Ultrafast Sources (SoSe 2021)

Francesca Calegari & Franz Kärtner, Bldg. 99, Room O3.111 & O3.097
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franz.kaertner@cfel.de, 040 8998 6350
Office hour: Tuesday, 14.00 - 15.00

Lectures: Tue 12:00-13:30 and Th 15:00-16:30, Online using Zoom and Slack
Recitations: Th 16:45-18:15

Start: 06.04.2019 with link

https://uni-hamburg.zoom.us/j/98925718145?pwd=d3hFOUZUVWZjTStXaFdSN2p4YjVMUT09

Meeting ID: 989 2571 8145

Passcode: 2021UFSo

Teaching Assistants:

Felix Rritzkowsky, Office 99.O3.129, phone 040 8998 - 6496,
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Vincent Wanie, Office 222.O1.110, phone 040 8998 - 3124,
E-mail: vincent.wanie@desy.de

Course Secretary: Uta Freydank
O3.095, phone x-6351, E-mail: uta.freydank@cfel.de

Class website: https://ufox.cfel.de/teaching/summer_semester_2021

Prerequisites: Basic courses in Electrodynamics and Quantum Mechanics

Required Text: Class notes can be downloaded.

Requirements: **7** Problem Sets, Term Paper, and Term paper presentation
Collaboration on problem sets is encouraged.

Grade breakdown: Problem set (25%), Participation (25%), Oral Exam (40%)

Recommended Text: Ultrafast Optics, A. M. Weiner, Hoboken, NJ, Wiley 2009.

Additional References:

- Waves and Fields in Optoelectronics, H. A. Haus, Prentice Hall, NJ, 1984
- Ultrashort laser pulse phenomena: fundamentals, techniques, and applications on a femtosecond time scale, J.-C. Diels and W. Rudolph, Academic Press, 2006.
- Principles of Lasers, O. Svelto, Plenum Press, NY, 1998.
- Fundamentals of Attosecond Science, Z. Chang, CRC Press, (2011).
- Nonlinear Optics, R. Boyd, Elsevier, Academic Press, (2008).
- Prof. Rick Trebino's course slides on ultrafast optics:
  http://frog.gatech.edu/lectures.html

Tentative Schedule

1 FK	6.4.2021 Tue	**Introduction to Ultrafast Sources**
2 FK	8.4.2021 Th	**Linear Pulse Propagation**
3 FK	13.4.2021 Tue	**Optical Pulses and Dispersion** *Problem Set 1 Out*
4 FK	15.4.2021 Th	**Nonlinear Pulse Propagation**
5 FK	20.4.2021 Tue	**Self-Phase Modulation (SPM) and Solitons** *Problem Set 1 Due, Problem Set 2 Out*
6 FK	22.4.2021 Th	**Soliton Perturbation Theory: Dispersive Waves and Kelly Sidebands**
7 FK	27.4.2021 Tue	**Review of Quantum Mechanics** *Problem Set 2 Due, Problem Set 3 Out*
8 FK	29.4.2021 Th	**Maxwell-Bloch Equations and Gain**
9 FK	4.5.2021 Tue	**Laser Rate Equations, CW-Operation and Relaxation Oscillations,** *Problem Set 3 Due, Problem Set 4 Out*

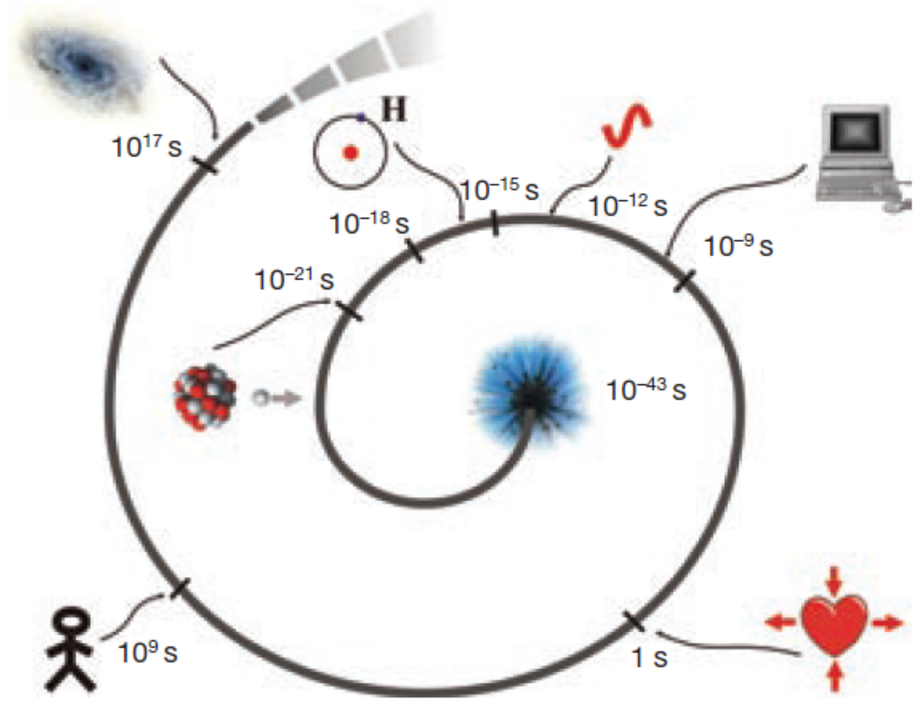
Tentative Schedule

10 FK	6.5.2021 Th	**Q-Switching**
11 FK	11.5.2021 Tue	**Master Equation and Active Mode-Locking** *Problem Set 4 Due, Problem Set 5 Out*
12 FK	13.5.2021 Th	**Passive Mode-Locking with Fast and Slow Saturable Absorbers**
13 FK	18.5.2021 Tue	**Artificial and Real Absorber Mode-Locking, APM, KLM, SESAM,** *Problem Set 5 Due, Problem Set 6 Out*
14 FK	20.5.2021 Th	**Stochastic Processes and Noise**
15 FK	25.5.2021 Tue	**Noise in Mode-Locked Lasers** *Problem Set 6 Due, Problem Set 7 Out*
16 FK	27.5.2021 Th	**Ultrafast Quantum Optics**
17 FK	1/6/2021 Tue	**Ultrafast Quantum Optics** *Problem Set 7 Due, Problem Set 8 Out*
18 CH	3/6/2021 Th	**Femtosecond Laser Frequency Combs**
19 FC	8/6/2021 Tue	**Laser Amplifiers** *Problem Set 8 Due*

Tentative Schedule

20 FC	10/6/2021 Th	**Pulse Characterization: Autocorrelation, FROG, SPIDER and 2DSI** *Build your own short pulse fiber laser*
21 FC	15/6/2021 Tue	**Introduction to Nonlinear Optics**
22 FC	17/6/2021 Th	**Parametric Interactions: OPA and OPO** *Build your own short pulse fiber laser*
23 FC	22/6/2021 Tue	**Broadband Parametric Amplification**
24 FC	24/6/2021 Th	**Pulse Compression (Hollow-Core)** *Build your own short pulse fiber laser*
25 CH	29/6/2021 Tue	**Pulse Compression (Multi-pass Cavities)**
26 FK	1/7/2021 Th	**Ultrafast electron sources and Electron Diffraction,** *Build your own short pulse fiber laser*
27 AT	6/7/2021 Tue	**Laser Induced Electron Diffraction**
28 All	8/7/2021 Th	**Lab Tours**

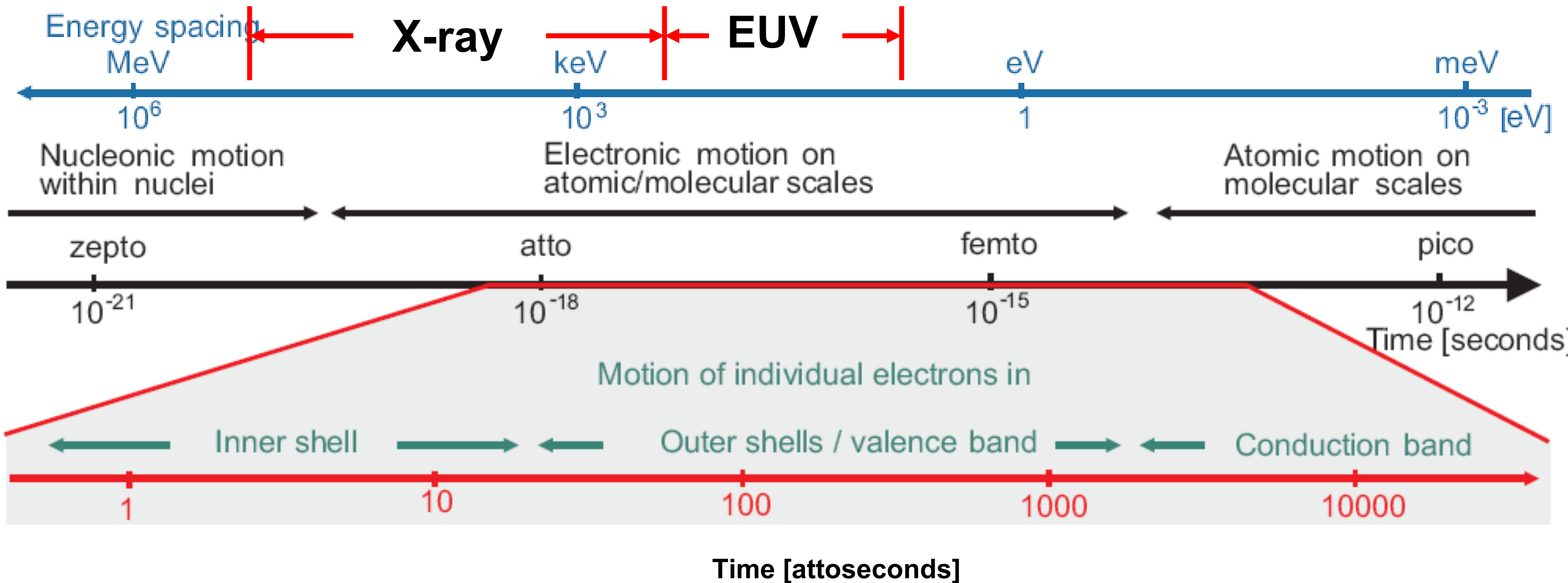
The long and short of time



Notable time scales, in seconds		Length by other measures	
5×10^{17} s	Estimated age of universe	14	billion years
2×10^{9} s	Average human lifetime	70	years
1 s	Length of a heartbeat	1	second
0.3×10^{-9} s	Current computer clock frequency	0.3	nanosecond
10^{-12} s	Length of a typical THz pulse	1	picosecond
3×10^{-15} s	Cycle length of laser	3	femtoseconds
1.5×10^{-16} s	Electron circles proton in Hydrogen atom	0.15	femtosecond
10^{-18} s	Next horizon for controllable laser pulses?	1	attosecond
10^{-21} s	Strong nuclear reactions	1	zeptosecond
10^{-43} s	Birth flash of the Big Bang		Planck time

A. E. Kaplan, "No-when: the long and short of time," Optics and Photonics News (2006, February)

Physics on femto- attosecond time scales?



