Chirped Pulse Amplification
Ultrafast Spectroscopy

Café Scientifique Talk
Nov 15, 2018
Discussion of the 2018 Nobel Prize in Physics for Chirped Pulse Amplications

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Nobel prize in physics 2018 was awarded “*for groundbreaking inventions in the field of laser physics*” to:

Arthur Ashkin
(prize share : 1/2)

“optical tweezers and their application to biological systems”

Gérard Mourou
(prize share : 1/4)

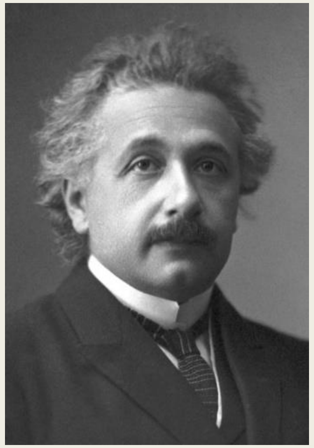
Donna Strickland
(prize share : 1/4)

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

https://www.nobelprize.org/prizes/physics/2018/summary/

LASER : Light Amplification by Stimulated Emission Radiation

- Theoretical foundation established by Albert Einstein in **1917**



Albert Einstein
(copyright © Nobel Media AB 2018)

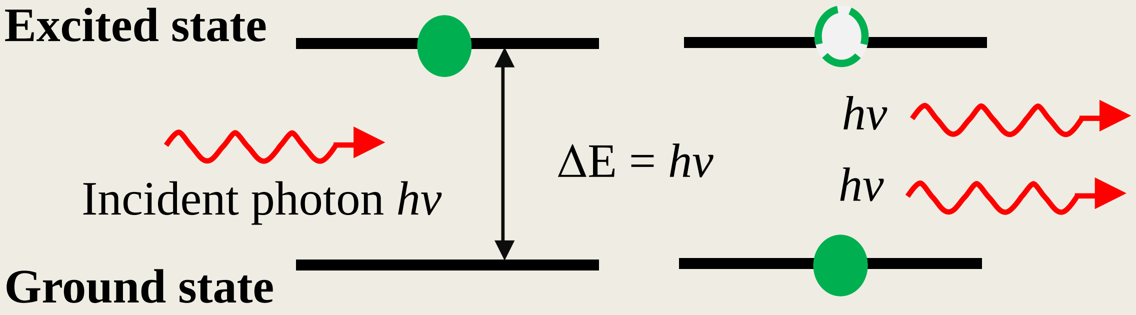
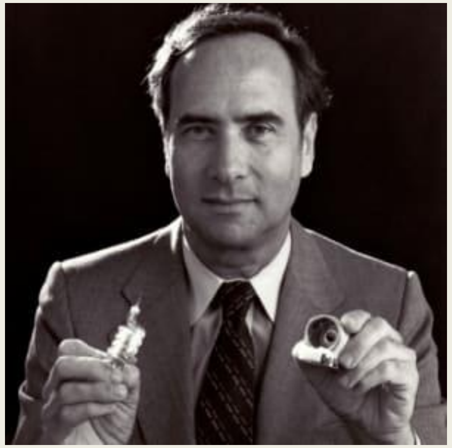

Excited state
Incident photon *hv*
$\Delta E = hv$
hv
hv
Ground state

Figure 1. Illustration of stimulated emission

- First working laser was invented by Theodore Harold Maiman in **1960**.[1]



Theodore Harold Maiman
(copyright©2014 National Academy of Sciences)

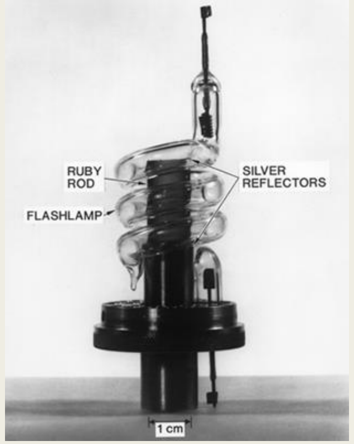


Figure 2. The first ruby laser in 1960
(copyright ©2018 American Institute of Physics)

