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

Mode-locked lasers as sensors, enhanced by resonant dispersion

Jean-Claude Diels

University of New Mexico

Siegman School
Barcelona
July 25-29, 2016

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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

The ring laser as a two level system *A. Schmitt-Sody, L. Arissian, A. Velten, J.-C. Diels, and D. Smith, PRA* ***78****:063802 (2008)*

Intracavity Phase Interferometry, *L. Arissian and J.-C. Diels, Laser and Photonics review 8:799 (2014)*

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

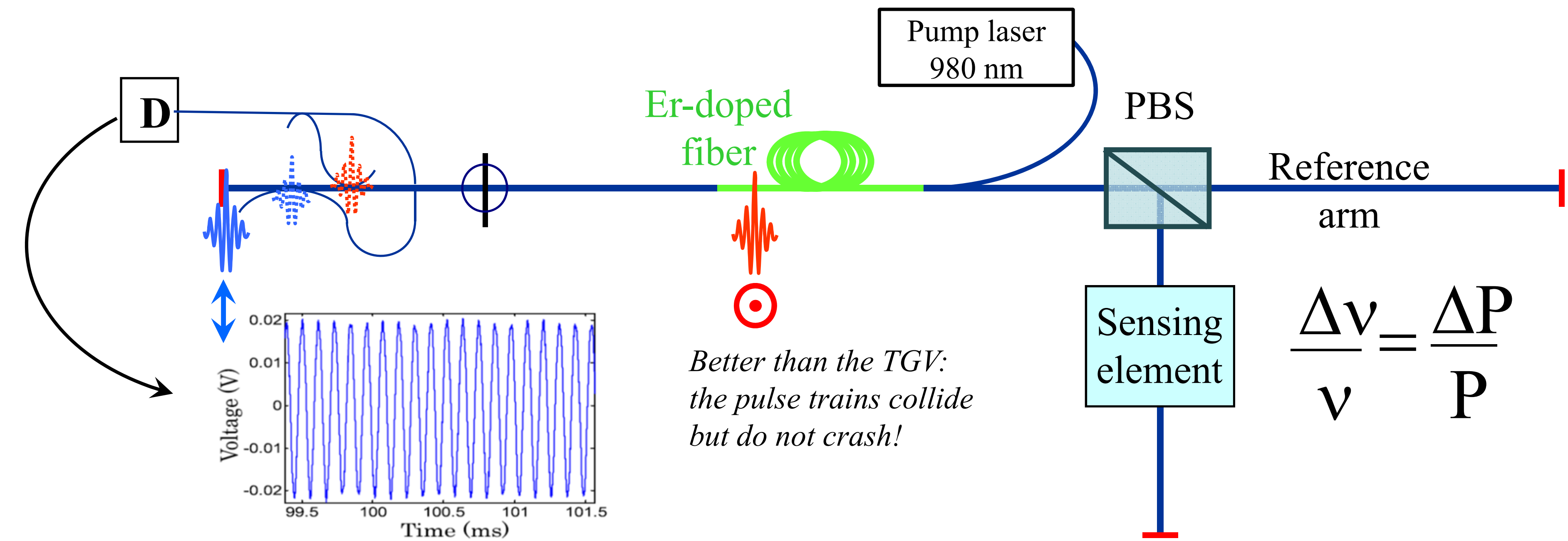
Nested frequency combs *K. Masuda, J. Hendrie, J.-C. Diels and L. Arissian, J. Phys. B* ***49****:085402 (2016)*

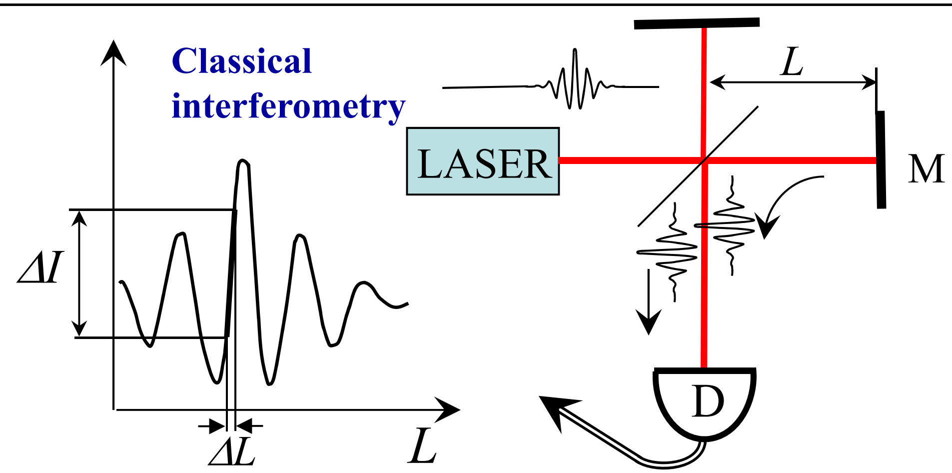
Frequency combs to detect phase changes of 10^{-8}: Intracavity Phase Interferometry Part II: we can do better!

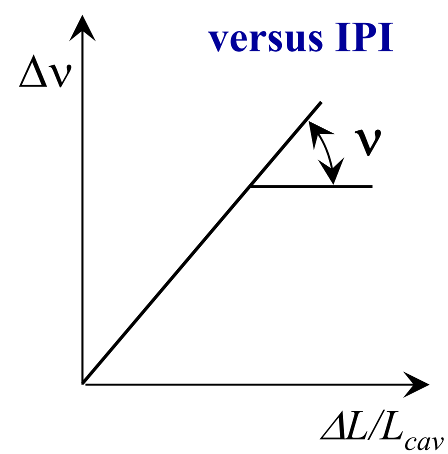
1) Modifying the phase response
2) Modifying the phase response for a mode-locked laser
3)
4) The light velocity, a definition?
5) Phase response enhancement/reduction: it has nothing to do with slow/fast light.
6) Can we make a purely optical accelerometer?

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







Intracavity Phase Interferometry: Ring cavity
It is a LASER GYRO

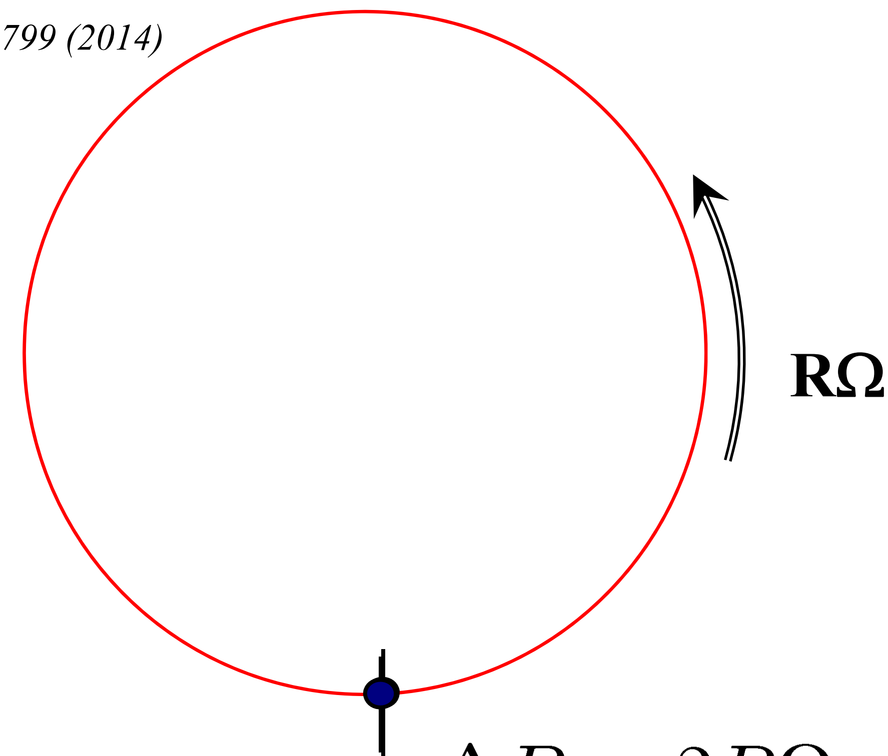
$$\Delta\nu = \frac{c}{\lambda}\frac{2R\Omega\times 2\pi R}{cP} = \frac{4A}{P\lambda}\Omega$$

$$\frac{\Delta\nu}{\nu} = \frac{\Delta P}{P}$$

L. Arissian and J.-C. Diels, Laser and Photonics review 8:799 (2014)

Koji Masuda, James Hendrie, Jean-Claude Diels and Ladan Arissian, "Envelope, Group and Phase velocities in a nested frequency comb", *Journal of Physics B*, **49**:085402 (2016)

J. Hendrie, M. Lenzner, H. Afkhamiardakani, J.-C. Diels and L. Arissian, "*Impact of giant resonant Dispersion on the response of intracavity phase Interferometry and laser gyros*", Under review.



$$\Delta P = 2R\Omega\tau_{rt}$$

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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) 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?

A lot of smart people have made VERY complex theories:

- U. Leonhardt and P. Piwnicki. Ultrahigh sensitivity of slow-light gyroscope. *Phys. Rev. A*, 62:055801, 2000.
- M. S. Shahriar, G. S. Pati, R. Tripathi, V. Gopal, M. Messall, and K. Salit. Ultrahigh enhancement in absolute and relative rotation sensing using fast and slow light. *Physical review A*, 75:053807, 2007.
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- D. D. Smith, *et al* Fast-light enhancement of an optical cavity by polarization mode coupling. *Physical Review A*, 89:053804, 2014.

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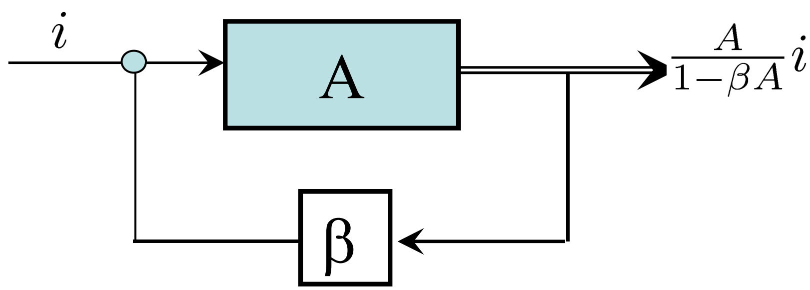
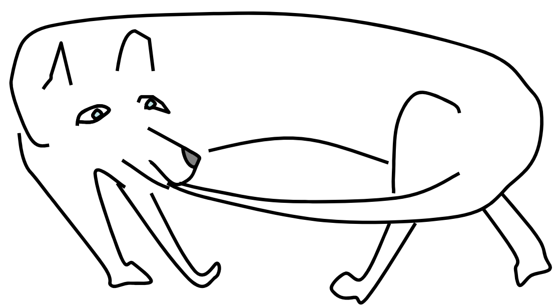
For the simple minded electrical engineer that I am, the concept is extremely simple: it is that of an amplifier with feedback





Modifying the phase response

$$\Delta\omega = \frac{\Delta\phi}{\tau_{ph}}$$

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

- transfer function $\tilde{\mathcal{T}}(\Omega) = |\tilde{\mathcal{T}}| \exp[-i\psi(\Omega)]$
- with giant dispersion $\left.\frac{d\psi}{d\Omega}\right|_{\omega}$

$\Rightarrow$

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

τ_{ph0}: Before putting the dispersive medium

$\left.\frac{d\psi}{d\Omega}\right|_{\omega}$: The effect of the dispersive medium on the round trip time

$\Rightarrow$

$$= \frac{\frac{d\phi}{\tau_{rt0}}}{1 + \frac{1}{\tau_{ph0}} \left.\frac{d\psi}{d\Omega}\right|_{\omega}} = \frac{\Delta\omega_0}{1 + \frac{1}{\tau_{ph0}} \left.\frac{d\psi}{d\Omega}\right|_{\omega}}$$

