University of New Mexico

# PHYC/ECE 568: NONLINEAR OPTICS

## Spring 2020

OPTICAL SCIENCE & ENGINEERING
University of New Mexico

THE UNIVERSITY OF NEW MEXICO


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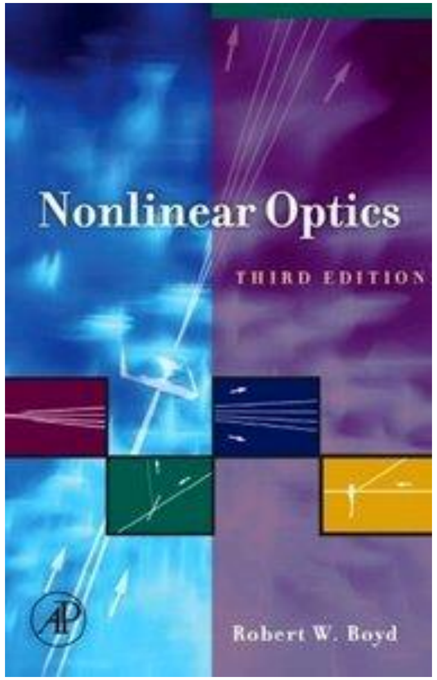
Office Hours: Make an appointment or stop by

**The final grade is weighted as follows:**

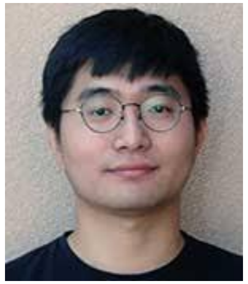
- ❖ Midterm Exam: 45%
- ❖ Final Project (paper + presentation): 40%
- ❖ Homework: 15% (nearly every 2 weeks)

Textbook




4th edition will be out in March


TA: Mingyang Zhang
myzhang@unm.edu

# Course Syllabus

- Introduction (*historical overview, applications of NLO*)
- Nonlinear Susceptibilities ($\chi^{(2)}$ *and* $\chi^{(3)}$ *processes, nonlinear refraction and absorption)*
- Classical Anharmonic Oscillator Model
- Properties of Nonlinear Susceptibilities (*symmetries, Kramers-Kronig dispersion relations)*
- Wave Propagation in NLO Media (*coupled amplitude equations for* $\chi^{(2)}$ *processes, phase matching, second harmonic generation, sum and difference frequency generation, optical parametric processes, cascading nonlinearities)*
- Quantum Mechanical Treatment of Nonlinear Susceptibilities
- $\chi^{(3)}$ Processes (*electronic, vibrational and rotational effects, optical Kerr effect, self-focusing, wave-mixing, bistability, phase-conjugation, beam coupling, solitons)*
- Photo-Refractive Nonlinearities
- Stimulated Light Scattering (*stimulated Raman, Brillouin, and Rayleigh scattering)*
- Recent advances in ultrafast NLO (high-harmonic generation, atto-physics, terahertz)

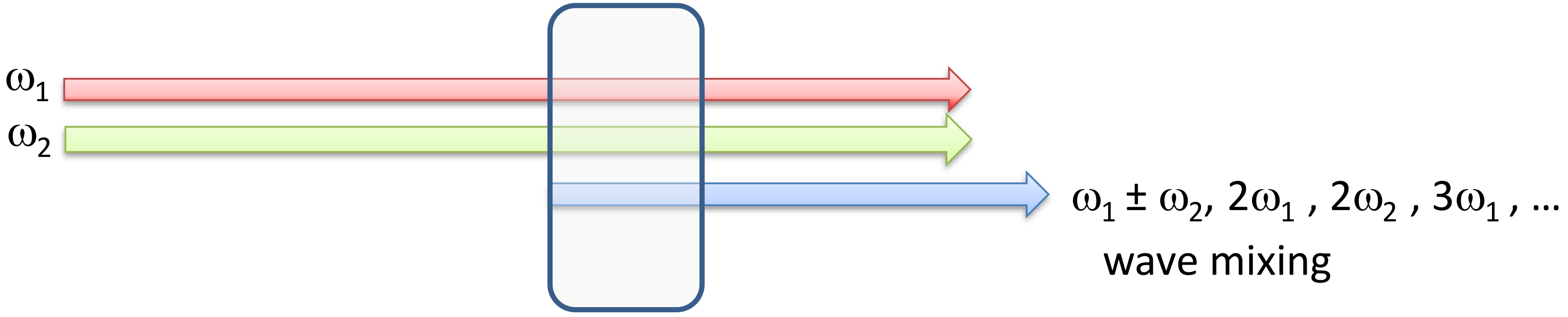
# What is Nonlinear Optics?

