High energy mid-IR ultrashort pulses: the parametric route

Pavel Malevich, Ignas Astrauskas, T. Kanai, S. S. Kangaparambil, A. Pugzlys, A. Baltuska

H. Hoogland, R. Holzwarth

Photonics Institute
Max Planck Institute of Quantum Optics
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

8 February 2018, Vienna

Outline

- Applications of ultrafast mid-IR sources
- Current state of ultrafast mid-IR sources
- 2 μm pump lasers
- Mid-IR OPAs in ZGP nonlinear crystal

Areas of usage of mid-infrared radiation

Applications

Spectroscopy

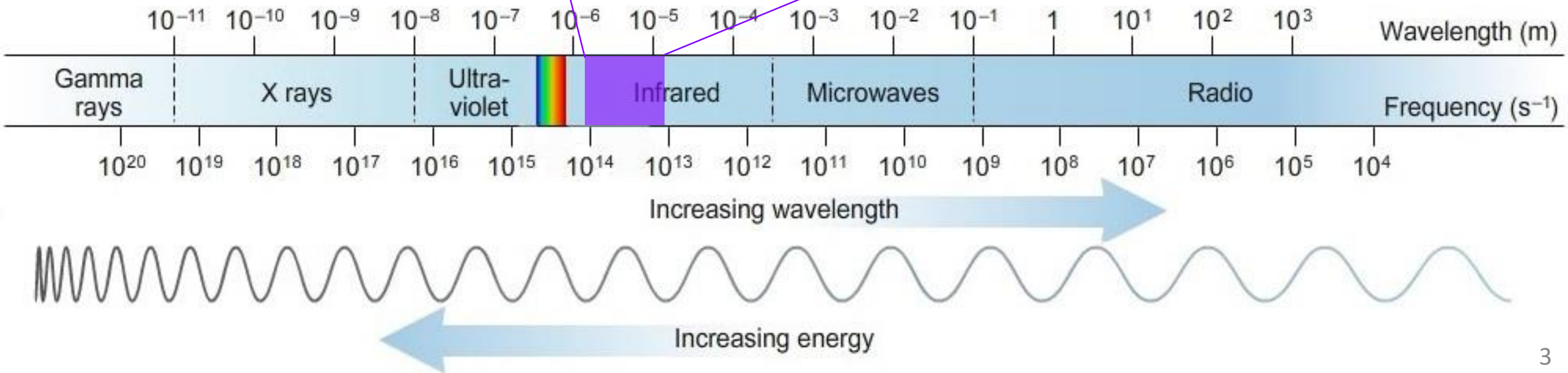
High field science

Medicine

Industry

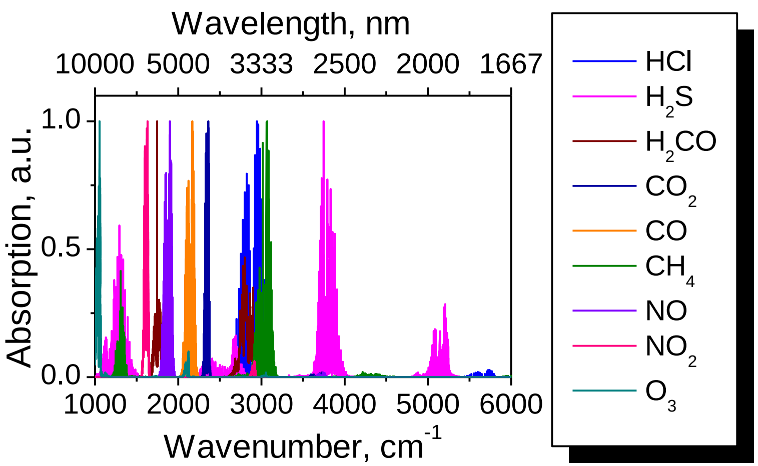
Ultrafast
mid-infrared source

- Duration
- Energy
- Repetition rate
- CEP stability



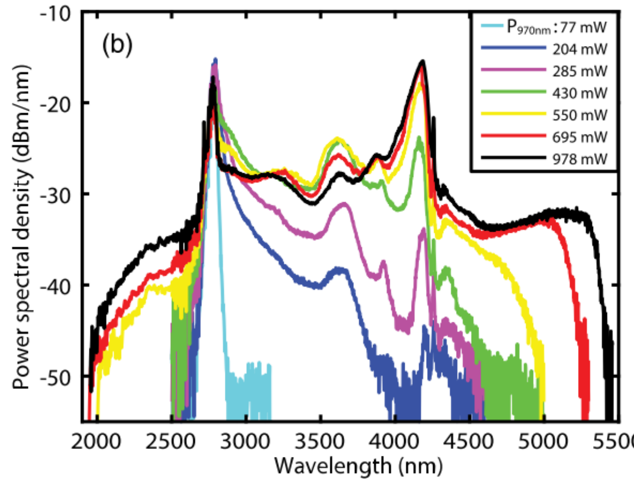
Spectroscopy and remote sensing

High sensitivity gas detection



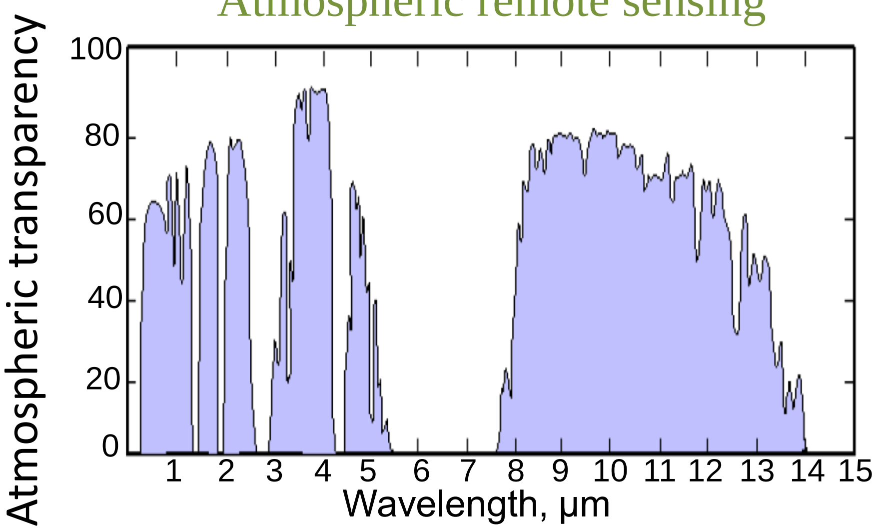
Mikhailenko S.N., *SPECTRA Information System*, http://spectra.iao.ru/1681x957/en/home/ based on HITRAN and GEISA databases

Stable supercontinuum

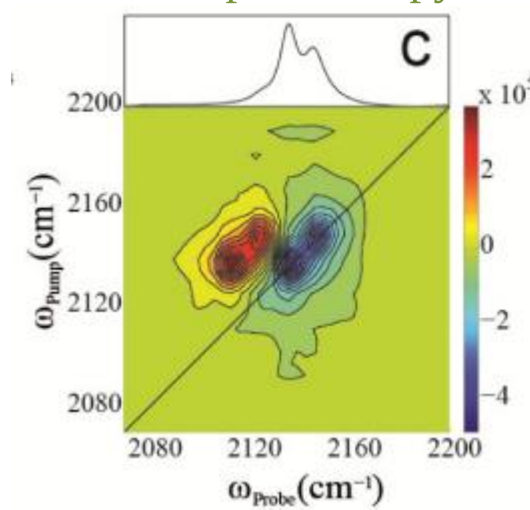


Gauthier, J.-C., *Opt. Lett. 41*, **8,** 1756 (2016)

Atmospheric remote sensing

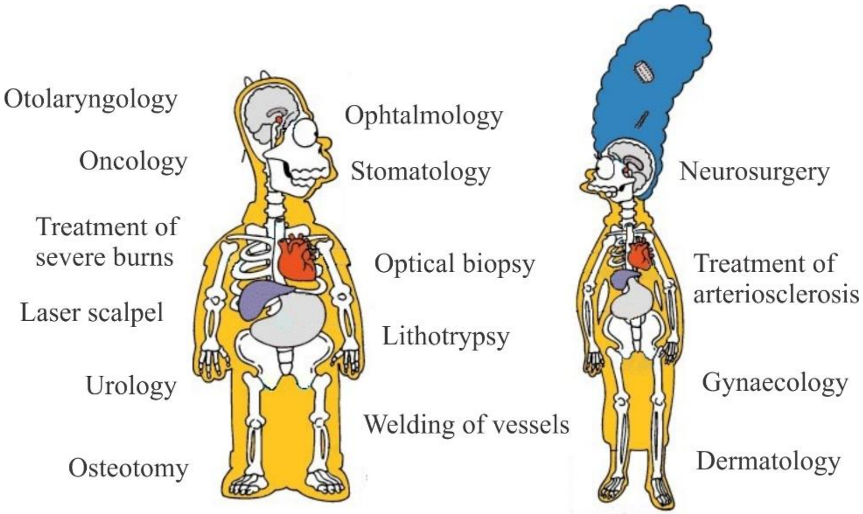


2D spectroscopy

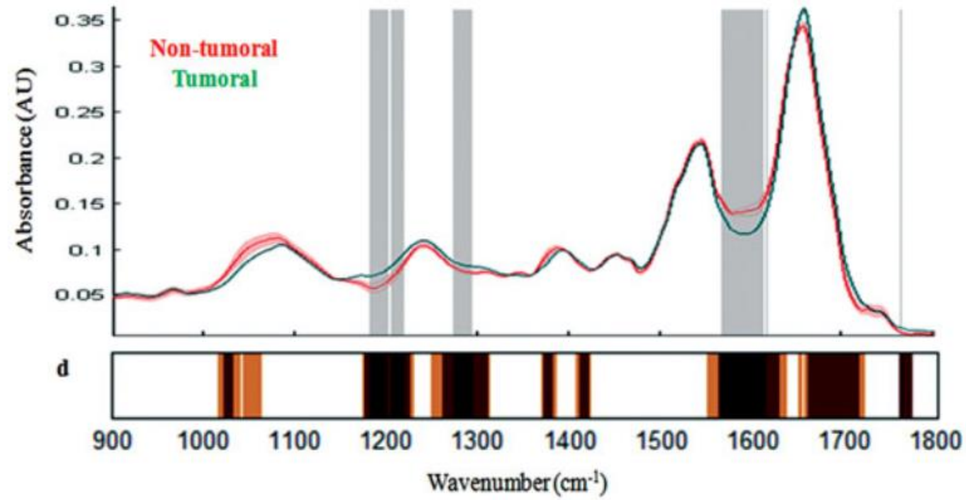


Luther M. B., *Opt. Exp.* **24**, 4, 4117 (2016)