*)

Light travels:

A second: from the moon to the earth

A picosecond: a fraction of a millimeter, through a blade of a knife

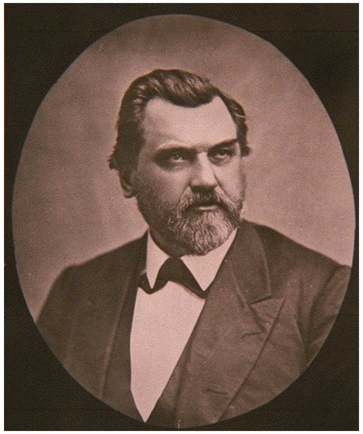
A femtosecond: the period of an optical wave, a wavelength

An attosecond: the period of X-rays, a unit cell in a solid

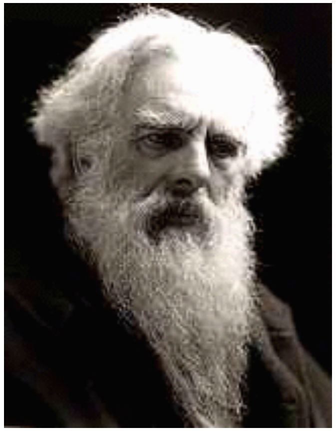
***F. Krausz and M. Ivanov, Rev. Mod. Phys. 81, 163 (2009)**

Birth of ultrafast technology

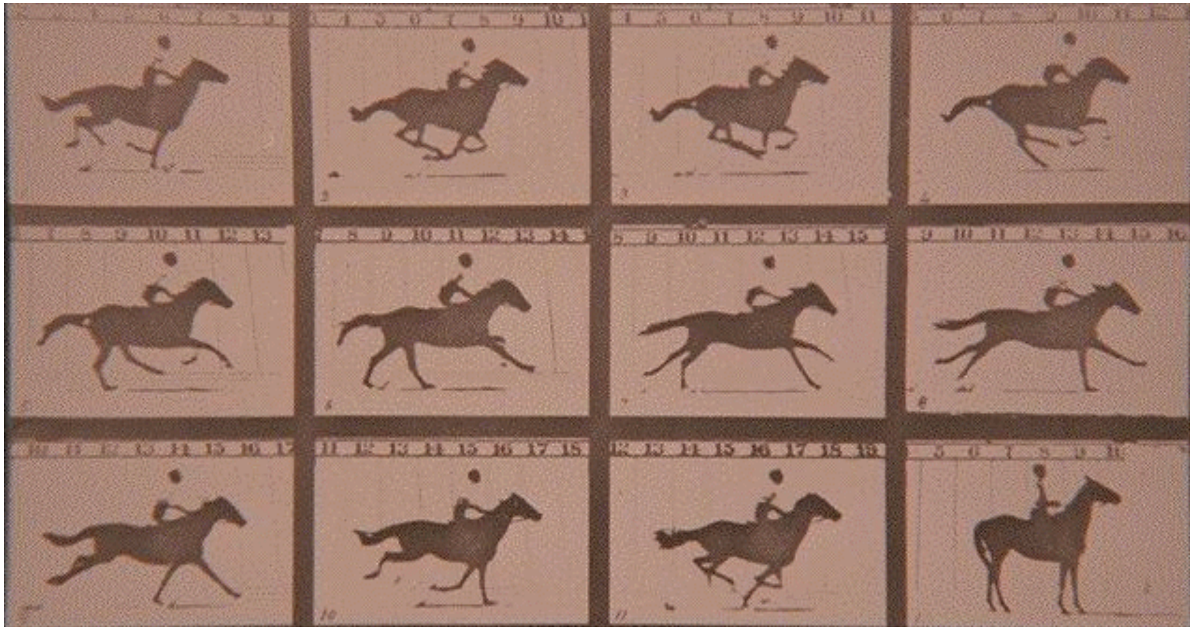
$25,000 bet: Do all four hooves of a running horse ever simultaneously leave the ground? (1872)



Leland Stanford

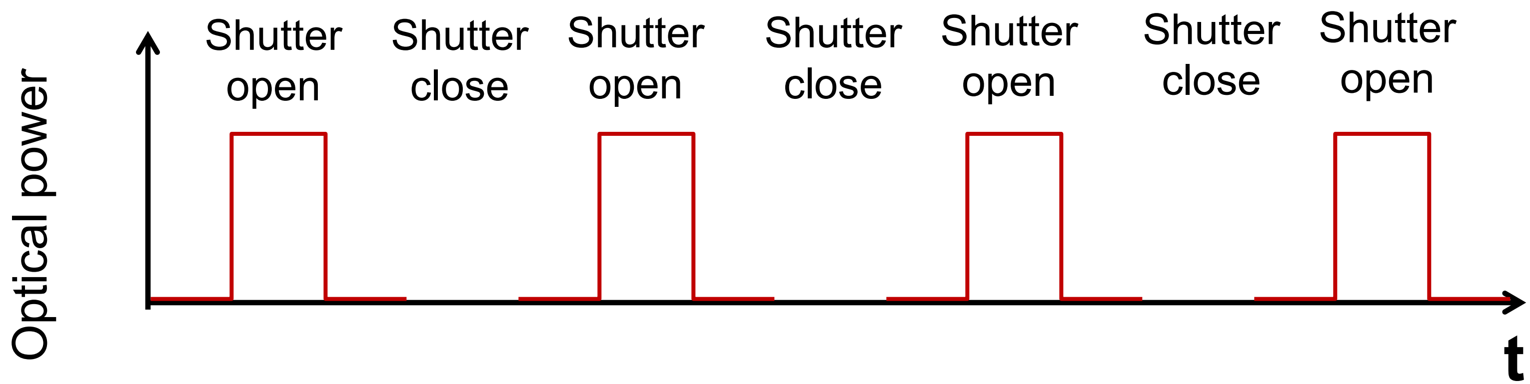


Eadweard Muybridge



What do we need to probe a fast event?

- The light signal received by the camera film is a train of optical pulse.



- We need a FASTER event to freeze the motion. Here the FASTER event is shutter opening and closing.

- If we have an optical pulse source, we can record images of a running horse in a dark room.

Early history of lasers

- 1917: *on the quantum theory of radiation* – Einstein's paper
- 1954: MASER by Charles Townes (1915—2015) *et al*.
- 1958: Charles Townes (Nobel Prize in 1964) and Schawlow (Nobel Prize in 1981) conceived basic ideas for a laser.

If you're a nobel prize winner, and 100 years old, you can comment other winners using harsh words:

Charles Townes

University of California, Berkeley, and 1964 Nobel Prize in Physics recipient

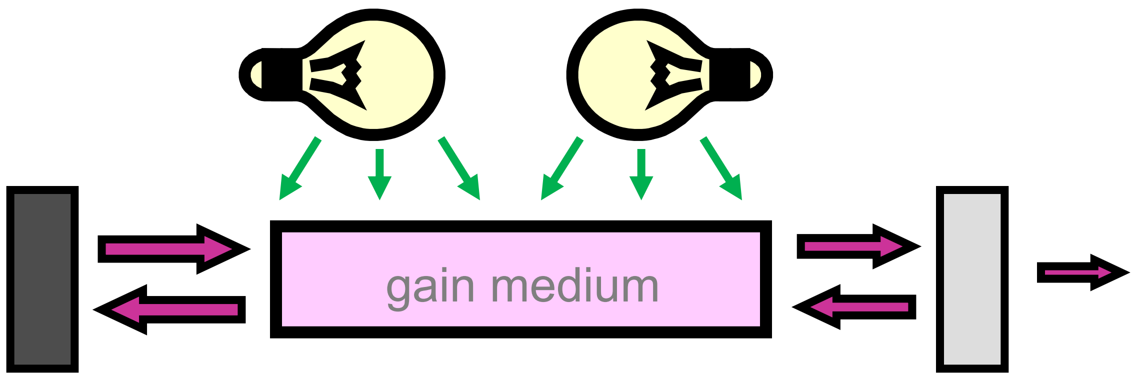
Jim Gordon was a fine person and a great scientist. He was also brave in doing research. When he worked for me as a graduate student trying to build the first maser, the chairman of the physics ~~department and the previous chairman both told him it would not work~~ and that he should stop, because the project was wasting the department's money. Both of them had Nobel Prizes, so presumably weren't stupid physicists. But Jim proceeded with his work and, about four months after they told him it wouldn't work, it did. From the maser also came the laser.

Optics & Photonics News, 2014

Jim didn't get the Nobel Prize with me, presumably because he was a student when the maser first worked, but I think he deserved it. He went on to do other important work. We should all celebrate him and his contributions.

