Phys 590B Condensed Matter Physics: Experimental Methods

Optical Spectroscopy of Advanced Materials

Basic optics, nonlinear and ultrafast optics

1858 150 2008
IOWA STATE UNIVERSITY

Jigang Wang

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions

Department of Physics, Iowa State University and Ames Lab- USDoE

Outline (Feb 9th -20th)

1. **Feb 9th, 11th and 13th: overview, basic optics and spectroscopy**
2. **Feb 16th,18th and 20th: Advanced optics, ultrafast and nonlinear spectroscopy**

- femtosecond lasers: case study; spectroscopy techniques: incoherent & coherent transient, magneto-optical, infrared & time-domain THz

General References:

Demtroder, Laser Spectroscopy: Basic Concepts and Instrumentation

Diels and Rudolph (DR), Ultrashort Laser Pulse Phenomena

Shah, Ultrashort Spectroscopy of Semiconductors and Semiconductor Nanostructures

Chemla, D.S., Ultrafast Transient Nonlinear Optical Processes in Semiconductors

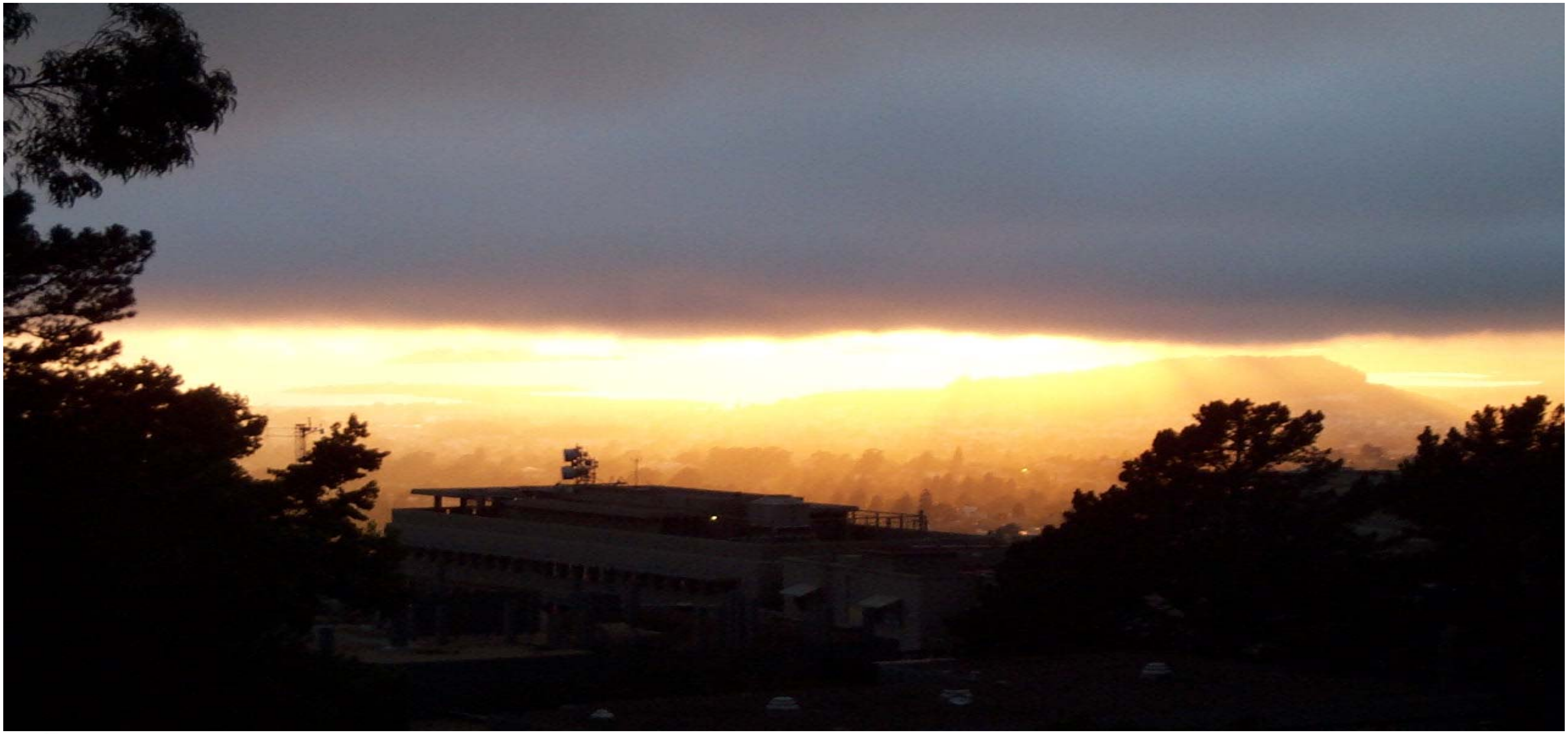
For example, see Copper, S.L, Optical Spectroscopy Studies of Metal-Insulator Transitions in Perovskite-related Oxides

Today

Overview and Introduction

“Light is, in short, the most refined form of matter.”

Louis de Broglie

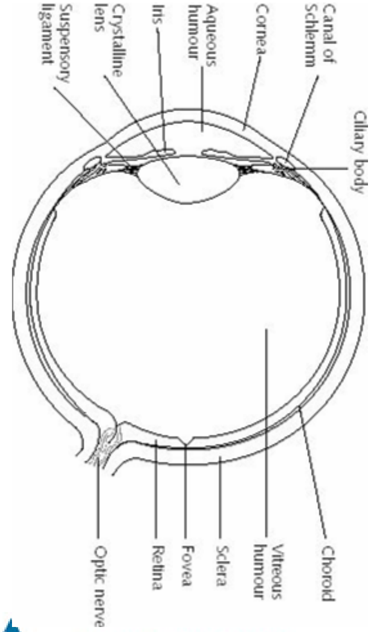


Berkeley, California

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions
IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

The first spectroscopy experiment



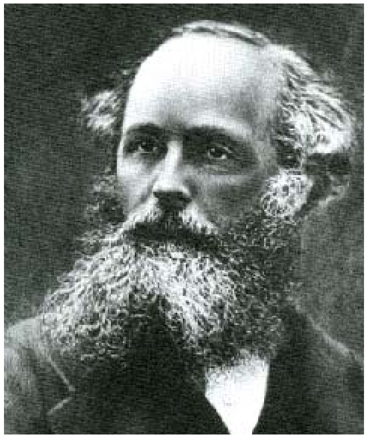
A brief history of optics

17th-century 18th-century 19th-century 20th-century

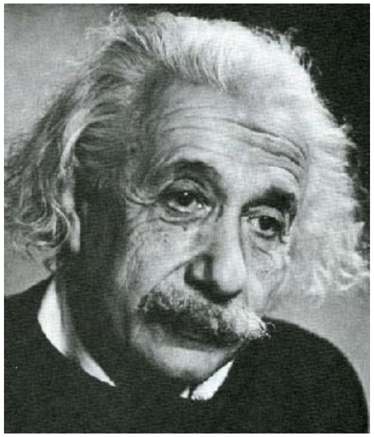
Kepler, Huygens ….

Newton…

Fresnel, Young…



Maxwell Michelson…



Einstein …

Total internal reflection, Telescope, geometrical optics, the wave theory, prism dispersion, the particle theory of light

Interference, diffraction, expressions for reflected and transmitted waves, unified electricity and magnetism

Light is
(1) “a phenomenon of empty space”
(2) both a wave and a particle

The equations of optics

Maxwell's equations

$$\vec{\nabla}\cdot\vec{E}=\rho/\varepsilon \qquad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

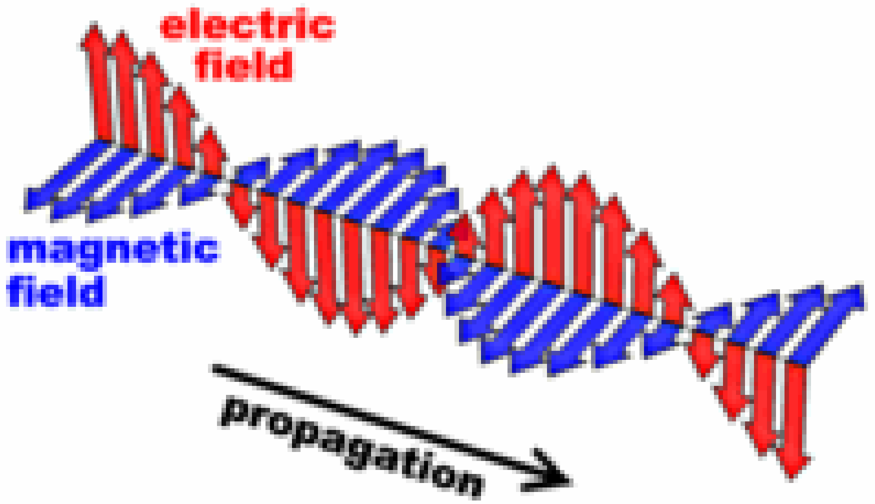
$$\vec{\nabla}\cdot\vec{B}=0 \qquad \vec{\nabla}\times\vec{B}=\mu\varepsilon\frac{\partial\vec{E}}{\partial t}$$

ε is the permittivity,
μ is the permeability of the medium

Solving Maxwell’s equations

$$\nabla^2\vec{E} - \mu\varepsilon\frac{\partial^2\vec{E}}{\partial t^2} = 0 \quad \Rightarrow \quad \vec{E}(\vec{r},t) \propto \cos(\omega t \pm \vec{k}\cdot\vec{r})$$

Light is an Electromagnetic Wave



Wave Properties – Velocity

$$\boxed{\frac{\partial^2 E}{\partial x^2} - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} = 0}$$

Phase velocity

$$\boxed{\frac{\omega}{k} = \mathrm{v} = \frac{1}{\sqrt{\mu\varepsilon}}}$$

Group velocity

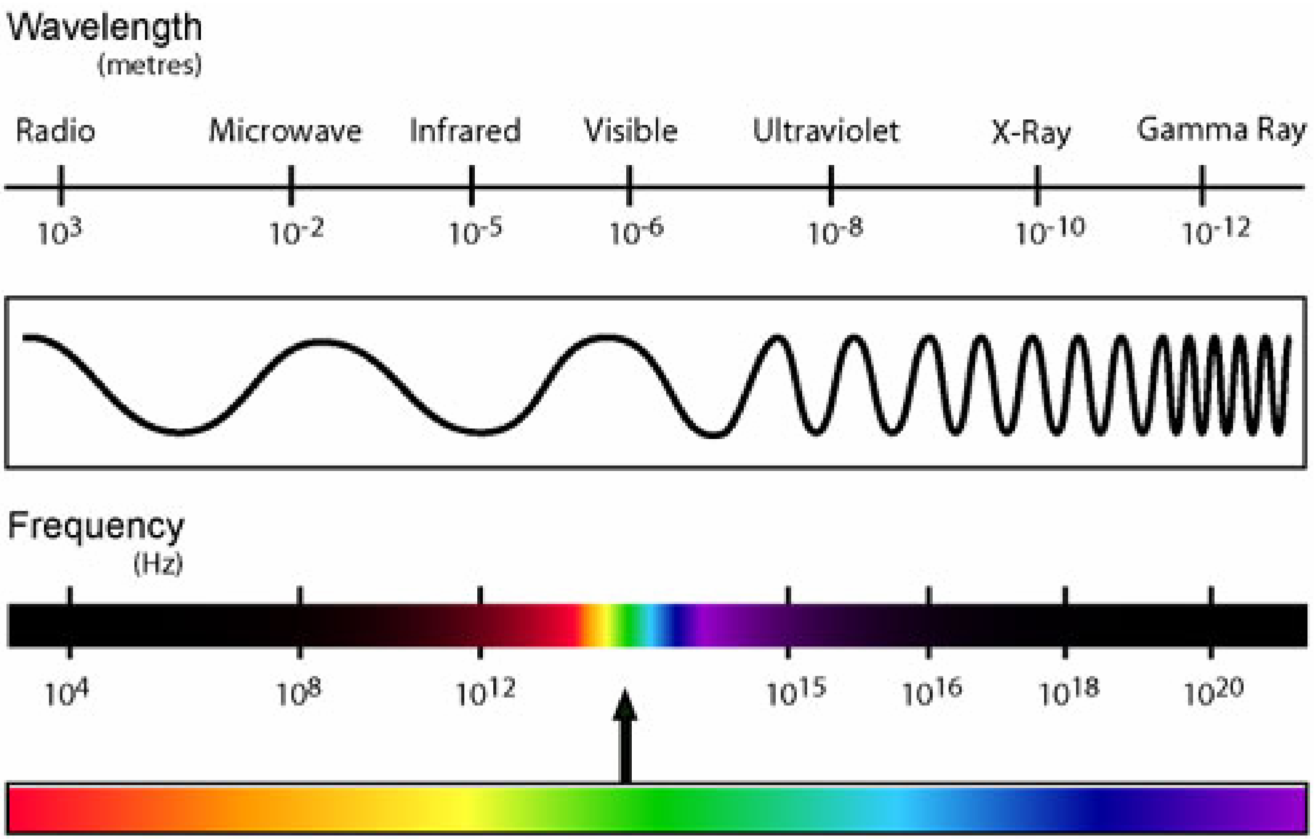
$$\boxed{\mathrm{v}_g \equiv \left[dk / d\omega\right]^{-1}}$$

$$\boxed{\mathrm{v}_g = \mathrm{v}_{phase} / \left(1 + \frac{\omega}{n}\frac{dn}{d\omega}\right)}$$

