Fundamentals and Applications of Slow Light and
An Introduction to Quantum Imaging

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

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

Implications for quantum information

What about fast light ($\nu > c$) and backwards light ($\nu$ negative)?

All-Optical Switch

input ports  switch  output ports

But what happens if two data packets arrive simultaneously?

Use Optical Buffering to Resolve Data-Packet Contention

Controllable slow light for optical buffering can dramatically increase system performance.

Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester
Some Approaches to Slow Light Propagation

- Use the linear response of atomic systems or (better) use quantum coherence (e.g., electromagnetically induced transparency) to modify and control this response.

- Use of artificial materials (to modify the optical properties at the macroscopic level).

  E.g., photonic crystals where strong spectral variation of the refractive index occurs near the edge of the photonic bandgap.

![Polystyrene photonic crystal](image.png)
Pulses propagate at the group velocity given by

\[ v_g = \frac{c}{n_g} \quad n_g = n + \omega \frac{dn}{d\omega} \]

Want large dispersion to obtain extreme group velocities.

Sharp spectral features produce large dispersion.

The group index can be large and positive (slow light), positive and much less than unity (fast light) or negative (backwards light).
How to Create Slow and Fast Light I – Use Isolated Gain or Absorption Resonance
How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature

Narrow dips in gain and absorption lines can be created by various nonlinear optical effects, such as electromagnetically induced transparency (EIT), coherent population oscillations (CPO), and conventional saturation.
M. D. Stenner, M. A. Neifeld, Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, Optics Express 13, 9995 (2005).
Linear Pulse Propagation in an Absorbing Medium

S. Chu and S. Wong
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 30 November 1981)

The pulse velocity in the linear regime in samples of GaP:N with a laser tuned to the bound A-exciton line is measured with use of a picosecond time-of-flight technique. The pulse is seen to propagate through the material with little pulse-shape distortion, and with an envelope velocity given by the group velocity even when the group velocity exceeds $3 \times 10^{10}$ cm/sec, equals $\pm \infty$, or becomes negative. The results verify the predictions of Garrett and McCumber.
Light speed reduction to 17 metres per second in an ultracold atomic gas

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\[ v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \varepsilon_0}{2 \omega_p |\Omega_c|^2} N \]

- $60 \text{ MHz}$
- $1.8 \text{ GHz}$
- $\lambda = 589 \text{ nm}$

- $\Omega_c$
- $\omega_p$
- $D_2$ line

- $\{1\}$ $\text{IF}=1, M_F=-1$
- $\{2\}$ $\text{IF}=2, M_F=-2$
- $\{3\}$ $\text{IF}=2, M_F=-2$
- $\{4\}$ $\text{IF}=3, M_F=-2$

- $T = 450 \text{ nK}$
- $\tau_{\text{Delay}} = 7.05 \pm 0.05 \mu \text{s}$
- $L = 229 \pm 3 \mu \text{m}$
- $v_g = 32.5 \pm 0.5 \text{ m s}^{-1}$

![Graph a: Transmission vs. Probe detuning (MHz)]

![Graph b: Refractive index vs. Probe detuning (MHz)]

![Graph c: PMT signal vs. Time (µs)]
Amplification of Light and Atoms in a Bose-Einstein Condensate


Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 27 June 2000)

A Bose-Einstein condensate illuminated by a single off-resonant laser beam (“dressed condensate”) shows a high gain for matter waves and light. We have characterized the optical and atom-optical properties of the dressed condensate by injecting light or atoms, illuminating the key role of long-lived matter wave gratings produced by the condensate at rest and recoiling atoms. The narrow bandwidth for optical gain gave rise to an extremely slow group velocity of an amplified light pulse (~1 m/s).

FIG. 3. Pulse delay due to light amplification. (a) About 20 ms delay was observed when a Gaussian pulse of about 140 ms width and 0.11 mW/cm² peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian fits to guide the eyes. (b) The observed delay \( t_D \) was proportional to \( \ln g \), where \( g \) is the observed gain.
Determination of the Velocity of Light*

“Astronomical” Methods

Römer (1676) First evidence that velocity of light is finite!