At low intensities light beams cross without any interaction (linear optics) $P = \epsilon_0 \chi^{(1)} E$

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2}$$

**Light beams interact with each other, or themselves at high intensities (nonlinear optics)**

$$P = \epsilon_0 (\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \cdots)$$




**Primary Manifestations:**

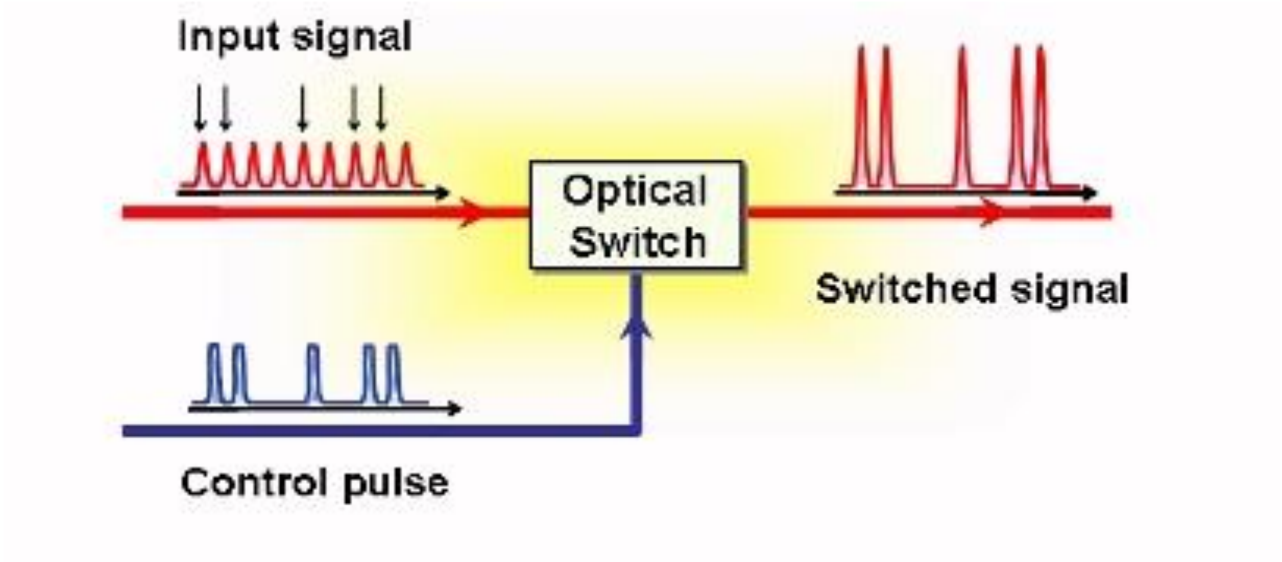
- sum, difference, harmonic frequency generation (new frequencies)
- modulating refractive index and absorption coefficient; examples: $n = n_0 + n_2 I$

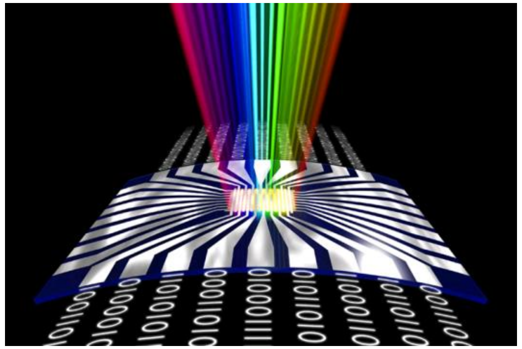
$$\alpha = \alpha_0 + \beta I$$

# Controlling Light with Light

$$n = n_0 + n_2 I$$

$$\alpha = \alpha_0 + \beta I$$



Optical Computers !

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# 59th Anniversary of Nonlinear Optics

# 1961: NLO was born!

$$P = \epsilon_0 \chi^{(2)} E^2$$

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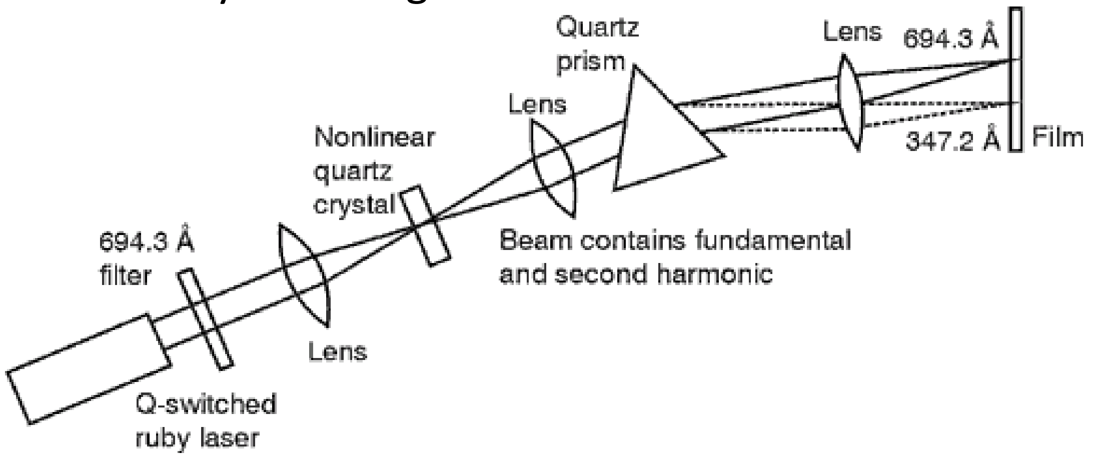