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions
1858 150 2008
IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Wave Properties – Spectrum



1 THz = 300 μm = 33 cm^{-1} = 4.1 meV

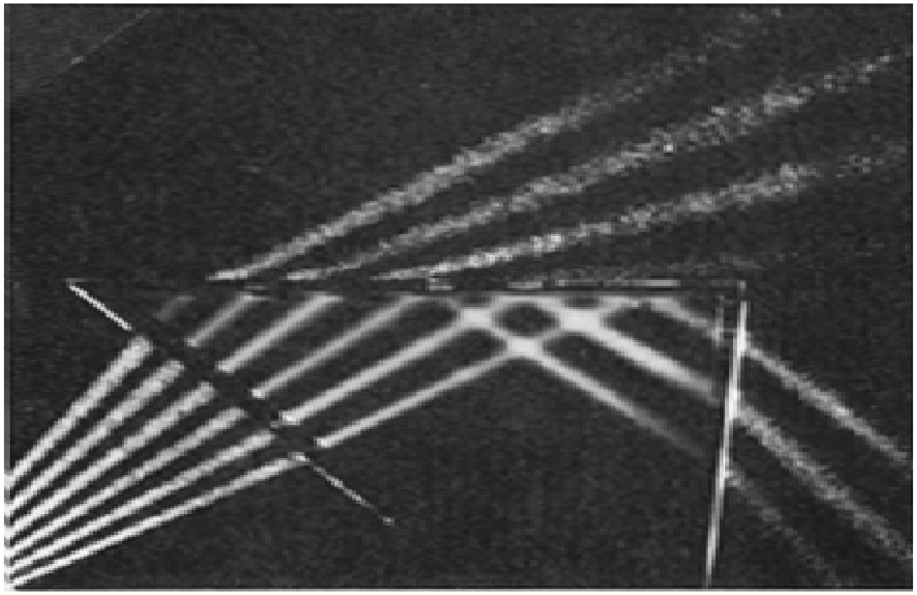
AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions

IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

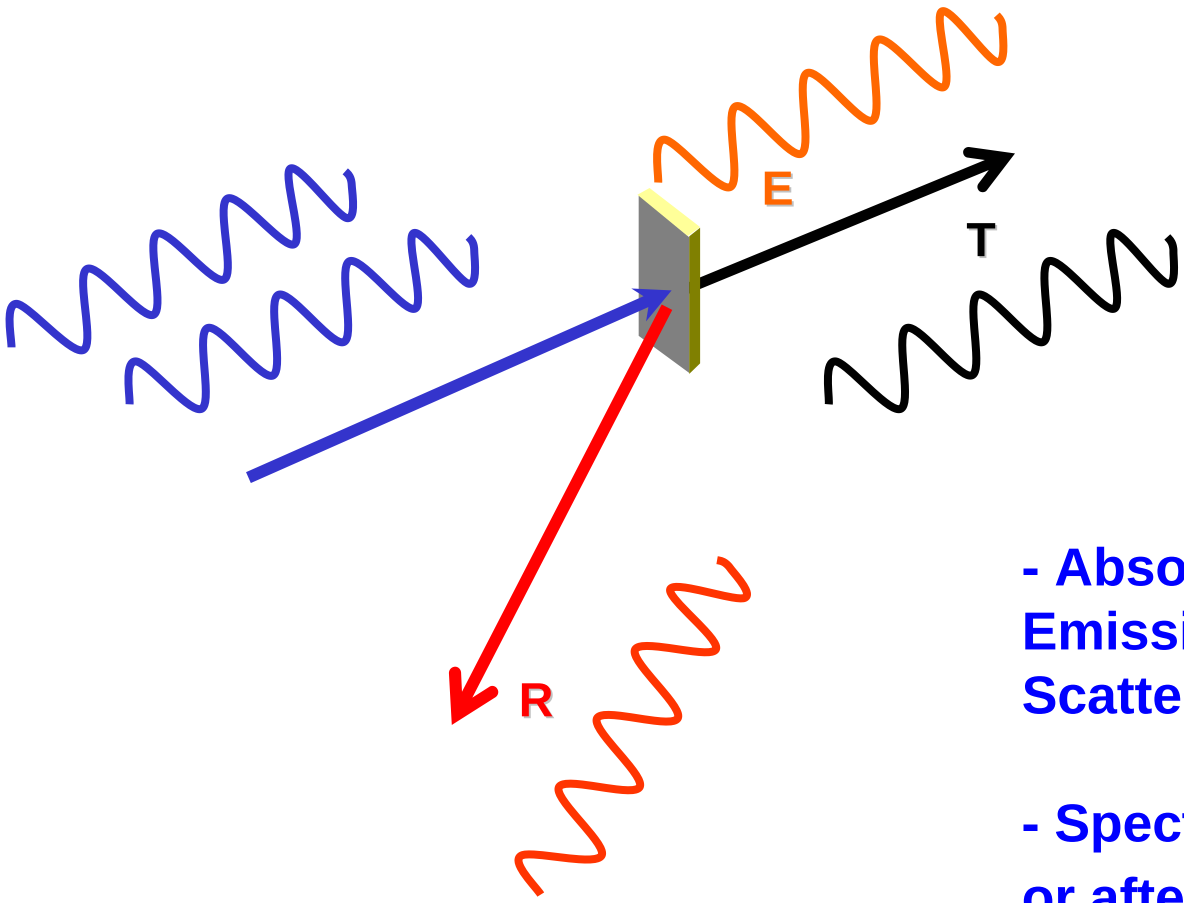
Refraction

At an oblique angle, light can be completely transmitted or completely reflected.



"Total internal reflection" is the basis of optical fibers, a billion dollar industry.

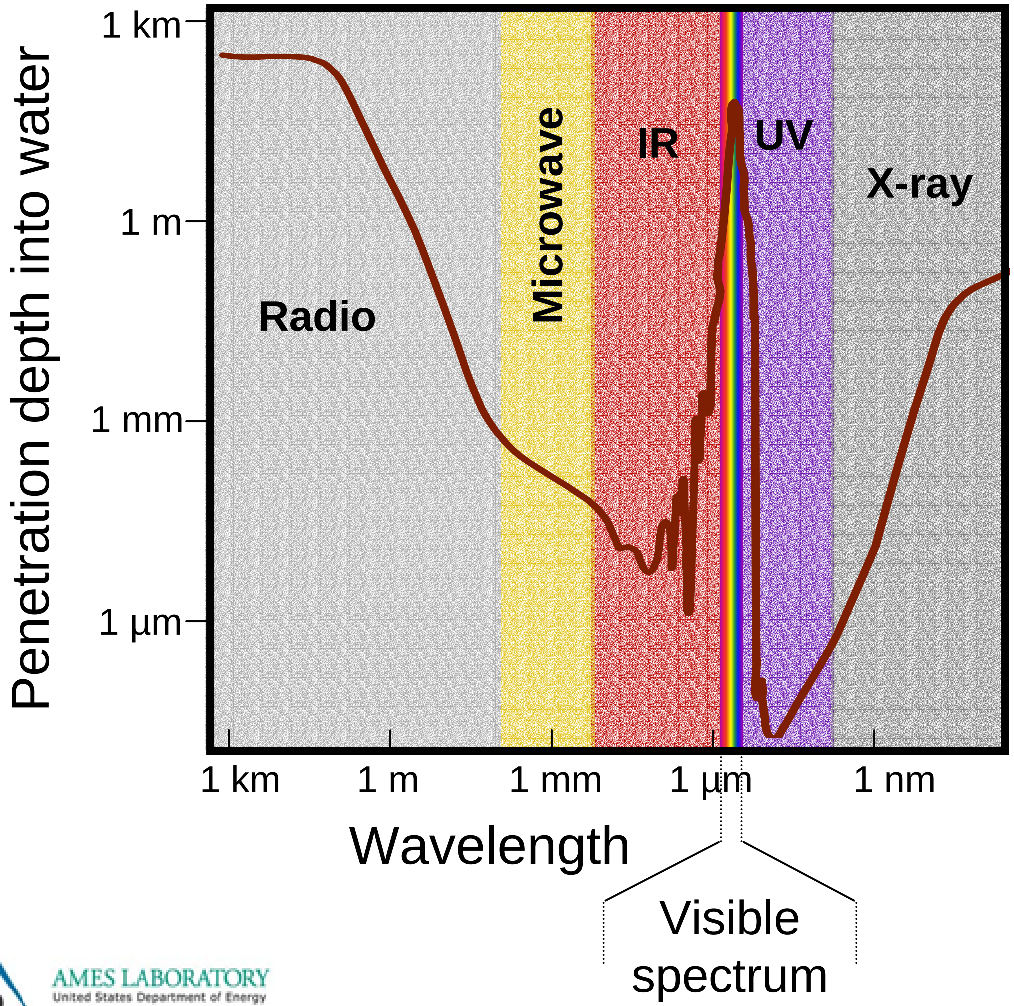
Conventional Spectroscopy Methods



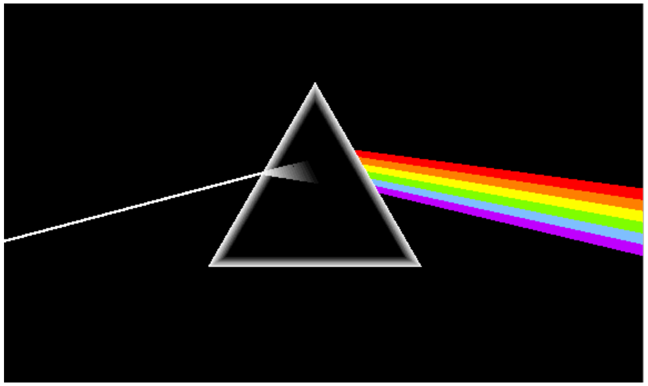
- Absorption, Reflection, Emission, Interference, Scattering
- Spectrally resolved before or after sample

