Influence of the cavity impedance in a passive resonant laser gyroscope

Y. H. Zhong, H. B. Zhang, K. Liu[1], X. H. Feng, Y. X. Chen, J. P. Yao, Y. W. Liu, Z. H. Lu and J. Zhang*

PGMF and School of Physics, Huazhong University of Science and Technology, Wuhan 430074, P. R. China

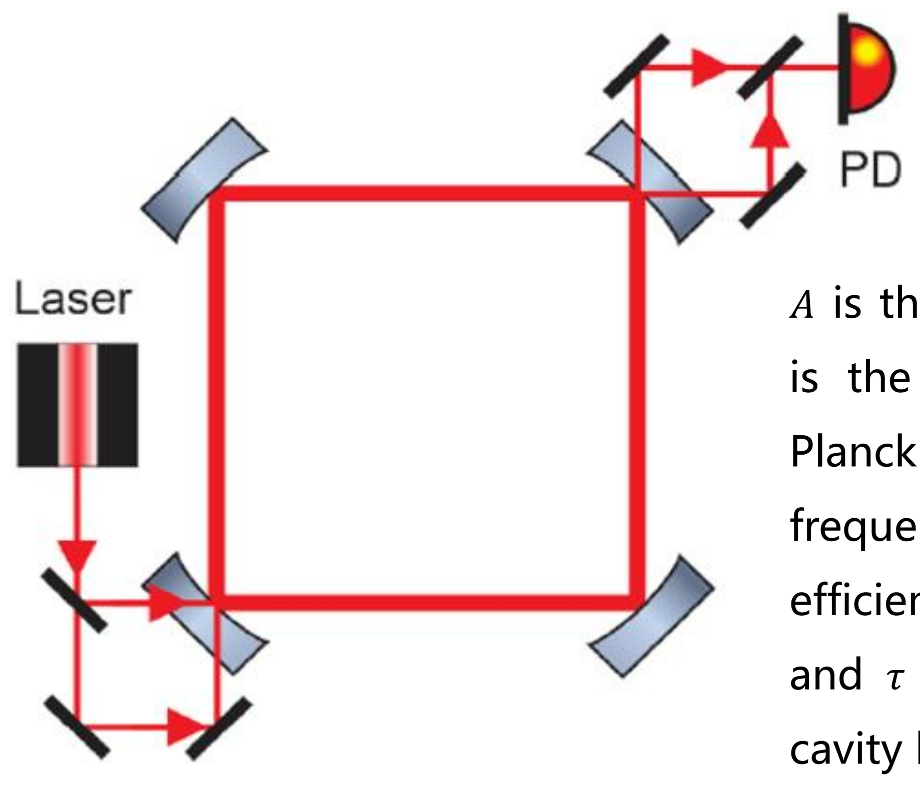
[1]MOE Key Laboratory of TianQin Mission, TianQin Research Center for Gravitational Physics & School of Physics and Astronomy, Frontiers Science Center for TianQin, CNSA Research Center for Gravitational Waves, Sun Yat-sen University (Zhuhai Campus), Zhuhai 519082, China

E-mail: jie.zhang@mail.hust.edu.cn

Abstract

The optical ring cavity is the core component of a laser gyroscope. Higher finesse and narrower linewidth are required. However, the property of cavity impedance matching is another key parameter for a passive resonant gyroscope (PRG). For a free-space PRG, the laser is locked to the cavity resonance by using the Pound-Drever-Hall (PDH) method. The balance of finesse and impedance matching factor can be optimized through the relationship of the discriminant slope with respect to the mirror parameters. Moreover, a proper impedance matching factor allows a higher intra-cavity laser power, which can also increase the ultimate sensitivity of the gyroscope.

PRG



Ultimate sensitivity

$$\delta\Omega = \frac{\lambda p}{4A}\cdot\frac{\sqrt{2h\nu\Delta\nu_c}}{\sqrt{\eta_D P\tau}}$$

A is the area, λ is the wavelength and p is the ring cavity perimeter. h is the Planck 's constant and ν is the laser frequency. η_D is the quantum detection efficiency, P is the detecting laser power and τ is the sampling time. $\Delta\nu_c$ is the cavity linewidth.

