Tuning laser frequency response from low to high with dispersion.

Eugeniy E. Mikhailov, Savannah Cuozzo [1] and David D. Smith[2]

1

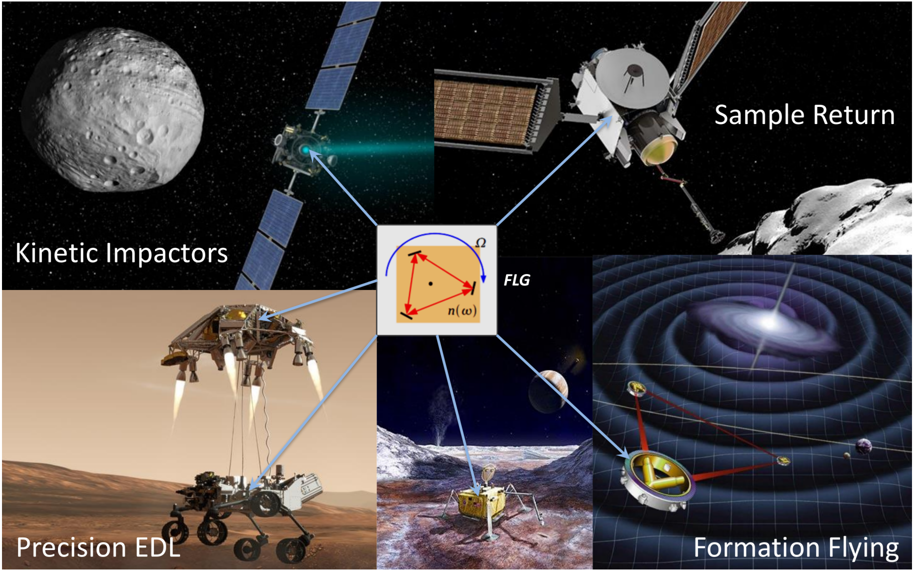
WILLIAM & MARY
CHARTERED 1693

2

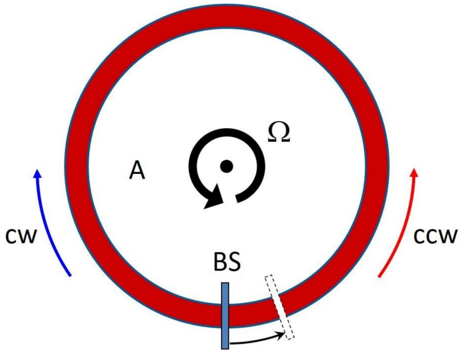
NASA Marshall Space Flight Center

PQE, January 8th 2020

Potential applications

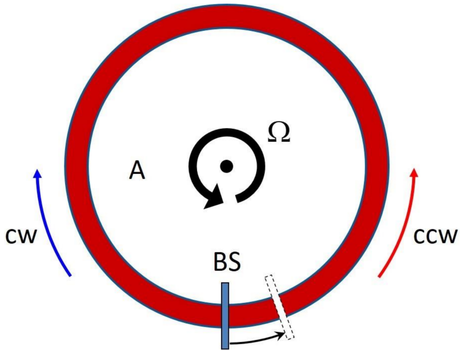


Dispersive cavity response



$$\Delta f = f_0 \frac{\Delta L}{L}$$

Dispersive cavity response



$$\Delta f = f_0 \frac{\Delta L}{L} \frac{1}{n_g} = \Delta f_{empty} \frac{1}{n_g}$$

Group index

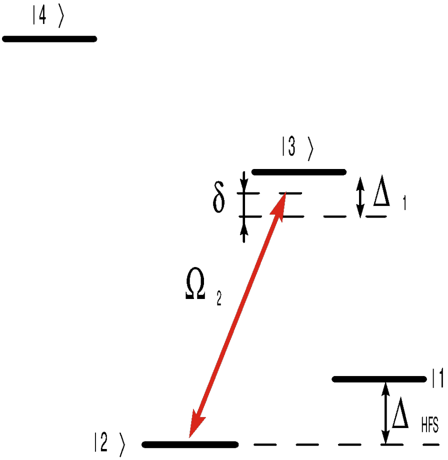
$$n_g(f) = n + f_0 \frac{\partial n}{\partial f}$$

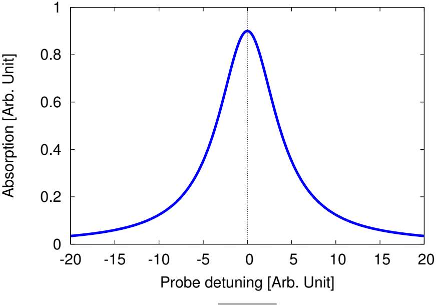
$$v_g = c/n_g$$

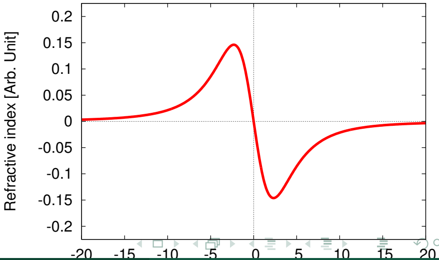
Cavity response enhanced if $n_g < 1$ i.e. under the fast light condition

Shahriar et al., PRA **75**, 053807 (2007)

Two level system - fast light

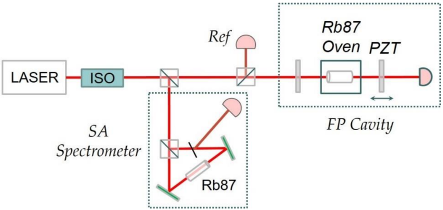


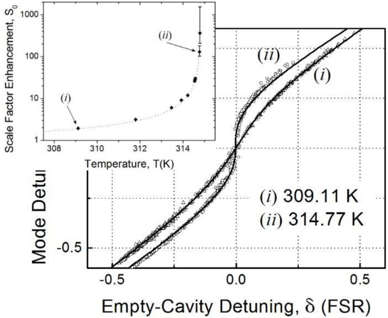


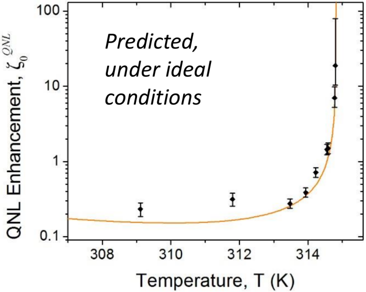


Passive fast light cavity

- First, largest, and most direct observation of enhanced scale-factor sensitivity ($S = 363$).
- Tuning of S by temperature (slow) and by optical pumping (fast).