Peter Franken (1929-1999)

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

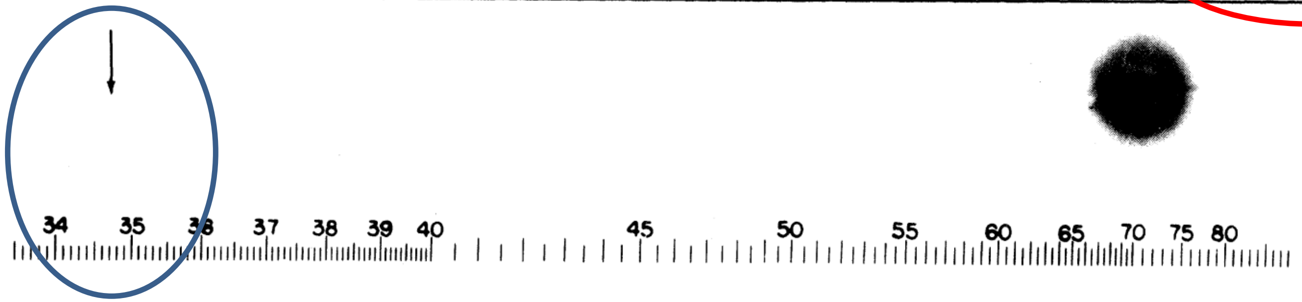
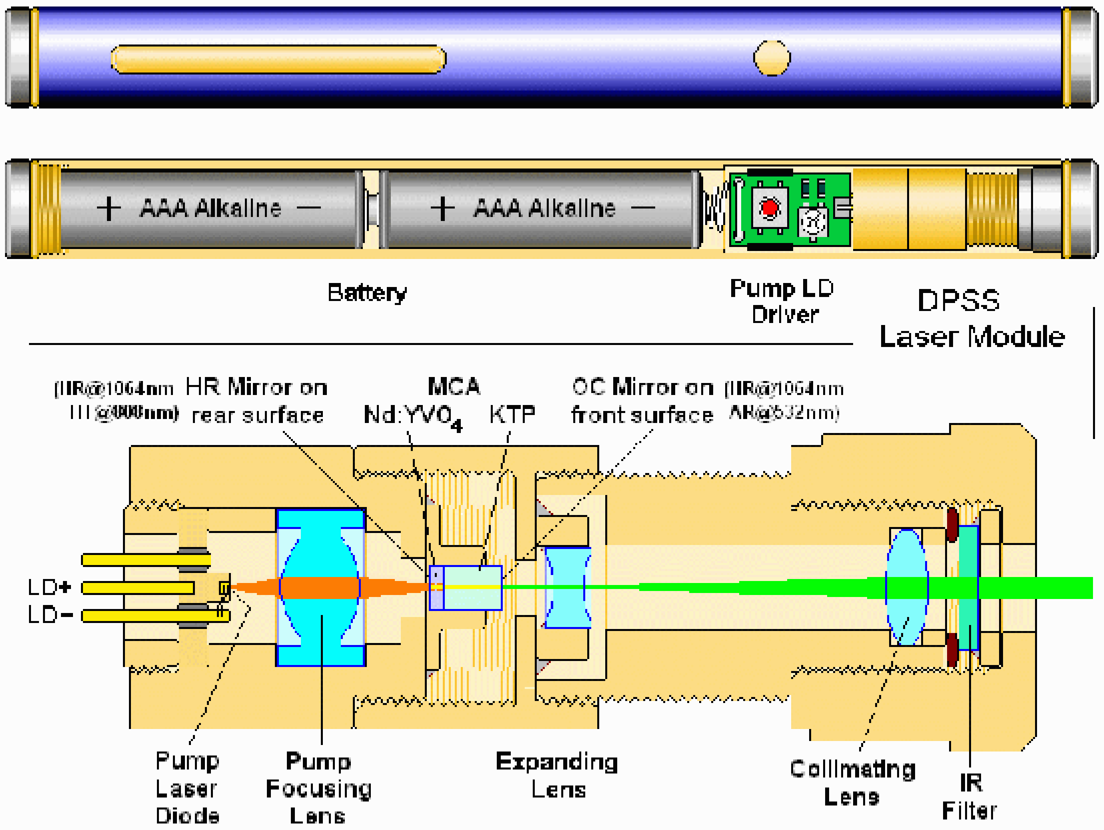



FIG. 1. A direct reproduction of the first plate in which there was an indication of second harmonic. The wavelength scale is in units of 100 A. The arrow at 3472 A indicates the small but dense image produced by the second harmonic. The image of the primary beam at 6943 A is very large due to halation.