Fig. 1: Principle of a PRG and the ultimate sensitivity of the PRG

Laser frequency locking

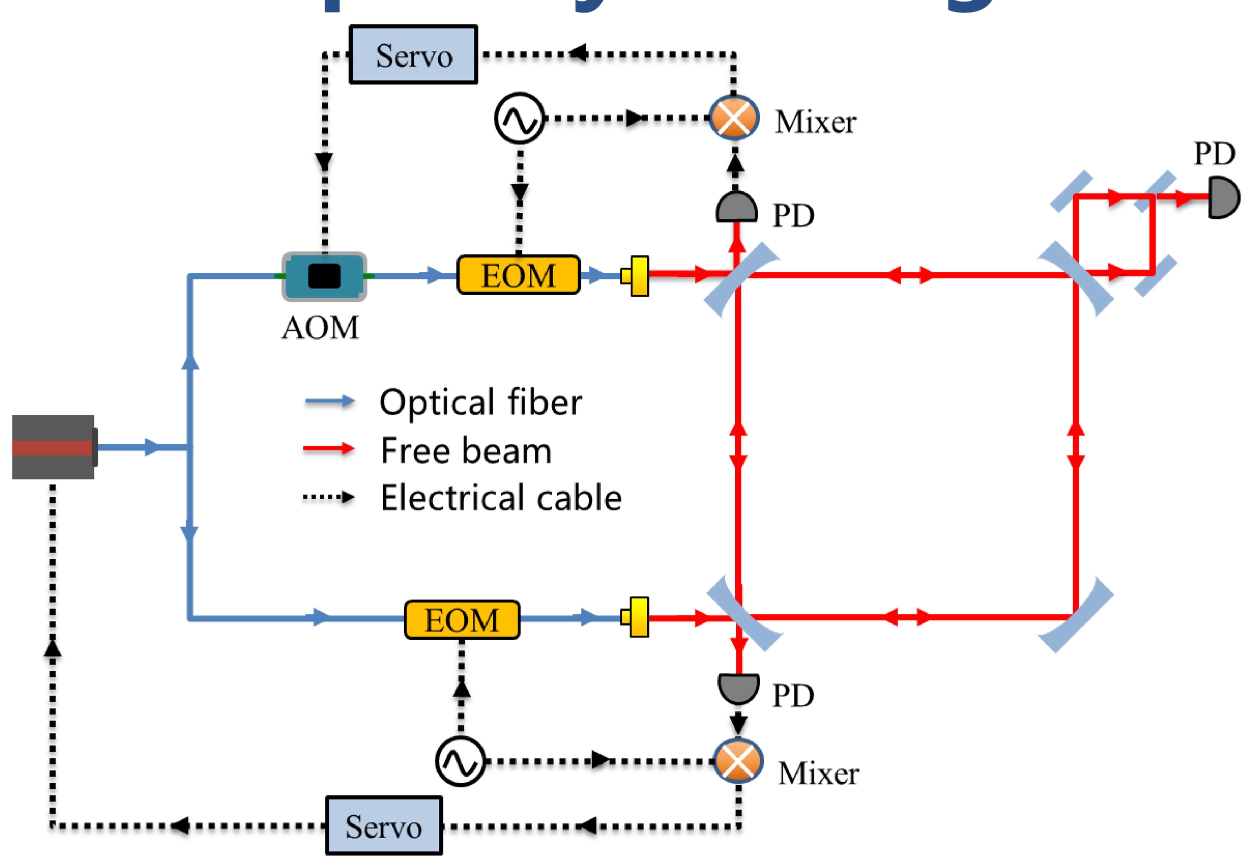
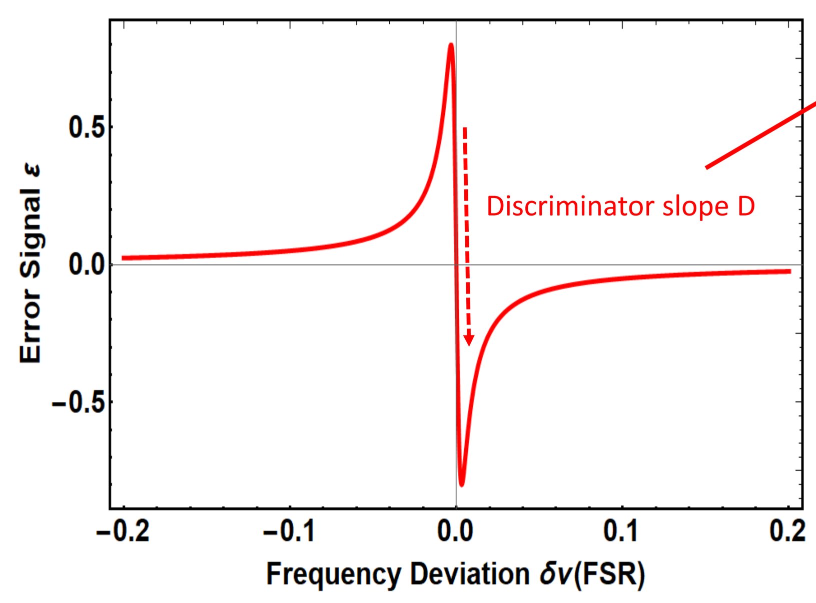