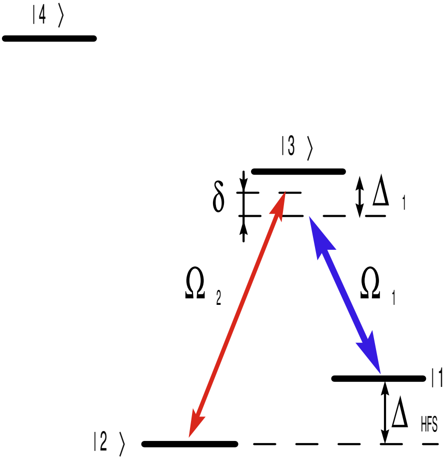


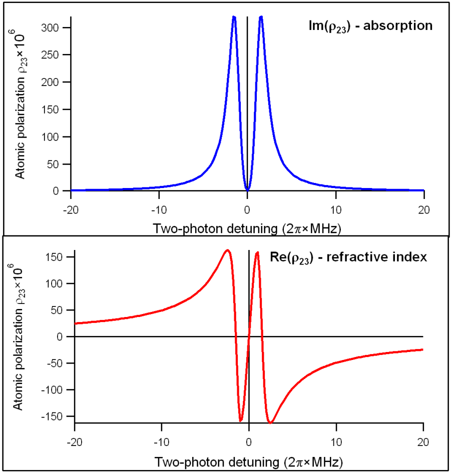
D. D. Smith et al., *Phys. Rev. A* 94, 023828, (2016).

Active lasing vs passive cavity

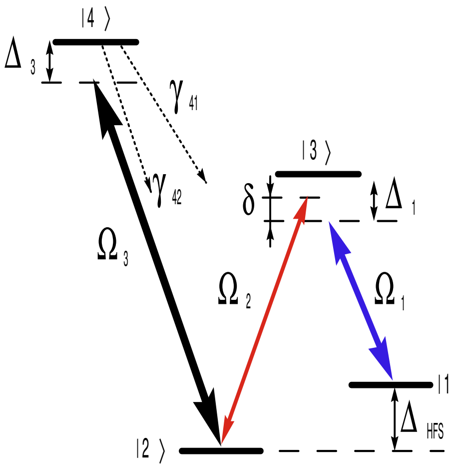
- No external lasers which require additional stabilization
- self-contained thus small
- self-referenced
- allow to measure frequency shift directly

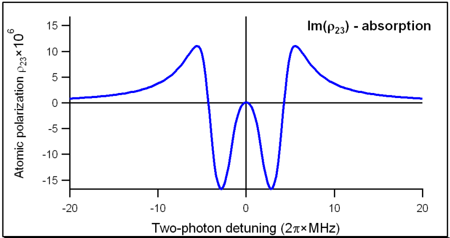
EIT - slow light

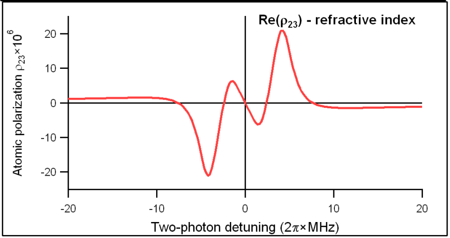




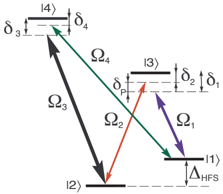
N-bar with four-wave mixing - fast and with gain

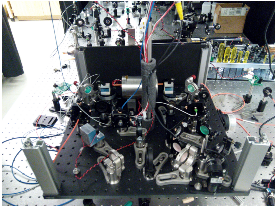


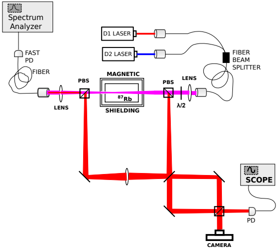




Setup and measured pulling factor



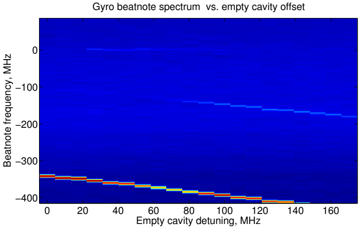


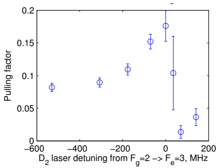


$$P.F. = \frac{\Delta f_{\text{dispersive}}}{\Delta f_{\text{empty}}}$$

$$= \frac{1}{n_g}$$

$$\Delta f_{\text{empty}} = f_0 \frac{\Delta L}{L}$$



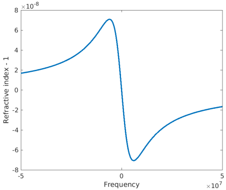


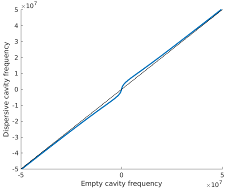
D. T. Kutzke, Optics Letters, Issue 14, **42**, 2846, (2017).

