Fast-Light Inertial Sensors

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Outline

- What is fast light?
- Why do we need it?
- How does fast light enhance optical gyro sensitivity and precision?
- Passive fast-light gyros
- Active fast-light gyros
- Coupled resonator gyros: Fast-light enhancement without a medium

What do we mean by “fast light”?

Phase Velocity

Monochromatic Plane Wave:

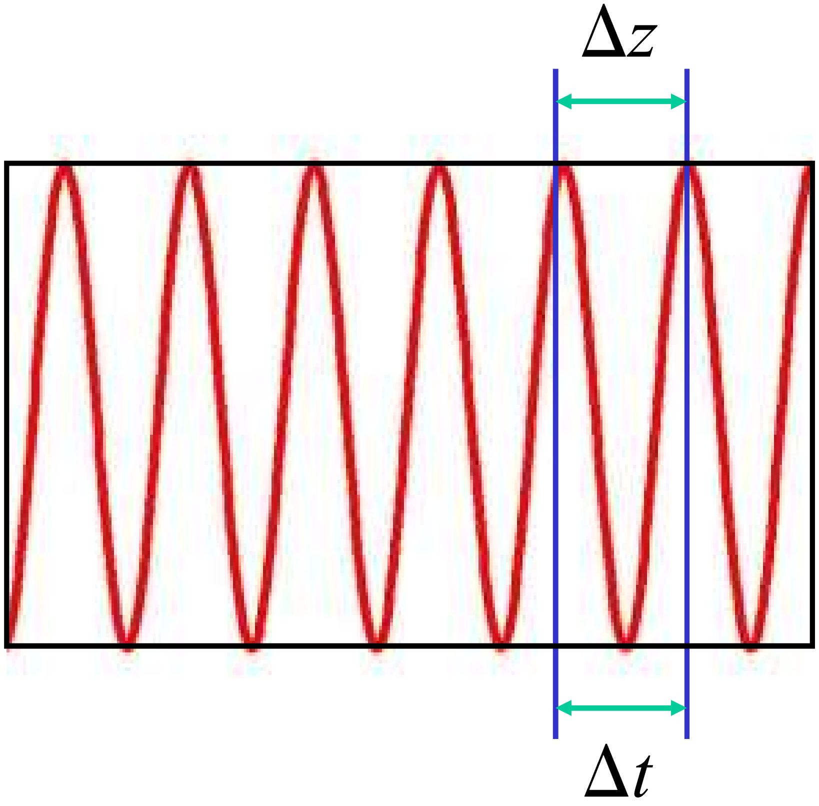
$$E(z,t) = E_0 \cos\phi(z,t)$$

$$\phi(z,t) = kz - \omega t$$

Dispersion relation:

$$k = \frac{n\omega}{c}$$

Constant phase front ϕ moves distance Δz in time Δt



$$k\Delta z = \omega\Delta t$$

Phase velocity: $\boxed{v_p = \frac{\Delta z}{\Delta t} = \frac{\omega}{k} = \frac{c}{n}}$

Group Velocity

Add two monochromatic plane waves:

$$E(z,t) \propto \cos(k_1 z - \omega_1 t) + \cos(k_2 z - \omega_2 t)$$

$$= \cos(k\,z - \omega\,t)\cos(\Delta k\,z - \Delta\omega\,t)$$

Rapidly Varying

$$\omega = (\omega_1 + \omega_2)/2$$

$$k = (k_1 + k_2)/2$$

Phase velocity:

$$\boxed{v_p = \frac{\omega}{k}}$$

Envelope

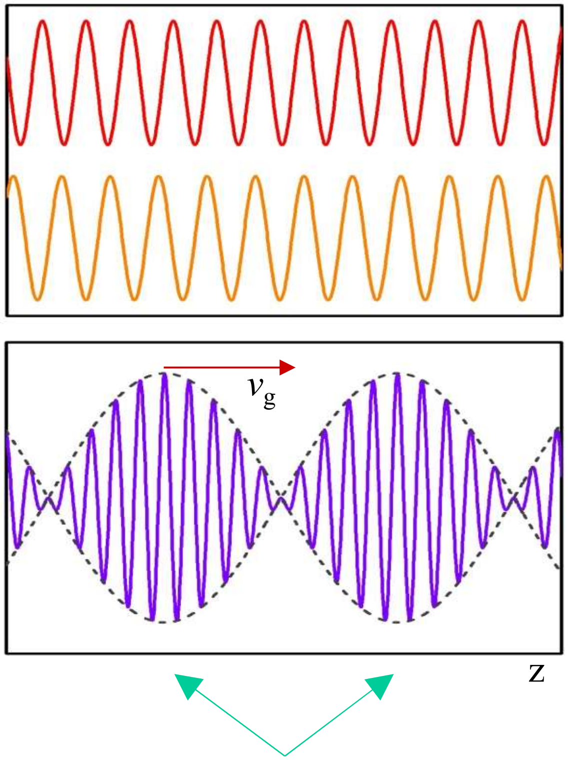
$$\Delta\omega = (\omega_1 - \omega_2)/2$$

$$\Delta k = (k_1 - k_2)/2$$

Group Velocity:

$$\boxed{v_g = \frac{\Delta\omega}{\Delta k}}$$

$v_g = v_p$ *if n constant*



Wave Groups

Slow and Fast Light

Multiple Fourier (frequency) components experience different index of refraction and add up in phase at peak of pulse, which propagates at

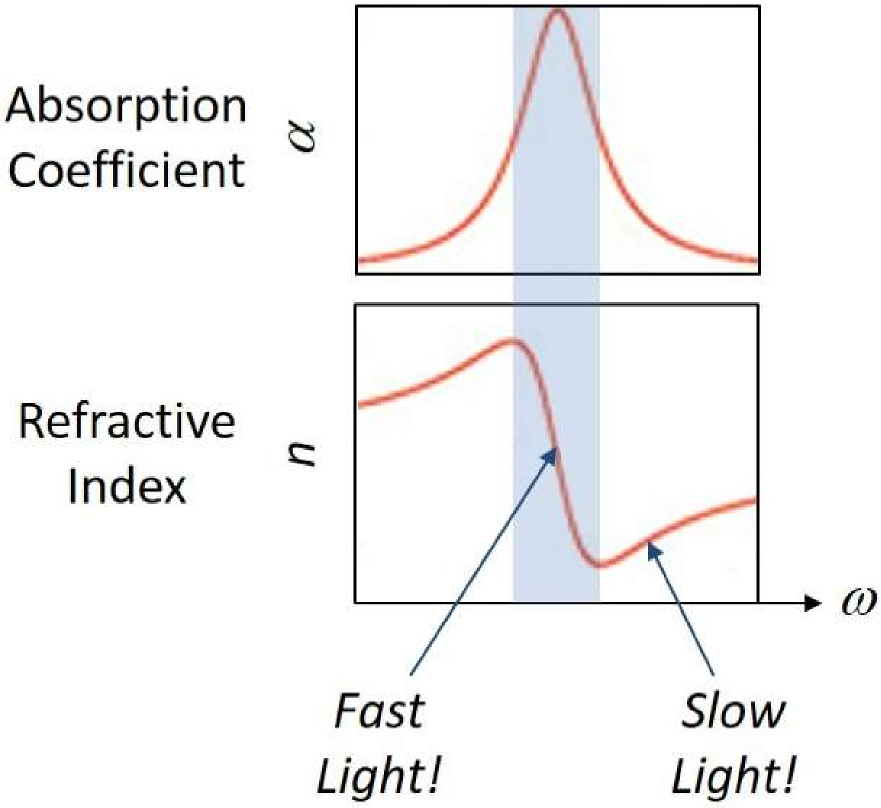
Group Velocity:

$$v_g = \frac{d\omega}{dk} = \frac{c}{n + \omega \frac{dn}{d\omega}} = \frac{c}{n_g}$$

$$\frac{dn}{d\omega} > 0$$ Normal Dispersion
Slow Light ($n_g > 1$)

$$\frac{dn}{d\omega} < 0$$ Anomalous Dispersion
Fast Light ($n_g < 1$)

$n_g = 0 \rightarrow$ *Critical Fast Light Condition!*



Pulse leaves medium at same moment it enters!

Violation of Relativity / Causality ?

$$\boxed{\upsilon_p = \frac{\omega}{k} = \frac{c}{n}}$$

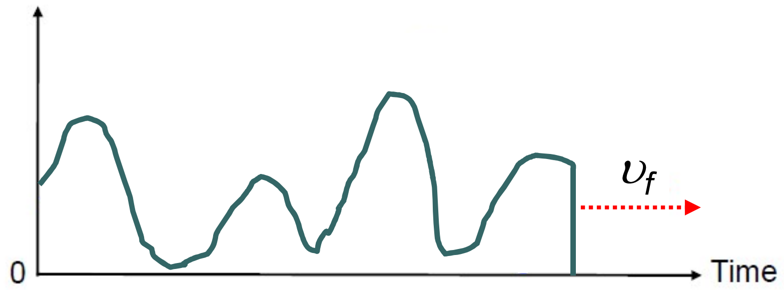
Phase Velocity ≡ velocity of a single frequency.

$$\boxed{\upsilon_g = \frac{d\omega}{dk} = \frac{c}{n_g}}$$

Group Velocity ≡ velocity of the peak of a pulse or packet containing several frequencies.

υ_p and υ_g can have any value!

Fast Light: $\upsilon_g > c$ (or < 0)
does not violate relativity or causality



υ_f must be less than c!

Front (or Information) Velocity ≡ velocity of a non-analytic step in the waveform

$\upsilon_f > c$
violates relativity and causality

Why are we interested in fast-light?

Relevance

- **Critical Need:** ***"NASA's future missions show a diverse set of navigational challenges that cannot be supported with current methods. Onboard autonomous navigation and maneuvering techniques are critical."*** NASA Technology Roadmap, TA-05

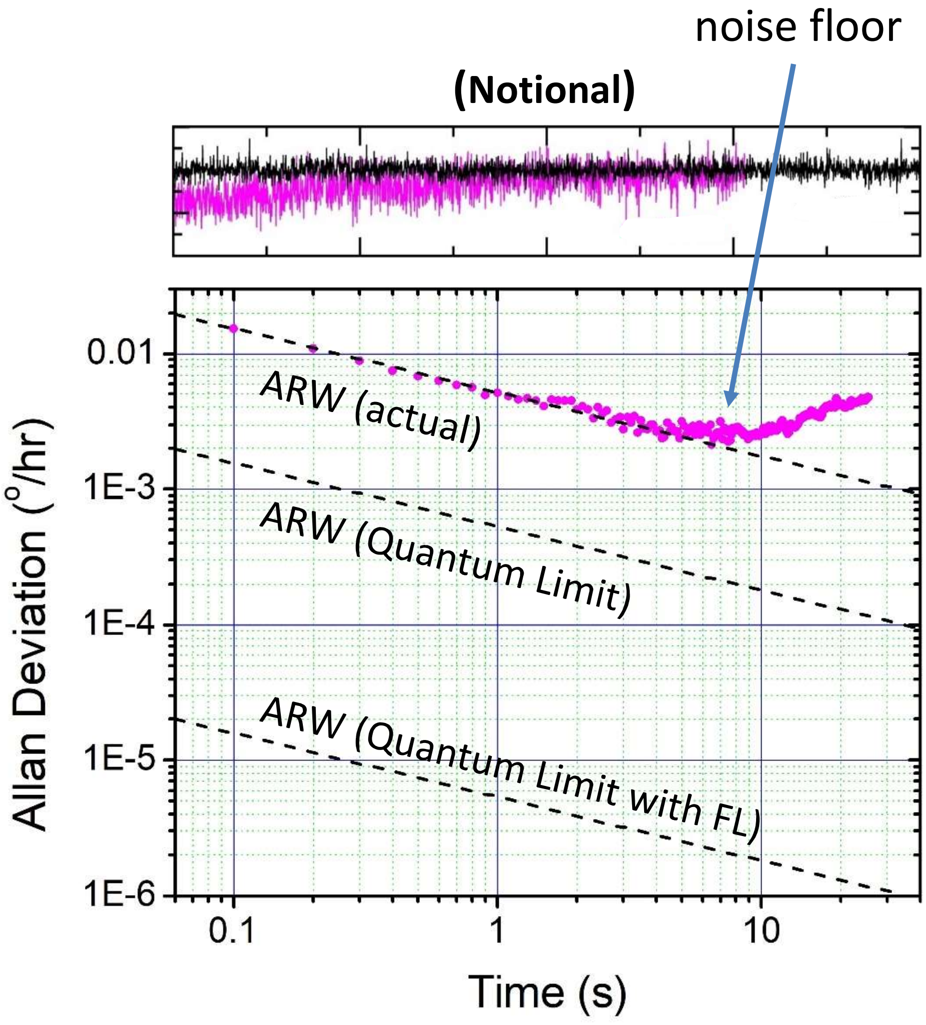
- **Problem:** Current inertial sensors limited in precision and require periodic updates.

  External signals (GPS, DSN, Star-trackers, XNAV) limited by large delays, low flux, and can be spoofed, blocked, misidentified, or unavailable.

  Usual methods to boost precision are to increase: (*a*) size (problematic in spaceflight), or (*b*) integration time (not useful for rapid accelerations).