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[1] T. H. Maiman, *" Stimulated Optical Radiation in Ruby"*, *Nature* **(1960)**, vol 187, pages 493–494

Higher peak power and intensity → Optical nonlinear processes in materials

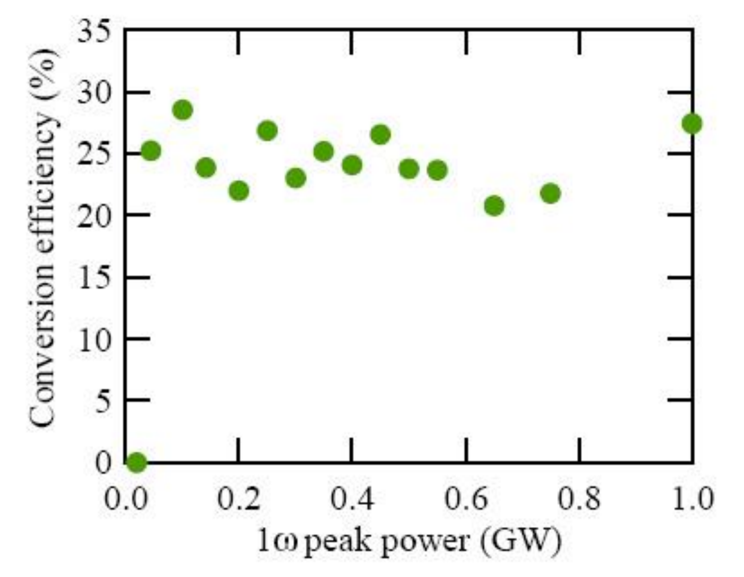


Figure 3. Conversion efficiency of second harmonic generation in BiBO crystal with respect to pump pulse peak power. [2]