# Second Harmonic Generation (SHG): Green Laser Pointer




Beam Paths: | 808 nm — | 1064+532 nm — 532 nm — |

Typical Green DPSS Laser Pointer Using MCA

# 1961: NLO was born!

$$P = \epsilon_0 \chi^{(3)} E^3$$

$$\alpha = \alpha_0 + \beta I$$

Two-photon absorption

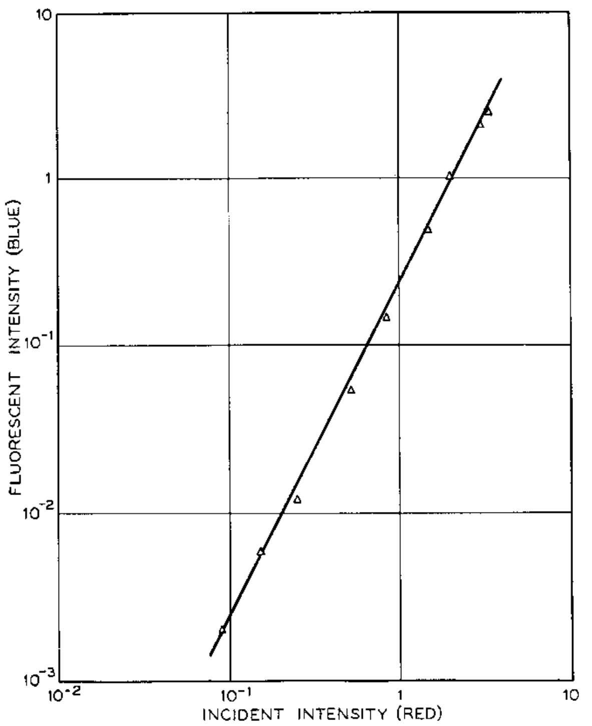
VOLUME 7, NUMBER 6 PHYSICAL REVIEW LETTERS SEPTEMBER 15, 1961

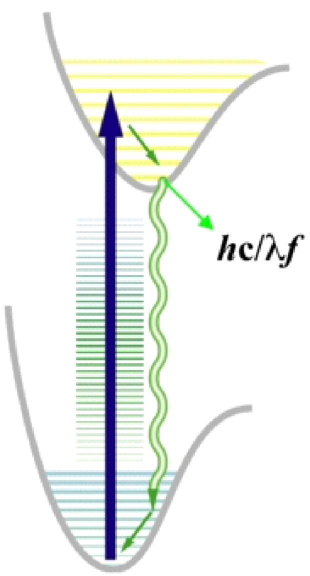
TWO-PHOTON EXCITATION IN $CaF_2:Eu^{2+}$

W. Kaiser and C. G. B. Garrett
Bell Telephone Laboratories, Murray Hill, New Jersey

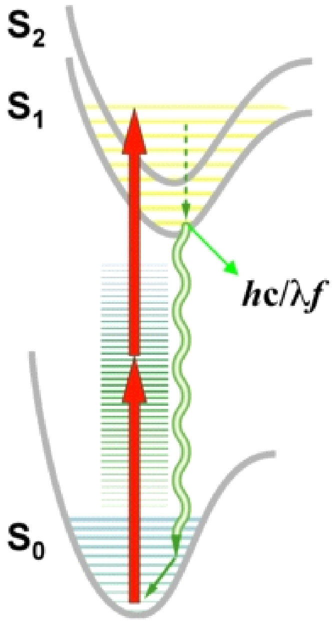
(Received August 28, 1961)

VOLUME 7, NUMBER 6 PHYSICAL REVIEW LETTERS

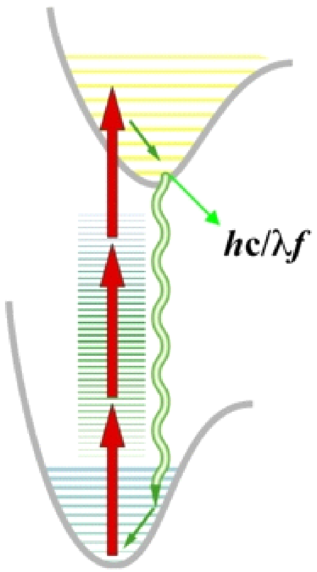



Linear (one-photon) fluorescence




Two-photon fluorescence (TPF)




Three-photon fluorescence (3PF)