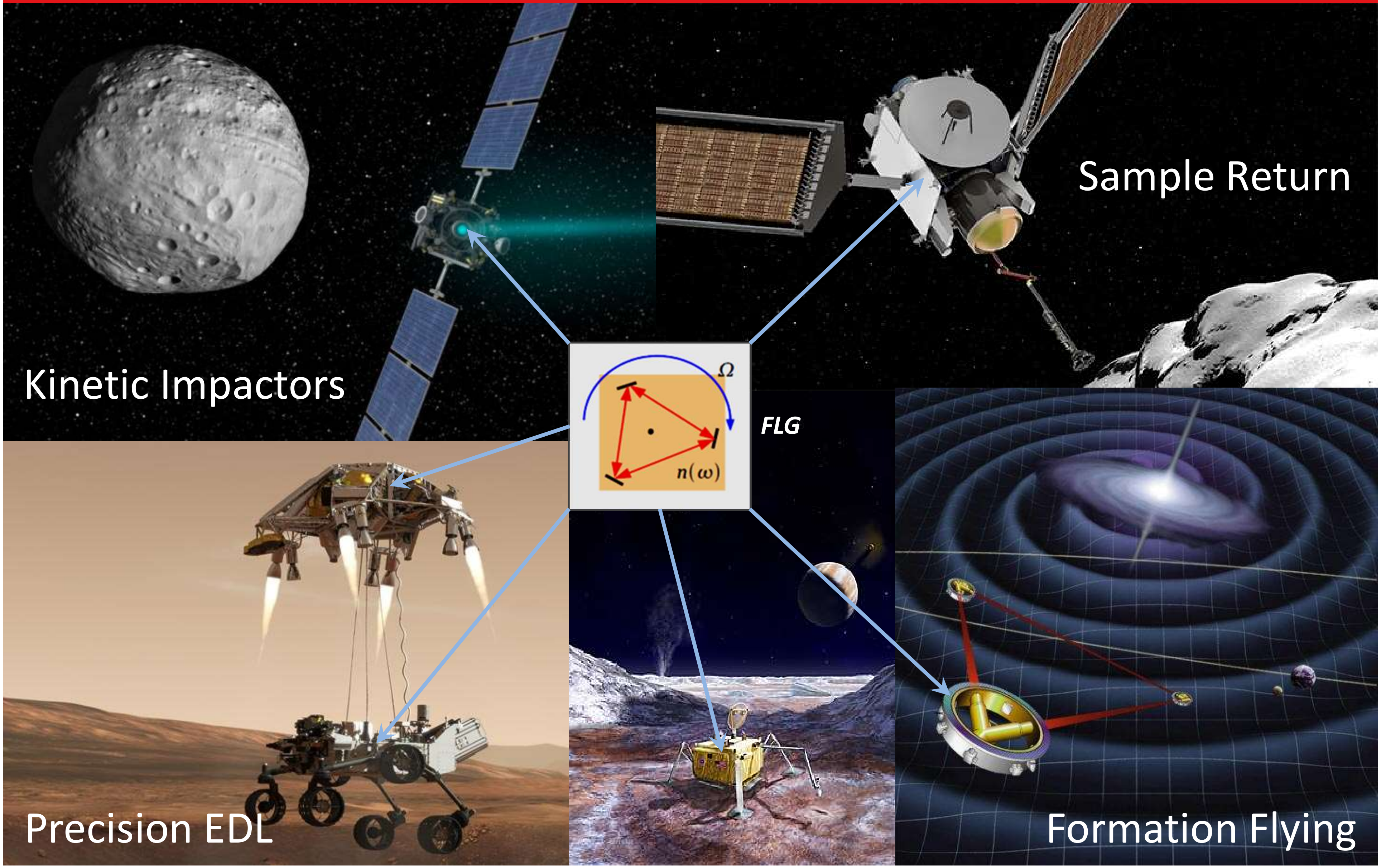
- **Conclusion:** ***Fundamental improvements needed in precision of inertial sensors - smaller, faster, more precise gyros that require fewer updates!***

Where FL has most benefits



- Largest benefit for integration times shorter than noise floor where ARW dominates
  - Rapid accelerations
  - Tight controls
- Increased precision can be traded off for faster measurements or smaller gyroscopes
  - Where precision and accuracy are important
  - Where size & weight are important
  - Where high sampling is needed

Potential Applications



Kinetic Impactors

Sample Return

Precision EDL

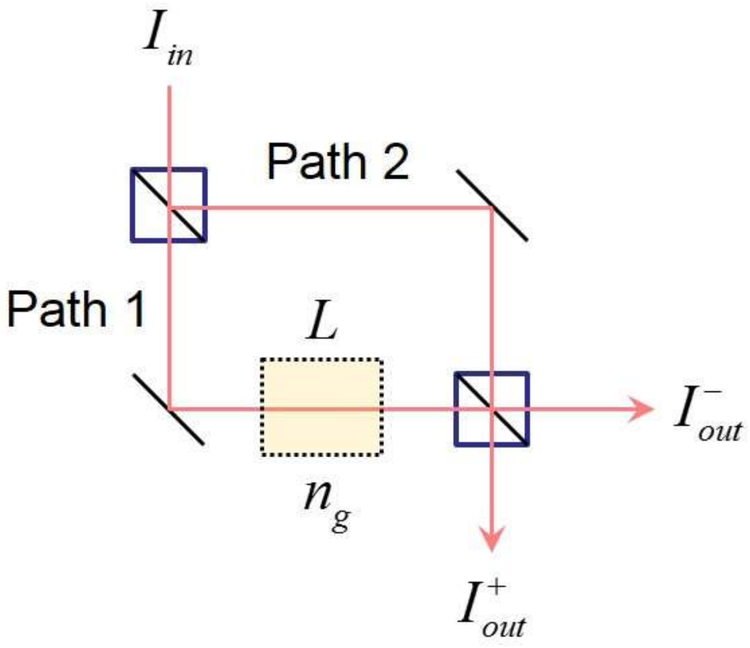
Formation Flying

How does it work?

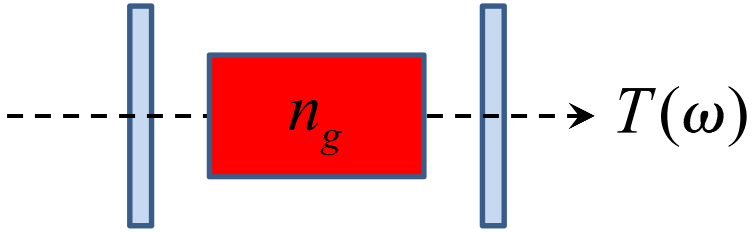
Interferometers with Dispersion

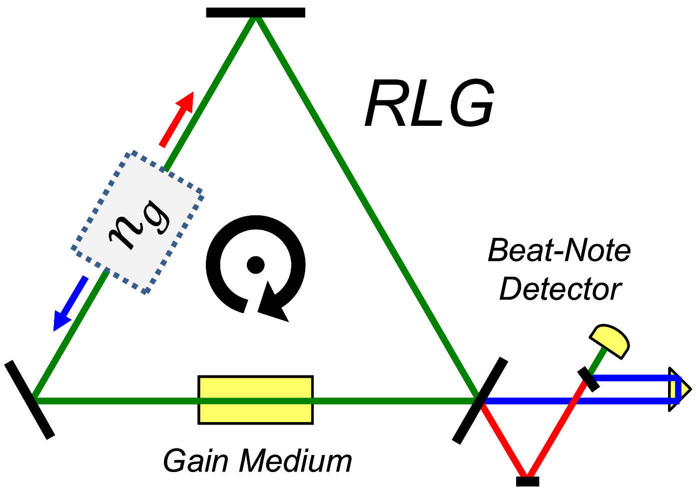
Idea: Put dispersive (slow or fast light) material into interferometer.

Two-beam Interferometer with dispersion



Multi-beam Interferometers (Cavities) with Dispersion





Slow or Fast Light?

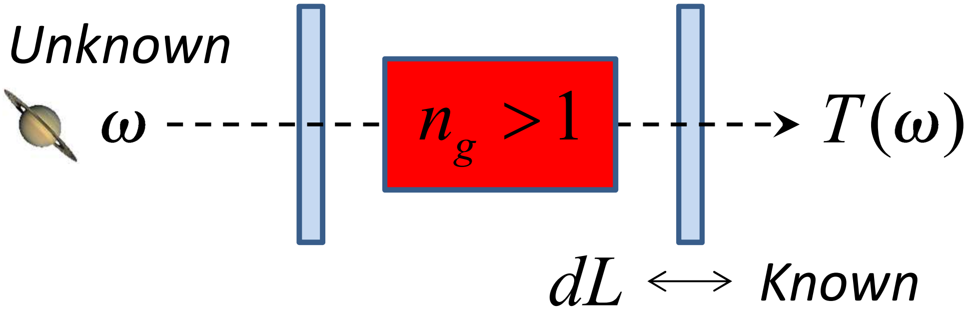
Q: Is it better to use slow light or fast light?

A: It depends on what you're trying to measure.

Spectroscopy:

$\Rightarrow$ use **SLOW** Light

Narrows cavity resonances



Unknown ω

$n_g > 1$

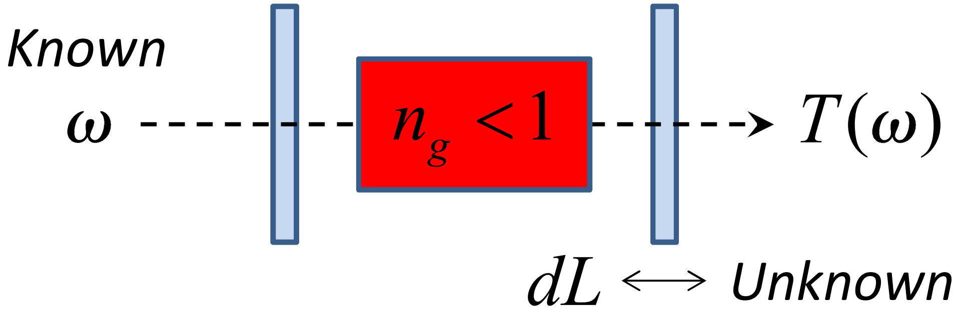
$T(\omega)$

$dL \longleftrightarrow$ *Known*

Detection of OPL change:

$\Rightarrow$ use **FAST** Light

Narrows input spectrum (in a relative sense)



Known ω

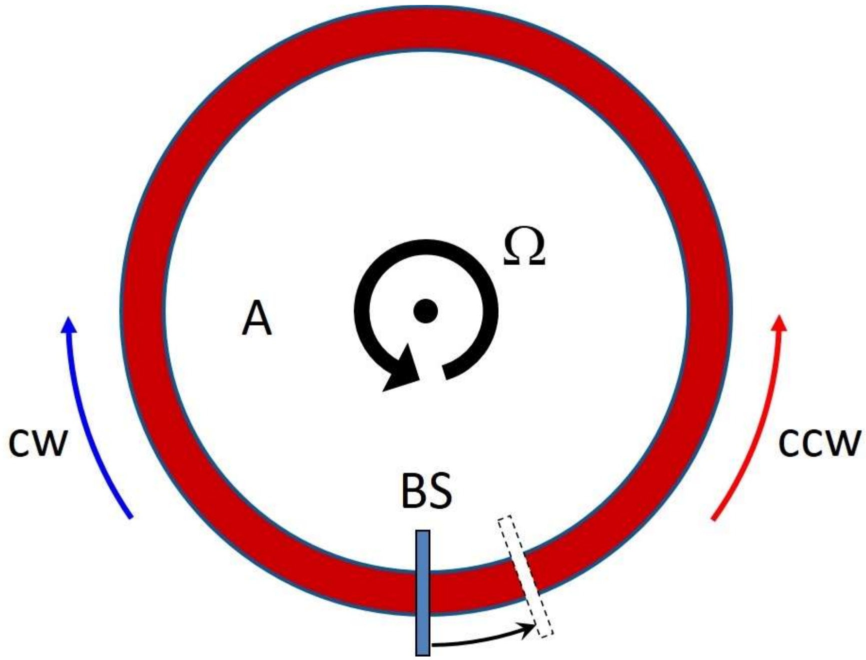
$n_g < 1$

$T(\omega)$

$dL \longleftrightarrow$ *Unknown*

Sagnac Effect

A phase difference between cw / ccw beams due to different travel times around moving ring.



Time-difference around loop:

$$\Delta t = t_{cw} - t_{ccw} = \frac{4\Omega \cdot A}{c^2(1-\beta^2)} \approx \frac{4\Omega \cdot A}{c^2}$$

$\beta = v / c << 1$

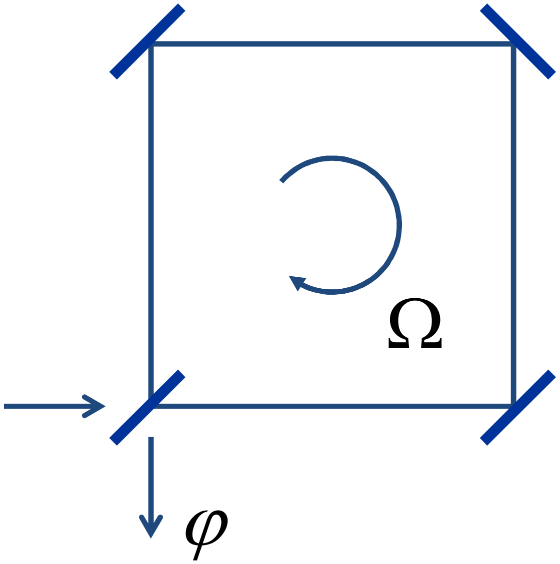
$$\Rightarrow \boxed{\phi_s = \omega \Delta t = \frac{8\pi\omega}{c^2}\Omega \cdot A}$$

Sagnac Phase Shift!

Types of Optical Gyros

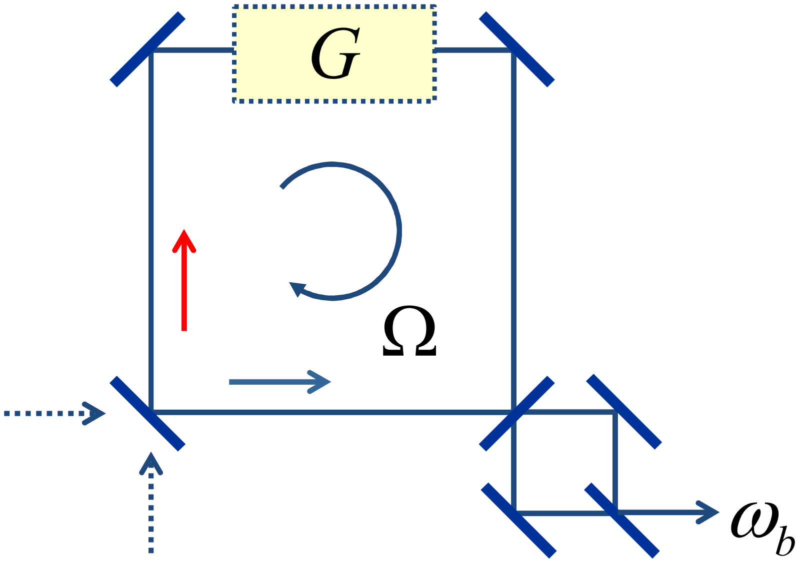
Interferometric:

(IFOG)



Ring Cavity (active & passive):

(PCG & RLG)



Sagnac phase shift independent of refractive index.

