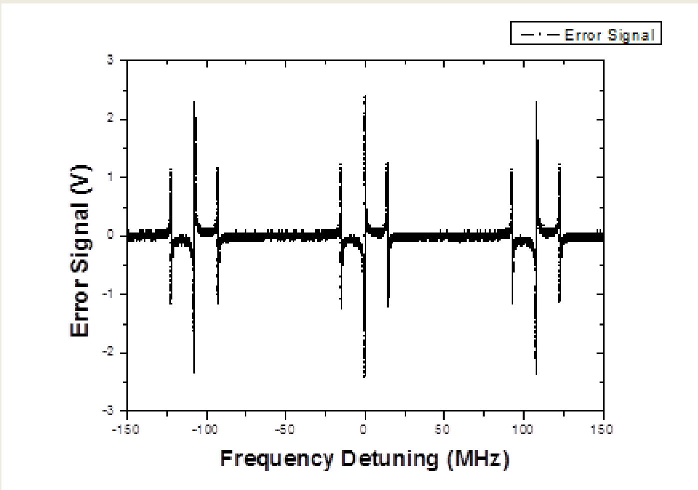
Fiber ring cavity for frequency stabilization of master laser of iKAGRA

6th Japan-Korea Workshop on KAGRA



Tai Hyun Yoon

ICRR Visiting Professor

- June 20 – Aug. 20, 2013
- June 18 – Aug. 19, 2014

Laser Physics Laboratory, Department of Physics, Korea University

Required Main Laser Parameters

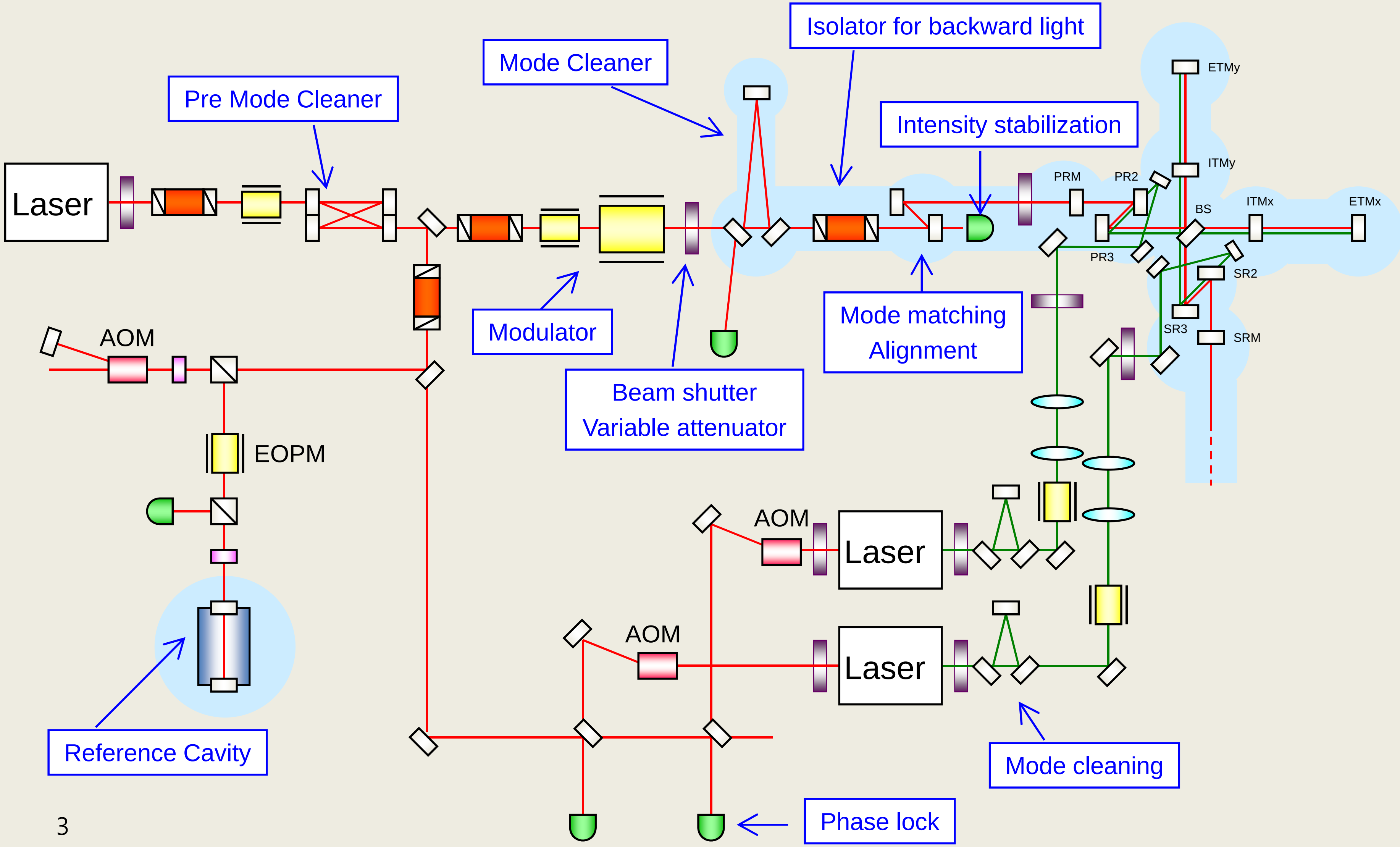
Wave length	1064 nm
Power	180 W
Oscillation mode	Single (longitudinal and transversal)
Polarization	Linear
Line-width	< a few kHz
Frequency noise	$100\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz
Frequency Control band-width	>800 kHz with an external EOM
Intensity noise (RIN)	$10^{-4}\sqrt{\mathrm{Hz}}$ at 100 Hz

bKAGRA

$$\frac{\Delta L}{L} = -\frac{\Delta f}{f} = \frac{100}{3\times10^{14}} = 3\times10^{-13} \text{ at 100 Hz}$$

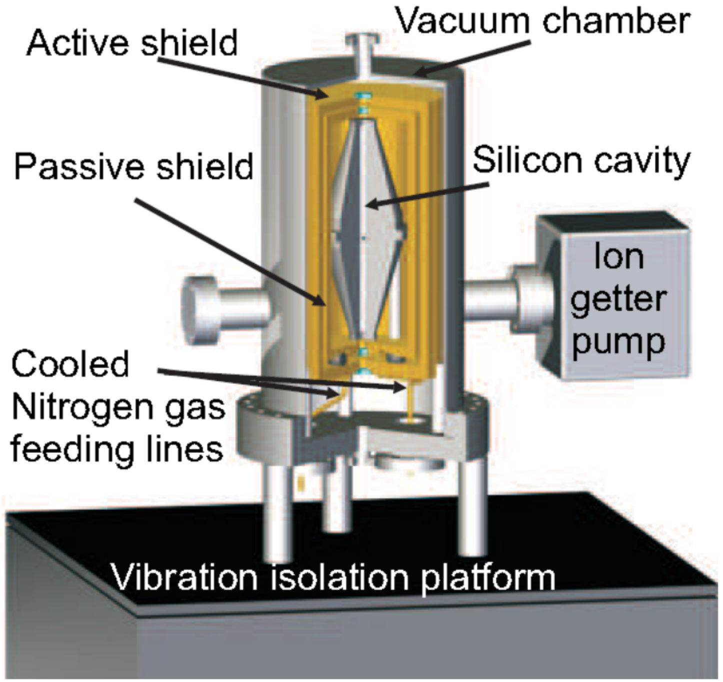
$$\Delta L = 3\times10^{-19} \text{ m at 100 Hz}$$