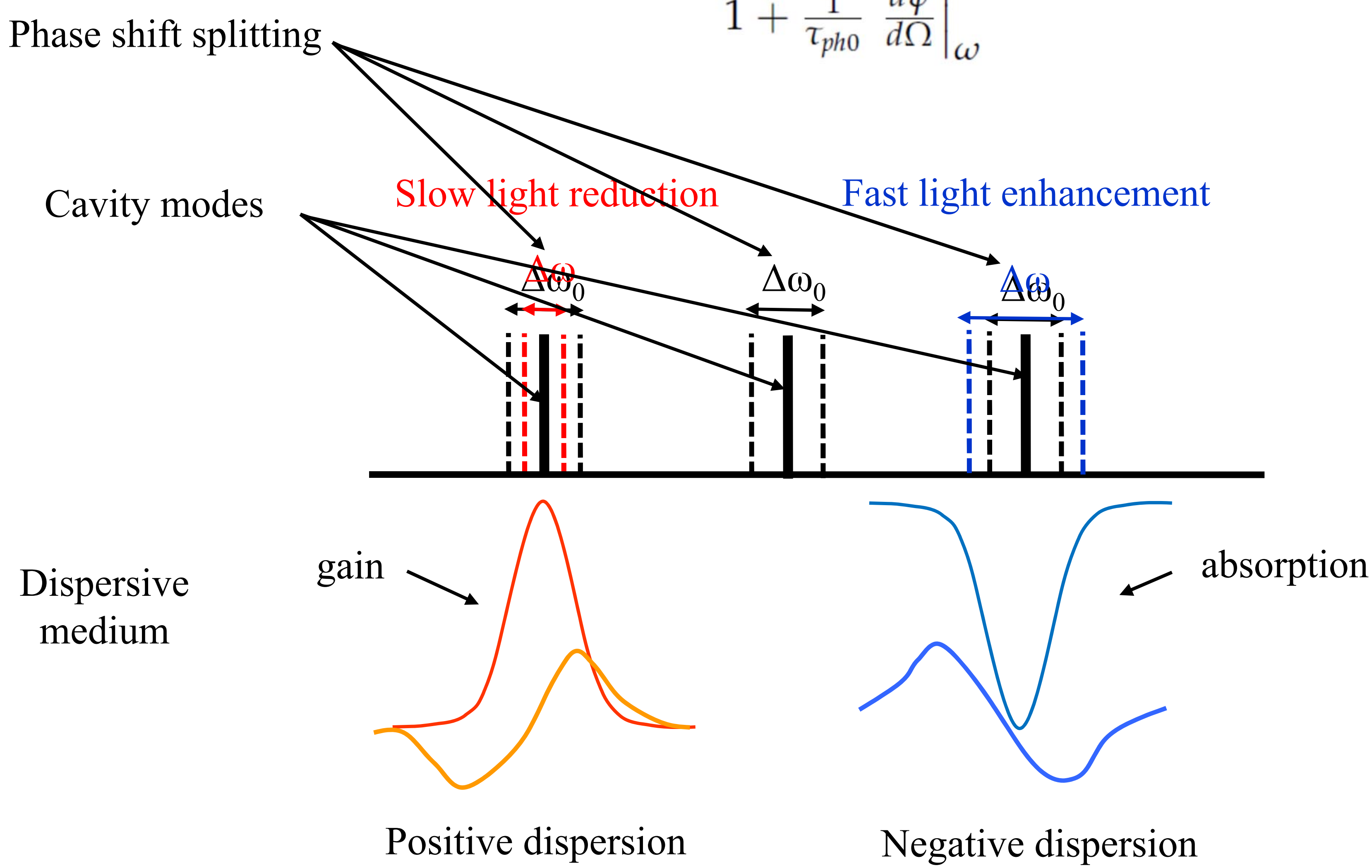
if $\left.\frac{d\psi}{d\Omega}\right|_{\omega}$

>0 "slow light" → Reduction in phase response

<0 "fast light" → Enhancement in phase response

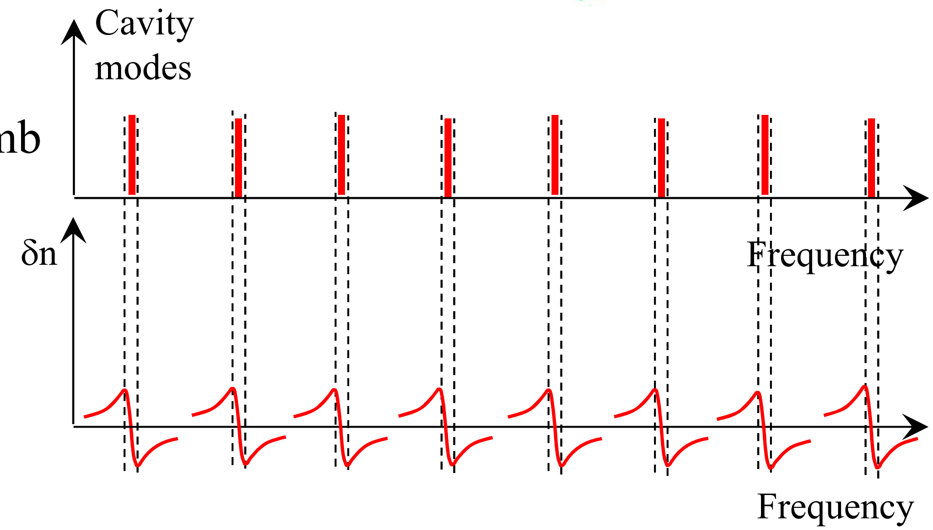
Modifying the phase response in a mode-locked laser

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



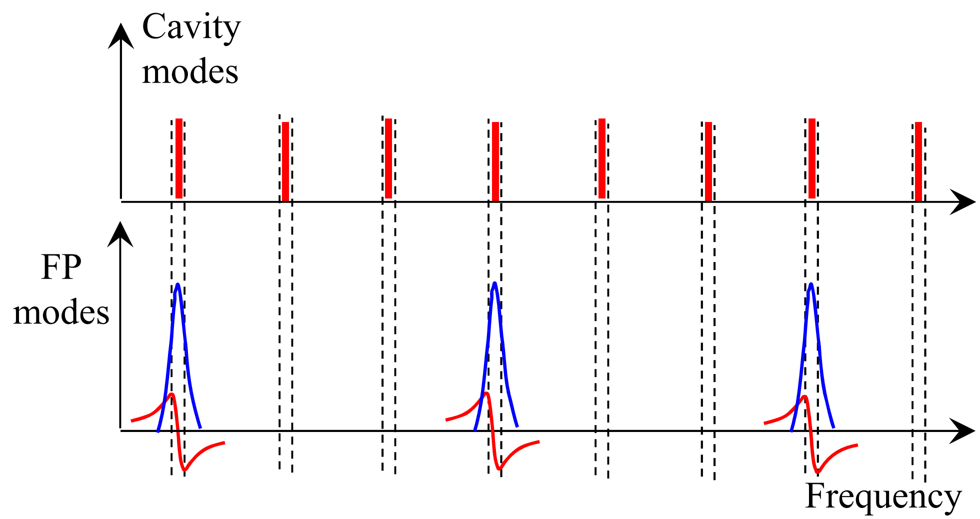
Modifying the phase response in a mode-locked laser

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:

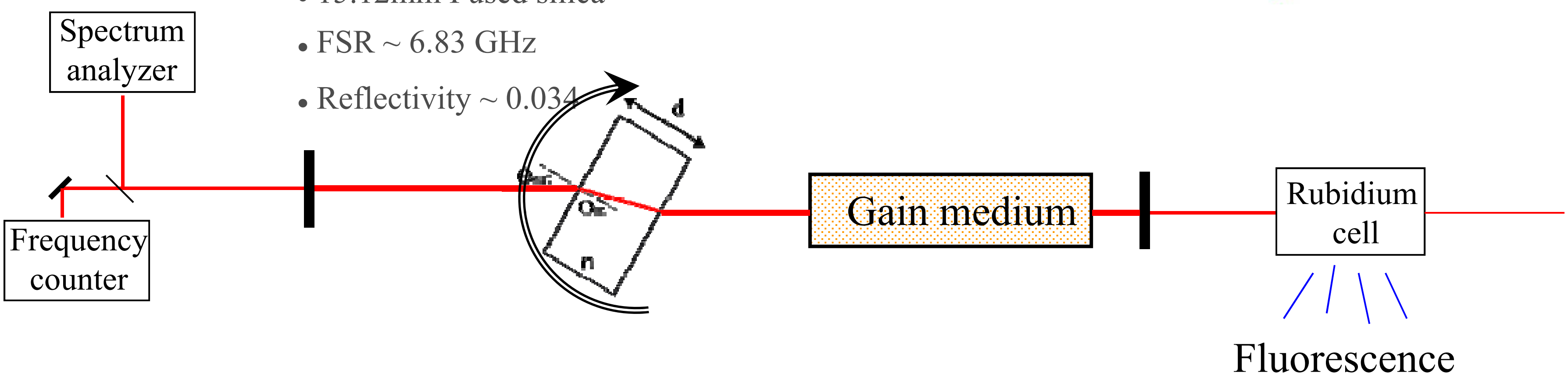


Next: **uncoated etalon inside a mode-locked laser cavity**

Nested frequency combs *K. Masuda, J. Hendrie, J.-C. Diels and L. Arissian, J. Phys. B* ***49***:*085402 (2016)*

Etalon inside a mode-locked laser: some quizzes

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

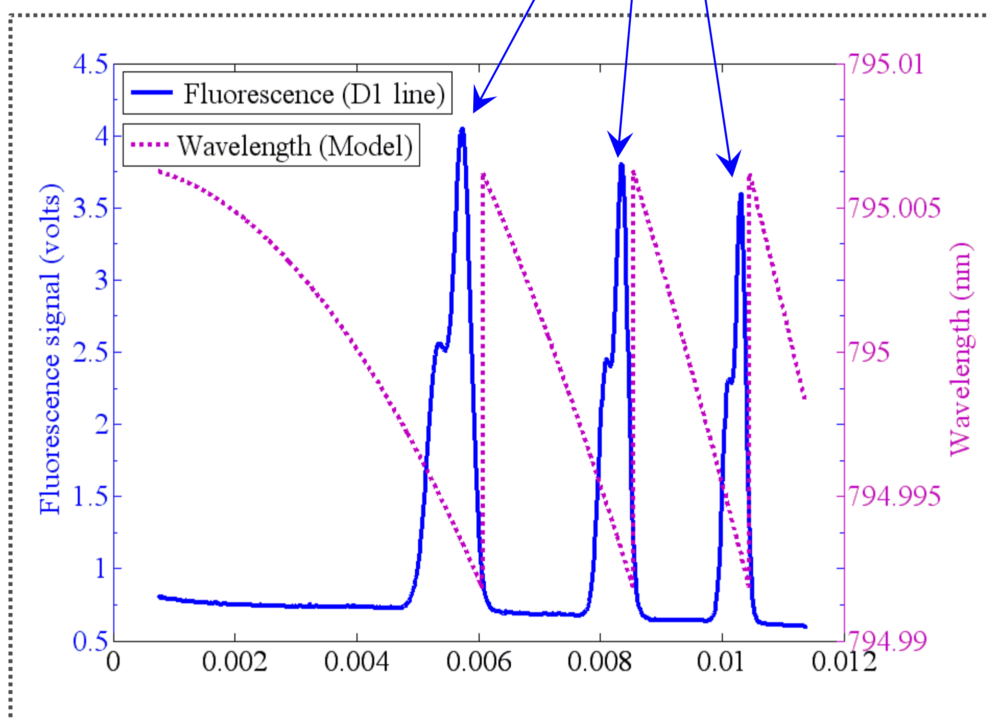


Quiz 1: How does the wavelength tune with $\boldsymbol{\theta}$?

