Nonlinear Optics (WiSe 2021/22)

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Office hour: Tuesday, 16-17 pm

Lectures: Mo, We 13:00 - 14:30, SemRm IV/V, Geb.99
Recitations: Th 15:00 - 16:30, SemRm IV/V, Geb.99
Start: 11.10.2021

- **Online Access Link:**
- https://uni-hamburg.zoom.us/j/64203244710?pwd=U3lzbzRpTEZIcHN6aUpJTnhVc0E4Zz09
- **Meeting ID:** 642 0324 4710

Passcode: NLO21-22

Teaching Assistants:

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Miguel Angel Silva Toledo, O3.093, phone 040-8998-6322, email: miguel.toledo@desy.de
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Office hour: Thursday, 9:30-11 am

Course Secretary: Uta Freydank 03.095, phone 040-8998-6351, email: uta.freydank@cfel.de

Nonlinear Optics (WiSe 2021/22)

Prerequisites: A basic course in Electrodynamics

Required Text: Class notes will be distributed in class.

Requirements: 11 Problem Sets, Collaboration on problem sets is encouraged.

Grade breakdown: Problem sets (30%), Participation (20%), Oral Ex.(50%)

Recommended Text:
Nonlinear Optics, R. W. Boyd, Academic Press, Third Edition (2008)

Additional References:
The Principles of Nonlinear Optics, Y. R. Chen, J. Wiley & Sons NY (1984).
The Elements of Nonlinear Optics, P. N. Butcher & D. Cotter, Cambridge Studies in Modern Optics 9 (1990).
Nonlinear Fiber Optics, G. P. Agrawal, Academic Press (1998).
Solitons: an introduction, P. G. Drazin & R. S. Johnson, Cambridge Texts In Applied Mathematics, NY (1989).
Extreme Nonlinear Optics, M. Wegener, Springer (2005).

Syllabus

1 FXK	11.10.2021 Mo	**Introduction to Nonlinear Optics**
2 FXK	13.10.2021 We	**Important Nonlinear Optical Processes Overview**
3 FXK	18.10.2021 Mo	**Nonlinear Optical Susceptibilities** *Problem Set 1 Out*
4 FXK	20.10.2021 We	**Susceptibility Tensors**
5 FXK	25.10.2021 Mo	**Nonlinear Wave Equation** *Problem Set 1 Due, Problem Set 2 Out*
6 TH	27.10.2021 We	**Second-Harmonic Generation**
7 FXK	1.11.2021 Mo	**Frequency Doubling of Pulses, Quasi-Phase Matching** *Problem Set 2 Due, Problem Set 3 Out*
8 FXK	3.11.2021 We	**Optical Parametric Oscillation/Amplification, Difference Frequency Generation**
9 TH	*8.11.2021* *Mo*	**Electro-Optic Effect and Modulators** *Problem Set 3 Due, Problem Set 4 Out*
10 TH	10.11.2021 We	**Acousto-Optic Modulators and Bragg Cells**
11 TH	15.11.2021 Mo	**Third-Order Nonlinear Effects** *Problem Set 4 Due, Problem Set 5 Out*
12 TH	17.11.2021 We	**Self-Phase Modulation and Self-Focusing**

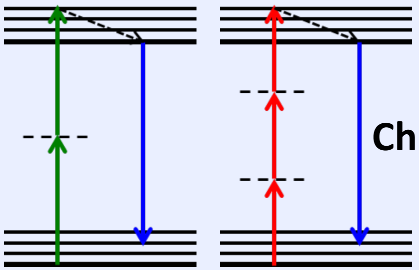
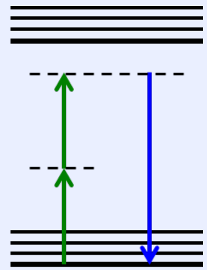
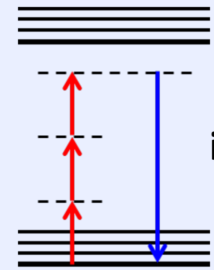
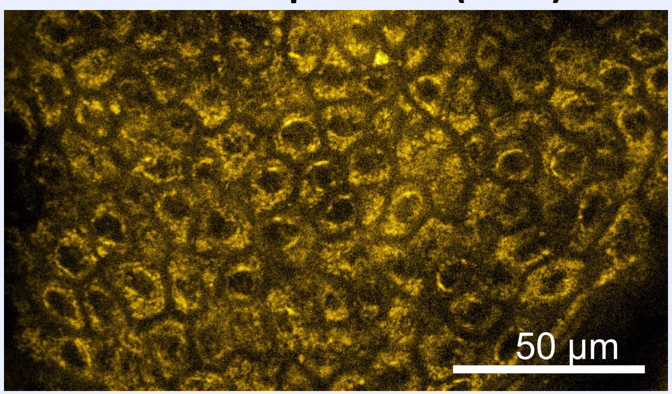
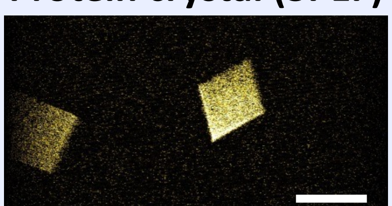
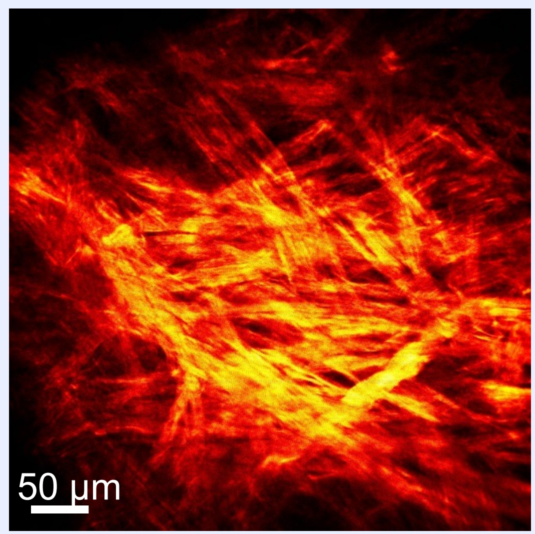
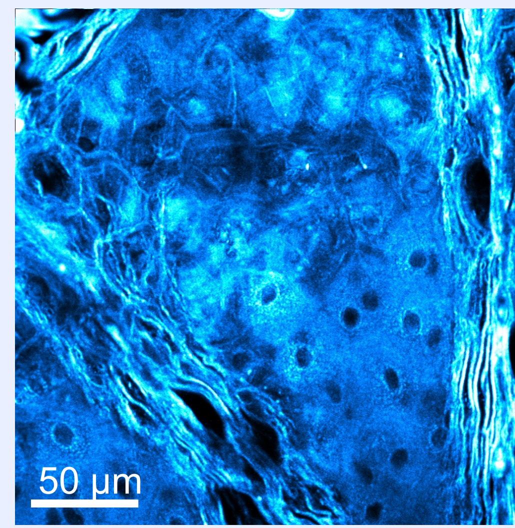
Syllabus

