Quantum Nonlinear Optics: Nonlinear Optics Meets the Quantum World

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Quantum Nonlinear Optics: 
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Outlook: NLO is a superb platform from which to explore new physical processes and to develop photonics applications.

Prospectus

1. Introduction to Nonlinear Optics and Quantum NLO
2. New Applications of “Slow Light”
3. Möbius Strips of Polarization
4. Huge Optical Nonlinearity in Epsilon-Near-Zero Materials
5. Quantum Communication with Multiple Bits per Photon
Simple Formulation of the Theory of Nonlinear Optics

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

Here \( P \) is the induced dipole moment per unit volume and \( E \) is the field amplitude. 
\( \chi^{(1)} \) describes linear optics, e.g., how lenses work: 
\[ \xrightarrow{\omega} \chi^{(2)} \xrightarrow{2\omega} \]
\( \chi^{(2)} \) describes second-order effects, e.g., second-harmonic generation (SHG)

\( \chi^{(3)} \) describes third-order effects such as third-harmonic generation, four-wave mixing, and the intensity dependence of the index of refraction.

THG \[ \xrightarrow{\omega} \chi^{(3)} \xrightarrow{3\omega} \]

FWM \[ \xrightarrow{\chi^{(3)}} \]

NL index
\[ n = n_0 + n_2 I \quad \text{where} \quad n_2 = \frac{3}{4n_0^2 \varepsilon_0 c} \chi^{(3)} \]
The elementary process of light-by-light scattering has never been observed in vacuum, but is readily observed using the nonlinear response of material systems.

Nonlinear material is fluorescein-doped boric acid glass (FBAG)

\[ n_2(\text{FBAG}) \approx 10^{14} n_2(\text{silica}) \quad \text{[But very slow response!]} \]

Intense Field and Attosecond Physics

Above Threshold Ionization Beyond the High Harmonic Cutoff

K. J. Schafer (1) Baorui Yang, (2) L. F. DiMauro, (2) and K. C. Kulander (1)
(1) Lawrence Livermore National Laboratory, Livermore, California 94550
(2) Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 2 December 1992)

Plasma Perspective on Strong-Field Multiphoton Ionization

P. B. Corkum
National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6
(Received 9 February 1993)

I > 10^{15} \text{ W/cm}^2

High-harmonic generation

Measuring the molecular nitrogen wavefunction

Attosecond pulses to sample a visible E-field; F. Krausz
Why Interest in Quantum Nonlinear Optics?

Explore the relation between traditional nonlinear optics (NLO) and phenomena in quantum information science (QIS).

QIS holds great promise for secure communication, quantum logic, quantum computing, etc.

Many processes in QIS rely on nonlinear optical interactions.
Parametric Downconversion: A Source of Entangled Photons

The signal and idler photons are entangled in:
(a) polarization
(b) time and energy
(c) position and transverse momentum
(d) angular position and orbital angular momentum

Entanglement is important for:
(a) Fundamental tests of QM (e.g., nonlocality, Bell tests)
(a) Quantum technologies (e.g., secure communications, Q teleportation)
• We discriminate among four orthogonal images using single-photon interrogation in a coincidence imaging configuration.

• Note that a single photon can carry more than one bit of information.

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“Slow,” “Fast” and “Backwards” Light

– Light can be made to go:
  slow: \( v_g \ll c \) (as much as \( 10^6 \) times slower!)
  fast: \( v_g > c \)
  backwards: \( v_g \) negative

Here \( v_g \) is the group velocity: \( v_g = c/n_g \) \( n_g = n + \omega (dn/d\omega) \)

– Velocity controlled by structural or material resonances

Slow and Fast Light Using Isolated Gain or Absorption Resonances

\[ n_g = n + \omega \left( \frac{dn}{d\omega} \right) \]
Observation of Superluminal and “Backwards” Pulse Propagation

- A strongly counterintuitive phenomenon
- But entirely consistent with established physics
- Observed by Gehring, Schweinsberg, Barsi, Kostinski, and Boyd Science 312, 985 2006.

\[ \frac{\partial A}{\partial z} - \frac{1}{v_g} \frac{\partial A}{\partial t} = 0 \]
Development of Miniaturized, Chip-Scale Spectrometers

Can We Beat the $1/L$ Resolution Limit of Standard Spectrometers?

- The limiting resolution of a broad class of spectrometers is given (in wave-numbers) by the inverse of a characteristic dimension $L$ of the spectrometer.

