Slow, Fast, and “Backwards” Light: Fundamentals and Applications

Robert W. Boyd

Institute of Optics and Department of Physics and Astronomy
University of Rochester

with George Gehring, Giovanni Piredda, Paul Narum, Aaron Schweinsberg, Zhimin Shi, Heedeuk Shin, Joseph Vornehm, Petros Zerom, and many others

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All-Optical Switch

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
- Optical Buffering – Need many pulse-widths of delay
  Use the conversion / dispersion method of Gaeta and others

- Regeneration of Pulse Timing –
  Single pulse-width of delay adequate, but need precise control
  Use “true” slow light (SBS?)
The group index can be large and positive (slow light). positive and much less than unity (fast light) or negative (backwards light).

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.
How to Create Slow and Fast Light I – Use Isolated Gain or Absorption Resonance
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.
Challenge / Goal (2003)

Slow light in 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.
• Ground state population oscillates at beat frequency $\delta$ (for $\delta < 1/T_1$).

• Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.

• Rapid spectral variation of refractive index associated with spectral hole leads to large group index.

• Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite by this process.

• Slow and fast light effects occur at room temperature!

PRL 90,113903(2003); Science, 301, 200 (2003)
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
Slow Light via Coherent Population Oscillations

- Ultra-slow light \((n_g > 10^6)\) observed in ruby and ultra-fast light \((n_g = -4 \times 10^5)\) observed in alexandrite at room temperature.

- Slow and fast light in an EDFA

- Slow light in a SC optical amplifier

- Slow light in PbS quantum dots
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** \( v_g = 0.5 \) c
- **Fast light** \( v_g = 5 \) c and \( v_g = -2 \) c

**CAUTION:** This is a very simplistic model. It ignores GVD and spectral reshaping.
Pulse Propagation through a Fast-Light Medium ($n_g = 0.2$, $v_g = 5 \, c$)
Pulse Propagation through a Backwards-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.)
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_x = 4c and B makes use of v'_x = 2c. The numbers in the example are chosen arbitrarily. The signal returns −1 s in the past in A.
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?
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 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.
Influence of Spectral Reshaping
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse

output pulse
slow-light

output pulse
fast-light

spectrally narrowed pulse

spectrally broadened pulse

double-humped pulse

for still longer propagation distances, the pulse breaks up spectrally and temporally
Numerical Results: Propagation through a Linear Dispersive Medium

Full (causal) model – solve wave equation with \( P = \chi E \) where \( \chi(\omega) = \frac{A}{\omega_0 - \omega - i\Gamma} \)

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

<table>
<thead>
<tr>
<th>Slow Light</th>
<th>Fast Light</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>1 pulse-width delay</td>
<td>1 pulse-width advance</td>
</tr>
<tr>
<td>2 pulse-widths delay</td>
<td>2 pulse-widths advance</td>
</tr>
<tr>
<td>4 pulse-width delay</td>
<td>4 pulse-widths advance</td>
</tr>
<tr>
<td>6 pulse-width delay</td>
<td>6 pulse-widths advance</td>
</tr>
</tbody>
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Vacuum

Time
Propagation of Full and Truncated Pulse Trains

Slow

Fast

Fast - truncated
Second output pulse is generated out of “nothing.”
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:

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

Here is why it works:


We use CdS_xSe_{1-x} as our slow-light medium

Our experimental results

experimental data

theory for a slow-light medium

theory for a non-dispersive medium

ng ≈ 4
High-Resolution Slow-Light Fourier Transform Interferometer

Conventional FT Interferometer
- Moving arm
- Beam splitter
- Detector
- Fixed arm
- Input field

Slow-light FT Interferometer
- Moving arm
- Tunable slow-light medium
- Beam splitter
- Detector
- Fixed arms
- Input field

Energy Levels

Theoretical Model

Results

Shi, Boyd, Camacho, Setu, and Howell
Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

There is no delay-bandwidth product limitation on slow light!

- coarse tuning: temperature
- fine tuning: optical pumping

Summary – Progress in Slow-Light Research

Delay of 3 pulse widths (1999)
Results of Hau, L

Delay of 80 pulse widths (2007)
Results of Howell

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

Pulse intensity

Air
275 ps pulses
increasing temperature

PMT signal (mV)

Time (\mu s)

Delay of 3 pulse widths (1999)
Results of Hau, L

Delay of 80 pulse widths (2007)
Results of Howell
Thank you for your attention!
Special Thanks to My Students and Research Associates