10 TH	10.11.2021 We	**Acousto-Optic Modulators and Bragg Cells**
11 TH	15.11.2021 Mo	**Third-Order Nonlinear Effects** *Problem Set 4 Due, Problem Set 5 Out*
12 TH	17.11.2021 We	**Self-Phase Modulation and Self-Focusing**
13 FXK	22.11.2021 Mo	**Raman and (Stimulated) Brillouin Scattering** *Problem Set 5 Due, Problem Set 6 Out*
14 FXK, TH	24.11.2021 We	Lab Demonstrations I
15 FXK	29.11.2021 Mo	**Optical Solitons** *Problem Set 6 Due, Problem Set 7 Out*
16 TH	1/12/2021 We	**Dispersion Engineering in Fiber**
17 TH	6/12/2021 Mo	**Integrated Waveguides** *Problem Set 7 Due, Problem Set 8 Out*
18 TH	8/12/2021 We	**FEM and FDTD Numeric Simulation of Waveguide and Nonlinear Structures**
19 TH	13/12/2021 Mo	**Supercontinua, NLSE and Numeric Simulation** *Problem Set 8 Due, Problem Set 9 Out*

Syllabus

20 TH	15/12/2021 We	**Similaritons, Dark Solitons, and Nonlinear Attractors**
21 FXK	03/01/2022 Mo	**Ultrafast Terahertz (THz) Sources** *Problem Set 9 Due, Problem Set 10 Out*
22 FXK	05/01/2022 We	**Applications of Ultrafast Terahertz (THz) Sources**
23 FXK	10/01/2022 Mo	**Ultrashort-Pulse Optical Parametric Amplification** *Problem Set 10 Due, Problem Set 11 Out*
24 FXK	12/01/2022 We	**Ultrashort-Pulse Optical Parametric Chirped Pulse Amplification**
25 FXK	17/01/2022 Mo	**High-Energy Few-Cycle Parametric Sources** *Problem Set 11 Due*
26 TH	19/01/2022 We	**Nonlinear Microresonators**
27 TH	24/01/2022 Mo	**Integrated combs, Brillouin and Raman laser, OPOs**
28 FXK, TH	26/01/2022 We	**Lab Demonstrations II**
29	27/01/2022	**BA and MS Thesis Topics**

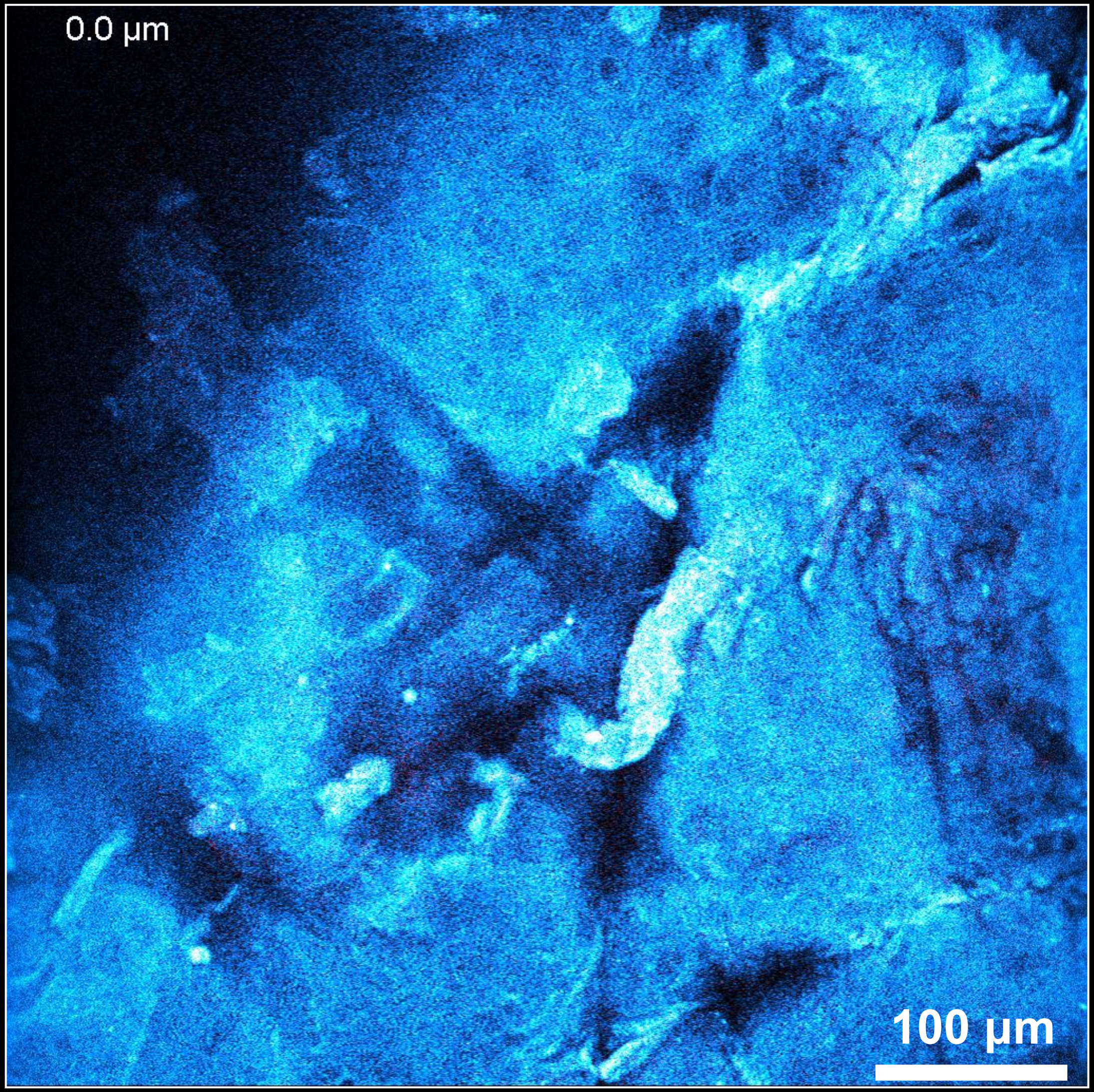
Multiphoton Microscopy (MPM)

N-photon excitation fluorescence (2PEF/3PEF)	Second-harmonic generation (SHG)	Third-harmonic generation (THG)
 Chromophores	 Optical non-centro-symmetry	 Optical inhomogeneity
Cells in epidermis (2PEF)  Protein crystal (3PEF) 	Collagen fibers in dermis 	Cells in epidermis 

Chung *et al.*, “Multimodal imaging platform for optical virtual skin biopsy ….,” Biomed. Opt. Exp. **10**, 514-525 (2018).