Cavity response in fast, slow, and super slow regimes

Fast

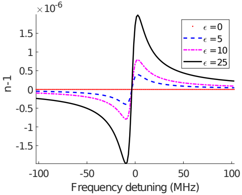
$dn/d\omega < 1$

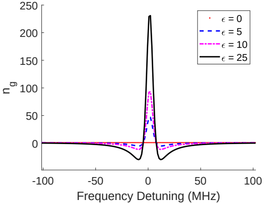


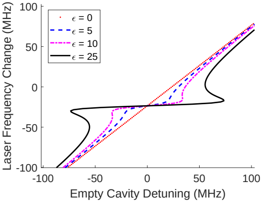


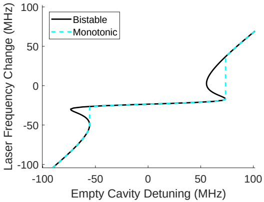
Slow

$dn/d\omega > 1$





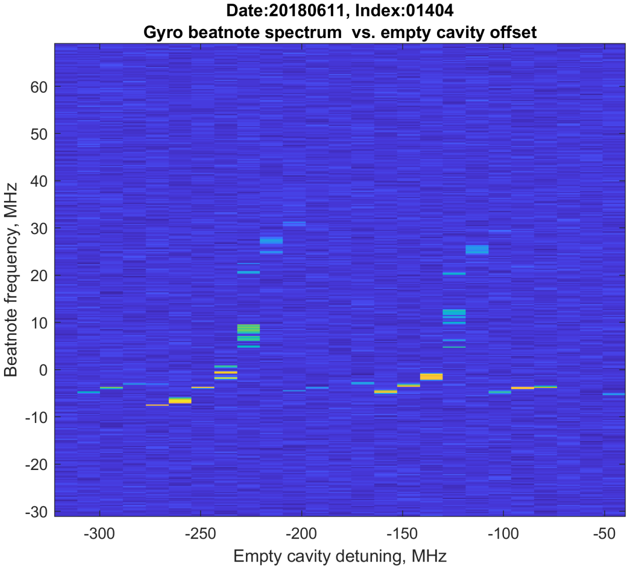




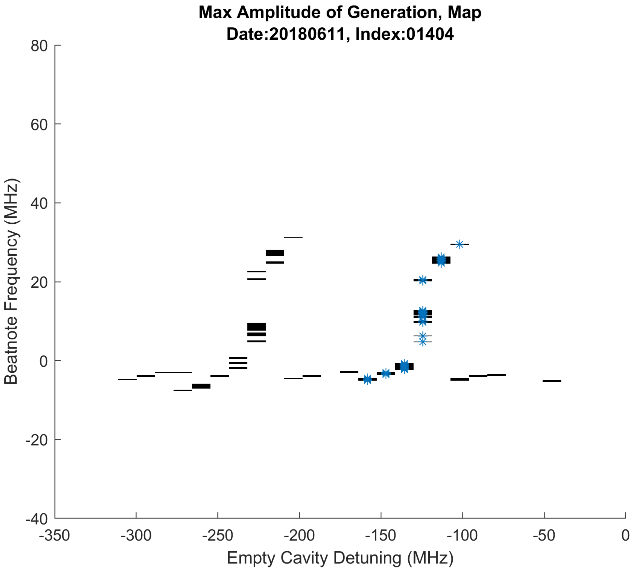
Lasing equation

$$n(\omega)L = m\lambda = mc\frac{2\pi}{\omega}$$

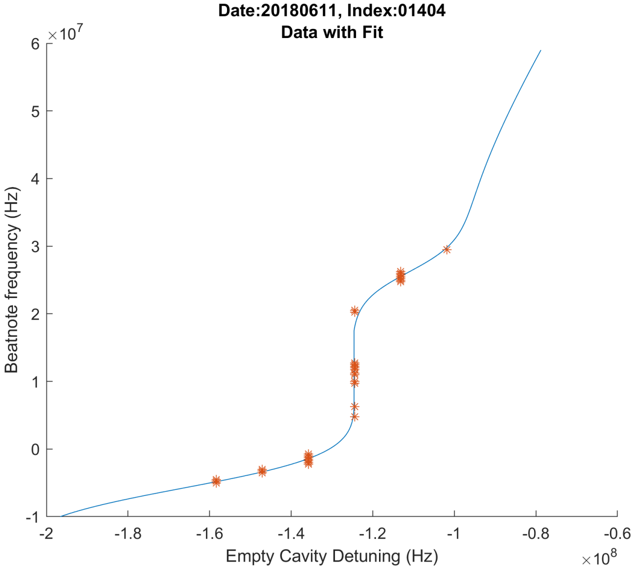
Beatnote map with “high” pulling factor



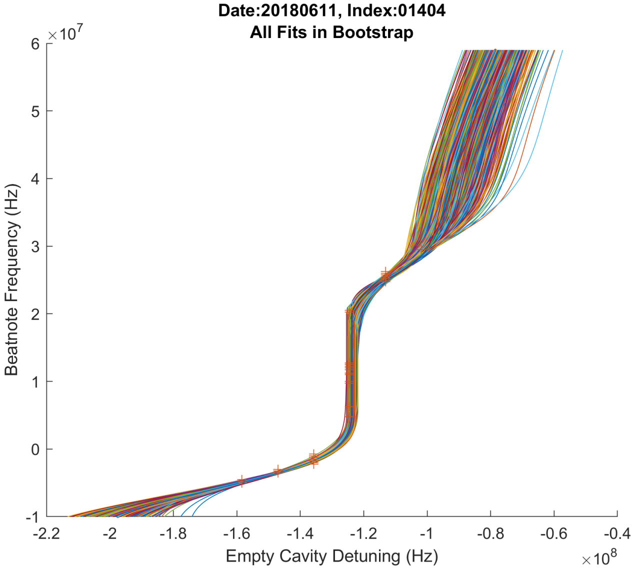
Beatnote map with “high” pulling factor



Beatnote map with “high” pulling factor

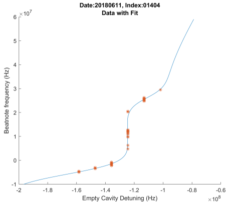


Beatnote map with “high” pulling factor

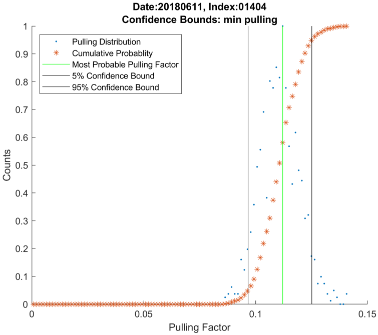


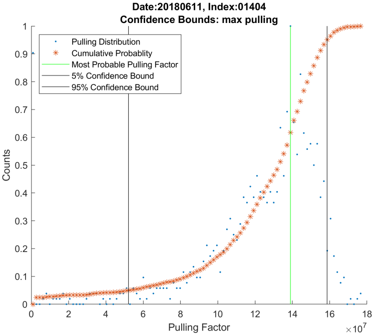
Confidence in “high” and “low” pulling factors

