008 (2015)

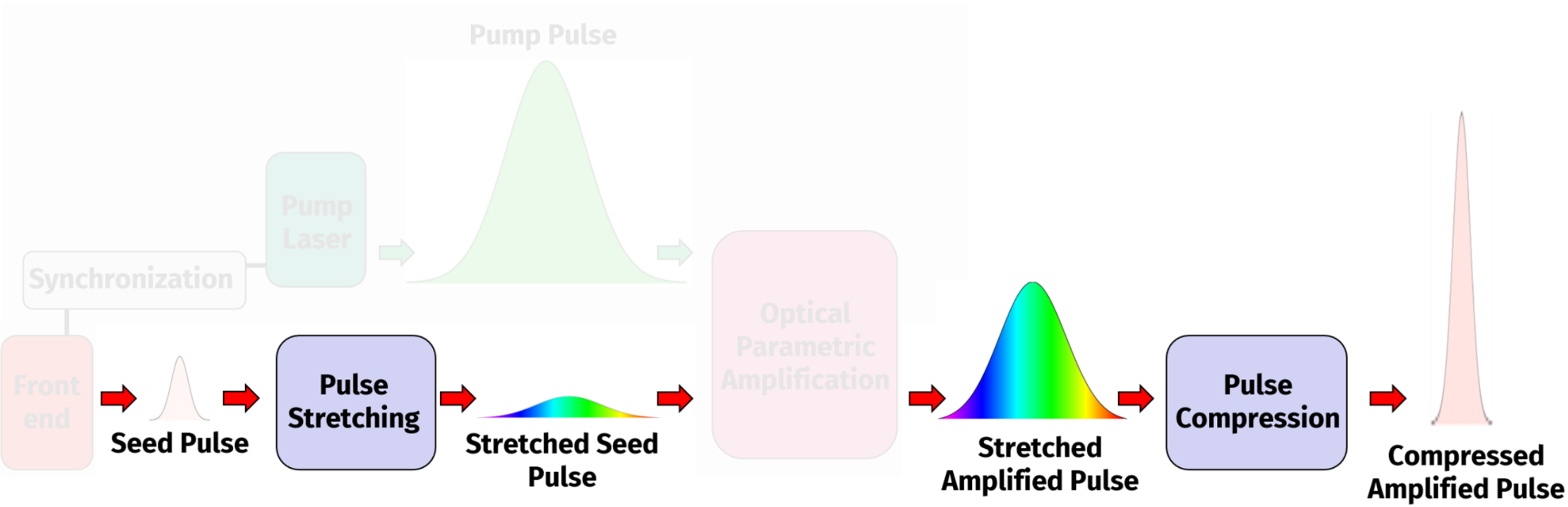
Synchronization

- Electronic synchronization
  - Oscillators locked to an external RF source
  - Residual jitter < 1ps



Ishii et al., Opt. Lett. 30, 567 (2005)

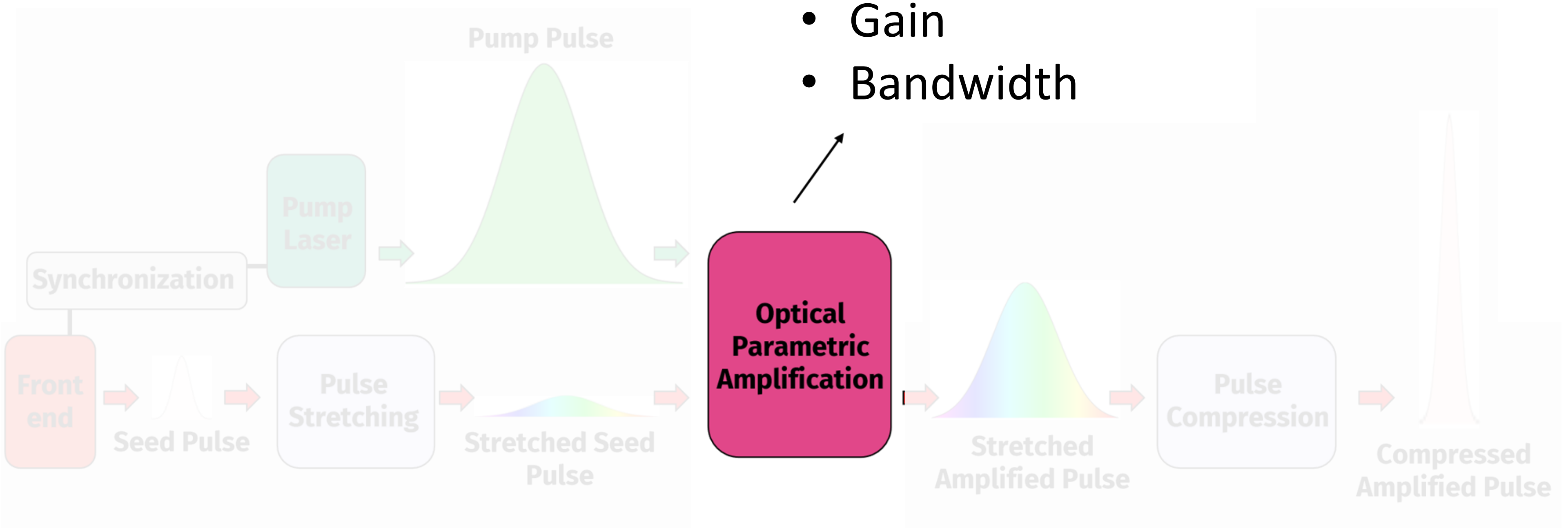
Building blocks



- Determines the chirp management
  - ns, ~100ps pulses ⇨ grating stretcher / compressor
  - Sub-10ps pulses ⇨ material dispersion / dispersive mirrors / prism pairs

Building blocks

- Spectral range
- Gain
- Bandwidth



OPCPA process

Coupled nonlinear differential equations for field envelopes: signal (s), idler (i) and pump (p)

$$\frac{\partial A_\mathrm{s}}{\partial z} + \sum_{n=1}^{\infty} \frac{(-\mathrm{i})^{n-1}}{n!} k^{(n)} \frac{\partial^n A_\mathrm{s}}{\partial t^n} = -\mathrm{i}\frac{\chi^{(2)}\omega_\mathrm{s}}{2n_\mathrm{s}c} A_\mathrm{p} A_\mathrm{i}^* \mathrm{e}^{-\mathrm{i}\Delta k \cdot z}$$

$$\frac{\partial A_\mathrm{i}}{\partial z} + \sum_{n=1}^{\infty} \frac{(-\mathrm{i})^{n-1}}{n!} k^{(n)} \frac{\partial^n A_\mathrm{i}}{\partial t^n} = -\mathrm{i}\frac{\chi^{(2)}\omega_\mathrm{i}}{2n_\mathrm{i}c} A_\mathrm{p} A_\mathrm{s}^* \mathrm{e}^{-\mathrm{i}\Delta k \cdot z}$$

$$\frac{\partial A_\mathrm{p}}{\partial z} + \sum_{n=1}^{\infty} \frac{(-\mathrm{i})^{n-1}}{n!} k^{(n)} \frac{\partial^n A_\mathrm{p}}{\partial t^n} = -\mathrm{i}\frac{\chi^{(2)}\omega_\mathrm{p}}{2n_\mathrm{p}c} A_\mathrm{s} A_\mathrm{i} \mathrm{e}^{\mathrm{i}\Delta k \cdot z}$$