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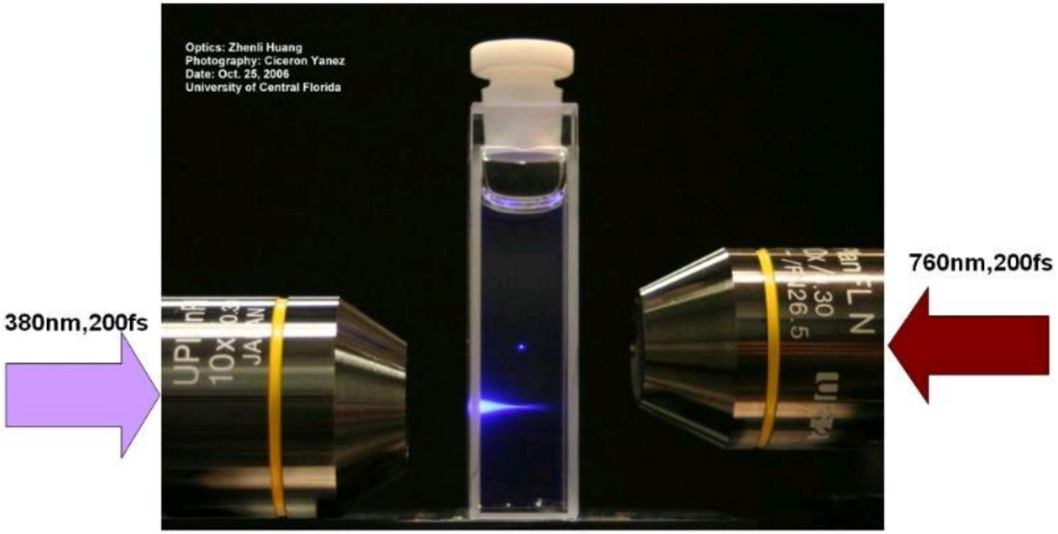
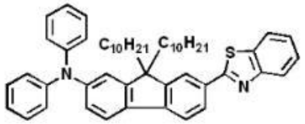
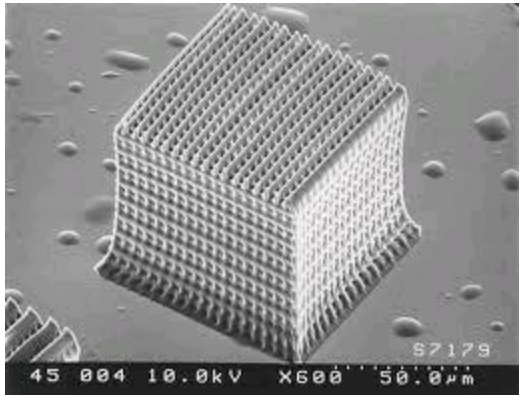
# Two-photon microscopy

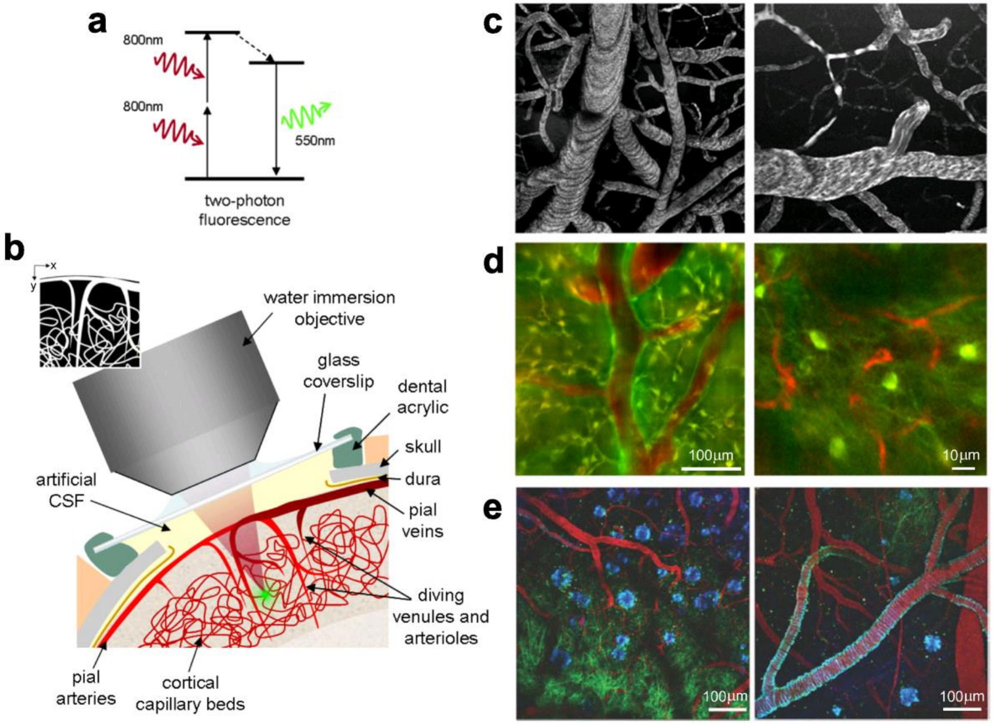



Fluorene 3






Two-photon polymerization

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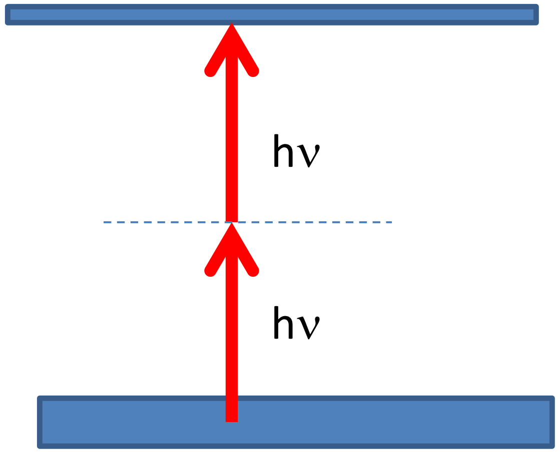
# Theoretical Foundations