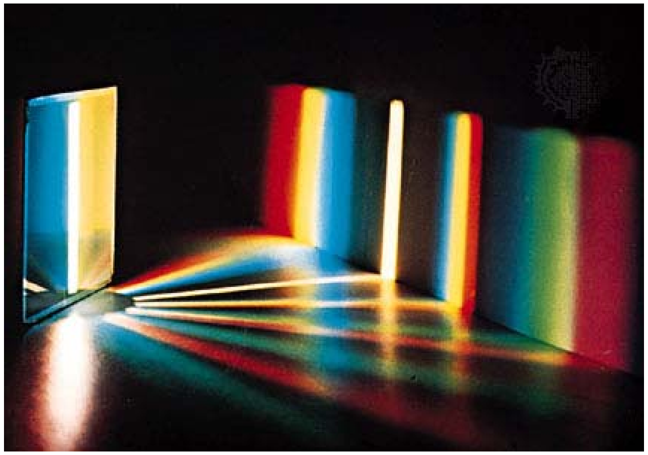
Absorption Spectroscopy

Penetration depth into water vs. wavelength

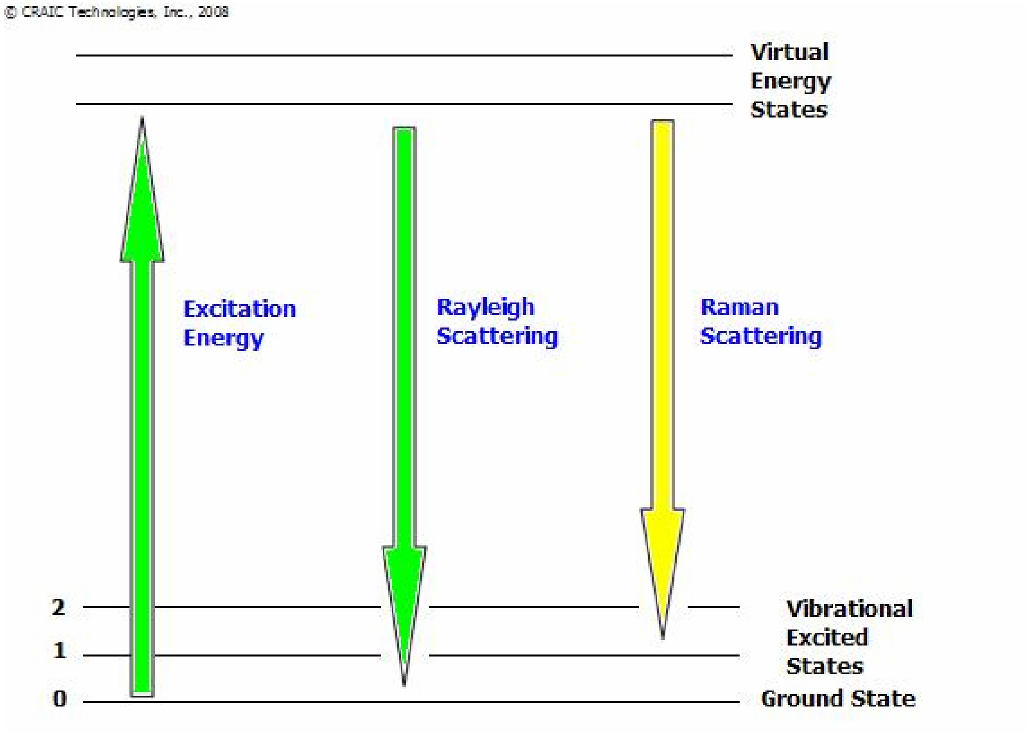


Dispersion elements





Scattering Spectroscopy


© CRAIC Technologies, Inc., 2008

Virtual Energy States

Excitation Energy

Rayleigh Scattering

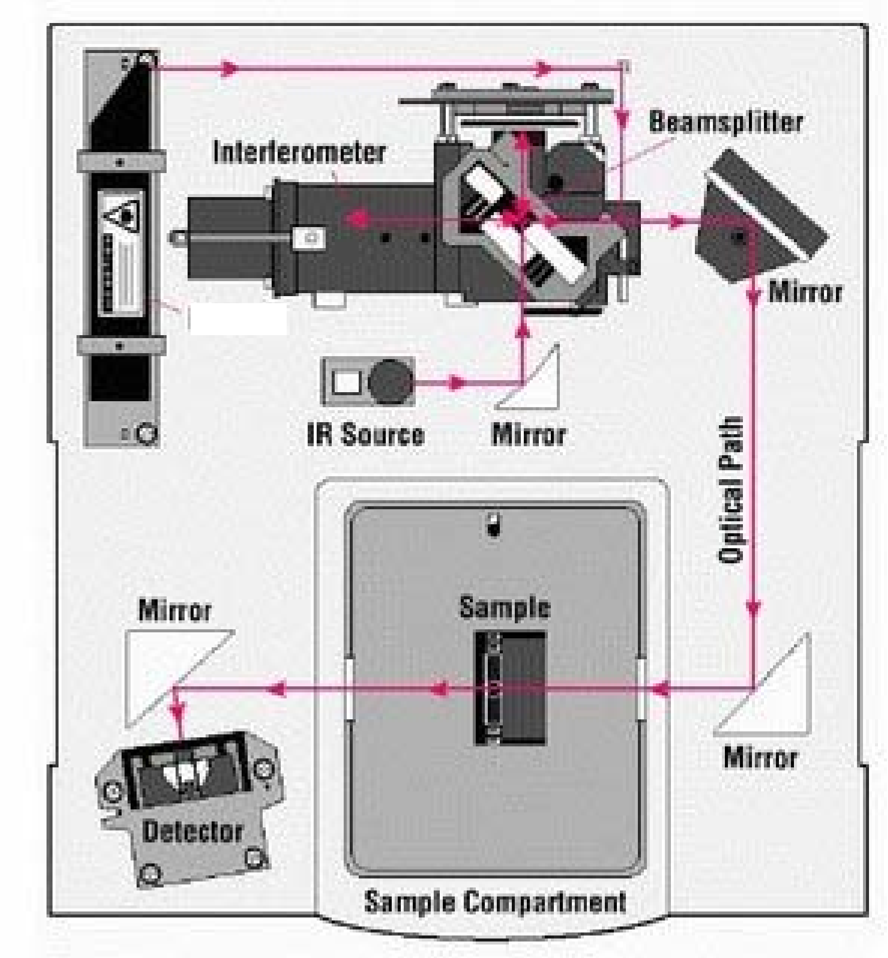
Raman Scattering

Vibrational Excited States

Ground State

$$I_{Raman} \propto \lambda^{-4}$$

Fourier Transform Infrared (FTIR) Spectrometer



White light *Interference*

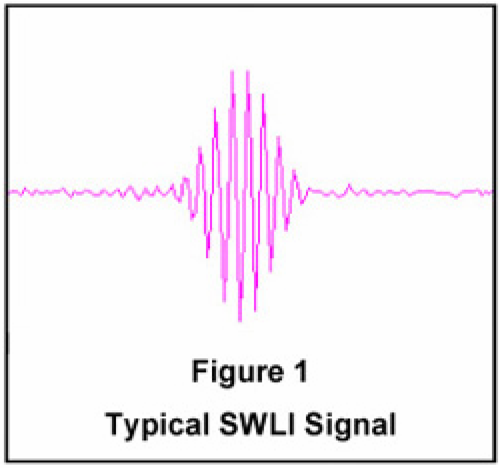


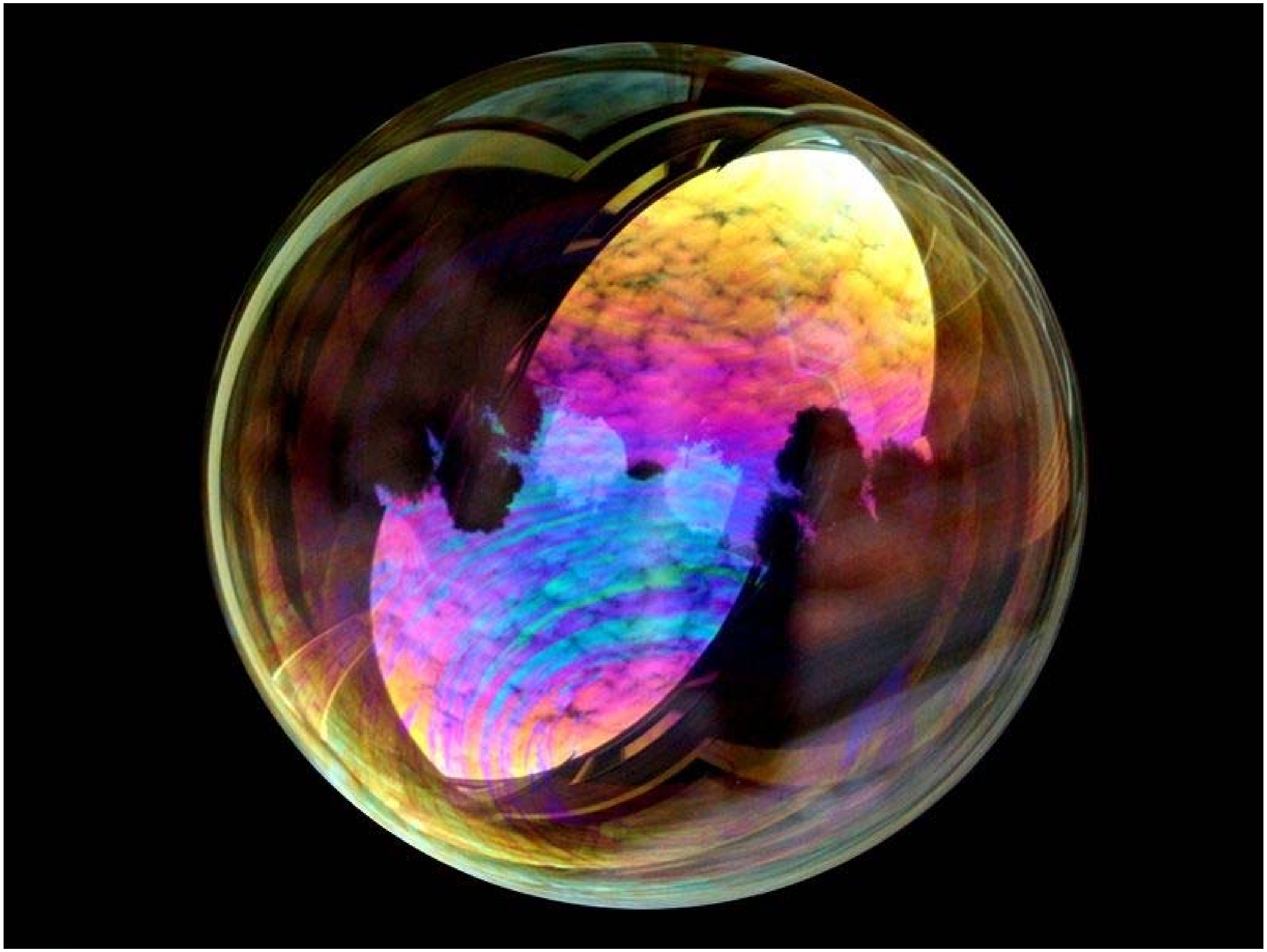
Figure 1

Typical SWLI Signal

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

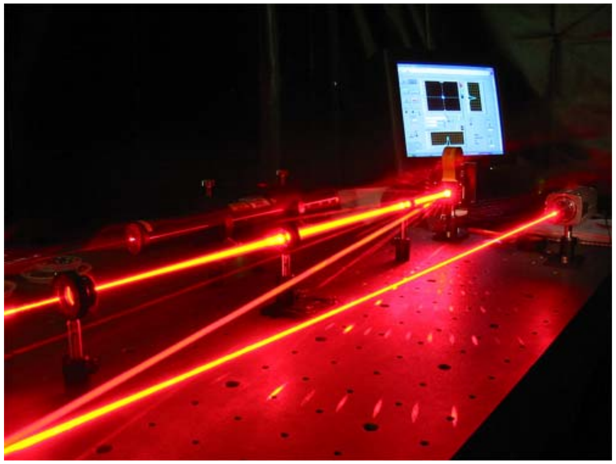
Nature can do similar tricks by itself

Nature knows interference

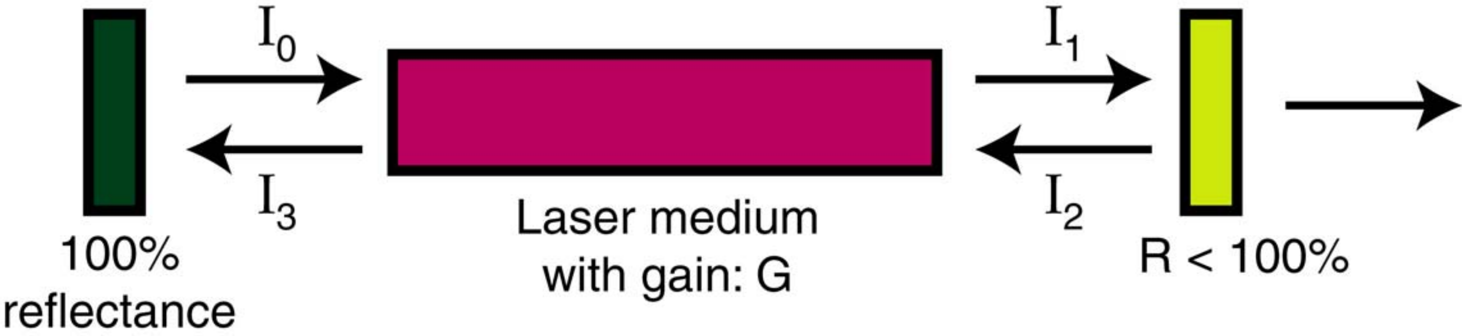


Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

The amazing light – Laser



Light amplification of stimulated emission of radiation (Laser)



