Physics and Applications of "Slow" Light

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Outline

• Information and optical pulses
• Optical networks: The Problem
• Possible solution: "Slow" and "Fast" light
• Review of pulse propagation in dispersive media
• Optical pulse propagation in a resonant systems
• Slow light via EIT
• Fast Light via Raman Scattering
• Our Experiments
• Fiber-Based Slow Light

Information and Optical Pulses: Basic Review

Digital Information

• computers only work with numbers - vast majority use binary
• need standards for converting "information" to a binary representation

Text:
ASCII (American Standard Code for Information Exchange)
developed years ago for teletype communication
1 byte (8 bits) needed for "standard" alphabet each character assigned a number
e.g.:  A = 41 (decimal) = 00101001 (binary)
      a = 97 = 01100001
Digital Information: Images

image is divided into pixels

each pixel is assigned a number using a standard
e.g.: 8-bit color: one byte per color, three colors
Red, Green, Blue

Using Light to Transmit Digital Information

Encode bits on a beam of light

... 01100001...

laser
modulator
to optical fiber

various modulation formats!
e.g., amplitude, phase, frequency

Modern Optical Telecommunication Systems:
NRZ common for <= 10 Gbit/s


NRZ data
clock

Modern Optical Telecommunication Systems:
RZ common for > 10 Gbits/s


RZ data
clock

Why Optics? Fast Data Rates!

can transmit data at high rates over optical fibers in comparison to copper wires (low loss, low distortion of pulses)

important breakthrough: use multiple wavelengths per fiber
each wavelength is an independent channel
(DWDM - Dense Wavelength Division Multiplexing)

Common Standard: OC-192 (10 Gbits/s)

"optical carrier" 192 times base rate of 51.85 Mbits/s

next standards: OC-768 (40 Gbits/s), OC-3072 (160 Gbits/s)

lab: > 40 Tbits/s every house in US can have an active internet connection!

Optical Networks

Ultra-High-Capacity Fiber-Optic Backbone

information sent to router in "packets" with header
- typical packet length (data) 100-1000 bits

router needs to read address, send data down new channel, possibly at a new wavelength

<= 10 Gbits/s: Optical-Electronic-Optical (OEO) conversion

Is OEO conversion feasible at higher speeds?
Ultra-High Speed Network Router

Possible Solution:
All-optical router

One (fairly major) unsolved problem:
There is no all-optical RAM or agile optical buffer

Need for Buffers: Contention Resolution

Resolution Schemes

Optical Buffers
- Random access dynamic optical memory
- Enables packet switching

Wavelength Shift
- Finite set of wavelengths

Deflection Routing
- Decreased throughput
- High latency

Problem: An unbuffered optical switch architecture may drop or misroute a packet when there is output port contention, causing increased latency and/or packet loss.

Source: Alan Willner, USC

Statement of the Problem

How do we make an all-optical, controllable delay line (buffer) or memory?

Possible Solution: "Slow" and "Fast" Light

Speed of Pulse MUCH slower or faster than the speed of light in vacuum

R.W. Boyd and D.J. Gauthier
"Slow and "Fast" Light, in Progress in Optics, Vol. 43, E. Wolf, Ed. (Elsevier, Amsterdam, 2002), Ch. 6, pp. 497-530.
Optical Pulse Propagation Review

Propagating Electromagnetic Waves: Phase Velocity

monochromatic plane wave

\[ E(z,t) = A e^{i(kz - \omega t)} + c.c \]

phase \[ \phi = k z - \omega t \]

Points of constant phase move a distance \( \Delta z \) in a time \( \Delta t \)

Propagating Electromagnetic Waves: Group Velocity

Lowest-order statement of propagation without distortion

\[ \frac{d\phi}{d\omega} = 0 \]

group velocity

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

Variation in \( v_g \) with dispersion

slow light

fast light
Schematic of Pulse Propagation at Various Group Velocities

- \( v < c \)
- \( v = c \)
- \( v > c \)
- \( v \) negative

Pulse Propagation: Slow Light
(Group velocity approximation)

Pulse Propagation: Fast Light
(Group velocity approximation)

Propagation "without distortion"

\[
k(\omega) = k_s + \frac{n_g}{c}(\omega - \omega_s) + \frac{1}{2c} \frac{dn_g}{d\omega}(\omega - \omega_s)^2 + \cdots
\]

- \( \frac{dn_g}{d\omega} = 0 \)
- pulse bandwidth not too large

"slow" light: \( v_g << c \quad (n_g >> 1) \)

"fast" light: \( v_g > c \quad or \quad v_g < 0 \quad (n_g < 1) \)