**Maria Goeppert-Mayer** (June 28, 1906 – February 20, 1972)

Two-photon absorption theory (1931, doctoral dissertation)

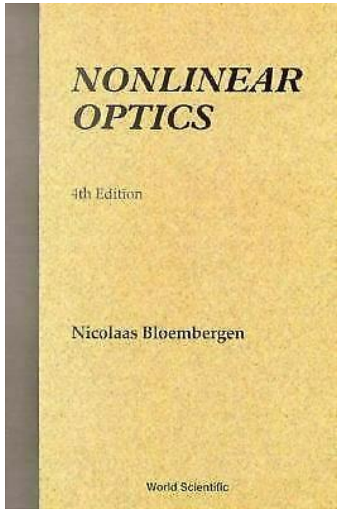


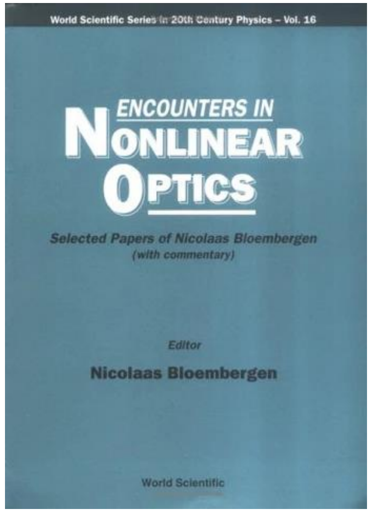

$$\alpha = \alpha_0 + \beta I$$



Awarded the Nobel Prize in Physics in 1963, shared with J. Hans D. Jensen and Eugene Paul Wigner.

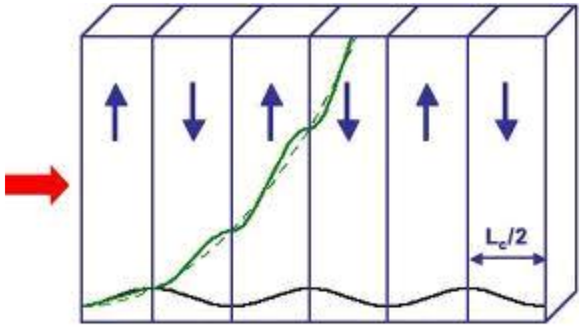
# Theoretical Foundations




## Nicholas Bloembergen
**1962- 2017**


Nobel Prize in Physics, 1981




$$\begin{cases} \dfrac{du_s}{dz} = \kappa u_p u_c \sin(\phi) \\ \dfrac{du_c}{dz} = \kappa u_p u_s \sin(\phi) \\ \dfrac{du_p}{dz} = -\kappa u_s u_c \sin(\phi) \end{cases}$$

(July 2011) in Hawaii (NLO Meeting)