Taken from Witte et al., Appl. Phys. B 87, 677 (2007)

OPCPA process

PHYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 15, 1962

Interactions between Light Waves in a Nonlinear Dielectric*

J. A. Armstrong, N. Bloembergen, J. Ducuing,† and P. S. Pershan
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts

(Received April 16, 1962)

Solutions for monochromatic plane waves. No pump depletion, large gain:

$$I_s \approx I_s(0)\frac{1}{4}e^{2gz}$$

$$g = \sqrt{(\chi^{(2)})^2 \frac{\omega_s \omega_i I_p(0)}{2\epsilon_0 n_s n_i n_p c^3} - (\frac{\Delta k}{2})^2}$$

Gain ~ 10^3-10^4 achievable

OPCPA process

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Interactions between Light Waves in a Nonlinear Dielectric*

J. A. ARMSTRONG, N. BLOEMBERGEN, J. DUCUING,† AND P. S. PERSHAN
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts
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Phase of signal independent of pump, and dependent on phase matching

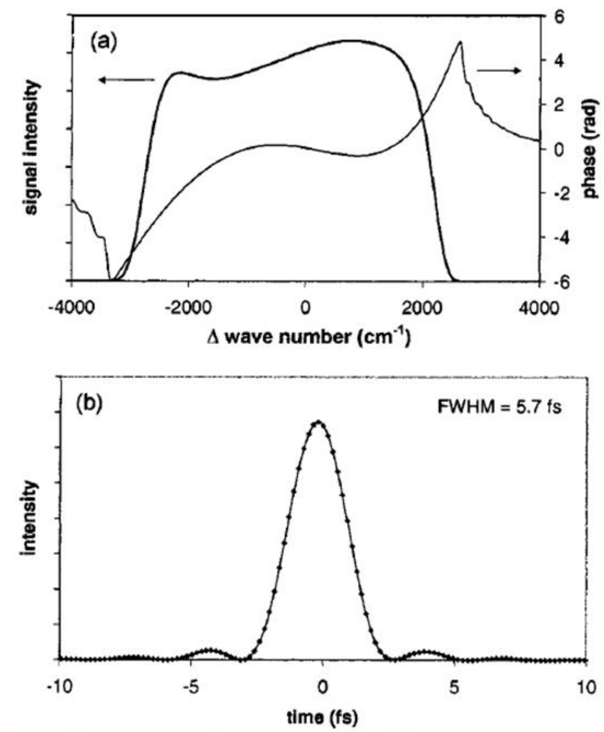

Fig. 9. Optimum performance of a BBO OPA of 1.5-mm length in noncollinear geometry for a 532-nm, 120-GW/cm^2 pump beam and 800-nm signal beam: (a) amplified spectral intensity and phase, and (b) pulse profile as determined by the Fourier transform of the spectral amplitude and phase after compensation for phase terms up to the quartic.

Ross et al., JOSA B **19**, 2945 (2002)

OPCPA process

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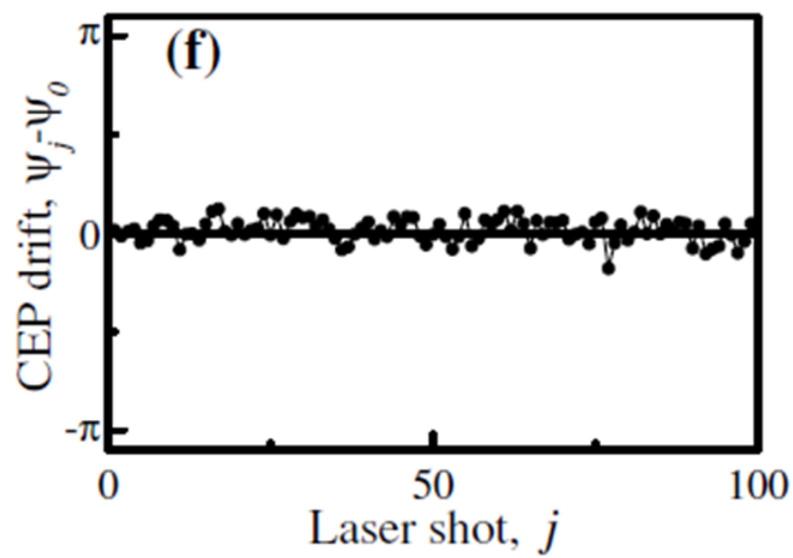
Volume 88, Number 13 PHYSICAL REVIEW LETTERS 1 April 2002

Controlling the Carrier-Envelope Phase of Ultrashort Light Pulses with Optical Parametric Amplifiers

Andrius Baltuška,* Takao Fuji, and Takayoshi Kobayashi
Department of Physics, Faculty of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
(Received 1 November 2001; published 18 March 2002)

Idler picks up phase difference between pump and signal

CEP-stable idler



OPCPA process

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Idler picks up phase difference between pump and signal

Check for updates

1672 Vol. 49, No. 7 / 1 April 2024 / *Optics Letters* Letter

Optics Letters

Toward high-energy few-cycle optical vortices with minimized topological charge dispersion

Federico J. Furch[1,*] and Gunnar Arisholm[2]

[1] Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Strasse 2A, Berlin 12489, Germany
[2] Norwegian Defence Research Establishment (FFI), PO Box 25, Kjeller 2027, Norway
[*] furch@mbi-berlin.de

Received 17 October 2023; revised 11 February 2024; accepted 23 February 2024; posted 23 February 2024; published 19 March 2024

OPCPA process

Amplification rate is frequency dependent (through phase matching and time-dependent gain)