Fig. 2: Laser frequency locking using the PDH method.

Discriminator slope



$$D \approx \frac{8J_0J_1P_{\rm inc}}{\Delta\nu_c}$$

J_0, J_1 is the 0, 1 order Bessel steps, $P_{\rm inc}$ is the Injected cavity laser power.

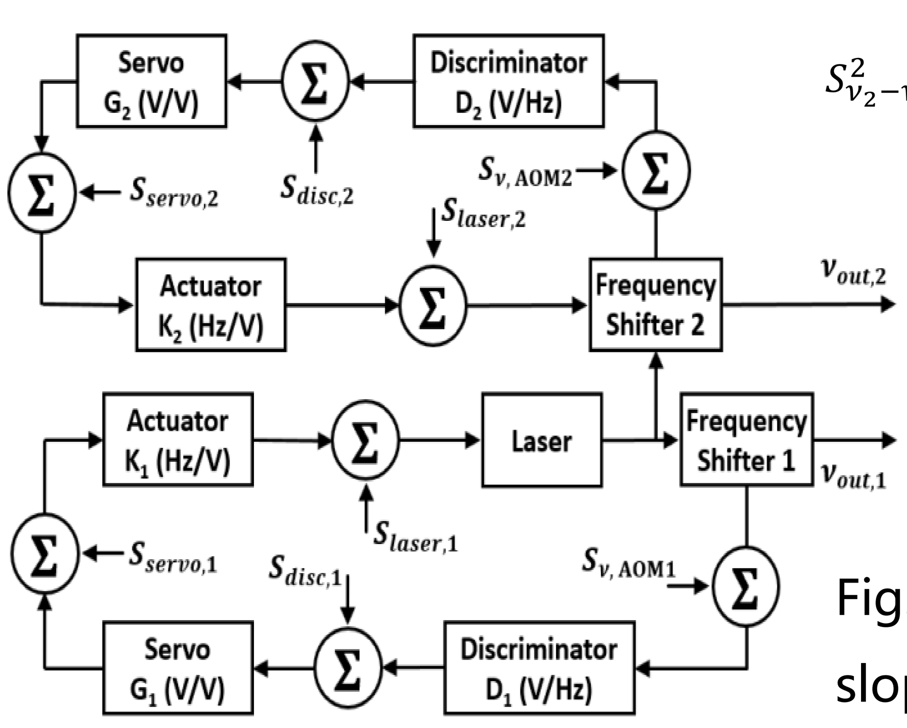
Consider impedance matching and mode matching

$$D = \frac{8\alpha(1-\zeta)J_0J_1P_{\rm inc}}{\Delta\nu_c}$$

α is mode matching efficiency, ζ is impedance matching factor.

Fig. 3: The discriminant slope is critical in PRG, indicating the sensitivity of the locking system to laser frequency shifts. It is related to cavity linewidth and impedance matching.

