Perspectives on Nonlinear Optics

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Nonlinear Optical Interactions

Light-by-Light Scattering

Phase Conjugation by Degenerate Four-Wave Mixing
Nanocomposite Materials for Nonlinear Optics

- Maxwell Garnett
  \[ \varepsilon^i \rightarrow \varepsilon^h \]

- Bruggeman (interdispersed)
  \[ \varepsilon_a \quad \varepsilon_b \]

- Fractal Structure

- Layered
  \[ \varepsilon_a \quad \varepsilon_b \]

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.
First Demonstration of Enhanced NLO Response

Alternating layers of TiO$_2$ and the conjugated polymer PBZT.

Measure NL phase shift as a function of the angle of incidence.

Enhanced EO Response of Layered Composite Materials

\[ \chi^{(eff)}_{ijkl}(\omega';\omega,\Omega_1,\Omega_2) = f_a \left[ \frac{\varepsilon^{(eff)}_{ij}(\omega')}{\varepsilon_{ij}(\omega')} \frac{\varepsilon^{(eff)}_{kl}(\omega)}{\varepsilon_{kl}(\omega)} \frac{\varepsilon^{(eff)}_{ij}(\Omega_1)}{\varepsilon_{ij}(\Omega_1)} \frac{\varepsilon^{(eff)}_{kl}(\Omega_2)}{\varepsilon_{kl}(\Omega_2)} \right] \chi^{(a)}_{ijkl}(\omega';\omega,\Omega_1,\Omega_2) \]

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

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

\[ \approx 3.2 \chi^{(3)}_{zzzz} (\text{AF-30} / \text{polycarbonate}) \]

3.2 times enhancement in agreement with theory

“Slow” Light in Nanostructured Devices

Robert W. Boyd

with

John Heebner, Nick Lepeshkin, Aaron Schweinsberg, and Q-Han Park

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Presented at PQE-2002
Nanofabrication

• Materials (artificial materials)

• Devices

  (distinction?)
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.
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.

A Real Whispering Gallery

St. Paul's Cathedral, London
**Alliance for Nanomedical Technologies**

**Photonic Devices for Biosensing**

**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 absence of absorber.
- Intensity distribution in presence of absorber.

FDTD
Microdisk Resonator Design

(Not drawn to scale)
All dimensions in microns

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
Nonlinear Optical Loop-De-Loop

J.E. Heebner and R.W.B.
Photonic Devices Written into PMMA Resist
Pattern Etched Into Silica Mask
Photonic Devices in GaAs/AlGaAs
Some Underlying Issues in Nonlinear Optics

- Self-Assembly/Self-Organization in Nonlinear Systems
- Stability vs. Instability (and Chaos) in Nonlinear Systems
Experimental Study of Soliton Propagation through 40 km of Dispersion-Decreasing Fiber

Andrew J. Stentz, Robert W. Boyd, University of Rochester
Alan F. Evans, Corning Inc.

- Solitons propagate without spreading because of exact balance between group velocity dispersion (GVD) and self-phase modulation (SPM).

$$i \frac{\partial U}{\partial \xi} = \text{sgn}(\beta_2) \frac{1}{2} \frac{\partial^2 U}{\partial \tau^2} - N^2 |U|^2 U$$

- Even the small attenuation (0.2 dB/km) of communications fibers can upset this local balance and lead to pulse spreading.

- Solution is to use a tapered fiber (15% in 40 km) so that the GVD decreases at the same rate as the pulse energy.
Chaos in Sodium Vapor

PRL 58, 2432 (1987); 61, 1827 (1988); 64 1721 (1990).
Laser Beam Filamentation

Spatial growth of wavefront perturbations

Fig. 17.2 Image of small-scale filaments at the exit windows of a CS$_2$ cell created by self-focusing of a multimode laser beam. [After S. C. Abbi and H. Mahr, Phys. Rev. Lett. 26, 604 (1971).]
Honey Comb Pattern Formation

Robert W. Boyd and C. R. Stroud, Jr., University of Rochester

Output from cell with single gaussian beam input

Exiting beam  |  Far field pattern

Quantum image?

Input power 150 mW
Input beam diameter 0.22 mm
$\lambda = 588.995 \text{ nm}$

Sodium vapor cell
T = 220° C
Spontaneous Pattern Formation in Sodium Vapor

A sodium vapor may be thought of as a medium composed of two-level atoms. Light whose frequency is near the atomic transition frequency experiences a refractive index \( n \) which depends strongly on the intensity \( I \):

\[
 n = 1 + \frac{1}{2} \left( 1 + \frac{0}{I/I_{\text{sat}}} \right)
\]

Since light refracts in the direction of increasing index, in a medium with negative saturable nonlinearity it refracts toward regions of higher intensity. This causes smooth beams to narrow or self-focus. But it also tends to destabilize a beam as small amplitude fluctuations grow due to local self-focusing. Thus beams with even small amplitude noise can spontaneously split into two or more separate beams.

\(^0\)For sodium at 200°C, \( c_0 \approx -0.05 \) and \( I_{\text{sat}} \approx 6 \text{ mW/cm}^2 \)

A simulation of spontaneous break-up into 3 stable beams:

![Simulation of spontaneous break-up into 3 stable beams](image)

Experimental observation of spontaneous break-up resulting in a striking far-field pattern:

![Experimental observation of spontaneous break-up](image)

beam entering sodium  
beam leaving sodium  
far-field pattern

*Pictures taken by R. Bennink, S. Lukisbova, and V. Wong.*
Experiment in Self Assembly

Joe Davis, MIT