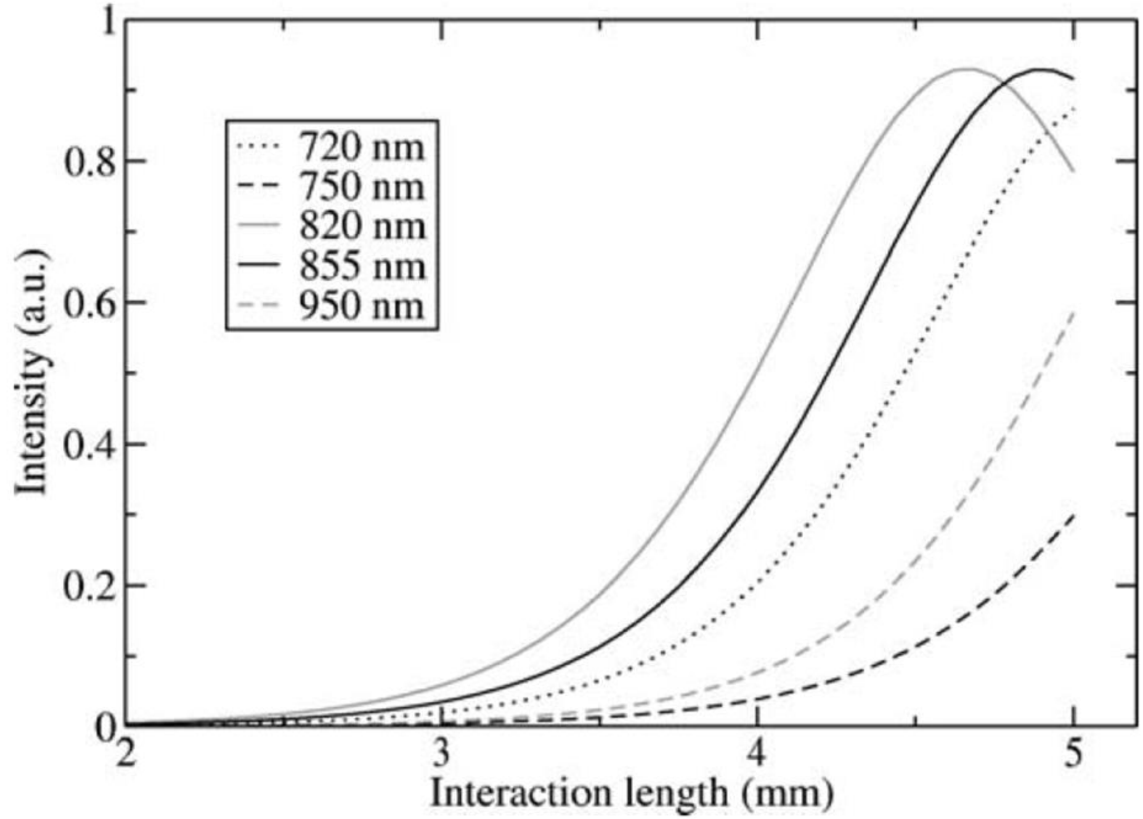


FIGURE 5 Wavelength-dependent gain saturation: Due to the differences in phase mismatch, the NOPCPA gain is frequency-dependent. Since all the frequencies are temporally separated in the chirped seed pulse, gain saturation and even backconversion independently occurs for every wavelength

Witte et al., Appl. Phys. B **87**, 677 (2007)

OPCPA process

Amplification rate is frequency dependent (through phase matching and time-dependent gain)

Direction of energy flow can be reversed: **Back conversion**

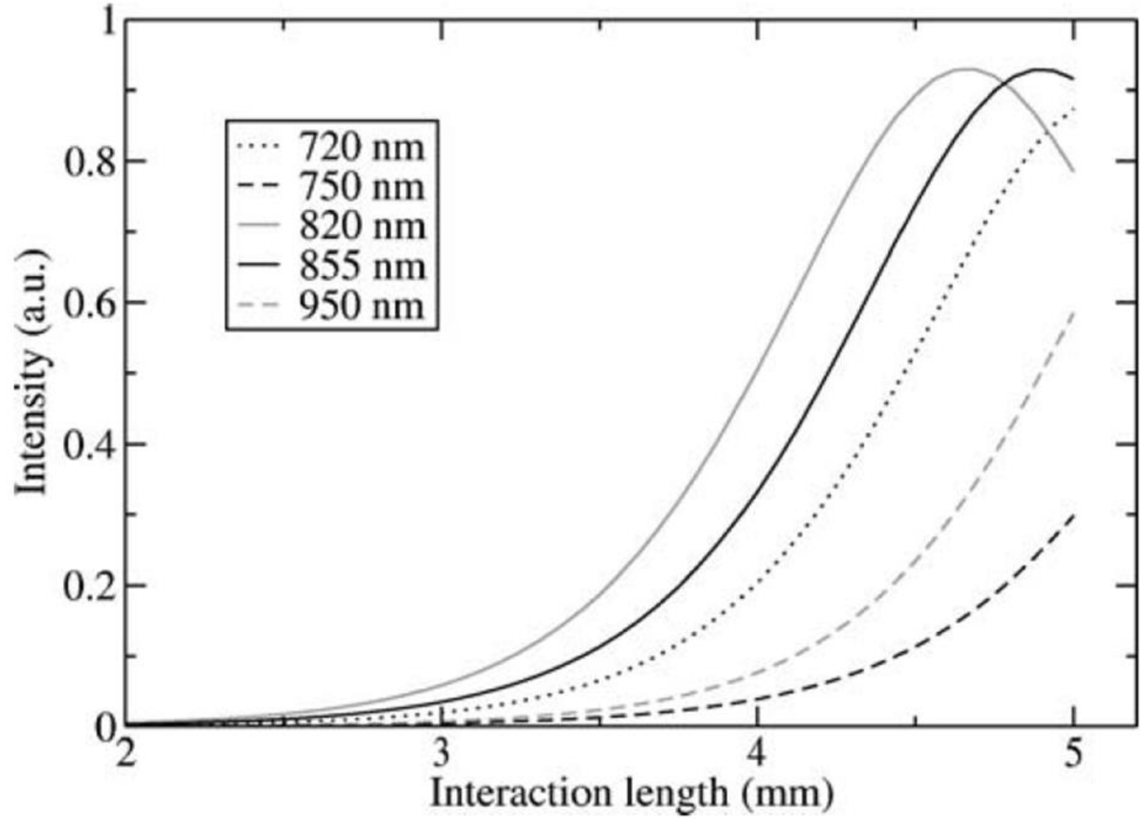


FIGURE 5 Wavelength-dependent gain saturation: Due to the differences in phase mismatch, the NOPCPA gain is frequency-dependent. Since all the frequencies are temporally separated in the chirped seed pulse, gain saturation and even backconversion independently occurs for every wavelength