Medicine

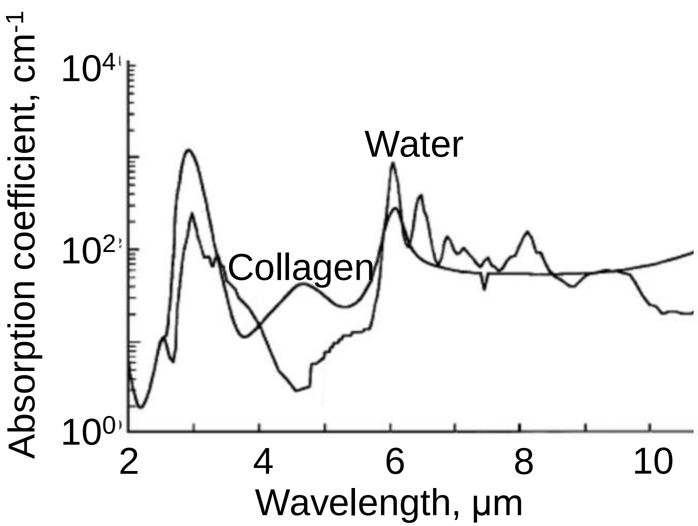


Detection of bio-markers



Nallala, J., *Cytometry. A*, **83**, 3, 294 (2013)

Selective influence on tissues



Serebryakov V. A., *J. Opt. Technol.* Vol **77,** No.1, 6 (2010)

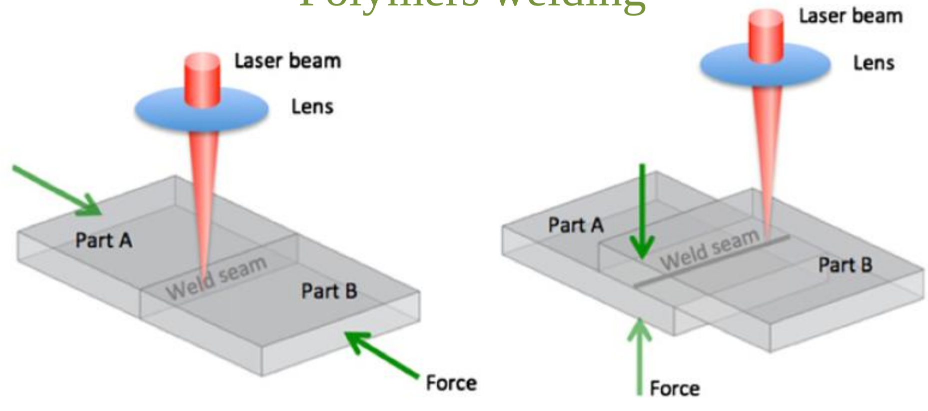
Quicker healing

Mutagenically safe

Less pain and irritation

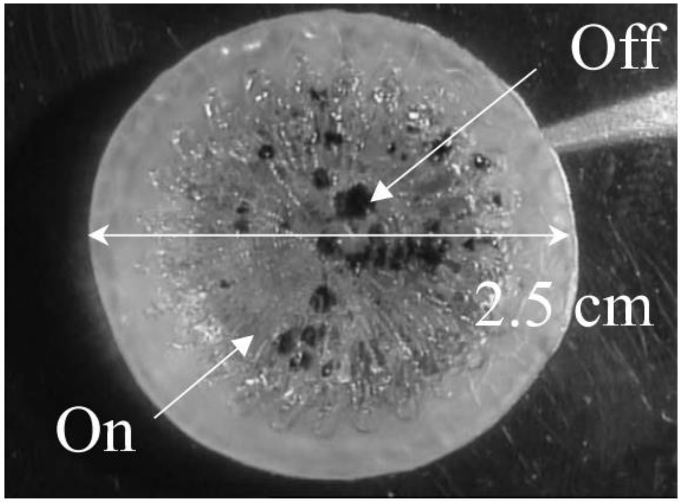
Industry

Polymers welding



Mingareev I, *Optics and Laser Technology* (2012)

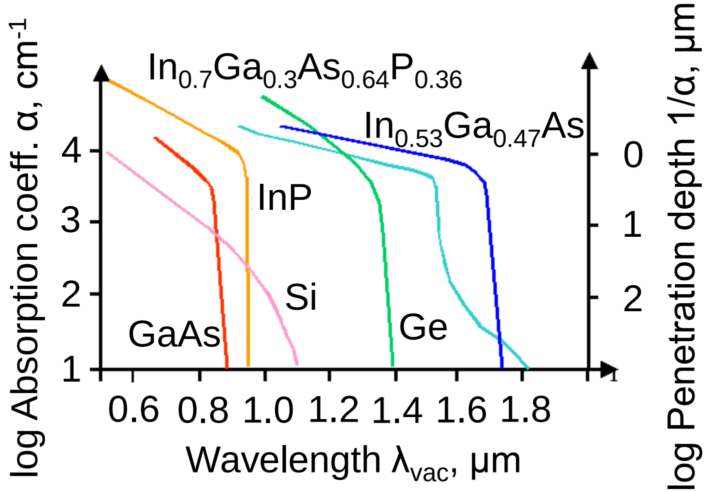
Polymeric film synthesis



Polystyrene target after on- and off- resonant deposition

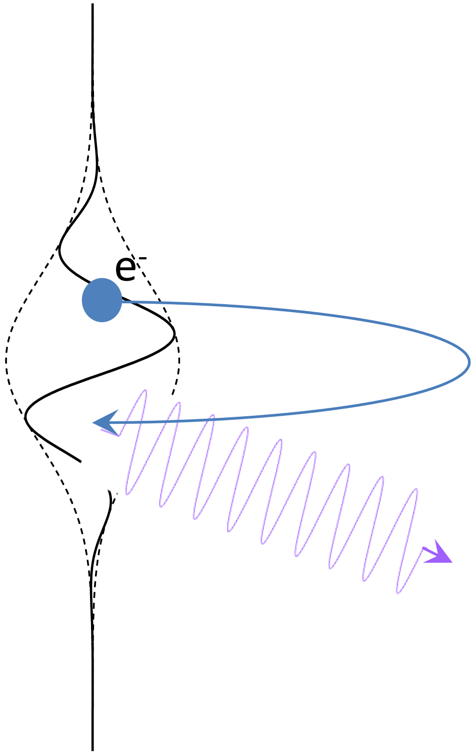
Bubb. D. M., *Chem. Phys. Lett.*, **352**, 3-4, 135 (2002)