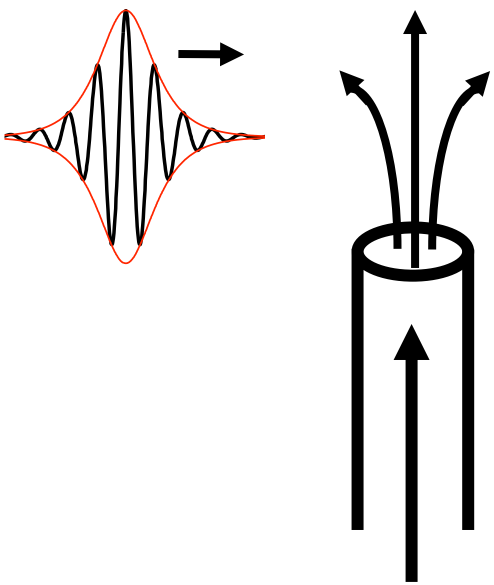
Optical virtual skin biopsy by SHG/THG

Excitation wavelength: 1.25 μm, SHG: fibrous tissue, THG: epidermal cells



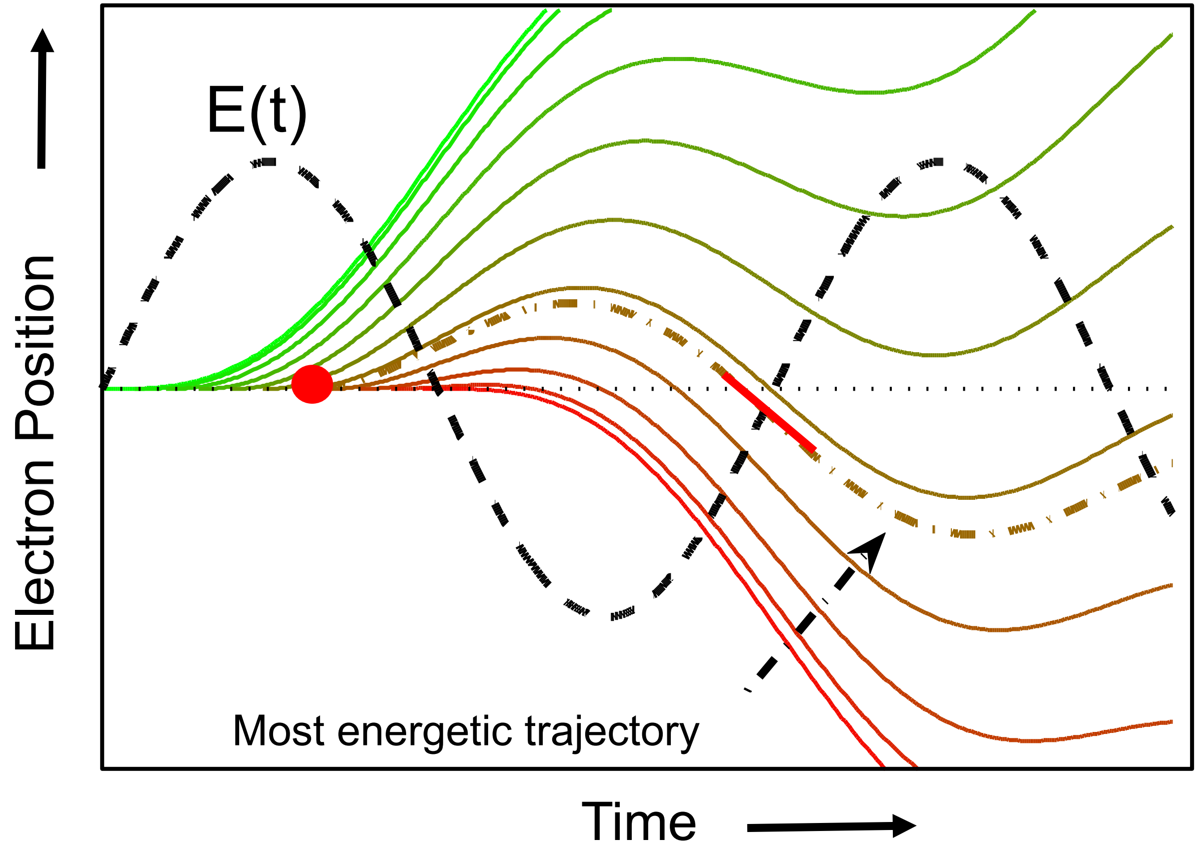
High Order Harmonic Generation (HHG)

High
Energy
Pulse



Gas nozzle

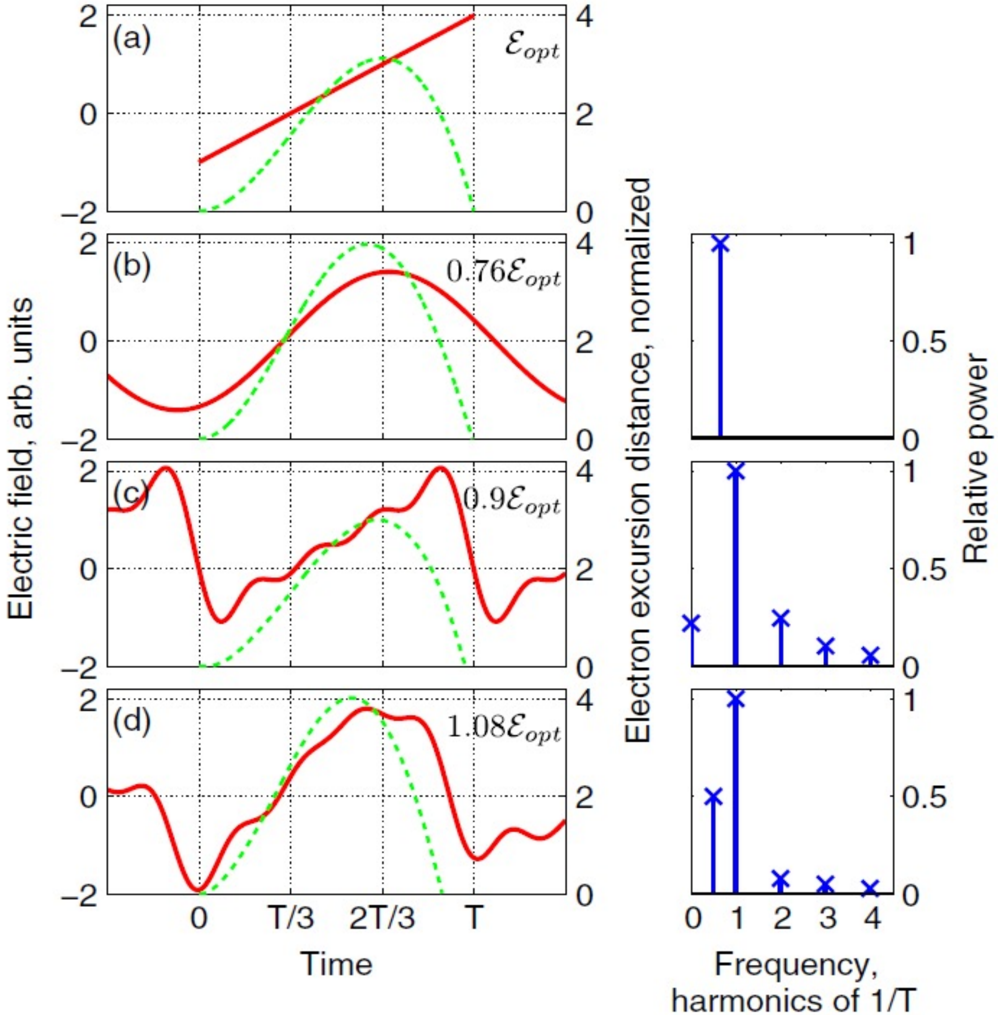
Tunnel Ionization + Propagation + Recombination