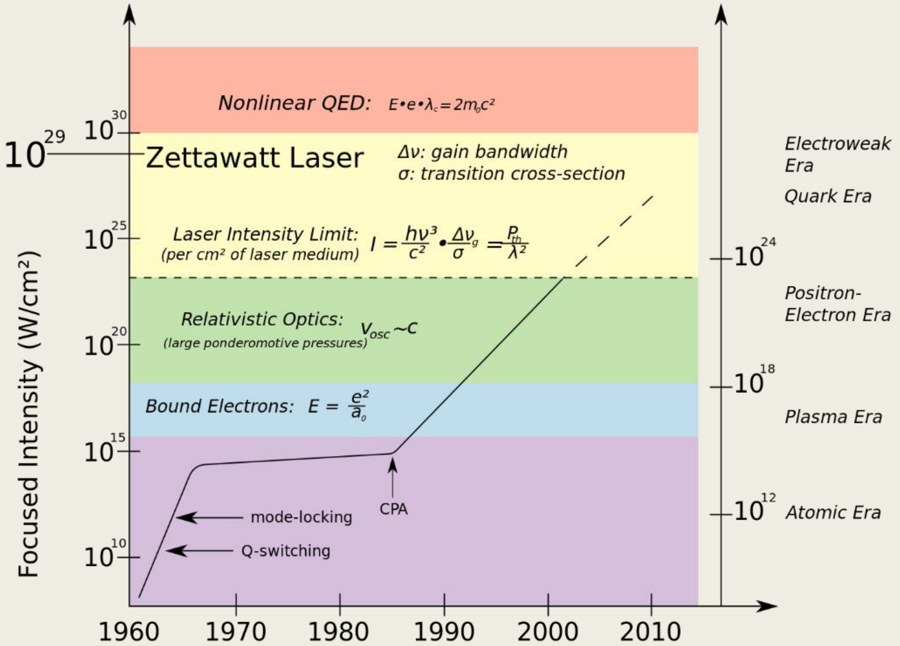
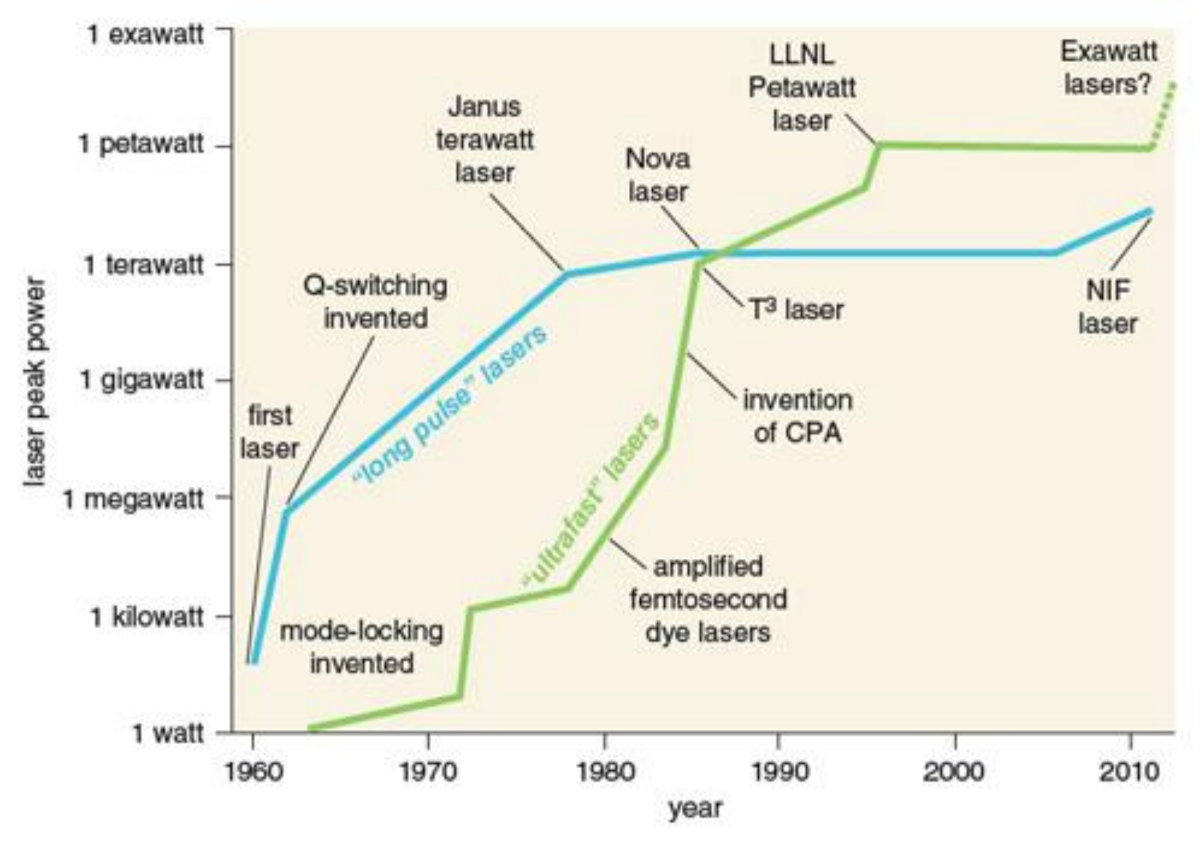


Figure 4. Laser peak output irradiance in decades

Q-switching and mode-locking through shortening pulse duration has increased peak power up to GW range.

[2]Tetsuo Harimoto, et al, "*Spectral properties of second-harmonic generation at 800 nm in a BiB_3O_6 crystal*", *Optics Express* **(2004),** Vol. 12, Issue 5, pp. 811-816

Q-switching versus mode locking



https://www.americanscientist.org/article/high-power-lasers

- Power station: 1-2 GW
- Power consumed in U.S.: 1 TW
- Most powerful amplified lasers: PW
- Output of our tabletop Ti:Sapphire oscillator:
  - 1 W average power
  - $(12\times10^{-9}$ s / 30×10^{-15} s $)\times 1.5$ W ~ 1 MW peak power
- Output of our tabletop amplified Ti:Sapphire:
  - 3 W average power
  - $(10^{-3}$ s / 10^{-13}s $)\times 3 = 30$ GW peak power
- Focus to 20 um:
  - Ti:Saph oscillator: 10^{11} W/cm2
  - Ti:Saph amplifier: 10^{16} W/cm2

