Nonlinear Optical Physics

especially

“Slow” and “Fast” Light in Room-Temperature Solids

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The Essence of Nonlinear Optics

Light-By-Light Scattering
Interest in Slow Light

Fundamentals of optical physics

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

Optical delay lines, optical storage, optical memories

Implications for quantum information
Slow Light

\[ \text{group velocity} \neq \text{phase velocity} \]
Group Velocity

Pulse (wave packet) \[ \rightarrow U_g \]

Group velocity given by \[ U_g = \frac{dw}{dk} \]

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

Thus \[ U_g = \frac{c}{n + w \frac{dn}{dw}} \equiv \frac{c}{n_g} \]

Thus \( n_g \neq n \) in a dispersive medium!
Light Propagation in Atomic Vapors

\[ n = \sqrt{\mathcal{E}} = \sqrt{1 + 4\pi \chi} \]
\[ \chi = \frac{Ne^2/2mw_0}{(w_0 - \omega) - i\gamma} \]

For \( N \) not too large, \( n = n' + in'' \approx 1 + 2\pi \chi \)

\[ n' = 1 + \frac{\pi Ne^2}{m w_0} \frac{w_0 - \omega}{(w_0 - \omega)^2 + \gamma^2} \]
\[ n'' = \frac{\pi Ne^2}{2m w_0 \gamma} \frac{\gamma^2}{(w_0 - \omega)^2 + \gamma^2} \]

\[ n_g = n' + \frac{wSn'(max)}{dw} \]

\[ \frac{wSn'(max)}{\gamma} \approx \frac{2\pi(5 \times 10^{14})(0.1)}{2\pi (1 \times 10^9)} = 5 \times 10^4 \sim (1) \]

\( n_g \) can range from \( +5 \times 10^4 \) to \( -5 \times 10^4 \).

(But with lots of absorption)
How to Produce Slow Light?

Group index can be as large as

\[ n_g \approx 1 + \frac{\hbar \Omega n^{(\text{max})}}{\gamma} \]

Use Nonlinear optics to

(1) decrease line width \( \gamma \)

(produce sub-Doppler linewidth)

(2) decrease absorption

(so transmitted pulse is detectable)
Slow Light in Atomic Media

Slow light propagation in atomic media (vapors and BEC), facilitated by quantum coherence effects, has been successfully observed by many groups.
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 $\frac{dn}{d\omega}$. (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

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

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

Population inversion:

\[
\left( \rho_{bb} - \rho_{aa} \right) = w = w(0) + w(-\delta) e^{i\delta t} + w(\delta) e^{-i\delta t}
\]

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

Probe-beam response:

\[
\rho_{ba}(\omega + \delta) = \frac{\mu_{ba}}{\hbar} \frac{1}{\omega - \omega_{ba} + i / T_2} \left[ E_3 w(0) + E_1 w(\delta) \right]
\]

Probe-beam absorption:

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

\( \text{linewidth } \beta = (1 / T_1) (1 + \Omega^2 T_1 T_2) \)
Spectral Holes in Homogeneously Broadened Materials

Occurs only in collisionally broadened media \((T_2 << T_1)\)

OBSERVATION OF A SPECTRAL HOLE DUE TO POPULATION OSCILLATIONS IN A HOMOGENEously BROADENED OPTICAL ABSORPTION LINE

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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

$T_{1,m} = 260 \text{ ms}$

Mirror Sites:

Inversion Sites:

$T_{1,i} \sim 50 \text{ ms}$
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, accepted for publication, 2003.
Slow and Fast Light -- What Next?

Longer fractional delay
(saturate deeper; propagate farther)

Find material with faster response
(technique works with shorter pulses)
Artificial Materials for Nonlinear Optics

Artificial materials can produce
- Large nonlinear optical response
- Large dispersive effects

Examples
- Fiber/waveguide Bragg gratings
- PBG materials
- CROW devices (Yariv et al.)
- SCISSOR devices
NLO of SCISSOR Devices
(Side-Coupled Integrated Spaced Sequence of Resonators)

Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrödinger equation

- Weak pulses spread because of dispersion

- But intense pulses form solitons through balance of dispersion and nonlinearity.
Slow Light and SCISSOR Structures

\[ \frac{2\pi F}{\pi} \]

\[ \frac{c}{F n R} \]

\[ \frac{k_{\text{eff}} - k_0}{L} \]

\[ \frac{2\pi F n}{c} \]

\[ n \]

\[ \frac{c}{F n R} \]

\[ \frac{c}{n R} \]

frequency, \( \omega \)
Microdisk Resonator Design

All dimensions in microns

GaAs
Al$_x$Ga$_{1-x}$As ($x = 0.4$)