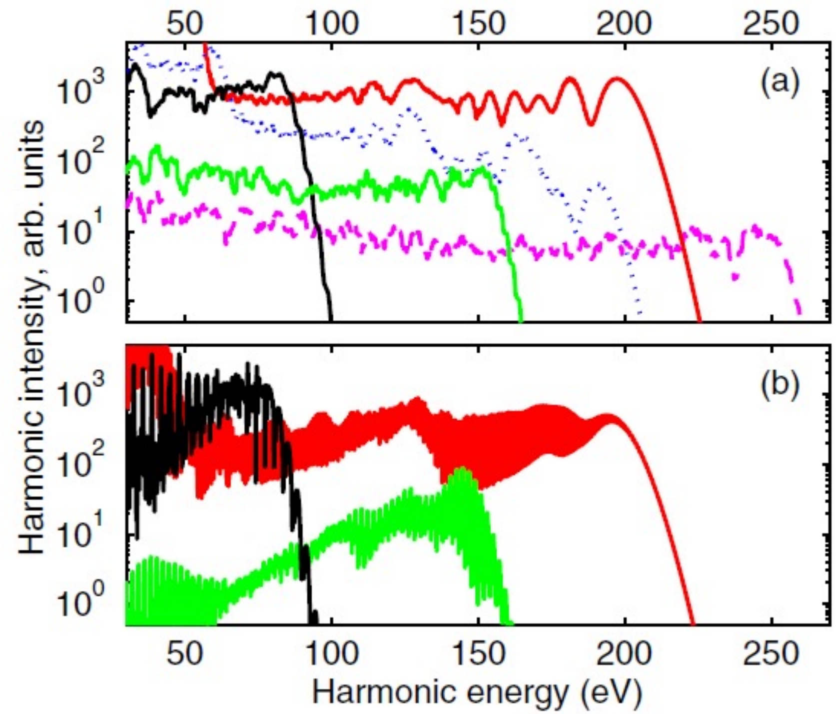


$$\hbar\omega_{\mathrm{cutoff}} = I_{\mathrm{p}} + 3.17U_{\mathrm{p}}$$

P. Corkum, Phys. Rev. Lett. 71, 1994 (1993)
K. C. Kulander, SILAP Conference (1992)

Maximizing the recollision energy within a period





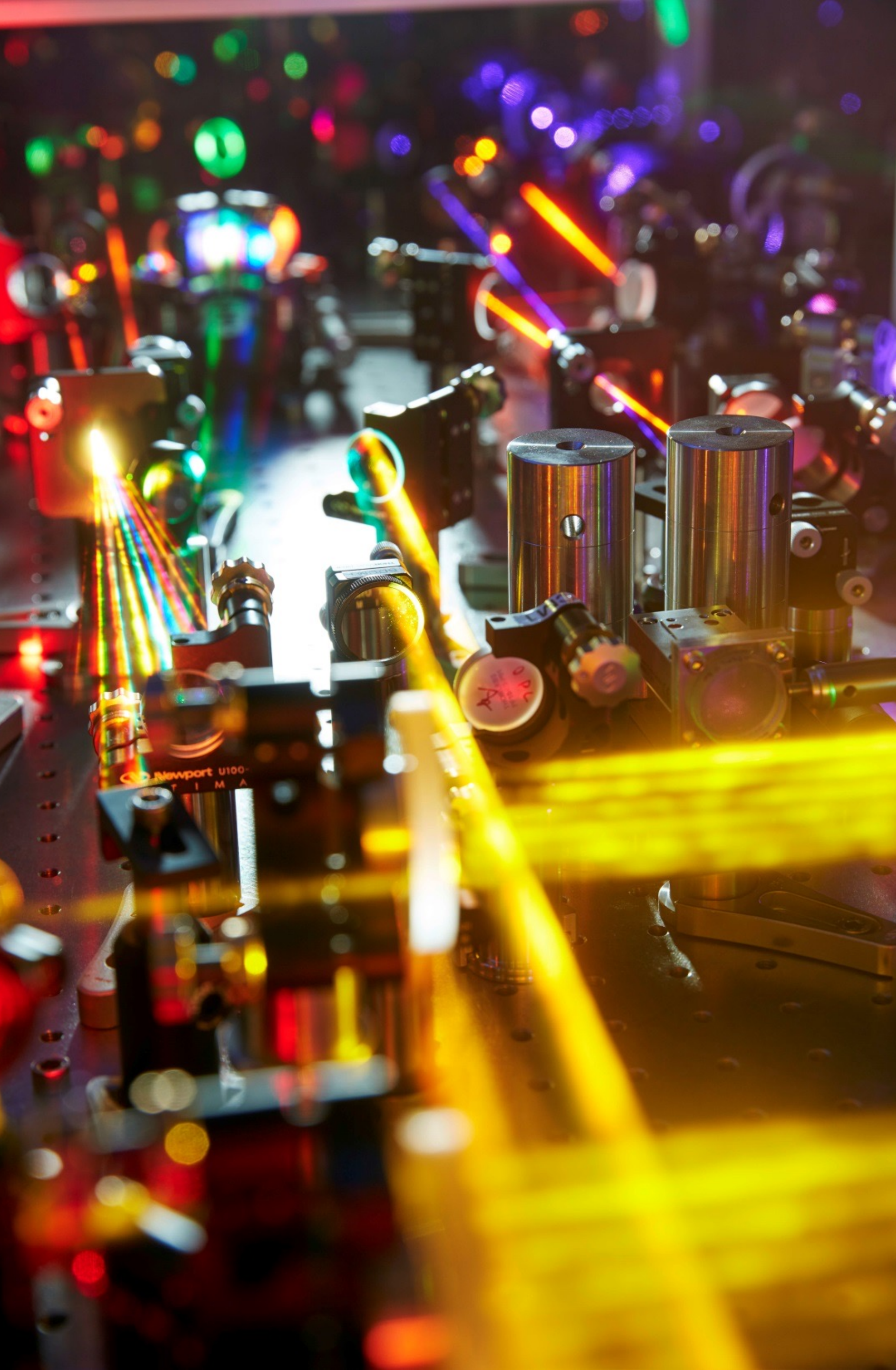
"perfect waveform" for HHG

maximize	cut-off energy
sinusoidal	~ $3.17U_P$
synthesized	~ $9U_P$

800nm + 400nm + 267nm + 200nm + 1600nm

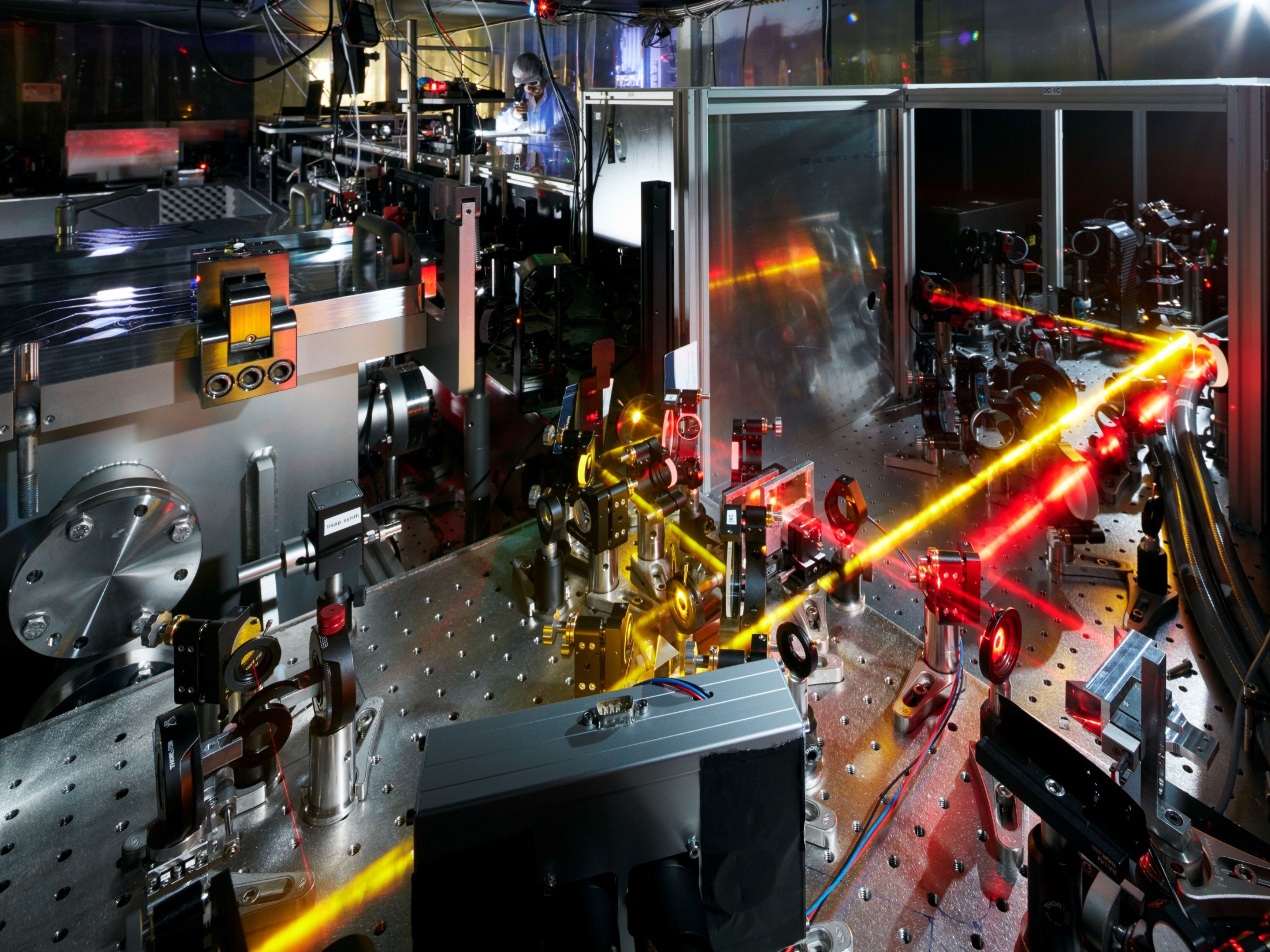
ω + 2ω + 3ω + 4ω + 0.5 ω

L. E. Chipperfield *et al.*, Phys. Rev. Lett. 102, 063003 (2009)
C. Jin *et al.*, Nature Commun. 5:4003 (2014)
S. Haessler *et al.*, Phys. Rev. X 4, 021028 (2014)



C. Manzoni *et al.* LPR **9**, 129 (2015)

G. M. Rossi *et al.*, Nature Photonics **14**, 629-635, (2020)


tisap synth

1.1 Why Nonlinear Optics?