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

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

$$\rightarrow k \rightarrow \lambda = \frac{2\pi}{k} \rightarrow$$



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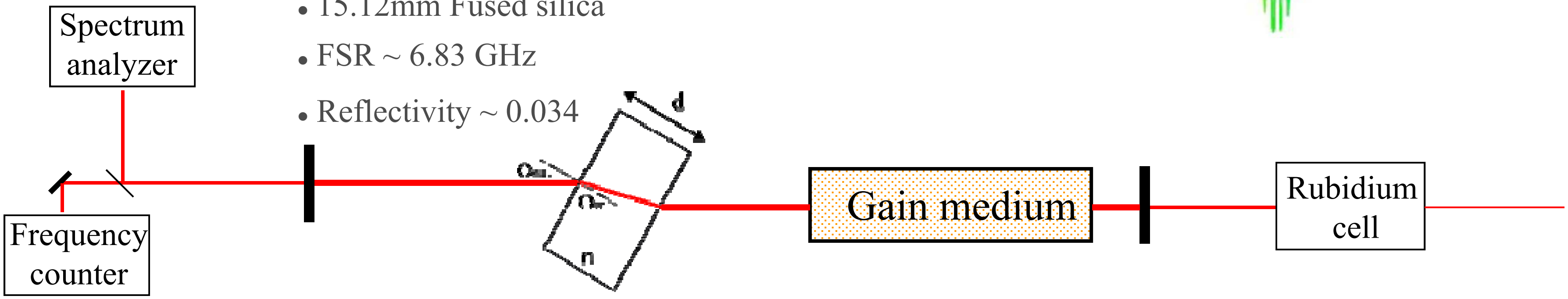
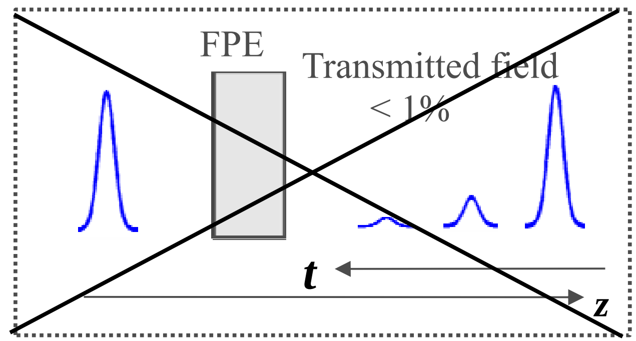
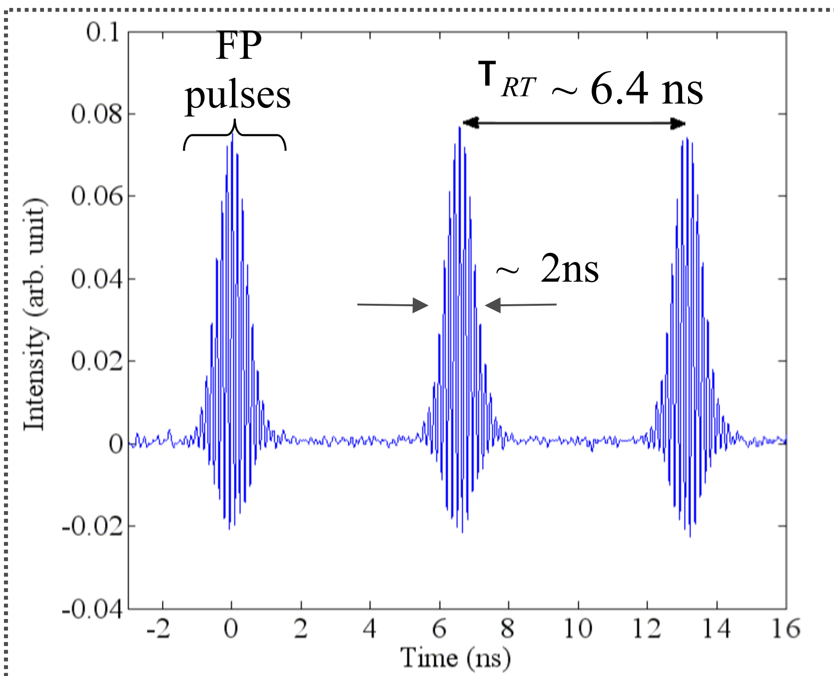


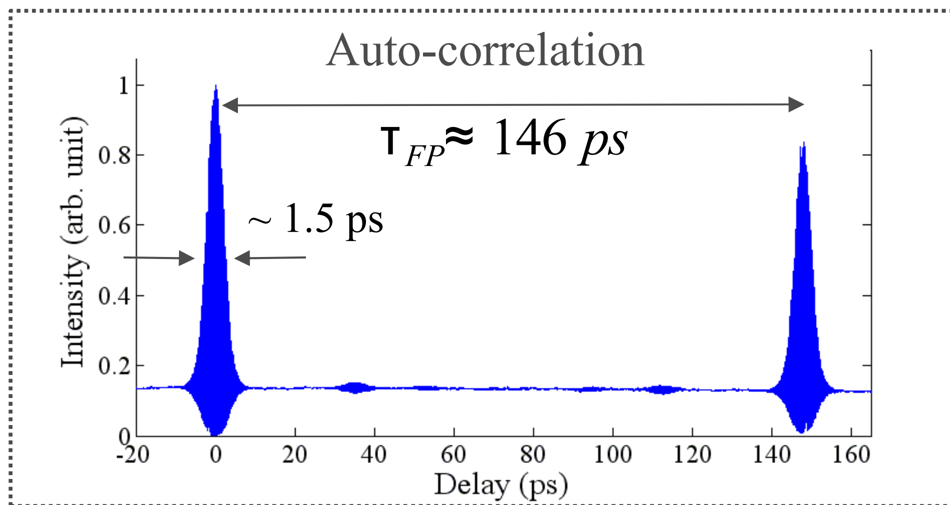
Quiz 2: What is the pulse transmission of the Fabry-Perot?

Wrong!

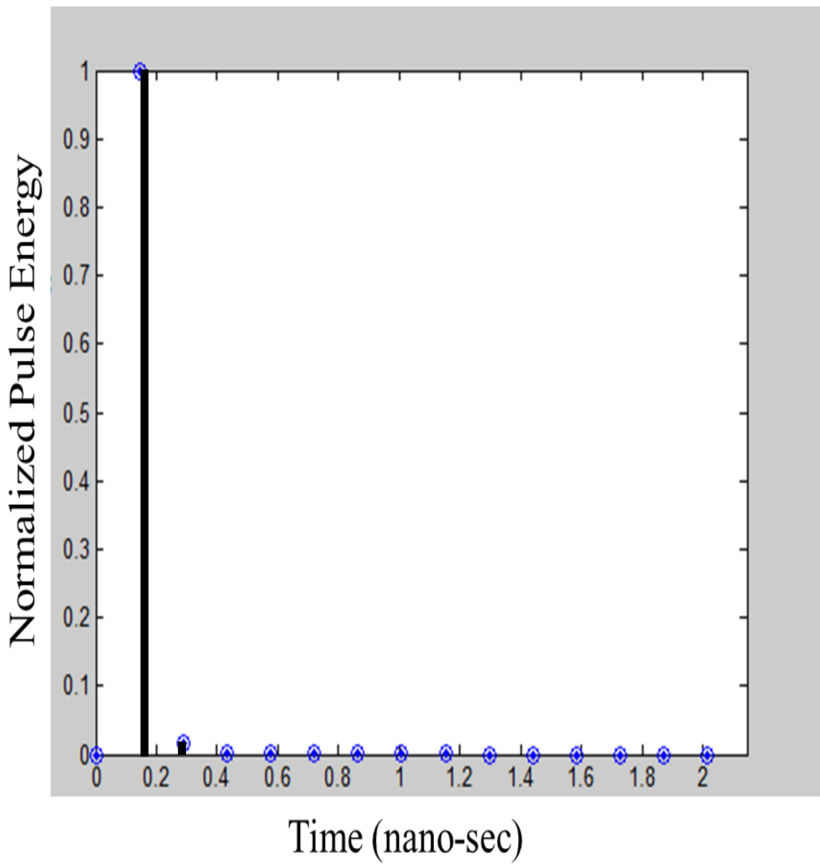
~~"Obviously": very small multiple reflections~~