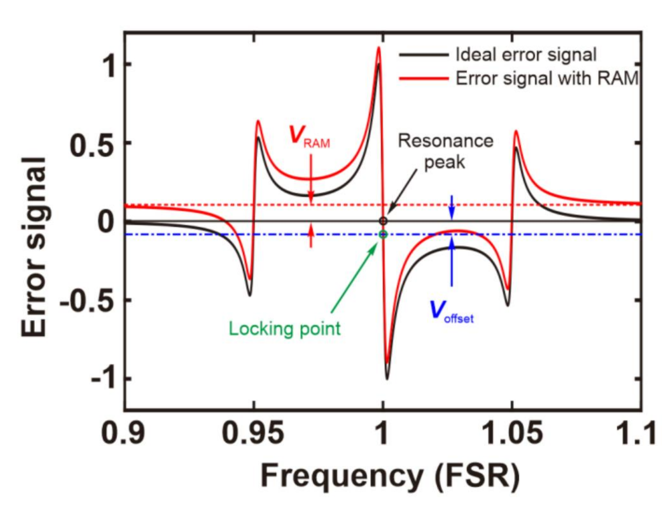
Locking noise



$$S^2_{\nu_2-\nu_1} \approx \frac{K_2^2G_2^2D_2^2S^2_{\nu,sagnac}}{|1+K_2G_2D_2|^2} + \frac{S^2_{\nu,\rm AOM2}}{|K_2G_2D_2|^2} + \frac{S^2_{laser,1}+S^2_{\nu,cavity}}{|K_1G_1D_1|^2} + \frac{S^2_{\nu,cavity}}{m^2} + \frac{S^2_{servo,1}}{G_1^2D_1^2} + \frac{S^2_{servo,2}}{G_2^2D_2^2} + \frac{S^2_{disc,1}}{D_1^2} + \frac{S^2_{disc,2}}{D_2^2} \approx \frac{S^2_{disc,1}}{D_1^2} + \frac{S^2_{disc,2}}{D_2^2}$$

Fig. 4: Increased discriminator slope helps to reduce locking noise.

Residual amplitude modulation (RAM) effect



$$\Delta\nu_{\rm offset} = \frac{V_{\rm offet}+V_{\rm RAM}}{D}$$

$\Delta\nu_{\rm offset}$ is the frequency deviation of the locking frequency from the cavity resonance peak, where $V_{\rm offet}$ is the error signal offset drift and $V_{\rm RAM}$ is the error signal offset drift due to RAM.

Fig. 5: Increased discriminator slope helps to reduce the offset drift of the frequency locking point and suppress the RAM noise.

Mirror parameters

Impedance matching factor

$$\zeta = \frac{\sqrt{R_1}-\sqrt{R_2R_3R_4}(1-L)}{1-\sqrt{R_1R_2R_3R_4}}$$

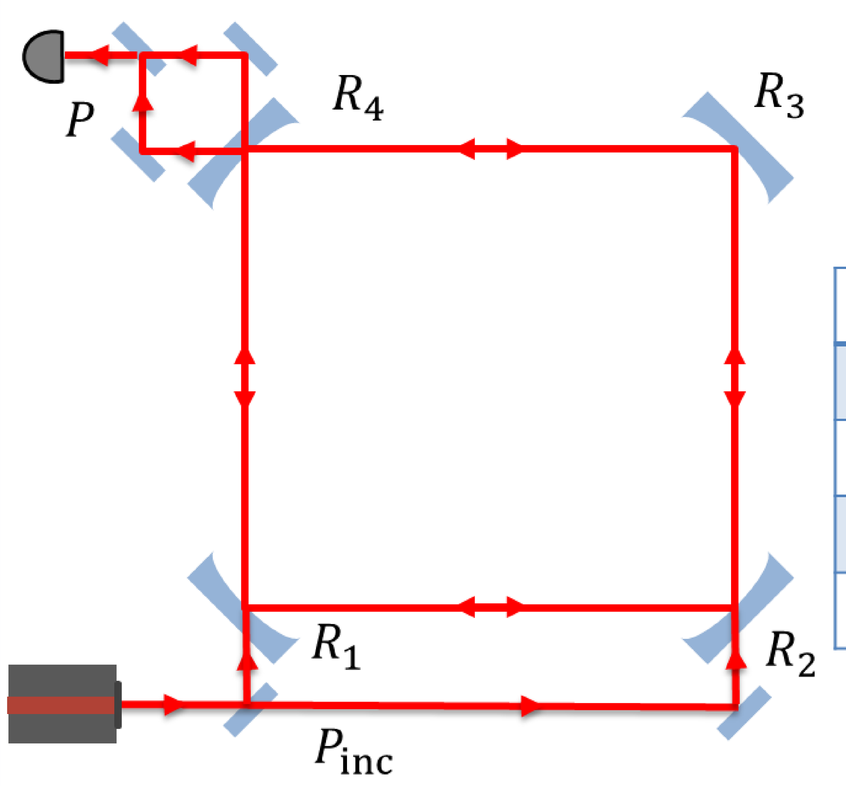
R_1, R_2, R_3, R_4 is the reflectivitis of four cavity mirrors, L is the absorption and scattering loss of the input mirror.