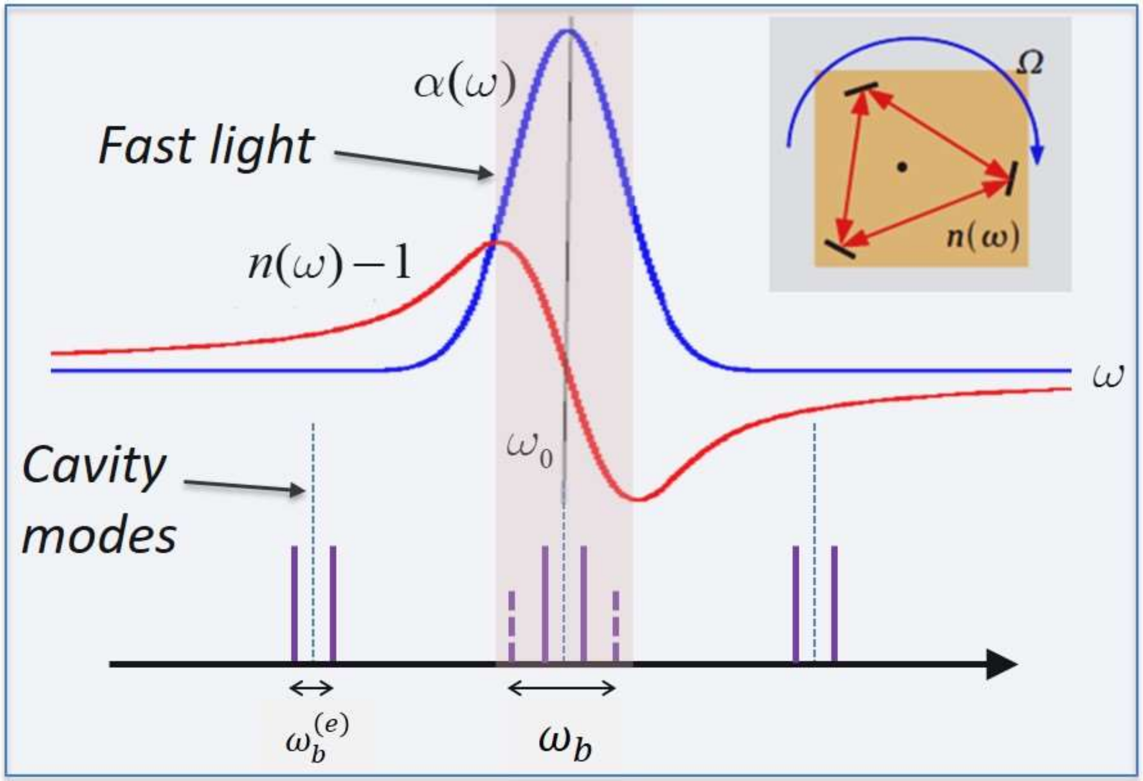
$\Rightarrow$ *Only the cavity types can be enhanced!*

Solution: Fast-Light (FL) Gyros

Scale Factors:

$$s^{(e)} = \frac{d\omega_b^{(e)}}{d\Omega} \propto Area$$

$$s = \frac{d\omega_b}{d\Omega}$$



Scale-Factor Enhancement:

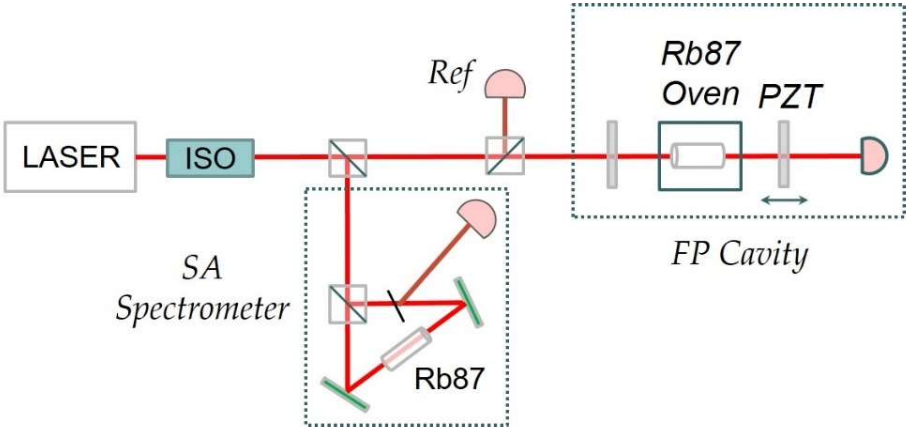
$$\boxed{S = \frac{s}{s^{(e)}} \approx \frac{1}{n_g(\omega_0)}} > 1 \text{ when } n_g < 1 \ (Fast\ Light!)$$

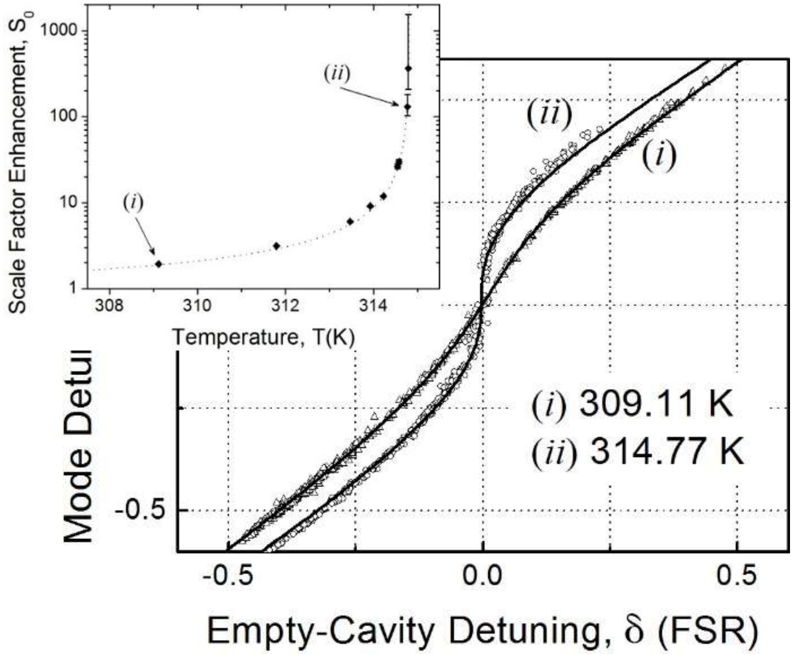
Increase in Error: $\varepsilon = \frac{\sigma}{\sigma^{(e)}}$ ⇒ *Enhancement in Precision when:* $\boxed{\zeta = \frac{S}{\varepsilon} > 1}$

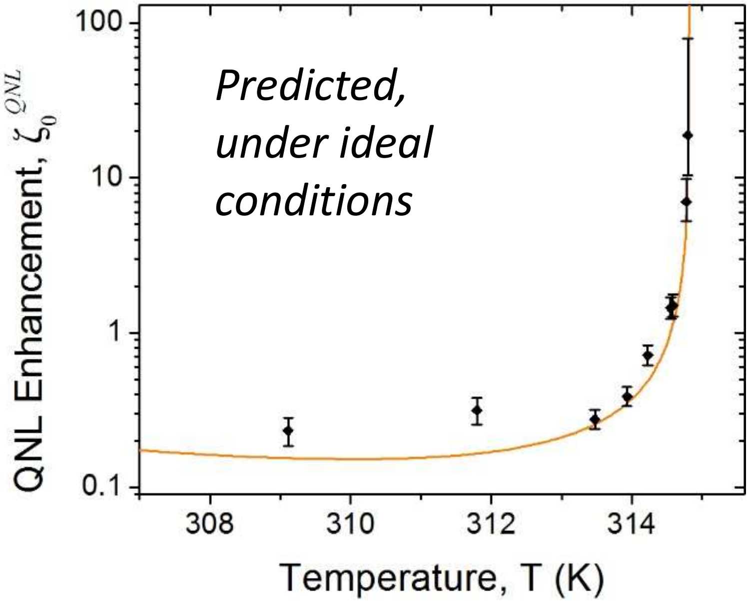
Passive Fast-Light Gyros

Passive FL 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).







Predicted, under ideal conditions

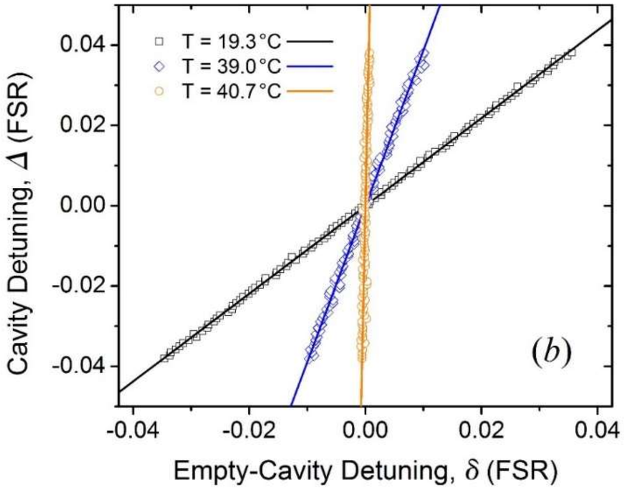
D. D. Smith et al., *Phys. Rev. A* 94, 023828, (2016).

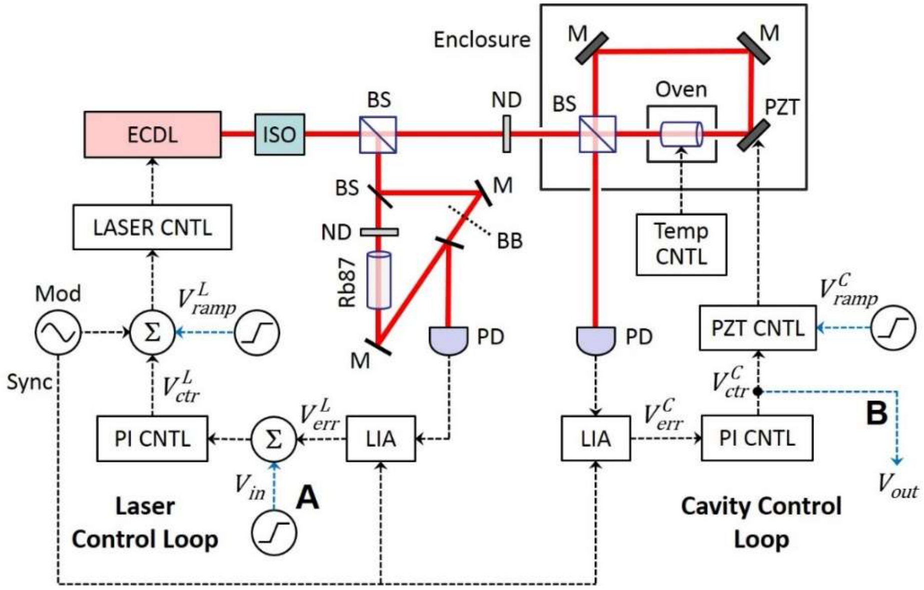
Limitations of Prior Experiments

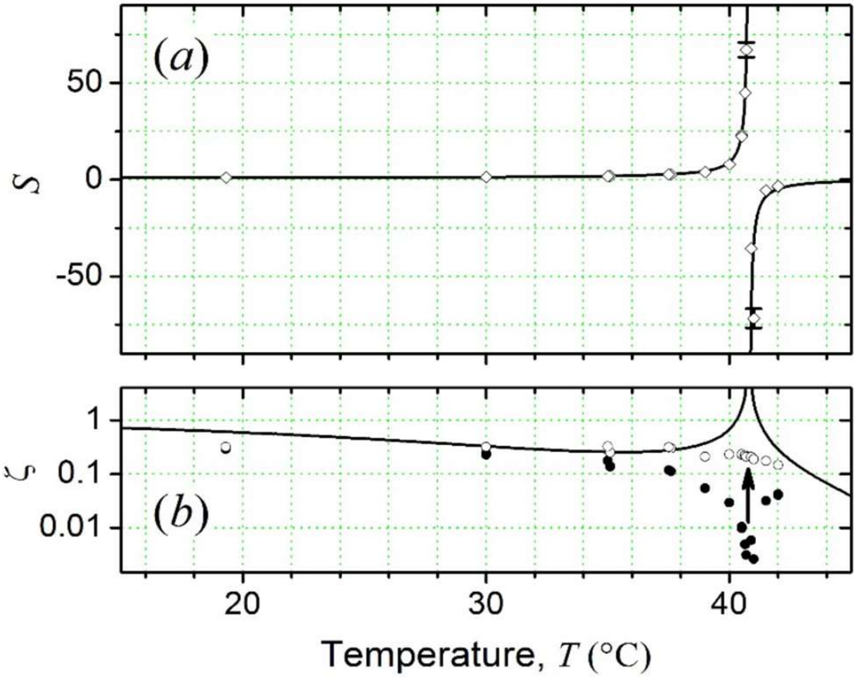
- Cavity detunings not measured directly in real time in an operating device. Instead *S* and ε are deduced, after the fact, from the spectra
  - → Slow (5 mins vs. <1 sec. for closed-loop). Large amount of unnecessary data recorded.
  - → No real experimental evidence of enhancement. ζ inferred for ideal (QNL & high-SNR) conditions only.
- Instability due to mode pushing → data scarce near resonance. Large uncertainty in *S*. Stabilization needed.