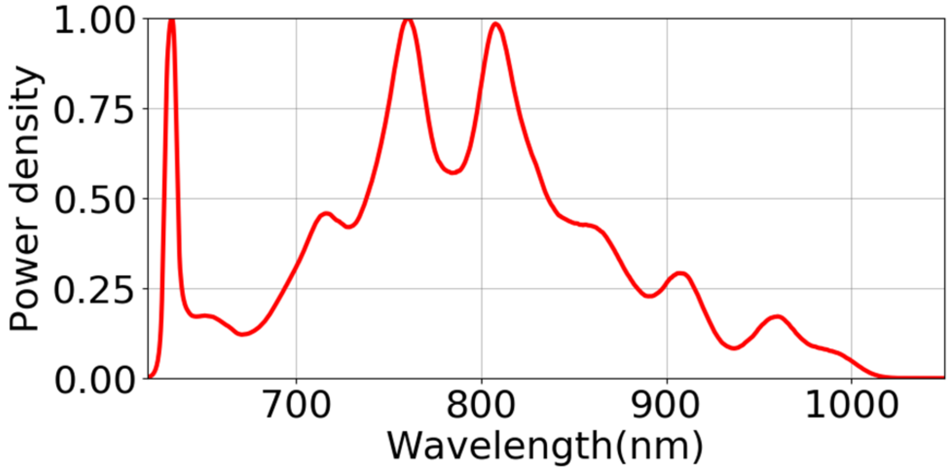
Witte et al., Appl. Phys. B **87**, 677 (2007)

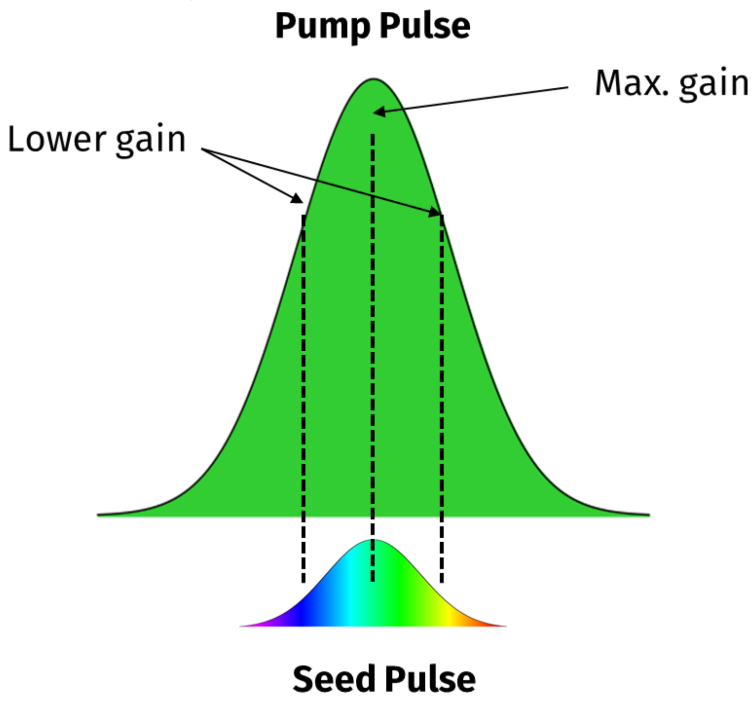
$$\frac{\partial A_p}{\partial z} + \sum_{n=1}^{\infty} \frac{(-i)^{n-1}}{n!} k^{(n)} \frac{\partial^n A_p}{\partial t^n} = -i \frac{\chi^{(2)} \omega_p}{2 n_p c} A_s A_i e^{i \Delta k \cdot z}$$

OPCPA process

Time dependent gain

Simulation with SISYFOS (G. Arisholm, Forsvarets forskningsinstitutt, Norway)
Seed: <6fs TL, 800fs^2 (>500fs), 2.5nJ
Pump: 1ps, 515nm, 100GW/cm^2, BBO 2.5 mm





OPCPA process

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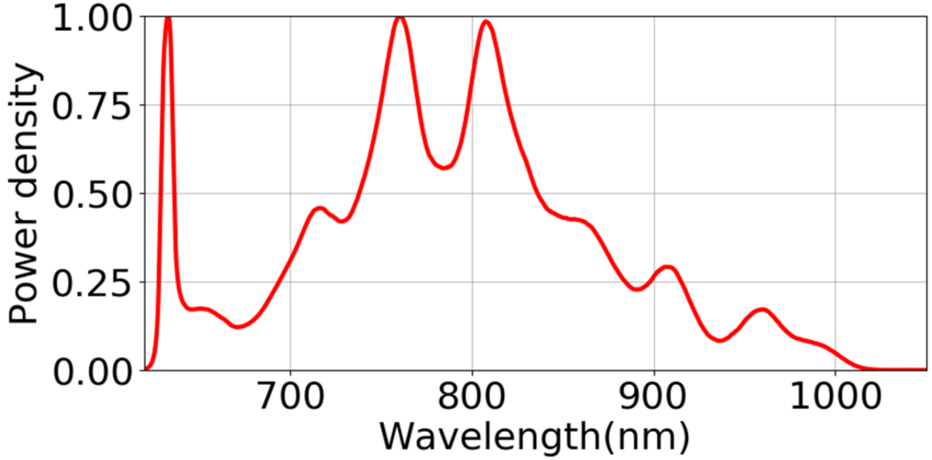
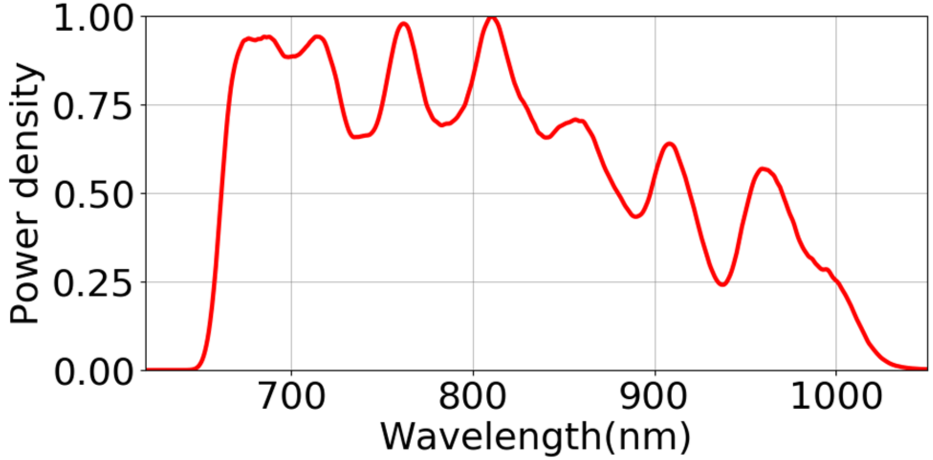
Pump to signal