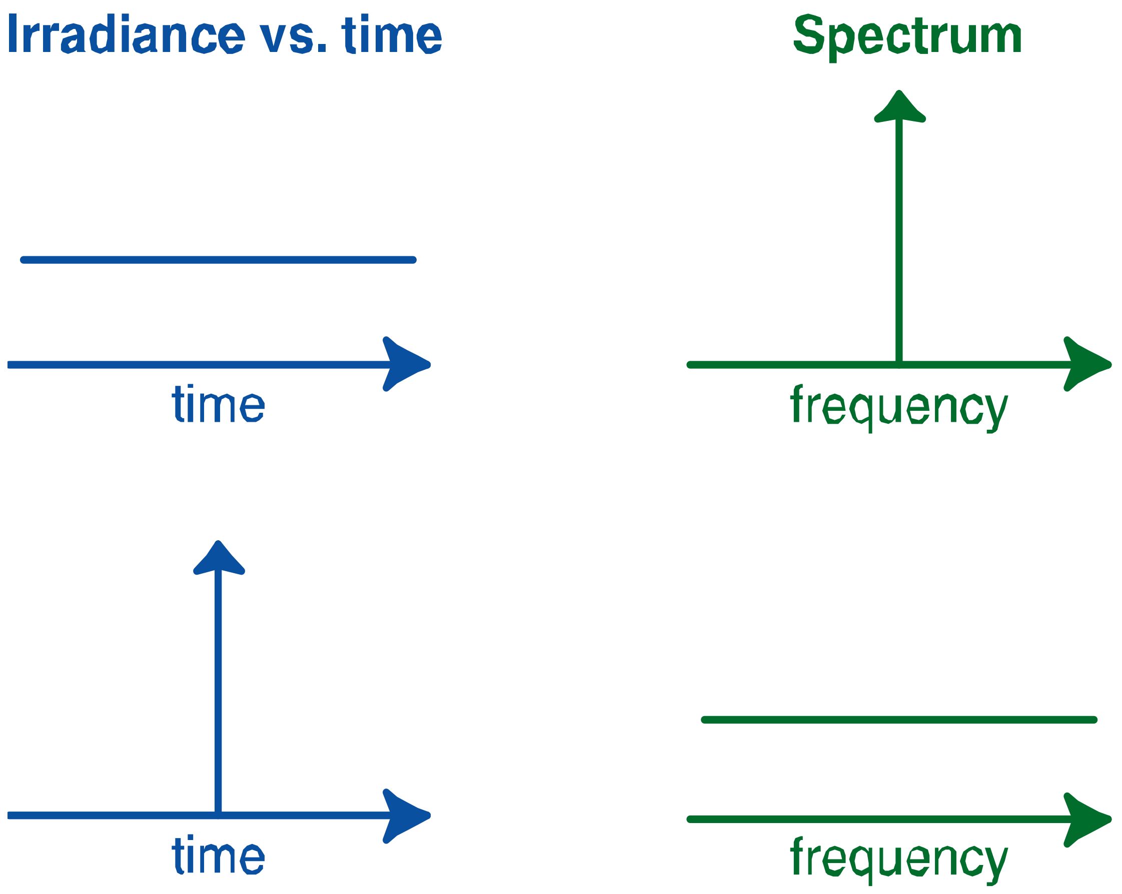
A laser will lase if the beam increases in irradiance during a round trip: that is, if $I_3 > I_0$.

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Continuous vs. ultrashort pulses of laser

Continuous beam:

Ultrashort pulse:

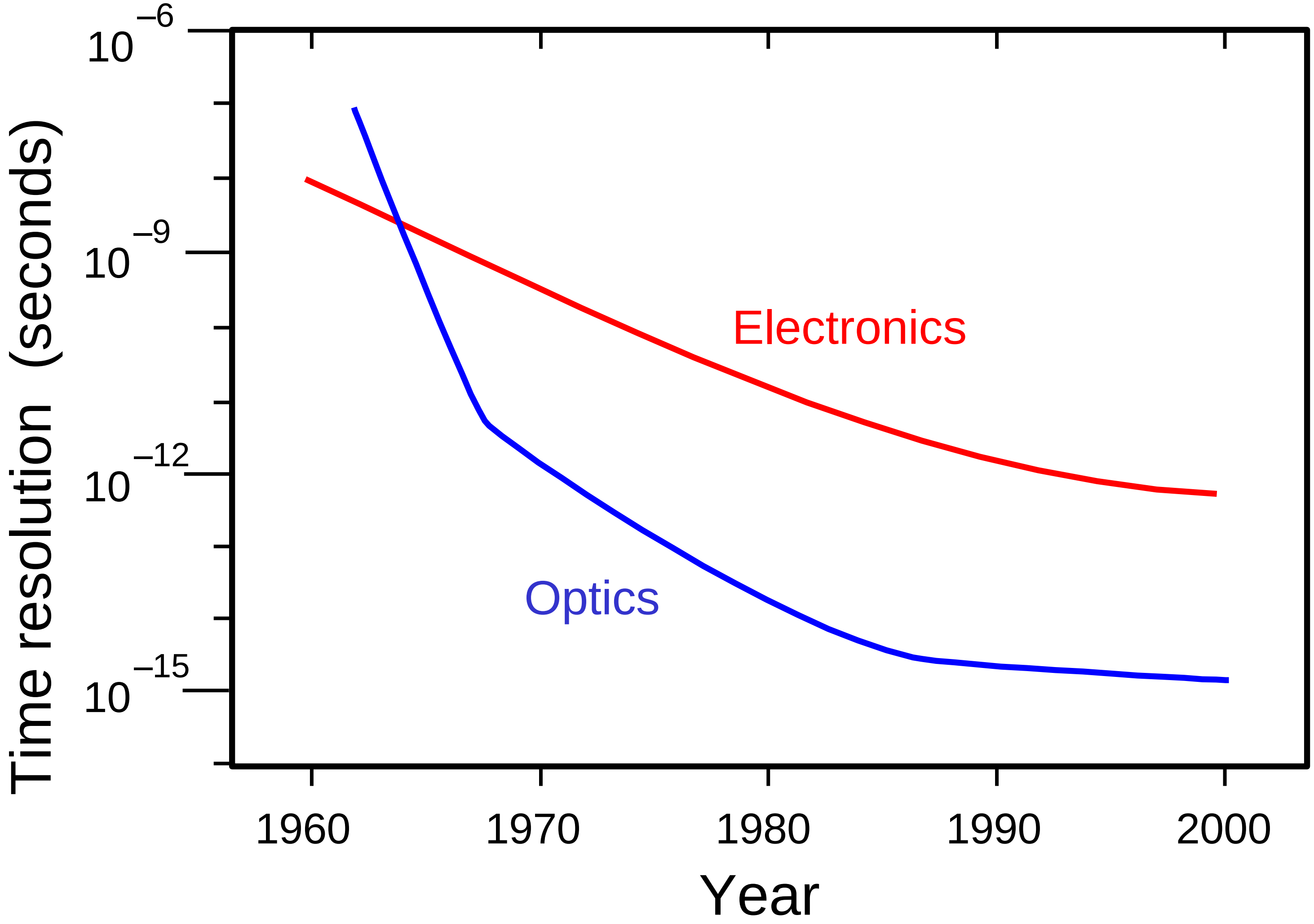


Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

How fast is Ultra-fast?

milli	10^{-3}
micro	10^{-6}
nano	10^{-9}
pico	10^{-12}
femto	10^{-15}
atto	10^{-18}

The evolution of pulse Lasers



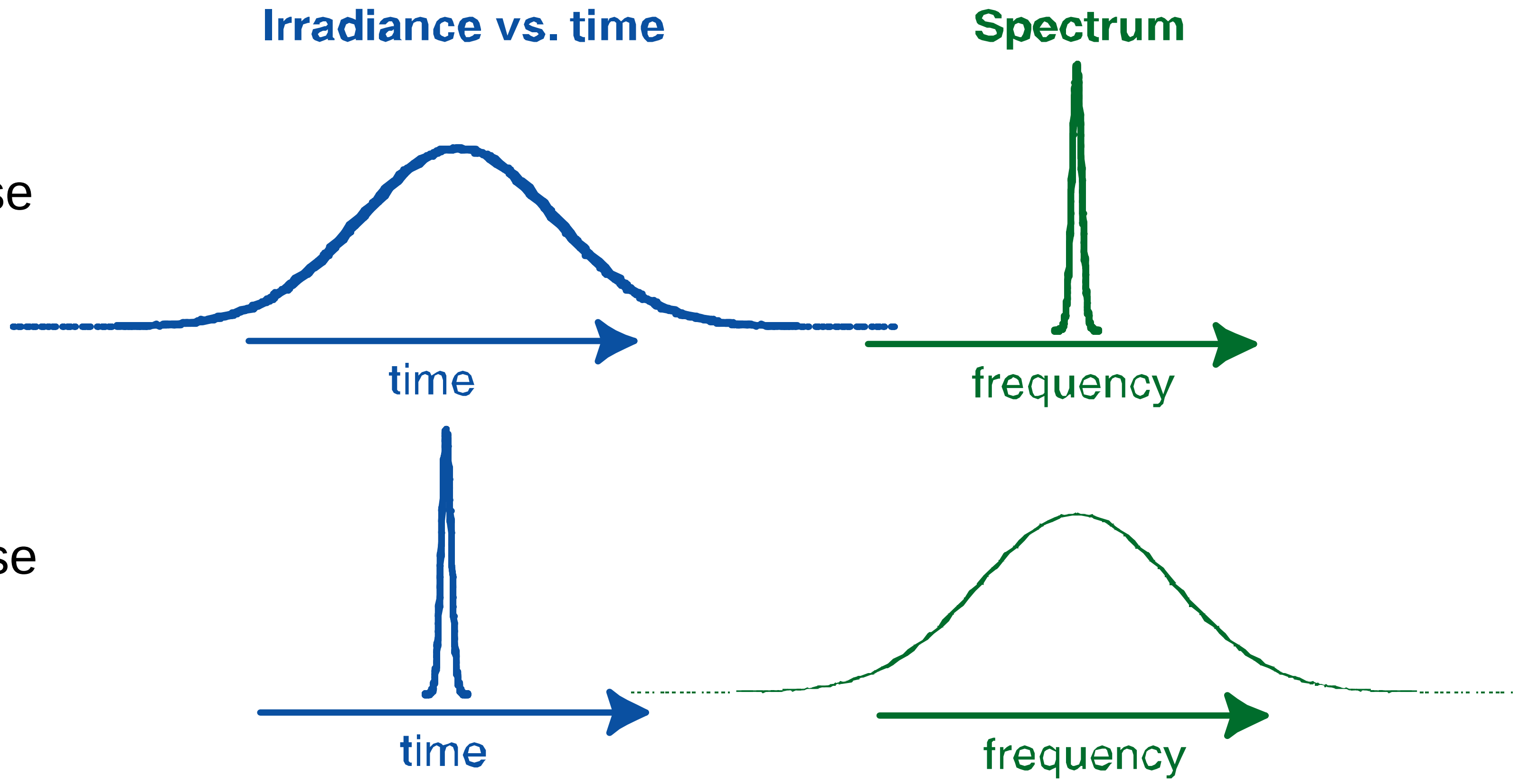
Courtesy of Trebino

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Long vs. short pulses of laser