Limitation of Q-switching and mode-locking techniques:

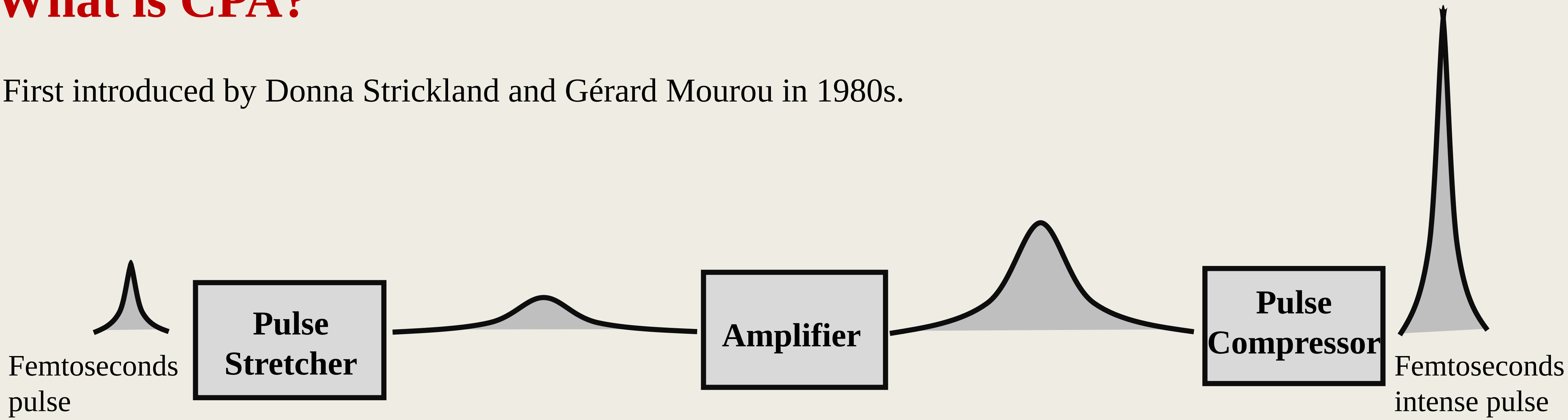
Kerr effect $n(I) = n_1 + n_2 I$ → Self-focusing → Damage the amplifier medium

Solution:

Chirped pulse amplification (CPA)

What is CPA?

First introduced by Donna Strickland and Gérard Mourou in 1980s.



Femtoseconds pulse

Pulse Stretcher

Amplifier

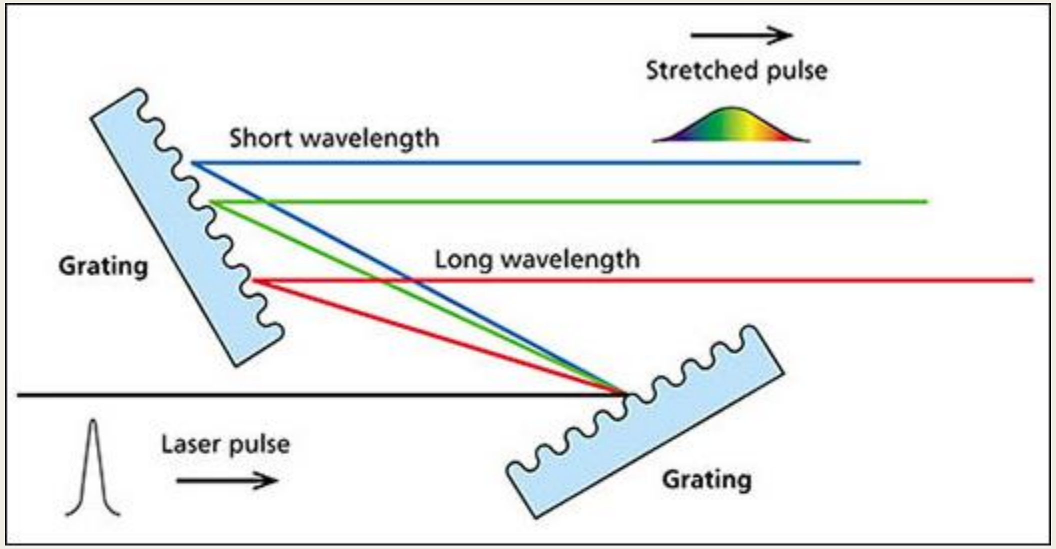
Pulse Compressor

Femtoseconds intense pulse

Figure 5. Simplified illustration of the chirped pulse amplification process.