Multi-photon processing of semiconductors

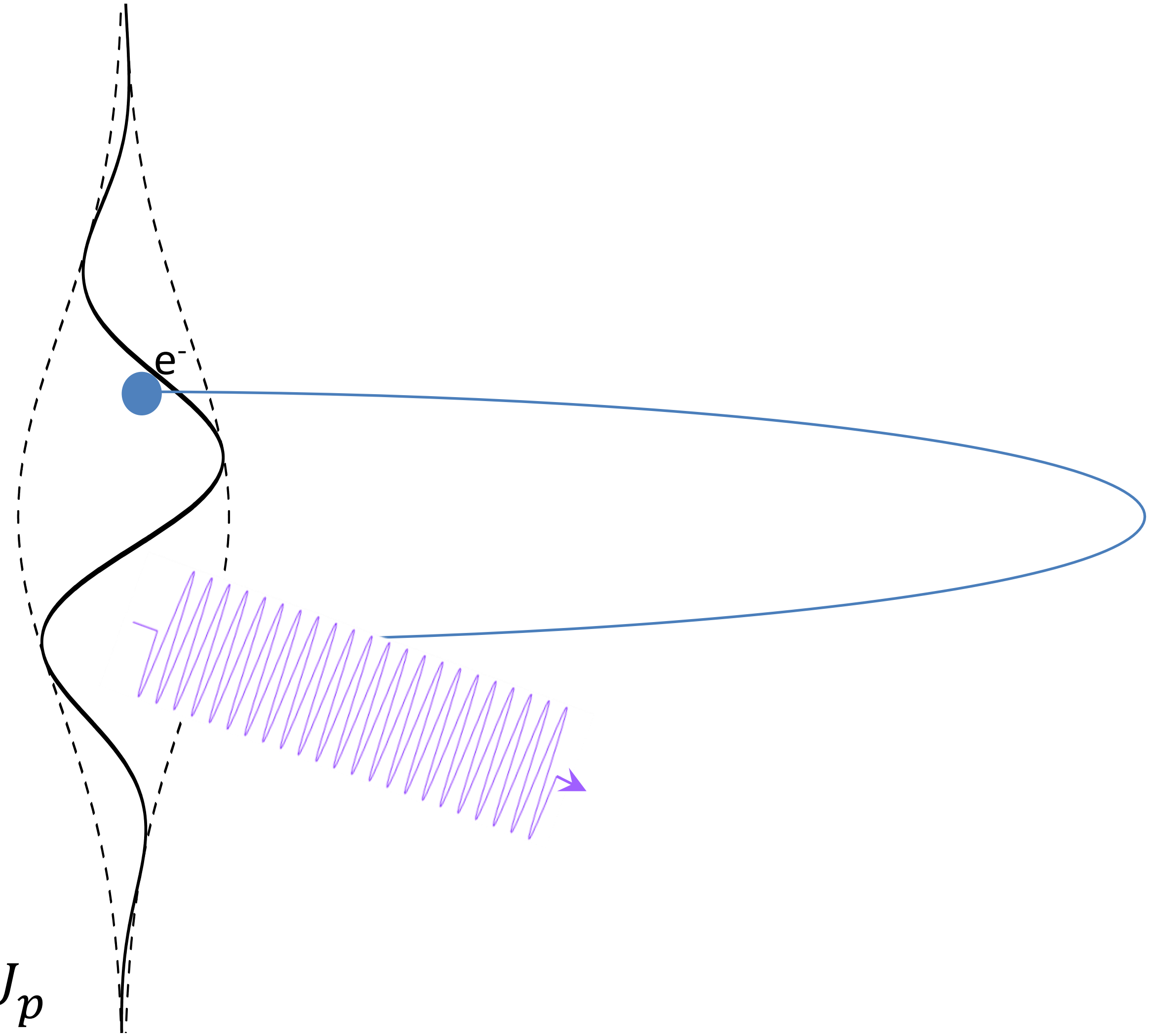


High field science (I)

High harmonics generation (HHG)



Short-wavelength driving pulse



Long-wavelength driving pulse

$$h\nu_{cut-off} = I_p + 3.17U_p$$

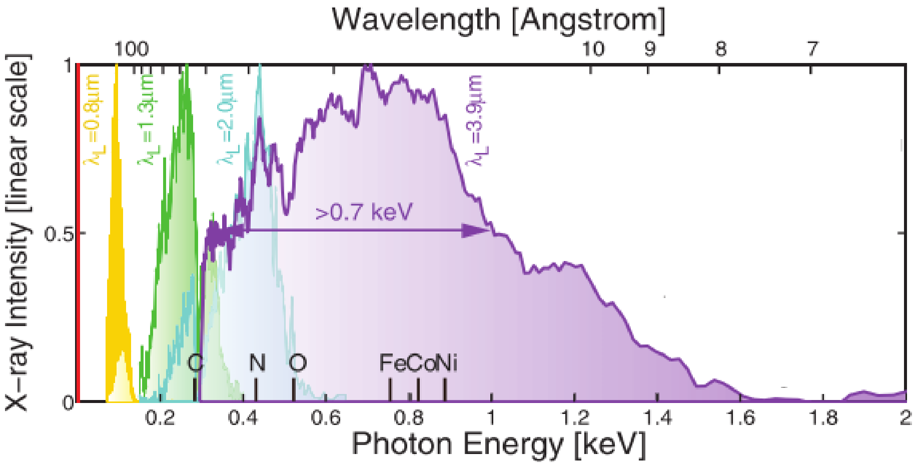
$$U_p \sim I \cdot \lambda^2$$

T. Popmintchev, *Opt. Lett.*, vol. 33, no. 18, p. 2128, Sep. 2008.

High field science (II)

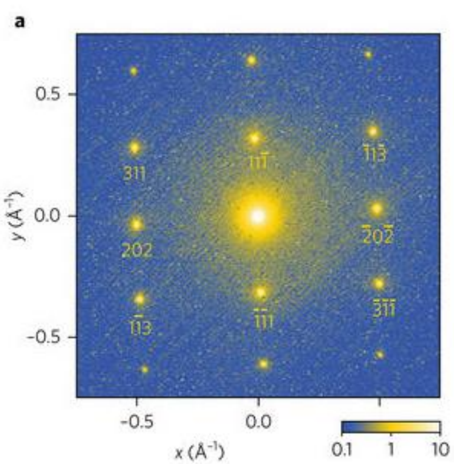
Applications

HHG with different driving lasers



T. Popmintchev et al, *Science*, **336**, 6086, 1287 (2012)

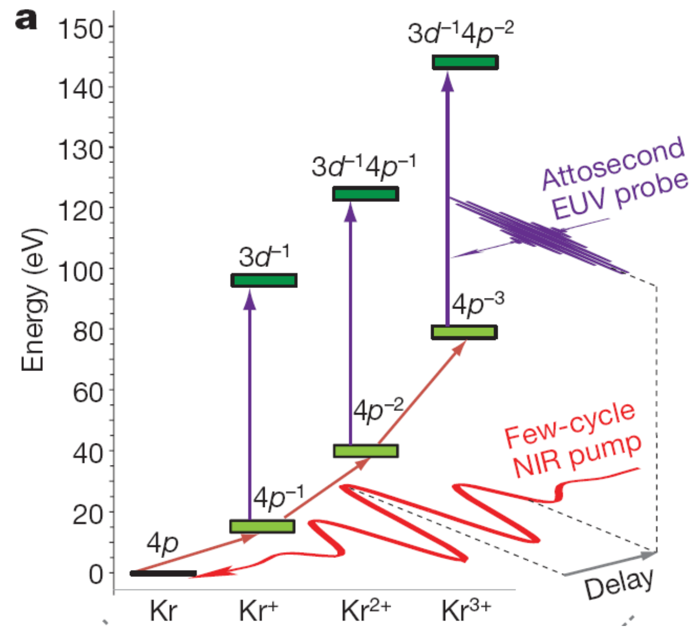
Spatial resolution

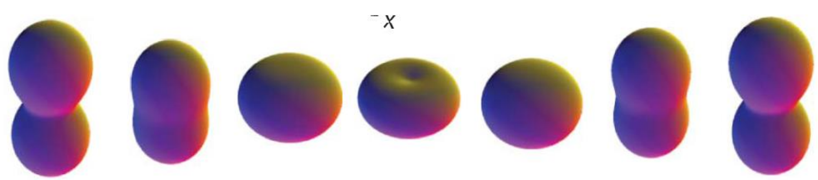


Si

Morimoto Y., *Nat. Phys. Lett*. nov 2017

Temporal resolution





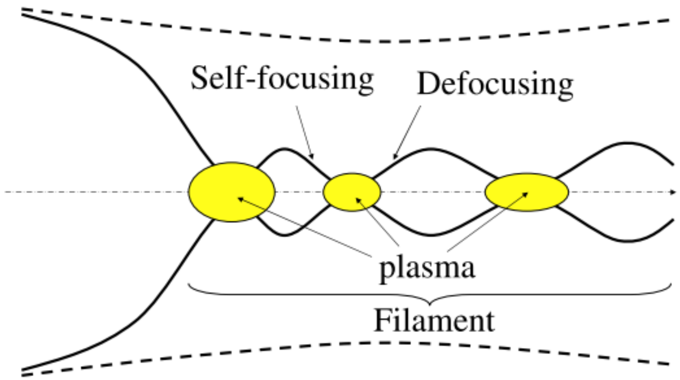
Reconstruction of valence-shell electron wave-packet motion

E. Goulielmakis, *Nat. Lett.* **466** (2010)

Filamentation

Applications

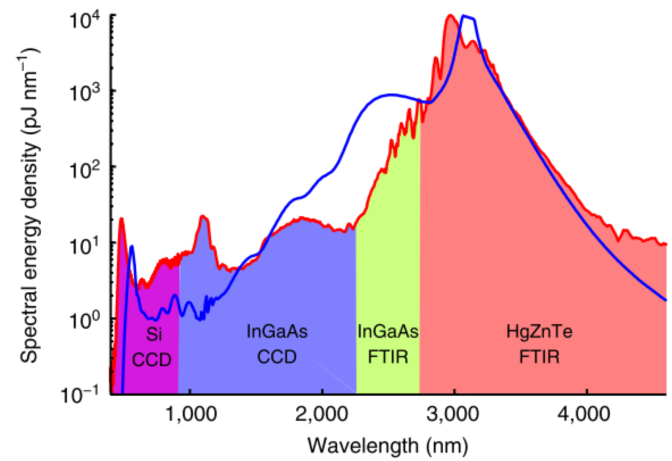
Filamentation



$$P_{cr} = 3.72 \frac{\lambda^2}{8\pi \, n_0 \, n_2}$$

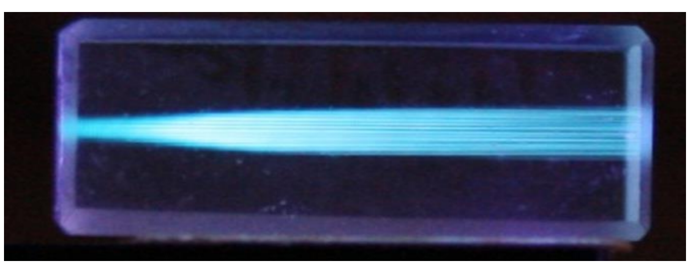
Couairon A., *Phys. Rep.* **441**, p. 47 (2007)