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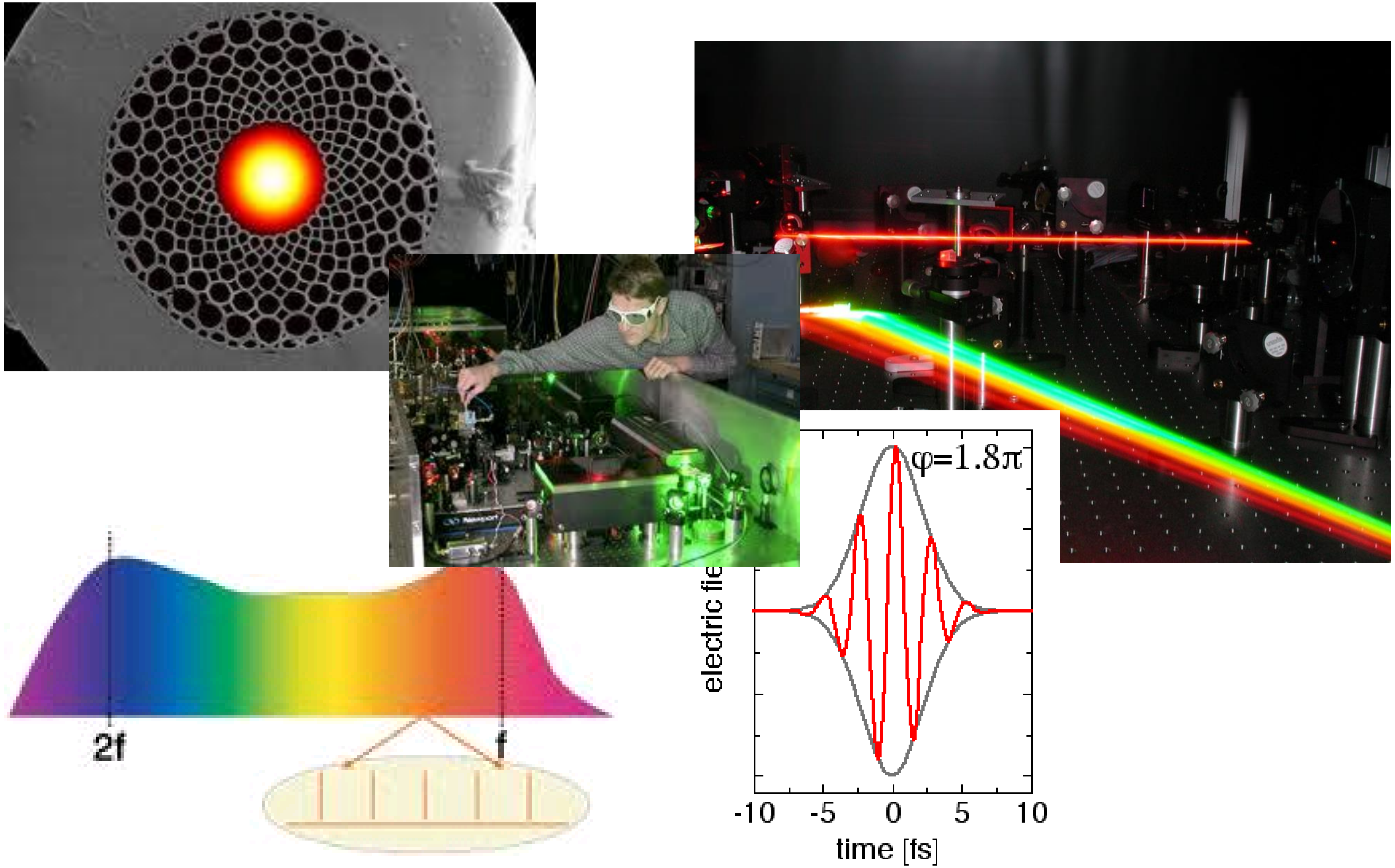
# Femtosecond Lasers, Frequency Combs and Optical Clocks

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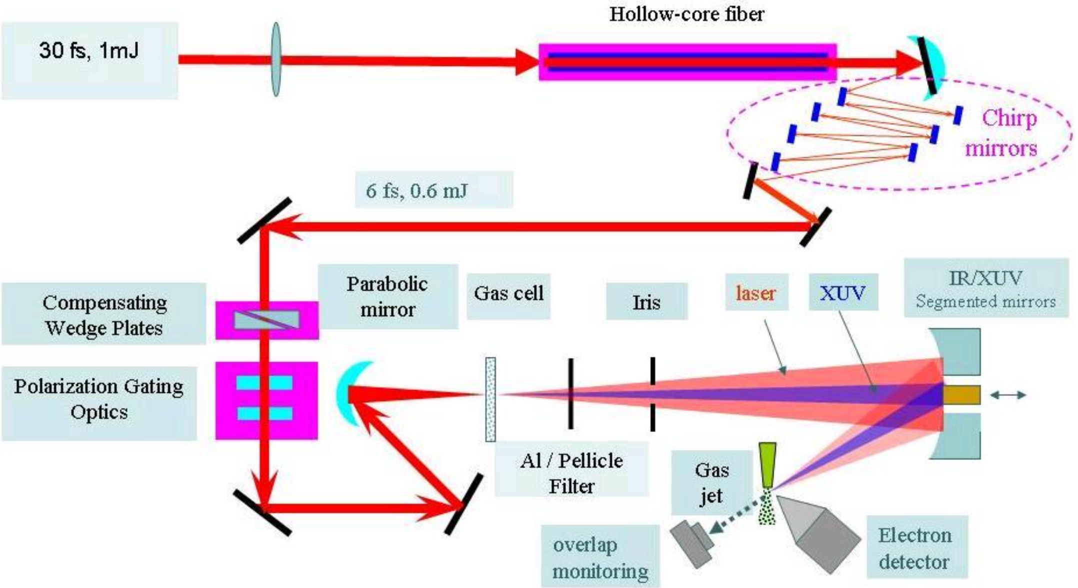
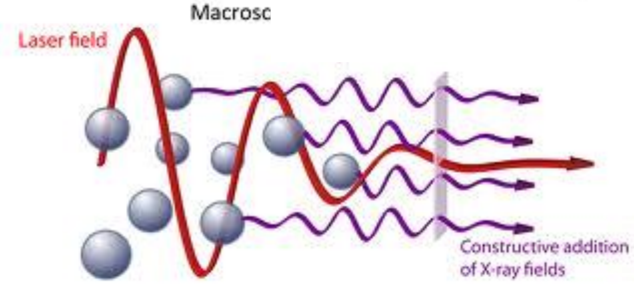
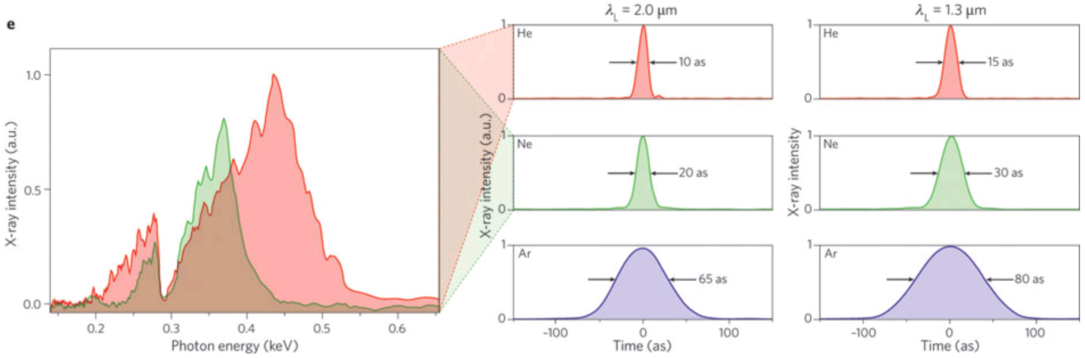
# Extreme Nonlinear Optics (X-ray bursts, attosecond pulses, and laser fusion)