Pulse Stretcher

Positive dispersion : higher frequencies take more time to travel through
Negative dispersion : higher frequencies take less time to travel through



$$d\sin\theta_m = m\lambda$$

d: spacing
θ_m: *diffracted angle*
m: m_{th} order
λ: wavelength of incident light

Figure 6. simplified illustration of a grating pulse stretcher (Copyright © 2018 Shimadzu Corporation)

varying the separation distance between two grating → Stretching ratio

For a typical Ti: sapphire-based CPA:

- ❑ Positive dispersion pulse stretcher (>90% broadband high-transmission efficiency [3])
- ❑ Pulse stretched to several hundred picoseconds

[3] H. Kiriyama, et al, ISRN optics, Vol. 2012, Article IA. 120827, (2012), DOI: 10.5402/2012/120827

Amplifier

Broad gain bandwidth laser material:

- ❑ Nd: YAG ($Y_3Al_5O_{12}$)[4]
  - widely used before 90s
  - Pulse width 10 ~ 100 ps
  - unstable due to high sensitivity to environmental perturbation
- ❑ Ti: Sapphire (Al_2O_3) [4]
  - Popular since 90s
  - Broader gain bandwidth (wavelength from 700nm to 1100nm)
  - High thermal conductivity
  - High gain
  - Produce pulse width ~ 20 fs
- ❑ Yb-doped solid state materials (Yb: YLF($LiYF_4$))[5],Yb: YGAG ($Y_3Ga_2Al_3O_{12}$)[6], Yb: YAG[7]-[8])
  - Investigated in the last decade
  - broad absorption and emission bandwidth
  - low quantum defect
  - simple electronic structures
  - suitable for direct diode pumping[5]

[4] Sterling Backus, et al, "high power ultrafast lasers", *Review of Scientific Instruments* 69, 1207 (1998); DOI: 10.1063/1.1148795
[5] T. Harimoto, et al, *Optics Express*, Vol. 15, Issue 8, pp 5018 – 5023, (2007), DOI: 10.1364/OE.15.005018
[6]Jaroslav Huynh, et al, *Optical Materials Express*, Vol. 8, Issue 3, pp. 615-621, DOI: 10.1364/OME.8.000615
[7]Yoshihiro Ochi, et al, *Optics Express*, Vol 23, Issue 11, pp. 15057 – 15062, (2015), DOI: 10.1364/OE.23.015057
[8]Sandro Klingebiel, et al, *Optics Express*, Vol 19, Issue 6, pp. 5357 – 5363, (2011), DOI: 10.1364/OE.19.005357