Long pulse

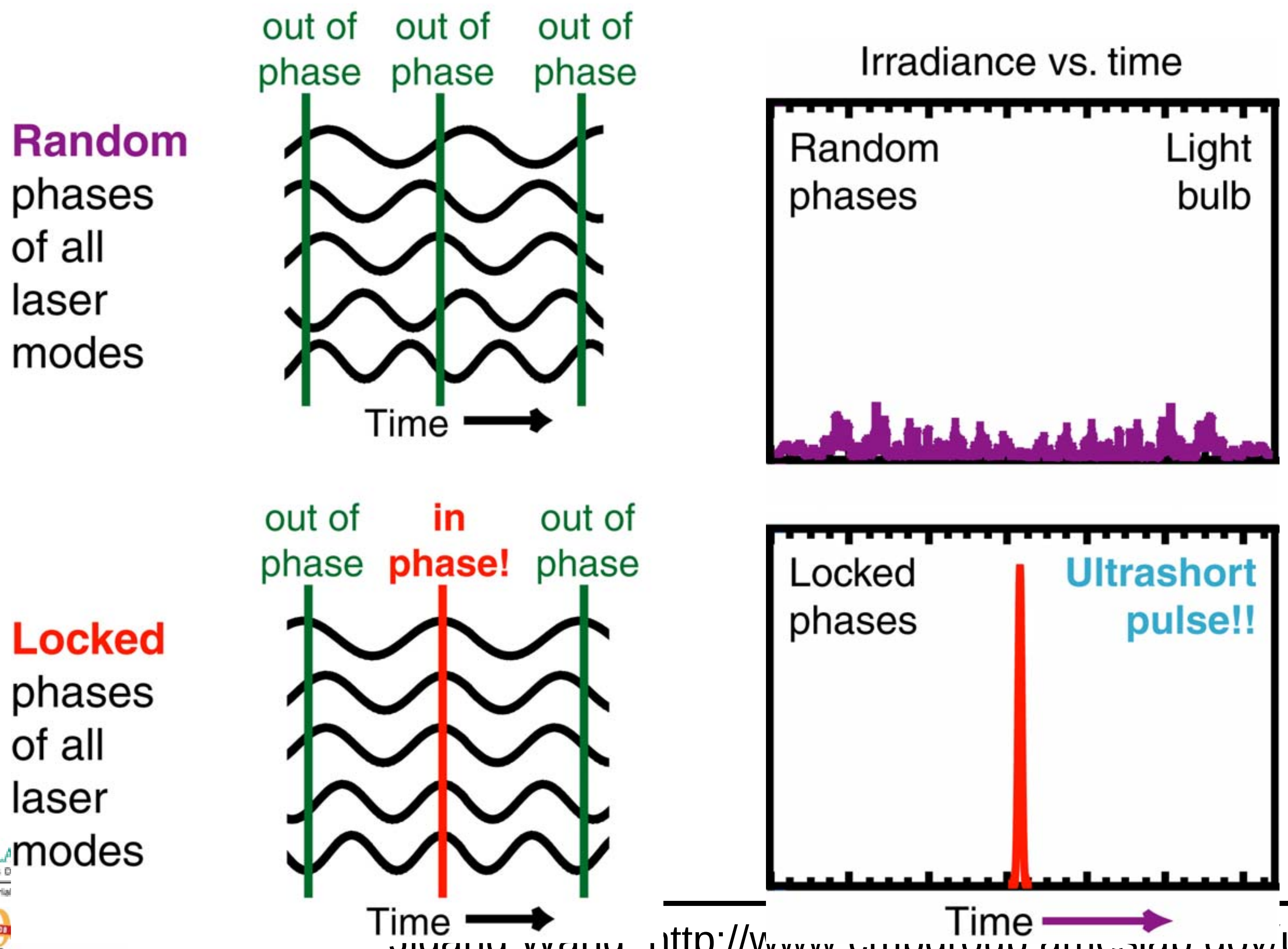
Short pulse



Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Generating short pulses = “mode-locking”

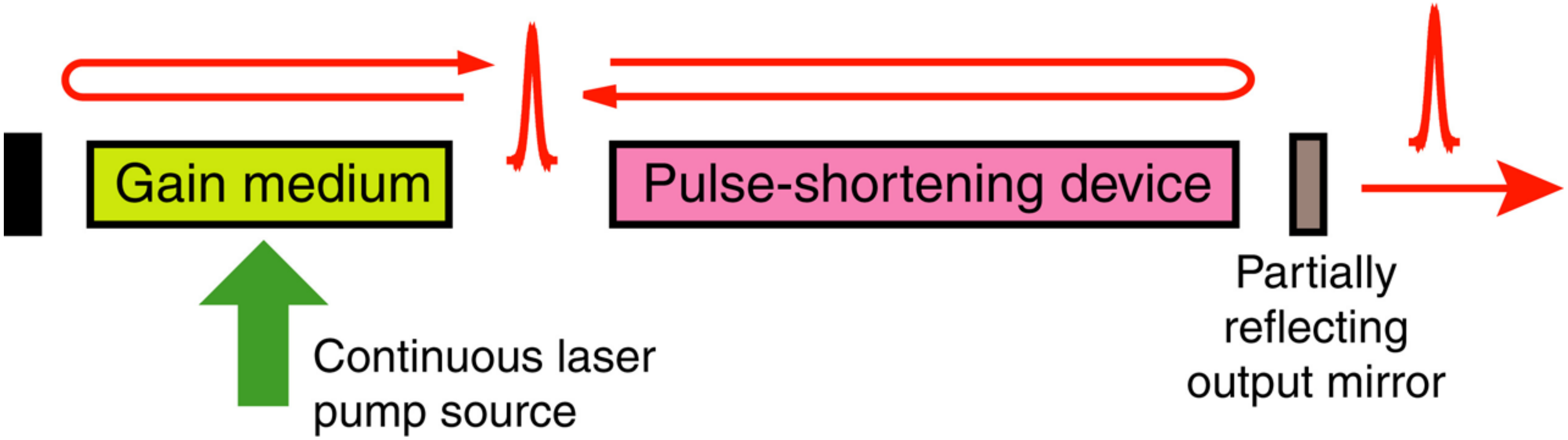
Locking the phases of the laser frequencies yields an ultrashort pulse.



Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

A generic ultrashort-pulse laser

A generic ultrafast laser has a broadband gain medium,a pulse-shortening device, and two or more mirrors:

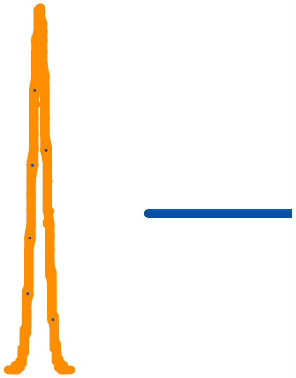


Pulse-shortening devices include:

- Saturable absorbers
- Phase modulators
- Dispersion compensators
- Optical-Kerr media

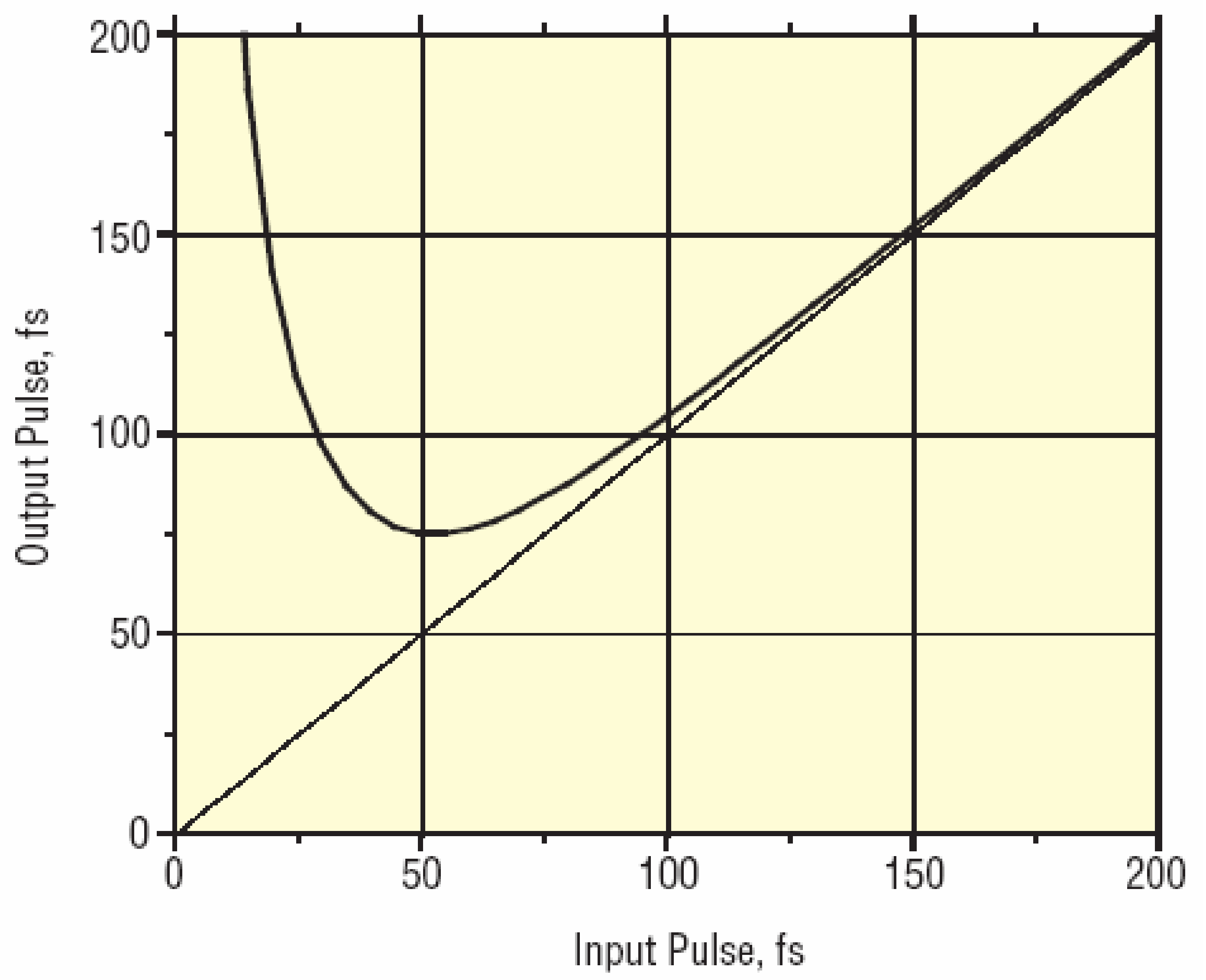
Ultrashort laser pulse broadening

Different fquenc
causing pulses



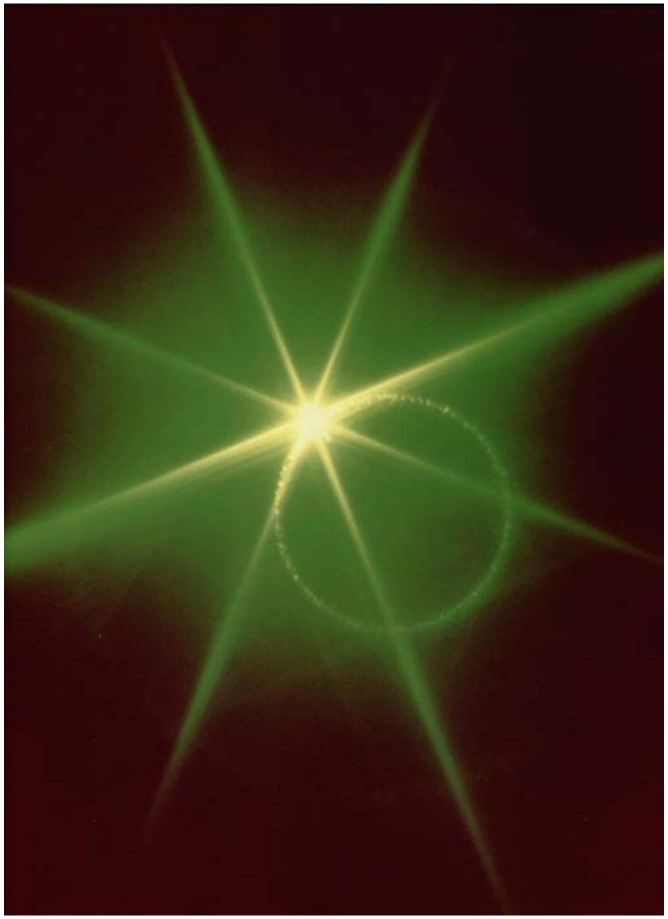
Input

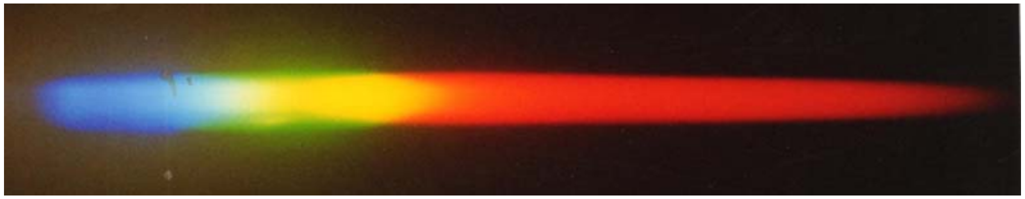
Input
ultrashort
pulse

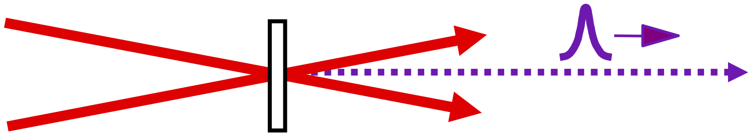


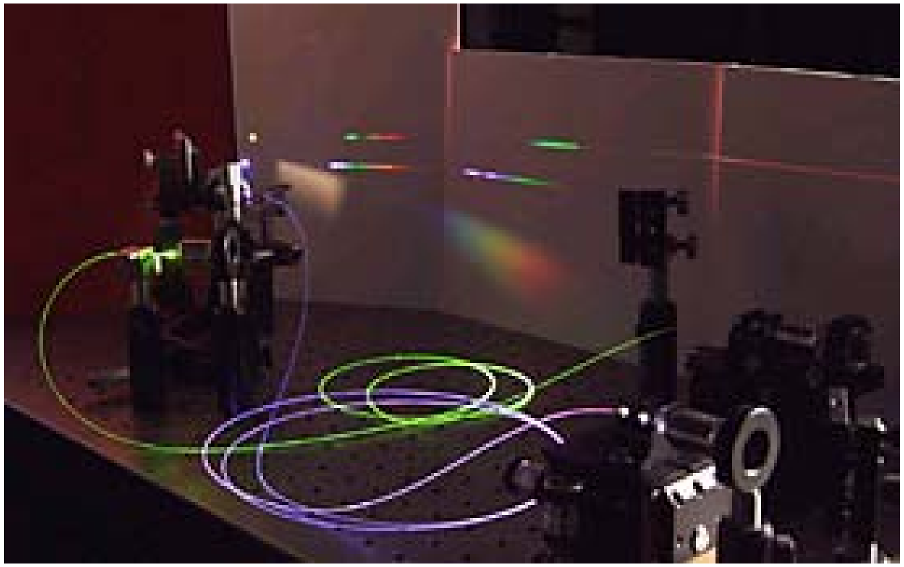
Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Ultrafast Optics is Nonlinear Optics