Generation of supercontinuum



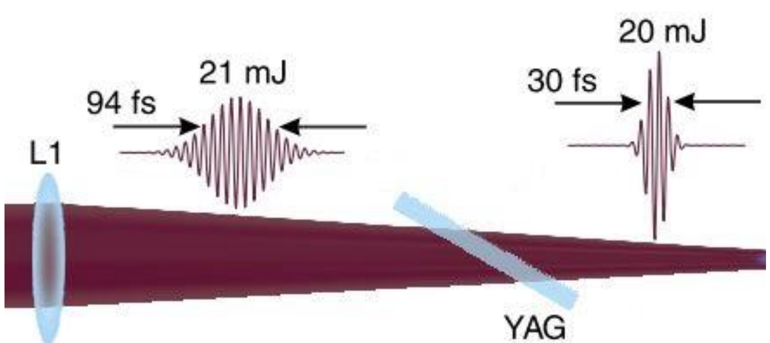
F. Silva, *Nat. Commun.* **3**, 807 (2012)

$$P \gg P_{cr}$$



High-energy beam delivery

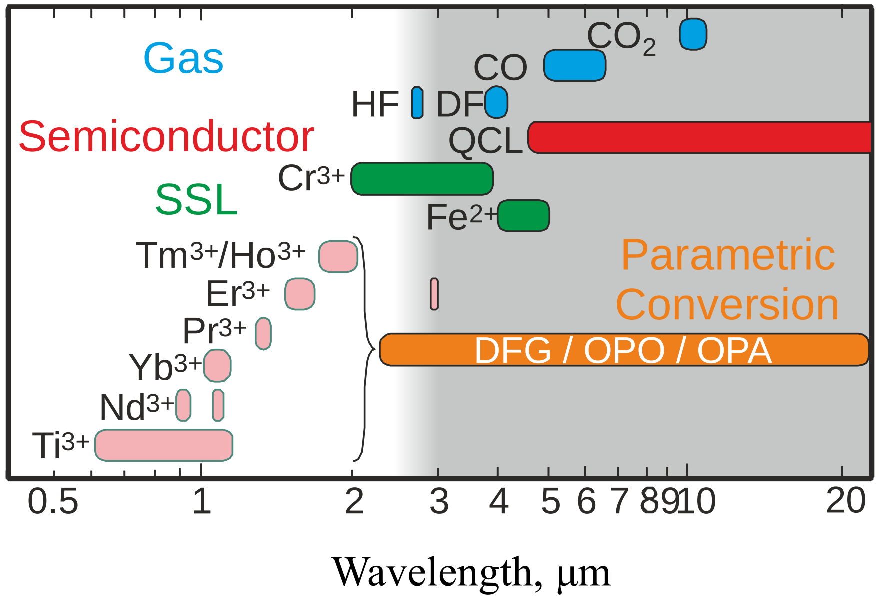
Self-compression



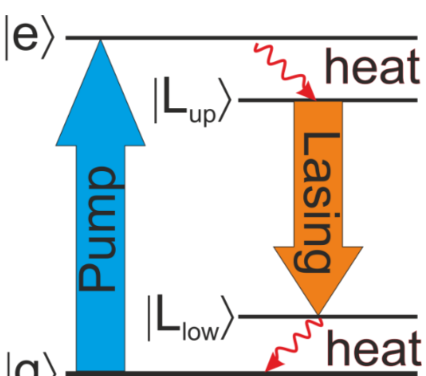
Shumakova V., *Nat. Commun.* **7**, 12877 (2016)

Current state of table-top Mid-IR sources

Current state

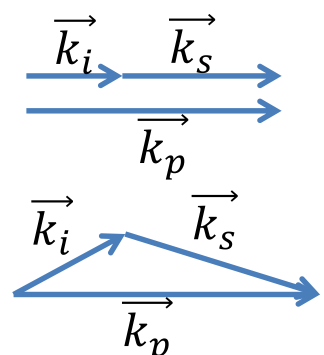


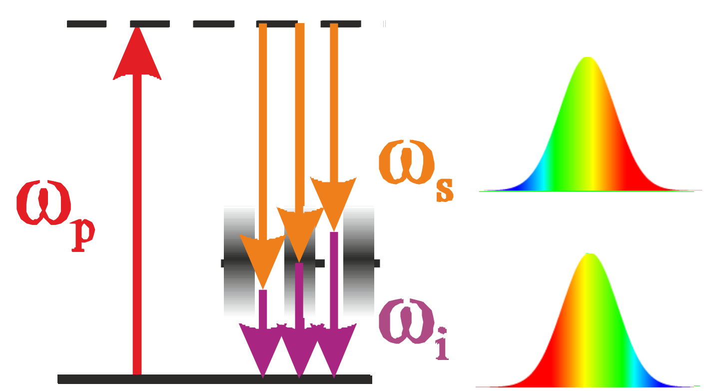
Laser medium



Nonlinear medium (parametric amplification)

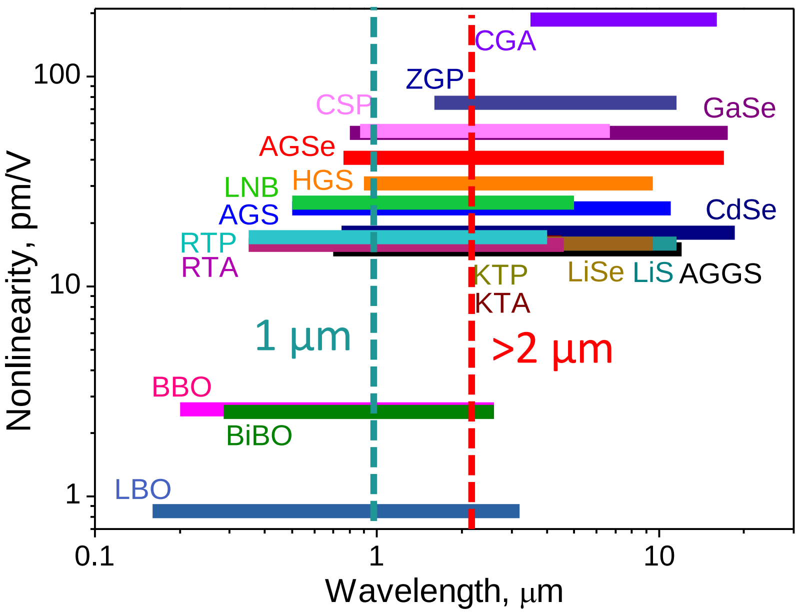
$$\vec{k}_s + \vec{k}_i = \vec{k}_p$$





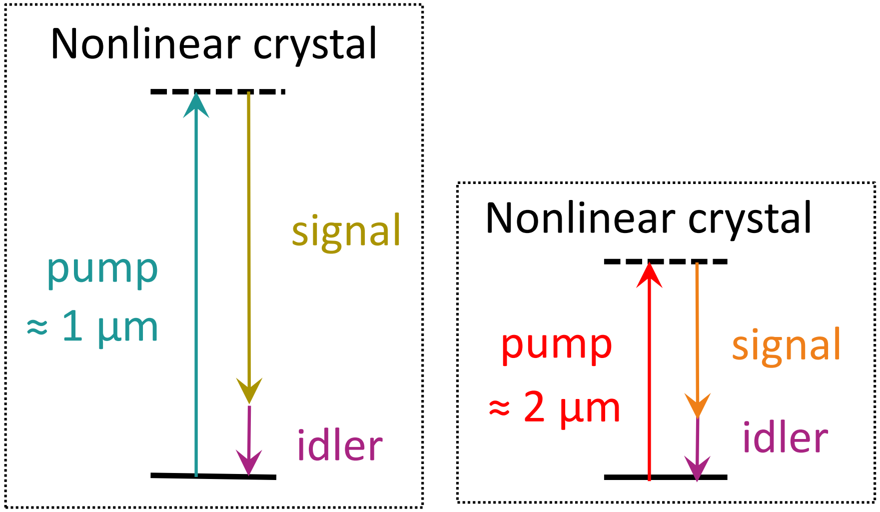
Nonlinear crystals

Current state

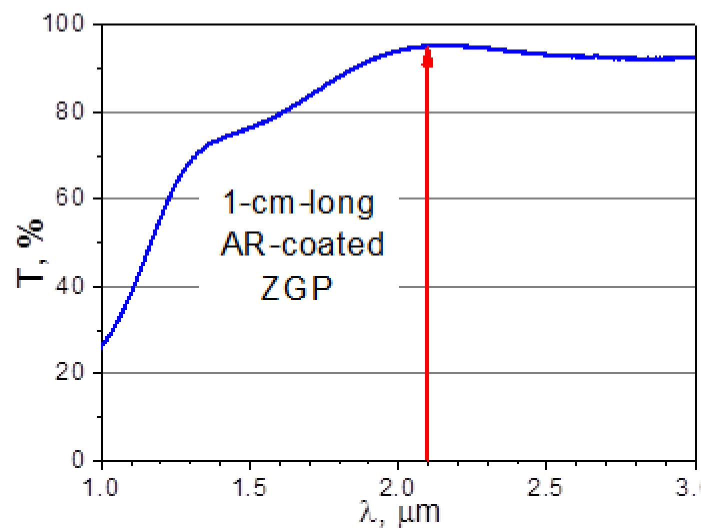


Transmission at 50% level

OPA with different pump sources



Crystal	Nonlinearity, pm/V	Damage threshold, J/cm²	Thermal conductivity, W·m⁻¹·K⁻¹	Pump wavelength, µm
AGS	11	1	1.5	1
BBO	2.2	13	1.2	<1
CGA	244	6	-	>3
KTA	2.2	15	2.1	1
ZGP	79	2	36	>2

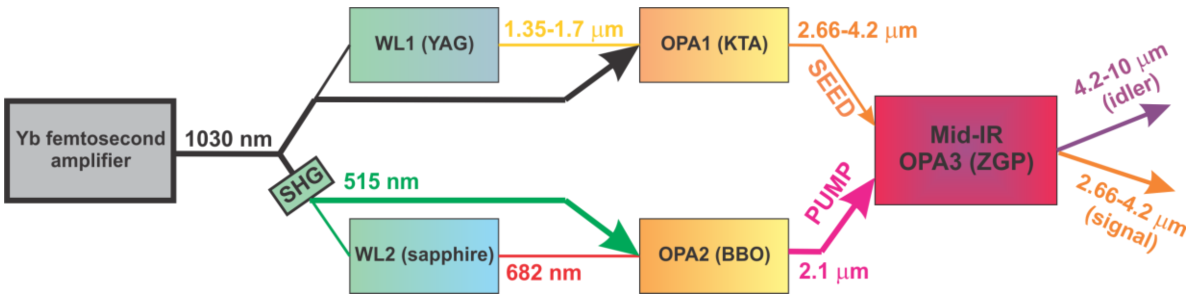


$ZnGeP_2$ (Zinc Germanium Phosphide)