**Fourier-transform spectrometer**

**Grating spectrometer**

$$\Delta \nu (\text{res}) \approx 1/L$$

- We use slow-light methods to design spectrometers with resolution that exceeds this conventional limit by a factor as large as the group index.
- This ability allows us to miniaturize spectrometers with no loss of resolution, for “lab-on-a-chip” applications.
Our Goal

Replace this:

with this:
Our Approach: Chip-Scale Slow-Light Spectrometer

- The spectral sensitivity of an interferometer is increased by a factor as large as the group index of a material placed within the interferometer.

- We want to exploit this effect to build chip-scale spectrometers with the same resolution as large laboratory spectrometers.

- Here is why it works:

  ![Beam Splitter](image1)  
  ![Slow Light Medium](image2)  
  ![Tunable Laser](image3)  
  ![Detector](image4)

  Slow-light interferometer:

\[ \frac{d \Delta \phi}{d\omega} = \frac{d}{d\omega} \frac{\omega n L}{c} = \frac{L}{c} \left( n + \frac{dn}{d\omega} \right) = \frac{\text{Ln}_g}{c} \]

- We use line-defect waveguides in photonic crystals as our slow light mechanism.

  Slow-down factors of greater than 100 have been observed in such structures.

Laboratory Characterization of the Slow-Light Mach-Zehnder Interferometer

- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm\(^{-1}\)
- (Slow-light waveguide is only 1 mm long!)

• Interference fringes

Magaña-Loaiza, Gao, Schulz, Awan, Upham, Dolgaleva, and Boyd, in review.
Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene ($\text{H}_2\text{C}_2$) from hydrogen cyanide (HCN)?

(data from our own lab)
On-chip spectrometer based on high-Q photonic crystal cavities

- The concept

- Cavity design

- Spectroscopy results

The Velocity of Light in Moving Matter: Fresnel Drag (or Ether Drag) Effects

- Fizeau (1859): Longitudinal photon drag:
  Velocity of light in flowing water.
  \[ V = 700 \text{ cm/sec}; \ L = 150 \text{ cm}; \ \text{displacement of 0.5 fringe}. \]

- Modern theory: relativistic addition of velocities

  \[ v = \frac{c/n + V}{1 + (V/c)(1/n)} \approx \frac{c}{n} + V \left(1 - \frac{1}{n^2}\right) \qquad \text{Fresnel “drag” coefficient} \]

- But what about slow-light media?
Fresnel Drag in a Highly Dispersive Medium

Light Drag in a Slow Light Medium (Lorentz)

\[
u \approx \frac{c}{n} \pm v \left(1 - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right)
\]

We Use Rubidium as Our Slow Light Medium

- Transmission spectrum of Rb around D2 transition:

\[
\begin{align*}
\text{Transmission} & \quad \text{Detuning frequency (GHz)} \\
\text{T = 30 °C} & \quad \text{Transmission} \\
\text{T = 150 °C} & \quad \text{Transmission}
\end{align*}
\]

- Group index of Rb around D2 line at T=130

\[
\begin{align*}
\text{Group index (n_g)} & \quad \text{Detuning frequency (GHz)} \\
\text{T = 30 °C} & \quad \text{Group index} \\
\text{T = 150 °C} & \quad \text{Group index}
\end{align*}
\]

Safari, De Leon, Mirhosseini, Magana-Loaiza, and Boyd

Lab Setup

- Change in phase velocity is much larger than velocity of rubidium cell. Implications for new velocimeters?
Quantum Nonlinear Optics:  
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New Nonlinear Optical Material for Quantum Photonics

• We want all-optical switches that work at the single-photon level
• We need photonic materials with a much larger NLO response
• We recently reported a new NLO material with an $n_2$ value 100 times larger than those previously reported (but with some background absorption).
• Material makes use of strong enhancement that occurs in the epsilon-near-zero (ENZ) spectral region.
• A potential game changer for the field of photonics

Implications of ENZ Behavior for Nonlinear Optics

Here is the intuition for why the ENZ conditions are of interest in NLO.

Recall the standard relation between $n_2$ and $\chi^{(3)}$

$$n_2 = \frac{3\chi^{(3)}}{4\varepsilon_0 c n_0 \Re(n_0)}$$

Note that for ENZ conditions the denominator becomes very small, leading to a very large value of $n_2$. 
Nonlinear Optical Properties of Indium Tin Oxide (ITO)

ITO is a degenerate semiconductor (so highly doped as to be metal-like).

It has a very large density of free electrons, and a bulk plasma frequency corresponding to a wavelength of approximately 1.24 μm.

Recall the Drude formula

$$
\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}
$$

Note that $\text{Re} \, \epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

The region near $\omega_0$ is known as the epsilon-near-zero (ENZ) region.

There has been great recent interest in studies of ENZ phenomena:

The Epsilon-Near-Zero (ENZ) region of Indium Tin Oxide (ITO)

Measured real and imaginary parts of the dielectric permittivity.