Observed an apparent variation of up to 22 minutes in the orbital period of the satellite Io in its orbit about Jupiter.

Deduced that $c = 225,000$ km/sec

(Actually, light transit time from sun to earth is just over 8 minutes, and $c = 299,793$ km/sec)

*See, for instance, Jenkins and White, 1976.
Determination of the Velocity of Light
Astronomical Methods

Bradley (1727); Aberration of star light.

Confirmation of the finite velocity of light.

\[ v(\text{earth}) \approx 30 \text{ km/s} \]

\[ \tan \alpha = \frac{v(\text{earth})}{c} \]

\[ \alpha = 20.5 \text{ arcsec} \]
Determination of the Velocity of Light
Laboratory Methods

Fizeau (1849) Time-of-flight method

720 teeth in wheel
maximum transmission at 25 revolutions/sec

\[ c = \frac{L}{T} = 320,000 \text{ km/s} \]
Determination of the Velocity of Light
Laboratory Methods

Michelson (1926); Improved time of flight method.

Rotating octagonal mirror

c = 299,296 km/s (or 299,298 km/s)
Foucault (1850) Velocity of light in water.

Is $v = c/n$ or $nc$?

Foucault finds that light travels more slowly in water!
Fizeau (1859); Velocity of light in flowing water.

\[ V = 700 \text{ cm/sec}; \ L = 150 \text{ cm}; \ \text{displacement of 0.5 fringe}. \]

Modern theory: relativistic addition of velocities

\[ v = \frac{c/n + V}{1 + (V/c)(1/n)} \approx \frac{c}{n} + V \left(1 - \frac{1}{n^2}\right) \]

\[ \text{Fresnel “drag” coefficient} \]
Slow light is a room-temperature, solid-state material.

Our solution:

Slow light via coherent population oscillations (CPO), a quantum coherence effect related to EIT but which is less sensitive to dephasing processes.
Slow Light in Ruby

Recall that \( n_g = n + \omega (dn/d\omega) \). Need a large \( dn/d\omega \). (How?)

Kramers-Kronig relations:
Want a very narrow feature in absorption line.

Well-known “trick” for doing 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).
Slow Light Experimental Setup

- Argon Ion Laser
- Function Generator
- Ruby laser rod (pink ruby)
- EO modulator
- Digital Oscilloscope
- Reference Detector
- Signal Detector
- Pinhole

7.25-cm-long 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
Advantages of Coherent Population Oscillations for Slow Light

Works in solids
Works at room temperature
Insensitive of dephasing processes
Laser need not be frequency stabilized
Works with single beam (self-delayed)
Delay can be controlled through input intensity
Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

At 476 nm, alexandrite is an inverse saturable absorber

Negative time delay of 50 μs corresponds to a velocity of -800 m/s

M. Bigelow, N. Lepeshkin, and RWB, Science, 2003
Numerically integrate the reduced wave equation

$$\frac{\partial A}{\partial z} - \frac{1}{v_g} \frac{\partial A}{\partial t} = 0$$

and plot $A(z,t)$ versus distance $z$.

Assume an input pulse with a Gaussian temporal profile.

Study three cases:

Slow light \quad v_g = 0.5 \ c

Fast light \quad v_g = 5 \ c \quad \text{and} \quad v_g = -2 \ c

CAUTION: This is a very simplistic model. It ignores GVD and spectral reshaping.

Pulse Propagation through a Slow-Light Medium ($n_g = 2, \ v_g = 0.5 \ c$)
Pulse Propagation through a Fast-Light Medium ($n_g = 0.2$, $v_g = 5\ c$)
Pulse Propagation through a Fast-Light Medium \( (n_g = -0.5, \, v_g = -2 \, c) \)
Slow and Fast Light in an Erbium Doped Fiber Amplifier

- Fiber geometry allows long propagation length
- Saturable gain or loss possible depending on pump intensity

Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier

We time-resolve the propagation of the pulse as a function of position along the erbium-doped fiber.

Procedure
- cutback method
- couplers embedded in fiber

Experimental Results: Backward Propagation in Erbium-Doped Fiber

Normalized: (Amplification removed numerically)
Observation of “Backwards” Pulse Propagation

- A strongly counterintuitive phenomenon
- But entirely consistent with established physics

Summary:

“Backwards” propagation is a realizable physical effect.