Pump for ZGP OPA

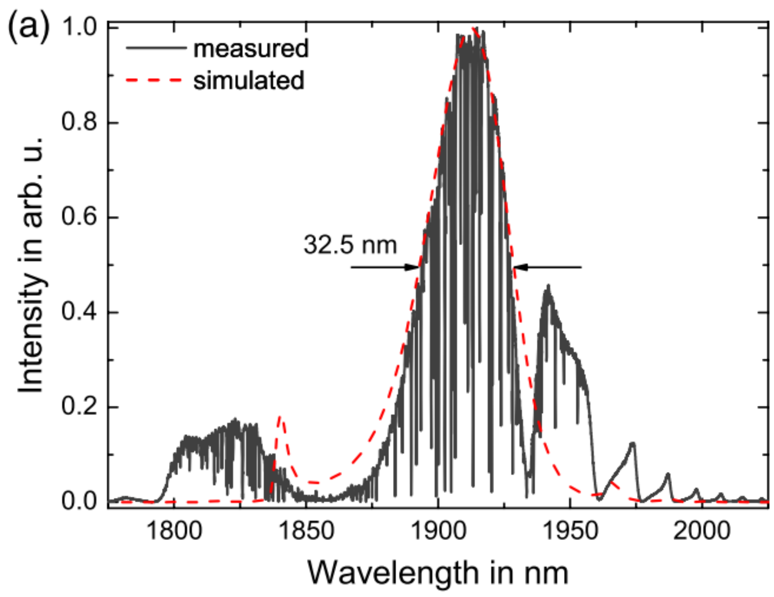
Current state

2 μm OPA



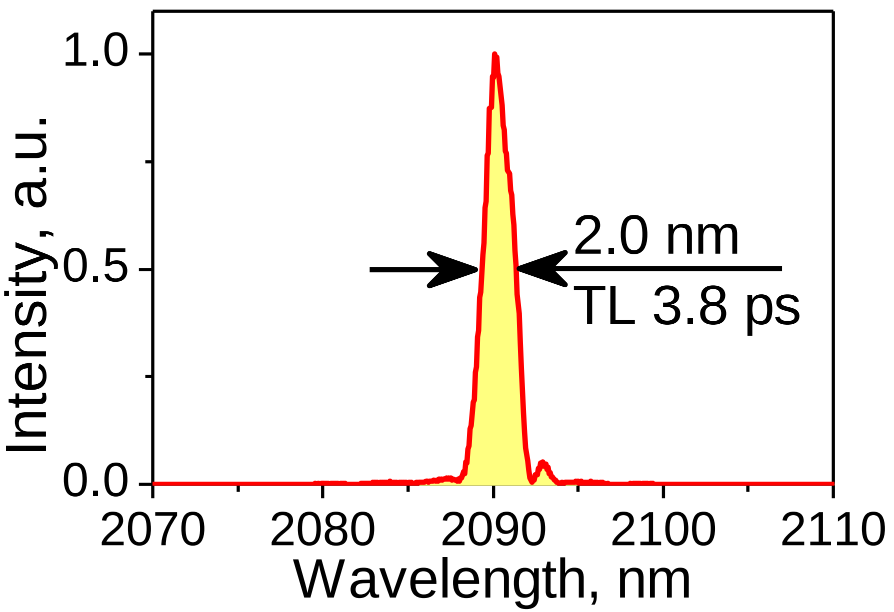
G. Andriukaitis, *CLEO* CF3B.6 (2012)

Tm:fiber



Wienke A., *Opt. Lett.* **37**, 13, 2466 (2012)

Ho:YAG



Malevich P., *Opt. Lett.* **38**, 15, p. 2746 (2013)

Current state of ultrafast 2 µm lasers

2 µm pump

- **Ho ions:**
- long upper state lifetime of (Ho:YAG **8 ms**)
- large emission cross-section (Ho:YAG **$1.2x10^{20}$ cm^2**)

→ **efficient energy extraction** in pulsed laser amplifiers

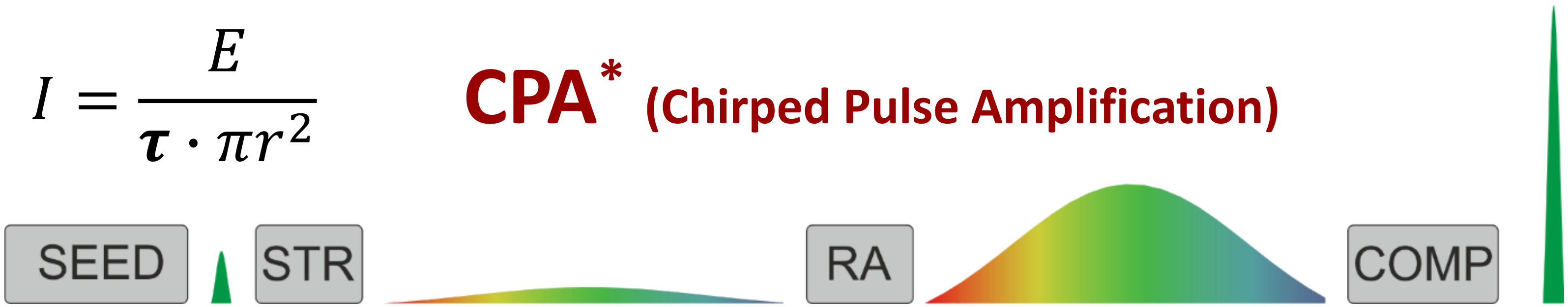
Laser material	Pump source	Seed source	λ_{em} µm	Energy mJ	Repetition rate Hz	Pulse duration ps	Reference
Cr:ZnSe	Ho:YLF	Cr:ZnSe	2.48	0.3	1000	0.3	E. Slobodchikov, *CLEO: Appl. & Tech., OSA Tech. Dig. PDPA10* (2011)
Ho:YLF	Tm:fiber	Ho:YLF	2.05	11	1000	300	Dergachev A., *Proc. SPIE*, 85990B (2013)
Ho:YLF	Tm:fiber	Er:fiber HNLF	2.05	5.5 (RA) 39 (Booster)	100	11	M. Hemmer, *Opt. Lett.* **40**, 4, p. 451 (2015)
Ho:YLF	Tm:fiber	Ho:fiber	2.05	13	10	530 (not compressed)	Kroetz P., *Opt. Lett.* **40**, 23, p. 5427 (2015)
Ho:YLF	Tm:fiber	Er:fiber HNLF	2.05	9.4 (RA) 34 (Booster)	1000	37	von Grafenstein L., *Opt. Expr.* **23**, 26, p. 33142 (2015)
Ho:YLF	Tm:fiber	Ho:fiber	2.05	2.2	1000	2.4	Murari K., *Opt. Lett.* **41**, 6, p. 1114 (2016)
Ho:YAG	-	-	2.09	0.7	1000	1.17	Wienke A., *ASSL*, ATh2A.39 (2015)
				This work:			
Ho:YAG	Tm:fiber	Tm,Ho:fiber Yb:KGW→OPA	2.09	3.8 5.5	1000	< 1	Malevich P., *Opt. Lett* **41**, 5, p. 930 (2016)

Chirp Pulse Amplification

Ho:YAG CPA

$$I = \frac{E}{\boldsymbol{\tau} \cdot \pi r^2}$$

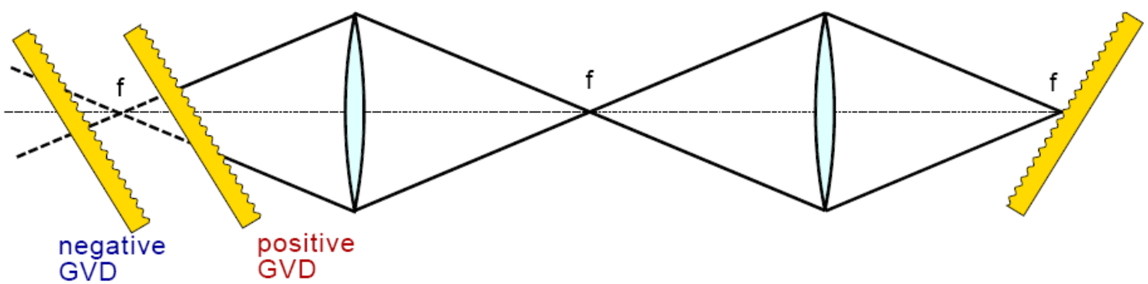
CPA* **(Chirped Pulse Amplification)**

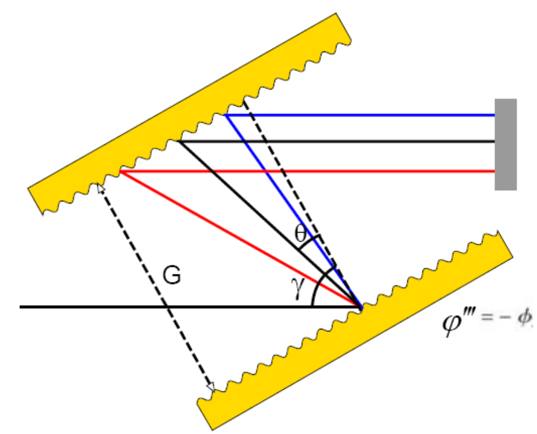


*D. Strickland and G. Mourou, *Opt. Commun.* 56, 219 (1985)