- Capacitiy limits to optical communications due to fiber nonlinearities
- Nonlinear laser spectroscopy
- Ultrashort pulse lasers, intrinsic nonlinearities
- Limits to laser amplifiers set by optical nonlinearities
- Frequency conversion, UV, EUV, MID-IR, THz, ….
- Strong-field physics in gases, liquids and solids
- High order harmonic generation (HHG)
- Micromachining of materials
- Laser Surgery
- Nonlinear Microscopy
- Microwave measurement techniques, such as electro-optical sampling and electro-optical conversion

The Nobel Prize in Physics 1981

Photo from the Nobel Foundation archive.

Nicolaas Bloembergen

Prize share: 1/4

Photo from the Nobel Foundation archive.

Arthur Leonard Schawlow

Prize share: 1/4

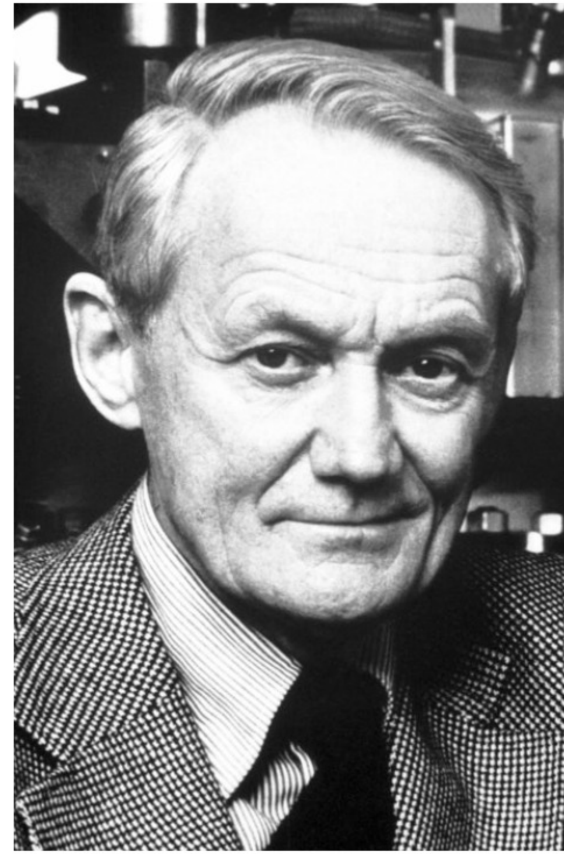


Photo from the Nobel Foundation archive.