(Of course, many other workers have measured negative time delays. Our contribution was to measure the pulse evolution within the material medium.)
Causality and Superluminal Signal Transmission

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.

Propagation of a Truncated Pulse through Alexandrite as a Fast-Light Medium

Smooth part of pulse propagates at group velocity
Discontinuity propagates at phase velocity
Information resides in points of discontinuity

How to Reconcile Superluminality with Causality

In principle, the information velocity is equal to $c$ for both slow- and fast-light situations. **So why is slow and fast light even useful?**

Because in many practical situations, we can perform reliable measurements of the information content only near the peak of the pulse.

In this sense, useful information often propagates at the group velocity.

In a real communication system it would be really stupid to transmit pulses containing so much energy that one can reliably detect the very early leading edge of the pulse.

which gives better S/N?
Interferometry and Slow Light

- Under certain (but not all) circumstances, the sensitivity of an interferometer is increased by the group index of the material within the interferometer!
- Sensitivity of a spectroscopic interferometer is increased

Typical interferometer:

We use CdS$_x$Se$_{1-x}$ as our slow-light medium

Here is why it works:

$$\frac{d\Delta \phi}{d\omega} = \frac{d}{d\omega} \left( \frac{\omega n L}{c} \right) = \frac{L}{c} \left( n + \omega \frac{dn}{d\omega} \right) = \frac{L n_g}{c}$$


Our experimental results
Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

Two primary mechanisms for pulse distortion in EDFA

– Spectral broadening, leading to **temporal compression**
  CPO gain dip causes spectral components in the wings to be amplified more than central components

– Temporal gain recovery, leading to **temporal broadening**
  Leading edge of signal pulse saturates gain, but for long pulses, the trailing edge can experience recovered gain

To minimize second effect, add a cw background to reduce the influence of gain recovery

For the proper choice of background power, the two effects exactly cancel!
Minimizing Pulse Distortion — Laboratory Results

- 980 nm laser
- 1550 nm laser
- function generator
- EOM
- ISO
- WDM
- EDF
- Polarizer
- WDM
- 980
- 1550

Pulse width ratio ($T_{out} / T_{in}$)

- Compression
- Broadening

Power ratio ($P_{bg} / P_{sig}$)

- 2 ms
- 5 ms
- 10 ms
- 40 ms
Summary

Slow-light techniques hold great promise for applications in telecommunications.

Good progress being made in developing new slow-light techniques and applications.

Backwards and superluminal propagation are strongly counterintuitive, but are fully explained by standard physics.
Research in Quantum Imaging

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

Can we "beat" the Rayleigh criterion?

What are the implications of “interaction free” and “ghost” imaging?

Quantum states of light: For instance, squeezed light or entangled beams of light.
Ghost and Interaction-Free Imaging

Stealth Imaging
Quantum Imaging by Interaction-Free Measurement

Ghost (Coincidence) Imaging

- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

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

INFN, 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!

• Good imaging can be obtained only in near field or far field.
• Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of ten.
Is Entanglement Really Needed for Ghost Imaging with an Arbitrary Object Location?

Gatti et al. (PRA and PRL, 2004) argue that thermal sources can mimic the quantum correlations produced by parametric down conversion. (Related to Brown-Twiss effect.)

Experimental confirmation of ghost imaging with thermal sources presented by Como and UMBC groups

But the contrast of the images formed in this manner is limited to $1/2$ or $1/N$ (depending on the circumstances) where $N$ is the total number of pixels in the image.
Quantum Lithography

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit.
- Process “in reverse” performs sub-Rayleigh microscopy, etc.
- Resolution $\approx \lambda / 2N$, where $N =$ number of entangled photons.


("al." includes Jon Dowling)
Quantum Lithography: Easier Said Than Done

- Need an $N$-photon recording material
  
  For proof-of-principle studies, can use $N$-th-harmonic generator, correlation circuitry, $N$-photon photodetector.
  
  For actual implementation, use ????
  