Compressor

Stretcher





positive dispersion

negative dispersion

O. E. Martinez, J. Opt. Soc. Am. B 3, 929 (1986)

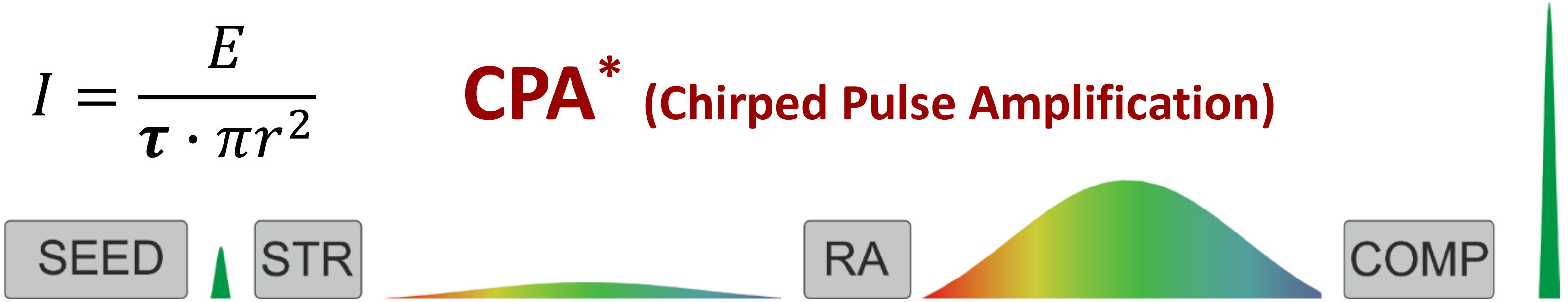
E. Treacy, IEEE J. Quantum Electron.5, 454 (1969)

Chirp Pulse Amplification

Ho:YAG CPA

$$I = \frac{E}{\boldsymbol{\tau} \cdot \pi r^2}$$

CPA* **(Chirped Pulse Amplification)**



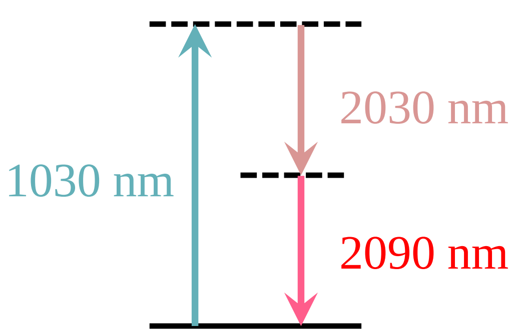
*D. Strickland and G. Mourou, *Opt. Commun.* 56, 219 (1985)

Optical Parametric Amplifier

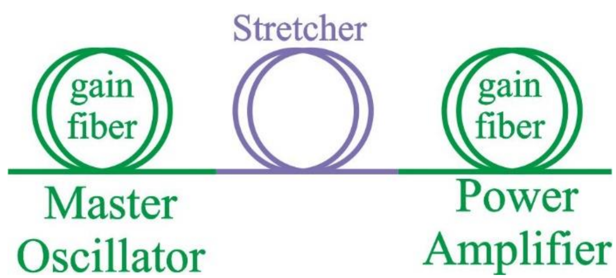
Seed

Tm,Ho:fiber Laser

Nonlinear crystal KTA



CEP stable

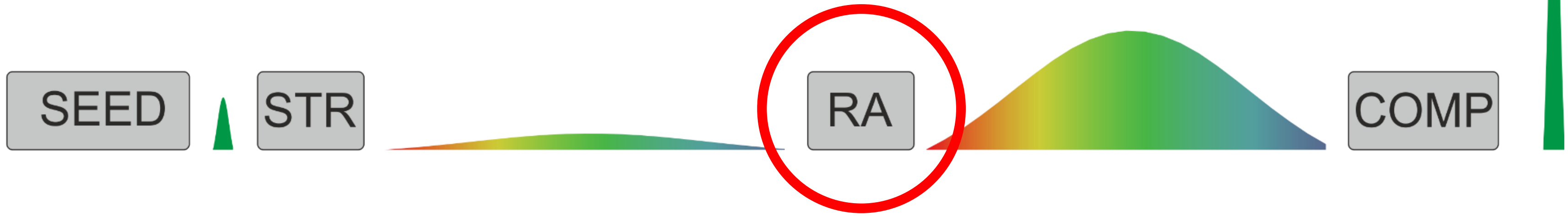


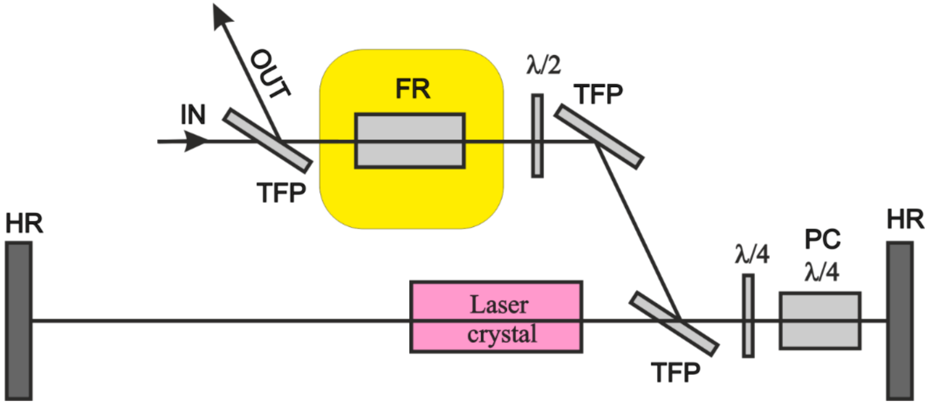
Malevich P., *Opt. Lett.* **38**, 15, p. 2746 (2013)

Hoogland H., *Opt. Lett.* **39**, 23, p. 6735 (2014)