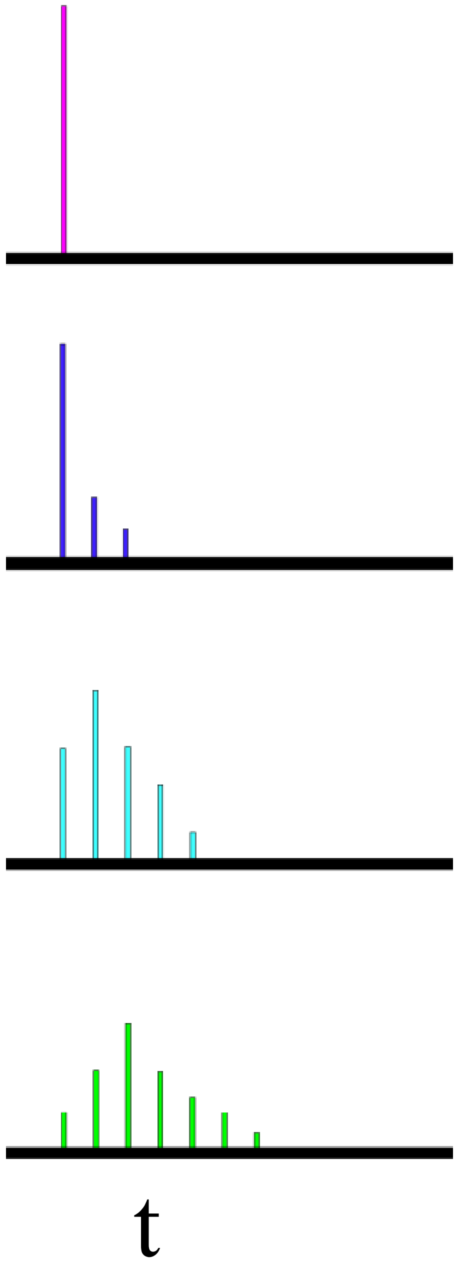






Generation of a nested pulse train





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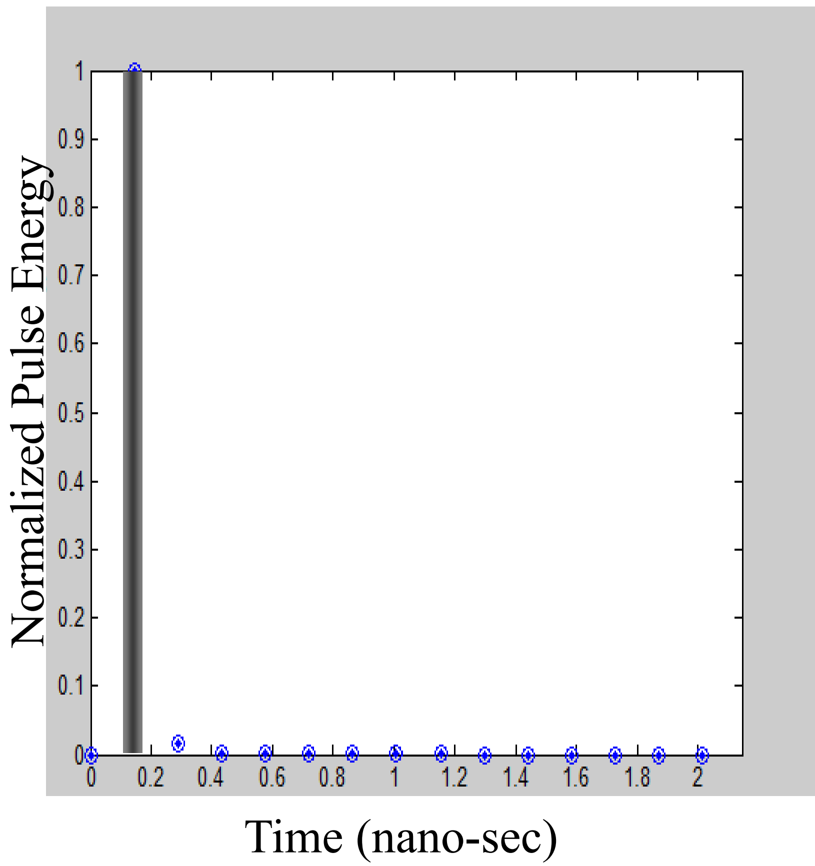
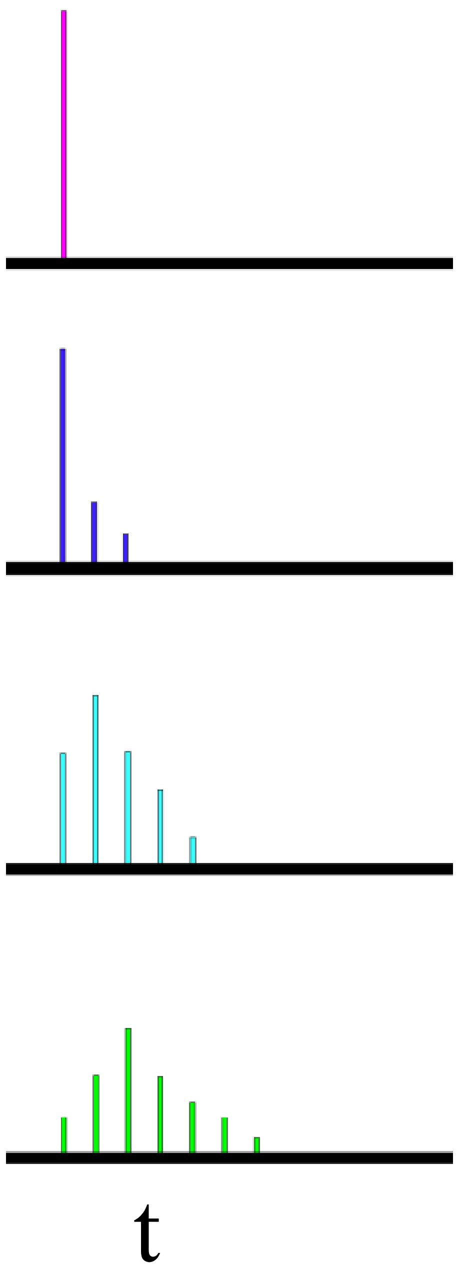
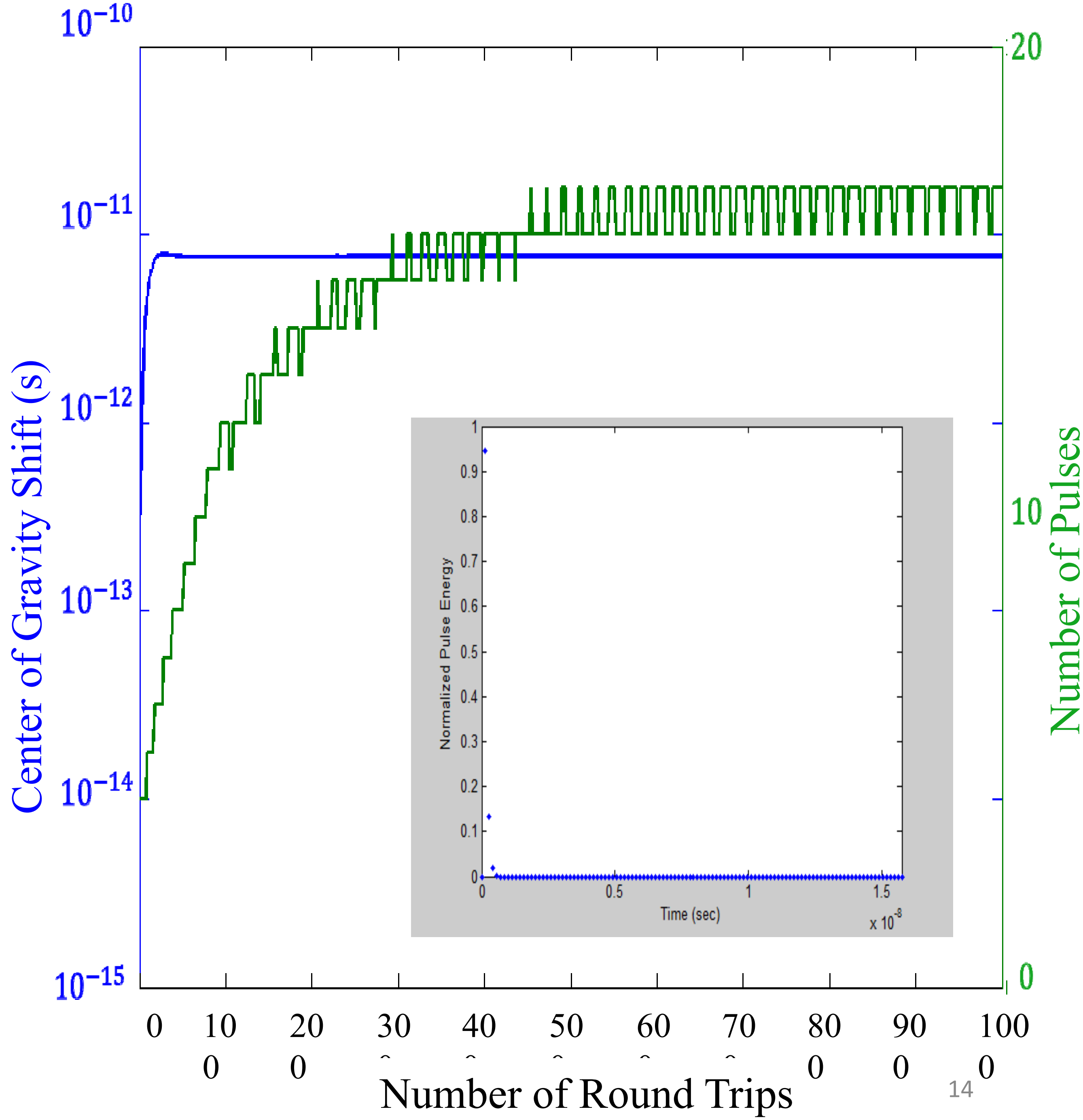




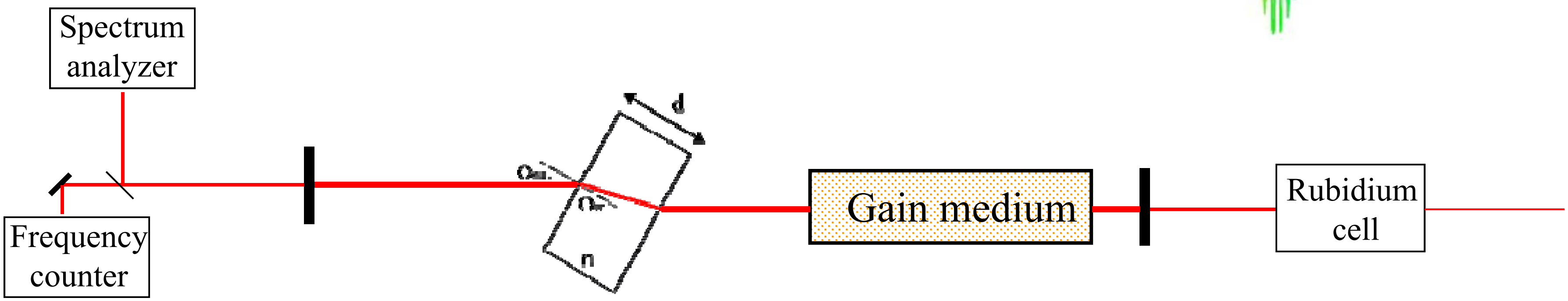
Generation of a nested pulse train

- Pulse minitrain reaches steady state condition after many roundtrips



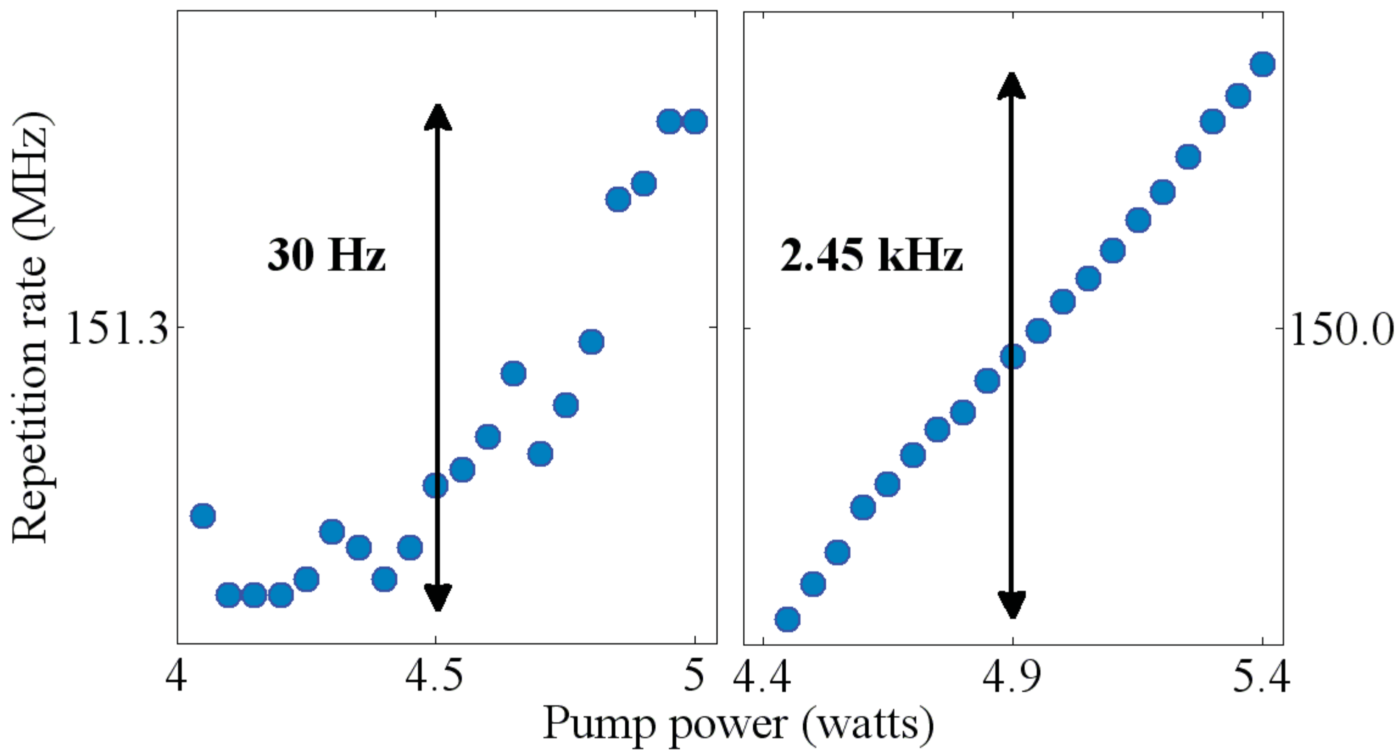
NRT = 1000
a = 0.0002
R = 0.05

Etalon inside a mode-locked laser: some quizzes

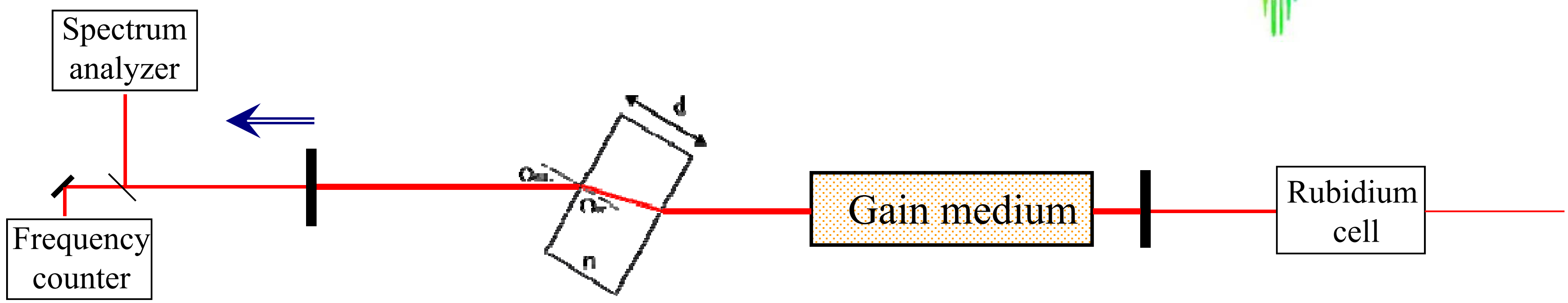


Quiz 3: Does the Fabry-Perot affect the repetition rate of the laser?

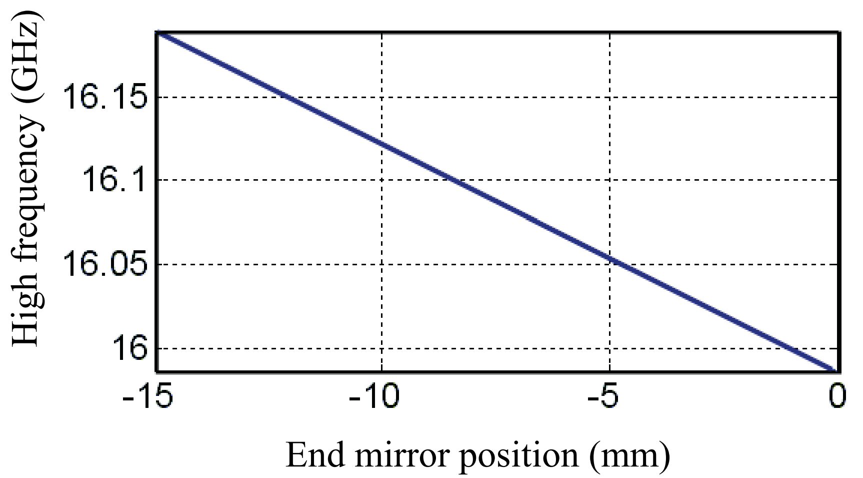
20% more thickness!!!???