KAGRA Input Optics



Fabry-Perot Cavity: $\upsilon\lambda = c$

Frequency standard (ν) → displacement ΔL



Ye, Nature Photonics, 2012

$$L = 210 \text{ mm}$$

$$Q = 4 \times 10^{15}$$

$$F = 240\ 000$$

$$\tau = \frac{F/\pi}{c/2L} = 0.1 \text{ ms}$$

$$\upsilon_q = q \times \frac{c}{2L}\text{: q} = 10^6 \sim 10^6,$$ **integer**

$$\frac{\delta \upsilon_q}{\upsilon_q} = -\frac{\delta L}{L} = -h$$

⇩

$$\delta \upsilon_q = -h \times \upsilon_q$$

F-P Cavity Airy Function

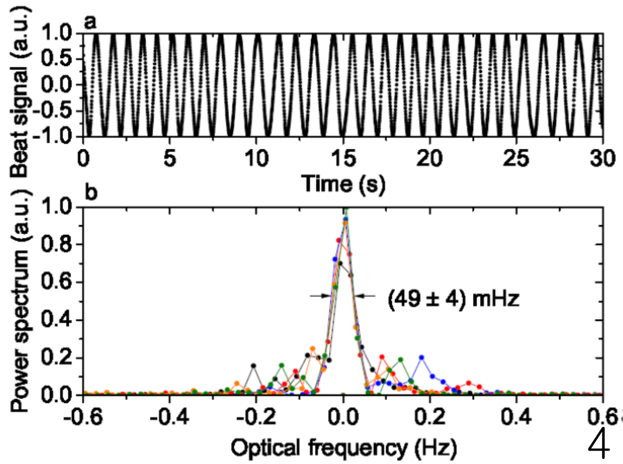
$$I(\nu) = \frac{I_{\max}}{1 + \left(\frac{\pi F}{4}\right)^2 \sin^2\left(\frac{\pi \nu}{f_{FSR}}\right)}$$

$$f_{FSR} = \frac{c}{2L} = 714 \text{ MHz}$$

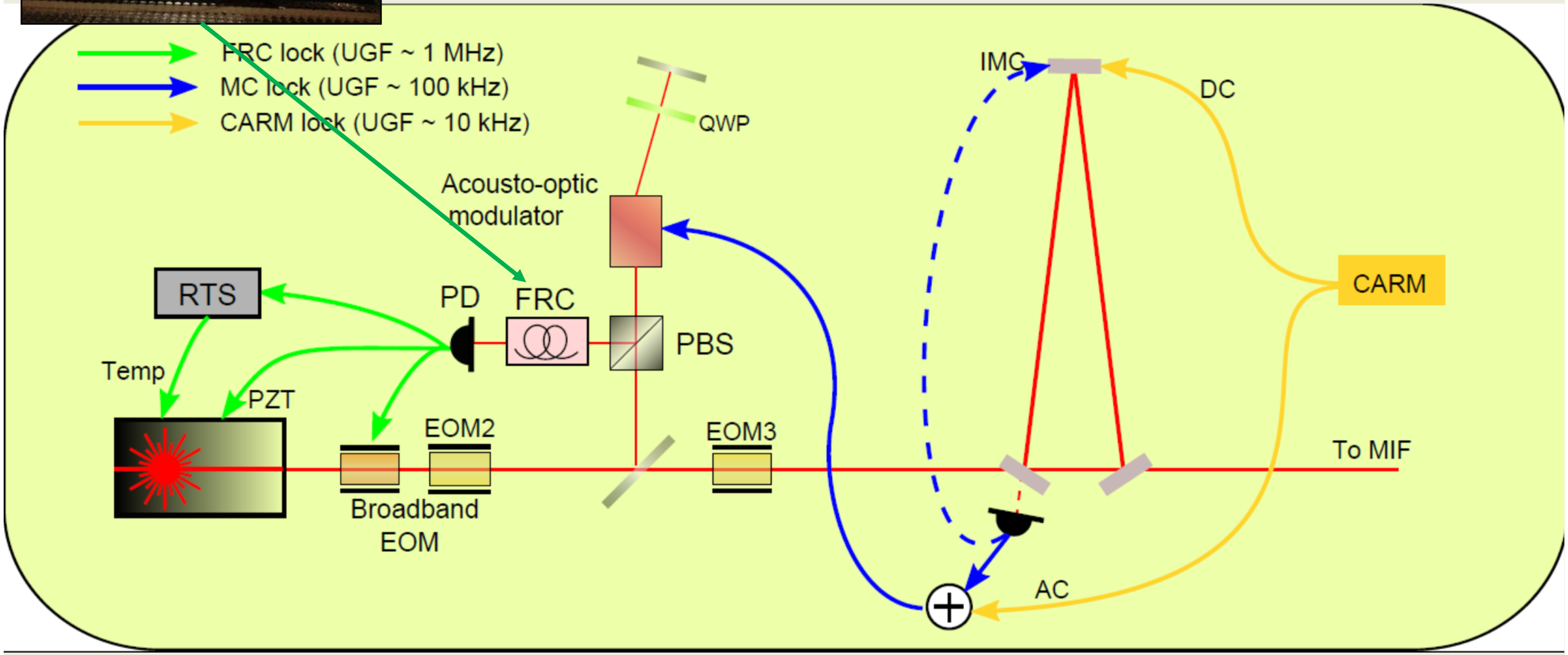
$$\delta f = 49 \text{ mHz}$$

$$q = \frac{c/\lambda}{f_{FSR}} = 280\ 112$$

$$\frac{\delta f}{f} = \frac{49 \text{ mHz}}{c/\lambda} = 2.4 \times 10^{-16}$$



iKAGRA Input Optics Layout



iLIGO Pre-stabilized Laser (PSL)

Technical Note LIGO–T990025–00–D 03/08/99

(Infrared) Pre-stabilized Laser (PSL) Final Design

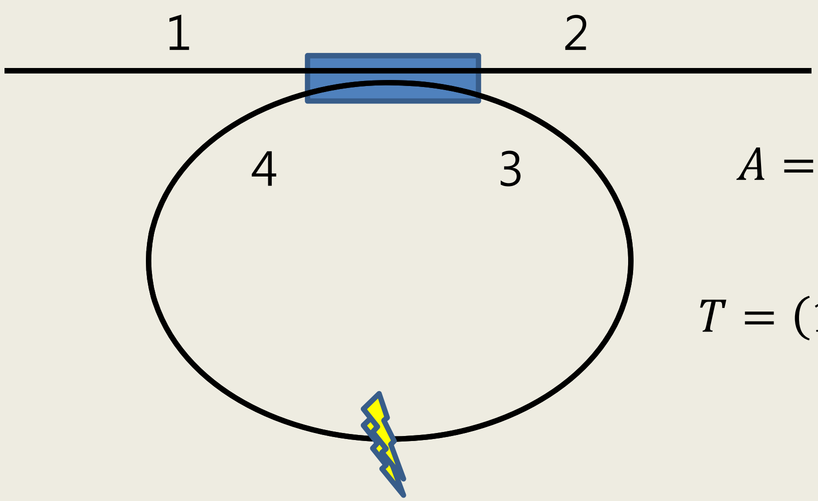
R. Abbott, P. King

iLIGO PSL includes;