Pulse Compressor

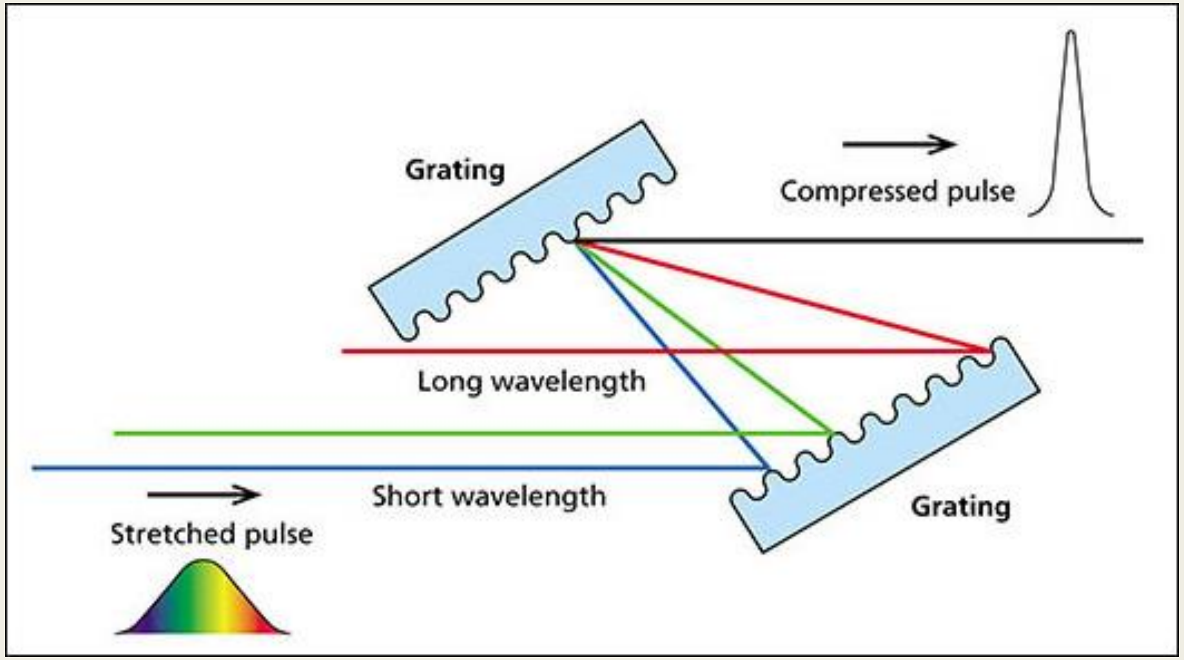


Figure 7. simplified illustration of a grating pulse compressor (Copyright © 2018 Shimadzu Corporation)

For a typical Ti: sapphire-based CPA:

- Negative dispersion pulse compressor (cancel out the dispersion by stretcher, 50% ~ 70% efficiency)
- Pulse compressed to ~ 100 femtoseconds

Ti-sapphire CPA laser in 180 IATL

780nm femtoseconds
laser (~10mW)

Pulse stretcher

780nm ~100fs
laser (~2.5W)

