Ultra-Slow (and Superluminal) Light Propagation in Room Temperature Solids

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Tuesday Evening

20:50  **Daniel J. Gauthier**, Duke University
The information velocity in fast- and slow-light media

21:10  **Lijun Wang**, NEC
Quantum fluctuation, causality, and Abraham force

21:30  **George R. Welch**, Texas A&M University
Buffer-gas induced absorption resonances and large negative pulse delay times in Rb vapor

21:50  **Andrey Matsko**, Jet Propulsion Laboratory
EIT in resonator chains: similarities and differences with atomic media

Wednesday Morning

8:40  **Kurt E. Oughstun**, University of Vermont
Accuracy of the Group Velocity Description and the Question of Superluminal Pulse Velocities

9:00  **Dmitry Strekalov**, Jet Propulsion Laboratory
Influence of inhomogeneous broadening on group velocity in coherently pumped atomic vapor

9:20  **Vladimir M. Shalaev**, Purdue University
Plasmonic Nanoantennae for Manipulating Light, Sensing Molecules, and Nanomanufacturing

9:50  **John Howell**, University of Rochester
Pixel entanglement: position-momentum quantum information processing
Fig. 6 Coordinates of two inertial observers A (0, 0) and B with O(x, t) and O'(x', t') moving with a relative velocity of 0.75c. The distance L between A and B is 2000000 km. A makes use of a signal velocity v_s = 4c and B makes use of v'_s = 2c. The numbers in the example are chosen arbitrarily. The signal returns −1 s in the past in A.
Interest in Slow Light

Intrigue: Can (group) refractive index really be $10^6$?

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

Implications for quantum information
**Group Velocity**

Pulse (wave packet) \[\rightarrow \mathbf{u}_g\]

Group velocity given by \[\mathbf{v}_g = \frac{d\mathbf{w}}{d\mathbf{k}}\]

For \[k = \frac{n\mathbf{w}}{c}\], \[\frac{d\mathbf{k}}{d\mathbf{w}} = \frac{1}{c} \left(n + w \frac{dn}{dw}\right)\]

Thus

\[\mathbf{v}_g = \frac{c}{n + w \frac{dn}{dw}} \approx \frac{c}{n_g}\]

Thus \(n_g \neq n\) in a dispersive medium!
Slow light propagation in atomic vapors, facilitated by quantum coherence effects (EIT, CPO), has been successfully observed by:

Hau and Harris
Welch and Scully
Budker
and others
Challenge/Goal

Slow light in room-temperature solid-state material.

- Slow light in room temperature ruby
  (facilitated by a novel quantum coherence effect)
- Slow light in a structured waveguide
Slow Light in Ruby

Need a large $dn/d\omega$. (How?)

Kramers-Kronig relations:

Want a very narrow absorption line.

Well-known (to the few people how know it well) how to do so:

Make use of “spectral holes” due to population oscillations.

Hole-burning in a homogeneously broadened line; requires $T_2 \ll T_1$.

PRL 90,113903(2003); see also news story in Nature.
Spectral Holes Due to Population Oscillations

\[ 2\gamma_{ba} = \frac{2}{T_2} \]

\[ \Gamma_{ba} = \frac{1}{T_1} \]

E3, \( \omega + \delta \) \[ \rightarrow \]

\[ \frac{E_1, \omega}{\text{atomic medium}} \]

measure absorption

\[ E_3, \omega + \delta \]

\[ \rightarrow \]

\[ E_1, \omega \]

Population inversion:

\[ \left( \rho_{bb} - \rho_{aa} \right) = w \]

\[ w(t) \approx w^{(0)} + w^{(-\delta)} e^{i\delta t} + w^{(\delta)} e^{-i\delta t} \]

population oscillation terms important only for \( \delta \leq 1 / T_1 \)

Probe-beam response:

\[ \rho_{ba}(\omega + \delta) = \frac{\mu_{ba}}{\hbar} \frac{1}{\omega - \omega_{ba} + i/T_2} \left[ E_3w^{(0)} + E_1w^{(\delta)} \right] \]

Probe-beam absorption:

\[ \alpha(\omega + \delta) \mu \left[ w^{(0)} - \frac{\Omega^2T_2}{T_1} \frac{1}{\delta^2 + \beta^2} \right] \]

linewidth \( \beta = (1 / T_1)(1 + \Omega^2T_1T_2) \)
Spectral Holes in Homogeneously Broadened Materials

Occurs only in collisionally broadened media ($T_2 \ll T_1$)

Observation of a spectral hole due to population oscillations in a homogeneously broadened optical absorption line

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![Graph showing attenuation vs. modulation frequency](image)

Fig. 3. Attenuation of the modulated component (probe beam) is plotted as a function of modulation frequency. The probe beam experiences decreased absorption at low modulation frequencies. The width of this hole is 37 Hz for low laser powers. The spectral hole is power broadened at high laser powers.
Experimental Setup Used to Observe Slow Light in Ruby

