“Everything Photonic”

or

Slow Light, Enhanced Optical Nonlinearities, and Photonic Biosensors based on Quantum Coherence and on Artificial Optical Materials

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Prospectus

Introduction to Slow Light and to Nonlinear Optics
Slow Light in Ruby
Slow Light in Artificial Materials
Slow-Light and Enhanced Optical Nonlinearities
Devices Based on Slow Light Concepts
Photonic Biosensors
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
Chapter 6

"Slow" and "fast" light

by

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Slow Light

group velocity $\neq$ phase velocity
**Group Velocity**

Pulse (wave packet) \[ \rightarrow \mathbf{v}_g \]

Group velocity given by \[ \mathbf{v}_g = \frac{d\mathbf{w}}{d\mathbf{k}} \]

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

Thus \[ \mathbf{v}_g = \frac{c}{n + \mathbf{w} \frac{dn}{dw}} = \frac{c}{n_g} \]

Thus \( n_g \neq n \) in a dispersive medium!
- Want $U_g$ very different from $U_p$
Need very large dispersion
Study resonances of atomic vapor

$$U_g = \frac{c}{n + w \frac{dn}{dw}}$$
Light Propagation in Atomic Vapors

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

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

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

\[ n'' = \frac{\pi Ne^2}{2mw_0\gamma} \frac{\gamma^2}{(w_0 - w)^2 + \gamma^2} \]

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

\[ \frac{\omega S_n^{(\text{max})}}{\gamma} \approx \frac{2\pi(5 \times 10^{14})(0.1)}{2\pi(1 \times 10^9)} = 5 \times 10^4 \approx (1) \]

\( n_g \) 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

$$n_g \approx 1 + \frac{\omega S n^{(\text{max})}}{\gamma}$$

Use nonlinear optics to

1) decrease line width $\gamma$  
   (produce sub-Doppler linewidth)

2) decrease absorption
   (so transmitted pulse is detectable)
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 $dn/d\omega$. (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 $T_2 \ll T_1$. 
Spectral Holes in Homogeneously Broadened Materials

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

Spectral Holes Due to Population Oscillations

Population inversion:

\[ (\rho_{bb} - \rho_{aa}) = w \]

\[ w(t) = w^{(0)} + w^{(-\delta)} e^{i\delta t} + w^{(\delta)} e^{-i\delta t} \]

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:

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

linewidth \( \beta = (1 / T_1)(1 + \Omega^2 T_1 T_2) \)
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, $v = 60$ m/s and $n_g = 5 \times 10^6$
Gaussian Pulse Propagation Through Ruby

No pulse distortion!

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

$ng = 2 \times 10^6$
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
Motivation

To exploit the ability of microresonators to enhance nonlinearities and induce strong dispersive effects for creating structured waveguides with exotic properties.

A cascade of resonators side-coupled to an ordinary waveguide can exhibit:

- slow light propagation
- induced dispersion
- enhanced nonlinearities
Ultrafast All-Optical Switch Based On Arsenic Triselenide Chalcogenide Glass

- We excite a whispering gallery mode of a chalcogenide glass disk.

- The nonlinear phase shift scales as the square of the finesse $F$ of the resonator. ($F \approx 10^2$ in our design)

- Goal is 1 pJ switching energy at 1 Tb/sec.

(implementation with Dick Slusher, Lucent)
NLO of SCISSOR Devices
(Side-Coupled Integrated Spaced Sequence of Resonators)

Displays slow-light, tailored dispersion, and optical solitons. Description by NL Schrodinger eqn. in continuum limit.

- Pulses spread when only dispersion is present
- But form solitons through balance of dispersion and nonlinearity

(J.E. Heebner, Q-Han Park and RWB)
Slow Light and SCISSOR Structures

\[
\frac{2\pi}{\omega} = \frac{c}{FnR} \\
\frac{k_{\text{eff}} - k_0}{L} = \frac{Fn}{c} \\
\frac{2\pi}{\omega} = \frac{c}{FnR} \\
\frac{n}{nR} = \frac{c}{nR} \\
\text{frequency, } \omega
\]
What is the relation between slow light and enhanced optical nonlinearity?

Comment: We know that there is a connection from the work of Hau, Harris, Lukin, Soljacic, Scully, Imamoglu, Bennink and many others.

Note: For $n\text{ (phase)} \approx 1$, there is no enhancement of the electric field within the material. Thus the enhancement must be of $\chi^{(3)}$, not of $E$.