$\eta \approx 17.3\%$

Saturation and back-conversion reshape spectrum





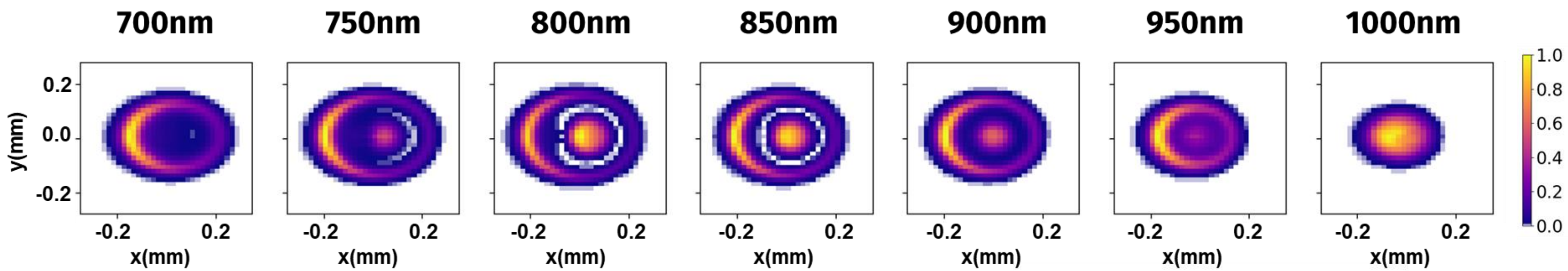
OPCPA process

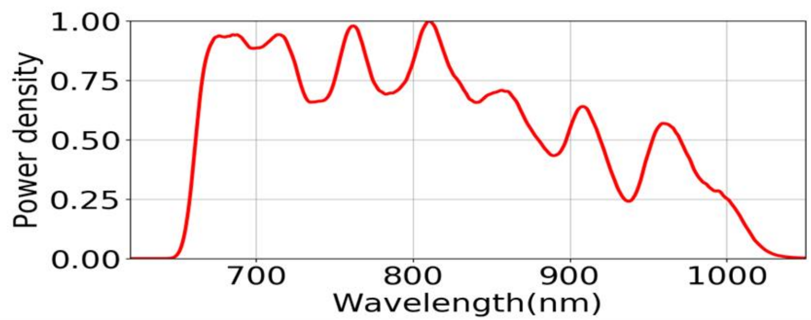
Spatially dependent gain

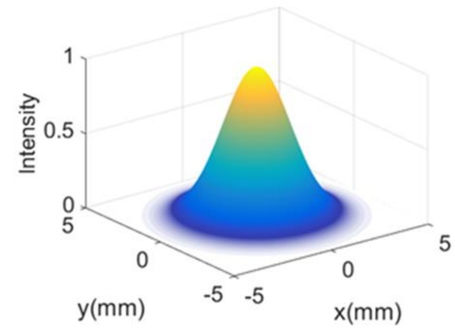
Pump to signal

$\eta \approx 17.3\%$

Saturation and back-conversion distort spatial distribution







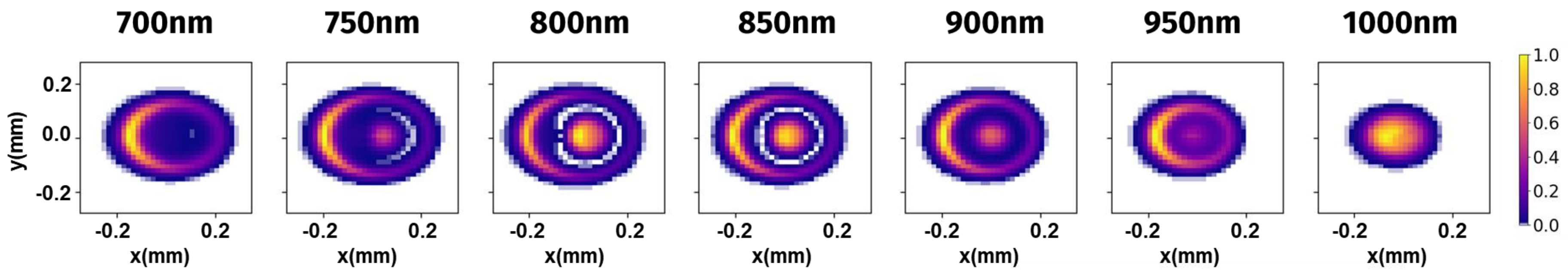
OPCPA process

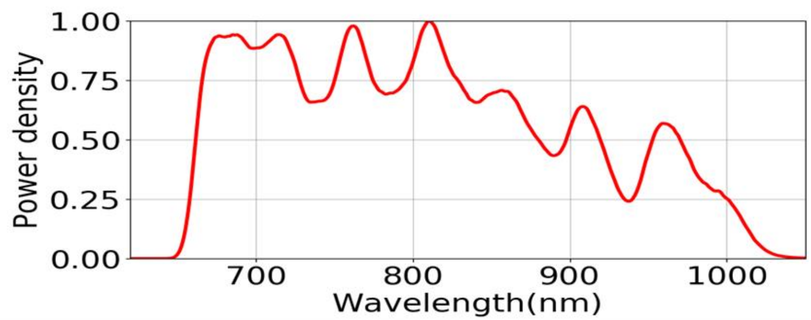
