Progress in Slow Light and Quantum Imaging

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with Aaron Schweinsberg, Hye Jeong Chang, Colin O’Sullivan-Hale
Petros Zerom, Giovanni Piredda, Zhimin Shi, Heedeuk Shin, and others.

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Interest in Slow Light

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

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

Implications for quantum information

And what about fast light ($v > c$ or negative)?

All-Optical Switch

But what happens if two data packets arrive simultaneously?

Controllable slow light for optical buffering can dramatically increase system performance.

Use Optical Buffering to Resolve Data-Packet Contention

input ports  switch  output ports

Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester
Challenge/Goal

Slow light in a room-temperature solid-state material.

Possible approaches:
1. Slow light based on photonic crystals
2. Slow light based on stimulated light scattering

My approach: Slow light enabled by coherent population oscillations (a quantum coherence effect that is relatively insensitive to dephasing processes).
Recall that \( n_g = n + \omega (dn/d\omega) \). Need a large \( dn/d\omega \). (How?)

Kramers-Kronig relations:
Want a very narrow feature in absorption line.

Well-known “trick” for doing 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).
Spectral Holes in Homogeneously Broadened Materials

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


pump-probe detuning (units of $1/T_2$)
Argon Ion Laser

Function Generator

EO modulator

Digital Oscilloscope

Reference Detector

Signal Detector

40 cm

Ruby

Pinhole

7.25-cm-long 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!

\[ v = 140 \text{ m/s} \]
\[ n_g = 2 \times 10^6 \]
Advantages of Coherent Population Oscillations for Slow Light

- Works in solids
- Works at room temperature
- Insensitive of dephasing processes
- Laser need not be frequency stabilized
- Works with single beam (self-delayed)
- Delay can be controlled through input intensity
Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

Inverse-Saturable Absorption Produces Superluminal Propagation in Alexandrite

At 476 nm, alexandrite is an inverse saturable absorber

Negative time delay of 50 $\mu$s corresponds to a velocity of -800 m/s

M. Bigelow, N. Lepeshkin, and RWB, Science, 2003
Numerical Modeling of Pulse Propagation Through Slow and Fast-Light Media

Numerically integrate the paraxial wave equation

$$\frac{\partial A}{\partial z} - \frac{1}{v_g} \frac{\partial A}{\partial t} = 0$$

and plot $A(z,t)$ versus distance $z$.

Assume an input pulse with a Gaussian temporal profile.

Study three cases:

- Slow light $v_g = 0.5 \ c$
- Fast light $v_g = 5 \ c$ and $v_g = -2 \ c$
Pulse Propagation through a Slow-Light Medium ($n_g = 2, \ v_g = 0.5 \ c$)
Pulse Propagation through a Fast-Light Medium ($n_g = .2$, $v_g = 5 \ c$)
Pulse Propagation through a Fast-Light Medium ($n_g = -0.5$, $v_g = -2 \, c$)
Some New Results
Slow and Fast Light in an Erbium Doped Fiber Amplifier

- Fiber geometry allows long propagation length
- Saturable gain or loss possible depending on pump intensity

![Graph showing fractional advancement vs. modulation frequency with different power levels.](image)

Advance = 0.32 ms
FWHM = 1.8 ms
PbS Quantum Dots (2.9 nm diameter) in liquid solution
Excite with 16 ps pulses at 795 nm; observe 3 ps delay
30 ps response time (literature value)
Limits on the Time Delay Induced by Slow-Light Propagation

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See also Phys. Rev. A 71, 023801 (2005)
Motivation: Maximum Slow-Light Time Delay

“Slow light”: group velocities < $10^{-6}$ c

Proposed applications: controllable optical delay lines, optical buffers, true time delay for synthetic aperture radar.