Possible explanation: In a slow light situation, the light spends more time interacting with the medium. Can this be the explanation for enhanced nonlinearity? (Ans: Yes and no.)

If this were the whole story, we would expect $\chi^{(3)}$, to scale in proportion to the group index $n\text{ (group)}$, which it does in some but not all situations.
What is the relation between slow light and enhanced optical nonlinearity?

The scaling laws seem to be very different for EIT media than for structured artificial materials (PBG, CROWs, SCISSORSs, etc), because in the latter case the E field is enhanced.

To first approximation:

- For EIT: $\chi^{(3)}$ scales as $n(\text{group})$
- For artificial materials: $\chi^{(3)}$ scales as the square of $n(\text{group})$
Detailed analyses of the relation between slow light and enhanced optical nonlinearity

- Heebner and Boyd show that the nonlinear phase shift scales as the square of the finesse of a ring resonator. Since $n_{\text{group}}$ scales as the finesse, it follows that $\phi_{\text{NL}}$ scales as the square of $n_{\text{group}}$.

- Lukin points out that the nonlinear phase shift can be expressed as $\phi_{\text{NL}} = \delta \omega T$, where $T = L / (c / n_g)$ is the interaction time and where 
  
  $$
  \delta \omega = \mu^2 E^2 / (h/2\pi)^2 \Delta
  $$

  is the Stark shift of the optical transition. This model predicts that $\phi_{\text{NL}}$ scales as $n_{\text{group}}$. 


Unwanted Complication in Two-Level-Atom EIT

Response in absence of control field ($\Omega_c = 0, \gamma = 0.5$)

Response with a moderate, centrally tuned control field ($\Omega_c = 2, \Delta_c = 0, \gamma = 0.5$)

Im $\chi^{(3)}$ is proportional to $n g$, but Re $\chi^{(3)}$ is not.

Response with a stronger, detuned control field ($\Omega_c = 9, \Delta_c = 3, \gamma = 0.5$)

What is the relation between slow light and enhanced optical nonlinearity?

Summary: This remains a somewhat open question.
Nanofabrication

- Materials (artificial materials)
- Devices

(distinction?)
Photonic Devices in GaAs/AlGaAs
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
"Fast" (Superluminal) Light in SCISSOR Structures

Requires **loss** in resonator structure

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

**Graphs:**
- **Frequency detuning, \( \omega - \omega_R \)**
- **Power (arb. units)**
- **Delay (ps)**

**Equations:**
- \( k_{\text{eff}} - k_0 \frac{2\pi}{L} \)
- \( \delta \omega \)
- \( \text{(time-advanced) propagation through undercoupled SCISSOR} \)
- \( \text{propagation through vacuum} \)
Frequency Dependence of GVD and SPM Coefficients

\[ k''_{\text{eff}} \left( \frac{2F T}{\pi} \right)^2 / L \]

(soliton condition)

\[ \gamma_{\text{eff}} \left( \frac{2F}{\pi} \right)^2 \left( \frac{2\pi R}{L} \right) \]

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

**Soliton Propagation**

**Weak Pulse**

- Pulse disperses

**Fundamental Soliton**

- Pulse preserved
Dark Solitons

SCISSOR system also supports the propagation of dark solitons.
Optical Power Limiting in a Nonlinear Mach-Zehnder Interferometer
**Objective:**
Obtain high sensitivity, high specificity detection of pathogens through optical resonance

**Approach:**
Utilize high-finesse whispering-gallery-mode disk resonator.

Presence of pathogen on surface leads to dramatic decrease in finesse.

**Simulation of device operation:**
Intensity distribution in absense of absorber.  
Intensity distribution in presence of absorber.

FDTD
Deposition of Surface Binding Layer

1) Bare device surface

2) SiO$_2$ layer deposited by PECVD

3) Silane coupling agent deposited on surface

4) Antibodies washed over surface / adhere to MPT

5) Pathogen captured by antibody layer
Demonstration of Selective Binding onto GaAs

biotin on GaAs

streptavidin over biotin on GaAs

biotin on silica-coated GaAs

streptavidin over biotin on silica-coated GaAs

biotin on microscope slide

streptavidin over biotin on microscope slide

Notes: 1. false-color images of fluorescent intensity are shown
2. streptavidin is tagged with the dye Cy3

University of Rochester/Corning Collaboration
Summary

Artificial materials hold great promise for applications in photonics because of

• large controllable nonlinear response
• large dispersion controllable in magnitude and sign