MASER: **M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation
(**M**eans of **A**cquiring **S**upport for **E**xpensive **R**esearch)

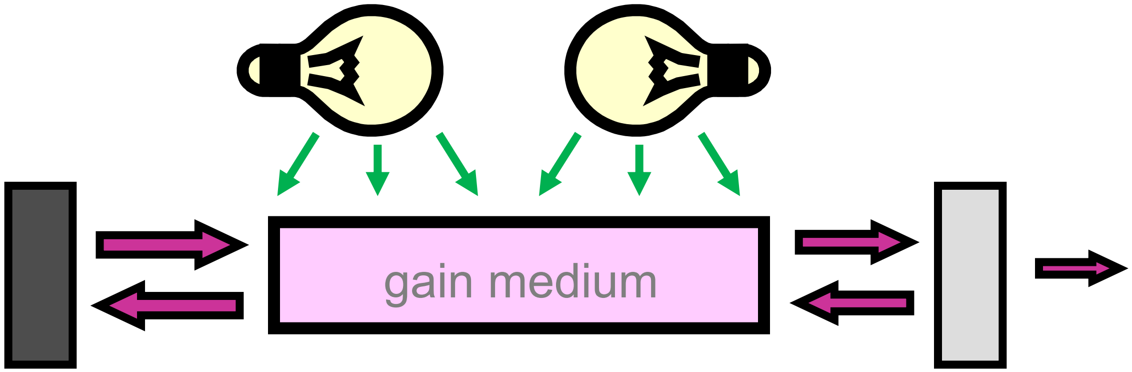
Laser basics: three key elements



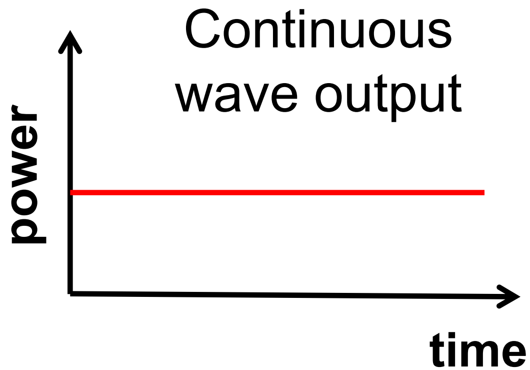
Continuous wave (CW) laser

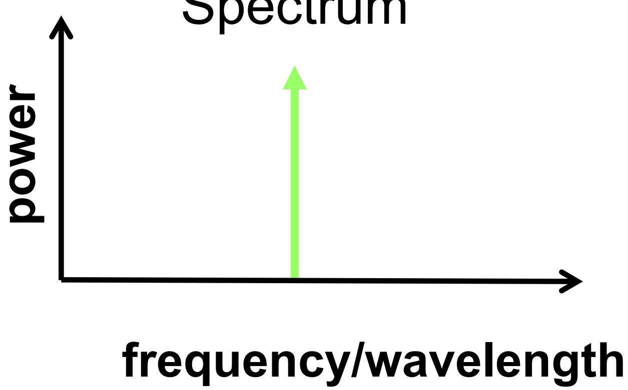
- **Gain medium**
  - Enable stimulated emission to produce identical copies of photons
  - Determine the light wavelength
- **Pump**
  - Inject power into the gain medium
  - Achieve population inversion
- **Resonator cavity**
  - make light wave oscillating to efficiently extract energy stored in the gain medium
  - Improve directionality and color purity of the light

Laser basics: three key elements

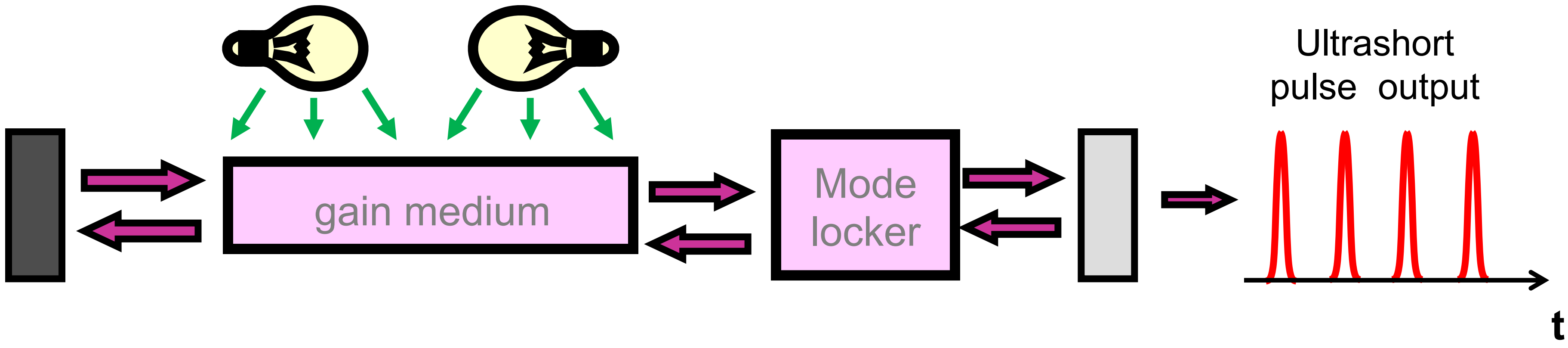


Continuous wave (CW) laser

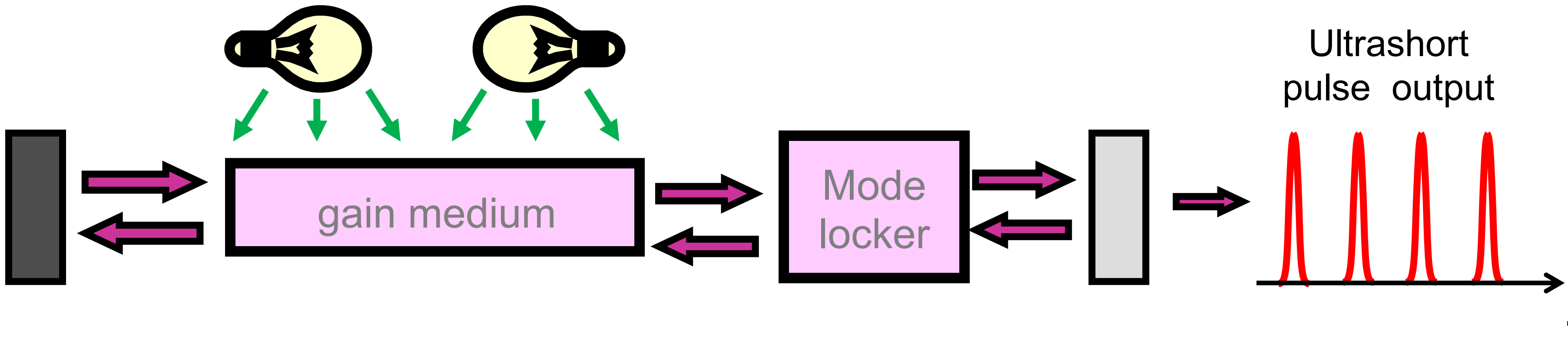


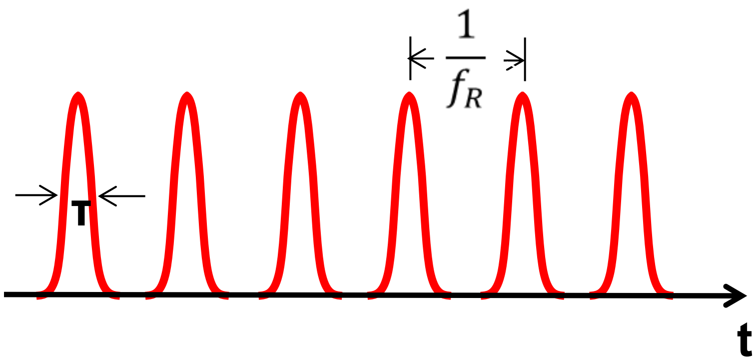


Ultrafast laser: the 4th element—mode locker

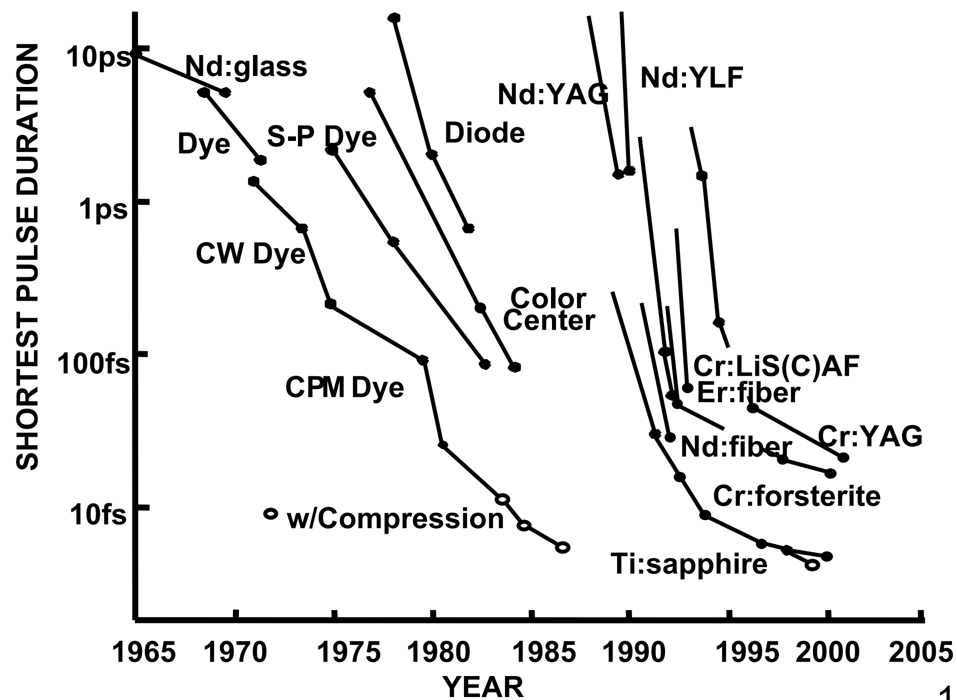


Ultrafast laser: the 4th element—mode locker





- <u>Pulse duration T (fs – ps)</u>

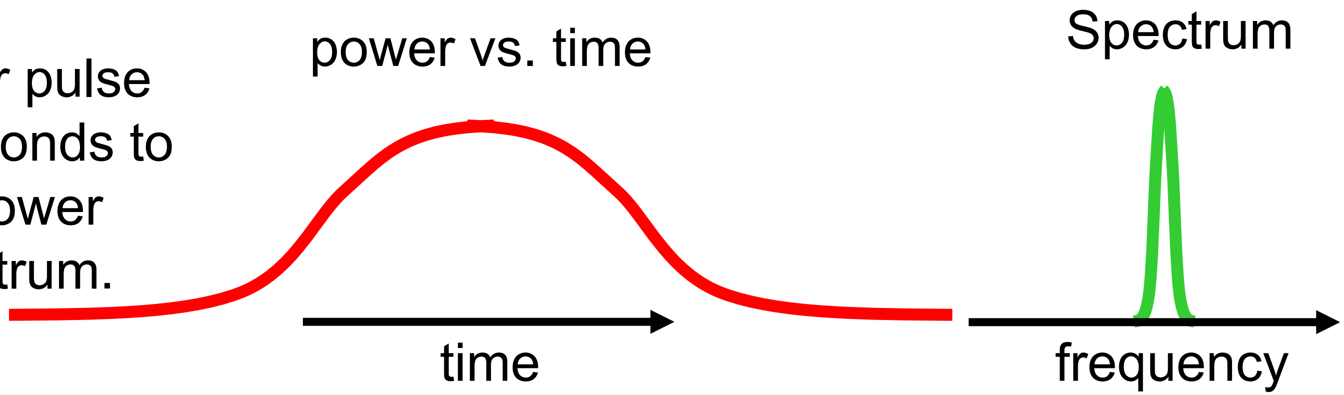


World shortest pulse: 67 attoseconds. The center wavelength is 20 nm. It is generated by high harmonic generation.