1. LIGO 10 W laser, called 126 MOPA laser by Lightwave Electronics with power supply and recirculating water chiller
2. Frequency stabilization electronics
3. Intensity stabilization electronics
4. Various optics and optical component mounting hardware
5. Optical table and optical table enclosure

6. It does not include any optics for the IOO or electronics for modulation frequencies used outside the PSL system

Fiber Ring Cavity (FRC)



$$A = (1-\kappa)(1-r)(1-a)\,e^{-2\alpha L};\ \text{loss factor}$$

$$T = (1-r)\left(1 - \frac{\kappa\,(1-\kappa-A)}{(1-\kappa)\,(1+A-2A^{1/2}\mathrm{Cos}[\beta L])}\right)$$

$$f_{\mathrm{FSR}} = \frac{c}{n\,L},$$

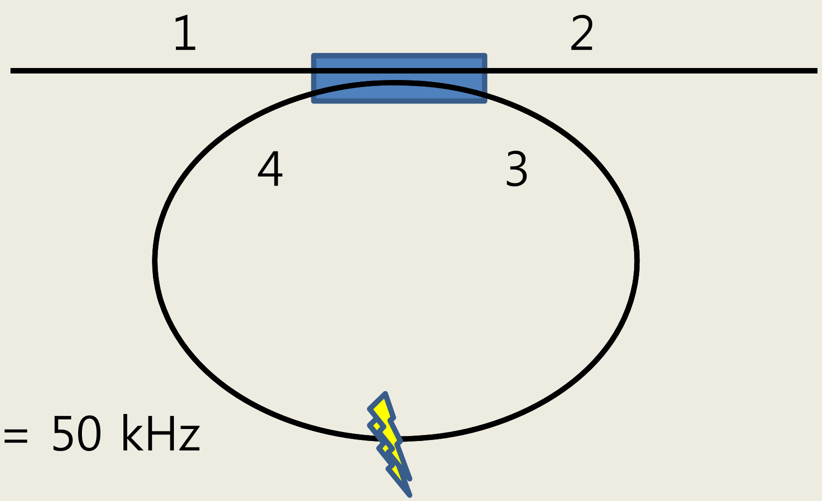
$$\Delta\nu = \frac{c\sqrt{\frac{\left(1-\sqrt{A}\right)^2}{\sqrt{A}}}}{L\,n\,\pi}$$

$$\mathcal{F} = \frac{\pi}{\sqrt{\frac{\left(1-\sqrt{A}\right)^2}{\sqrt{A}}}}$$

κ : Coupling Ratio
r : Insertion Loss
a : Splicing Loss
α : Fiber Loss
L : Cavity Length
β : Wave number

Ref. "All-single-mode fiber resonator", L.F. Stokes, et al., Opt. Lett. 7, 288 (1982).