Kai M. Siegbahn

Prize share: 1/2

The Nobel Prize in Physics 2005

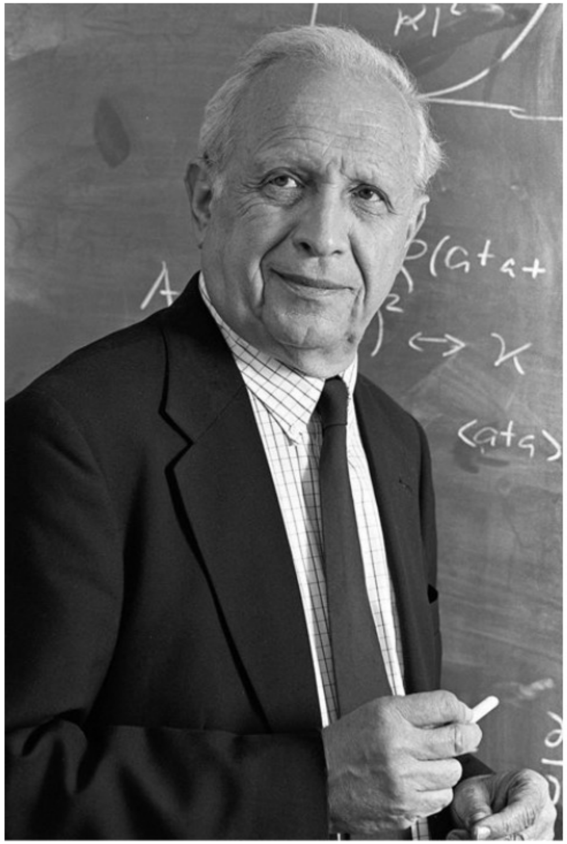


Photo: J.Reed

Roy J. Glauber

Prize share: 1/2

Photo: Sears.P.Studio

John L. Hall

Prize share: 1/4

Photo: F.M. Schmidt

Theodor W. Hänsch

Prize share: 1/4

The Nobel Prize in Chemistry 2014

Eric Betzig

Prize share: 1/3

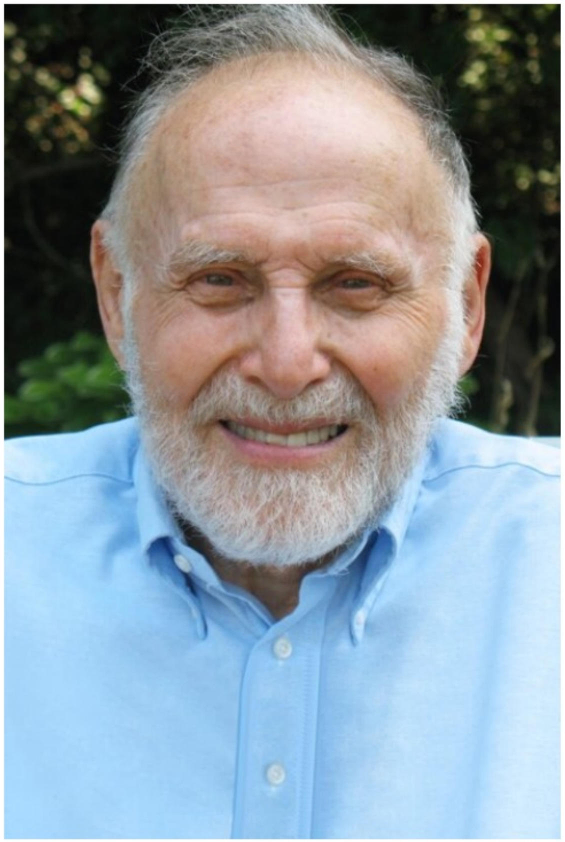
Stefan W. Hell

Prize share: 1/3

William E. Moerner

Prize share: 1/3

The Nobel Prize in Physics 2018



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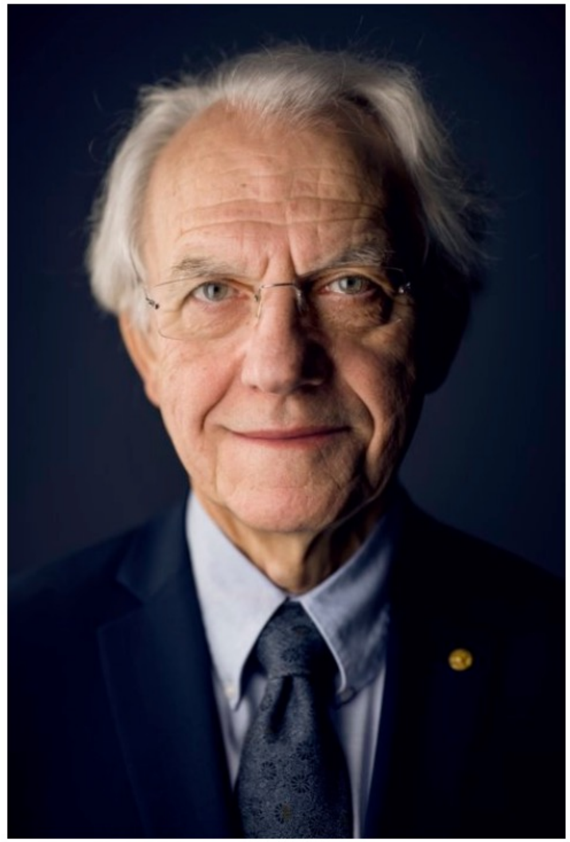

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Gérard Mourou

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Donna Strickland

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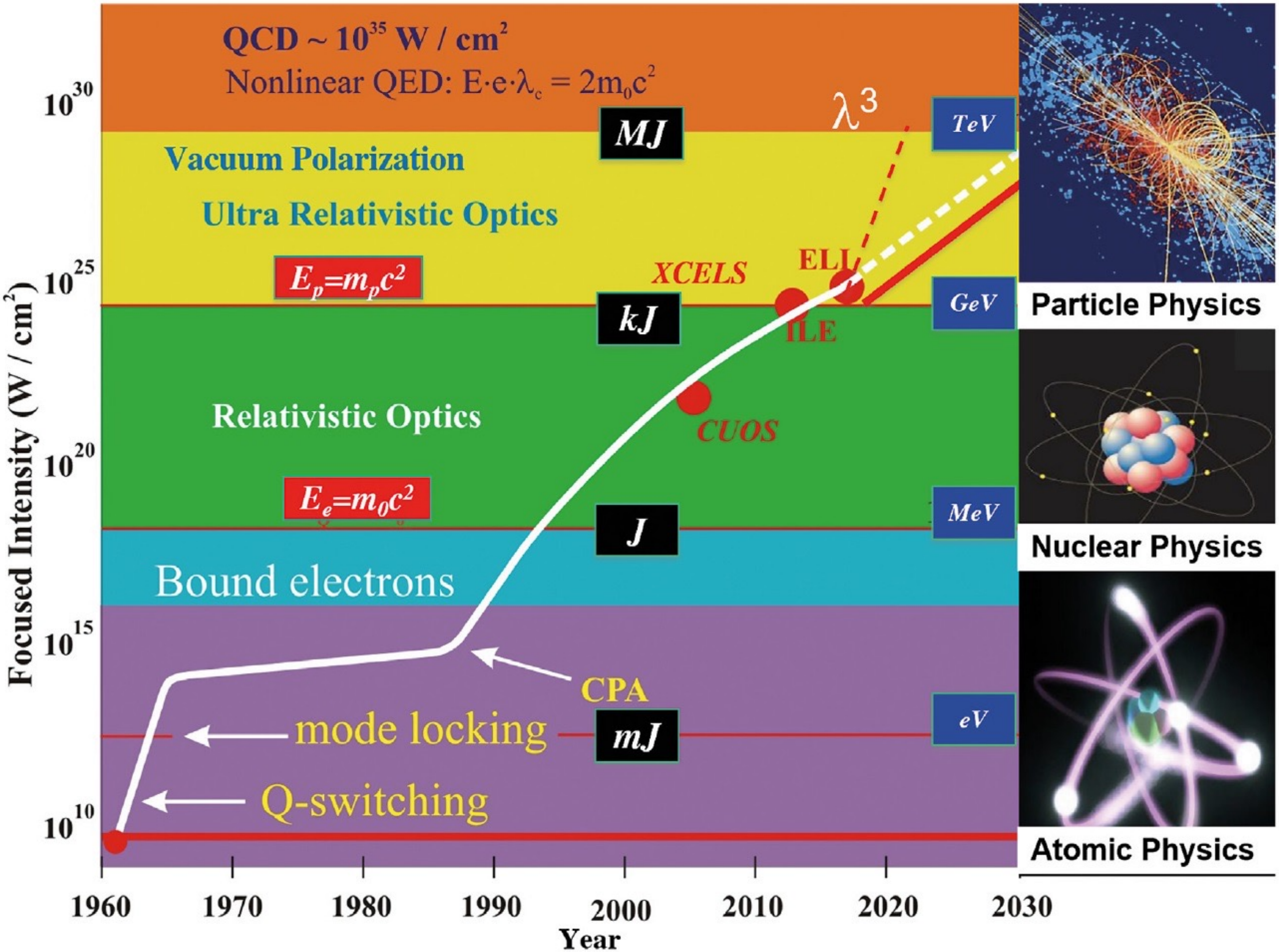
Typical optical nonlinearities are weak