Spatially dependent gain

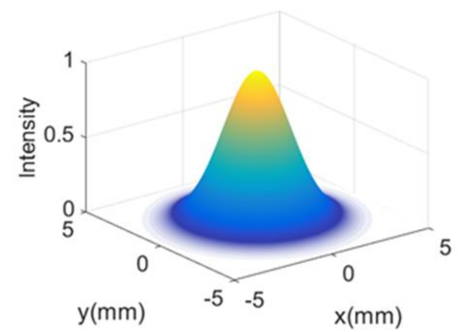
Pump to signal

$\eta \approx 17.3\%$

Saturation and back-conversion distort spatial distribution

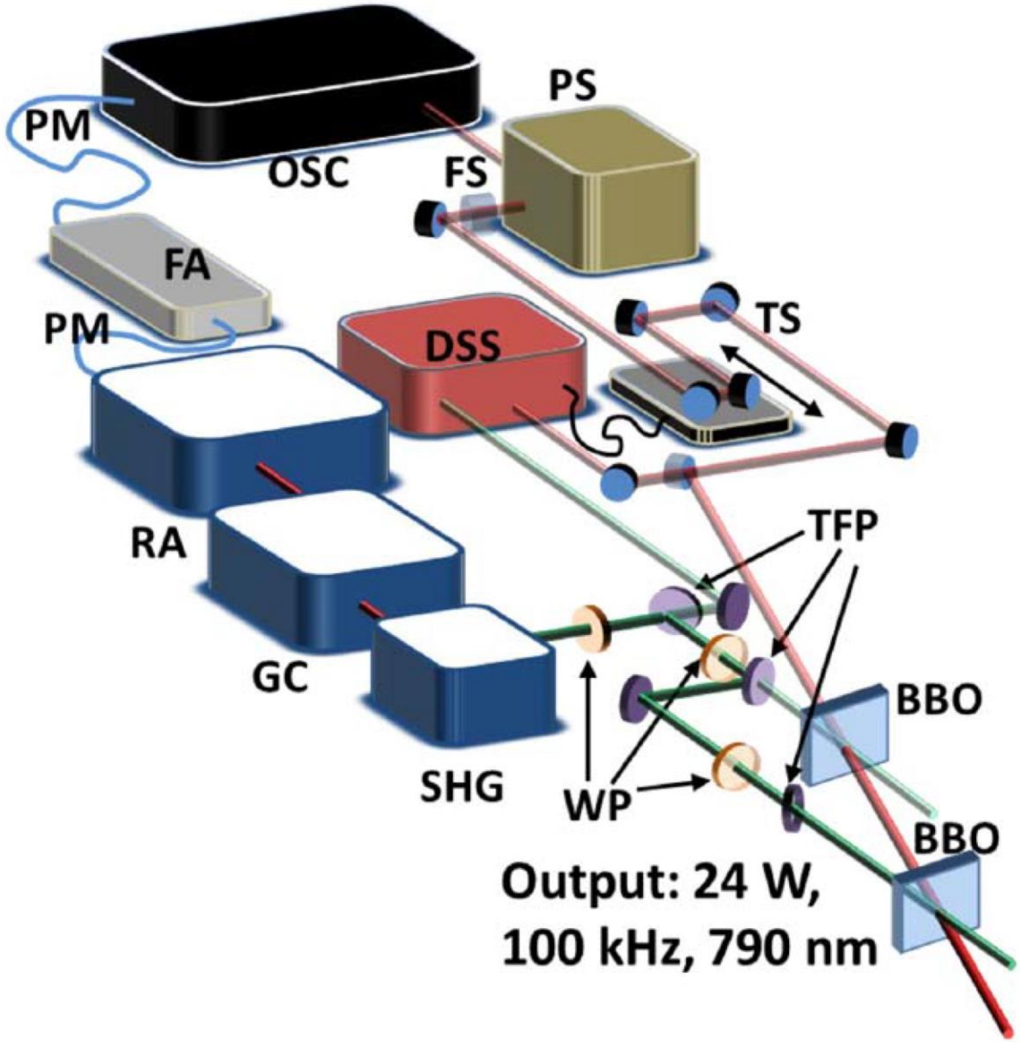






$$E\,(x,y,z,t) \neq E_{sp}(x,y,z)E_{temp}(t) \longrightarrow$$ **Degradation of peak intensity**

Example: high rep. rate OPCPA at 800nm



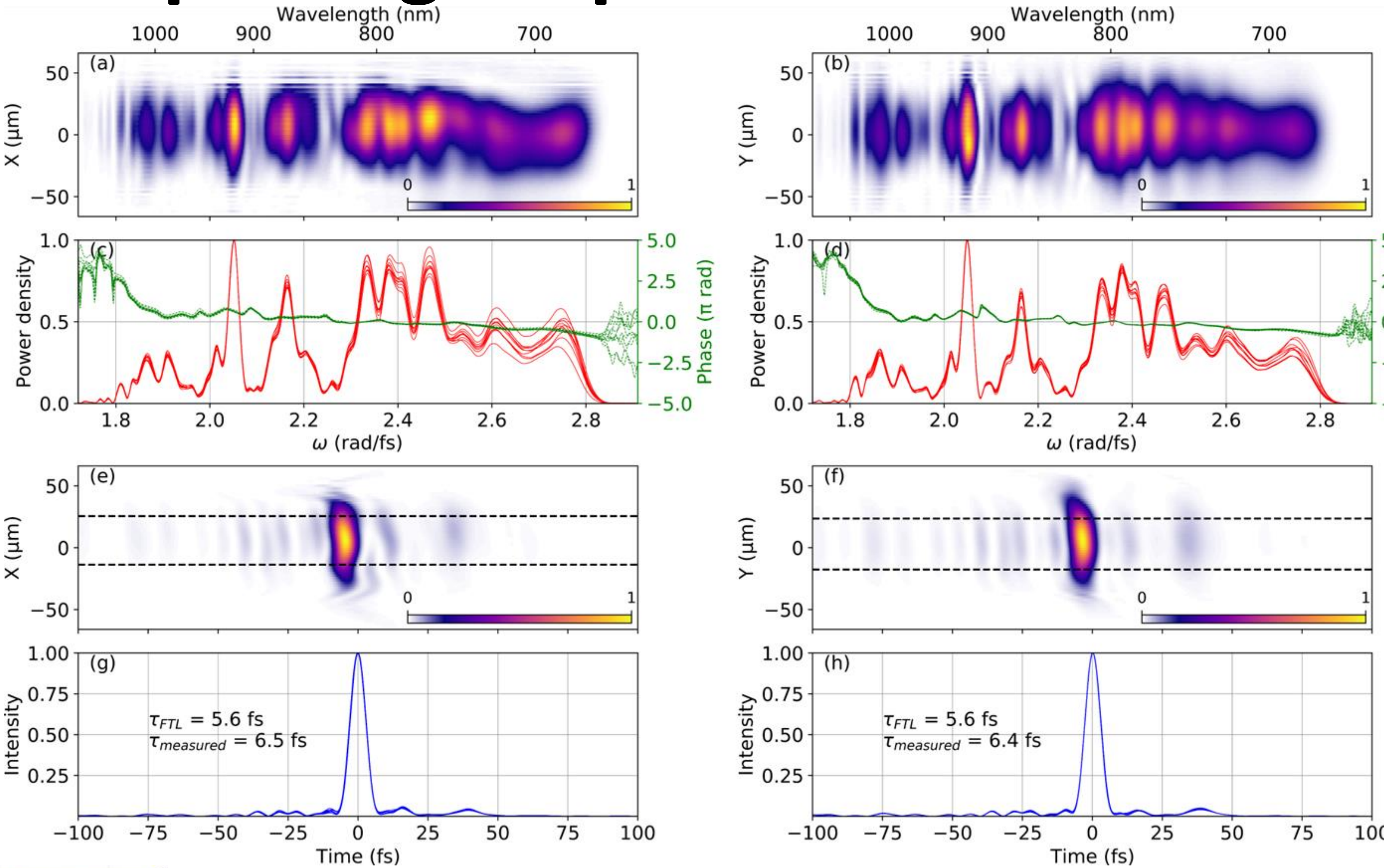
Seed: Ti:Sapphire oscillator (<1nJ, <6fs, 80MHz)

