Frequency combs to detect phase changes of
Intracavity Phase Interferometry
Part II

Mode-locked lasers as sensors,
enhanced by resonant dispersion

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Frequency combs to detect phase changes of $10^{-8}$:
Intracavity Phase Interferometry
Part I

Interactions inside a mode-locked laser: it is a field full of surprises


Mode-locked laser as a differential interferometer, detecting phase shifts > $10^{-8}$ (optical $\Delta P=0.5$ fm)


Frequency combs to detect phase changes of $10^{-8}$:
Intracavity Phase Interferometry
Part II: we can do better!

1) Modifying the phase response
2) Modifying the phase response for a mode-locked laser
3)
4) The light velocity, a definition?
5) Phase response enhancement/reduction: it has nothing to do with slow/fast light.
6) Can we make a purely optical accelerometer?
Intracavity Phase Interferometry: 2 combs, same spacing, 2 CEO’s

Linear fiber laser implementation

Polarization maintaining fiber laser: unique possibility to have two orthogonally polarized pulses circulating inside the cavity.

Pump laser 980 nm

Er-doped fiber

PBS

Reference arm

Sensing element

Classical interferometry

\[ \frac{\Delta v}{v} = \frac{\Delta P}{P} \]

Better than the TGV: the pulse trains collide but do not crash!

\[ \Delta L / L_{cav} \] versus IPI

\[ \Delta I \] versus time (ms)

\[ \Delta L \]

\[ \Delta v \]
Intracavity Phase Interferometry: Ring cavity
It is a LASER GYRO

\[ \Delta \nu = \frac{c}{\lambda} \frac{2R \Omega \times 2\pi R}{c \beta} = \frac{4A}{P \lambda} \Omega \]

\[ \frac{\Delta \nu}{\nu} = \frac{\Delta P}{P} \]


Koji Masuda, James Hendrie, Jean-Claude Diels and Ladan Arissian,
"Envelope, Group and Phase velocities in a nested frequency comb",

A lot of smart people have made VERY complex theories:


**Intracavity Phase Interferometry Part II: we can do better!**

1. Frequency combs to detect phase changes of $10^{-8}$
2. Modifying the phase response for a mode-locked laser
3. Nested frequency combs: Fabry-Perot inside a mode-locked laser
4. The light velocity - a definition?
5. Phase response enhancement/reduction: it has nothing to do with slow/fast light.
6. Can we make a purely optical accelerometer?
For the simple minded electrical engineer that I am, the concept is extremely simple: it is that of an amplifier with feedback.
Modifying the phase response

\[ \Delta \omega = \frac{\Delta \phi}{\tau_{ph}} \]

By making the round trip time \((\tau_{ph})\) frequency dependent through an element having

\[ \tau_{ph} = \tau_{ph0} + \left. \frac{d\psi}{d\Omega} \right|_\omega \]

transfer function

\[ \tilde{\mathcal{F}}(\Omega) = |\tilde{\mathcal{F}}| \exp[-i\psi(\Omega)] \]

with giant dispersion

Before putting the dispersive medium

The effect of the dispersive medium on the round trip time

\[ = \frac{\frac{d\phi}{\tau_{ri0}}}{1 + \frac{1}{\tau_{ph0}} \left. \frac{d\psi}{d\Omega} \right|_\omega} = \frac{\Delta \omega_0}{1 + \frac{1}{\tau_{ph0}} \left. \frac{d\psi}{d\Omega} \right|_\omega} \]

if

\[ >0 \quad \text{“slow light”} \quad \rightarrow \quad \text{Reduction in phase response} \]

\[ <0 \quad \text{“fast light”} \quad \rightarrow \quad \text{Enhancement in phase response} \]
Modifying the phase response in a mode-locked laser

\[ \Delta \omega = \frac{\Delta \omega_0}{1 + \frac{1}{\tau_{ph0}} \frac{d\psi}{d\Omega}|_\omega} \]

Phase shift splitting

Cavity modes

Slow light reduction

Fast light enhancement

Dispersive medium

gain

Positive dispersion

Negative dispersion

absorption
Modifying the phase response in a mode-locked laser

Mode-locked laser, the giant dispersion has to be applied to every single mode of the comb

Or does it?