Pulse compressor

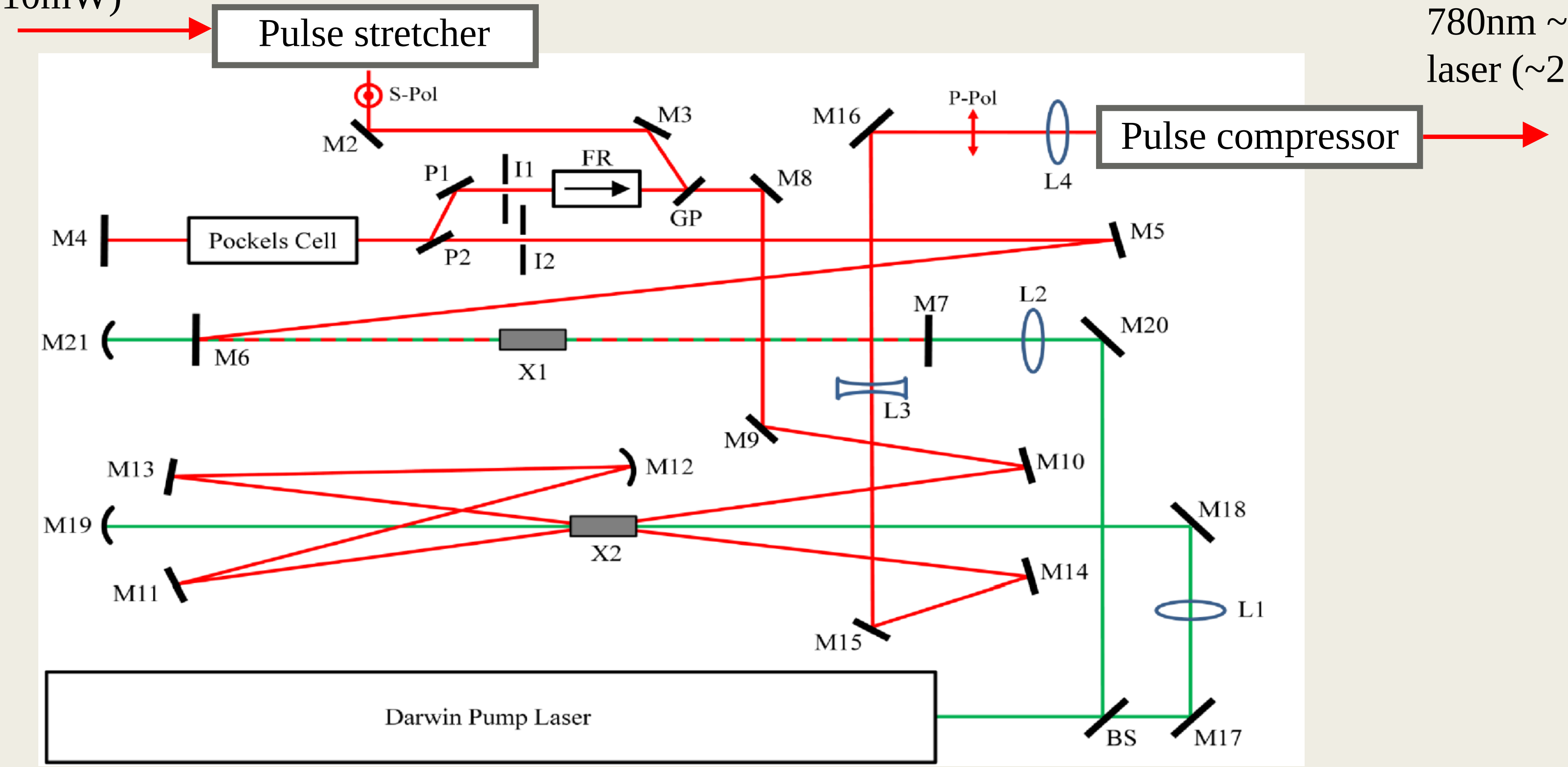
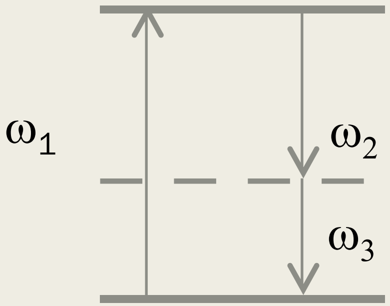


Figure 8. Schematic diagram of the Ti:sapphire CPA system. M: mirror, L: lens, P: thin-film polarizer, I: iris, GP: Glan polarizer, FR: Faraday rotator, BS: beam splitter, X: Ti:sapphire crystal

High power amplified Ti:Sapphire (780 nm) can be used to drive nonlinear crystals to extend the lasing wavelength to 1-18 μm

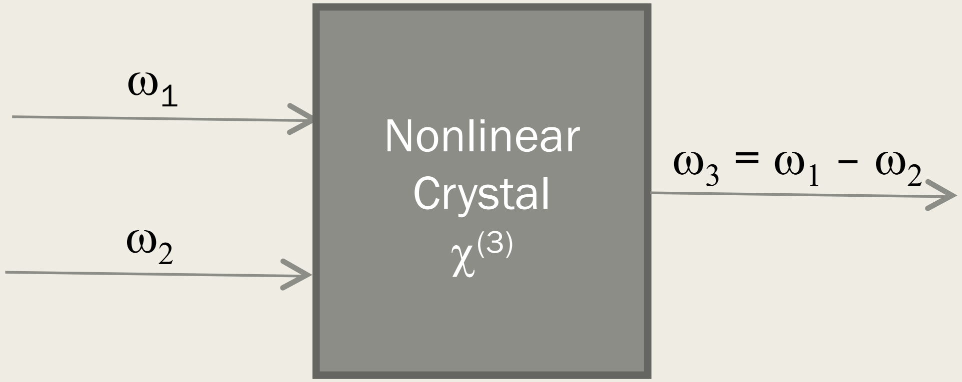
$$P = \varepsilon_0 \chi^{(1)} E(t) + \varepsilon_0 \chi^{(2)} E(t)^2 + \varepsilon_0 \chi^{(3)} E(t)^3 + \dots$$



