Nanostructured Artificial Materials for Photonics

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with

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Prospectus

Introduction to Nonlinear Optics

Development of New NLO Materials

Development of New Photonic Devices
What is Nonlinear Optics?

\[ P = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \]

- \( \chi^{(1)} \): linear optics, e.g.,

- \( \chi^{(2)} \): second-order effects, e.g., second-harmonic generation

\[ \omega \rightarrow \square \rightarrow 2\omega \]

- \( \chi^{(3)} \): third-order effects, e.g.

- Four-wave mixing
- Intensity-dependent refractive index

\[ n = n_0 + n_2 E \]

\[ n_2 = \frac{12 \pi^2}{n_0^2 c} \chi^{(3)} \]
The Promise of Nonlinear Optics

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-Phase-matched 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 TiO₂ and the conjugated polymer PBZT.

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

Thus field is concentrated in lower index material.

- Measure NL phase shift as a function of angle of incidence

Enhanced EO Response of Layered Composite Materials

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

- AF-30 (10%) in polycarbonate (spin coated)
  \( n=1.58 \quad \varepsilon(\text{dc}) = 2.9 \)
- barium titante (rf sputtered)
  \( n=1.98 \quad \varepsilon(\text{dc}) = 15 \)
  \( \chi_{zzzz}^{(3)} = (3.2 + 0.2i) \times 10^{-21} \ (m / V)^2 \pm 25\% \)
  \( \approx 3.2 \chi_{zzzz}^{(3)} \) (AF-30 / polycarbonate)

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!

Nanofabrication

- Materials (artificial materials)
- Devices

(distinction?)
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)
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)
A Real Whispering Gallery

St. Paul's Cathedral, London
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

RWB - 10/4/01
Photonic Devices Written into PMMA Resist
**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.

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**Simulation of device operation:**

Intensity distribution in absence of absorber.

Intensity distribution in presence of absorber.

FDTD
Is This a Good Idea?

Protein detection by optical shift of a resonant microcavity

Deposition of Surface Binding Layer

1) Bare device surface

GaAs or AlGaAs

2) SiO2 layer deposited by PECVD

~300 nm

GaAs or AlGaAs

SiO2

3) Silane coupling agent deposited on surface

~1.2 nm

Silane coupling agent

3-Mercaptopropyl
Trimethoxysilane (MPT)
(C₆H₁₆O₃SSi)

GaAs or AlGaAs

SiO2

4) Antibodies washed over surface / adhere to MPT

~12 nm

Antibodies

GaAs or AlGaAs

SiO2

5) Pathogen captured by antibody layer

~1-5 microns

Pathogen

target

GaAs or AlGaAs

SiO2
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
Optical Logic On A Chip

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