  Maybe best bet is UV lithographic material excited in the visible or a broad bandgap material such as PMMA excited by multiphoton absorption.

- Need an intense source of individual biphotons (Inconsistency?)
  
  Maybe a high-gain OPA provides the best tradeoff between high intensity and required quantum statistics

3PA in PMMA breaks chemical bond, modifying optical properties.
Problem: self healing
Classically Simulated (Non-Quantum) Quantum Lithography

Concept: average $M$ shots with the phase of shot $k$ given by $2\pi k/M$

Demonstration of Fringes Written into PMMA

\[ \theta = 70 \text{ degrees} \]
write wavelength = 800 nm
pulse energy = 130 \( \mu \text{J} \) per beam
pulse duration = 120 fs
period = \( \lambda / (2 \sin \theta) \) = 425 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water

PMMA is a standard lithographic material
Quantum lithography has a good chance of becoming a reality.

The quantum vs. classical nature of ghost imaging is more subtle than most of us had appreciated.

Many of our cherished “quantum effects” can be mimicked classically.

There is still work to be done in the context of quantum imaging to delineate the quantum/classical frontier.
Special Thanks to My Students and Research Associates
Thank you for your attention!
Physics is all about asking the right questions

Just ask

Evelyn Hu

Watt Webb (or James Watt)

Michael Ware

Wen I Wang

Kam Wai Chan

Not to mention

Lene Hau
Slow-Light via Stimulated Brillouin Scattering

- Rapid spectral variation of the refractive response associated with SBS gain leads to slow light propagation
- Supports bandwidth of 100 MHz, large group delays
- Even faster modulation for SRS

Business was slow at the local Hampton Inn

This door is locked for our guest’s safety and security. Please use your guest key for entry.
Thank you for your attention!

And thanks to NSF and DARPA for financial support!

Our results are posted on the web at:

http://www.optics.rochester.edu/~boyd
Business was slow at the local Hampton Inn

This door is locked for our guest’s safety and security. Please use your guest key for entry.
Fundamental Limits on Slow and Fast Light

Slow Light: There appear to be no fundamental limits on how much one can delay a pulse of light (although there are very serious practical problems).*

Fast Light: But there do seem to be essentially fundamental limits to how much one can advance a pulse of light.

Why are the two cases so different?**

* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

** We cannot get around this problem simply by invoking causality, first because we are dealing with group velocity (not information velocity), and second because the relevant equations superficially appear to be symmetric between the slow- and fast-light cases.
Why can one delay (but not advance) a pulse by an arbitrarily large amount?

Two crucial differences between slow and fast light

(1) First, note that we cannot use gains greater than approximately \( \exp(32) \) at any frequency to avoid ASE. And we cannot have absorption larger than \( T = \exp(-32) \) at the signal frequency, so signal can be measured. (Of course, the argument does not hinge on the value 32.) When examined quantitatively, these constraints impose a limit of at most several pulse-widths of delay or advancement.

\[
\frac{\Delta T}{T} = \frac{1}{2} \sqrt{\alpha L}
\]

One can overcome these constraints by using a deep hole in an absorption feature, but this trick works only for slow light, as we have just seen.

(2) Spectral reshaping of the pulse is the dominant competing effect in most slow/fast light systems. This also behaves differently for slow and fast-light systems, as we shall now see.
Influence of Spectral Reshaping
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse

output pulse
slow-light

T(\omega)
spectrally narrowed pulse

output pulse
fast-light

G(\omega)
spectrally broadened pulse

for still longer propagation distances, the pulse breaks up spectrally and temporally

double-humped pulse
Why is there no limit to the amount of pulse delay?

At the bottom of the dip in the absorption, the absorption can in principle be made to vanish. There is then no limit on how long a propagation distance can be used.

This “trick” works only for slow light.
Numerical Results: Propagation through a Linear Dispersive Medium

Fast light:
Lorentzian absorption line
\( T = \exp(-32) \)
vary line width to control advance

Slow light:
Lorentzian gain line
\( T = \exp(+32) \)
vary line width to control delay

Same Gaussian input pulse in all cases

![Graphs showing propagation through a linear dispersive medium with fast and slow light](image-url)