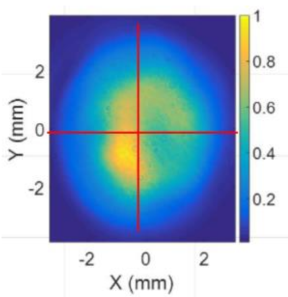
Pump: Yb:YAG thin-disk CPA system + SHG (1.2 mJ, 1ps, 100kHz, 515nm)

OPCPA output: sub-7fs, ≈0.2mJ,100kHz, CEP-stable

F. Furch et al., Optics Letters 42, 2495 (2017)

Example: high rep. rate OPCPA at 800nm





SEA-F-SPIDER characterization

F. Furch et al., J. Phys Photonics 4, 032001 (2022)

F. Furch et al., Optics Letters 42, 2495 (2017)

Example: high rep. rate OPCPA at 800nm

Research Article Vol. 9, No. 2 / February 2022 / *Optica* 145

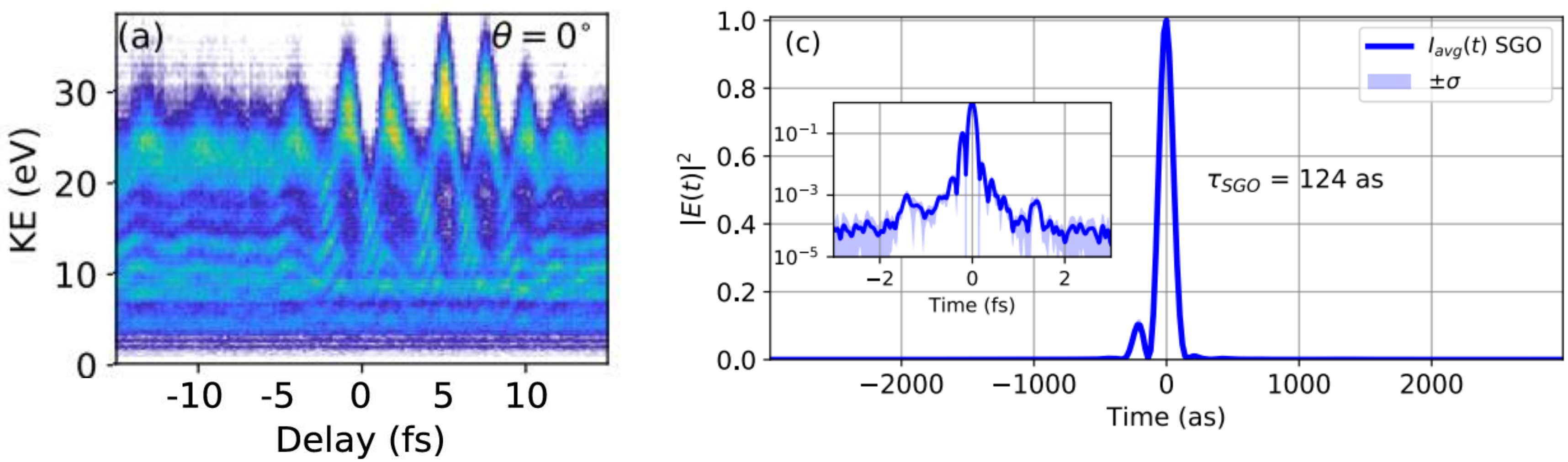
OPTICA

Generation and characterization of isolated attosecond pulses at 100 kHz repetition rate

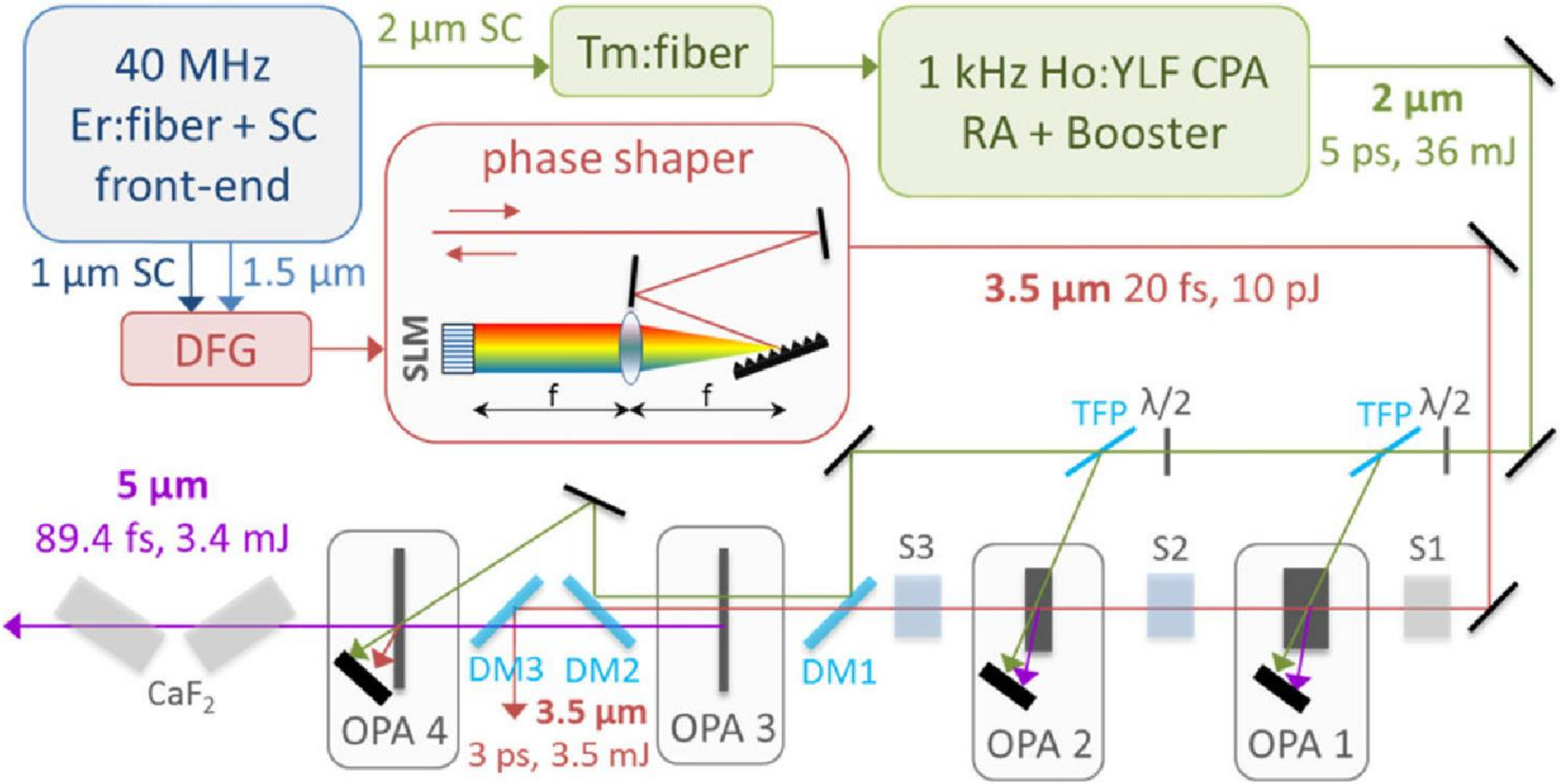
TOBIAS WITTING,[1,*] MIKHAIL OSOLODKOV,[1] FELIX SCHELL,[1] FELIPE MORALES,[1] SERGUEI PATCHKOVSKII,[1] PETER ŠUŠNJAR,[1] FABIO H. M. CAVALCANTE,[2] CARMEN S. MENONI,[2] CLAUS P. SCHULZ,[1] FEDERICO J. FURCH,[1,3] AND MARC J. J. VRAKKING[1]