Demonstration of slow light propagation in ruby
Thank you for your attention.
SCISSOR Dispersion Relations

**Single-Guide SCISSOR**
- No bandgap
- Large intensity buildup

**Double-Guide SCISSOR**
- Bandgaps occur
- Reduced intensity buildup

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**Single-Guide SCISSOR**
- No bandgap
- Large intensity buildup

**Double-Guide SCISSOR**
- Bandgaps occur
- Reduced intensity buildup

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**Graphs:**
- **wavelength (μm):** 1.498, 1.522, 1.546, 1.571, 1.597
- **Intensity build-up:** 20, 0, \(-\frac{\pi}{L}\), \(-\frac{\pi}{2L}\), \(\frac{\pi}{2L}\), \(\frac{\pi}{L}\)
- **Bloch vector \(k_{\text{eff}}\):**
- **Graph features:**
  - Bragg gap
  - Resonator gap
  - Separation = 1.5 \(\pi R\)
**Optical Logic On A Chip**

- **Pathogen**
  - none: Out(1) = 1, Out(2) = 0
  - P(1): Out(1) = 1, Out(2) = 1
  - P(2): Out(1) = 1, Out(2) = 1
  - P(1) and P(2): Out(1) = 0, Out(2) = 0
Is This a Good Idea?

Protein detection by optical shift of a resonant microcavity

Nonlinear optical techniques hold great promise for applications including:

- Photonic Devices
- Quantum Imaging
- Quantum Computing/Communications
- Optical Switching
- Optical Power Limiters
- All-Optical Image Processing

But the lack of high-quality photonic materials is often the chief limitation in implementing these ideas.
Approaches to the Development of Improved NLO Materials

- New chemical compounds
- Quantum coherence (EIT, etc.)
- Composite Materials:
  (a) Microstructured Materials, e.g. Photonic Bandgap Materials, Quasi-Phasematched Materials, etc
  (b) Nanocomposite Materials

These approaches are not incompatible and in fact can be exploited synergistically!
Nanocomposite Materials for Nonlinear Optics

• Maxwell Garnett

• Bruggeman (interdispersed)

• Fractal Structure

• Layered

scale size of inhomogeneity $\ll$ optical wavelength
Gold-Doped Glass

A Maxwell-Garnett Composite

gold volume fraction approximately $10^{-6}$
gold particles approximately 10 nm diameter

- Composite materials can possess properties very different from their constituents.
- Red color is because the material absorbs very strongly at the surface plasmon frequency (in the blue) -- a consequence of local field effects.
Demonstration of Enhanced NLO Response

- Alternating layers of TiO$_2$ and the conjugated polymer PBZT.
- Measure NL phase shift as a function of angle of incidence.

\[ \nabla \cdot \mathbf{D} = 0 \text{ implies that } (\varepsilon \mathbf{E})_\perp \text{ is continuous.} \]

Thus field is concentrated in lower index material.

Enhanced EO Response of Layered Composite Materials

\[ \chi_{ijkl}^{(eff)}(\omega', \omega, \Omega_1, \Omega_2) = \frac{1}{f_a} \left[ \frac{\varepsilon_{eff}(\omega')}{\varepsilon_a(\omega')} \right] \left[ \frac{\varepsilon_{eff}(\omega)}{\varepsilon_a(\omega)} \right] \left[ \frac{\varepsilon_{eff}(\Omega_1)}{\varepsilon_a(\Omega_1)} \right] \left[ \frac{\varepsilon_{eff}(\Omega_2)}{\varepsilon_a(\Omega_2)} \right] \chi_{ijkl}^{(a)}(\omega'; \omega, \Omega_1, \Omega_2) \]

- **AF-30 (10%)** in polycarbonate (spin coated)
  \[ n=1.58 \quad \varepsilon(\text{dc}) = 2.9 \]
- **barium titante** (rf sputtered)
  \[ n=1.98 \quad \varepsilon(\text{dc}) = 15 \]

\[ \chi_{zzzz}^{(3)} = (3.2 + 0.2i) \times 10^{-21} (m / V)^2 \pm 25\% \]

3.2 times enhancement in agreement with theory

Accessing the Optical Nonlinearity of Metals with Metal-Dielectric PBG Structures

- Metals have very large optical nonlinearities but low transmission.
- Low transmission is because metals are highly reflecting (not because they are absorbing!).
- Solution: construct metal-dielectric PBG structure.
  (linear properties studied earlier by Bloemer and Scalora)

40 times enhancement of NLO response is predicted!