FRC design parameter



FSR = 100 MHz
$\Delta\nu$ = 200 kHz

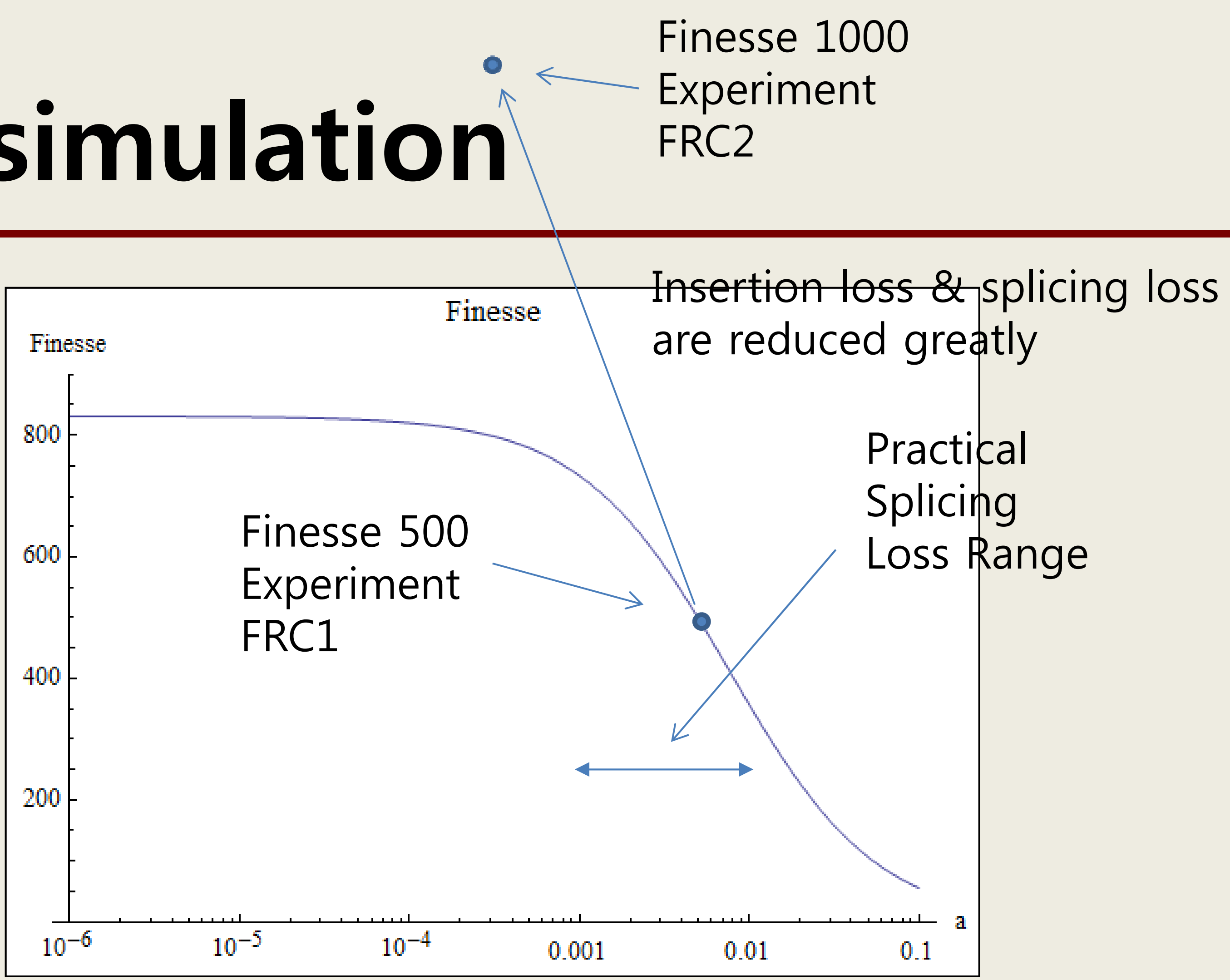
KAGRA interferometer FSR = 50 kHz

Design Parameter

L : 2 m	**κ : 0.002**
n : 1.46	**r : 0.003**
α : 1.5 dB/km	**FSR : 100 MHz**

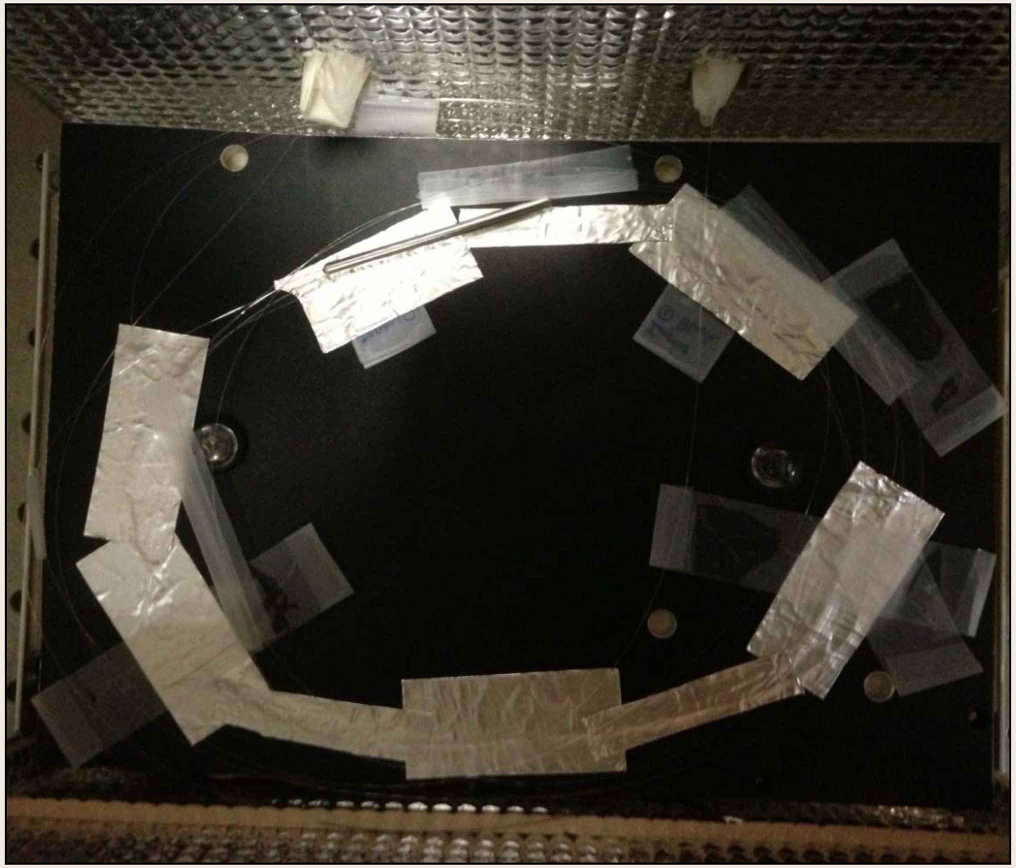
κ : Coupling Ratio
r : Insertion Loss
a : Splicing Loss
α : Fiber Loss
L : Cavity Length

FRC simulation

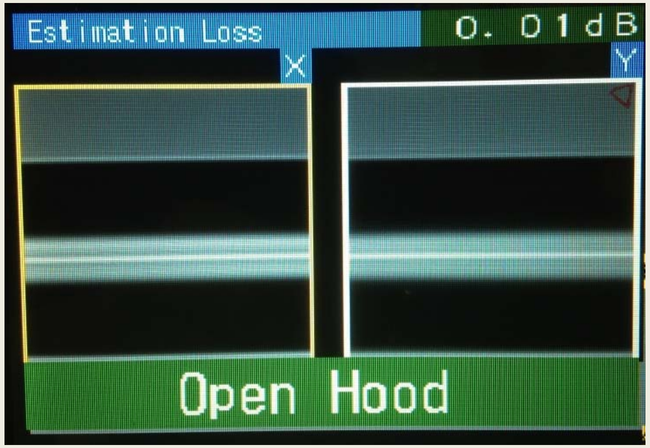


Splicing loss

FRC fabrication



Micro core
DCM Fusion Splicer Type-39



$r \cong 0.0023$

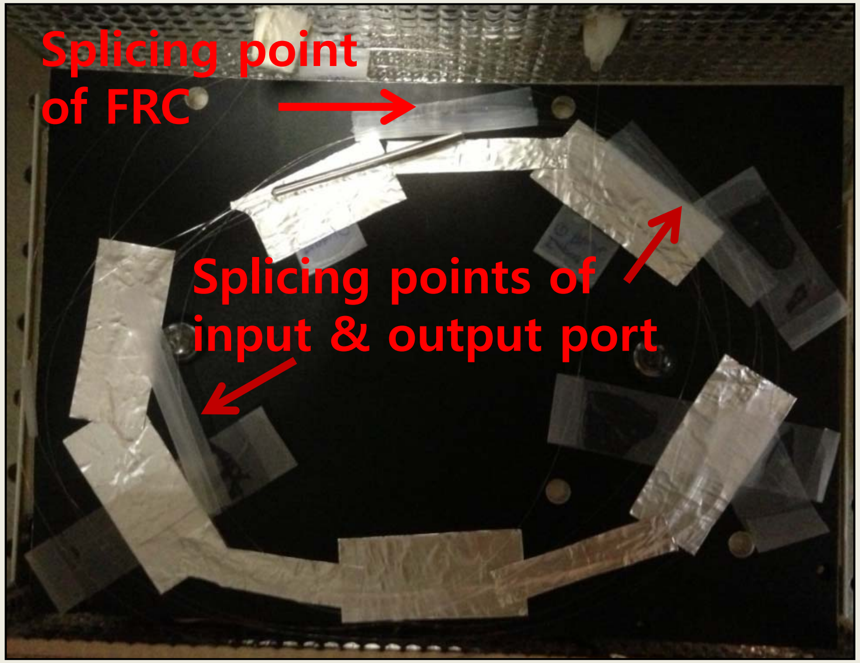
Finesse ≅ 500

OPNETI Single Mode Standard Coupler (99.8 % : 0.2 %)

Courtesy of fiber splicer
Prof. Kobayashi, ISSP

FRC fabrication

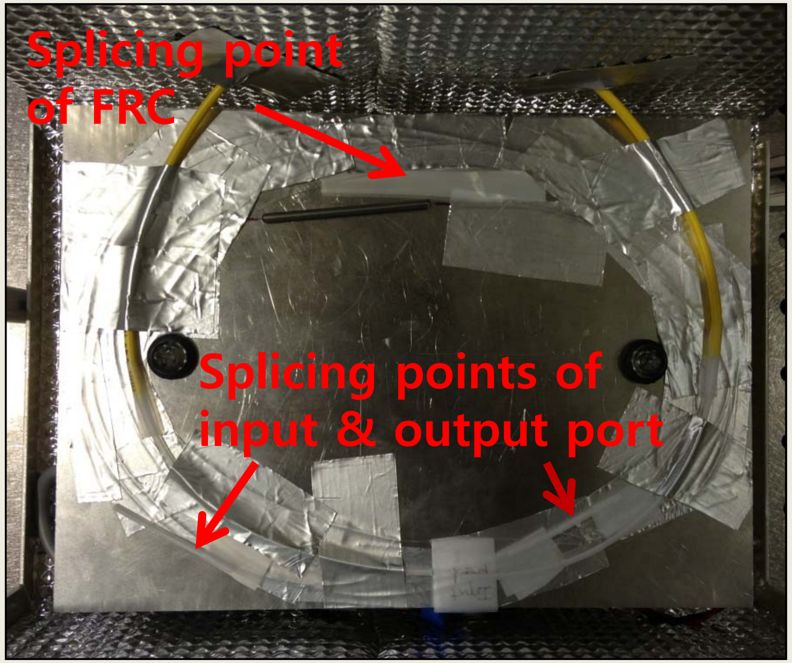
1st Fiber Ring Cavity



Splicing Loss : 0.01 dB, $a \cong 0.0023$

OPNETI SM Coupler (99.8 % : 0.2 %)