[1]*Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Strasse 2A, 12489 Berlin, Germany*
[2]*Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado 80523, USA*
[3]*e-mail: furch@mbi-berlin.de*
**Corresponding author: tobias.witting@mbi-berlin.de*

Received 15 September 2021; revised 30 November 2021; accepted 19 December 2021; published 28 January 2022

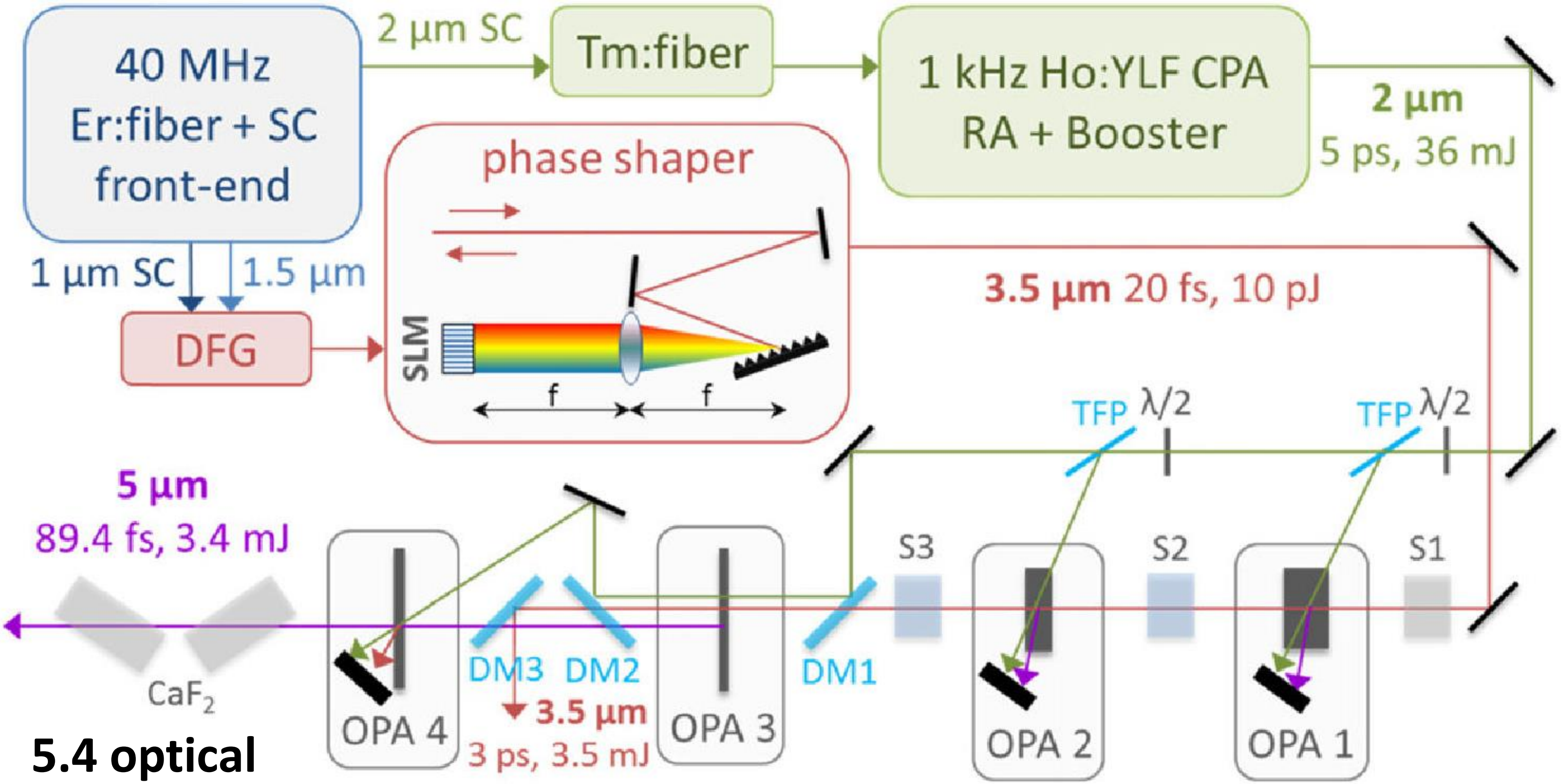


Example: high energy pulses at 5 microns



L. von Grafenstein et al., Optics Letters 45, 5998 (2020)

Example: high energy pulses at 5 microns



5.4 optical cycles

L. von Grafenstein et al., Optics Letters 45, 5998 (2020)

Useful materials for further reading:

C Manzoni and G Cerullo, Tutorial: Design criteria for ultrafast optical parametric amplifiers, J. Opt. 18 103501 (2016)

Hanieh Fattahi, et al., "Third-generation femtosecond technology," Optica 1, 45-63 (2014)

F. Furch et al., J. Phys Photonics 4, 032001 (2022)

Dubietis and Matijošius, Opto-Electronic Advances 6, 220046 (2023)