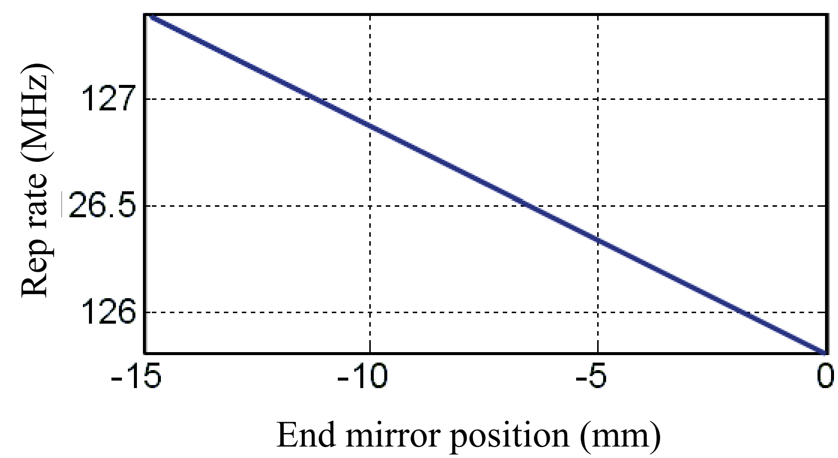


2. Etalon inside a mode-locked laser: some quizzes

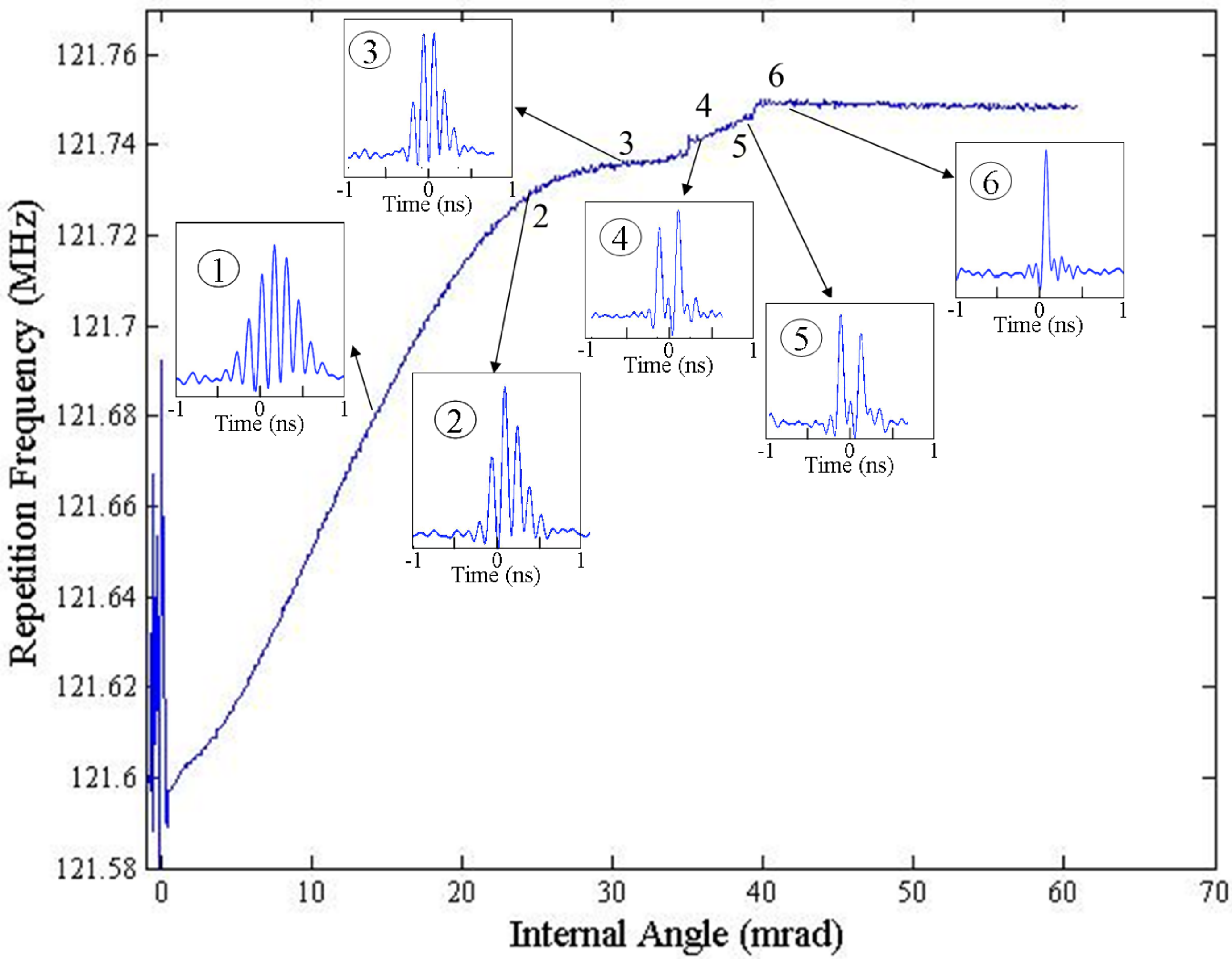


Quiz 4: Is the high frequency affected by the low frequency (cavity length)?





Laser repetition rate versus angle

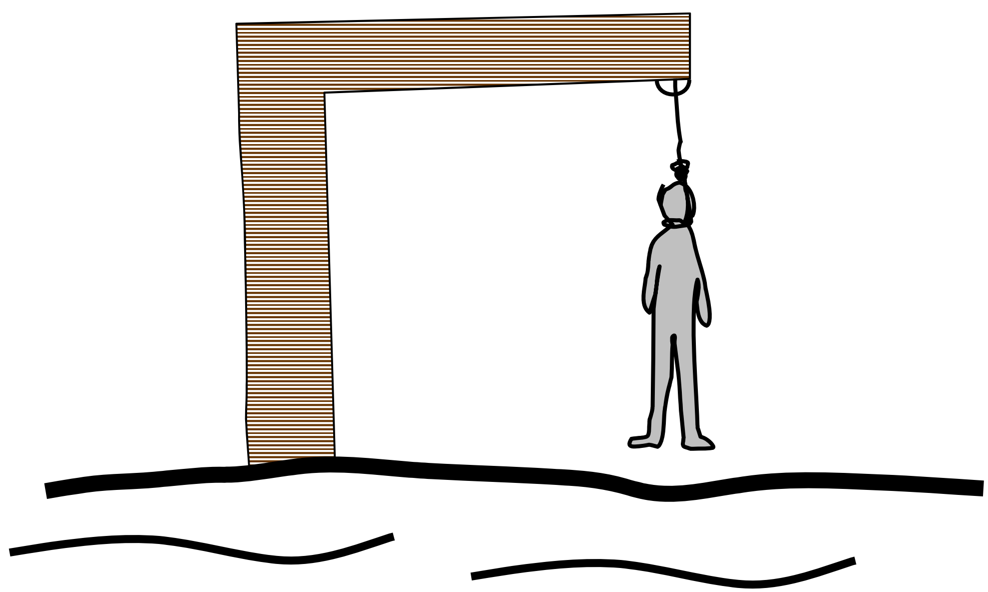


We achieve fine wavelength and group velocity control by adjusting the FP angle

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:



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4) The light velocity, a definition?

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6) Can we make a purely optical accelerometer?

We all know what the speed of light is…

Light velocities

Phase velocity	c/n	
Ray velocity	velocity of energy flow in crystals	
Group velocity	dk/dΩ	"Fast light, Slow light"
Mode velocity	in a waveguide or optical fiber	
Envelope velocity	None of the above velocities are relevant when dealing with absorber, gain or active laser cavities	

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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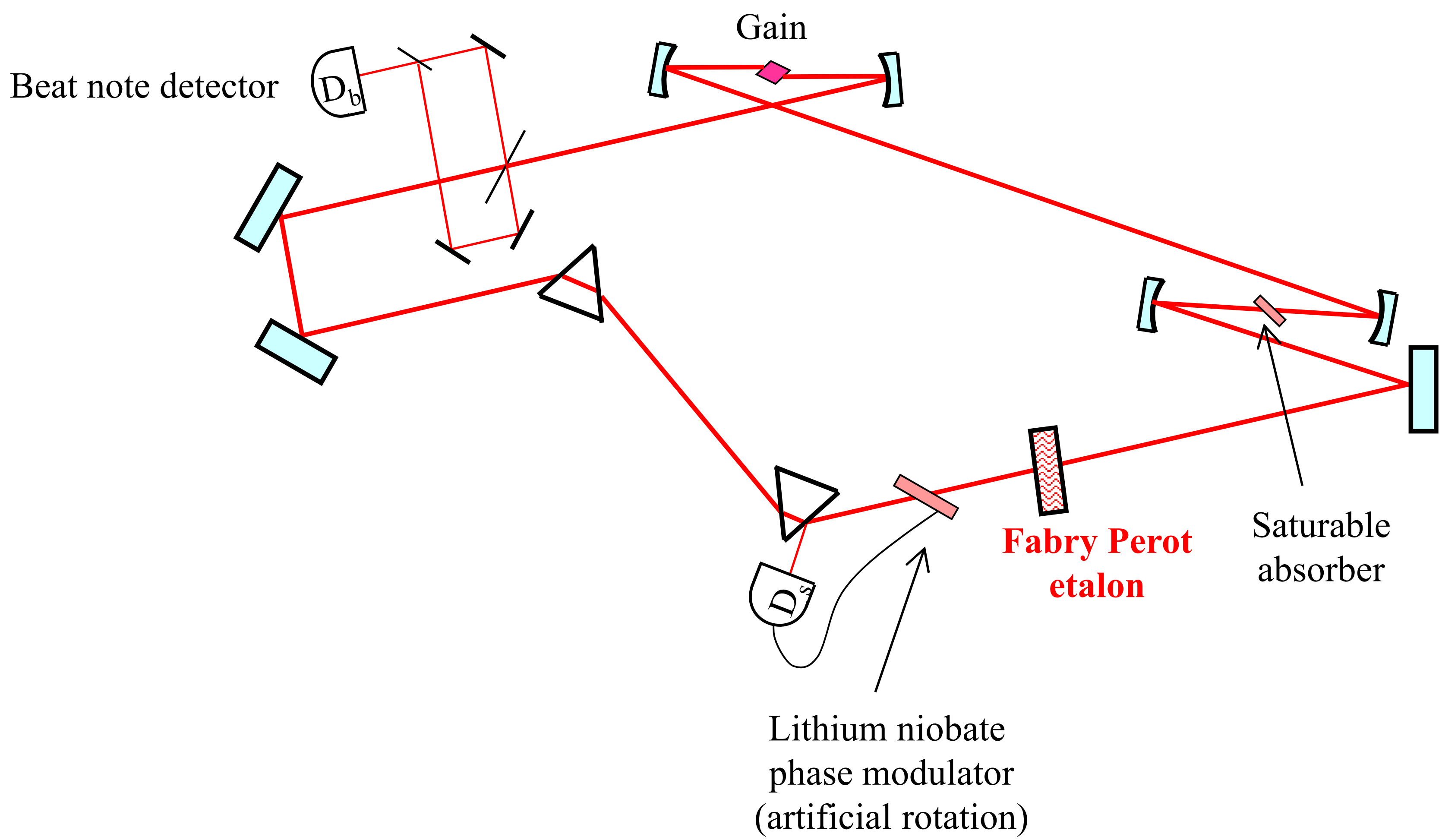
Changing the beat note response in a ring laser with a Fabry-Perot