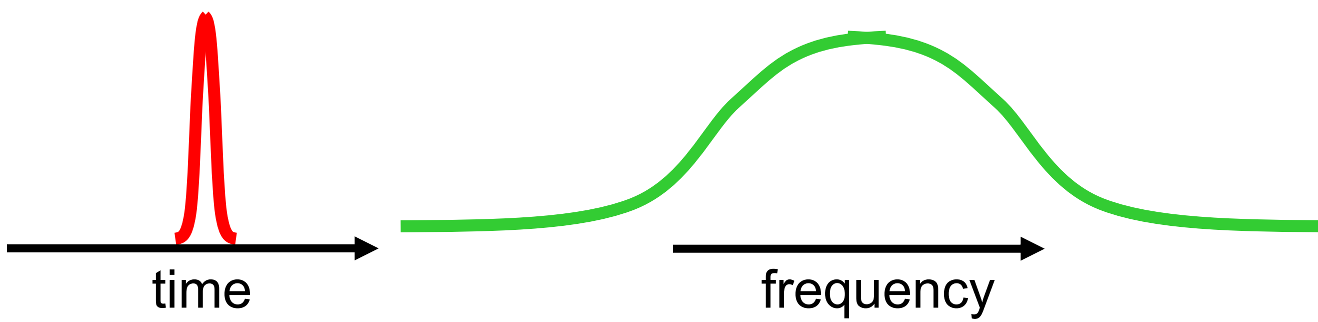
<u>K. Zhao et al., "Tailoring a 67 attosecond pulse through advantageous phase-mismatch," Opt. Lett. 37, 3891 (2012)</u>

Long vs. short pulses of light

Longer pulse corresponds to narrower spectrum.



Shorter pulse corresponds to broader spectrum.



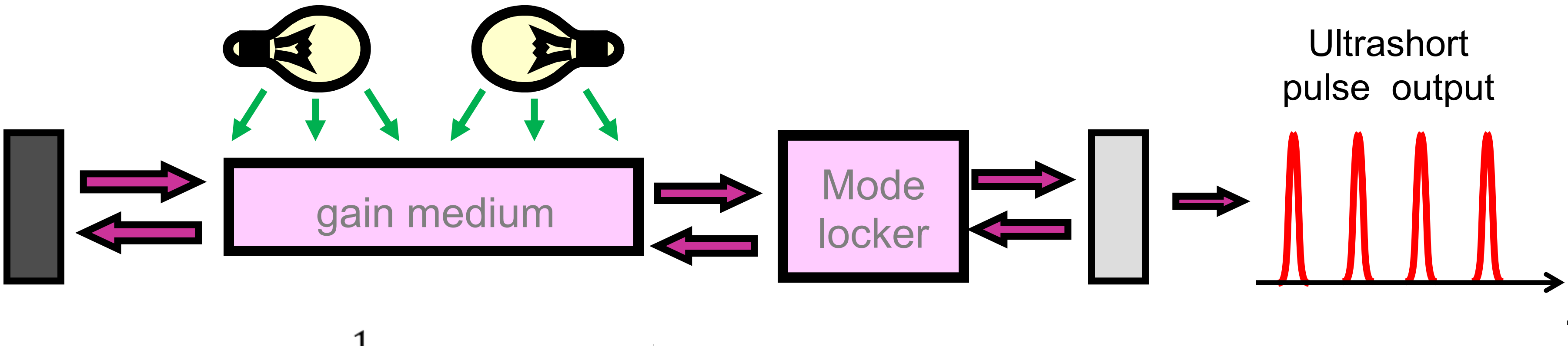
But a light bulb is also broadband.

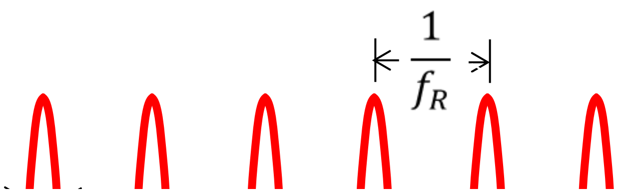
What exactly is required to make an ultrashort pulse?

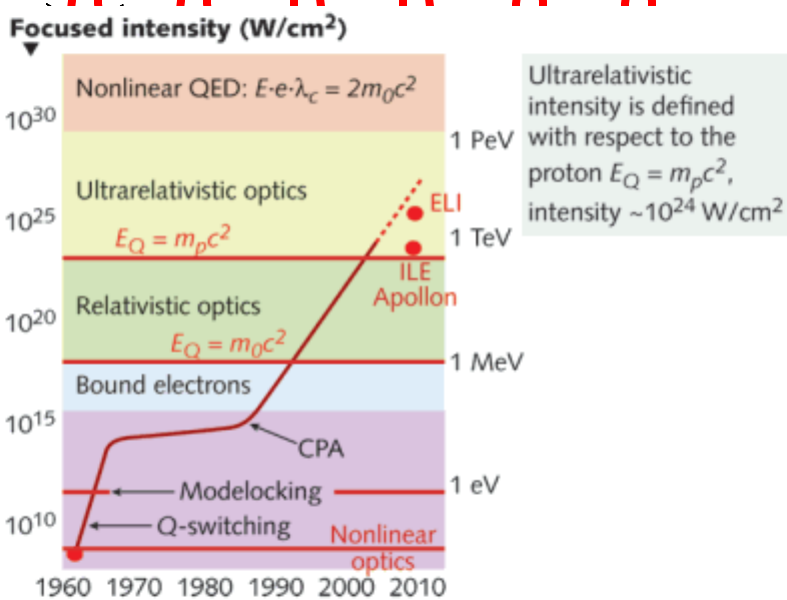
Answer: A broadband coherent spectrum, e.g. from a mode-locked laser

Adapted from Rick Trebino's course slides

Ultrafast laser: the 4th element—mode locker

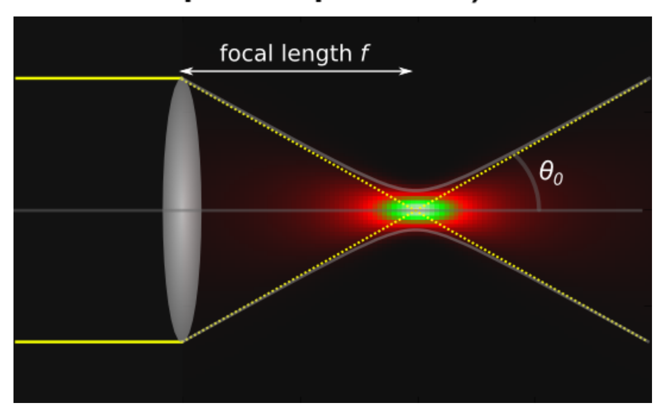




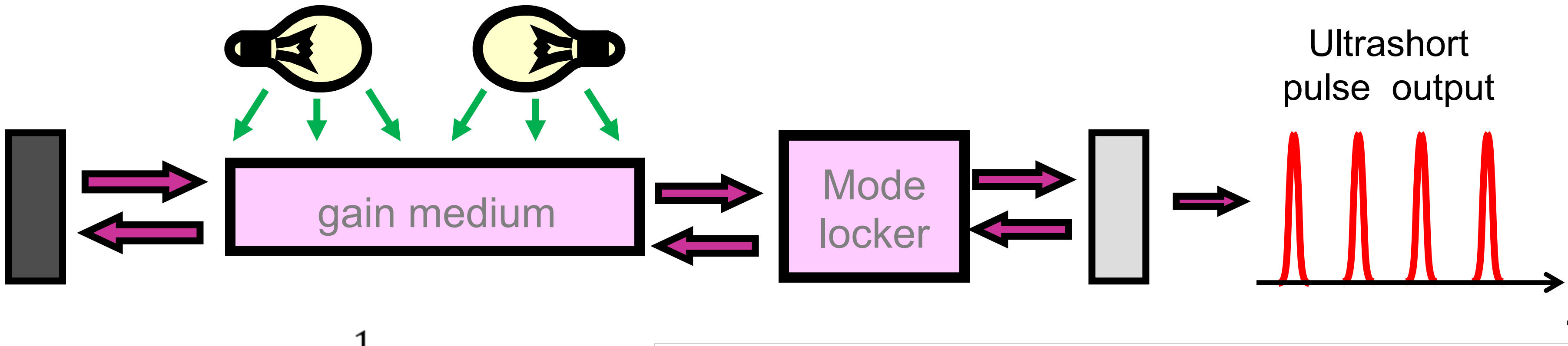


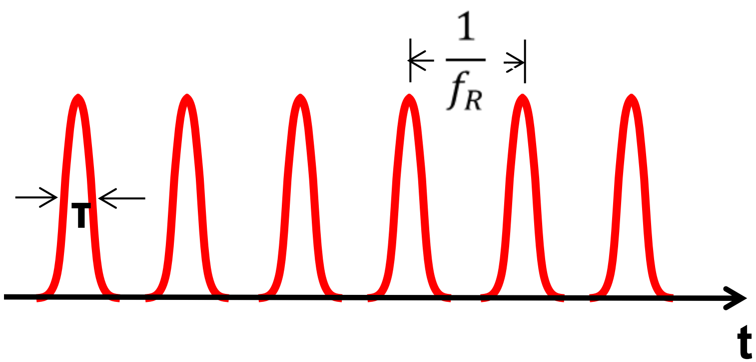
- Pulse duration T (fs – ps)
- Pulse energy E (pJ – mJ)
- Peak power P_p (1 kW – 1 PW)

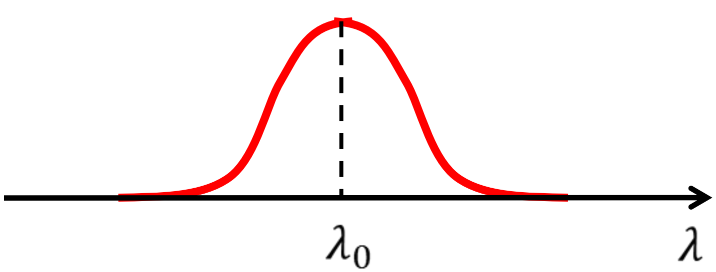
  $P_p \approx E/T$ (e.g., 1 nJ, 100 fs pulse leads to 10 kW peak power.)