Low PF$= 0.112$
with 90% bounds
$(0.096, 0.125)$

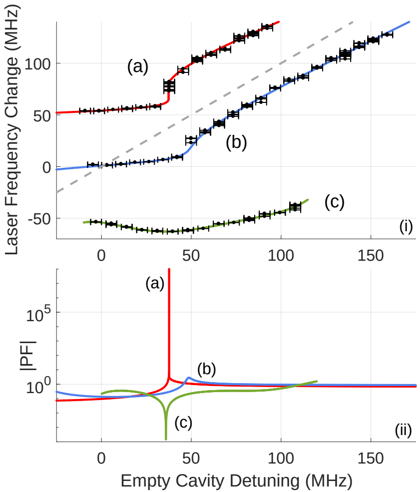


High PF$= 120 \times 10^6$
with 90% bounds
$(52 \times 10^6, 158 \times 10^6)$

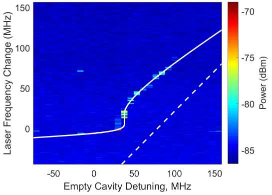




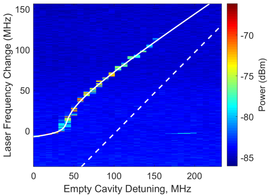
Pulling factor zoo



Power 98 mW

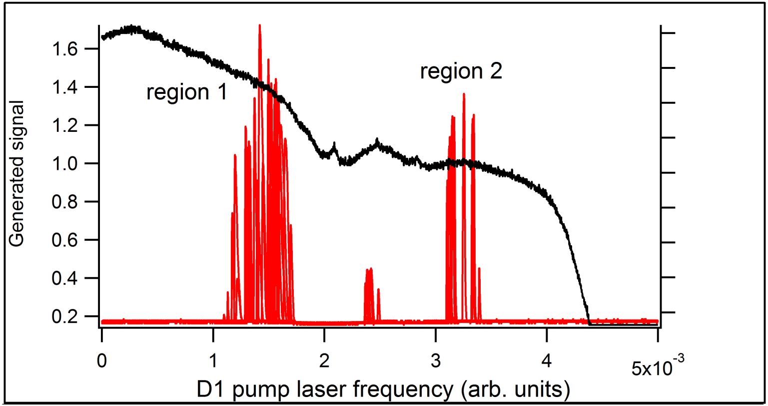


Power 147 mW



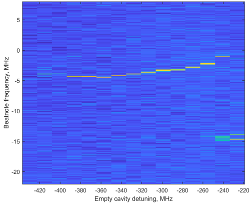
Savannah L. Cuozzo, Eugeniy E. Mikhailov,
Phys. Rev. A, 100, 023846, (2019).

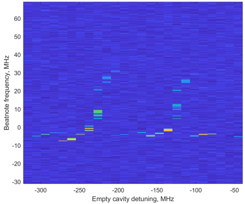
Pulling factor vs detuning dependence



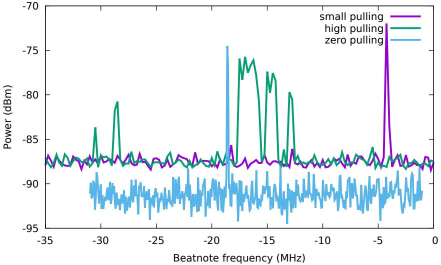
- Region 1: Pulling factor ≤ 1 (no discontinuities), high laser output
- Region 2: Large pulling $\gg 1$
- Region 3 (middle): vibration free regime

Beatnotes width comparison





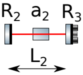
Quantum linewidth $\sim 1/n_g^2 = (P.F.)^2$

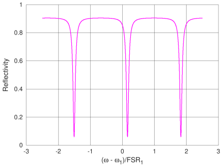


Vibrations-broadened linewidth $\sim 1/n_g = P.F.$

C. Henry, IEEE Journal of Quantum Electronics 18, 259 (1982).

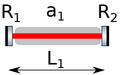
Coupled cavities setup. No lasing yet.

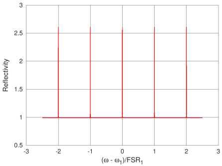


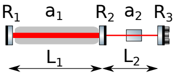


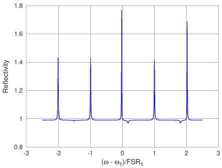
$$\rho_{23} = -r_2 + \frac{(a_2 r_3)(1 - r_2^2) e^{i\phi_2}}{1 - (a_2 r_3) r_2 e^{i\phi_2}}$$

$$\phi_2 = (\omega - \omega_2) t_2 = (\Delta - \delta) t_2$$





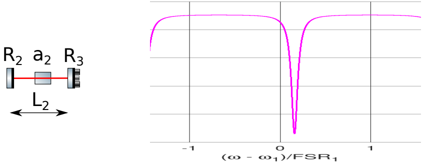




$$\rho_{123} = -r_1 + \frac{a_1 \rho_{23}(1 - r_1^2) e^{i\phi_1}}{1 - a_1 \rho_{23} r_1 e^{i\phi_1}}$$

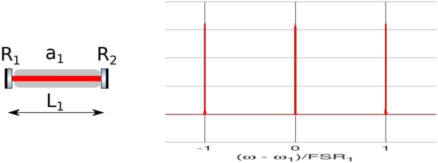
$$\phi_1 = (\omega - \omega_1) t_2 = \Delta t_1$$