Recent experiments on fast and slow light conducted in the regime of low distortion
Optical Pulse Propagation in a Resonant System

Set Optical Carrier Frequency Near an Atomic Resonance

\[ \omega_o = \omega_{eg} \]

\[ |e\rangle \]

\[ |g\rangle \]

\[ \chi = \frac{N\varepsilon^2}{2m\omega_{eg}} \left(\omega_o - \omega_{eg}\right) + i\gamma \]

atomic energy eigenstates

resonant enhancement

Dispersion Near a Resonance

\[ n = n' + in'' \approx 1 + 2\pi\chi \]

refractive index \( \delta n^{(\text{max})} \approx 0.1 \)

absorption index

Problem: Large Absorption!

\[ n' \]

\[ n'' \]

\[ n_g \]

\[ n_g^{(\text{max})} \approx 10^5 \]

\[ 1 + \left(\omega \delta n^{(\text{max})}/2\gamma\right) \]

\[ 1 - \left(\omega \delta n^{(\text{max})}/2\gamma\right) \]
Slow Light via EIT

Solution: Electromagnetically Induced Transparency

\[ \omega_o = \omega_{eg}, \Omega_s \]


Group Index for EIT

Experimental Setup of Hau et al.

\[ n_g \sim 10^6 \]

relevant sodium energy levels
Slow Light Observations of Hau et al.

\[ v_g \text{ as low as } 17 \text{ m/s } \]

\[ n_g \text{ of the order of } 10^6! \]

Fast Light via Atomic Raman Scattering

Fast-light via a gain doublet

\[ \frac{d n}{d \omega} \]

Steingberg and Chiao, PRA 49, 2071 (1994)
(Wang, Kuzmich, and Dogariu, Nature 406, 277 (2000))

Achieve a gain doublet using stimulated Raman scattering with a bichromatic pump field

Our Experiments on "Fast" and "Slow" Light

Experimental observation of fast light

$n_b \approx -310$

... but the fractional pulse advancement is small

Important Quantity for our Work: Pulse Advancement

$A = t_{adv}/t_p$

Key Observation

$A \sim (\text{gain coefficient}) \times (\text{length of medium})$

Does NOT depend on $v_g$ directly

Adjust spectral width of atomic resonance to optical spectrum of the pulse
Fast light in a laser driven potassium vapor

Steinberg and Chiao, PRA 49, 2071 (1994)

Some of our toys

Observation of large pulse advancement

t_p = 263 ns  A = 10.4%  v_g = -0.051c  n_g = -19.6

some pulse compression (1.9% higher-order dispersion)

large fractional advancement - can distinguish different velocities!

Slow Light via a single amplifying resonance
Surely Dr. Watson, you must be joking ...

- Experiments in Slow and Fast Light use atoms
- Effect only present close to a narrow atomic resonance
- Works for long pulses - slow data rates!
- Not easily integrated into a telcom system!

**Key Observation**

\[ A \sim (\text{gain coefficient}) \times (\text{length of medium}) \]

Does NOT depend on \( v_g \) directly

Adjust spectral width of atomic resonance to optical spectrum of the pulse

- short pulses \( \rightarrow \) broad resonance

any resonance can give rise to slow light!!

- e.g., Stimulated Brillouin and Raman Scattering

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**Fiber-Based Fast and Slow Light**
Slow-Light via Stimulated Brillouin Scattering

Characterization of stimulated Brillouin scattering spectra by use of optical single-sideband modulation

Alayna Loayza, Ruben Hernandez, David Beets, and Sonia Galech
Department of Electrical and Electronic Engineering, Public University of Navarre, Pamplona, Spain

Gain and Dispersion 6.4-km-Long SMF-28 Fiber

\[ P_{\text{pump}} = 7.1 \text{ mW} \]

others:
- 4.7 mW
- 1.9 mW

should see "large" relative delay

To Do

- Measure slow light via Brillouin scattering in a fiber for a single optical pulse
- Optimize
- Multiple pulses
- Large relative pulse delay
- Measure slow light via Raman scattering (broader resonances for shorter pulses)
- Delay a packet
- Integrate into a telcomm router (in my dreams ...)
- Integrate into a telcomm clock/data synchronizer

Summary

- Future ultra-high-speed telecommunication systems require all-optical components
- Data-rate bottleneck in network (routers)
- Slow and Fast Light pulse propagation with large pulse delay or advancement may provide a solution
- It is possible to observe slow and fast light using telcomm-compatible components
- Additional research needed to determine whether technology is competitive with other approaches

http://www.phy.duke.edu/research/photon/qelectron/proj/infv/