Ultrafast laser: the 4th element—mode locker







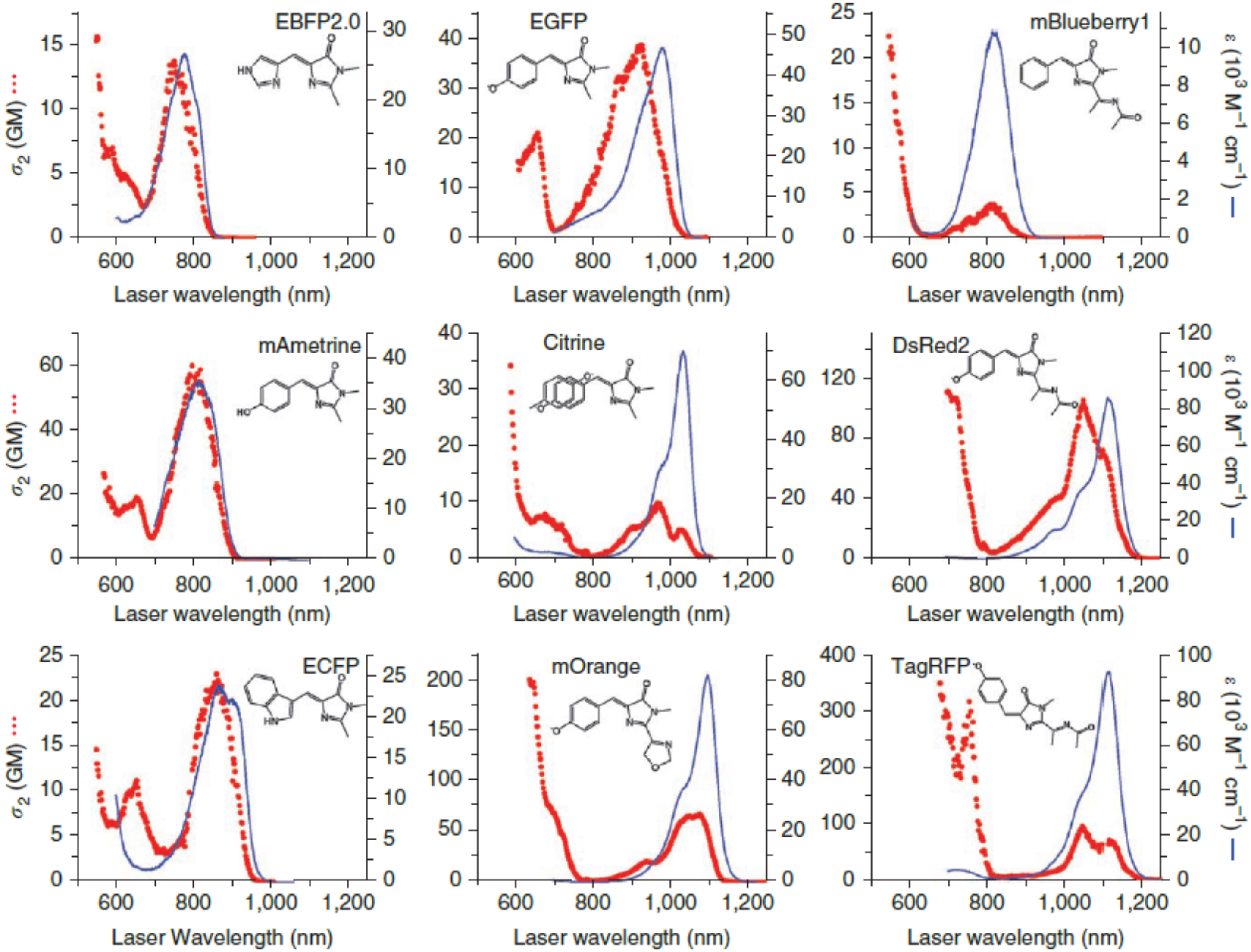
- Pulse duration T (fs – ps)
- Pulse energy E (pJ – mJ)
- Peak power P_p (1 kW – 1 PW)
  $P_p \approx E/T$ (e.g., 1 nJ, 100 fs pulse leads to 10 kW peak power.)
- Repetition rate f_R (10 MHz – 10 GHz)
- Average power P (10 mW – 100 W)
  $P = E \times f_R$ (e.g., 1 nJ, 100 MHz rep-rate laser produces 100 mW average power.
- Center wavelength λ_0 (700 nm – 2000 nm)

Examples of ultrafast solid-state laser media

Solid-state laser media have broad bandwidths and are convenient.

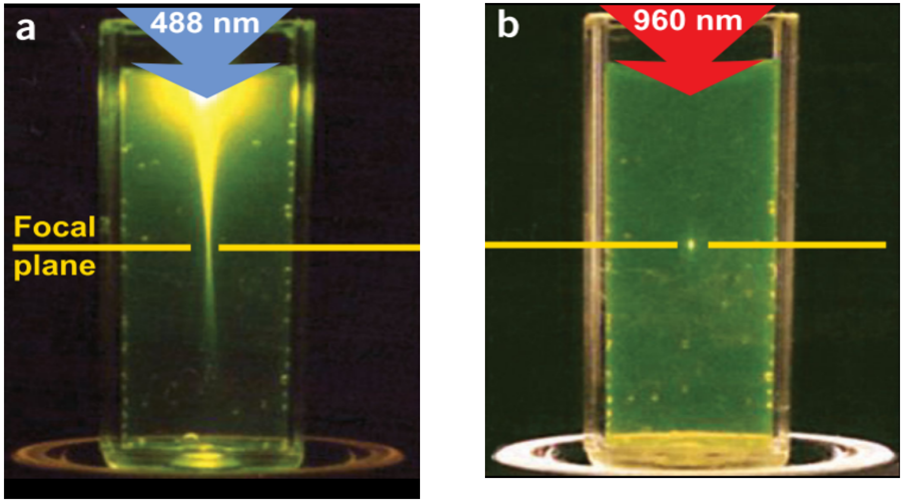
Laser Materials	Absorption Wavelength	Average Emission λ	Band Width	Pulse Width
Nd:YAG	808 nm	1064 nm	0.45 nm	$\sim$ 6 ps
Nd:YLF	797 nm	1047 nm	1.3 nm	$\sim$ 3 ps
Nd:LSB	808 nm	1062 nm	4 nm	$\sim$ 1.6 ps
Nd:YVO_4	808 nm	1064 nm	2 nm	$\sim$ 4.6 ps
Nd:fiber	804 nm	1053 nm	22-28 nm	$\sim$ 33 fs
Nd:glass	804 nm	1053 nm	22-28 nm	$\sim$ 60 fs
Yb:YAG	940, 968 nm	1030 nm	6 nm	$\sim$ 300 fs
Yb:glass	975 nm	1030 nm	30 nm	$\sim$ 90 fs
Ti:Al_2O_3	480-540 nm	796 nm	200 nm	$\sim$ 5 fs
Cr^{4+}:Mg_2SiO_4:	900-1100 nm	1260 nm	200 nm	$\sim$ 14 fs
Cr^{4+}:YAG	900-1100 nm	1430 nm	180 nm	$\sim$ 19 fs

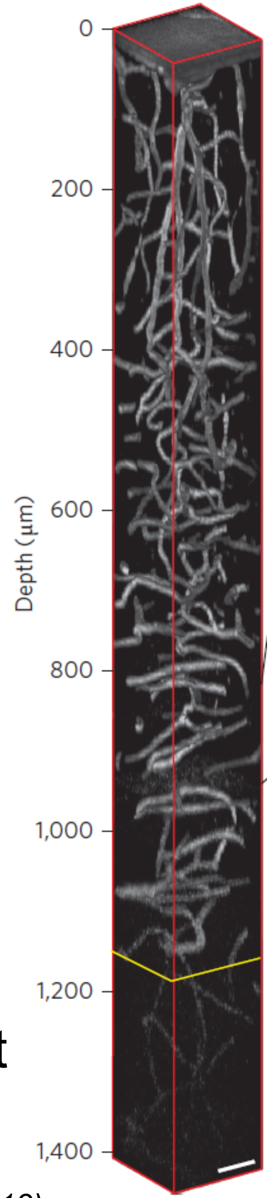
Two-photon absorption properties of fluorescent proteins



M. Drobizhev et al., "Two-photon absorption properties of fluorescent proteins" Nat. Methods 8, 393 (2011).

Nonlinear optical microscopy





- Intrinsic sectioning ability, making 3D imaging possible.
- Longer excitation wavelength, which reduces tissue scattering and allows larger penetration depth.
- New contrast mechanisms: N-photon excitation fluorescence, Harmonic generation, Coherent Raman scattering, etc.
- Ultrashort pulses as the excitation source – many ultrafast optics technologies can be employed.