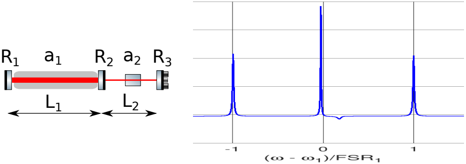
Coupled cavities setup. No lasing yet.



$$\rho_{23} = -r_2 + \frac{(a_2 r_3)(1 - r_2^2) e^{i\phi_2}}{1 - (a_2 r_3) r_2 e^{i\phi_2}}$$

$$\phi_2 = (\omega - \omega_2) t_2 = (\Delta - \delta) t_2$$





$$\rho_{123} = -r_1 + \frac{a_1 \rho_{23} (1 - r_1^2) e^{i\phi_1}}{1 - a_1 \rho_{23} r_1 e^{i\phi_1}}$$

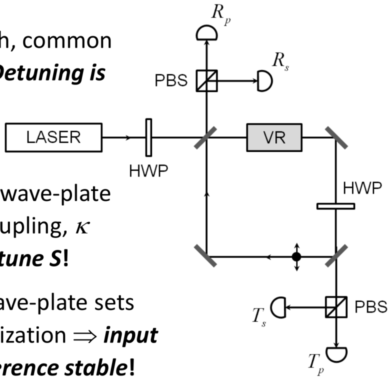
$$\phi_1 = (\omega - \omega_1) t_2 = \Delta t_1$$

Enhancement with passive coupled cavities

Soln: Polarization Coupling in a Single Cavity

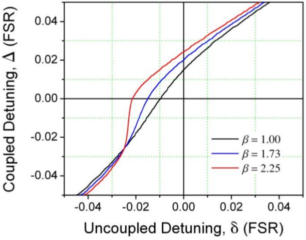
- Shared path, common mode. ⇒ ***Detuning is stable***!
- Intracavity wave-plate controls coupling, κ ⇒ ***Easy to tune S***!
- External wave-plate sets input polarization ⇒ ***input phase difference stable***!

→ Allows fast coherent control of S, *without changing anything inside cavity*.

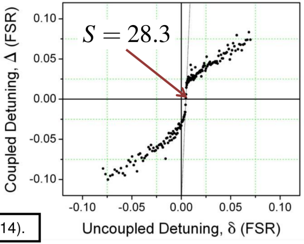


D. D. Smith et al., *Phys. Rev. A* **89**, 053804 (2014).

Coherent Control of S



Critical FL Condition

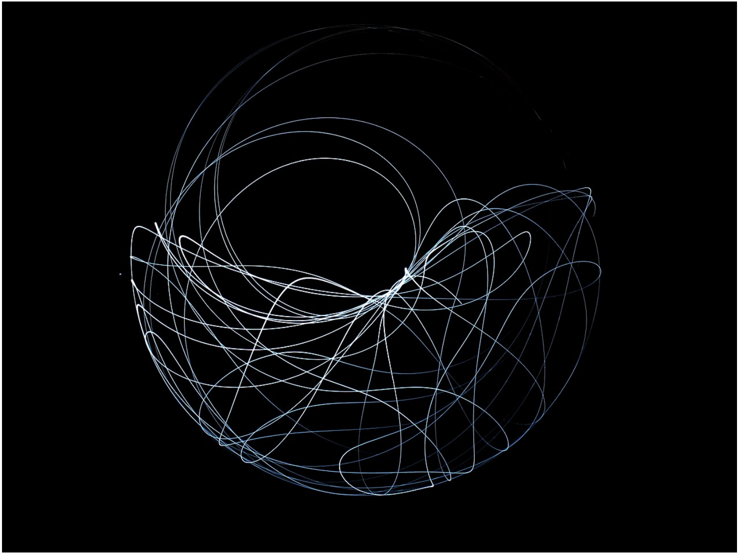


Active lasing vs passive cavity

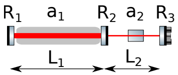
- No external lasers which require additional stabilization
- self-contained thus small
- self-referenced
- allow to measure frequency shift directly

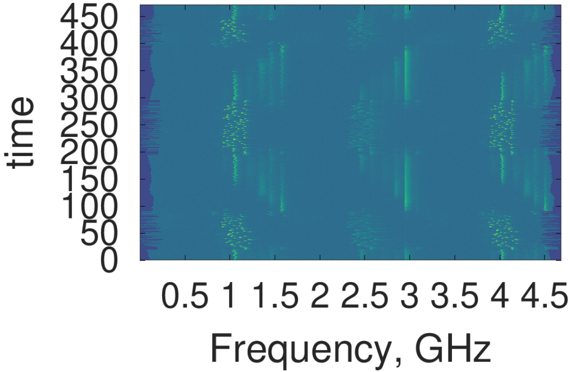
Let’s talk about cows

Let's talk about CHAOS



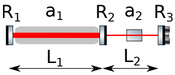
CHAOS in a laser with extra feedback



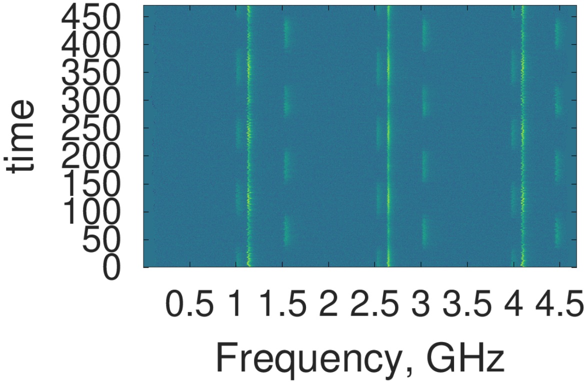


"Chaotic He-Ne laser" by Tom A Kuusela ,European Journal of Physics, Volume 38, Number 5, 2017

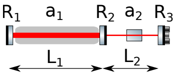
Lesson learned: larger loss - less CHAOS