Closed-Loop Passive FL Cavity

- First direct measurement of boost in *S* in a ***closed-loop device***. ⇒ Paves way for passive FL gyro.
- Cavity stays locked through critical temperature. Both positive and negative values of *S* observed.
- Increase in ζ not yet observed due to classical noise. ⇒ Gyro geometry needed.



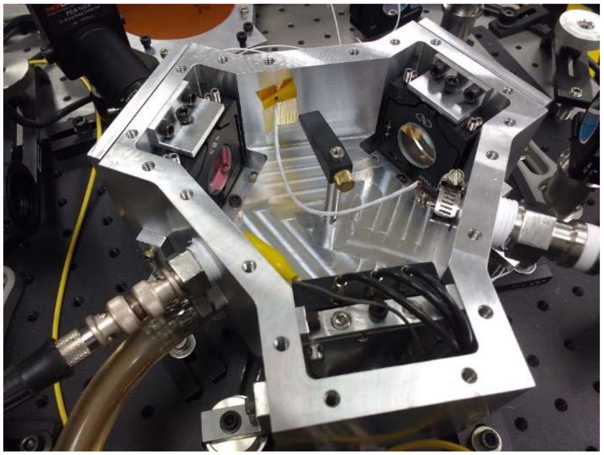




D. D. Smith et al., *Opt. Expr.* 26, 14905, (2018).

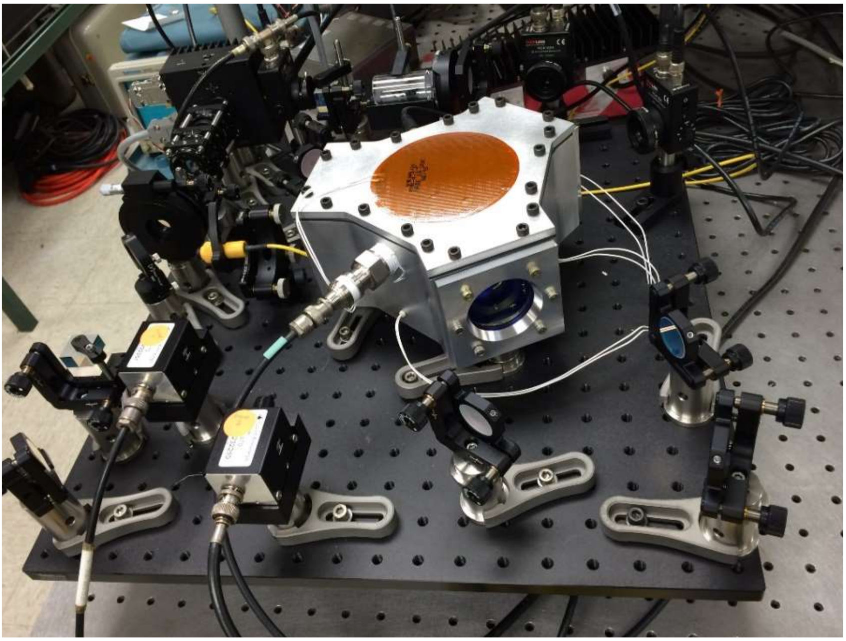
Passive FL Gyro (Atomic Vapor)

- Objective: Scale-factor enhancement for rotation has never been demonstrated in any experiment.



Passive Cavity

Table Shaker



Laser and Cavity on Rotation Stage

- Monolithic, vacuum-enclosed, magnetically-shielded, and temperature-stabilized to reduce noise.

Passive FLG: Advantages & Limitations

Advantages

- Simpler and less costly to obtain preliminary data
- Avoids nonlinear dynamics from gain medium
- Only systems so far to have shown boost in *S* to OPL changes.

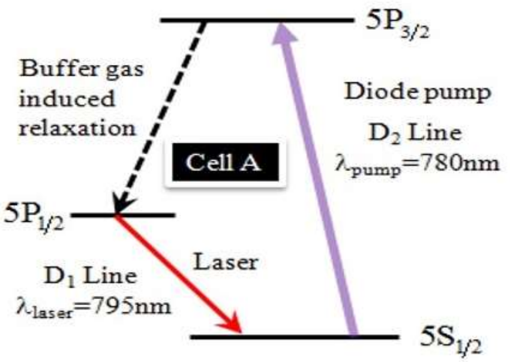
Limitations

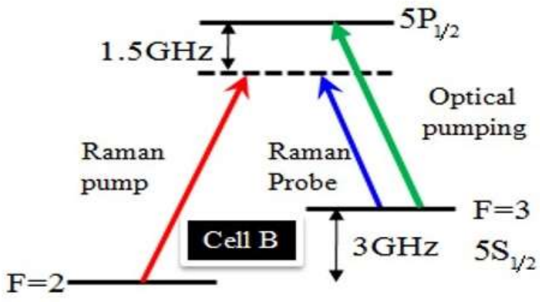
- Cavity modes attenuated by absorption. Reduced signal to noise.
- Saturation alters lineshape, couples counterpropagating beams, and limits achievable signal to noise.
- Require complicated closed-loop locking schemes
- Cavity linewidth also broadens. May not be true for active cavities. **Active FL gyros may achieve higher enhancement in precision!**

Active Fast-Light Gyros

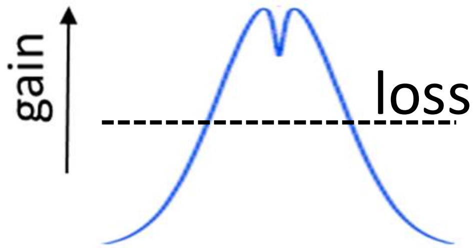
Active FLG: DPAL with SRS

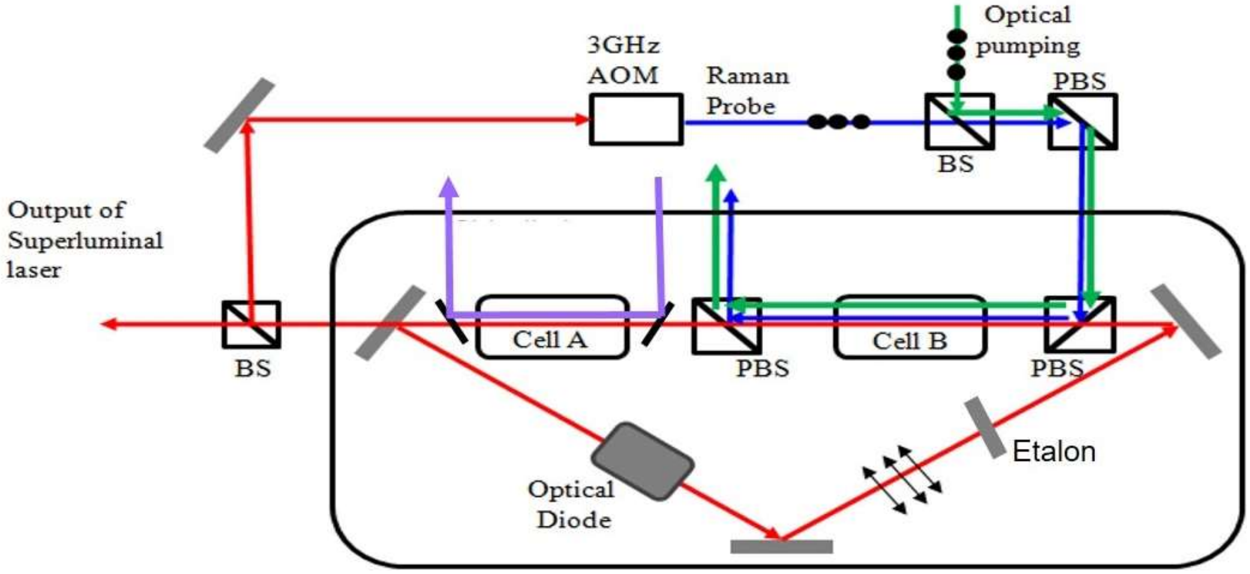
SRS = Stimulated Raman Scattering





Dip in gain produced by SRS in second Rb cell





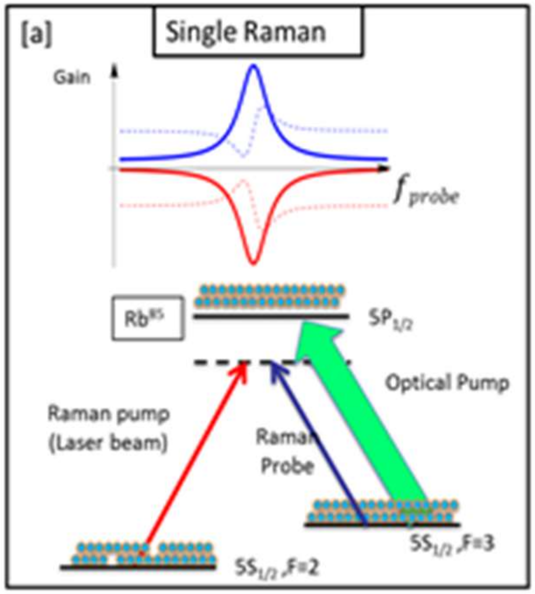
Diode-pumped Alkali laser (DPAL)

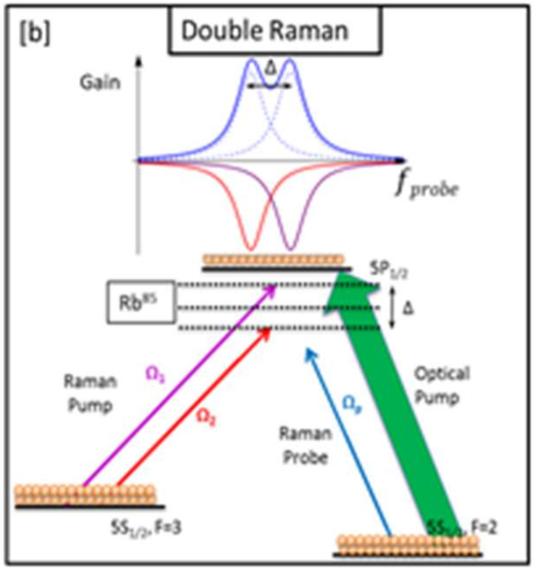
S = 190 (Implied)

H. N. Yum et al., *Opt. Expr.* 18, 17658 (2010).

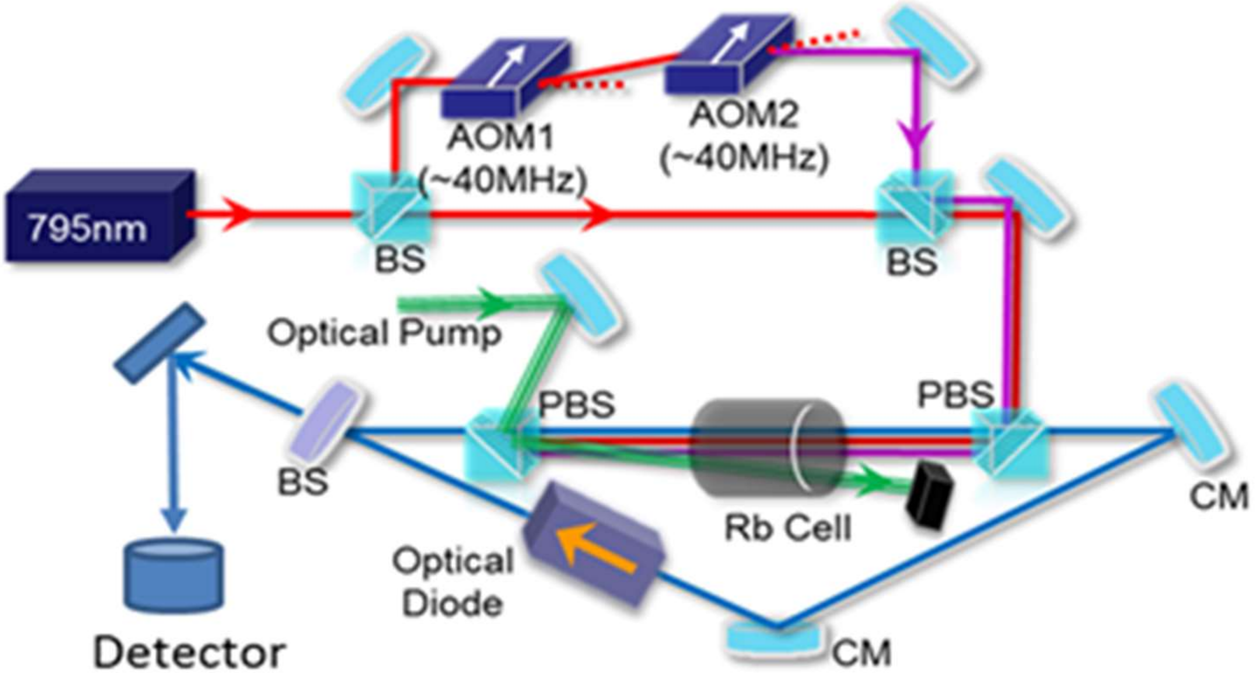
J. Yablon et al., *Opt. Expr.* 24, 27444 (2016).