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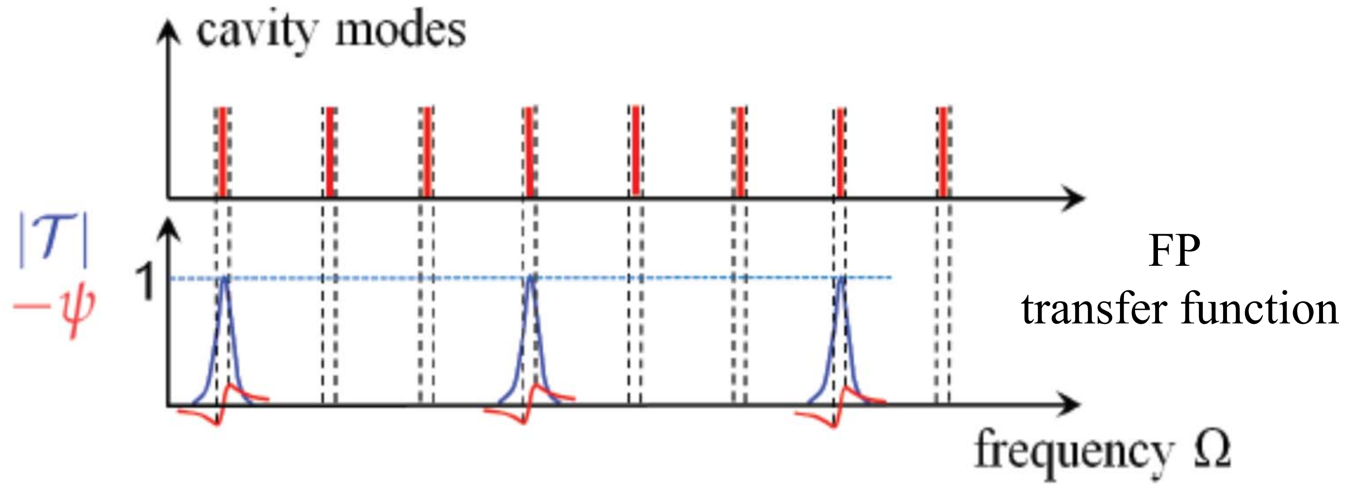

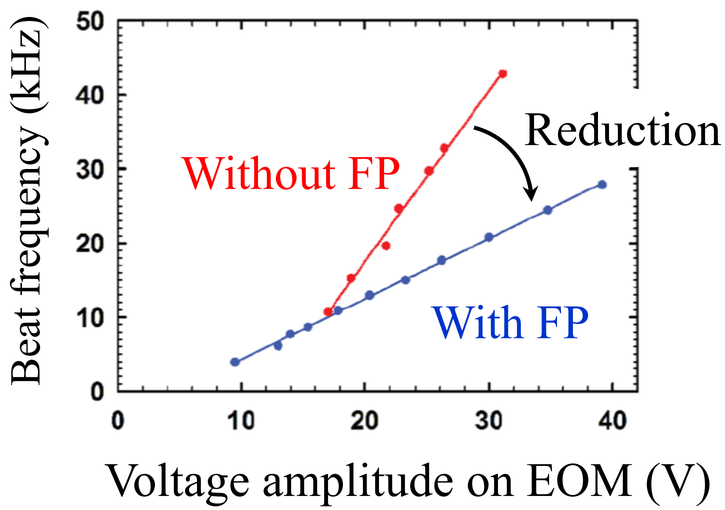

$$\left|\frac{d\psi}{d\Omega}\right|_{\omega_0} \approx \frac{1+R}{1-R}\frac{nd}{c} > 0$$

Fabry-Perot reflectivity of 4%. Because of coupling to the cavity, it appears as having R=98%.

J. Hendrie, M. Lenzner, H. Afkhamiardakani, J.C. Diels, L. Arissian, "Impact of so-called slow/fast light on the response of intracavity phase interferometry and laser gyro" (submitted to Optica)

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A factor of 1.9!!!

if $\left.\frac{d\psi}{d\Omega}\right|_{\omega}$

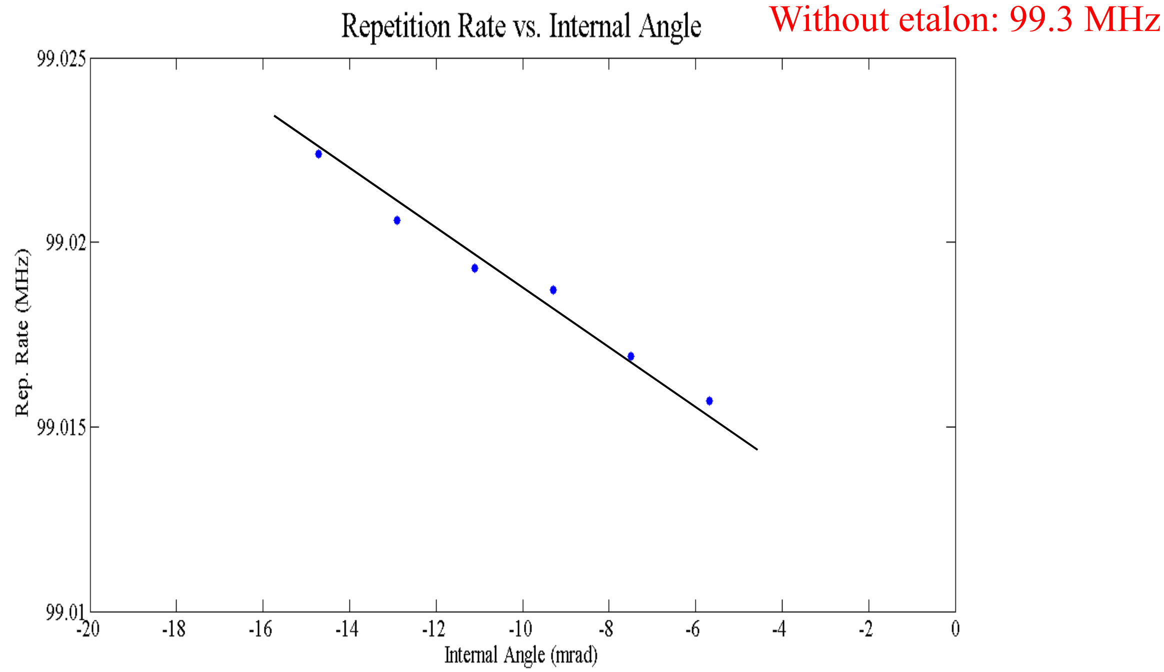
>0 "slow light" → Reduction in phase response

<0 "fast light" → Enhancement in phase response

Is it slow light?

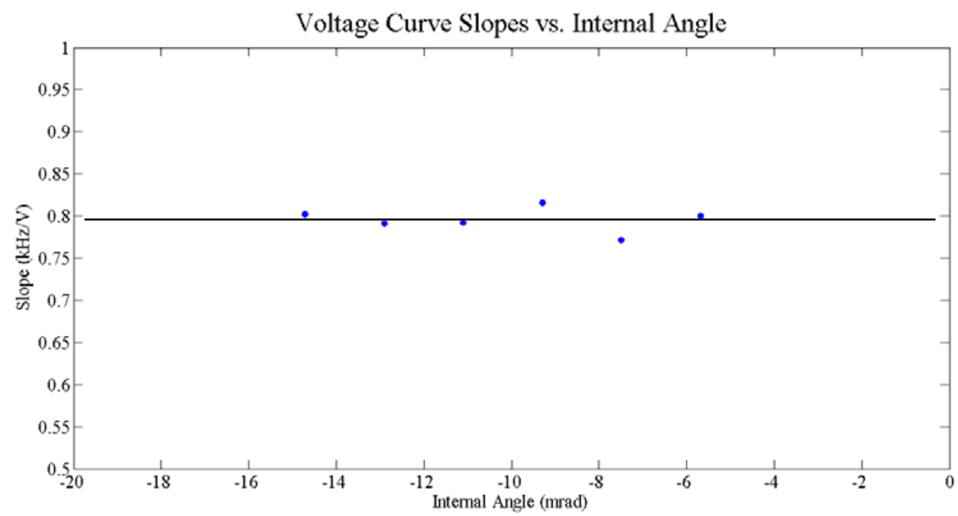
It is not!

The pulse velocity changes with Fabry-Perot angle



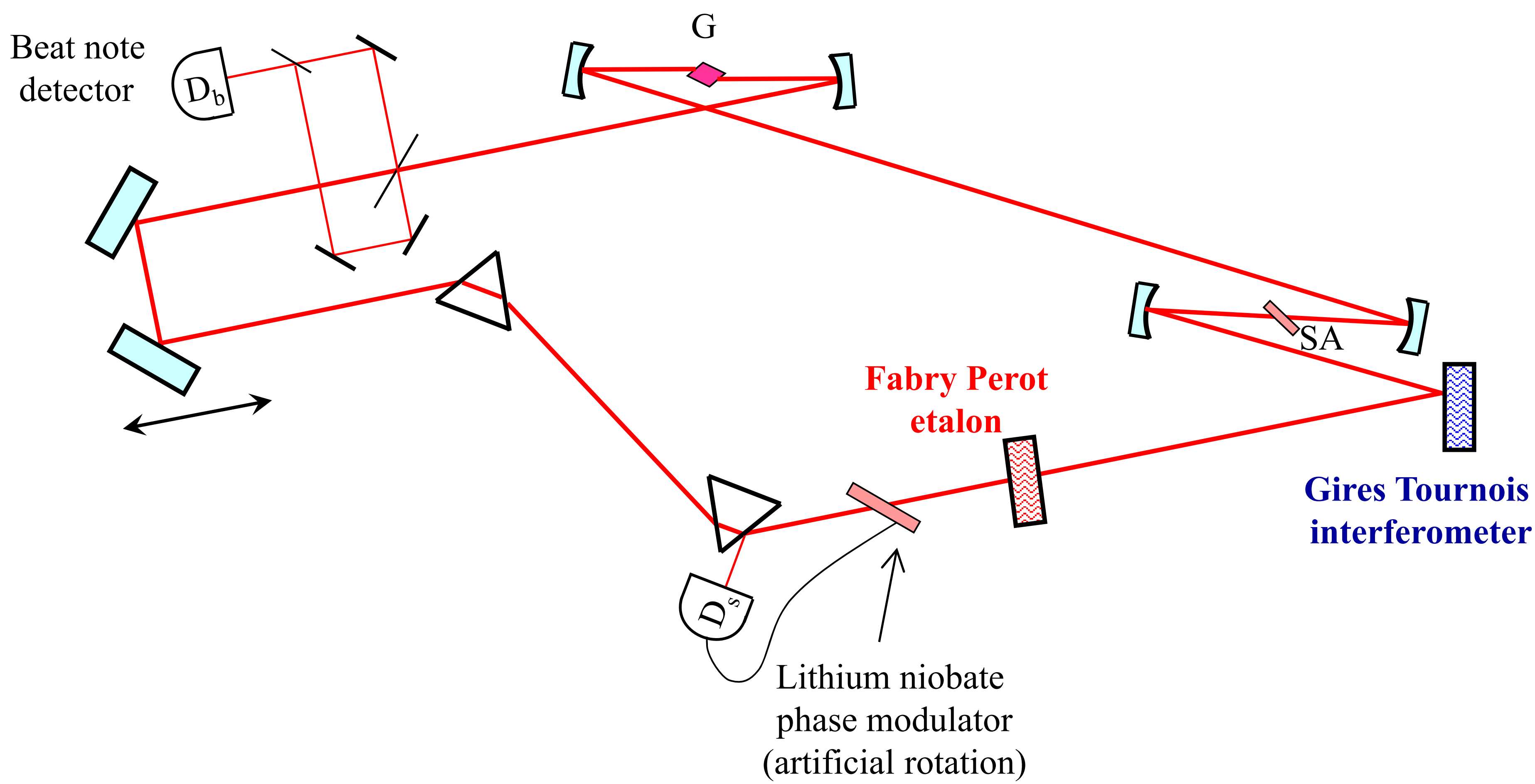
But…

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:



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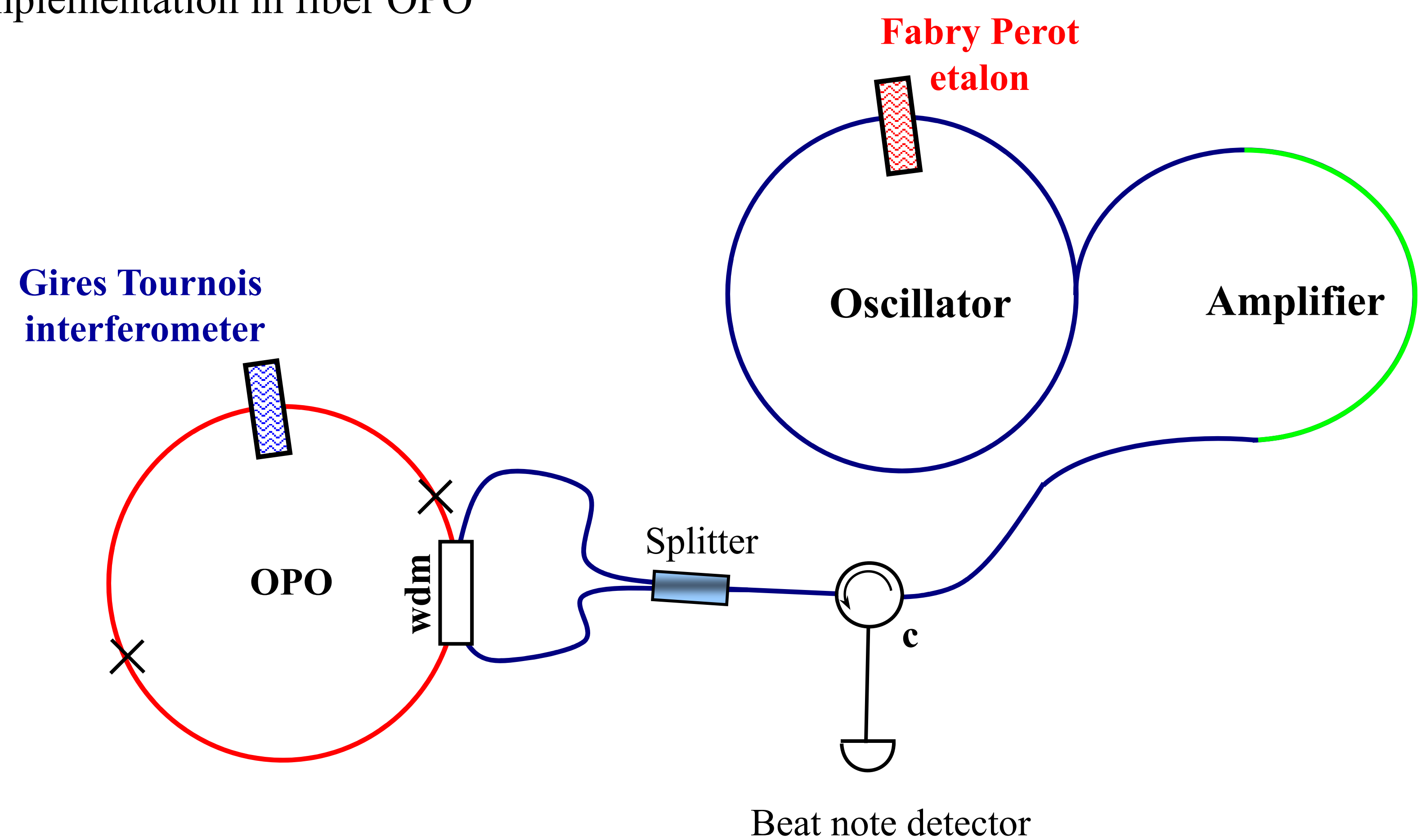
Implementation in fiber OPO



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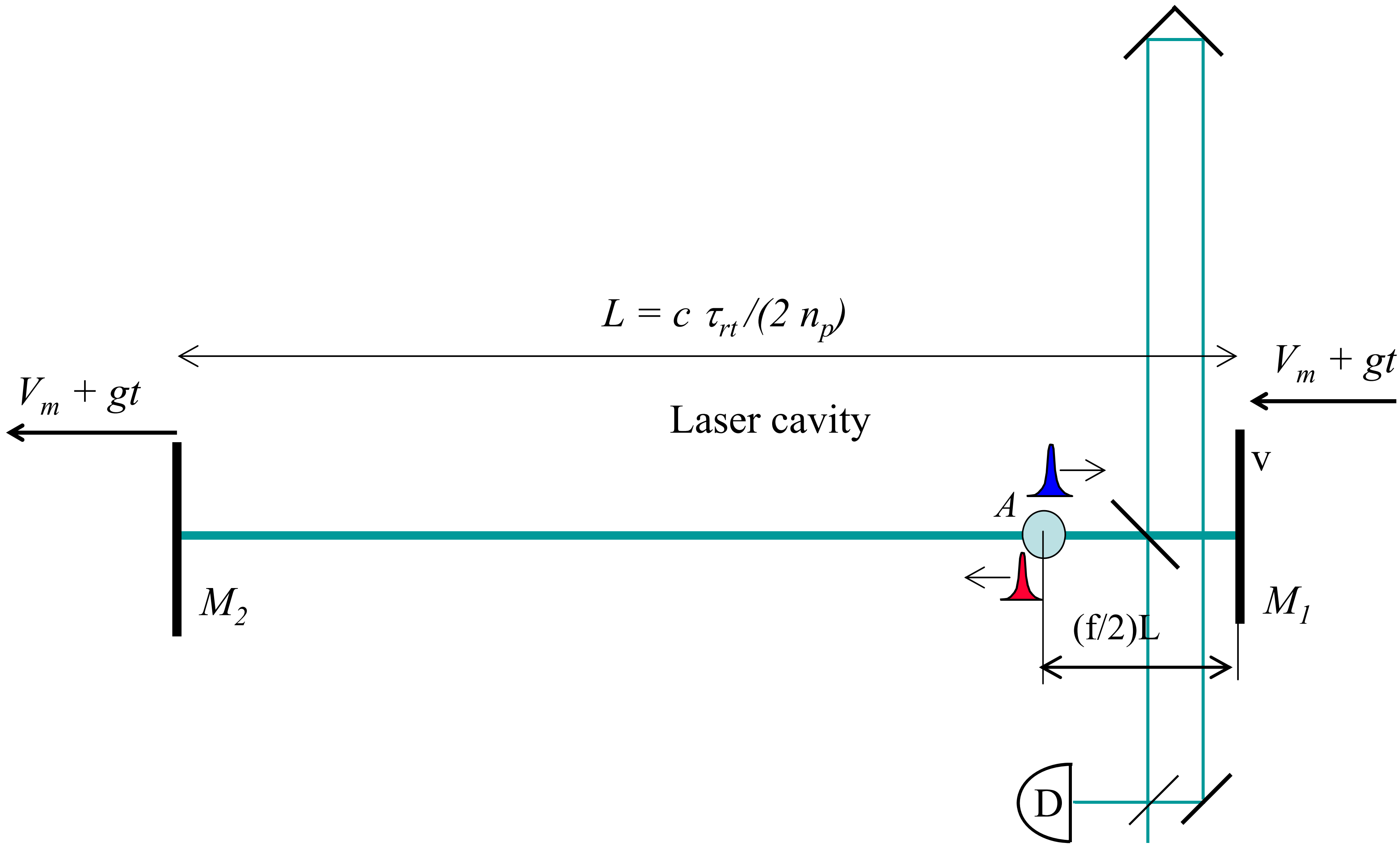
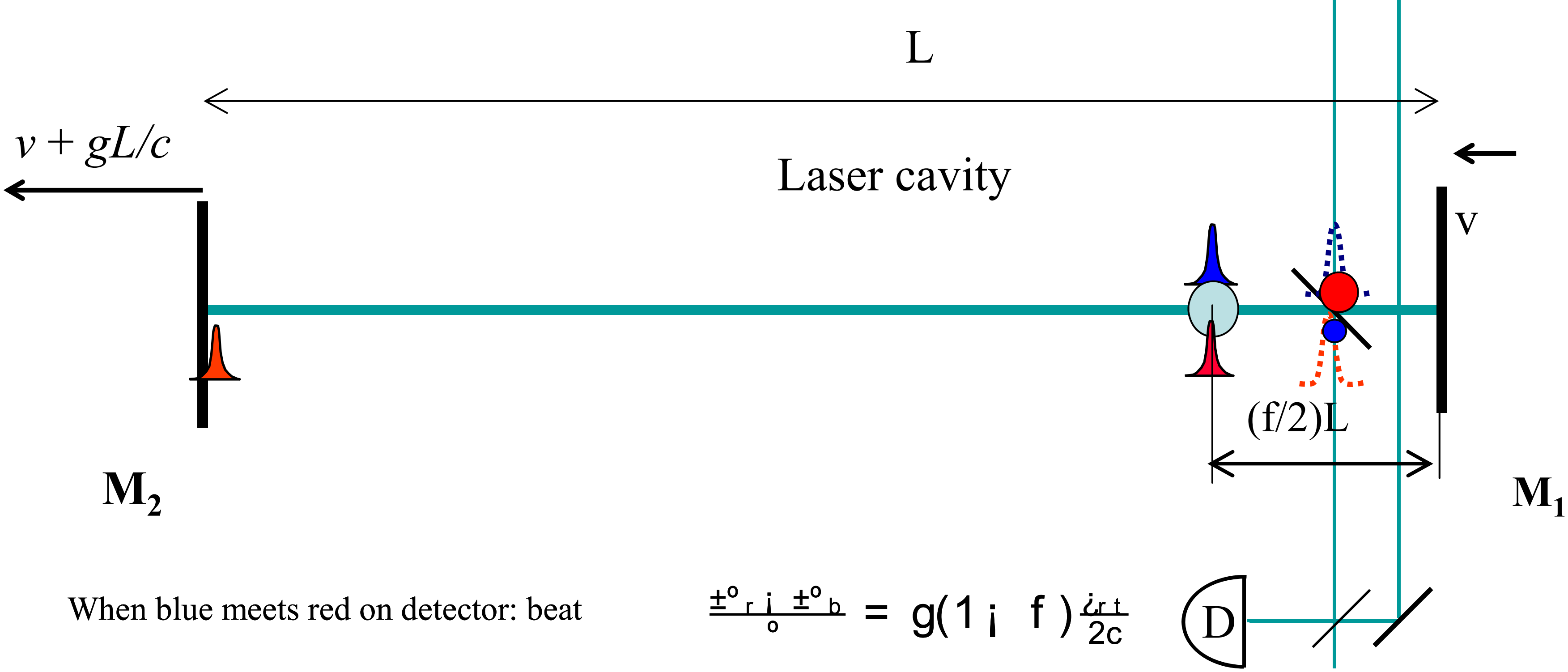


$L = c\ \tau_{rt}/(2\ n_p)$
$V_m + gt$
$V_m + gt$
Laser cavity
v
A
M_2
M_1
(f/2)L
D

$t_1 = \frac{f}{2}\frac{\tau_{rt}}{2}$ when blue hits M1, gets a Doppler shift $\frac{\delta\nu_b}{\nu} = \frac{v}{c} + g\frac{f}{2}\frac{\tau_{rt}}{2c}$

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

$t_2 = \frac{\tau_{rt}}{2}\left(1 - \frac{f}{2}\right)$ **when red hits M2, gets a Doppler shift** $\frac{\delta\nu_r}{\nu} = \frac{v}{c} + g\left(1 - \frac{f}{2}\right)\frac{\tau_{rt}}{2c}$



When blue meets red on detector: beat $\frac{\delta\nu_r - \delta\nu_b}{\nu} = g(1 - f)\frac{\tau_{rt}}{2c}$