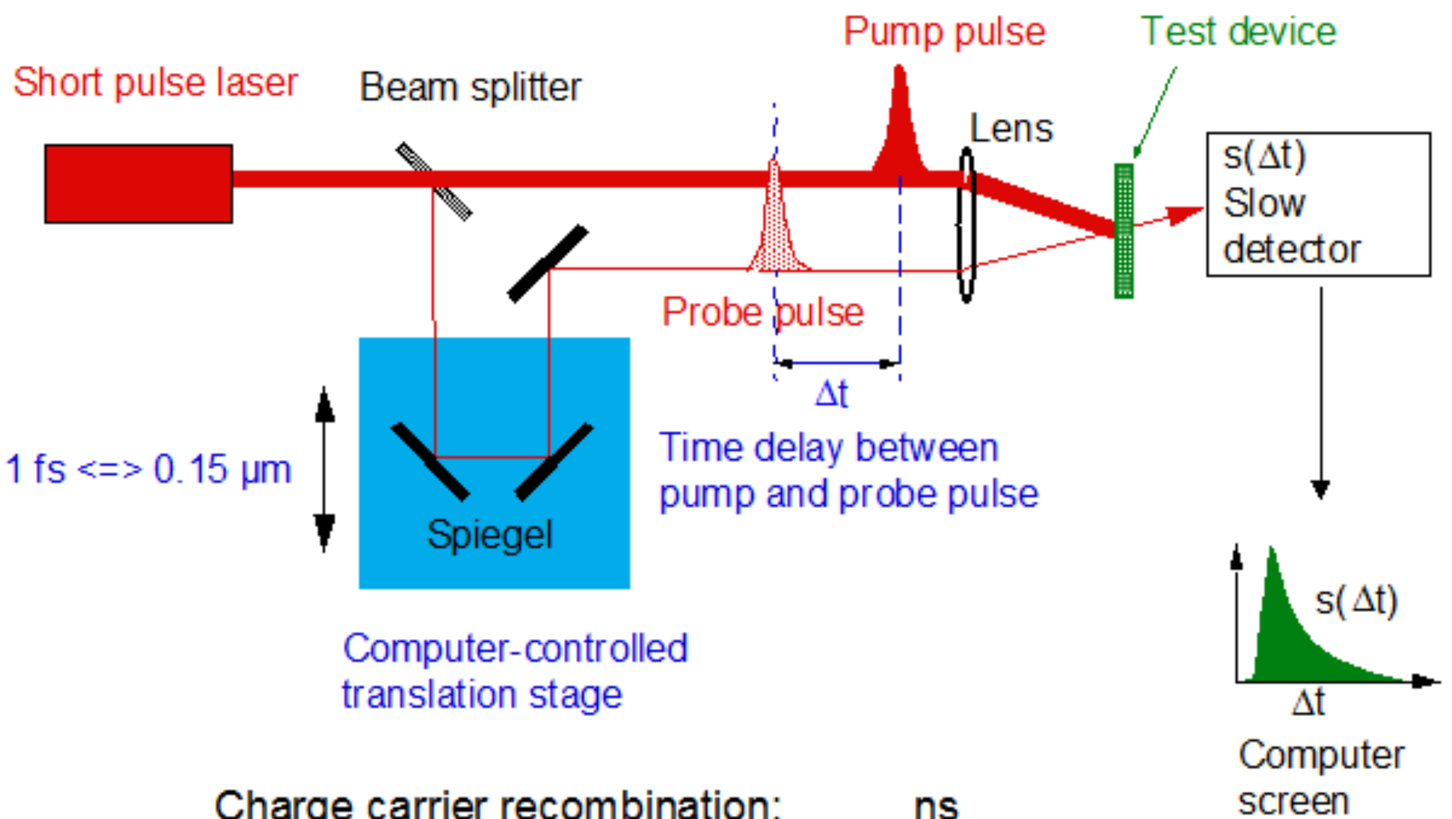
W. R. Zipfel et al., Nat. Biotechnol. 21,1369(2003). N. G. Norton et al, Nat. Photonics 7, 205 (2013).

Main workhorse: Ti:sapphire oscillator

Typical parameters of a commercial product

- Pulse duration: ~100 fs
- Pulse energy: 1-10 nJ
- Pulse rep-rate: 50-100 MHz
- Average power: 300-1000 mW
- Center wavelength: tunable in 700-1000 nm.

Ultrafast: pump-probe spectroscopy

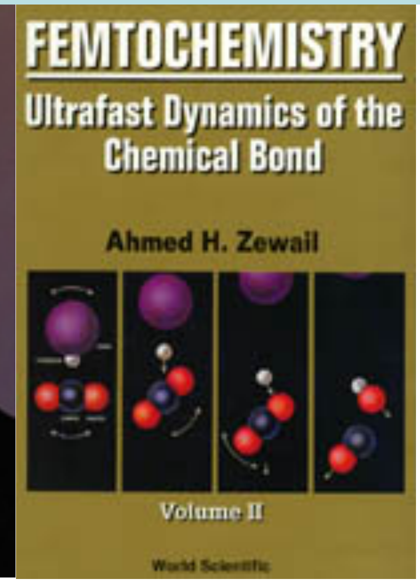


Charge carrier recombination: ns

Thermalization electrons with lattice: ps

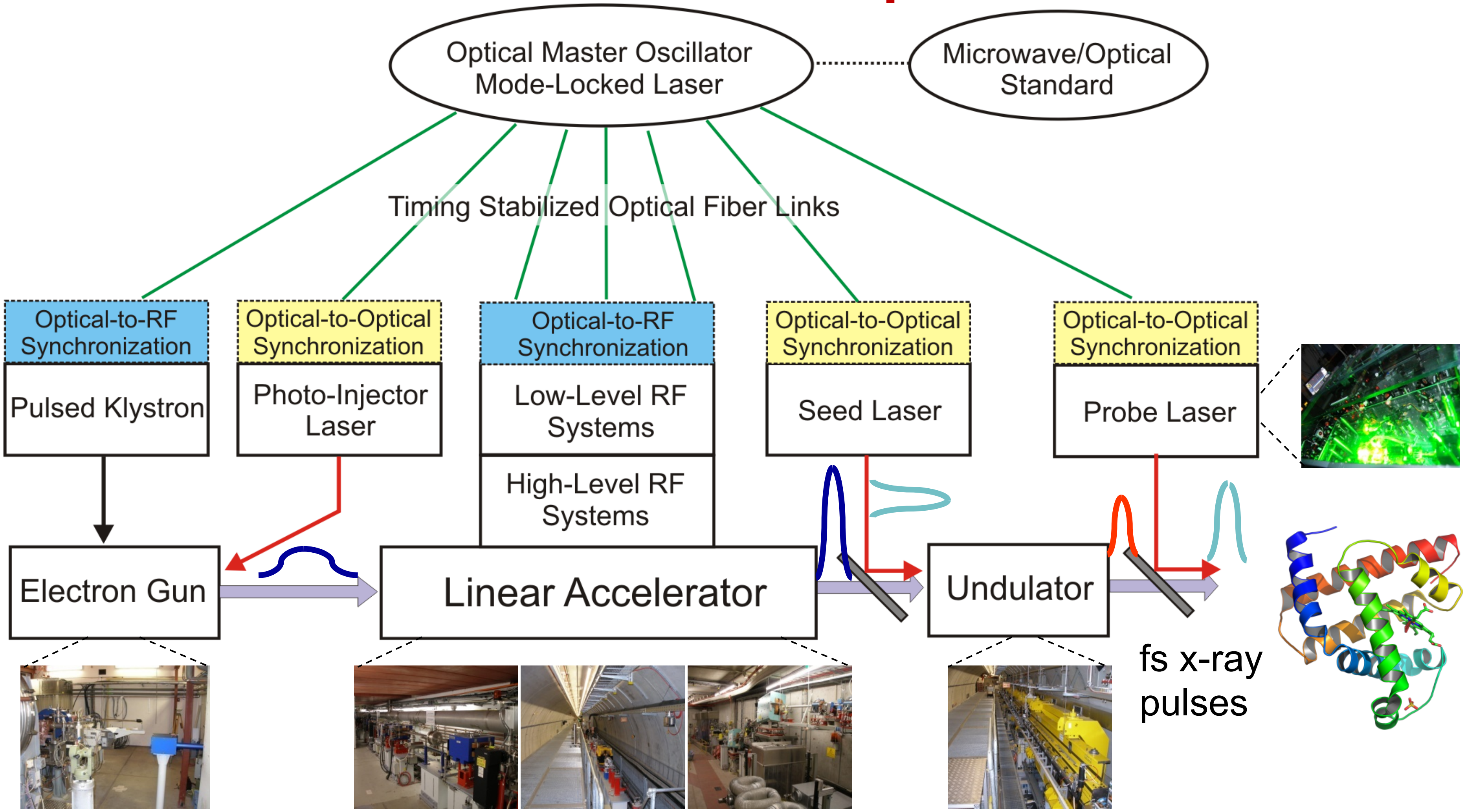
Thermalization electron gas: 10 -100 fs

Applications of ultrafast lasers: femtosecond chemistry



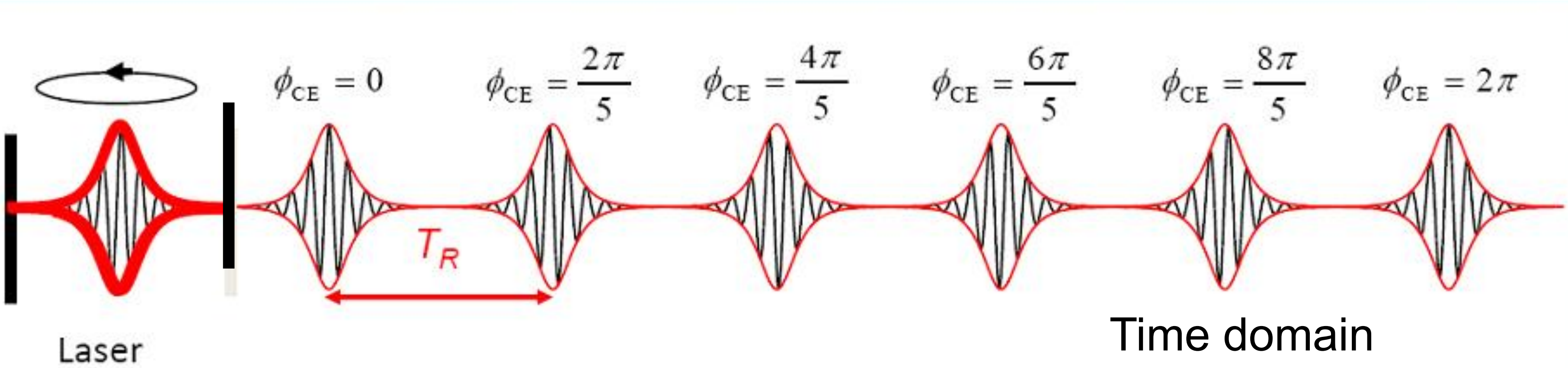
Prof. Ahmed Zewail from Cal Tech used ultrafast-laser techniques to study how atoms in a molecule move during chemical reactions (1999 Nobel Prize in Chemistry).