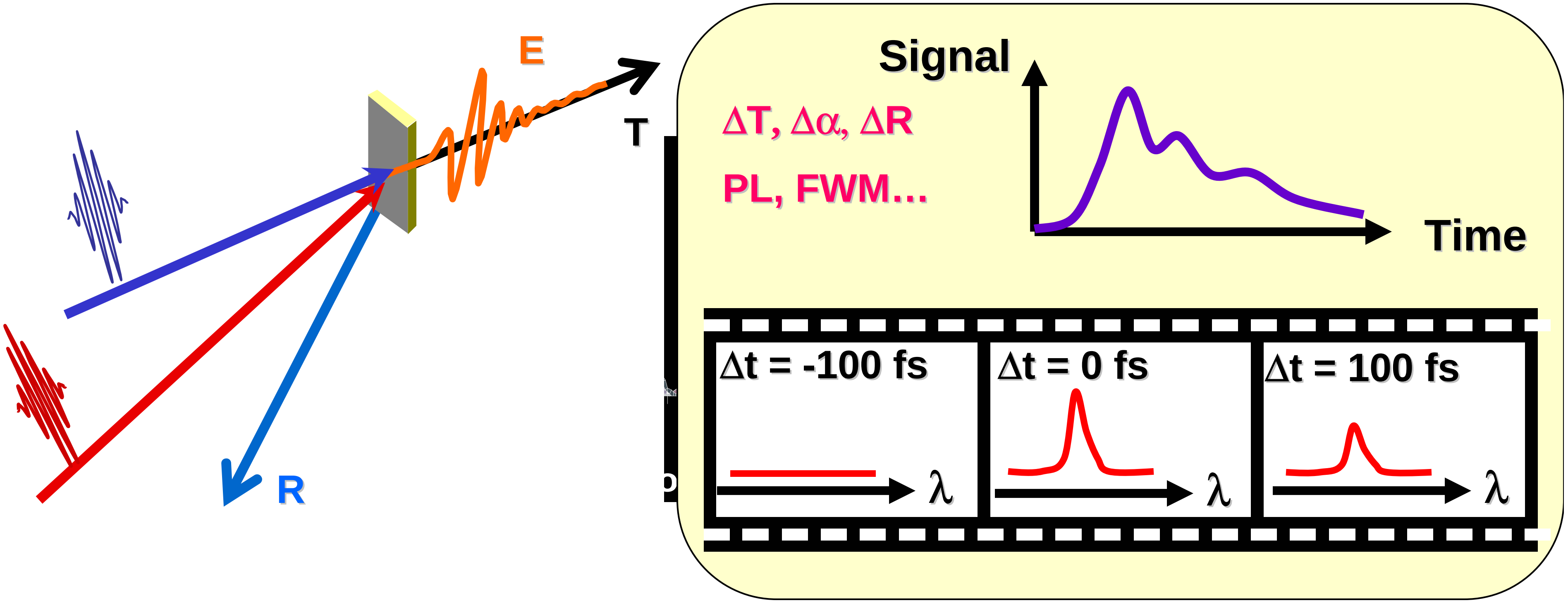


AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions

1858 150 2008
IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Ultrashort & Ultrabroadband



Signals -> M, p, σ, $\chi^{(2)}$, $\chi^{(3)}$ ...

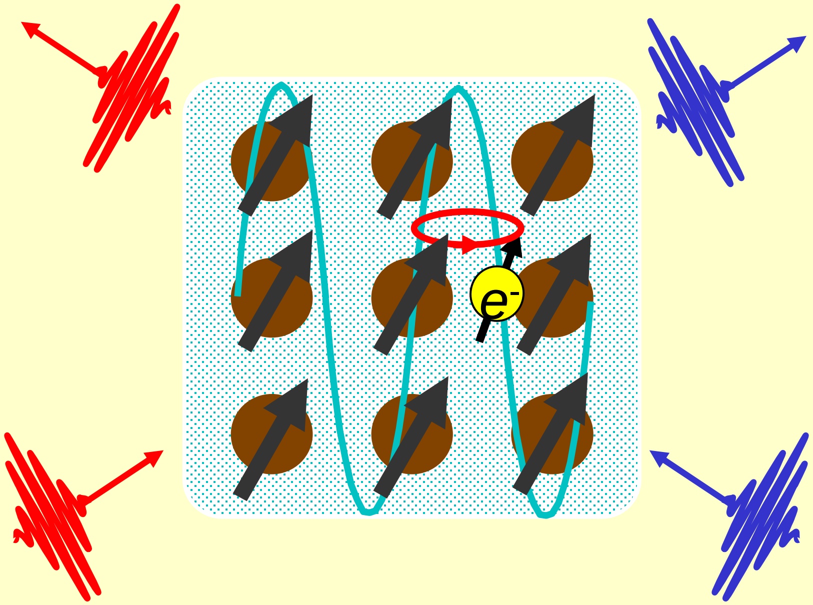
Simultaneous high temporal and spectral resolution