Commercial ITO sample, 310 nm thick on a glass substrate

Drude fit
\[ \epsilon_\infty = 3.77 \]
\[ \gamma = 0.0468 \omega_p \]
\[ \omega_p / 2\pi = 473 \text{ THz} \]

Note that \( \text{Re}(\epsilon) \) vanishes at 1.24 mm, but that the loss-part \( \text{Im}(\epsilon) \) is non-zero.
The NLO Response Is Even Larger at Oblique Incidence

Standard boundary conditions show that:

\[ E_{\text{in},\parallel} = E_{\text{out},\parallel} = E_{\text{out}} \cos \theta \]

\[ D_{\text{in},\perp} = D_{\text{out},\perp} \Rightarrow E_{\text{in},\perp} = E_{\text{out},\perp}/\varepsilon = E_{\text{out}} \cos \theta /\varepsilon \]

Thus the total field inside of the medium is given by

\[ E_{\text{in}} = E_{\text{out}} \sqrt{\cos^2 \theta + \frac{\sin^2 \theta}{\varepsilon}} \]

Note that, for \( \varepsilon < 1 \), \( E_{\text{in}} \) exceeds \( E_{\text{out}} \) for \( \theta \neq 0 \).

Note also that, for \( \varepsilon < 1 \), \( E_{\text{in}} \) increases as \( \theta \) increases.
Huge Nonlinear Optical Response of ITO

- Z-scan measurements for various angles of incidence

<table>
<thead>
<tr>
<th>Angle of incidence $\theta$ (deg)</th>
<th>$\beta^{(\text{eff})}$ $(10^{-3}\text{ cm/GW})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.030</td>
</tr>
<tr>
<td>0.95</td>
<td>0.060</td>
</tr>
<tr>
<td>1.05</td>
<td>0.090</td>
</tr>
<tr>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>1.35</td>
<td></td>
</tr>
</tbody>
</table>

- Both $n_2$ and nonlinear absorption increase with angle of incidence

- Note that $n_2$ is positive (self focusing) and $\beta$ is negative (saturable absorption).

- $n_2$ shows a maximum value of $0.11 \text{ cm}^2/\text{GW} = 1.1 \times 10^{-10} \text{ cm}^2/\text{W}$ at $1.25 \mu\text{m}$ and 60 deg. This value is 2000 times larger than that away from ENZ region.

Peak laser intensity was 50 GW cm$^{-2}$.
What Makes a Good (Kerr-Effect) Nonlinear Optical Material?

- We want $n_2$ large ($\Delta n = n_2 I$). We also want $\Delta n^{(\text{max})}$ large. These are distinct concepts! Damage and saturation can limit $\Delta n^{(\text{max})}$

- For ITO at ENZ wavelength, both $n_2$ and $\Delta n^{(\text{max})}$ are extremely large ($n_2 = 1.1 \times 10^{-10}$ cm$^2$/W and $\Delta n^{(\text{max})} = 0.8$)

- $n_2$ is $3.4 \times 10^5$ times larger than that of silica glass
  $\Delta n^{(\text{max})}$ is 2700 times larger than that of silica glass
  (For silica glass $n_2 = 3.2 \times 10^{-16}$ cm$^2$/W, $I_{\text{damage}} = 1$ TW/cm$^2$, and thus $\Delta n^{(\text{max})} = 3 \times 10^{-4}$)

Beyond the $\chi^{(3)}$ limit

The nonlinear change in refractive index is so large as to change the transmission, absorption, and reflection!

Note that transmission is increased at high intensity.

Here is the refractive index extracted from the above data.

Note that the total nonlinear change in refractive index is $\Delta n = 0.8$.

The absorption decreases at high intensity, allowing a predicted NL phase shift of 0.5 radians.
Measurement of Response Time of ITO

- We have performed a pump-probe measurement of the response time. Both pump and probe are 100 fs pulses at 1.2 μm.
- Data shows a rise time of no longer than 200 fs and a recover time of 360 fs.
- Results suggest a hot-electron origin of the nonlinear response.
- ITO will support switching speeds as large as 1.5 THz.
Implications of the Large NLO Response of ITO

Indium Tin Oxide at its ENZ wavelength displays enormously strong NLO properties:

\[ n_2 \text{ is } 3.4 \times 10^5 \text{ times larger than that of fused silica} \]
\[ n_2 \text{ is } 200 \text{ times larger than that of chalcogenide glass} \]
Nonlinear change in refractive index as large as 0.8

Note that the usual “power-series” description of NLO is not adequate for describing this material. (We can have fun reformulating the laws of NLO!)