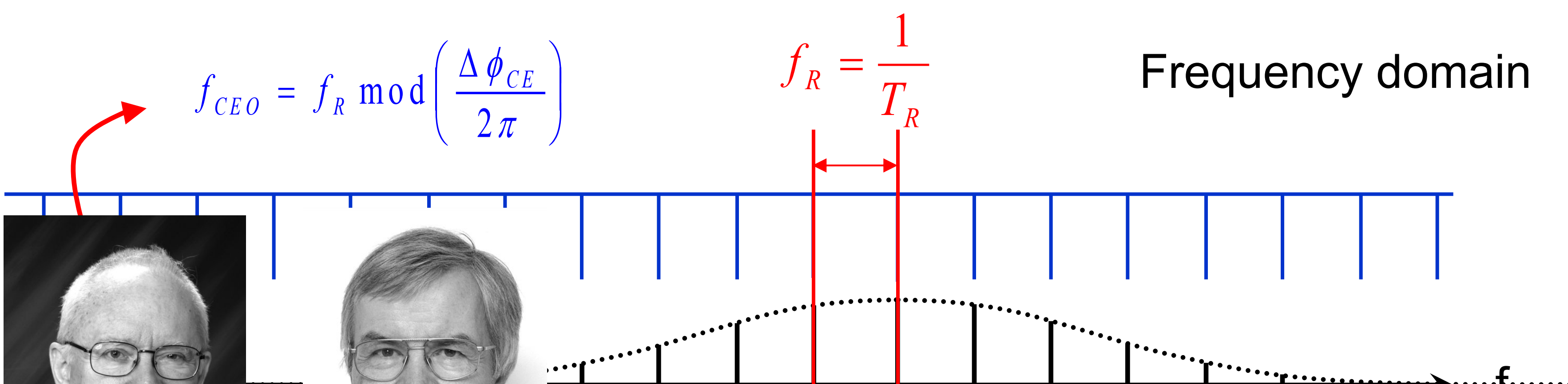
Ultra-high precision: Timing and aynchronization via femtosecond laser pulse trains

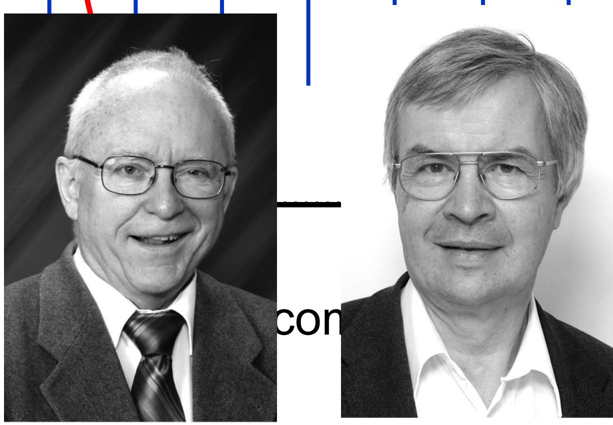


Jungwon Kim et al., Nature photonics 2, 733 (2008)

Ultra-high precision: Optical frequency measurements via femtosecond laser frequency combs





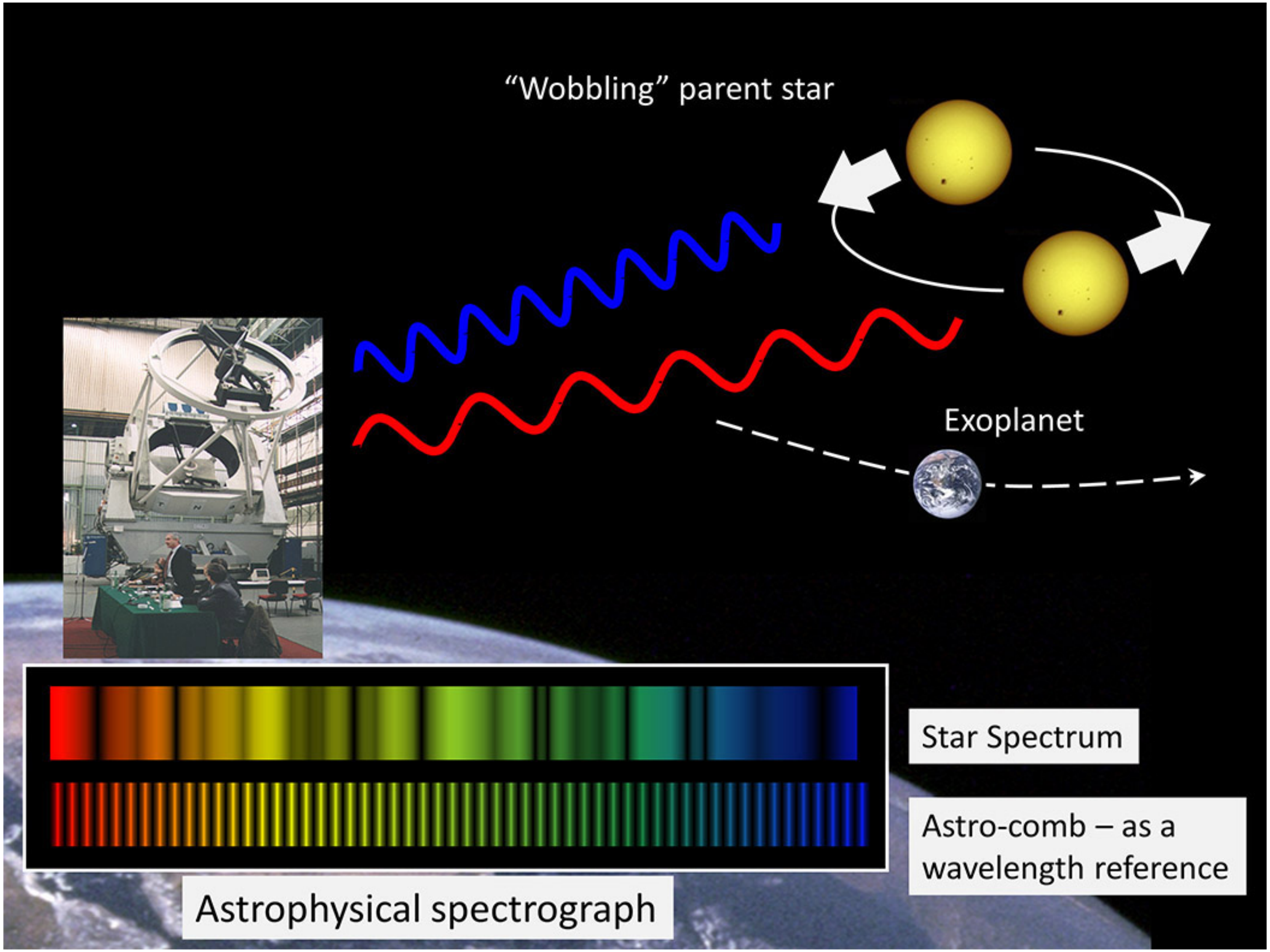


con … egrees of freedom: $f = nf_R + f_{CEO}$

J. L. Hall T. W. Hänsch

2005 Physics Nobel Prize for Hall and Hänsch

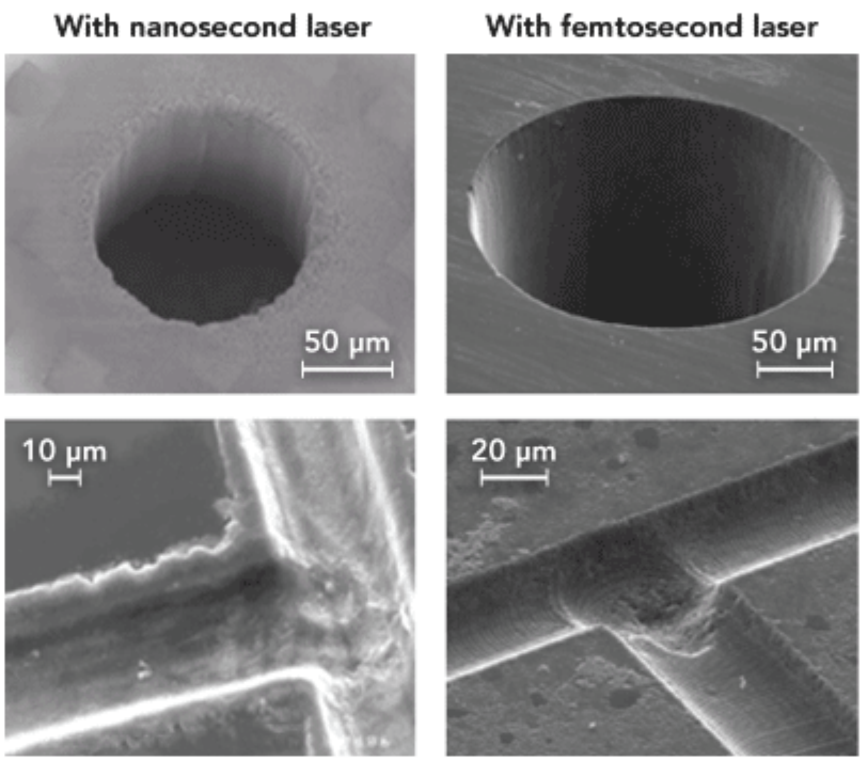
Ultra-high precision: fs laser frequency comb



C.-H. Li et al., Nature 452, 610 (2008).