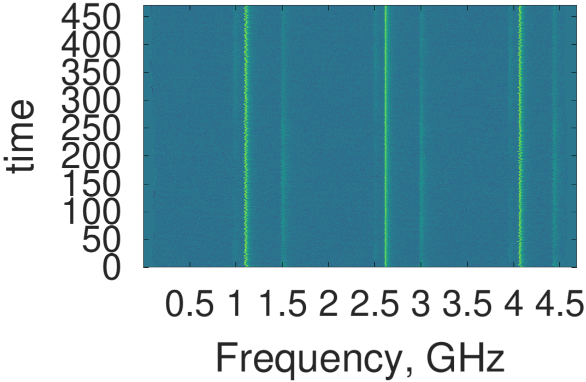
survival a_2 is 10%



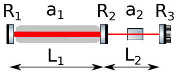
Lesson learned: larger loss - less CHAOS



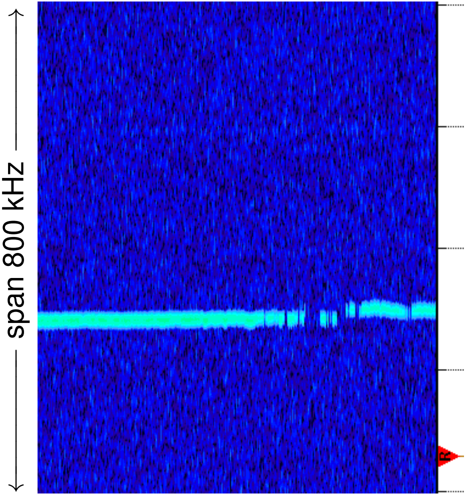
survival a_2 is 0%



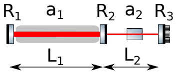
Laser shift vs empty cavity shift



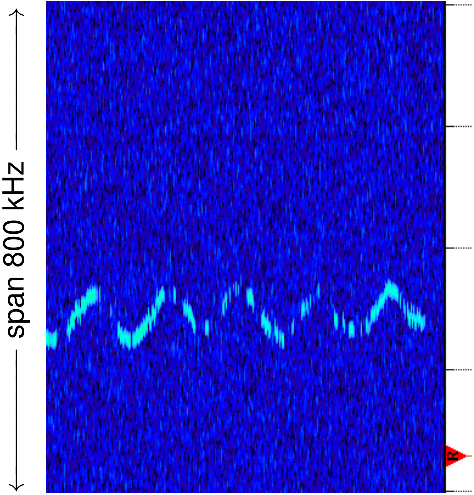
survival a_2 is 0%



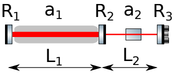
Laser shift vs empty cavity shift



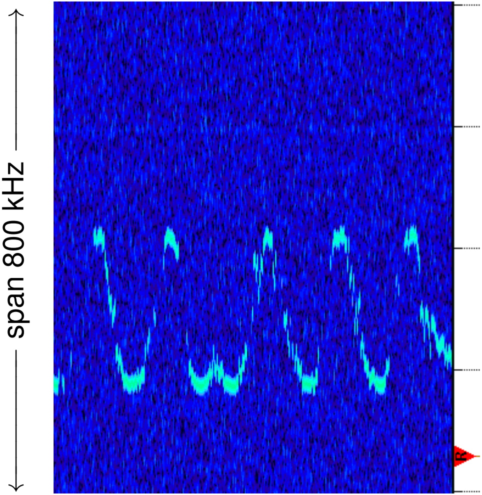
survival a_2 is 3%



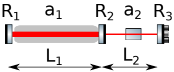
Laser shift vs empty cavity shift



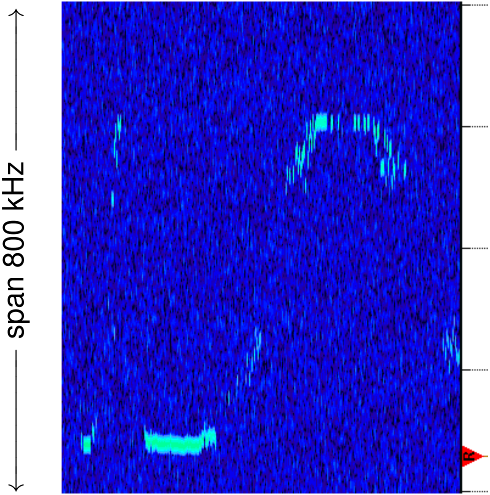
survival a_2 is 10%



Laser shift vs empty cavity shift



survival a_2 is 20%

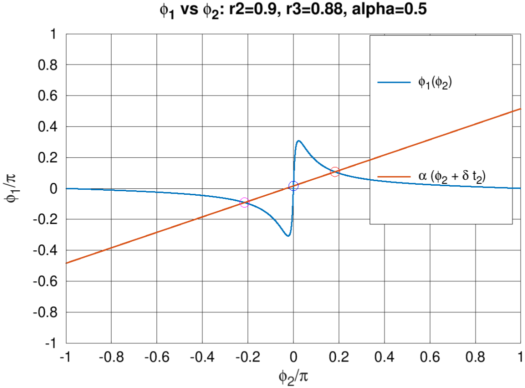


Maximal P.F.$= 600\mathrm{kHz}/1.5\mathrm{GHz} = 4 \times 10^{-4}$

Back to lasing analysis

$$\rho_{123} = -r_1 + \frac{a_1 \rho_{23} (1 - r_1^2) e^{i\phi_1}}{1 - a_1 \rho_{23} r_1 e^{i\phi_1}}$$

