Slow-Light-Enhanced Spectrometers and Photon Drag in Slow-Light Media

Robert W. Boyd

Department of Physics and
Max-Planck Centre for Extreme and Quantum Photonics
University of Ottawa

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester

Department of Physics and Astronomy
University of Glasgow

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Slow-Light-Enhanced Spectrometers and Photon Drag in Slow-Light Media

1. Introduction
2. What is slow light?
3. How slow light enhances spectrometers
4. Our development of a chip-scale slow-light medium for spectroscopy
5. Resonator-based spectrometers
6. Photon Drag Effects
Chip-Scale Spectrometers for Chem-Bio Identification

- Spectroscopy is the standard laboratory procedure for identifying chemical species.
- Can we fabricate miniaturized, chip-scale spectrometers without sustaining a loss in resolution?
Current On-Chip Spectrometers

- **Echelle grating** (NRC, Canada)
- **Arrayed Waveguide Grating** (UCSB)
- **Digital Phase Holography** (LBNL et al.)
- **Super-prism** (GaTech)
- **Donut resonator** (GaTech)

**Spatial FT based** (Swift) (Université de Grenoble)
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.
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Controlling the Velocity of Light

“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:
\[
v_g = \frac{c}{n_g} \quad n_g = n + \omega \left( \frac{dn}{d\omega} \right)
\]

- Velocity controlled by structural or material resonances

**Group Velocity**

Pulse (wave packet)  \[ \rightarrow \mathbf{v}_g \]

Group velocity given by \[ \mathbf{v}_g = \frac{d\mathbf{w}}{dk} \]

For \[ k = \frac{n\mathbf{w}}{c} \] \[ \frac{dk}{d\mathbf{w}} = \frac{1}{c} \left( n + \mathbf{w} \frac{dn}{d\mathbf{w}} \right) \]

Thus \[ \mathbf{v}_g = \frac{c}{n + \mathbf{w} \frac{dn}{d\mathbf{w}}} \equiv \frac{c}{n_g} \]

Thus \( n_g \neq n \) in a dispersive medium!
Slow and Fast Light Using Isolated Gain or Absorption Resonances

$$n_g = n + \omega \frac{dn}{d\omega}$$
Slow-Light-Enhanced Spectral Interferometers

1. Introduction
2. What is slow light?
3. How slow light enhances spectrometers
4. Our development of a chip-scale slow-light medium for spectroscopy
5. Relation between slow light and optical resonators
6. Resonator-based spectrometer for threat reduction
7. Other work
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:**

  Simple analysis

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

- 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.

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Nano-fabrication process

SOI wafer

e-beam resist deposition

e-beam lithography

develop resist

Si
SiO₂
Si

step 1

step 2

step 3

step 4

Final PhC membrane structure

isotropic under-cut

e-beam resist removal

ICP etching

step 5

step 6

step 7

step 8
Laboratory Characterization of 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!)
Quantitative Results: Photonic-Crystal, SLow-Light Spectrometer

- Spectral resolution is proportional to fringe density
- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm$^{-1}$
- Slow-light waveguide is only 1 mm long
Next Step: All-On-Chip Slow-Light Spectrometer
Long-Term Goal: All-On-Chip Spectrometer with Order Sorting

Output

<table>
<thead>
<tr>
<th>High Resolution</th>
<th>Order-Sorter 1</th>
<th>Order-Sorter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>In</td>
<td>Out-1</td>
<td>Out-2</td>
</tr>
</tbody>
</table>

FSR=Δ  
FSR=2Δ  
FSR=4Δ  

After Stage 1

After Stage 2

Output
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Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene (H₂C₂) 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

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

Books

- Nonlinear Optics, Second E... 1962
- Radiometry and the detection... 1983
- Not by Genes Alone 2005
- Mathematics... models of social ev... 2007
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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
  \[ v = \frac{c/n + V}{1 + (V/c)(1/n)} \approx \frac{c}{n} + V \left(1 - \frac{1}{n^2}\right) \]
  Fresnel “drag” coefficient

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

Light Drag in a Slow Light Medium (Lorentz)

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

We Use Rubidium as Our Slow Light Medium

- Transmission spectrum of Rb around D2 transition:

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

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

\[ \text{Temperature } ^\circ\text{C} \]

\[ \text{Change in phase velocity} \]

\[ \text{Theory --- Experiment *} \]

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

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

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

- Change in phase velocity is much larger than velocity of rubidium cell. Implications for new velocimeters?
Thank you for your attention!