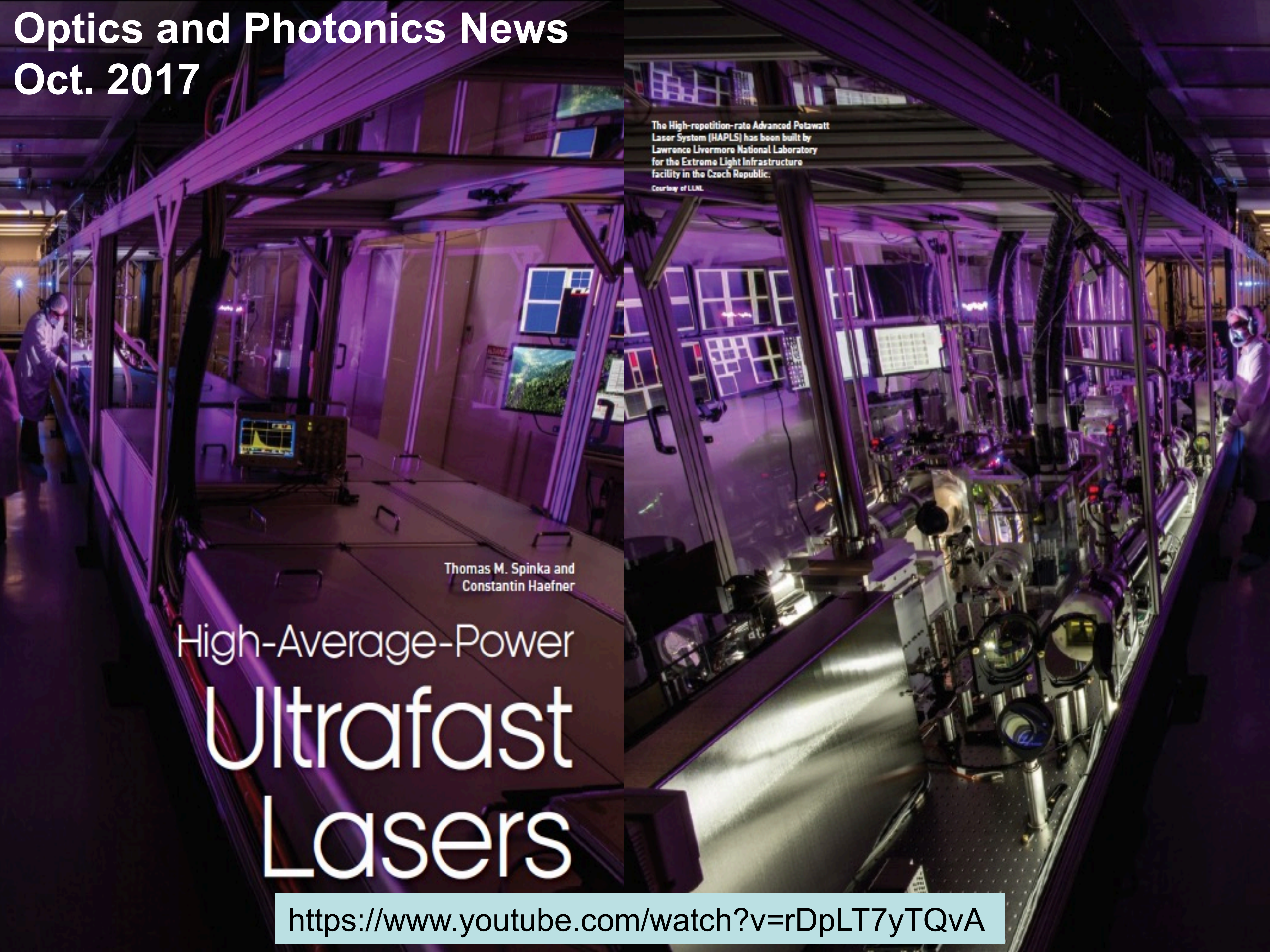
	typ. Ti:sa CPA	L3-HAPLS @ ELI	SULF 10 PW
pulse energy E_p	5 mJ	$\geq$30 J	130 J
repetition rate f_r	1 kHz	10 Hz	
pulse duration τ_p	30 fs	$\leq$30 fs	24 fs
peak power P	166 GW	$\geq$1 PW	5.4 PW
peak intensity I	3×10^{15} W/cm^2	3.5×10^{19} W/cm^2	2×10^{22} W/cm^2
peak field E	1.6 GV/cm	162 GV/cm	3.9 TV/cm

Table 1.1: Ti:sapphire laser source parameters for a typical Ti:sapphire chirped-pulse amplifier (CPA) commonly used in attoscience, the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) [16] designed/built by Lawrence Livermore National Laboratory (LLNL) for the Extreme Light Infrastructure (ELI), and the Shanghai Superintense Ultrafast Laser Facility (SULF) [17, 18, 19], which will be scaled up to the 100-PW Station of Extreme Light (SEL) until 2023 [17]. $P = E_\mathrm{p}/\tau_\mathrm{p}$, $I = P/A$. For the typical Ti:sa CPA, $A = \pi r^2$ with $r = 40\,\mu$m. For L3-HAPLS, focusing is assumed to reach a laser strength parameter $a_0 = 4$, with $a_0 = 0.85 \times 10^{-9}\,\lambda[\mu\mathrm{m}]\,\left(I[\mathrm{W/cm}^2]\right)^{1/2}$. $E = \sqrt{2Z_0 I}$ with $\mathrm{Z}_0 = 377\,\Omega$.