Active FLG: Dual-pumped SRS





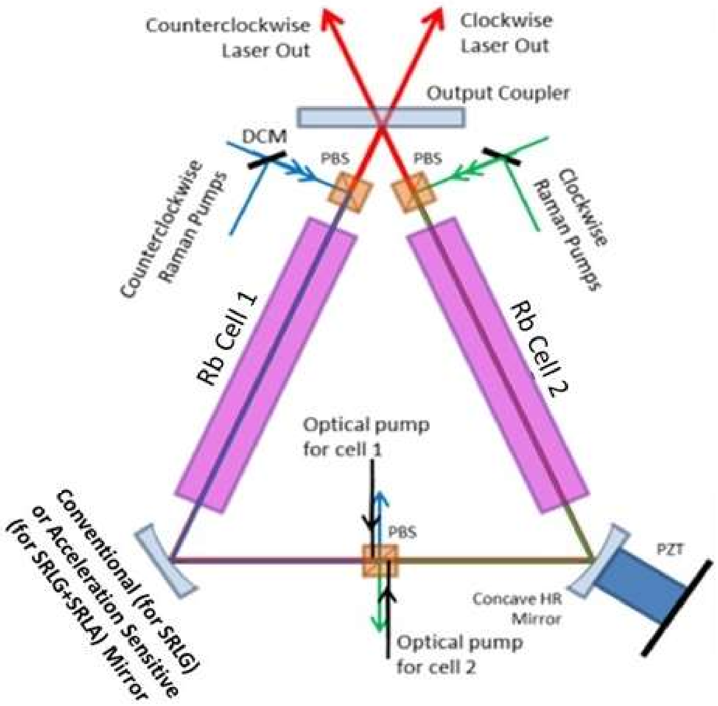
SRS = Stimulated Raman Scattering

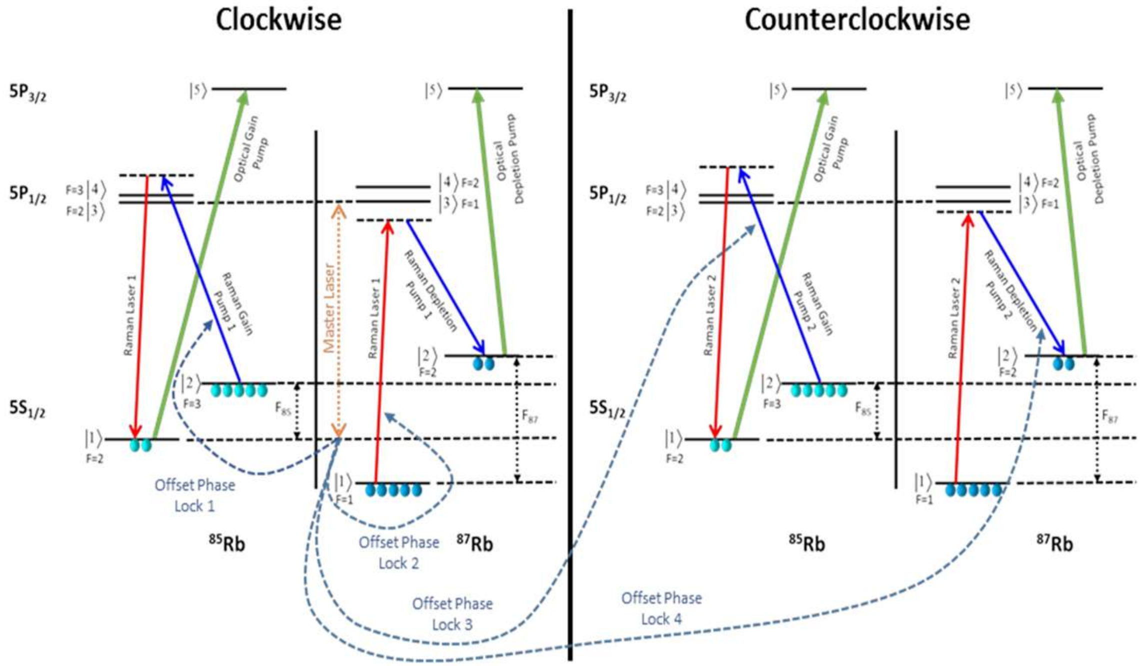


Two-color pump → dip in gain → **Fast Light!**

Courtesy: Digital Optics Technologies

Bidirectional SRS Gyro



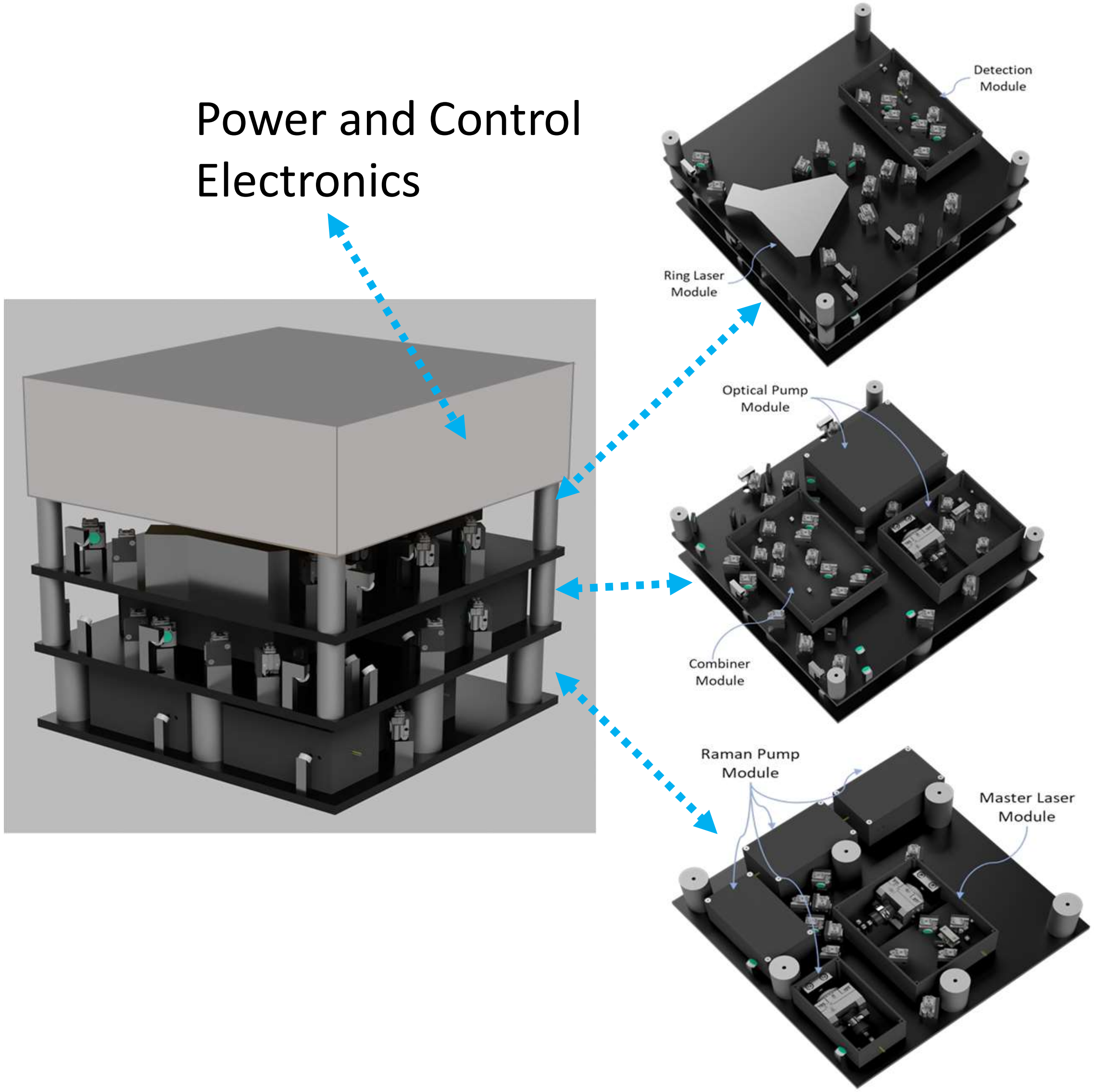


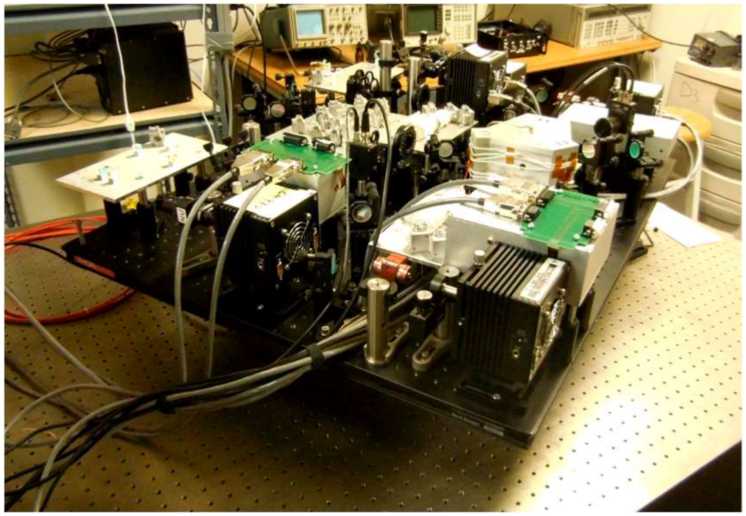
Quadruple Offset Phase Locking

- Two Raman lasers using dual-isotope vapor cells. Use different optical and Raman pumps for each isotope to produce a narrow dip in the gain. Apply Raman pumps for the two cells at different detunings resulting in a bias.
- Common path, bidirectional, self-biased FL gyro ⇒ Bias eliminates dead-band and direction ambiguity. Improved common-mode rejection. Lower power.

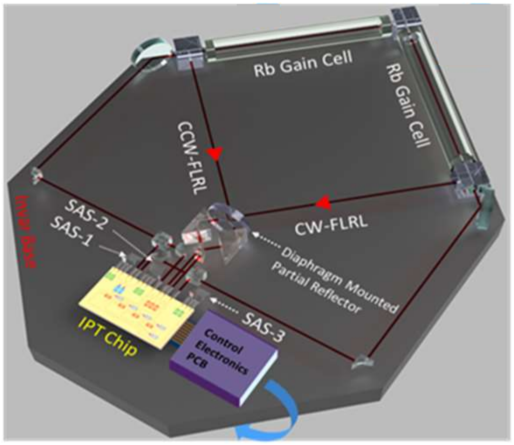
Courtesy: Digital Optics Technologies

Portable SRS FLG in Development


Power and Control Electronics



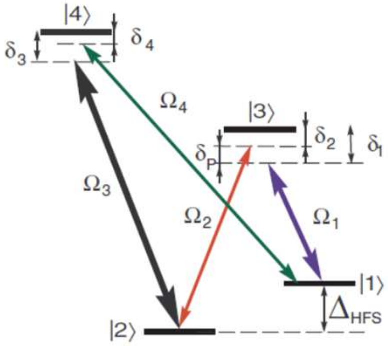
Future: FLG on a chip

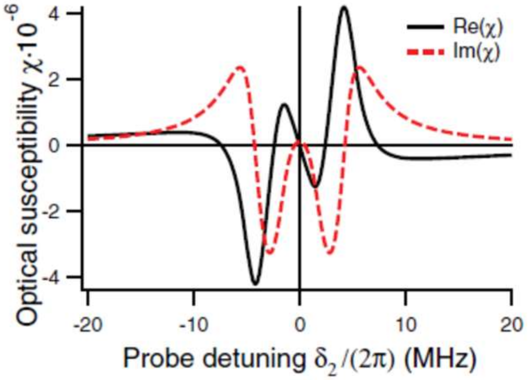


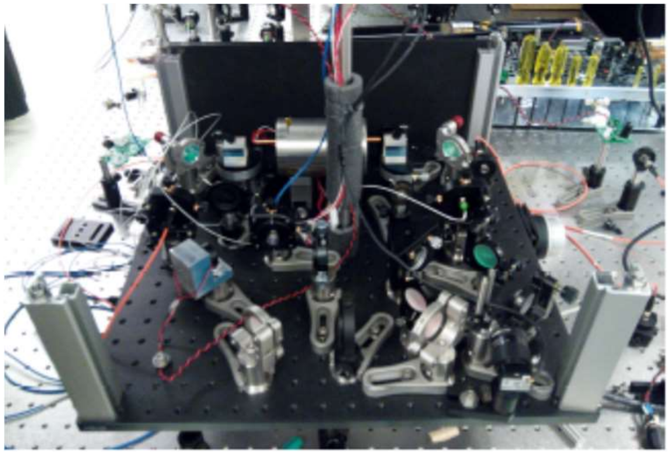
Courtesy: Digital Optics Technologies

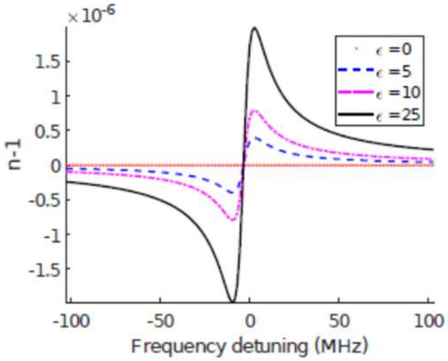
Active FLG: FWM Gyro

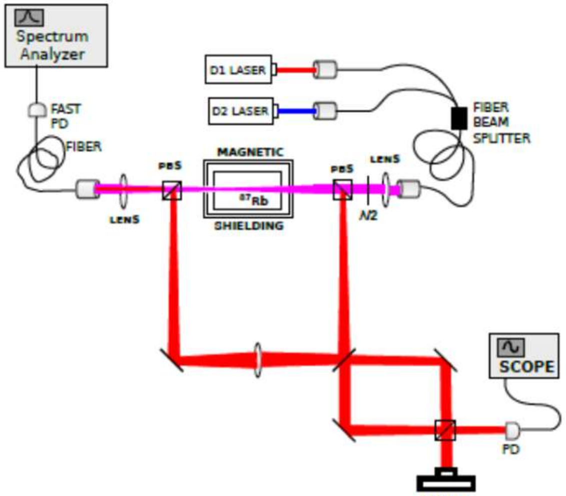
FWM = Four-Wave Mixing



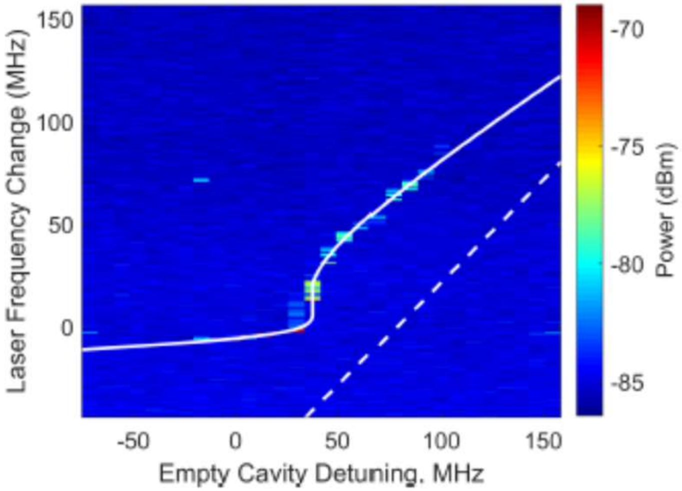


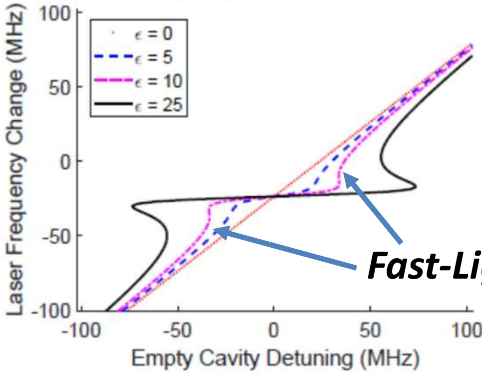






First Enhancement to OPL in Active System!