2nd Fiber Ring Cavity

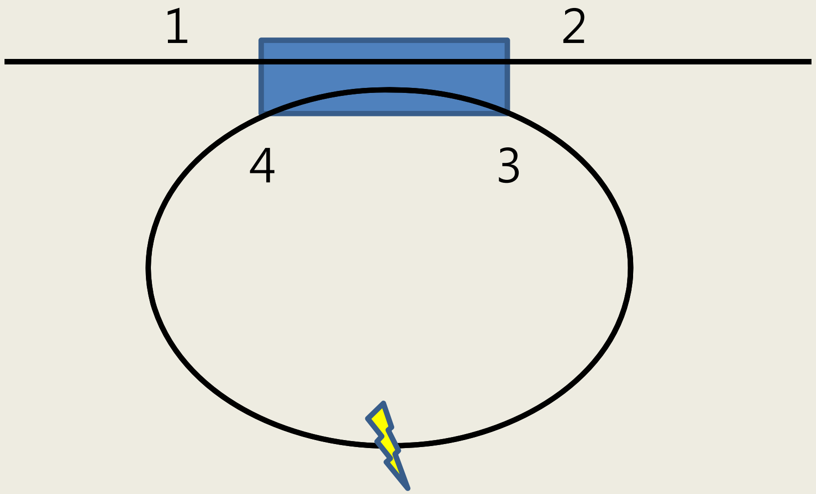


Splicing Loss : 0.00 dB, $a < 0.0012$

Gooch & Housego
SM Coupler (99.999 % : 0.001 %)

Fiber Splicer : Micro core - DCM Fusion Splicer Type-39

FRC Specifications



κ : Coupling Ratio	
r : Insertion Loss	
a : Splicing Loss	
α : Fiber Loss	
L : Cavity Length	