$$r_2 + \frac{1 - r_2^2}{r_2 - r_3 e^{i\phi_2}} = (r_1 a_1) e^{i\phi_1}$$



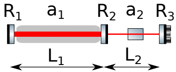
Round trip phase shifts

$$\phi_1 = (\omega - \omega_1) t_2 = \Delta t_1$$

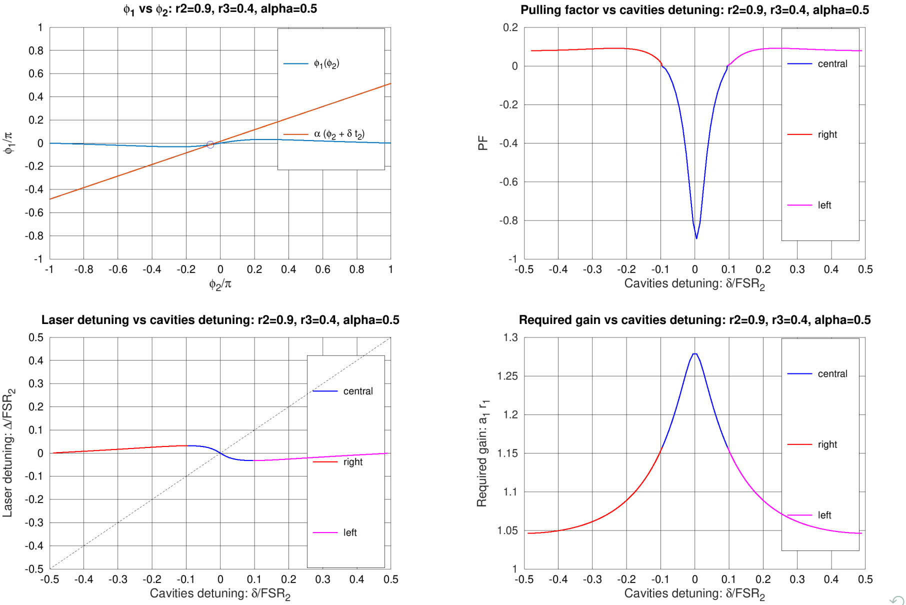
$$\phi_2 = (\omega - \omega_2) t_2 = (\Delta - \delta) t_2$$

Ratio of round trip times

$$\alpha = t_1 / t_2$$

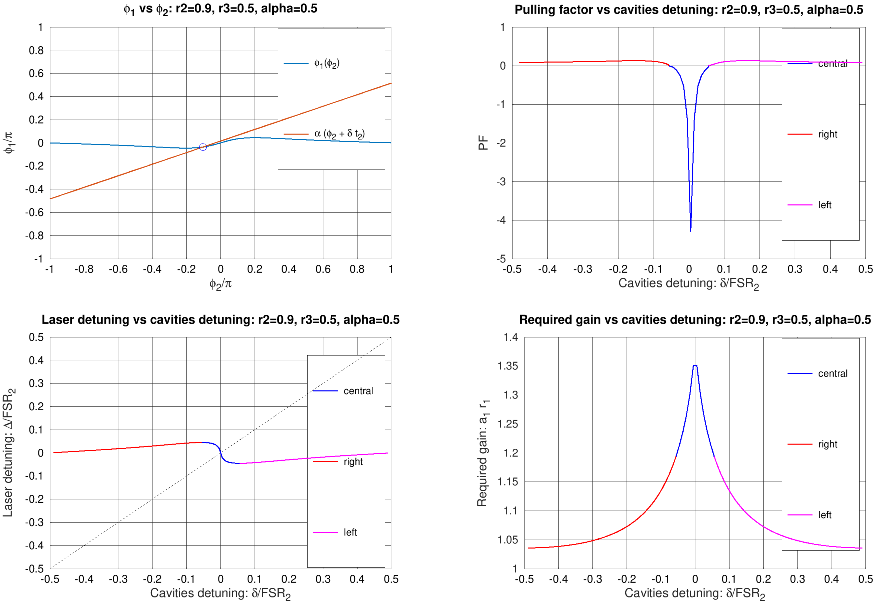


$a_2 r_3 = .4$



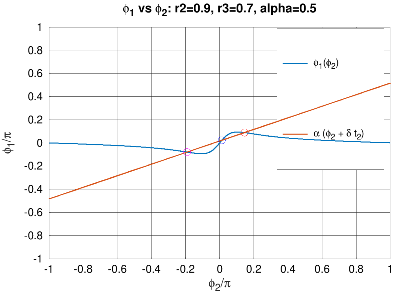
φ1 vs φ2: r2=0.9, r3=0.4, alpha=0.5
φ1(φ2)
α (φ2 + δ t2)
φ1/π
φ2/π
Pulling factor vs cavities detuning: r2=0.9, r3=0.4, alpha=0.5
PF
central
right
left
Cavities detuning: δ/FSR2
Laser detuning vs cavities detuning: r2=0.9, r3=0.4, alpha=0.5
Laser detuning: Δ/FSR2
central
right
left
Cavities detuning: δ/FSR2
Required gain vs cavities detuning: r2=0.9, r3=0.4, alpha=0.5
Required gain: a1 r1
central
right
left
Cavities detuning: δ/FSR2

$a_2 r_3 = .5$

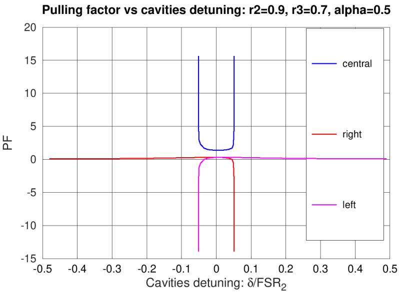


ϕ1 vs ϕ2: r2=0.9, r3=0.5, alpha=0.5
ϕ1(ϕ2)
α (ϕ2 + δ t2)
ϕ1/π
ϕ2/π
Pulling factor vs cavities detuning: r2=0.9, r3=0.5, alpha=0.5
central
right
left
PF
Cavities detuning: δ/FSR2
Laser detuning vs cavities detuning: r2=0.9, r3=0.5, alpha=0.5
Laser detuning: Δ/FSR2
Required gain vs cavities detuning: r2=0.9, r3=0.5, alpha=0.5
Required gain: a1 r1