Cavity linewidth

$$\Delta\nu_c = \frac{c(1-R_1R_2R_3R_4)}{2\pi p}$$

Finesse

$$\mathcal{F} = \frac{FSR}{\Delta\nu_c}$$

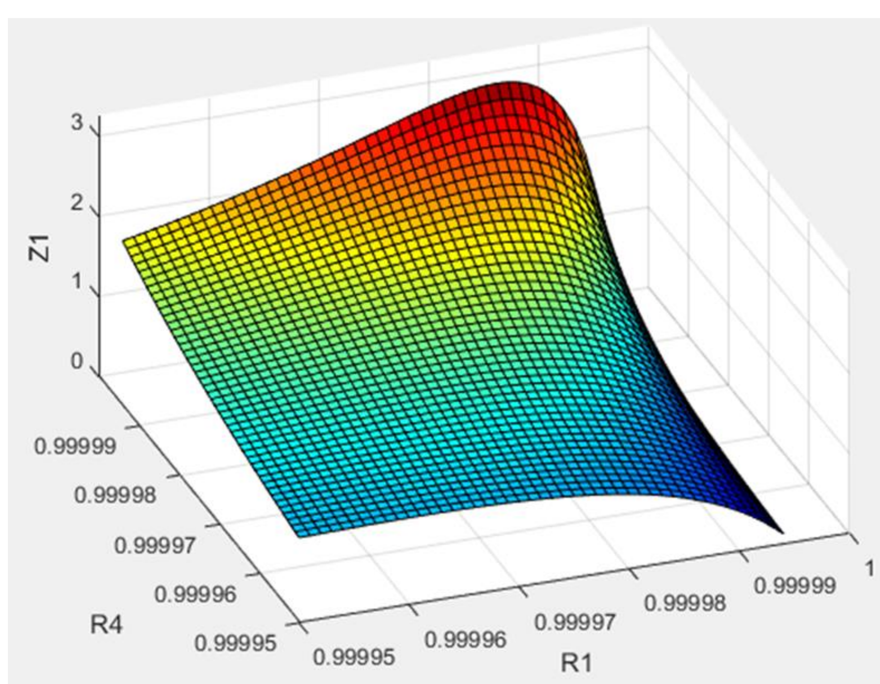


Current Mirror Parameters

$R_i (i=1,2,3,4)$	0.999994(1)
L	5 (1) ppm
$\Delta\nu_c$	950(50) Hz
$\mathcal{F}$	$2.6(3)\times10^5$
ζ	0.91(3)

Fig. 6: Laser injection scheme for PRG and current measured mirror parameters.

Improved discriminator slope



$$Z_1 = \frac{D}{D_{\rm V1}} = \frac{8\alpha(1-\zeta)J_0J_1P_{inc}}{\Delta\nu_cD_{\rm V1}}$$

$$R_1 = R_2,\quad R_3 = 0.999994$$

$D_{\rm V1}$ is the discriminant slope of the current PRG. Keep R_3 constant, R_1 and R_2 are equal.

R_1	0.999985(5)	$\Delta\nu_c$	1700 (300)Hz
R_2	0.999985(5)	$\mathcal{F}$	$1.5(3)\times10^5$
R_3	0.999994(1)	ζ	0.52(10)
R_4	0.999994(1)	$D/D_{\rm V1}$	3.2(3)
L	5(1) ppm	$\delta\Omega_{\rm V1}/\delta\Omega$	1~3

Fig. 7: By changing the mirror parameters, we can balance impedance matching factor and cavity linewidth to give an optimum value of D. In addition, although the cavity linewidth is increased by reducing the reflectivity, the optical power in the cavity is also increased. As a by-product, the ultimate sensitivity is also improved.