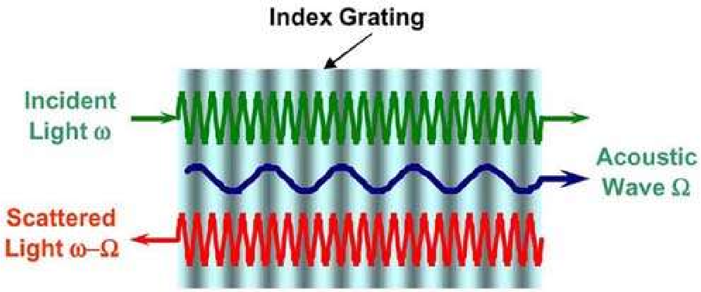


Fast-Light Enhancement

S. L. Cuozzo et al., arXiv:1812.08260 (2018)

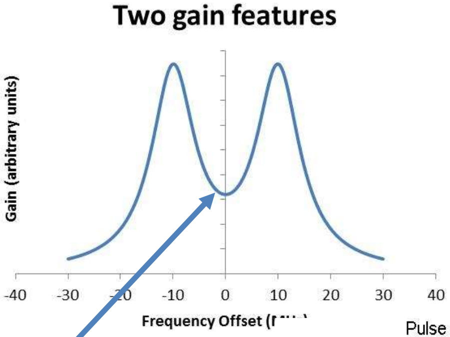
Active FLG: SBS Gyro

SBS = Stimulated-Brillouin Scattering



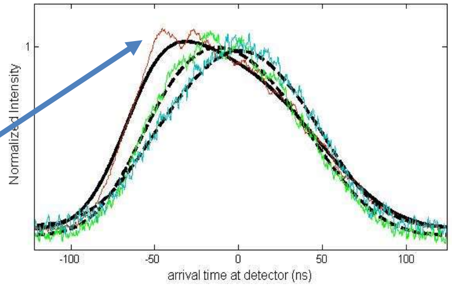
Problem: SBS gain produces slow light

Solution: ***Dual (two-color) pumping!***

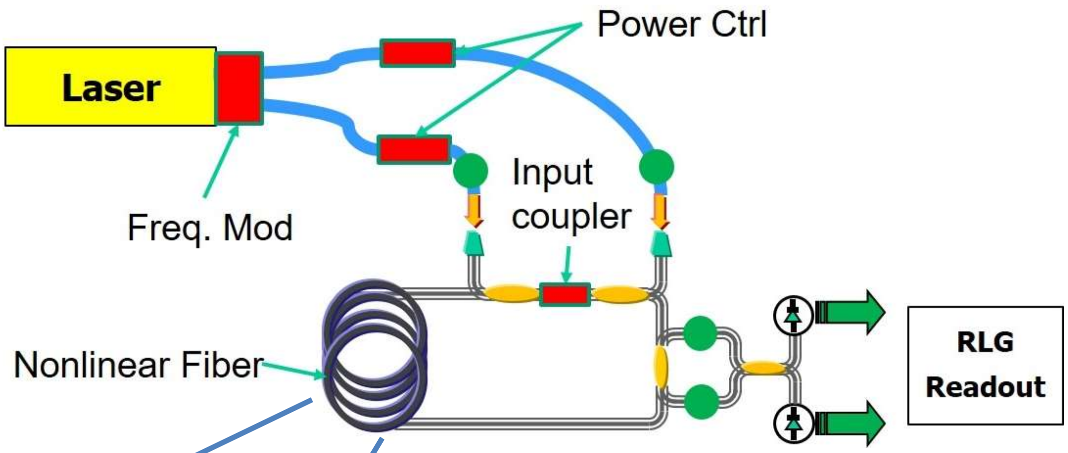


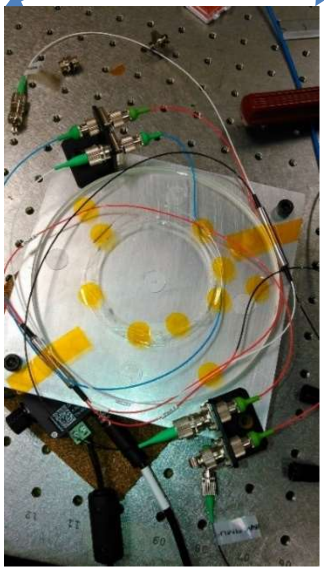
Fast Light!

Pulse Advancement through Fast Light



Pulse Advancement!





- ➢ Compact Design. First solid-state gyro. No gain competition!
- ➢ Lock-in effect eliminated by bias at FSR. No deadband!
- ➢ Dual pumping produces FL.
- ➢ Lasing at dip, and bidirectional with dual pump demonstrated.

Christensen et al., Proc. SPIE 8722, 87220J (2013).

Challenges for Active FL Gyros

- Gain competition ⇒ unidirectional lasing
- Lock-in ⇒ dead-band
- Dynamics of gain medium cancels FL enhancement to some degree.
- Often rely on NLO processes generated by additional pump beams
  - → Significantly more complex. **Difficult to miniaturize.**
  - → Sophisticated control schemes required
  - → Added sensitivity to environmental effects
- Enhancement in sensitivity, S, still not demonstrated directly to OPL changes, only inferred.

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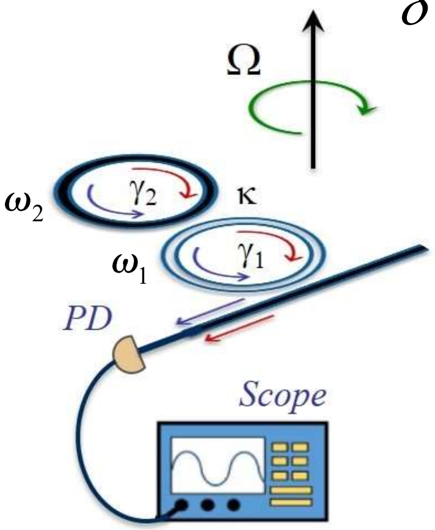
Limitations of Atomic-Vapor FL Gyros

- Difficult to miniaturize
- Sophisticated control schemes
- Rely on discrete material transitions
  - → Temperature dependent - requires SOA stabilization techniques.
  - → Limited operation wavelength - inhibits wide adoption, manufacturers want to stick with He-Ne wavelengths.

Coupled-Resonator Gyros

Solution: Coupled-Resonator (CR) Gyros



$\delta = \omega_1 - \omega_2$ $\gamma = \gamma_1 - \gamma_2$

$\tilde{\delta} = \delta - i\frac{\gamma}{2}$ *Complex detuning*

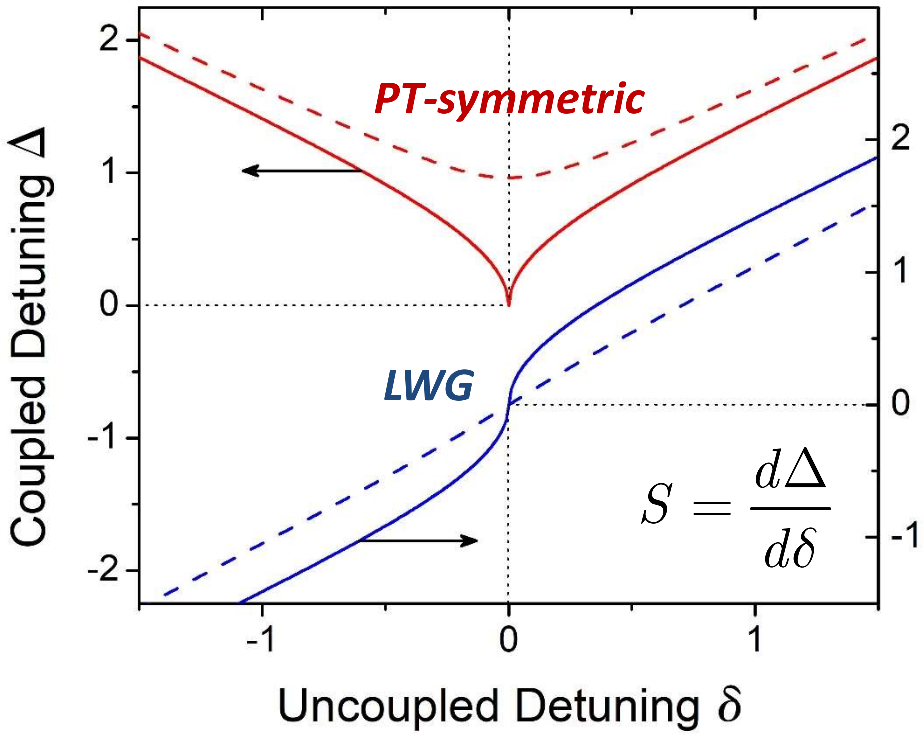
$\gamma \neq 0 \quad \therefore$ **Non-Hermitian**

Complex Eigenvalues: $\pm\tilde{\Omega}/2$

$$\tilde{\Omega} = \left[\tilde{\delta}^2 + \kappa^2\right]^{1/2} \to 0 \ \ at\ EP$$

$$\boxed{\kappa_{EP} = |\gamma/2|}$$

Exceptional point!
Degenerate Eigenvalues.



Beat Frequency: $\Delta = \mathrm{Re}\,\tilde{\Omega} \sim \sqrt{\delta}$ *at EP*

$$\boxed{\therefore S(0) \to \infty}$$

Exceptional Point (EP) = Fast Light (FL) Enhancement!

Advantages of CR Gyros

- Easy to miniaturize via microfabrication
- Entirely linear effect, no saturation ⇒ higher signal-to-noise
- Eliminates temperature dependence of atomic absorption ⇒ better scale-factor stability.
- Not limited to operation at atomic resonance frequencies. **Any lasing wavelength possible, including He-Ne.**

Limitations of CRs

- **Not common path.** Resonators suffer from independent amounts of noise and drift.
  ⇒ Detuning between resonators not stable

- **Coupling not easily controlled**
  ⇒ *S* not easily tunable

- **Coherent control of *S* requires two input beams with a stable phase difference** (an interferometer)
  ⇒ Random phase between input beams.

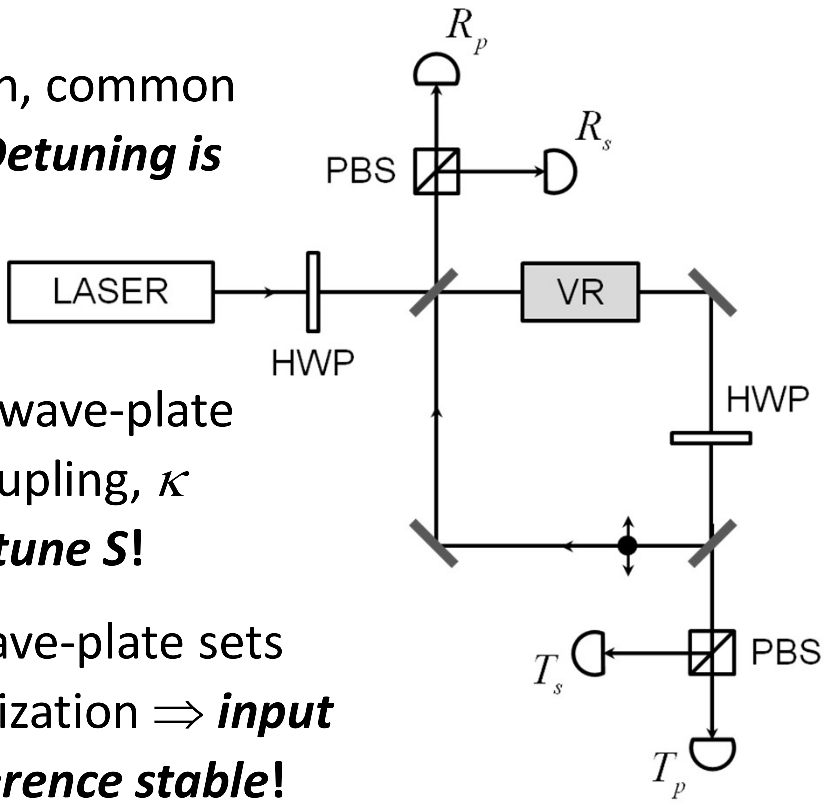
- Enhancement strongly implied, but active CR lasers still haven't shown <u>definitive</u> boost in sensitivity.