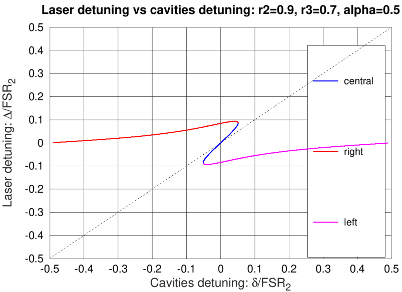
$a_2 r_3 = .7$



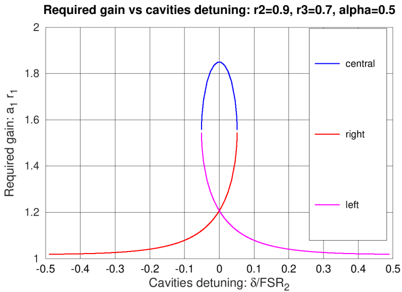
ϕ_1 vs ϕ_2: r2=0.9, r3=0.7, alpha=0.5
ϕ_1/π
ϕ_2/π
$\phi_1(\phi_2)$
$\alpha\ (\phi_2 + \delta\ t_2)$



Pulling factor vs cavities detuning: r2=0.9, r3=0.7, alpha=0.5
PF
Cavities detuning: δ/FSR_2
central
right
left

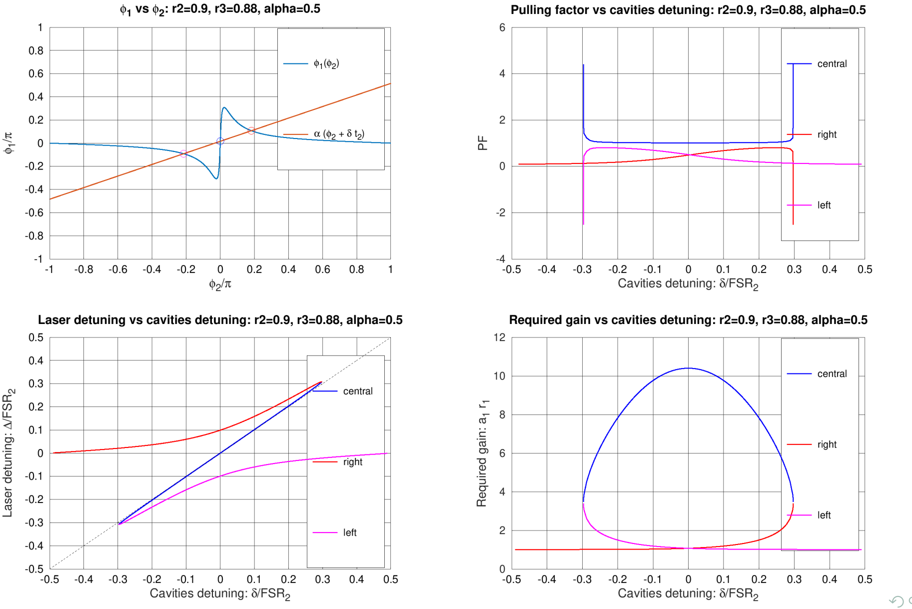


Laser detuning vs cavities detuning: r2=0.9, r3=0.7, alpha=0.5
Laser detuning: Δ/FSR_2
Cavities detuning: δ/FSR_2
central
right
left



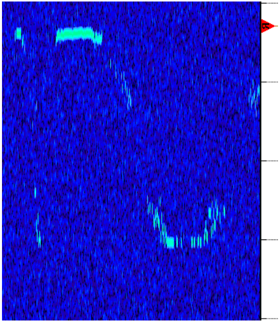
Required gain vs cavities detuning: r2=0.9, r3=0.7, alpha=0.5
Required gain: $a_1\ r_1$
Cavities detuning: δ/FSR_2
central
right
left

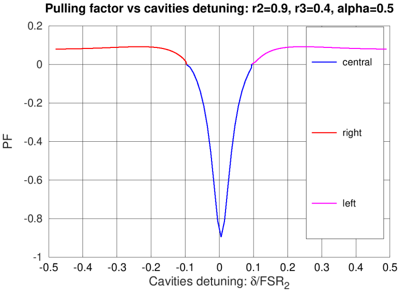
$a_2 r_3 = .88$

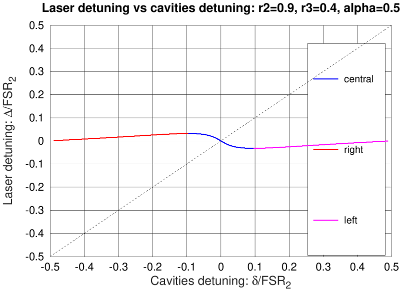


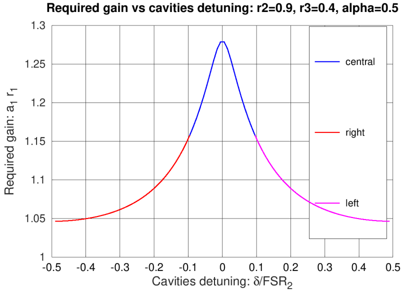
φ1 vs φ2: r2=0.9, r3=0.88, alpha=0.5
φ1(φ2)
α (φ2 + δ t2)
φ1/π
φ2/π
Pulling factor vs cavities detuning: r2=0.9, r3=0.88, alpha=0.5
central
right
left
PF
Cavities detuning: δ/FSR2
Laser detuning vs cavities detuning: r2=0.9, r3=0.88, alpha=0.5
Laser detuning: Δ/FSR2
Required gain vs cavities detuning: r2=0.9, r3=0.88, alpha=0.5
Required gain: a1 r1

What are we capable now?



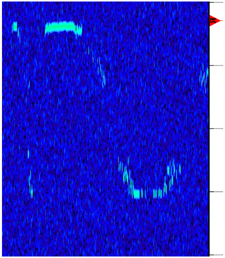






Summary

- Coupled cavities laser would be useful for enhancing optical gyroscopes, and thus for better navigation systems.
- We demonstrated laser response control assisted by the atomic dispersion and in the coupled cavities lasing regime.
- The experiment seems to be in the agreement with our model.



→