Regenerative amplifier

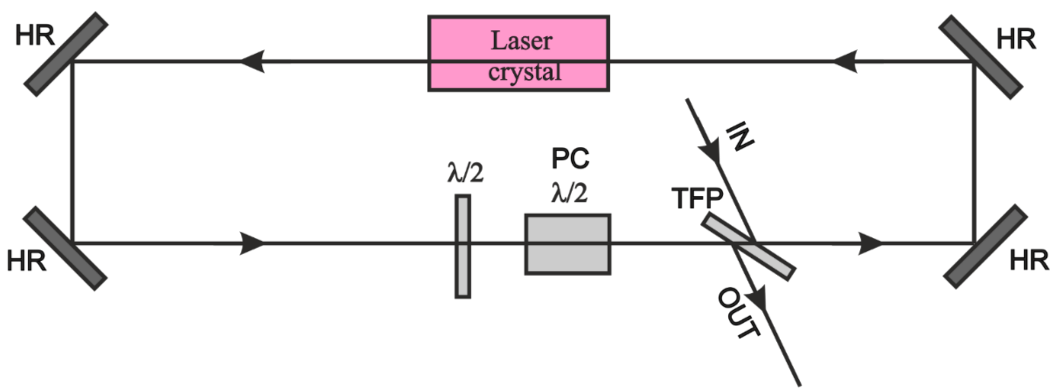
Ho:YAG CPA





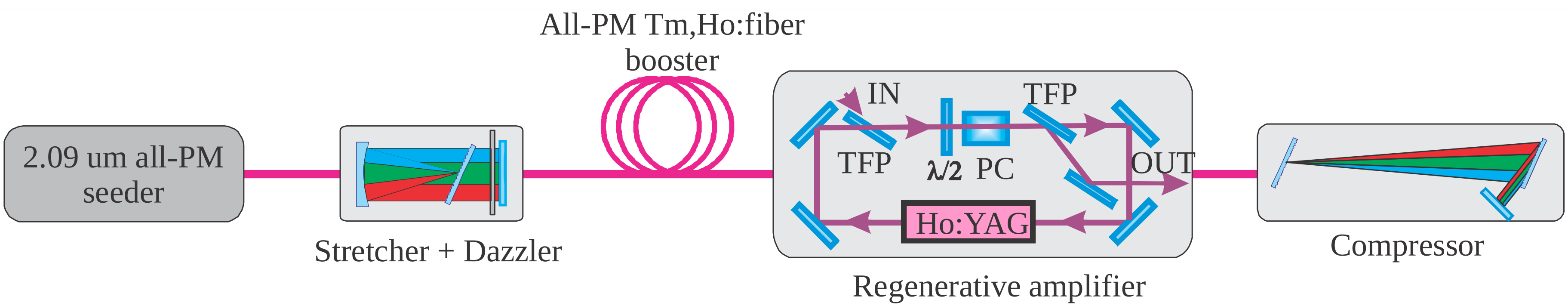
“TYPICAL” STANDING-WAVE CAVITY

RING CAVITY

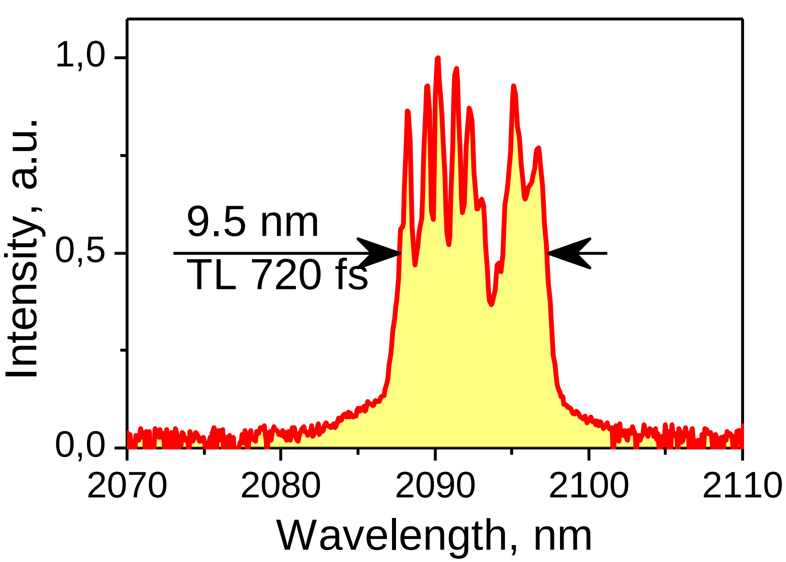


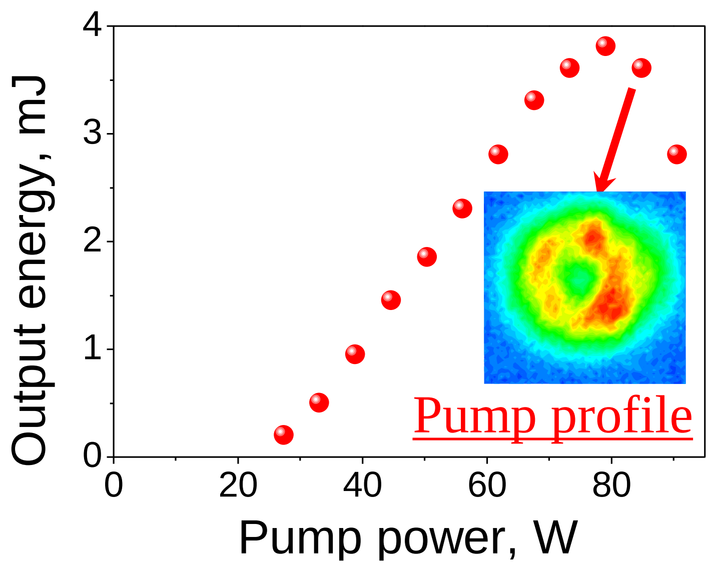
Ho:YAG RA performance

Ho:YAG CPA



RA output





Output

Fiber seeder

3.8 mJ
0.98 ps

OPA seeder

5.5 mJ
0.8 ps

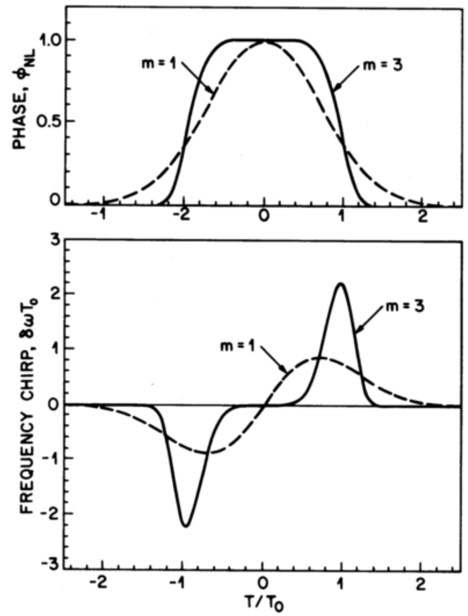
Seed generation

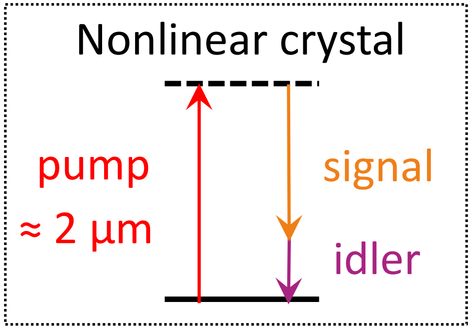
Self-phase modulation (SPM) = White Ligth Generation

