Applications of Slow Light in Telecommunication and Optical Switching

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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

And what about fast light ($v > c$ or negative)?

**Group Velocity**

Pulse (wave packet) → $v_g$

Group velocity given by $v_g = \frac{dw}{dk}$

For $k = \frac{nW}{c}$, $\frac{dk}{dw} = \frac{1}{c} (n + w \frac{dn}{dw})$

Thus

$v_g = \frac{c}{n + w \frac{dn}{dw}} = \frac{c}{n_g}$

Thus $n_g \neq n$ in a dispersive medium!
Approaches to Slow Light Propagation

• Use of quantum coherence (to modify the spectral dependence of the atomic response)
  e.g., electromagnetically induced transparency

• Use of artificial materials (to modify the optical properties at the macroscopic level)
  e.g., photonic crystals (strong spectral variation of refractive index occurs near edge of photonic bandgap)
- Want $\tilde{V}_g$ very different from $V_p$
- Need very large dispersion
- Study resonances of atomic vapor

\[ \tilde{V}_g = \frac{c}{n + \omega \frac{dn}{dw}} \]
Light speed reduction to 17 metres per second in an ultracold atomic gas

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\[ v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0 |\Omega_c|^2}{2 \omega_p |\mu_{13}|^2 N} \]
Review of Slow-Light Fundamentals

slow-light medium, \( n_g >> 1 \)

\[
\text{group velocity: } \quad v_g = \frac{c}{n_g}
\]

\[
\text{group index: } \quad n_g = n + \omega \frac{dn}{d\omega}
\]

\[
\text{group delay: } \quad T_g = \frac{L}{v_g} = \frac{Ln_g}{c}
\]

\[
\text{controllable delay: } \quad T_{\text{del}} = T_g - \frac{L}{c} = \frac{L}{c}(n_g - 1)
\]

To make controllable delay as large as possible:

- make \( L \) as large as possible (reduce residual absorption)
- maximize the group index
Systems Considerations: Maximum Slow-Light Time Delay

“Slow light”: group velocities $< 10^{-6} \, c$

Proposed applications: controllable optical delay lines, optical buffers, true time delay for synthetic aperture radar.

Key figure of merit:
normalized time delay $= \frac{\text{total time delay}}{\text{input pulse duration}} \approx \text{information storage capacity of medium}$

Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

But data packets used in telecommunications contain $\approx 10^3$ bits

What are the prospects for obtaining slow-light delay lines with $10^3$ bits capacity?
Slow Light and Optical Buffers

All-Optical Switch

input ports switch output ports

But what happens if two data packets arrive simultaneously?

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

Use Optical Buffering to Resolve Data-Packet Contention

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
Challenge/Goal

Slow light in a room-temperature solid-state material.

Solution: Slow light enabled by coherent population oscillations (a quantum coherence effect that is relatively insensitive to dephasing processes).
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 $T_2 << T_1$.

PRL 90,113903(2003).
Spectral Holes in Homogeneously Broadened Materials

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


pump-probe detuning (units of $1/T_2$)
Slow Light Experimental Setup

7.25-cm-long ruby laser rod (pink ruby)
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!

$\nu = 140 \text{ m/s}$

$\nu_g = 2 \times 10^6$
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
PbS Quantum Dots (2.9 nm diameter) in liquid solution
Excite with 16 ps pulses at 795 nm; observe 3 ps delay
30 ps response time (literature value)
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
Numerical Modeling of Pulse Propagation Through Slow and Fast-Light Media

Numerically integrate the paraxial 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** \( v_g = 0.5 \ c \)
- **Fast light** \( v_g = 5 \ c \) and \( v_g = -2 \ c \)
Pulse Propagation through a Slow-Light Medium ($n_g = 2, \ v_g = 0.5 \ c$)
Pulse Propagation through a Fast-Light Medium \((n_g = .2, v_g = 5 \text{ c})\)
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

Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo
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
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier
Summary:

“Backwards” propagation is a realizable physical effect.
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 velocity)

Pulses are not distinguishable "early."

$V_i \leq c$
Information Velocity – Tentative Conclusions

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?
Slow-light techniques hold great promise for applications in telecom and quantum information processing.

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

Different methods under development possess complementary regimes of usefulness.
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Our results are posted on the web at:

http://www.optics.rochester.edu/~boyd