Search for Anisotropy in the One-Way Speed of Light Using an Optical Ring Cavity

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Self-introduction

• Tsubono Group, Dept. of Physics, U. of Tokyo got master’s in March 2012 starting Phd

• what I have been doing
  - DECIGO Pathfinder prototype FP experiment
  - KAGRA (LCGT) ASC simulation
  - anisotropy search in the speed of light (master’s thesis)
  - lock 40m IFO
Abstract

• tested Special Relativity (Lorentz invariance in photons) by testing isotropy in the **one-way** speed of light

• new idea: use asymmetric optical ring cavity

• got the **world’s best limit** (more than x2 better)
  \[ \hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10} \]
  set upper limit on the anisotropy to a level of
  \[ |\delta c/c| \lesssim 10^{-13} \]

\[ \begin{align*}
  c - \delta c &\quad \rightarrow \quad c + \delta c \\
  \text{lab velocity with respect to preferred frame} &\quad (\text{CMB rest frame})
\end{align*} \]
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1. Background
SR and Lorentz violation

• Special Relativity (1905) speed of light is constant
• Lorentz invariance in electrodynamics
• no one could find any violation
• but…
  - quantum gravity theory suggests violation at some level
e.g. $\frac{\delta c}{c} \sim 10^{-17}$
  
  D. Colladay and V. Alan Kostelecký: PRD 58 (1998) 116002
  
  - anisotropy in CMB
    CMB rest frame: possible preferred frame?
  
  $\rightarrow$ we have to test SR!
Testing SR

- most traditional way to test SR
- constancy of the speed of light consists from
  - isotropy in the one-way speed of light
  - isotropy in the two-way speed of light
  - independence of the speed of light from the lab. velocity
Test theory of SR: MS Theory

- test theory proposed by Mansouri & Sexl (1977)

- speed of light in MS theory

\[ c(\theta) = 1 - 2\hat{\alpha}v \cos \theta \]

one-way anisotropy

\[-(\hat{\beta} - \hat{\delta})v^2 \sin^2 \theta\]

two-way anisotropy

\[-(\hat{\alpha} - \hat{\beta})v^2\]

independence of \( c \) from \( v \)

Diagram:
- Preferred frame \( \Sigma \)
- Lab frame \( S \)
- Lab velocity with respect to preferred frame (CMB rest frame)
Previous Test for Two-Way c

- Michelson-Morley experiment (1887)
  Michelson interferometer
- compare the resonant freqs of crossed FP in a single block (2009)
  \[ \hat{\beta} - \hat{\delta} = (-1.6 \pm 6 \pm 1.2) \times 10^{-12} \]

|δc/c| \lesssim 10^{-17}

(Laser round trip)


S. Herrmann+: PRD 80 (2009) 105011.)

PD

Round trip

Round trip

55mm
Previous Test for One-Way $c$

- Ives-Stilwel experiment (1938)
  measure Doppler shifted resonant freq of ions
- most recent IS-type experiment (2007)
  \[
  \hat{\alpha} = (-4.8 \pm 8.4) \times 10^{-8}
  \]

\[|\delta c/c| \lesssim 10^{-10}\]

have to measure the absolute value of the resonant frequency
• one-way test is 7-orders of magnitude less precise than two-way test!
• can’t test one-way c using ordinary interferometers
• one-way anisotropy term cancels in a closed loop
  \[ c(\theta) = 1 - 2\hat{\alpha}v \cos \theta + \mathcal{O}(v^2) \]
  → how can we deal with it?

Starting Point

[Diagram of Michelson interferometer, FP cavity, and ring cavity]
2. Experimental Principle
Asymmetric Ring Cavity

• putting a medium in the optical path makes an asymmetry
  → ring cavity will be sensitive to the one-way anisotropy

• asymmetric Sagnac experiment was first done by Trimmer+ (1973) W. S. N. Trimmer+: PRD 8 (1973) 3321

• cavity type proposed by Exirifard (2010)

Resonant Frequencies

- One-way term remains because of asymmetry

\[ c(\theta) = 1 - 2\hat{\alpha}v \cos \theta + \mathcal{O}(v^2) \]

<table>
<thead>
<tr>
<th></th>
<th>CCW without medium</th>
<th>CW with medium</th>
<th>freq. shift ( \propto \hat{\alpha} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>no anisotropy</td>
<td>( \nu_+ = \nu_0 )</td>
<td>( \nu_+ = \nu )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \nu_- = \nu_0 )</td>
<td>( \nu_- = \nu )</td>
<td></td>
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<tr>
<td>anisotropy</td>
<td>( \nu_+ = \nu_0 )</td>
<td>( \nu_+ = \nu - \delta \nu )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \nu_- = \nu_0 )</td>
<td>( \nu_- = \nu + \delta \nu )</td>
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</table>
Counter Propagating Modes