Intracavity etalon coupled to the modes:

Next: uncoated etalon inside a mode-locked laser cavity
Etalon inside a mode-locked laser: some quizzes

- 15.12mm Fused silica
- FSR ~ 6.83 GHz
- Reflectivity ~ 0.034

Quiz 1: How does the wavelength tune with $\theta$?

$$\mathcal{T}(\omega) = \frac{(1-R)e^{i\delta/2}}{1-Re^{i\delta}} = \mathcal{T}(\omega)e^{i\psi}$$

$$\delta_N = -\frac{2kd\cos \theta}{c} = 2\pi N$$

$\rightarrow k \rightarrow \lambda = \frac{2\pi}{k}$
Etalon inside a mode-locked laser: some quizzes

- 15.12mm Fused silica
- FSR ~ 6.83 GHz
- Reflectivity ~ 0.034

Quiz 2: What is the pulse transmission of the Fabry-Perot?

Wrong!

“Obviously”: very small multiple reflections

\[ \tau_{FP} \approx 146 \text{ ps} \]

\[ \tau_{RT} \approx 6.4 \text{ ns} \]

\[ \tau \approx 1.5 \text{ ns} \]

\[ \tau \approx 2 \text{ ns} \]
Generation of a nested pulse train
Generation of a nested pulse train
Generation of a nested pulse train

- Pulse minitrain reaches steady state condition after many roundtrips

NRT = 1000
a = 0.0002
R = 0.05
Etalon inside a mode-locked laser: some quizzes

Quiz 3: Does the Fabry-Perot affect the repetition rate of the laser?

20% more thickness!!!???
2. Etalon inside a mode-locked laser: some quizzes

Quiz 4: Is the high frequency affected by the low frequency (cavity length)?

![Graph showing the relationship between high frequency and end mirror position](image)

![Graph showing the relationship between repetition rate and end mirror position](image)
Laser repetition rate versus angle
We achieve fine wavelength and group velocity control by adjusting the FP angle.

The “duty cycle” or duration of the HF burst is adjustable by the etalon finesse.

Using thinner FP, a HF to 28 GHz was achieved.

Educational impact: the final word on the quizzes is the “Teacher Evaluation” by students:
1) Modifying the phase response

2) Modifying the phase response for a mode-locked laser


4) The light velocity, a definition?

5) Phase response enhancement/reduction: it has nothing to do with slow/fast light.

6) Can we make a purely optical accelerometer?
We all know what the speed of light is…

### Light velocities

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase velocity</td>
<td>$c/n$</td>
</tr>
<tr>
<td>Ray velocity</td>
<td>velocity of energy flow in crystals</td>
</tr>
<tr>
<td>Group velocity</td>
<td>$dk/d\Omega$</td>
</tr>
<tr>
<td>Mode velocity</td>
<td>in a waveguide or optical fiber</td>
</tr>
<tr>
<td>Envelope velocity</td>
<td>None of the above velocities are relevant when dealing with absorber, gain or active laser cavities</td>
</tr>
</tbody>
</table>

All these velocities mixed in a ratatouille called “advanced Optics course” without giving too much consideration to the sanity of the students.
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Changing the beat note response in a ring laser with a Fabry-Perot

Beat note detector

Gain

Fabry Perot etalon

Saturable absorber

Lithium niobate phase modulator (artificial rotation)
Changing the beat note response in a ring laser with a Fabry-Perot

Without FP

With FP

Modifying the phase response

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By making the round trip time (\( \tau_{ph} \)) frequency dependent through an element having

transfer function

\[ \tilde{\mathcal{T}}(\Omega) = |\tilde{\mathcal{T}}| \exp[-i\psi(\Omega)] \]

with giant dispersion

Before putting the dispersive medium

The effect of the dispersive medium on the round trip time

\[ \tau_{ph} = \tau_{ph0} + \left. \frac{d\psi}{d\Omega} \right|_{\omega} \]

\[ \Delta \omega = \frac{\Delta \phi}{\tau_{ph}} = \frac{\frac{d\phi}{\tau_{ri0}}}{1 + \frac{1}{\tau_{ph0}} \left. \frac{d\psi}{d\Omega} \right|_{\omega}} = \frac{\Delta \omega_0}{1 + \frac{1}{\tau_{ph0}} \left. \frac{d\psi}{d\Omega} \right|_{\omega}} \]

if

\[ \left. \frac{d\psi}{d\Omega} \right|_{\omega} > 0 \] “slow light” → Reduction in phase response

\[ \left. \frac{d\psi}{d\Omega} \right|_{\omega} < 0 \] “fast light” → Enhancement in phase response

A factor of 1.9!!!
Is it slow light?