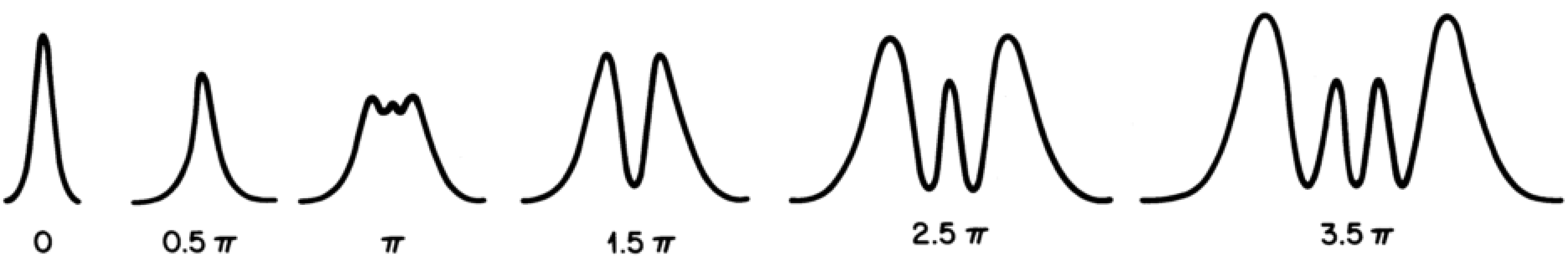
$$n = n_0 + n_2 \cdot I$$

$$\omega_0 \rightarrow \omega_0 \pm \Delta\omega$$

$$\varphi_{SPM} = \varphi_p$$



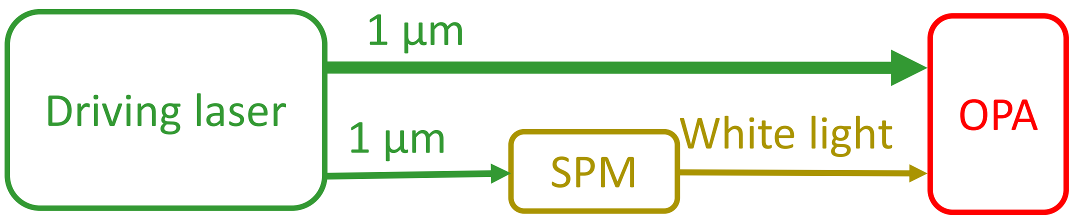




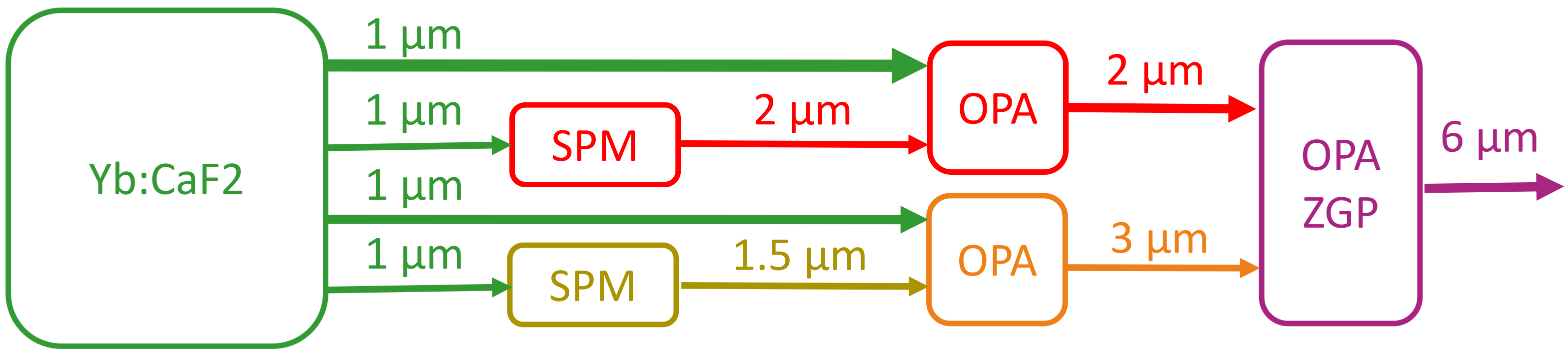
φ φ φ φ φ φ

G. P. Agrawal, *Nonlinear fiber optics*, Third Edit. San Diego, CA: Academic Press, 2001

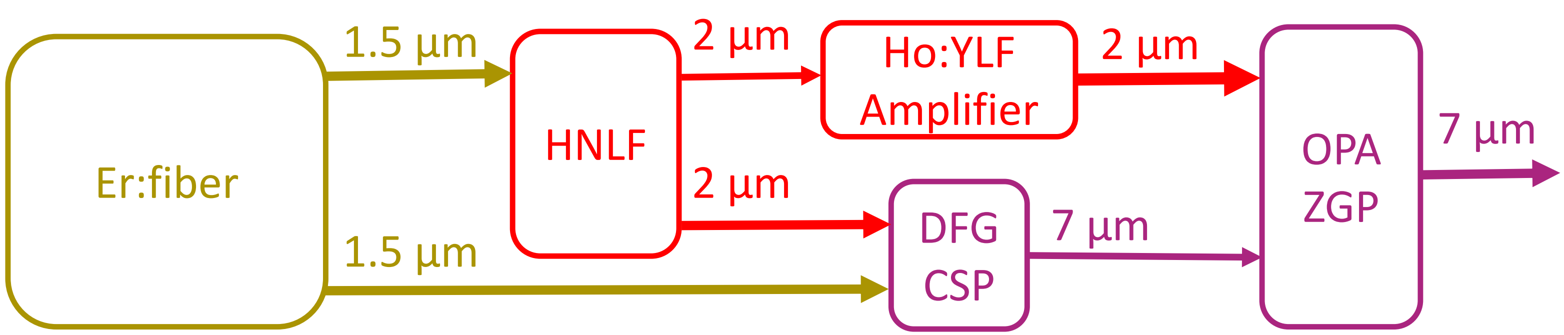
Dispersion of materials in mid-IR



Demands
pulse duration
<1 ps

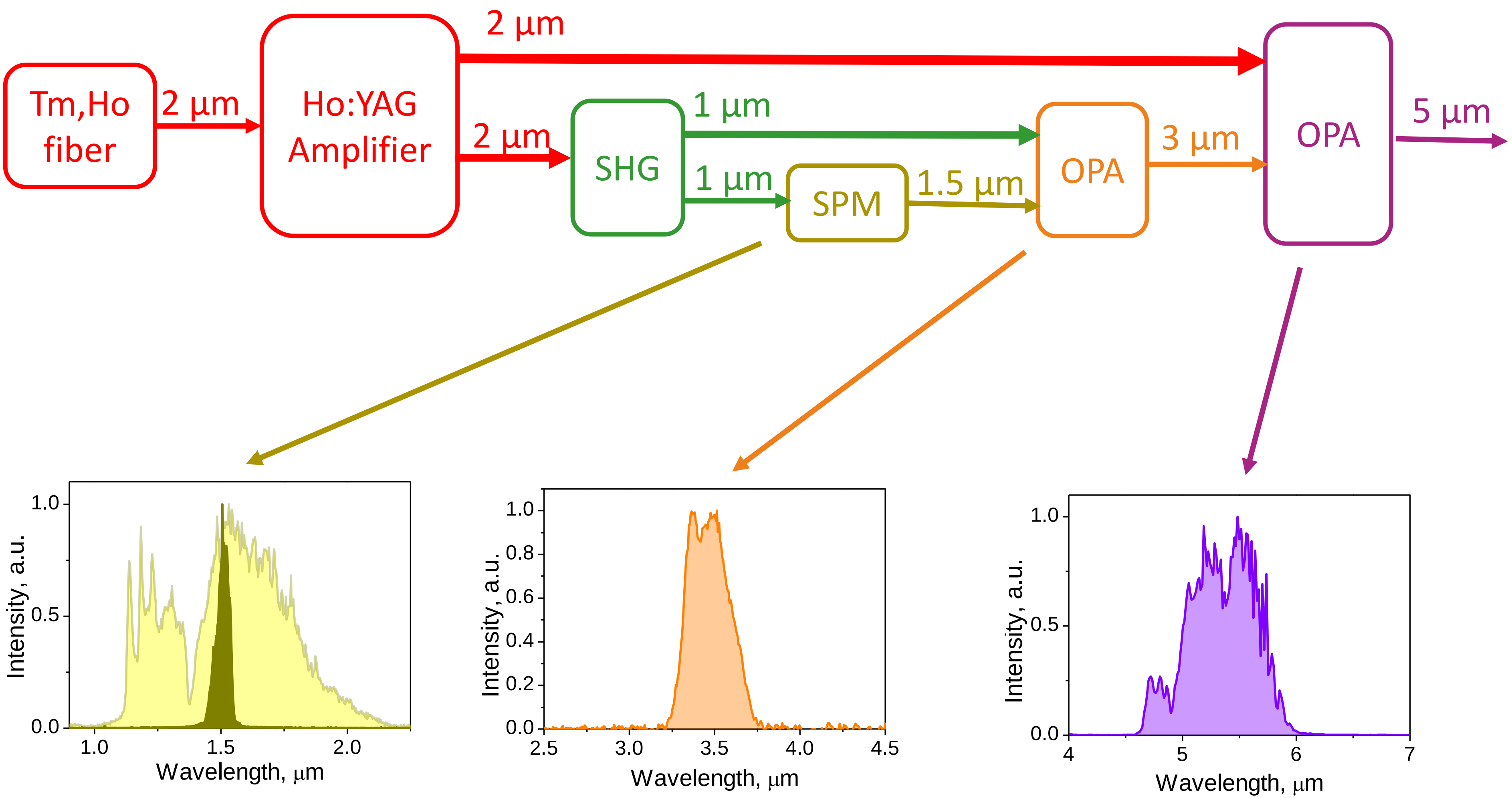


G. Andriukaitis, *CLEO* CF3B.6 (2012)



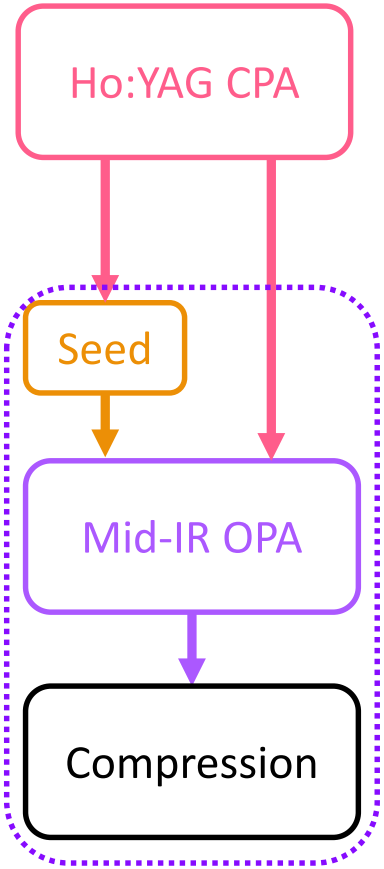
D. Sanchez, *Optica* **3**, 2, 147 (2016)

Mid-IR OPA with ~1 ps pulses



Supports 70 fs
Compressed to 99 fs

Summary



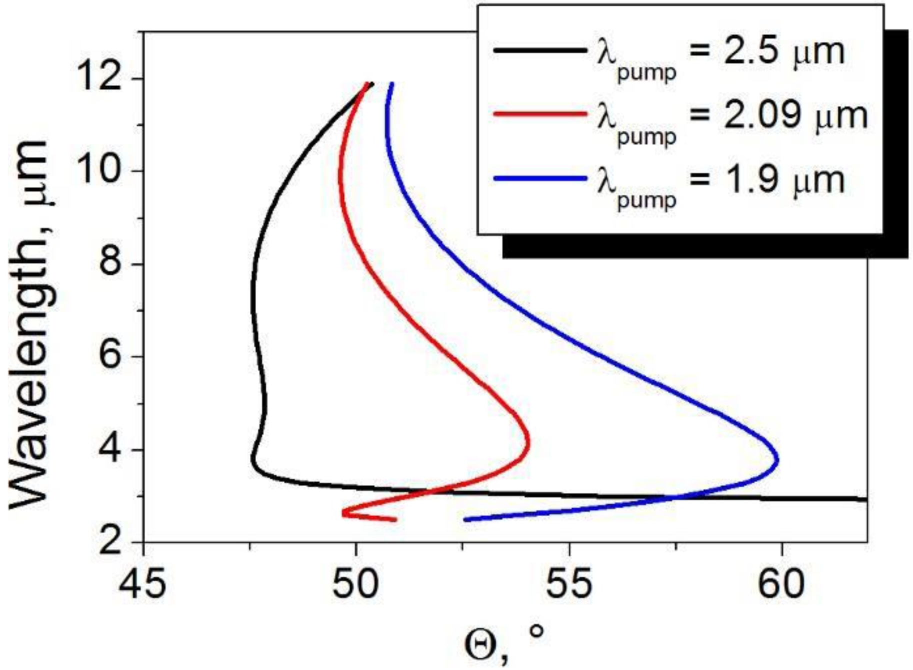
- √ 1 kHz 5.5 mJ 0.8 ps
- √ CEP stable
- √ Cascaded white light amplification
- √ 80 μJ 99 fs
- √ Bulk dispersion control

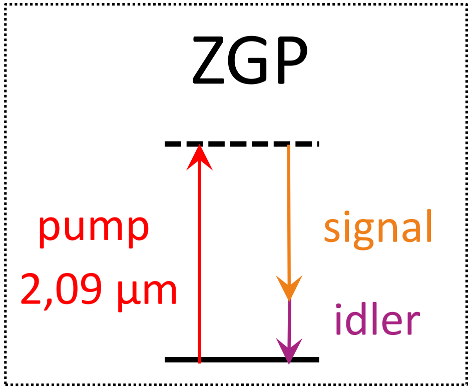
Thank you!

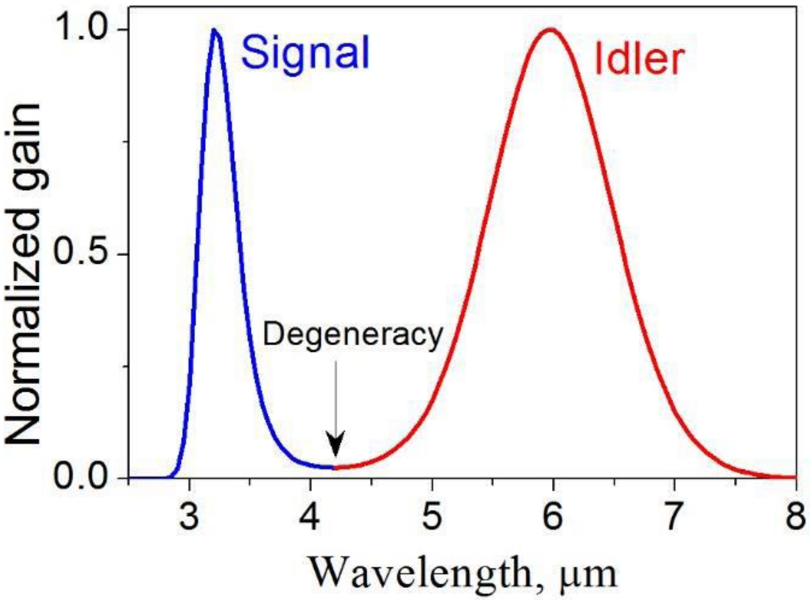
Mid-IR generation in ZGP

Current state

ZGP tuning with different pumps







8 mm ZGP gain spectrum with 2.09 μm pump