J. E. Heebner and R. W. Boyd
Photonic Device Fabrication Procedure

1. MBE growth
2. Deposit oxide
3. Spin-coat e-beam resist
4. Pattern inverse with e-beam & develop
5. RIE etch oxide
6. Remove PMMA
7. CAIBE etch AlGaAs-GaAs
8. Strip oxide

AlGaAs-GaAs structure
Oxide (SiO₂)
PMMA
AlGaAs-GaAs structure
Oxide (SiO₂)
PMMA
Disk Resonator and Optical Waveguide in PMMA Resist

AFM
All-Pass Racetrack Microresonator

10 micron diameter
2.5 micron height
100 nanometer gap
500 nanometer guide width

Thanks to P.T. Ho and R. Grover, U. Maryland, for help with final etch.
Five-Cell SCISSOR with Tap Channel

5 microns

100 nanometer gaps
500 nanometer guides
2.5 micron height
Resonator-Enhanced Mach-Zehnder Interferometers

~100 nanometer gaps  500 nanometer guides  2.5 micron height
Laboratory Characterization of Photonic Structures

• Characterization of fiber ring-resonator devices (Proof of principle studies)

• Characterization of nanofabricated devices
Fiber optical delay line:

First study one element of optical delay line:

variable wavelength pulse
Transmission Characteristics of Fiber Ring Resonator

Measure transmission vs. $\lambda$ for various values of the finesse

- overcoupled
- critically coupled
- undercoupled

circumference = 31 cm
Laboratory Characterization of Photonic Structures

• Characterization of fiber ring-resonator devices (Proof of principle studies)

• Characterization of nanofabricated devices
Microresonator-Based Add-Drop Filter

output for on-resonance input

variable wavelength input

output for off-resonance input

transmission

wavelength (micrometers)
Phase Characteristics of Micro-Ring Resonator

Transmission

Induced phase shift

(normalized linear transmission)

(wavelength (microns))

(effective phase shift)

(wavelength (microns))
All-Optical Switching in a Microresonator-Enhanced Mach-Zehnder Interferometer

increasing pulse energy (~1 nJ)

output intensity (arb. units)

output position (x)

output port #1

output port #2
Summary

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

Argue that artificial materials hold great promise for applications in photonics because of

• large controllable nonlinear response
• large dispersion controllable in magnitude and sign
Special Thanks to my Students and Research Associates
Thank you for your attention.
Photonic Structures -- What Next?
Performance of SCISSOR as Optical Delay Line

Input (duty factor = 1/3)

Output --delayed one time slot by six resonators in linear limit

Output --delayed four time slots by 26 resonators in linear limit

Output --delayed four time slots by 26 resonators in nonlinear limit
Frequency Dependence of GVD and SPM Coefficients

\[
\begin{align*}
\frac{k''_{\text{eff}}}{(2FT/\pi)^2/L} & \quad \text{(GVD)} \\
\gamma_{\text{eff}} & \gamma(2F/\pi)^2 (2\pi R/L) \quad \text{(SPM)} \\
\end{align*}
\]

soliton condition

normalized detuning, \( \phi_0 \)
5 μm diameter resonators with a finesse of 30

SCISSOR may be constructed from 100 resonators spaced by 10 μm for a total length of 1 mm

Soliton may be excited via a 10 ps, 125mW pulse

Simulation assumes a chalcogenide/GaAs-like nonlinearity
Dark Solitons

SCISSOR system also supports the propagation of dark solitons.
SCISSOR Dispersion Relations

Single-Guide SCISSOR
No bandgap
Large intensity buildup

Double-Guide SCISSOR
Bandgaps occur
Reduced intensity buildup

wavelength (μm)

20 0 -π/L -π/2L π/2L π/L

intensity build-up Bloch vector (k_{eff})

separation = 1.5 π R

Bragg + resonator gap
resonator gap
Bragg gap
Phase Characteristics of Fiber Ring Resonator

Place ring resonator inside Mach-Zhender interferometer and measure transmission versus wavelength.

![Diagram showing transmission vs. wavelength for different coupling conditions: undercoupled, critically coupled, and overcoupled.](image)
Phase Characteristics of Fiber Ring Resonator

Extracted phase structure

- **Critically coupled**
- **Undercoupled**
- **Overcoupled**

![Extracted phase structure diagram](image)

Graphs showing phase vs. wavelength detuning for different coupling conditions:

- $F = 51$
- $F = 40$
- $F = 30$
- $F = 17$
- $F = 12$
- $F = 7.3$
- $F = 6.8$
- $F = 4.4$

Graphs illustrate phase changes with increasing wavelength detuning for each coupling condition.
"Fast" (Superluminal) Light in SCISSOR Structures

Requires **loss** in resonator structure