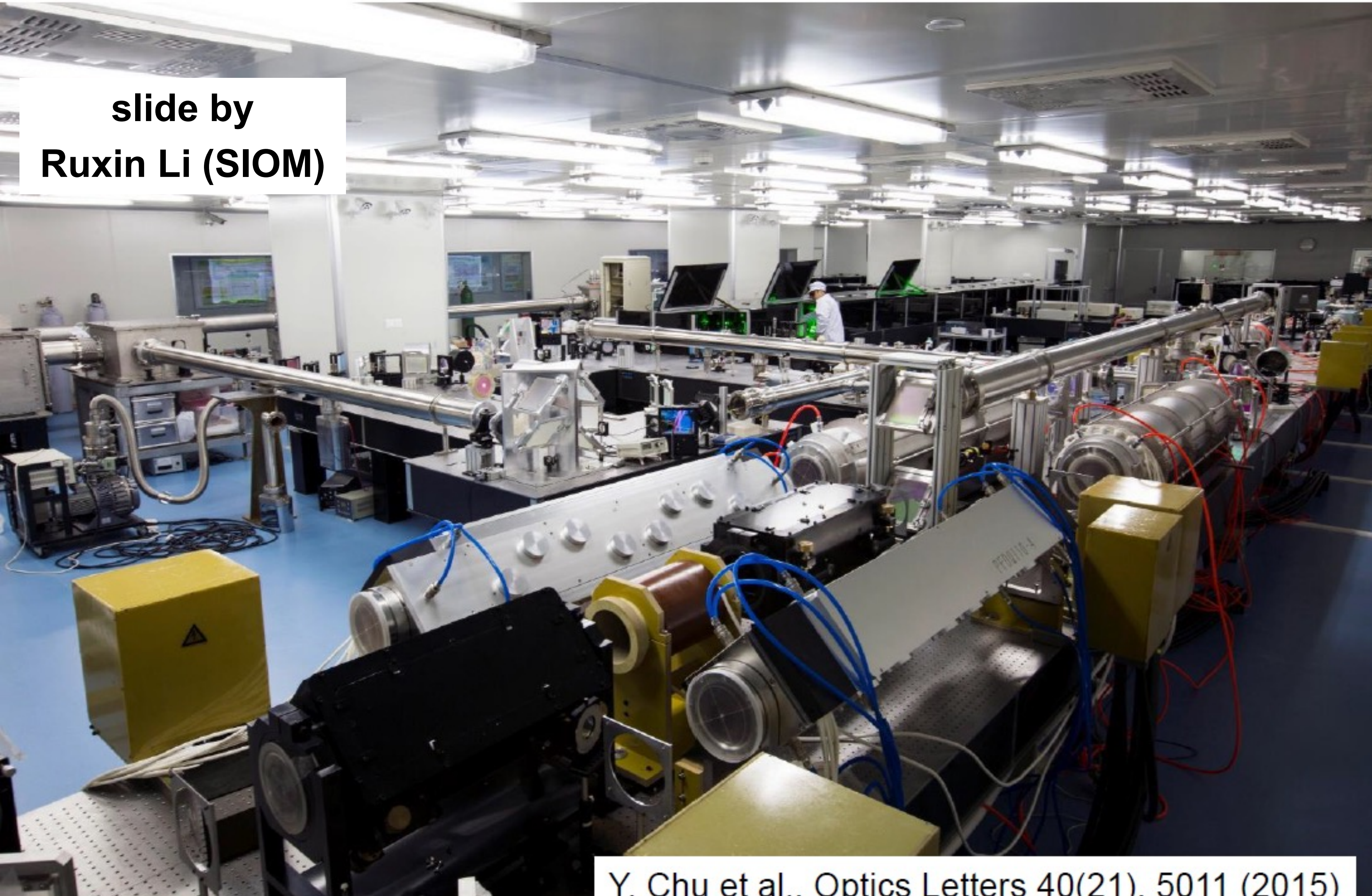
G. Mourou, J. A. Wheeler, and T. Tajima, Europhys. News **46**, 31 (2015)

Optics and Photonics News
Oct. 2017



https://www.youtube.com/watch?v=rDpLT7yTQvA

SULF The 5PW CPA amplifier (2014)



slide by
Ruxin Li (SIOM)

Y. Chu et al., Optics Letters 40(21), 5011 (2015)

1.2 How does Nonlinear Optics work?

P: Polarization (Dipole moment / unit volume)

p: dipole moment per atom or molecule
***N*: Number density**

$$\mathbf{P} = N\mathbf{p}$$

***q*: charge that is displaced**
l: displacement

$$\mathbf{p} = q \cdot \mathbf{l}$$

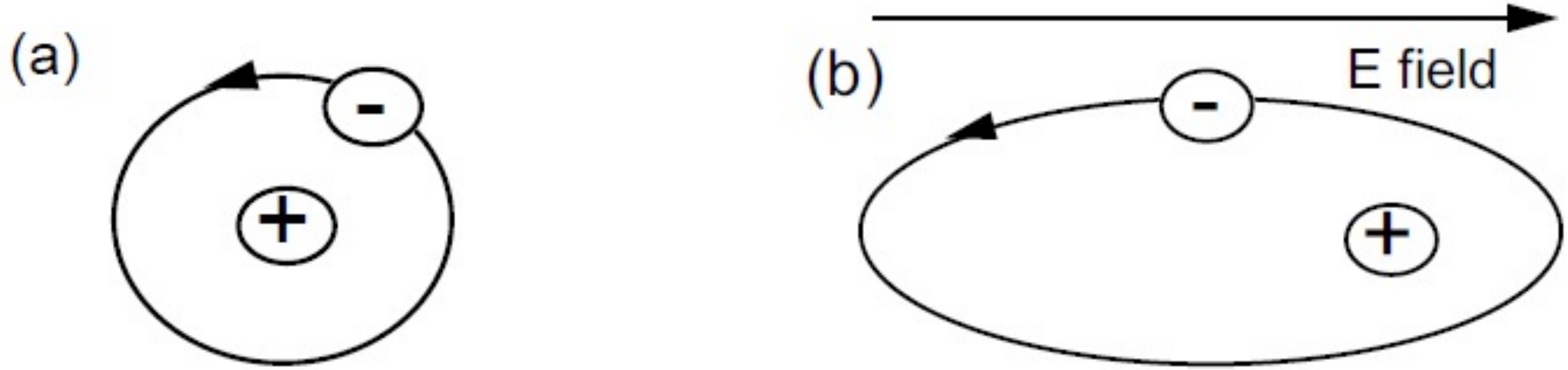


Figure 1.1: **A simple atom model** explaining the effect of in optical electric field on the induced polarization in an atom: (a) without field, (b) with field.

Perturbation Expansion

p: nonlinear dipole moment of atom or molecule

$$\mathbf{p} = q\mathbf{l} = q\left\{\alpha^{(1)}\left(\frac{E}{E_a}\right) + \alpha^{(2)}\left(\frac{E}{E_a}\right)^2 + \alpha^{(3)}\left(\frac{E}{E_a}\right)^3 + \cdots\right\}\frac{\mathbf{E}}{|\mathbf{E}|}. \qquad (1.1)$$

$\alpha^{(i)}$: typical excursion of electron cloud at the critical field is on the order of the Bohr radius

$$\alpha^{(i)} = d_a = 10^{-10}\mathrm{m}$$

E_a : critical field where perturbation theory breaks down: ionization field strength

$$E_a = \frac{e_0}{4\pi\epsilon_0 d_a^2} = 1.4 \cdot 10^{11}\frac{V}{m} = 1.4GV/cm, \qquad (1.2)$$

$$\epsilon_0 = 8.854 \cdot 10^{-12}\ \mathrm{F/m\ the\ vacuum\ dielectric\ constant}$$

Estimate for nonlinear susceptibilities

1 mol, i.e. the typical density is $N_A = 6 \cdot 10^{23}\ \mathrm{cm}^{-3}$

Nonlinear susceptibilities

$$P = \epsilon_0 \left[\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \cdots \right], \qquad (1.3)$$

order i	$\chi^{(i)}$	model value	typ. material value
1	$\chi^{(1)} = \frac{Ne\alpha^{(1)}}{\epsilon_0 E_a}$ ≈ 7.5	n=2.9	Quartz: n=1.45
2	$\chi^{(2)}$ $= 5.$		
3	$\chi^{(3)}$ $= 3.$		

Table 1.2: Linear and nonlinear optical susceptibilities from a simple atom model. We used n_0(KDP)= 2.3, $d_a = \alpha^{(i)} = 10^{-10}$ m, $e = e_0 = 1.6 \cdot 10^{-19}$ C, $\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m, $E_a = \frac{e_0}{4\pi\epsilon_0 d_a^2} = 1.4 \cdot 10^{11}$ V/m, $N = 6 \cdot 10^{23} \cdot 10^6 \mathrm{m}^{-3}$.

Estimate for (nonlinear) susceptibilities

Refractive index:

$$n^2 = \left(1 + \chi^{(1)}\right) . \tag{1.4}$$

As table (1.2) shows, the model predicts

$$\chi^{(1)} = \frac{N e_0 d_a}{E_a \varepsilon_0} \tag{1.5}$$

refractive index $n = 2.9$

About right!