Strategic advantages

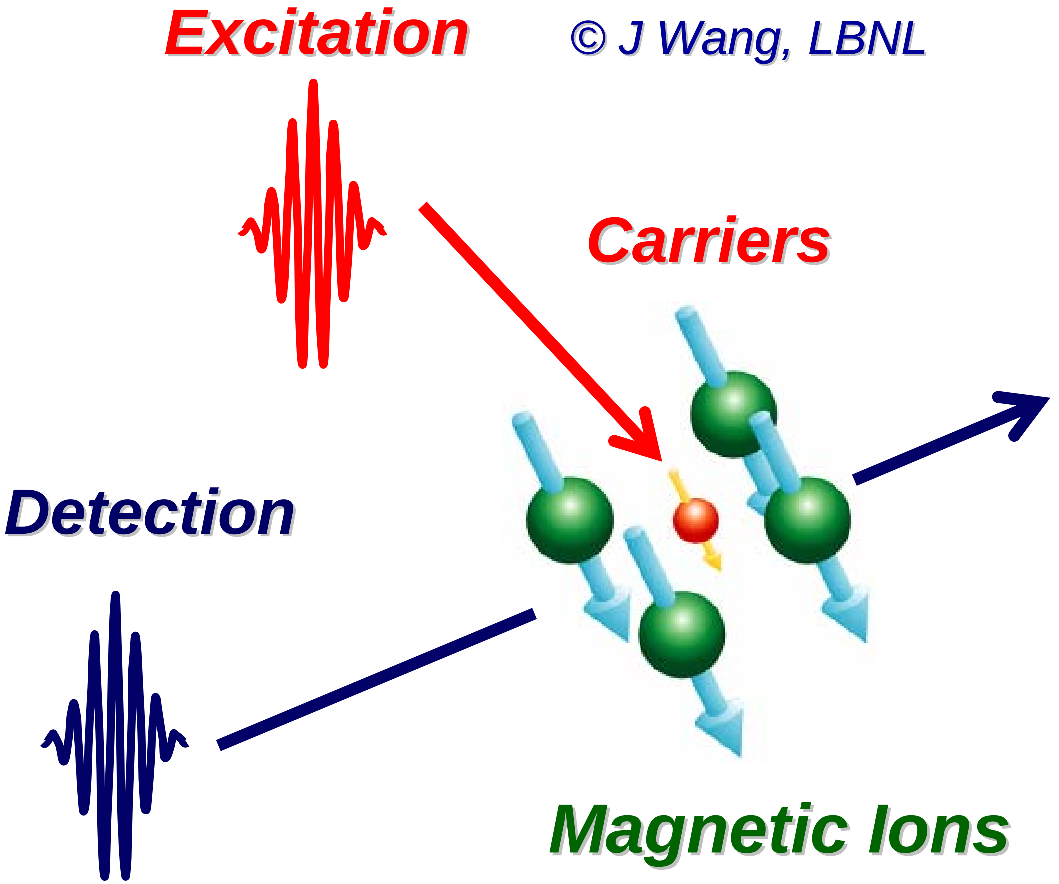
Ultrafast

Ultrabroadband

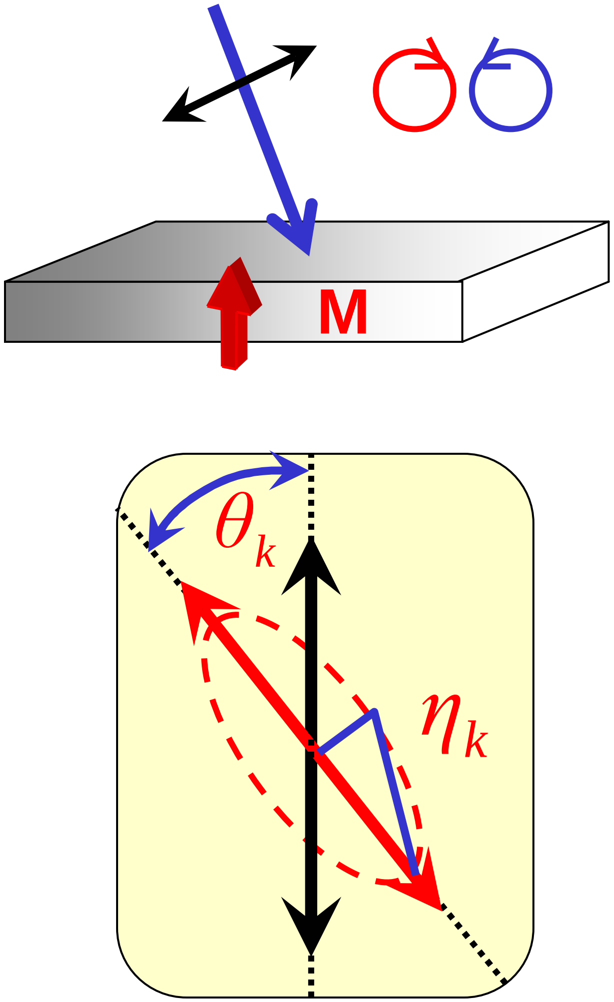
Manipulation



Ultrafast Magneto-optical Spectroscopy



© J Wang, LBNL

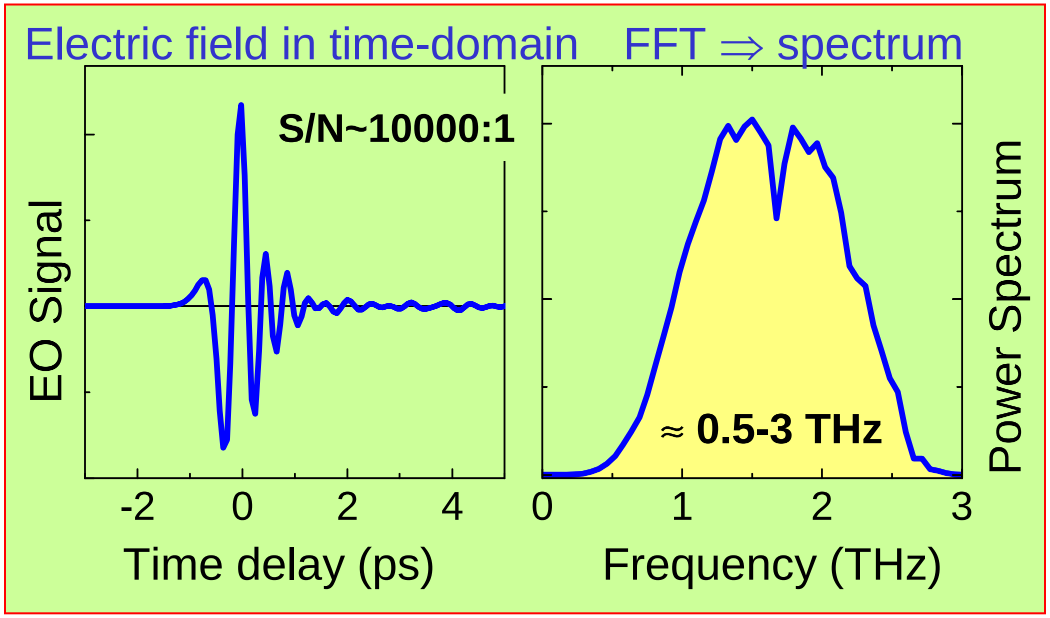


Tunable pump-probe from MIR, NIR to visible

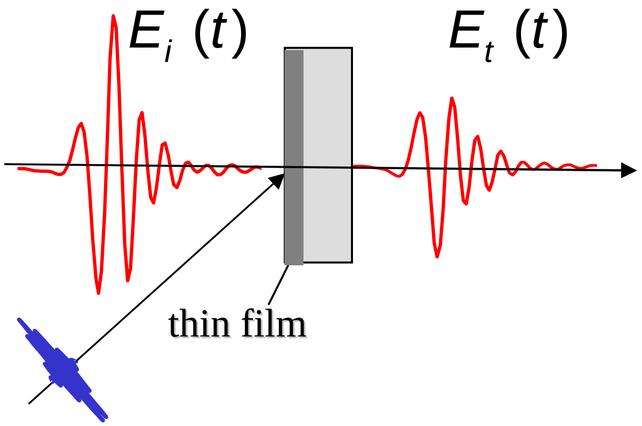
Highly sensitive to time reversal symmetry breaking

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions
1858 150 2008
IOWA STATE UNIVERSITY

Ultrafast THz Spectroscopy



Field-resolved Detection



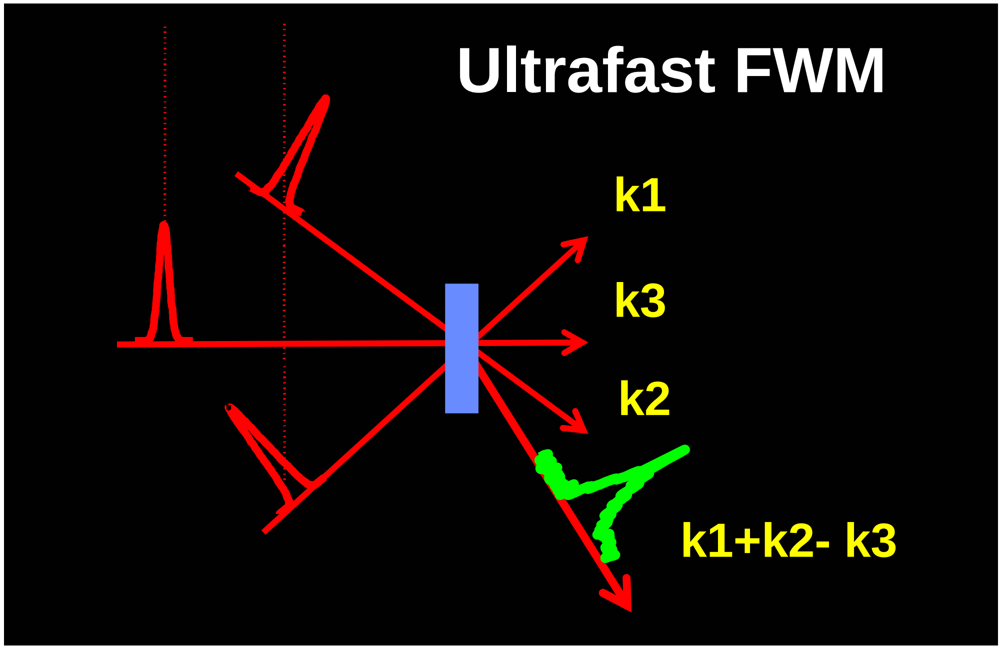
Complex transmission coefficient

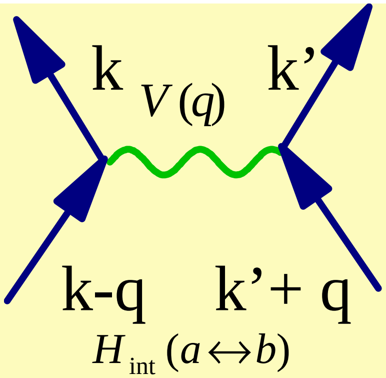
$$t(\omega) \equiv \frac{E_{OUT}(\omega)}{E_{IN}(\omega)} \approx \frac{2}{1+n_S + d\,Z_0\,\sigma(\omega)}$$

Amplitude *and* Phase information

➔ Real & Imaginary Part of σ(ω), ε(ω)

Coherent Transient Spectroscopy



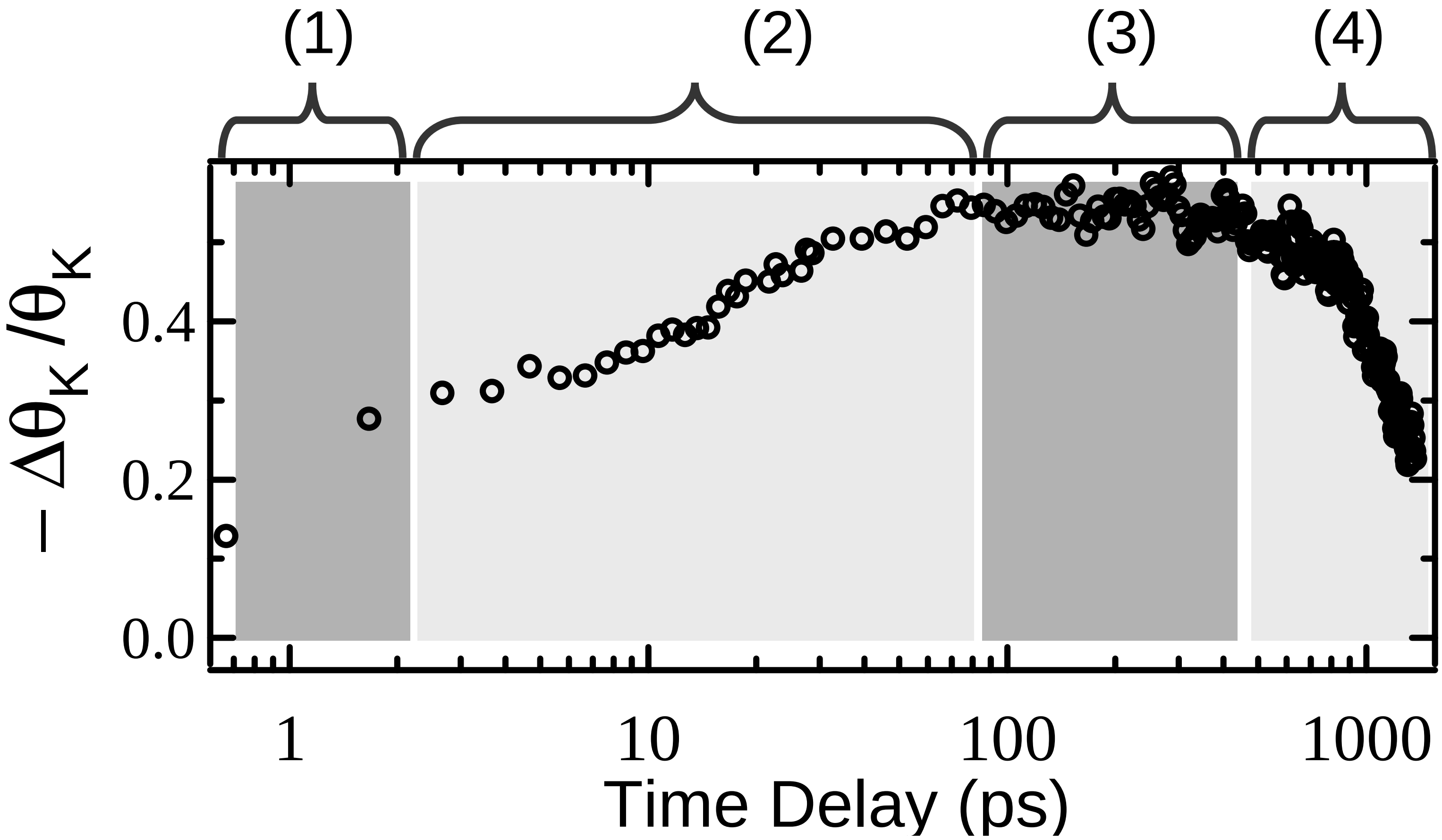


'Residual' coulomb interactions
→ the dynamics between quasiparticles

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions
1858 150 2008
IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Ultrafast demagnetization

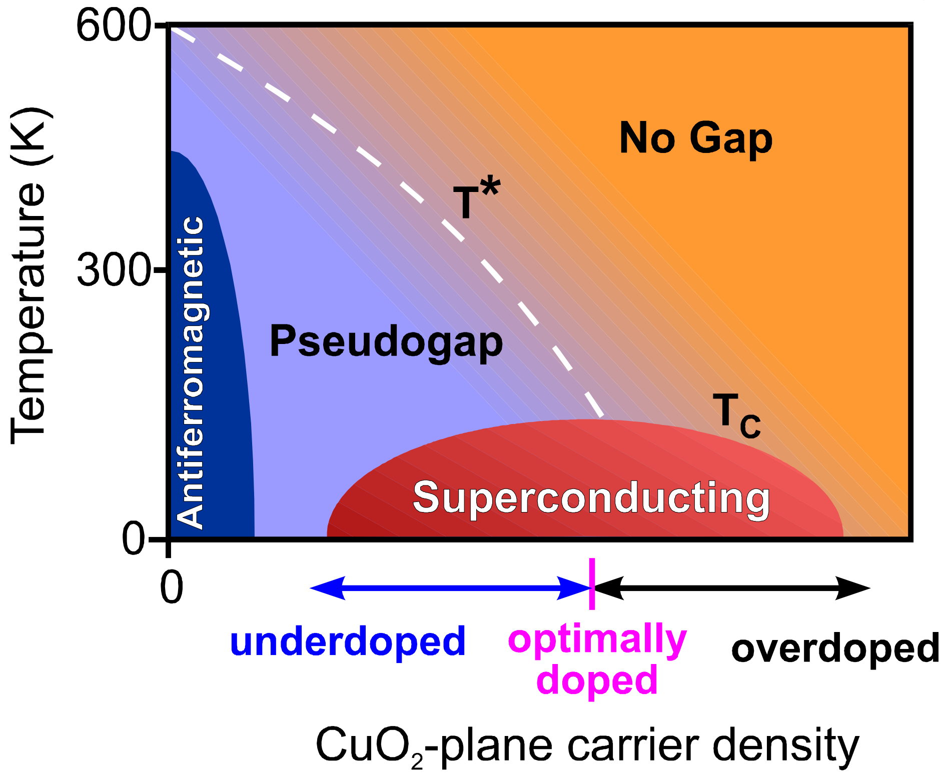


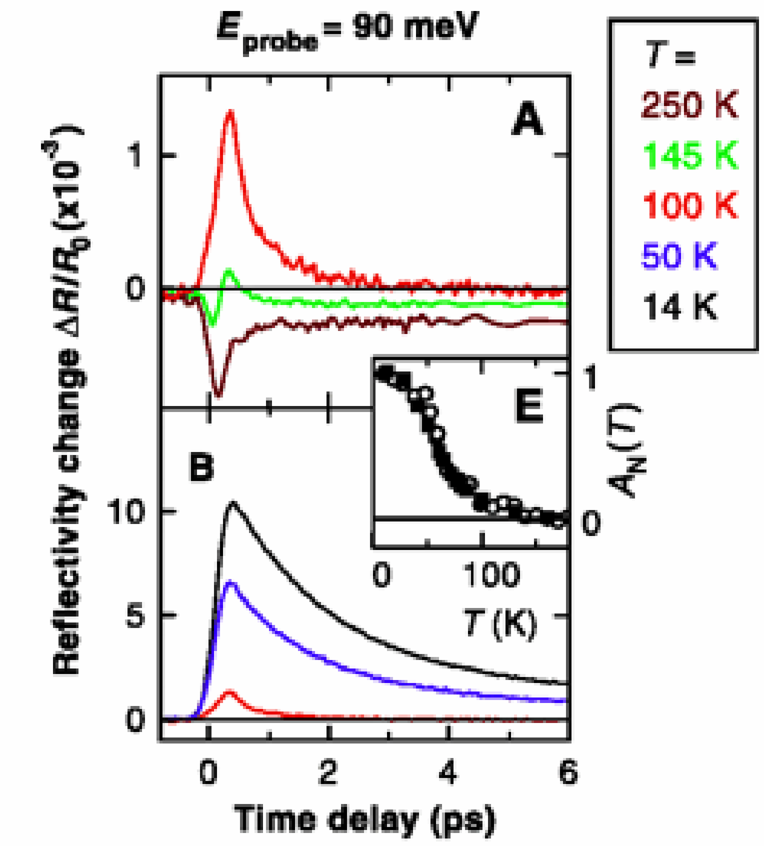
AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions
1858 150 2008
IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Ultrafast spectroscopy of HTc superconductor