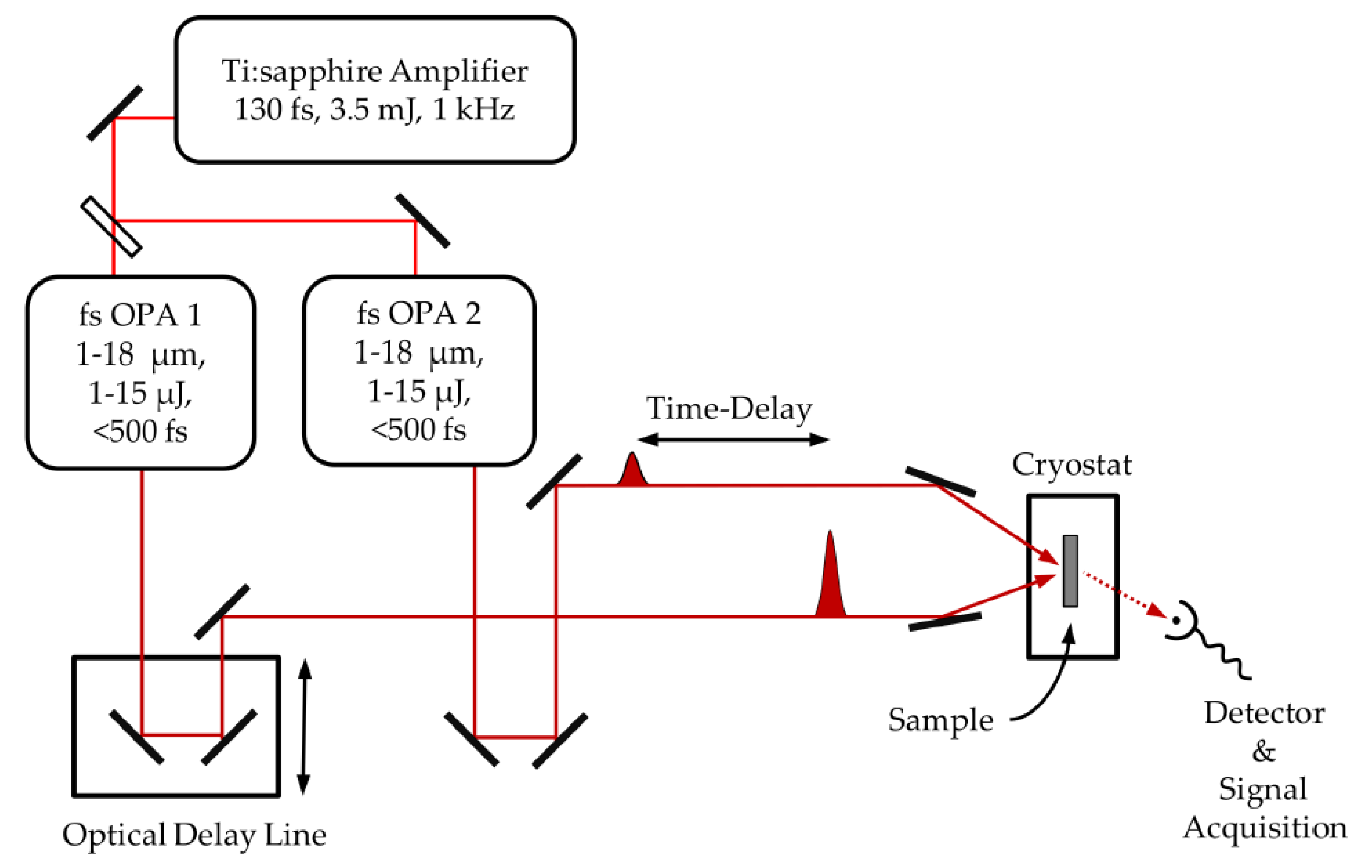
$\omega_1 = \omega_2 + \omega_3$

$k_1 = k_2 + k_3$ Phase matching

Difference frequency generation



Ultrafast pump-probe spectroscopy



Can also temporally or spectroscopically resolve probe

Used to study carrier dynamics in materials . . .

InAs/InAsSb core shell nanowires