New Results in Quantum Photonics

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New Results in Quantum Photonics

Prospectus

1. New Applications of “Slow Light”
2. Möbius Strips of Polarization
3. Quantum Communication with Multiple Bits per Photon
Controlling the Velocity of Light

“Slow,” “Fast” and “Backwards” Light

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

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

– Velocity controlled by structural or material resonances

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.

\[ \Delta \nu \text{(res)} \approx \frac{1}{L} \]

- 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:

  Slow-light interferometer:

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

  Simple analysis

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

  - 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

- Interference fringes

- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm\(^{-1}\)

- (Slow-light waveguide is only 1 mm long!)

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.
  \[ V = 700 \text{ cm/sec}; \quad L = 150 \text{ cm}; \quad \text{displacement of 0.5 fringe}. \]

- Modern theory: relativistic addition of velocities
  \[ v = \frac{c/n + V}{1 + (V/c)(1/n)} \approx \frac{c}{n} + V \left(1 - \frac{1}{n^2}\right) \text{ Fresnel “drag” coefficient} \]

- 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 D$_2$ transition:

- Group index of Rb around D$_2$ line at T=130

Change in phase velocity

\[ \Delta u \text{ (m/s)} \]

\[ v = 1 \text{ m/s} \]

\[ L = 7.5 \text{ cm} \]

\[ T = 30 \text{oC} \]

\[ T = 150 \text{oC} \]

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

- Change in phase velocity is much larger than velocity of rubidium cell. Implications for new velocimeters?
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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

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.

- LG0\textsubscript{00} \quad \delta = 0 \quad \text{LHC}
- LG0\textsubscript{0-1} \quad \delta = \pi \quad \text{RHC}
- \delta = \pi/2 \quad \text{Super-Position “Star”}
Observation of Polarization Möbius Strips

q = -1/2
3/2 twists

q = -3/2
5/2 twists

structure possesses |q|+1 half 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.

Quantum Nonlinear Optics:  
Nonlinear Optics Meets the Quantum World

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. Quantum Communication with Multiple Bits per Photon
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**

\[
\text{Laguerre-Gaussian Basis} \quad \ell = -13, \ldots, 13
\]

\[
\Psi_{AB}^N = \frac{1}{\sqrt{27}} \sum_{\ell=-13}^{13} \text{LG}_{\ell,0} \exp \left( i 2\pi N\ell / 27 \right)
\]
Our Laboratory Setup

We use a seven-dimensional state space.

Laboratory Results - OAM-Based QKD

- error bounds for security

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,
Quantum Nonlinear Optics: 
Nonlinear Optics Meets the Quantum World

Summary: NLO is a superb platform from which to explore new physical processes and to develop photonics applications.

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Thank you for your attention!
Why We Shouldn’t Always Trust Google

Robert W. Boyd

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

Born: 1948, Buffalo, NY
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Books

Radiometry and the detection of... 1983
Not by Genes Alone 2002
Mathematical models of social ev... 2007