Cuprate SC: Generic Phase Diagram

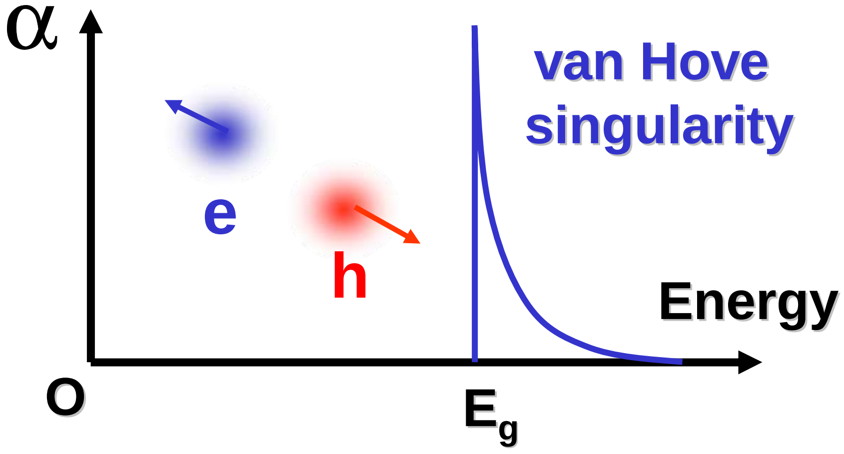




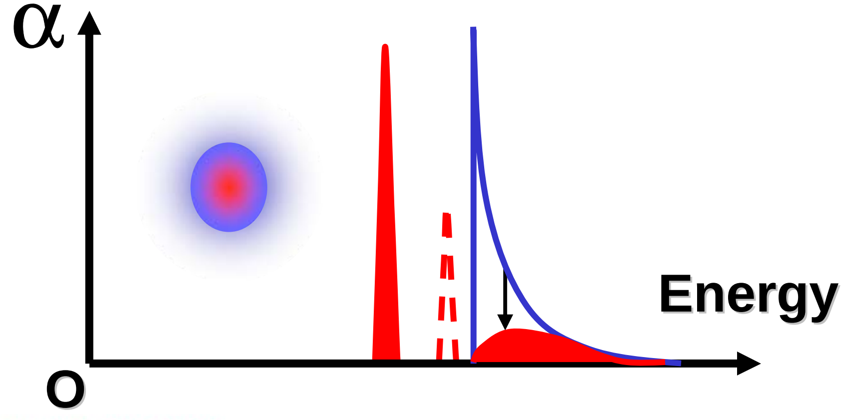
R. A Kaindl et al., Science, 287, 470 (2000)

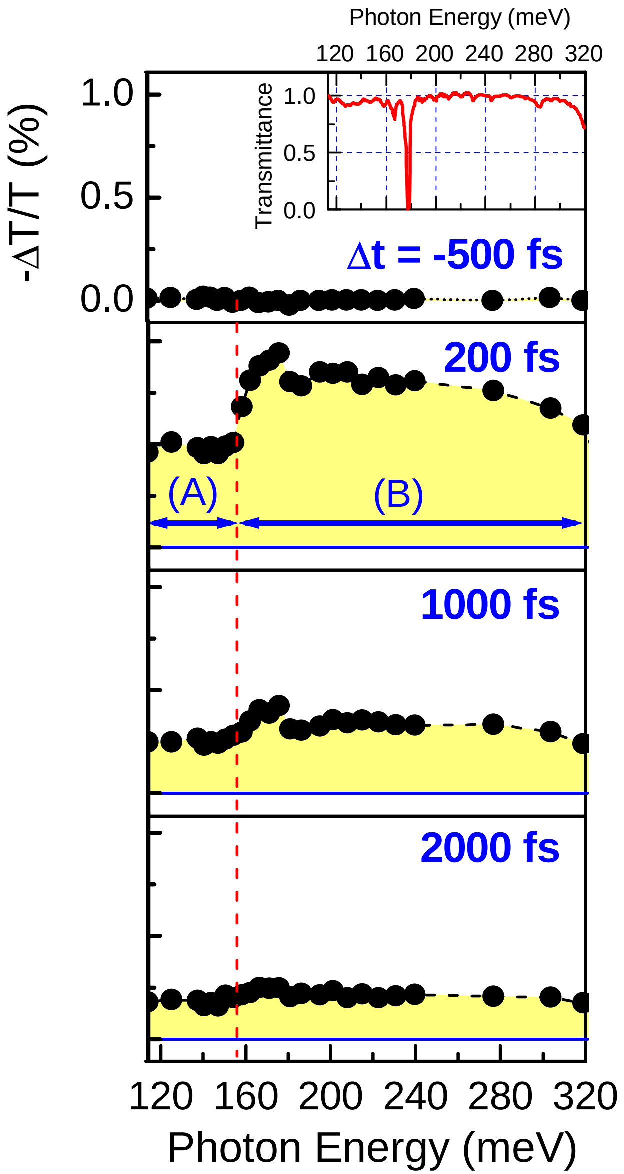
Many-body Effects in SWCN

1D Band picture



1D Exciton picture





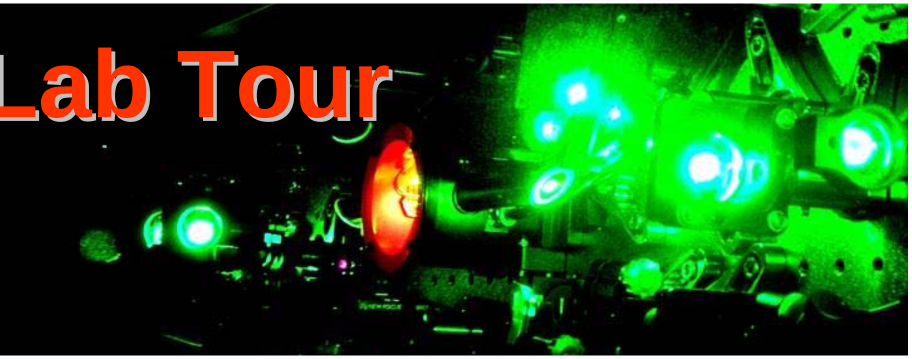
AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions

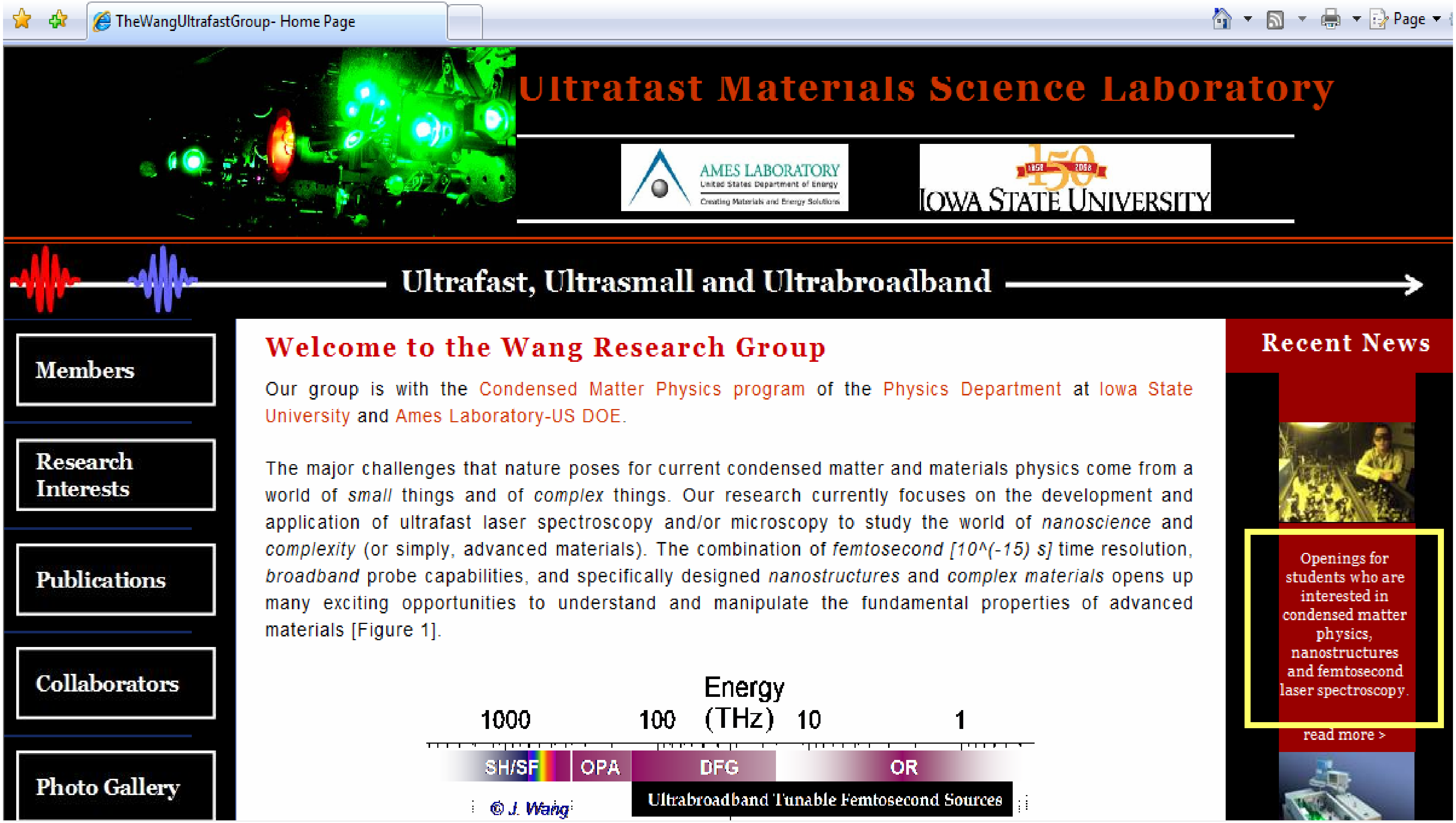
1858 150 2008
IOWA STATE UNIVERSITY

Jigang Wang, http://www.cmpgroup.ameslab.gov/ultrafast/

Ultrafast Laser Lab Tour

www.cmpgroup.ameslab.gov/ultrafast/





Welcome to the Wang Research Group

Our group is with the Condensed Matter Physics program of the Physics Department at Iowa State University and Ames Laboratory-US DOE.

The major challenges that nature poses for current condensed matter and materials physics come from a world of *small* things and of *complex* things. Our research currently focuses on the development and application of ultrafast laser spectroscopy and/or microscopy to study the world of *nanoscience* and *complexity* (or simply, advanced materials). The combination of *femtosecond [10^(-15) s]* time resolution, *broadband* probe capabilities, and specifically designed *nanostructures* and *complex materials* opens up many exciting opportunities to understand and manipulate the fundamental properties of advanced materials [Figure 1].

Openings for students who are interested in condensed matter physics, nanostructures and femtosecond laser spectroscopy.

read more >