• comparing resonant frequencies of counter propagating modes
  → high CMRR to cavity length change
  no need for high vacuum
  seismic isolation
  temperature control (or cryogenic)

• first experiment done by Baynes+ (Oct 2011)


\[ \nu_+ = \nu - \delta \nu \]
\[ \nu_- = \nu + \delta \nu \]
Optical Setup of Baynes+(2011)

- lock freqs of two lasers to $\nu_+,$ $\nu_-$
- have to shift two laser freqs to avoid the lock-in problem (not a null experiment)

$\nu_+ = \nu_1 - \delta\nu$

$\nu_- = \nu_2 + \delta\nu$

CCW

n, $d$

medium

CW

Laser1

Laser2

$\nu_+$

$\nu_-$

lock laser freq to $\nu_+$

lock laser freq to $\nu_-$
Our New Idea: Double-Pass

- double-pass makes null measurement
- only one beam; no need to care about lock-in

\[ \nu_+ = \nu - \delta \nu \]

CCW

\[ \nu_- = \nu + \delta \nu \]

CW

\[ \propto \nu_+ - \nu_- \]

lock laser freq to \( \nu_+ \)
Anisotropy Signal

- \( \delta \nu \equiv \nu_+ - \nu_- \)

\[
\delta \nu = \frac{4(n - 1)d}{L + (n - 1)d} \hat{\alpha} \nu \cos \theta
\]

lab speed with respect to CMB \( \nu \approx 10^{-3} \)

round trip length

rotate cavity to modulate

putting a medium is essential

larger \( n \), bigger signal

\( \rightarrow \) let’s use silicon with 1550nm

(\( n = 3.69 \))

\[ \propto \hat{\alpha} \]

\( \nu \)

\( \theta \)

\( n, d \)

rotate \( \omega_{\text{rot}} \)
Summary (first half)

• measure anisotropy in one-way speed of light using a ring cavity
  - silicon inside
  - compare counter-propagating resonant freqs high CMMR
  - double pass null measurement

• rotate the cavity to modulate anisotropy signal
3. Experimental Setup
Whole Setup

Laser

PM fiber

1550 nm
10 mW

frequency lock

intensity stabilization

vacuum desiccator (0.1-1 kPa)

ring cavity

silicon

rotation table

anisotropy signal
Setup

DFB fiber laser

isolator

electronics

AOM

PM fiber

vacuum desiccator

300 mm
Optics Inside Desiccator
**Ring Cavity**

- spacer made of Super Invar
- silicon inside
- mirrors

**ring cavity spec**
- incident power: \( \sim 1 \) mW
- finesse: \( \sim 125 \)
- round-trip length: 140 mm
- silicon length: 20 mm
- end mirror RoC: 200 mm
It’s Rotating

- movie
Sensitivity

- below requirement (but $① \neq ②$)

![Diagram showing relative frequency noise $\delta \nu / \nu$ versus frequency $f$ with logarithmic scales. The graph compares in-loop frequency noise, free run, anisotropy signal, and requirement. The inset diagram shows a laser setup with points ① and ② indicating different conditions.]
4. Data Analysis
Data Analysis Flow

- FFT the signal in rotation frequency (0.125 Hz)
- eliminate the effect of Earth rotation
  (convert Fourier amplitudes from Lab to Sun Frame)
- derive $\alpha$ for each cavity rotation
Result of the Analysis

- ~26,000 rotation for 2 weeks in Nov 2011
- used quiet ~10,000 rotation for data analysis

10,000 Fourier complex amplitudes in Lab Frame
Result of the Analysis

- ~26,000 rotation for 2 weeks in Nov 2011
- used quiet ~10,000 rotation for data analysis

10,000 Fourier complex amplitudes in Sun Frame
Upper Limit on the Anisotropy

- histogram of $\hat{\alpha}$ from our data

$\rightarrow \hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10}$

statistical error (1σ)
Comparison with Previous Exp.

- more than factor of 2 better

\[ \hat{\alpha} = ( -2.3 \pm 2.6 ) \times 10^{-10} \]

Baynes+(2011) not double-pass
\[ \hat{\alpha} = ( 3.2 \pm 6.4 ) \times 10^{-10} \]

Reinhardt+(2007) Doppler experiment using ions
\[ \hat{\alpha} = ( -4.8 \pm 8.4 ) \times 10^{-8} \]
5. Current Status and Summary
Current Status

- reduced noise! (ADC noise was the limiting source…)
- now we have systematic errors > statistic error
  lab light, polarization, tilt of optical table
Summary

• tested SR (Lorentz invariance in photons) by testing isotropy of one-way speed of light
• developed new setup for the anisotropy search silicon inside ring cavity double-pass configuration
• took anisotropy signal data for ~10,000 rotations (1.2 days)
• analyzed data, and got the world’s best limit
  \[ \hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10} \]
• already reduced noise by an order of magnitude
• working on making it insensitive to tilt