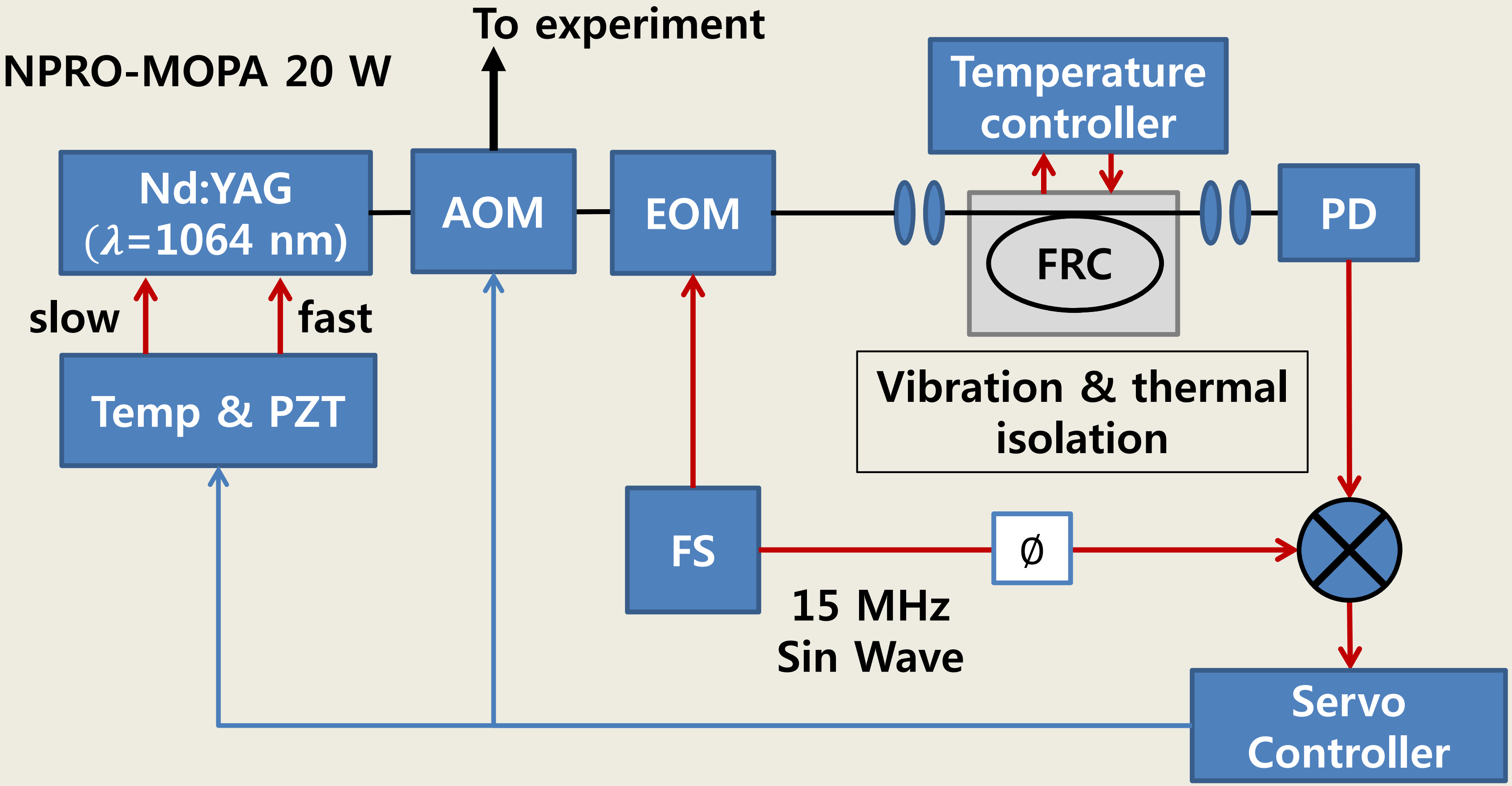
1st Fiber Ring Cavity

L : 2 m	κ : 0.002
n : 1.46	r : 0.003
α : 1.5 dB/km	FSR : 100 MHz

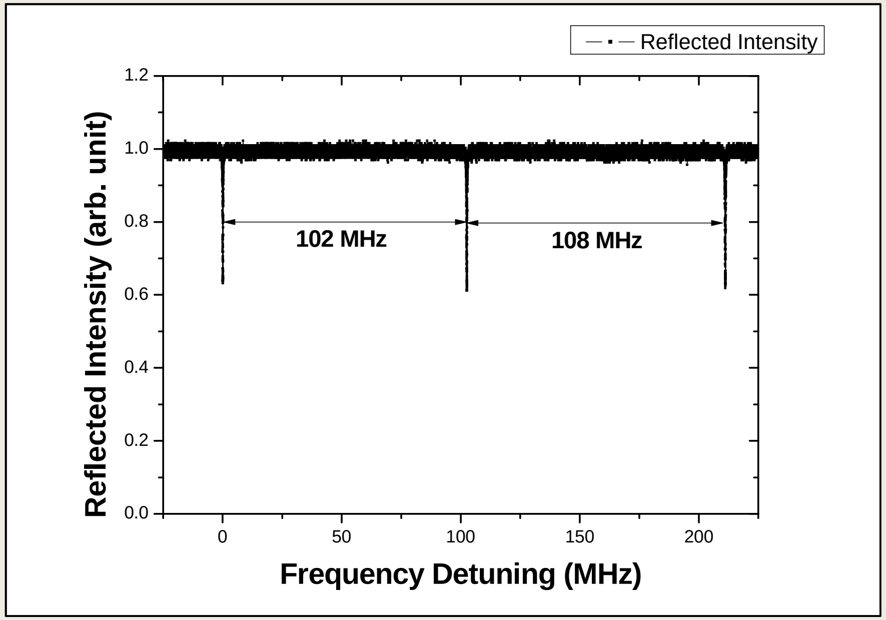
2nd Fiber Ring Cavity

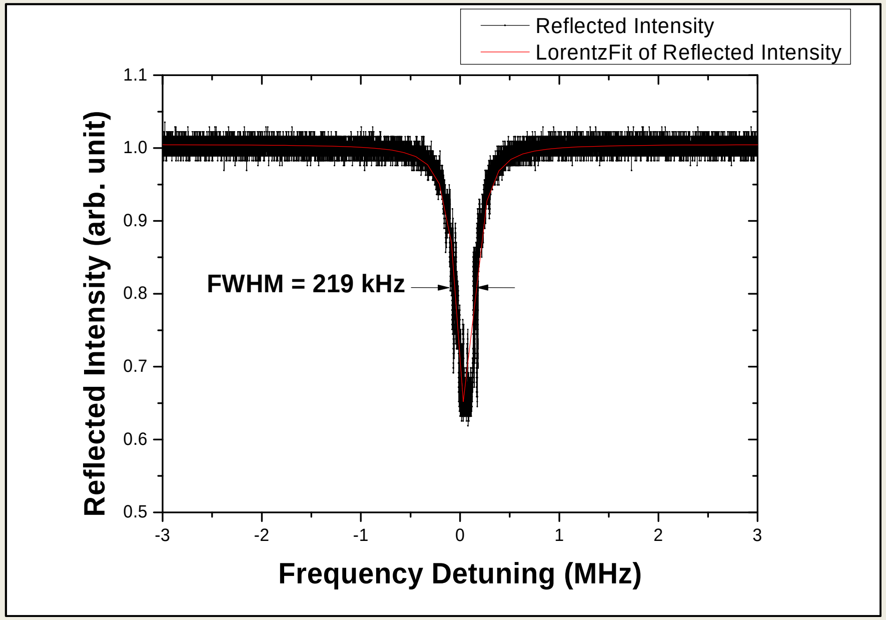
L : 2 m	κ : 0.00001
n : 1.46	r : -
α : 1.5 dB/km	FSR : 100 MHz