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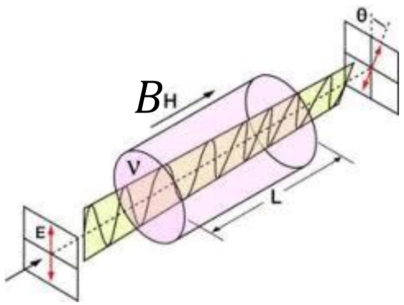
# Other Historical Perspectives (19th Century)

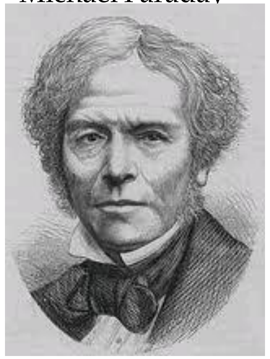
- Faraday Effect (magneto-optic) - 1845:

$$\theta = V \times B \times L$$

$V$ *is the Verdet constant*

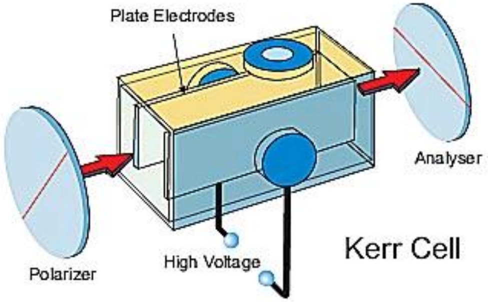



Michael Faraday



- Kerr Effect- 1875:

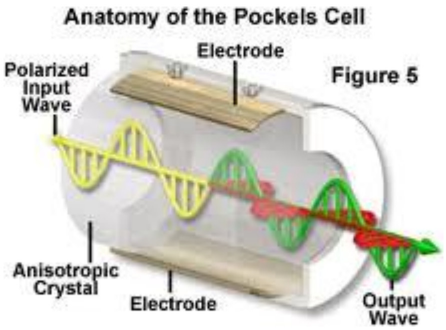
$$\Delta n = \lambda K E^2,$$



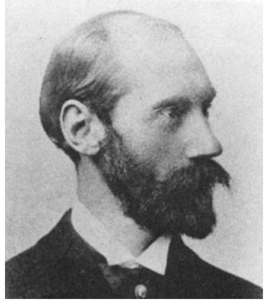

John Kerr


- Pockels Effect- 1893:

$$\Delta n = r \cdot n^3 E$$




Friedrich Pockels



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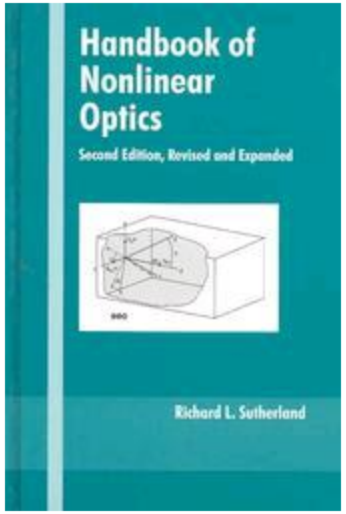
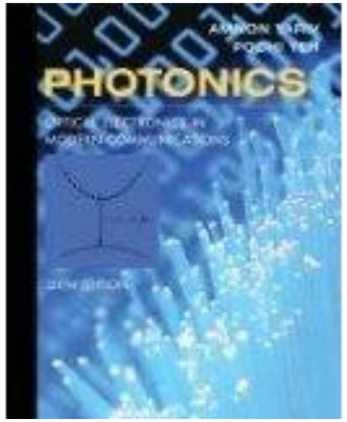
# Other References

Handbook of Nonlinear Optics
*Richard Sutherland*




Photonics: Optical Electronics in Modern Communications
*Amnon Yariv and Pochi Yeh*




Fundamentals of Nonlinear Optics
*Peter Bowers*