Key figure of merit:
normalized time delay = total time delay / input pulse duration
≈ information storage capacity of medium

Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

But data packets used in telecommunications contain ≈ $10^3$ bits

What are the prospects for obtaining slow-light delay lines with $10^3$ bits capacity?
Exciting possibilities exist for optical buffering and other photonics applications if normalized time delays in the range of 10 – 1000 can be achieved.

There are no fundamental limitations to the maximum normalized pulse delay.

However, there are serious practical limitations, primarily associated with residual absorption.

To achieve a longer fractional delay saturate deeper to propagate farther.

Exciting possibilities exist for optical buffering and other photonics applications if normalized time delays in the range of 10 – 1000 can be achieved.

Next: Find material with faster response (semiconductors?) (to allow delay of shorter pulses)
Prospects for Large Fractional Delays Using CPO

\( \omega + \delta \rightarrow \omega \)

collection of two-level atoms \( \omega + \delta \rightarrow \omega \)

Strong pumping leads to high transparency, large bandwidth, and increased fractional delay.

Boyd et al., Laser Physics 2005.
Can images be formed with higher resolution or better sensitivity through use of quantum states of light?

Can we "beat" the Rayleigh criterion?

Quantum states of light: For instance, squeezed light or entangled beams of light.
Ghost (Coincidence) Imaging

- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

Progress in Quantum Lithography


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Quantum Lithography

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit.
- Process “in reverse” performs sub-Rayleigh microscopy, etc.
- Resolution $\approx \frac{\lambda}{2N}$, where $N$ = number of entangled photons.

("al." includes Jon Dowling)
Quantum Lithography: Easier Said Than Done

• Need an intense source of individual biphotons (Inconsistency?)
  Maybe a high-gain OPA provides the best tradeoff between high intensity and required quantum statistics

• Need an $N$-photon recording material
  For proof-of-principle studies, can use $N$-th-harmonic generator, correlation circuitry, $N$-photon photodetector.
  For actual implementation, use ????
  Maybe best bet is UV lithographic material excited in the visible or a broad bandgap material such as PMMA excited by multiphoton absorption.

3PA in PMMA breaks chemical bond, modifying optical properties.
Non-Quantum Quantum Lithography

Concept: average $M$ shots with the phase of shot $k$ given by $2\pi k/M$

Spatial Resolution of Various Systems

• Linear optical medium
  \[ E = 1 + \cos kx \]

• Two-photon absorbing medium, classical light
  \[
  E = (1 + \cos kx)^2 = 1 + 2 \cos kx + \cos^2 kx \\
  = \frac{3}{2} + 2 \cos kx + \frac{1}{2} \cos 2kx
  \]

• Two-photon absorbing medium, entangled photons
  \[ E = 1 + \cos 2kx \]

where \( k = 2(\omega/c) \sin \theta \)
Demonstration of Fringes Written into PMMA

\[ \theta = 70 \text{ degrees} \]

write wavelength = 800 nm

pulse energy = 130 \( \mu \text{J} \) per beam

pulse duration = 120 fs

period = \( \frac{\lambda}{2 \sin \theta} \) = 425 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water

PMMA is a standard lithographic material
Demonstration of Sub-Rayleigh Fringes (Period = $\lambda/4$)

$\theta = 70$ degrees

two pulses with 180 deg phase shift
write wavelength = 800 nm
pulse energy = 90 $\mu$J per beam
fundamental period = $\lambda / (2 \sin \theta) = 425$ nm
period of written grating = 212 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water
Significance of PMMA Grating Results

• Provides an actual demonstration of sub-Rayleigh resolution by the phase-shifted grating method

• Demonstrates an N-photon absorber with adequate resolution to be of use in true quantum lithography
Quantum Lithography Prospects

Quantum lithography (as initially proposed by Dowling) has a good chance of becoming a reality.

Classically simulated quantum lithography may be a realistic alternative approach, and one that is much more readily implemented.
Special Thanks to My Students and Research Associates
Thank you for your attention!

Our results are posted on the web at:

http://www.optics.rochester.edu/~boyd