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

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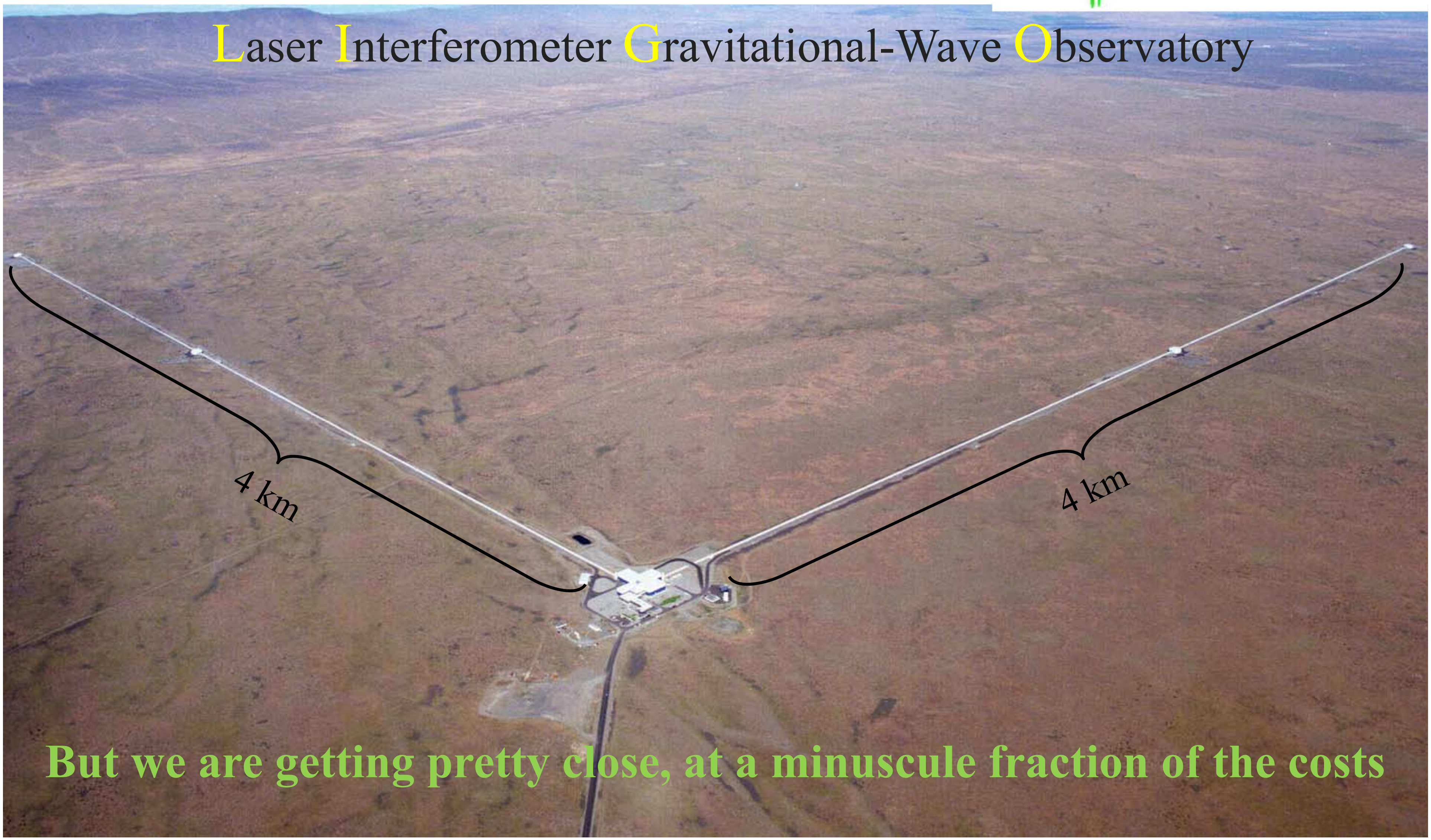
WE ARE NOT HERE YET

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?

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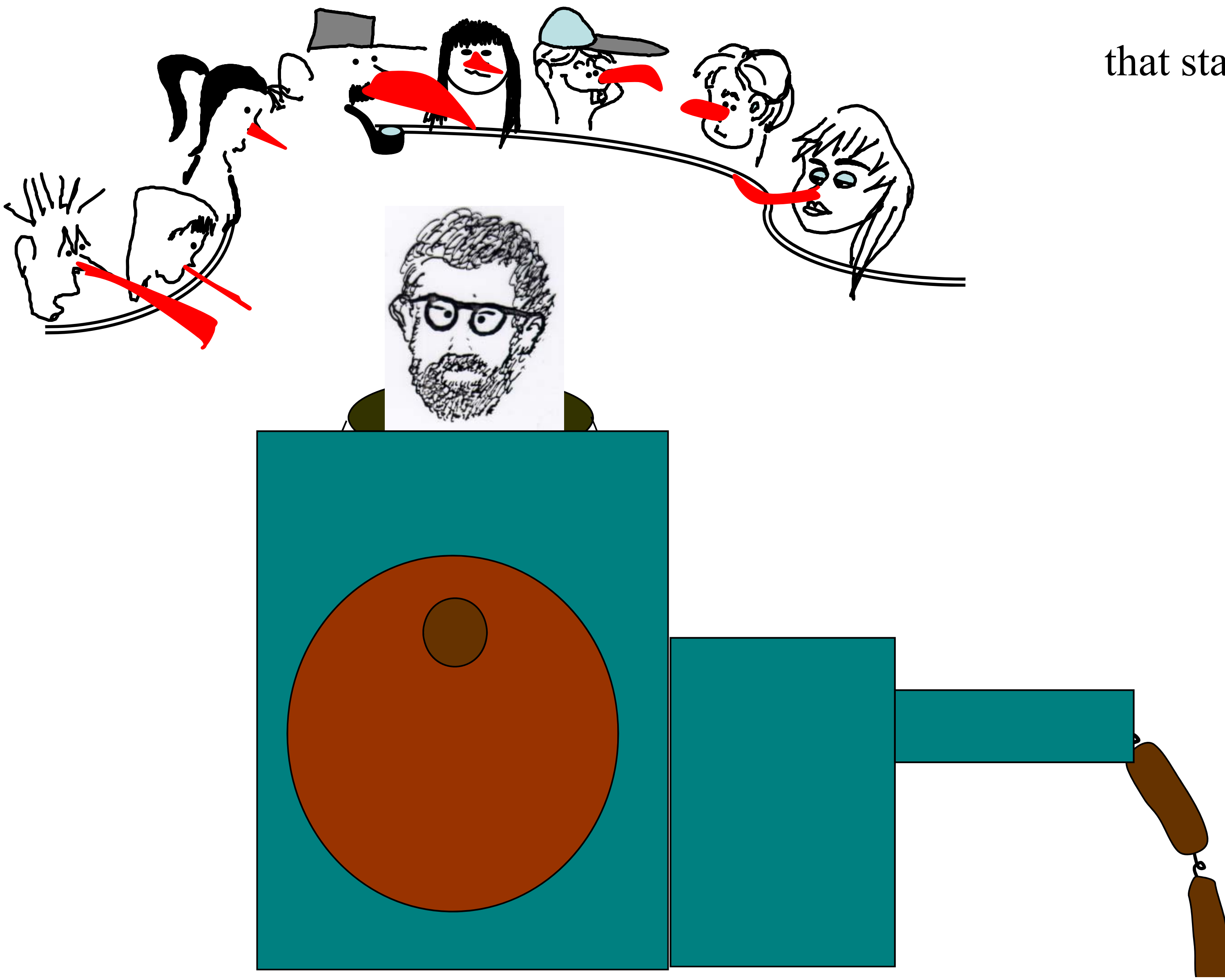
What if, some perfectly normal people, grow a huge red nose…

What will happen to the one

that stays normal?



Dirk Neidhardt	M.S.	1990 (UNM)	Bistable interfaces
C. Rao	PhD	[illegible] (UNM)	Ultrafast [illegible] injection
Olivier Chalus	PhD	2007 U. Strasbourg	Filaments with long UV pulses
Yule Zhang	PhD	(UNM)	Vanadate laser gyro
Andreas Velten	PhD	2005 (UNM)	Diode-pumped Cr:LISAF OPO
Alexandro Ruiz	PhD	2006 (CICESE)	Femtosecond laser amplifier

6. Thanks to those who contributed

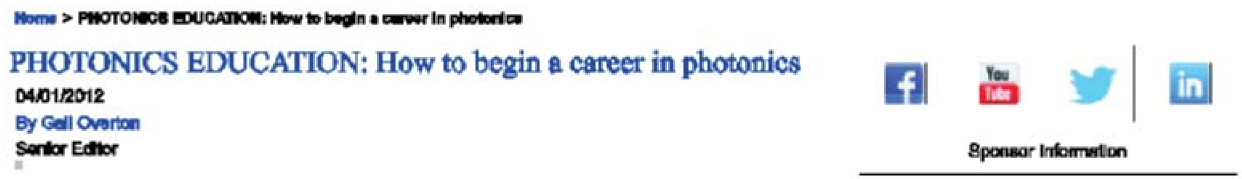
Special thanks to the dedicated PhD students that went through 6 years (+) of research with me

Name	Degree	Graduation	Topic
James Hendrie	PhD	(UNM)	Magnetometry by IPI
Haniel Afkhamiardakani	PhD	(UNM)	Fiber sensors
Ning Hsu	PhD	(UNM)	Intracavity OPO
Ali Rastegari	PhD	(UNM)	Laser induced discharges
Patrick Rambo	PhD	2000 (UNM)	Laser guided discharges
Aaron Bernstein	PhD	2004 (UNM)	Filamentation in air
Jens Schwartz	M.S.	1999 (UNM)	Multiphoton ionization
Xianmei Meng	PhD	2003 (UNM)	Ultrashort-pulse optical parametric oscillator sensor

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''

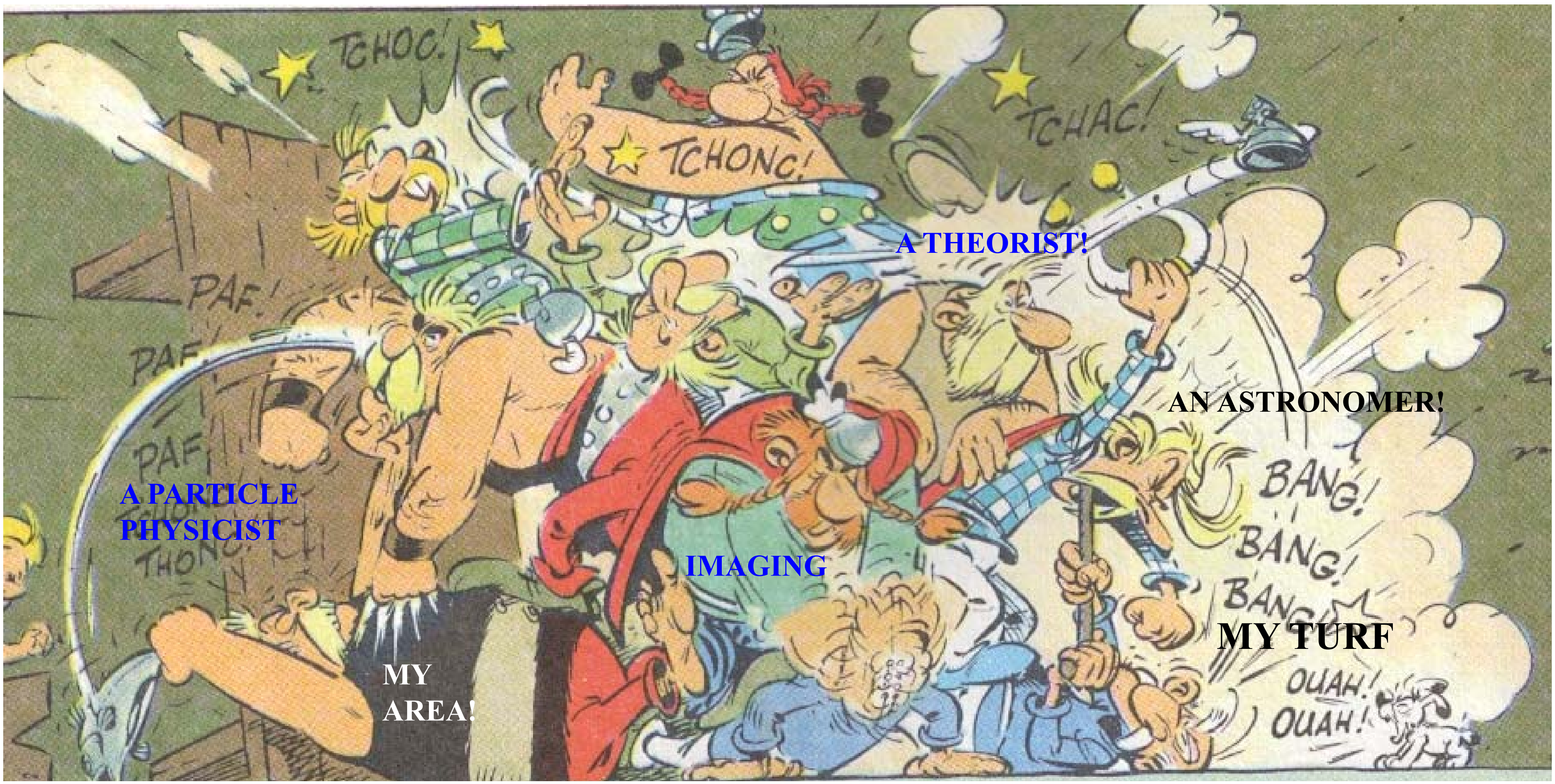
The US cream of the crop **…OSC; Tucson, AZ,** U. of **Rochester** director Xi-Cheng Zhang

Heriot-Watt University Tianjin University, etc et … but NOT UNM

Semiconductor Manufacturing

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

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

but the MOLE

…with blinders