Open-aperture Z-scan
(measures $\text{Im} \chi^{(3)}$)

$I = 500 \text{ MW/cm}^2$
$\lambda = 640 \text{ nm}$
Spectral Dependence of the Nonlinear Response

- PBG
- Bulk

OPG:
- $t = 25$ ps
- $Q = 2$ to $5$ mJ
- $I \approx 100$ MW/cm$^2$
By arranging a spaced sequence of resonators, side-coupled to an ordinary waveguide, one can create an effective, structured waveguide that supports pulse propagation in the NLSE regime.

Propagation is unidirectional, and there is NO photonic bandgap to produce the enhancement. Feedback is intra-resonator and not inter-resonator.

Nonlinear Schrödinger Equation (NLSE)
\[ \frac{\partial}{\partial z} A = -i \frac{1}{2} \beta_2 \frac{\partial^2}{\partial t^2} A + i \gamma |A|^2 A \]

Fundamental Soliton Solution
\[ A(z,t) = A_0 \text{sech} \left( \frac{t}{T_p} \right) e^{i \frac{1}{2} \gamma |A_0|^2 z} \]
Balancing Dispersion & Nonlinearity

Resonator-induced dispersion can be 5-7 orders of magnitude greater than the material dispersion of silica!

Resonator enhancement of nonlinearity can be 3-4 orders of magnitude!

An enhanced nonlinearity may be balanced by an induced anomalous dispersion at some detuning from resonance to form solitons

A characteristic length, the soliton period may as small as the distance between resonator units!

\[
A_0 = \sqrt{\frac{|\beta_2|}{\gamma T_p^2}} = \sqrt{\frac{T^2}{\sqrt{3} \gamma 2\pi R T_p^2}}
\]

adjustable by controlling ratio of transit time to pulse width
Microdisk Resonator Design

(Not drawn to scale)
All dimensions in microns

0.25
0.45
2.0
trench
trench

s1 = 0.08
s2 = 0.10
s3 = 0.12
s4 = 0.20

d = 10.5

J. E. Heebner and R. W. Boyd
Pulse Distortion on Propagation through SCISSOR Structure

Maximum delay, but pulse distorted by higher-order dispersion.

Slightly reduced delay, no distortion, but spreading due to GVD.

Slightly reduced delay, no distortion, SPM compensates for spreading

Graphs showing:
- Weak pulse, on resonance
- Weak pulse, at GVD extremum
- Strong pulse, at GVD extremum
Photonic Device Fabrication Procedure

1. MBE growth
   - AlGaAs-GaAs structure

2. Deposit oxide
   - Oxide (SiO₂)
   - AlGaAs-GaAs structure

3. Spin-coat e-beam resist
   - PMMA
   - Oxide (SiO₂)
   - AlGaAs-GaAs structure

4. Pattern inverse with e-beam & develop
   - PMMA
   - Oxide (SiO₂)
   - AlGaAs-GaAs structure

5. RIE etch oxide
   - PMMA
   - Oxide (SiO₂)
   - AlGaAs-GaAs structure

6. Remove PMMA
   - Oxide (SiO₂)
   - AlGaAs-GaAs structure

7. CAIBE etch AlGaAs-GaAs
   - Oxide (SiO₂)
   - AlGaAs-GaAs structure

8. Strip oxide
   - AlGaAs-GaAs structure

RWB - 10/4/01
Properties of a Single Microresonator

Assuming negligible attenuation, this resonator is, unlike a Fabry-Perot, of the "all-pass" device - there is no reflected or drop port.

\[
\begin{pmatrix}
E_4 \\
E_2
\end{pmatrix} = \begin{pmatrix}
r & it \\
it & r
\end{pmatrix} \begin{pmatrix}
E_3 \\
E_1
\end{pmatrix}
\]

Intensity Enhancement (\(|E_3/E_1|^2\))

Build-up Factor \(|E_3/E_1|^2\)

- \(r^2 = 0.75\)
- \(r^2 = 0.90\)
- \(r^2 = 0.00\)
- \(r^2 = 0.25\)

Modified Dispersion Relation (\(\beta\) vs. \(\omega\))

- \(r^2 = 0.00\)
- \(r^2 = 0.75\)
- \(r^2 = 0.25\)
- \(r^2 = 0.90\)

Definitions

- Finesse \(F = \frac{\pi}{1-r}\)
- Transit Time \(T = \frac{n2\pi R}{c}\)