7.25 cm ruby laser rod (pink ruby)
Measurement of Delay Time for Harmonic Modulation

For 1.2 ms delay, \( v = 60 \text{ m/s} \) and \( n_g = 5 \times 10^6 \)
Gaussian Pulse Propagation Through Ruby

No pulse distortion!

\[ v = 140 \text{ m/s} \]
\[ n_g = 2 \times 10^6 \]
Matt Bigelow and Nick Lepeshkin in the Lab
Comparison of University of Rochester and University of Arizona

Bob and Ruby

Hyatt and Galina
Alexandrite Displays both Saturable and Inverse-Saturable Absorption

$T_{1,m} = 260 \, \mu s$

$T_{1,i} \sim 50 \, \text{ms}$
At 476 nm, alexandrite is an inverse saturable absorber

Negative time delay of 50 $\mu$s corresponds to a velocity of -800 m/s

M. Bigelow, N. Lepeshkin, and RWB, Science, 2003
Slow and Fast Light -- What Next?

Longer fractional delay
(saturate deeper; propagate farther)

Find material with faster response
(technique works with shorter pulses)

Produce slow light in optical waveguides
(to enable new applications)
Slow Light in an Erbium-Doped Fiber Amplifier

\[
L = 10 \text{ m} \\
v_g = 1.7 \times 10^3 \text{ m/s} \\
n_g = 1.8 \times 10^5
\]

with S. Jarabo, University of Zaragoza
Implications of “Slow” Light

1. Controllable optical delay lines
   (a) Large total delay versus large fractional delay
   (b) True time delay for synthetic aperture radar
   (c) Buffers for optical processors and routers

2. New interactions enabled by slow light (e.g., SBS)

3. New possibilities with other materials
   (a) Semiconductor (bulk and heterostructures)
   (b) Laser dyes (gain, Q-switch, mode-lock)
   (c) rare-earth doped solids, especially EDFA’s

4. How weak a signal can be used with these method?

5. Relation between slowness and enhanced nonlinearity
Related Work: EIT

Resonance Structure of the Sodium D1 Line
13 Pump-Probe Resonances of the Na D1 Line

Artificial Materials for Nonlinear Optics

Artificial materials can produce
  Large nonlinear optical response
  Large dispersion and Slow light

Examples
  Fiber/waveguide Bragg gratings
  PBG materials
  CROW devices (Yariv, et al.)
  SCISSOR devices

Note also talks in Tuesday Nanophotonics sessions
Microresonator-Based Photonic Devices

Resonator-Enhanced Mach-Zehnder Interferometers

Five-Cell SCISSOR with Tap Channel

~100 nanometer gaps  
500 nanometer guides  
2.5 micron height

5 microns  
100 nanometer gaps  
500 nanometer guides  
2.5 micron height
Fiber optical delay line:

First study one element of optical delay line:

variable wavelength pulse

with Deborah Jackson, JPL
Third Harmonic Generation in a 3-D Photonic Crystal

polystyrene photonic crystal

Direct THG visible by eye!

Phase matching provided by PBG structure.
Joint with P.N. Prasad et al., SUNY Buffalo
Accepted for publication in PRL.
Research in Quantum Imaging

Can the images be formed with higher resolution or better sensitivity through use of quantum states of light?

Can we “beat” the Rayleigh criterion?

Quantum states of light: For instance, squeezed light or entangled beams of light.

Founders: Fabre, Klyshko, Kolobov, Kumar, Lugiato, Saleh, Sergienko, Shih, Teich.
Research in Quantum Imaging

Quantum Imaging or Quantum Imogene?
Quantum Lithography and Microscopy

- Entangled photons can be used to form interference patterns with detail finer than the Rayleigh limit
- Process “in reverse” performs sub-Rayleigh microscopy

Non-Quantum Quantum Lithography

Concept: average $M$ shots with the phase of shot $k$ given by $2\pi k/M$
Quantum(?) Coincidence Imaging

Obvious applicability to remote sensing!

We have performed coincidence imaging with a demonstrably classical source.
Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

*INFM, Dipartimento di Scienze CC.FF.MM., Università dell’Insubria, Via Valleggio 11, 22100 Como, Italy*

(Received 11 October 2002; published 3 April 2003)

We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603

PACS numbers: 42.50.Dv, 03.65.Ud
Near- and Far-Field Imaging Using Quantum Entanglement

Good imaging observed in both the near and far fields.

R. Bennink, S. Bentley, R. Boyd, and J. Howell; Howell, Wed 9:50; Bennink, Thur 12:40
Summary

Demonstration of room temperature superluminal propagation in alexandrite and slow light in ruby

Observation of the quantum signature of coincidence imaging and demonstration of position-momentum EPR paradox
Special Thanks to my Students and Research Associates
Thank you for your attention.