Some possible new effects
  Waveguiding outside the “weakly-guiding” regime
  Efficient all-optical switching
  No need for phase-matching
  Control of radiative processes
A Metasurface for Large Nonlinear Refraction

M. Zahirul Alam\textsuperscript{1}, S. A. Schulz\textsuperscript{1}, J. Upham\textsuperscript{1}, I. De Leon\textsuperscript{1,2} and R. W. Boyd\textsuperscript{1,3}

\textsuperscript{1}Department of Physics and Max Planck Centre for Extreme and Quantum Optics, University of Ottawa, Canada.

\textsuperscript{2}School of Engineering and Sciences, Tecnológico de Monterrey, Mexico.

\textsuperscript{3}Institute of Optics, University of Rochester.
Other Reports of Highly Nonlinear Response in ENZ Material and Metamaterials


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Observation of Optical Polarization Möbius Strips

- Möbius strips are familiar geometrical structures, but their occurrence in nature is extremely rare.
- We generate such structures in the nanoscale in tightly focused vector light beams and confirm experimentally their Möbius topology.

Prediction of Optical Möbius Strips

An “ordinary” Möbius strip

A polarization Möbius strip (introduced by Isaac Freund)

• Isaac Freund discovered, described, and investigated these unusual structures

• To observe these structures, one needs to create a very special field distribution (e.g., a Poincaré beam)

• One also needs to observe the field distribution in a very special way (measure polarization as a function of position around a very tightly focused light beam)

1 Wikipedia
2 Isaac Freund, Bar-Ilan Univ., Talk: Optical Möbius Strips and Twisted Ribbons, Conf. on Singular Optics, ICTP Trieste, Part II, 30 May 2011
Nanoparticle-based probing technique for vector beam reconstruction

1. A dipole-like spherical nanoparticle (90 nm diameter) is scanned through the beam
2. The forward- and backward-scattered light for each position of the nanoparticle relative to the beam in the focal plane is measured

Measured intensity (can also measure polarization and phase)

Full amplitude and phase reconstruction scheme:
Lab Setup to Observe a Polarization Möbius Strip

- q-plate: waveplate with a spatially varying orientation (q is the topological charge)
- output beam has a spatially varying state of polarization (vector beam, Poincaré beam, etc.)

Tight focusing enhances the Möbius effect, which depends on the z component of the field.
Observation of Polarization Möbius Strips

q = -1/2
3/2 twists

q = -3/2
5/2 twists

Remarks

• First observation of a polarization Möbius strip
• Light fields can possess rich spatial structure on subwavelength scales
• Current technology is capable of controllably creating beams with such structures and measuring it at subwavelength distances.
Why We Shouldn’t Always Trust Google

Robert Boyd is an American physicist noted for his work in optical physics and especially in nonlinear optics. Wikipedia

Born: 1948, Buffalo, NY
Education: University of California, Berkeley
Doctoral advisor: Charles H. Townes
Residence: United States of America, Canada

Books
- Radiometry and the detection of electromagnetic energy 1983
- Not by Genes Alone 2005
- Mathematics of social evolution 2007

Robert Boyd (anthropologist) - Wikipedia, the free encyclopedia
Robert Boyd (born February 11, 1948) is an American anthropologist. He is Professor of the Department of Anthropology at the University of California, Los Angeles.

Robert W. Boyd - Wikipedia, the free encyclopedia
Robert William Boyd (born 8 March 1948) is an American physicist noted for his work in optical physics and especially in nonlinear optics. He is currently...
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Use of Quantum States for Secure Optical Communication

- The celebrated BB84 protocol for quantum key distribution (QKD) transmits one bit of information per received photon.
- We have built a QKD system that can carry more than one bit per photon.
  - Note that in traditional telecom, one uses many photons per bit!
- Our procedure is to encode using beams that carry orbital angular momentum (OAM), such as the Laguerre-Gauss states, which reside in an infinite dimensional Hilbert space.
We are constructing a QKD system in which each photon carries many bits of information. We encode in states that carry OAM such as the Laguerre-Gauss states. We also need a second basis composed of linear combinations of these states.

Single Photon States

Laguerre-Gaussian Basis \( \ell = -13, \ldots, 13 \)

Angular” Basis (mutually unbiased with respect to LG)

\[
\Psi_{AB}^N = \frac{1}{\sqrt{27}} \sum_{\ell=-13}^{13} \text{LG}_{\ell,0} \exp(i2\pi N\ell/27)
\]
Our Laboratory Setup

We use a seven-dimensional state space.

We use a 7-letter alphabet, and achieve a channel capacity of 2.1 bits per sifted photon.

We do not reach the full 2.8 bits per photon for a variety of reasons, including dark counts in our detectors and cross-talk among channels resulting from imperfections in our sorter.

Nonetheless, our error rate is adequately low to provide full security,
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Thank you for your attention!