PDH Frequency Stabilization of Nd:YAG NPRO MOPA for iKAGRA



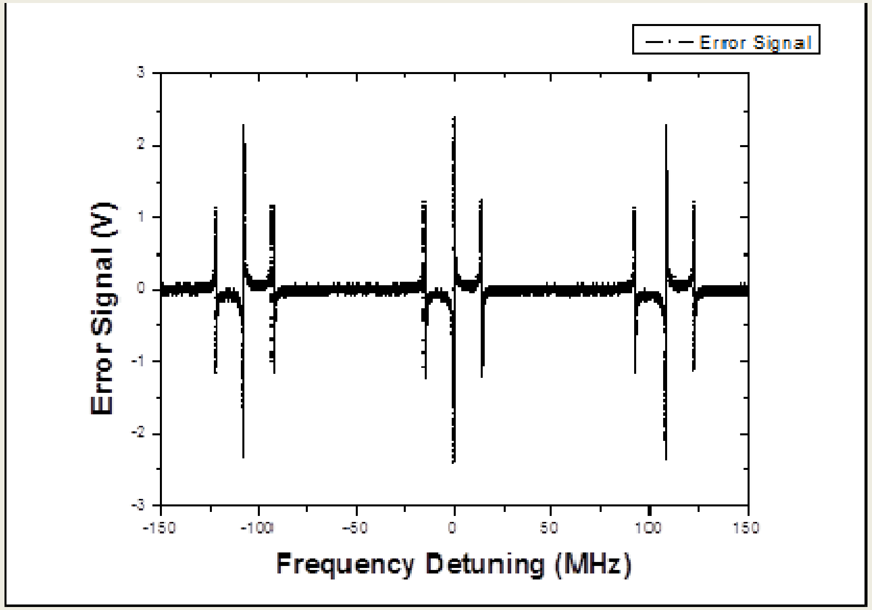
Finesse measurement

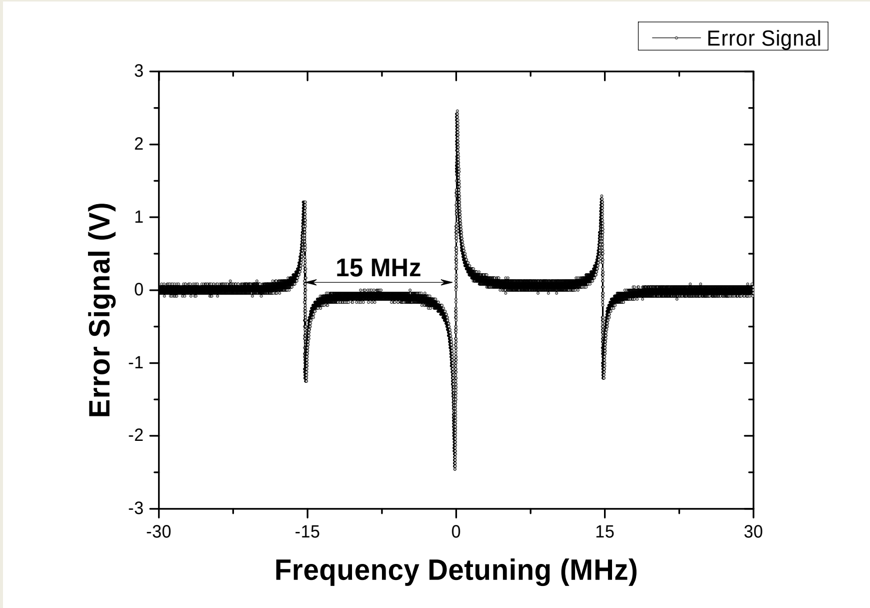




Finesse ≅ 500

PDH error signal

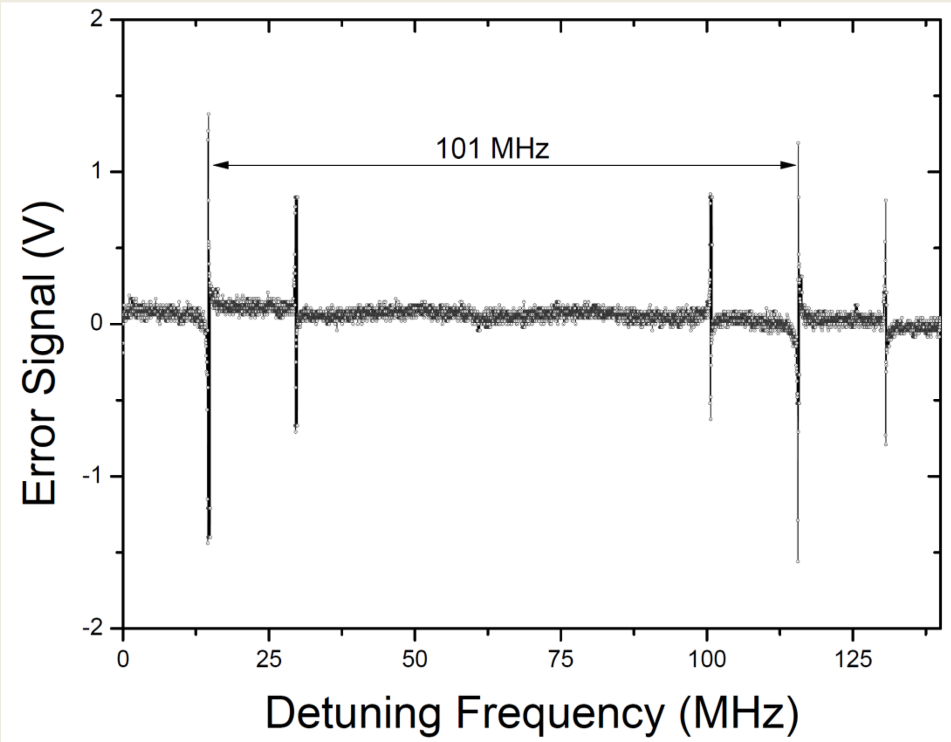


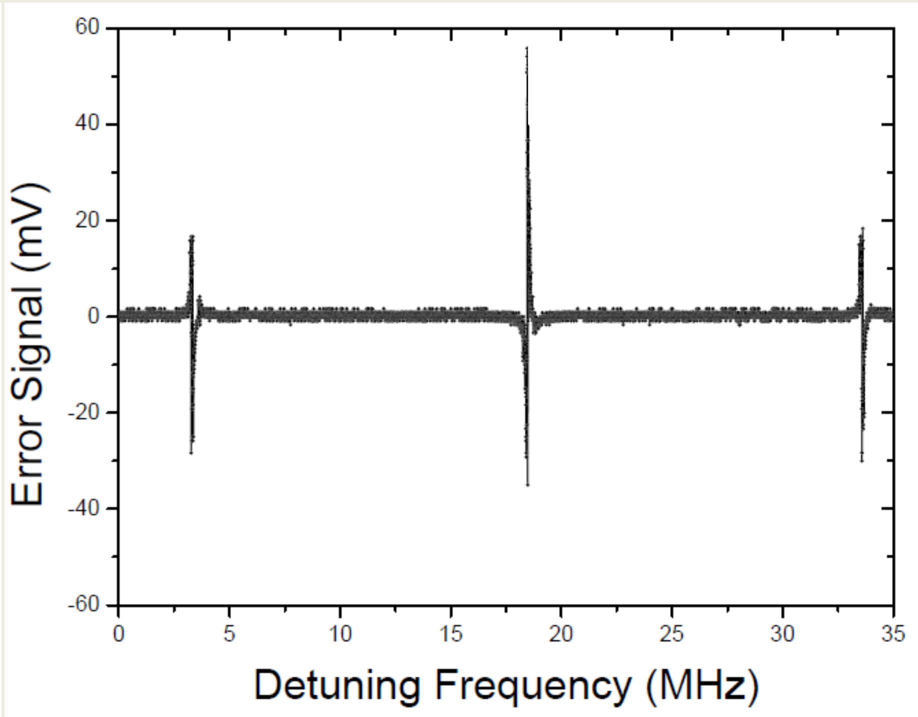


Thermal frequency scanning; nonlinear

f_{EOM} = 15 MHz

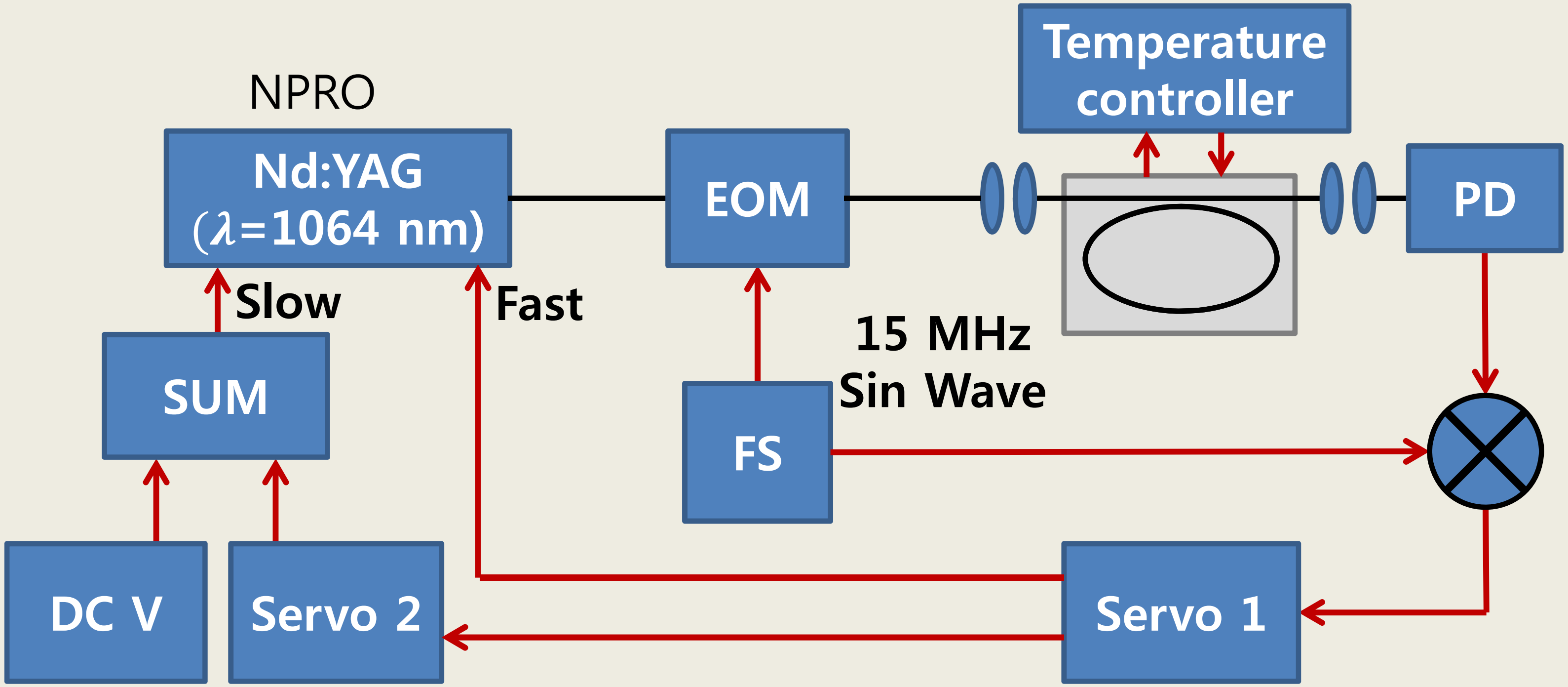
Linewidth < 100 kHz



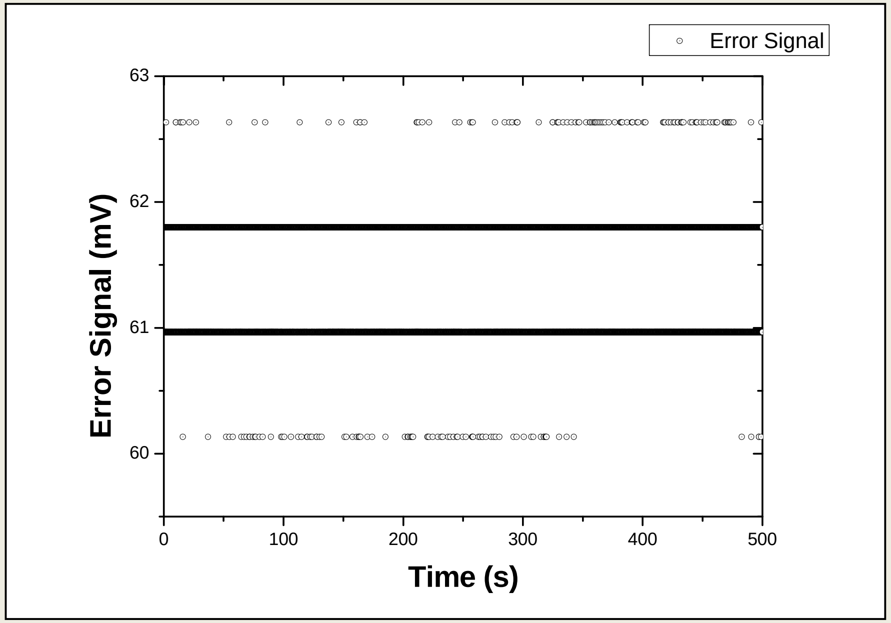


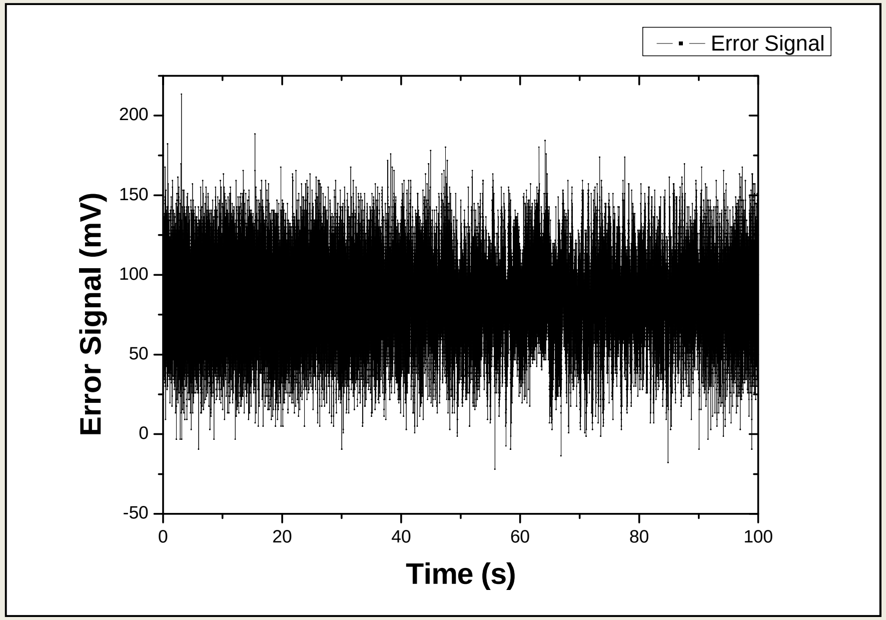
Finesse ≅ 1000

Frequency stabilization of NPRO



Stabilized in-loop error signal

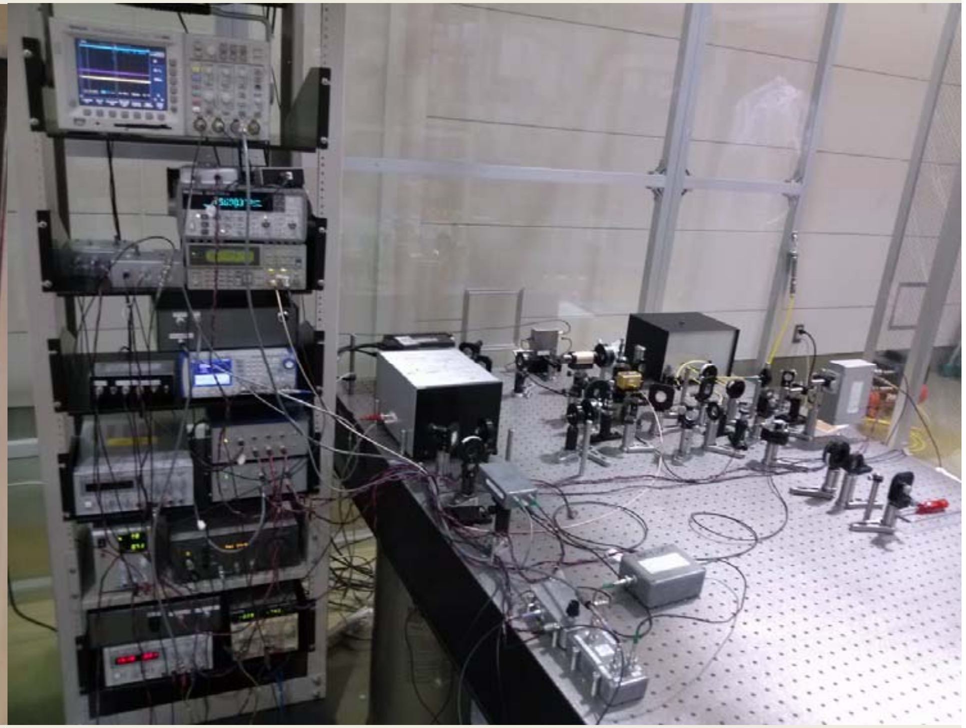




160 Hz with 1 Hz LPF

5.4 kHz without LPF


Tek Stop
Ch4 Coupling & Impedance
DC
AC
GND
Ω
1M
50
Ch2 5.00mV
M 1.00 s
Pattern
Ch3↓10.0mV
Ch4 100mV
Coupling AC
Invert Off
Bandwidth Full
Fine Scale 100mV /div
Position 340mdiv
Offset 59.60mV
Probe Setup 1 X



FRC fabrication: Final design for iKAGRA

3rd Fiber Ring Cavity

Splicing Loss : 0.01 dB, $\alpha \cong 0.0023$

Gooch & Housego SM Coupler (99.9 % : 0.1 %)

Reducing line-width 3times

Length: 5.8 m

f_{FSR} = 35 MHz

$\Delta\nu$ = 80 kHz

Finesse = 540

Contrast: 27 %

Results

- We have fabricated two fiber ring cavities with $\kappa = 10^{-3}$ and 10^{-5} with measured free spectral range of 100 MHz and finesse of 500 and 1000, respectively.
- Frequency of a NPRO Nd:YAG laser at 1064 nm is stabilized by PDH method to FRC1
- Will compare long-term frequency stability of two systems by using an AOM
- Hopefully, these FRCs can be used for laser frequency stabilization of iKAGRA lasers, e.g., master NPRO, etc.

Line-width measurement of FRC-stabilized NPRO: Plan