Passive CRs: Polarization Mode Coupling

Soln: Polarization Coupling in a Single Cavity

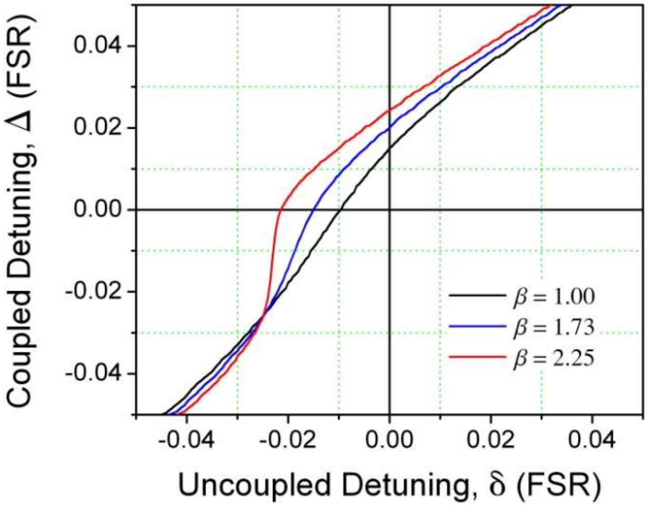
- Shared path, common mode. ⇒ ***Detuning is stable***!
- Intracavity wave-plate controls coupling, κ ⇒ ***Easy to tune S***!
- External wave-plate sets input polarization ⇒ ***input phase difference stable***!

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

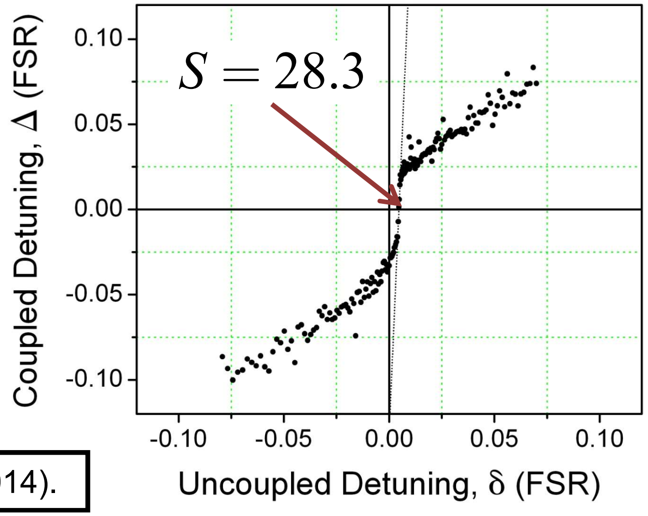


D. D. Smith et al., *Phys. Rev. A* **89**, 053804 (2014).

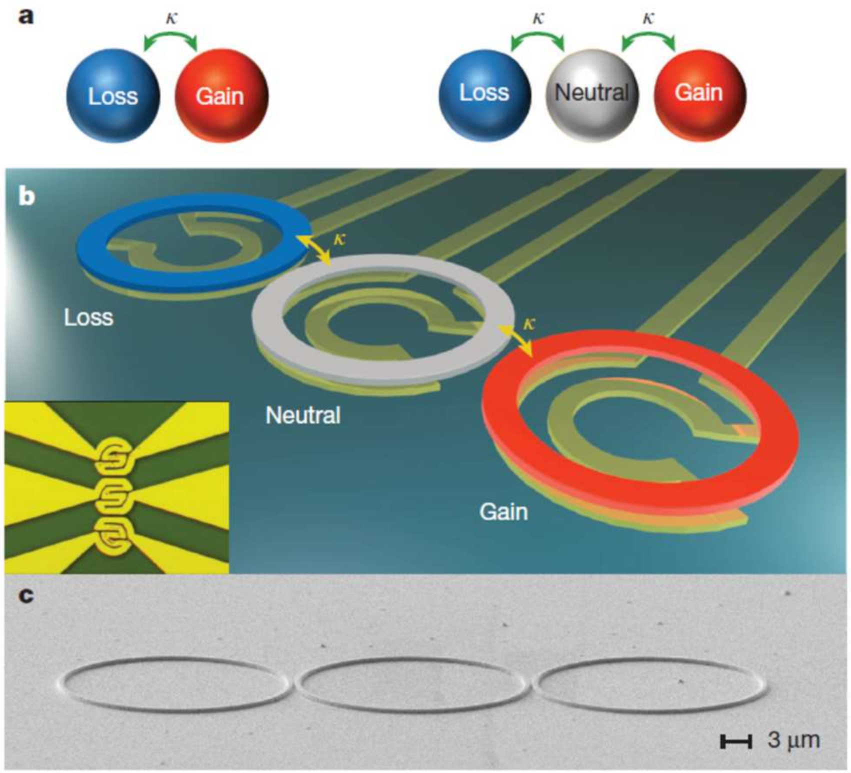
Coherent Control of S



Critical FL Condition



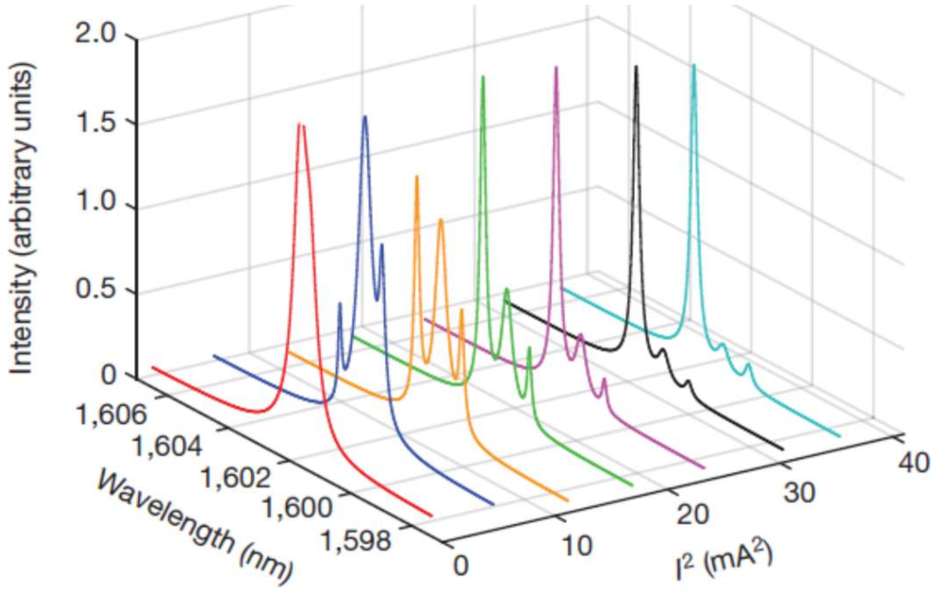
Active CRs: PT-Symmetric Systems

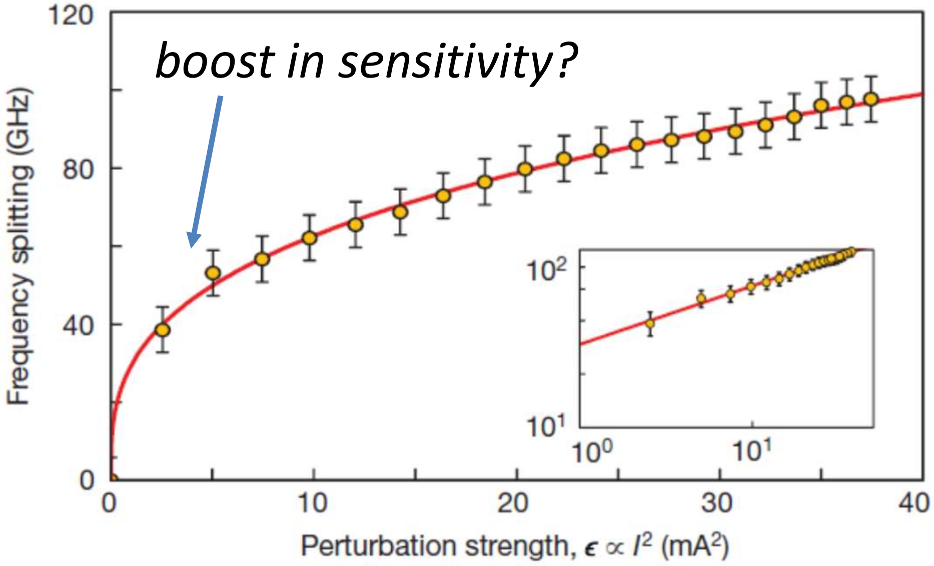


second-order EPs ⇒ square-root
third-order EPs ⇒ cube-root

Strong implication of enhancement

H. Hodaei et al., *Nature* **548**, 187 (2017).

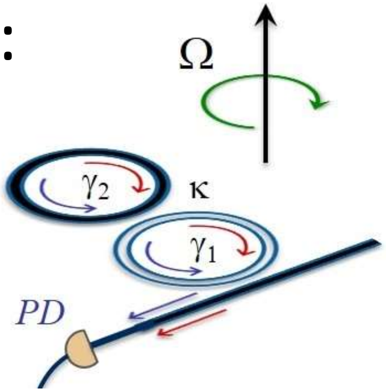



boost in sensitivity?

Limitations of PT-Symm. Gyros

Parity-time (PT) symmetric gyros proposed by:

J. Ren et al., *Opt. Lett.* **42**, 1556 (2017).



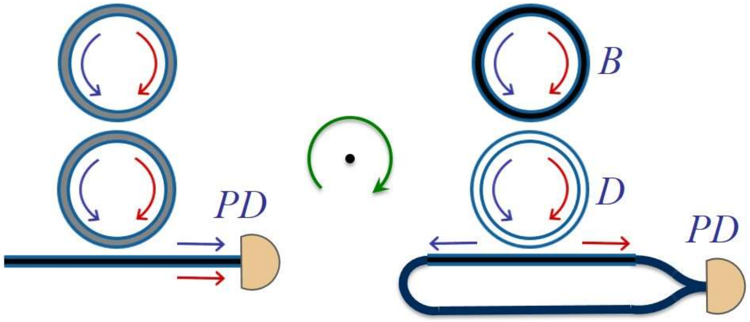
Balanced gain/loss: $\gamma_2 = -\gamma_1$

Limitations:

- Strong, undamped power oscillations $\Rightarrow$ can produce false rotation signal via Kerr effect
- Enhancement only obtained very close to EP
- Ambiguity in the direction of rotation
- Must operate at very small rotation rates and very close to threshold (otherwise one of the output frequencies disappears $\Rightarrow$ no beat signal).

Active CRs: Lasing Without Gain

PT-symmetric **LWG**



$$\gamma_{TOT} = \gamma_1 + \gamma_2 = 0 \qquad \gamma_{TOT} < 0$$

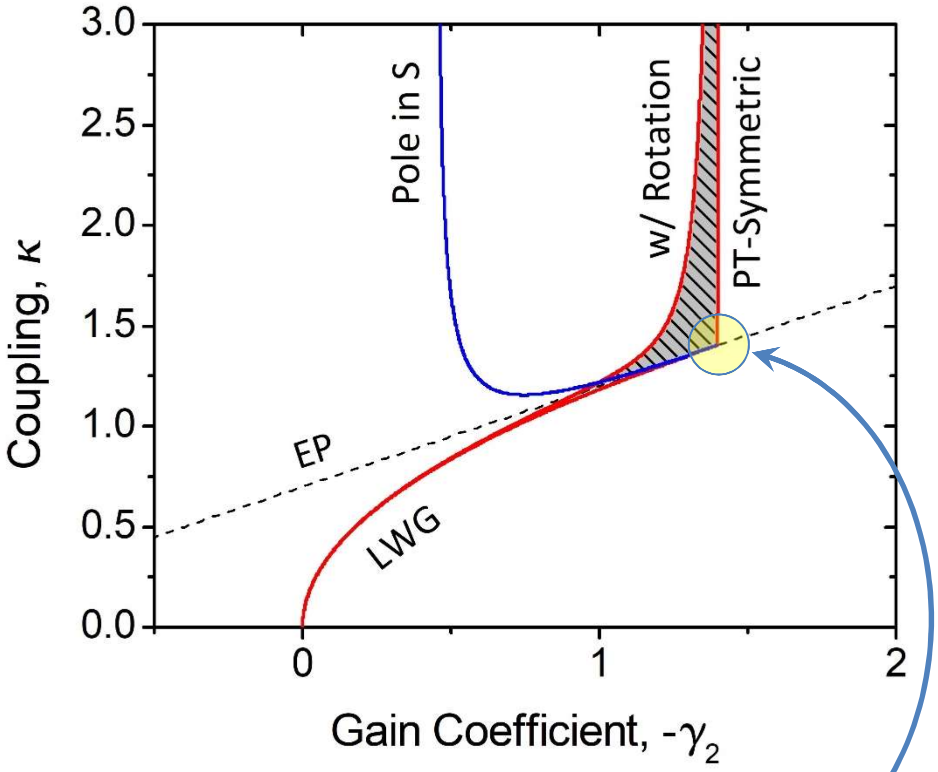
Usual lasing condition

Lasing when net gain negative!