It is not!

The pulse velocity changes with Fabry-Perot angle

But…

The slope of the gyro response is unaffected
How to change the sign of the dispersion? Use a Gires Tournois interferometer

Implementation with free space components:

Beat note detector

G

Fabry Perot etalon

Lithium niobate phase modulator (artificial rotation)

Gires Tournois interferometer
How to change the sign of the dispersion? Use a Gires Tournois interferometer

Implementation in fiber OPO

Gires Tournois interferometer

OPO

Oscillator

Amplifier

Beat note detector

Fabry Perot etalon
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$L = c \frac{\tau_{rt}}{(2 n_p)}$

Laser cavity

$V_m + gt$

$M_2$

$M_1$

$(f/2)L$

$D$

$A$

$V$

$V_m + gt$
\[ t_1 = \frac{\frac{v}{2} - \frac{L}{2}}{c} \text{ when blue hits M1, gets a Doppler shift } \frac{\delta v_B}{v} = \frac{v}{c} + g\frac{\frac{v}{2} - \frac{L}{2}}{2c} \]

This is the blue that will interfere with the next red on the detector

\[ t_2 = \frac{\frac{v}{2} (1 - \frac{L}{2})}{c} \text{ when red hits M2, gets a Doppler shift } \frac{\delta v_R}{v} = \frac{v}{c} + g(1 - \frac{L}{2})\frac{v}{2c} \]

When blue meets red on detector: beat

\[ \frac{\delta v_B}{v} = g(1 - f)\frac{v}{2c} \]
A simple conclusion

Most sensitive sensing is not achieved *with* a laser beam,
but *inside* a laser

A mode-locked laser is required to prevent coupling between the two intracavity beams
Laser Interferometer Gravitational-Wave Observatory

But we are getting pretty close, at a minuscule fraction of the costs.
It is not slow light/fast light!

What is the price for contradicting all these smart people and their VERY complex theories?

What if, some perfectly normal people, grow a huge red nose…

What will happen to the one that stays normal?
6. Thanks to those who contributed

Special thanks to the dedicated PhD students that went through 6 years (+) of research with me

<table>
<thead>
<tr>
<th>Name</th>
<th>Degree</th>
<th>Graduation</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patrick Rambo</td>
<td>PhD</td>
<td>2000 (UNM)</td>
<td>Laser guided discharges</td>
</tr>
<tr>
<td>Hanieh Afkhami</td>
<td>PhD</td>
<td>2004 (UNM)</td>
<td>Filamentation in air</td>
</tr>
<tr>
<td>Ning HSu</td>
<td>PhD</td>
<td>1999 (UNM)</td>
<td>Multiphoton ionization</td>
</tr>
<tr>
<td>Ali Rastegari</td>
<td>PhD</td>
<td>2003 (UNM)</td>
<td>Ultrashort pulse optical parametric oscillator sensor</td>
</tr>
</tbody>
</table>
Optical Sciences Program at UNM – the pride of the nation in the 1980’s – 1990.
One out of 3 Universities to offer a PhD in Optics

NOW:

This article highlights the optics/photonics educational programs at several institutions worldwide

...top optics/photonics institutions like CREOL at UCF or École Polytechnique,
+ ``myriad lesser-known colleges and universities”

The US cream of the crop …OSC; Tucson, AZ, U. of Rochester director Xi-Cheng Zhang
Heriot-Watt University Tianjin University, etc et … but NOT UNM
Lost to the program – Atomic and Molecular Optics (Howard Bryant, Charles Beckel, Wilhelm Becker) M.O Scully and too many to list whose operation was eliminated

The position of a retiree is left to intra-departmental demagogy, rather than rational considerations about preserving the intellectual and material legacy of Federal grants.
In view of the great vision of UNM, their mascot should not be:

The lobo

but the MOLE

There is a need for a policy to transfer the infrastructure destined to be scraped, to another institution having a successful and promising program

...with blinders