Ultra-intense: Femtosecond laser micro-machining

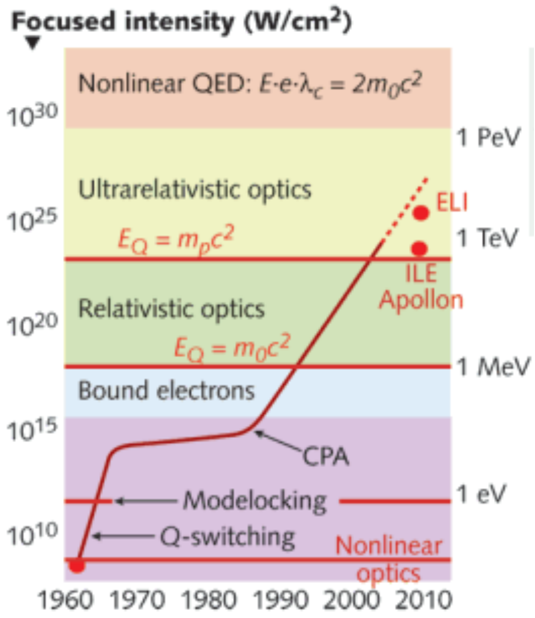
- **Sub-micron material processing:** Material milling, hole drilling, grid cutting
- **Surface structuring:** Photolithographic mask repair, surface removal or smoothing without imparting any thermal influence into the underneath sub-layers or the substrate
- **Photonics devices:** Machining of optical waveguides in bulk glasses or silica, and inscription of grating structure in fibers
- **Biomedical devices:** Use of femtosecond lasers for stent manufacture or eye surgery
- **Microfluidics:** Microfluidic channels and devices
- **Displays and solar:** Thin-film ablation, solar cell edge isolation

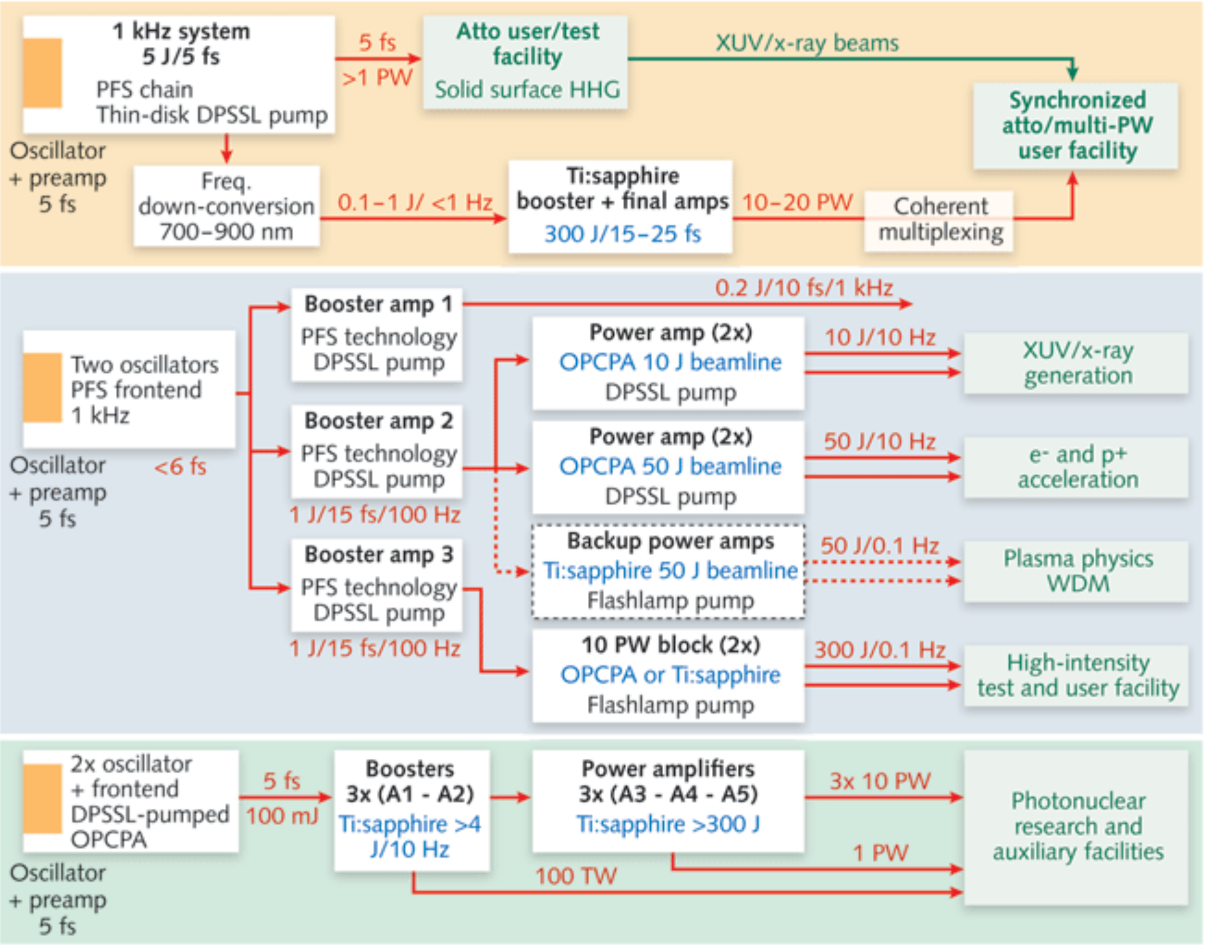


Laser processing examples on glass with a 266 nm (UV) ns-laser (left side) and with a 780 nm 100-fs laser (right side).

L. Lucas and J. Zhang, "Femtosecond laser micromachining: A back-to-basics primer," Industrial Laser Solutions (2012)

Ultra-intense: Extreme light infrastructure (ELI)





ELI's goal is to explore new frontiers in physics, including trying to trigger the breakdown of the vacuum—the fabric of space-time itself.

Designs of the three pillars are shown. Top: Hungarian attosecond pillar. Middle: Czech beam-line pillar. Bottom: Romanian photonuclear pillar.

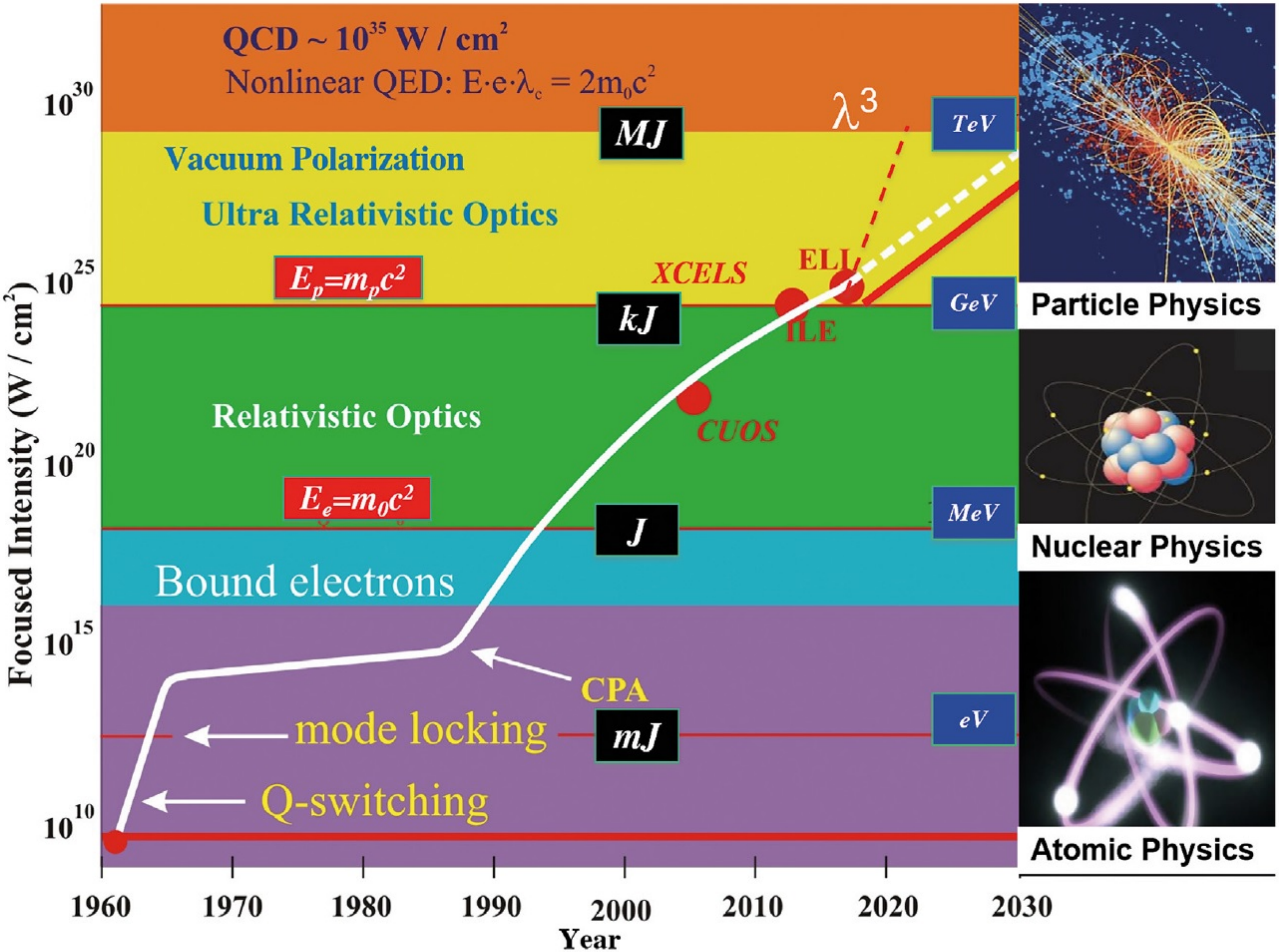
J. Hecht, "Photonic frontiers: the extreme light infrastructure: the ELI aims to break down the vacuum," Laser Focus World (2011)

Nobel Prize in Physics 2018

"for the optical tweezers and their application to biological systems"

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

chirped-pulse amplification (CPA)



G. Mourou, J. A. Wheeler, and T. Tajima, Europhys. News **46**, 31 (2015)

Parametric Waveform Synthesizer:
A look into an optics lab.