- ☹ Power oscillations
- ☹ Must be close to EP
- ☹ Direction ambiguity
- ☺ Unidirectional

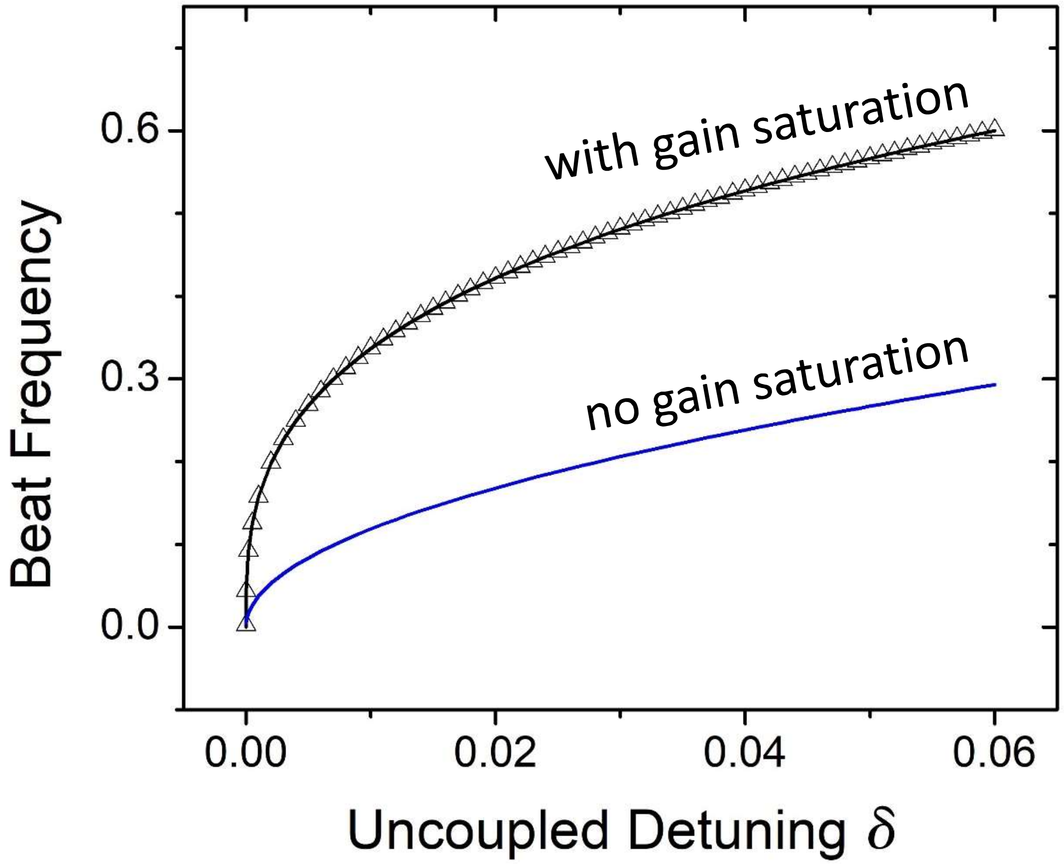
- ☺ No oscillations
- ☺ Works far from EP
- ☺ No ambiguity
- ☹ Bidirectional
  - → Dead-band

Gain Sat. OR
High Rot. Rate



EP, pole in S,
laser threshold
all coincide

Effects of Gain Saturation



Enhancement even larger than expected!

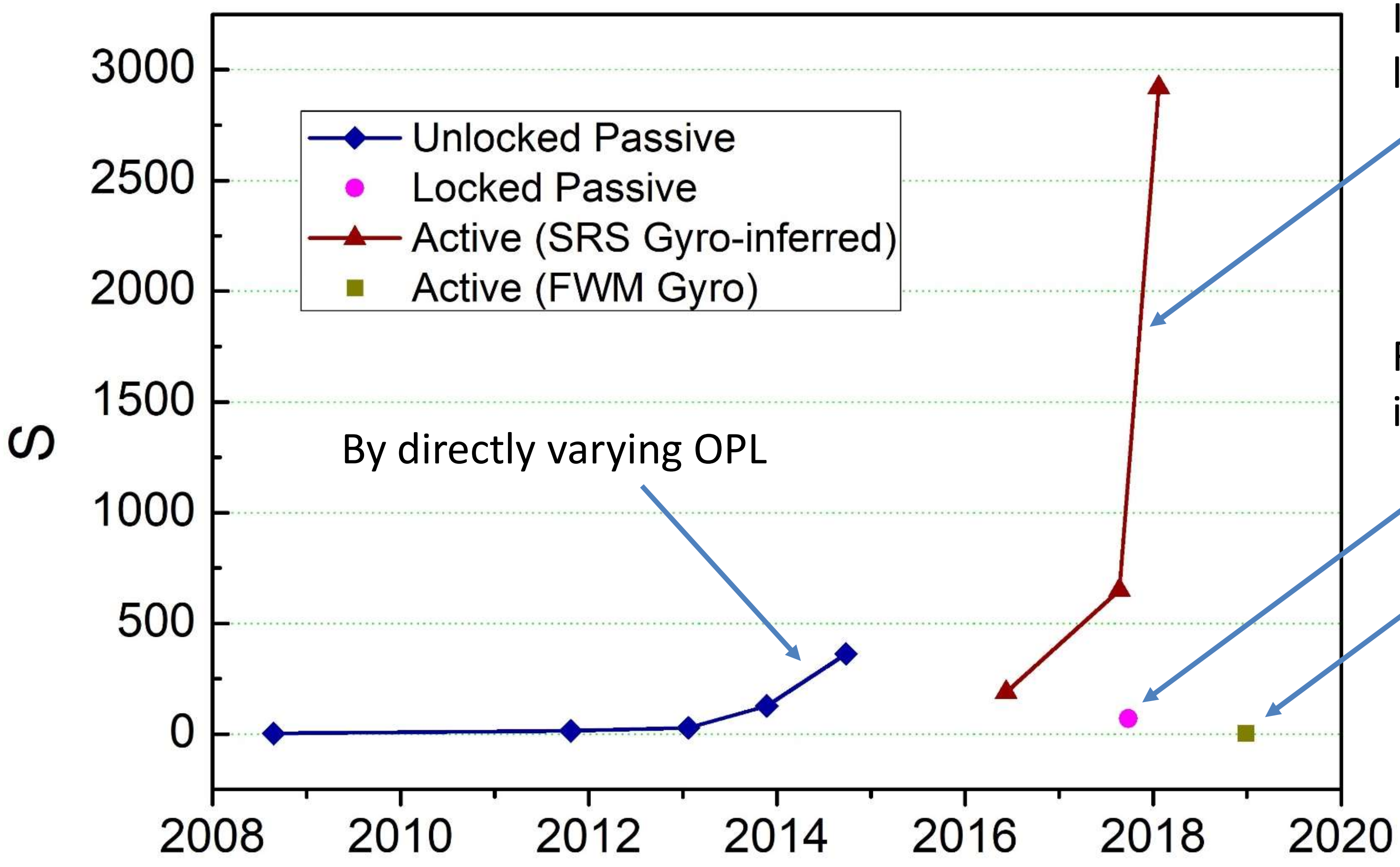
Gain Saturation:

- Eliminates power oscillations
- Prevents one of the output frequencies from lasing
- Removes directional ambiguity
- **Boosts sensitivity enhancement**
- **Enlarges parameter space around EP over which enhancement occurs**

Final Comments

Increase in SOA over Time

Sensitivity Enhancement, *S*



By directly varying OPL

Inferred from lasing spectrum

First measurement in a device

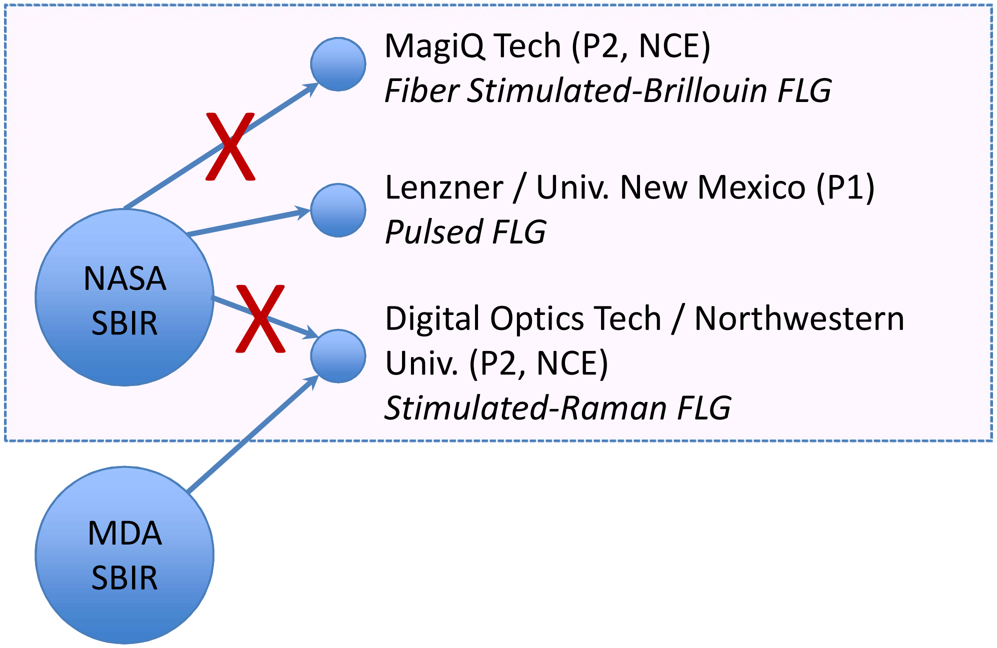
First by varying OPL in Active System

What is still needed

- Demonstrate scale-factor enhancement, S, to rotation.
- Demonstrate enhancement in precision, ζ.
- FL gyros that:
  - → Are common path
  - → Are not limited in signal to noise
  - → Do not require complicated stabilization schemes
  - → Permit operation at any wavelength (especially He-Ne)
  - → Can be easily miniaturized
  - → Are relatively insensitive to environmental (e.g. temperature, G-level) variations

Development Plan

External Program



NASA SBIR

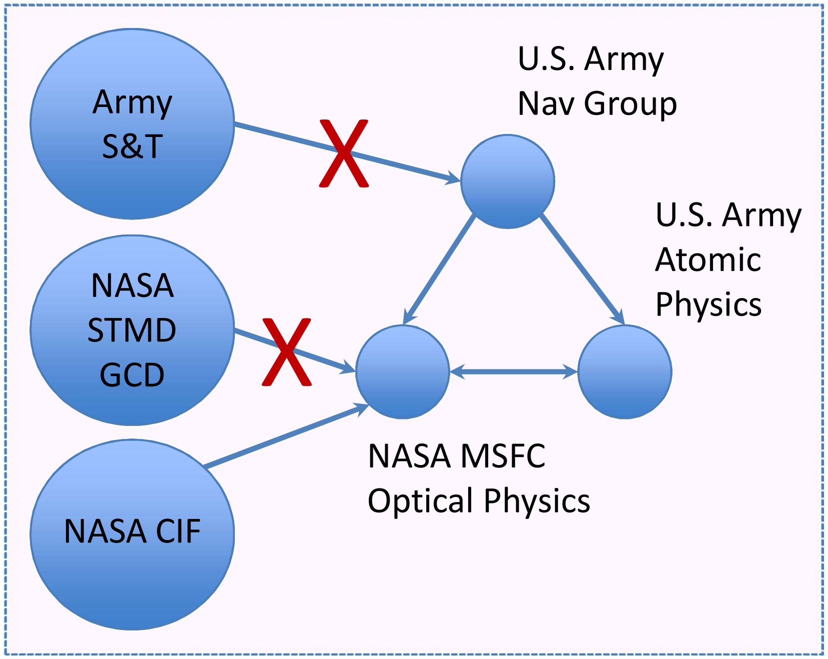
MDA SBIR

MagiQ Tech (P2, NCE)
Fiber Stimulated-Brillouin FLG

Lenzner / Univ. New Mexico (P1)
Pulsed FLG

Digital Optics Tech / Northwestern Univ. (P2, NCE)
Stimulated-Raman FLG

In-house Program



Army S&T

NASA STMD GCD

NASA CIF

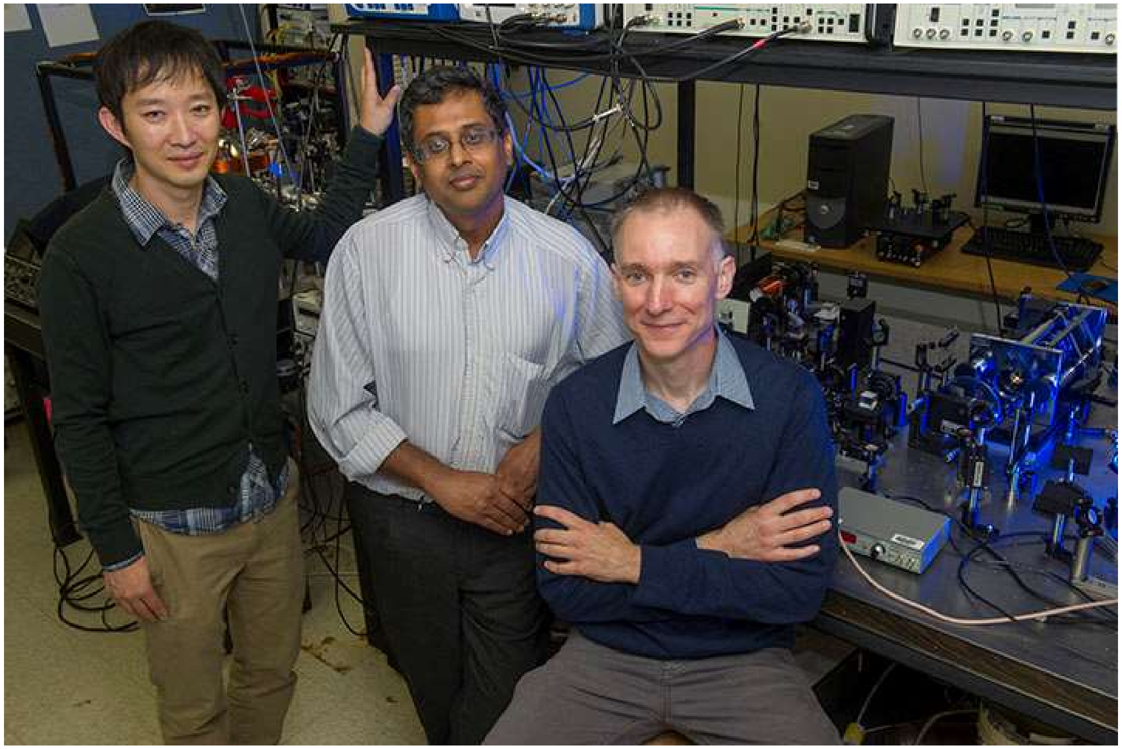
U.S. Army Nav Group

U.S. Army Atomic Physics

NASA MSFC Optical Physics

Others Past & Present: Torch, Triad, Aegis, Honeywell, Los Gatos Research, Photodigm, Vescent, Freedom Photonics, Rochester Scientific, College of William and Mary.

International Efforts: Tel Aviv Univ. (Israel), National Univ. of Defense Technology (China), Harbin Institute of Technology (China), Thales Aerospace (France).



Thank You!

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Digital Optics Technologies / Selim Shahriar (NU)

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