Feedback-free optical cavity with self-resonating mechanism for laser-Compton scattering sources

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LCWS2015 @ the Fairmont Chateau Whistler Hotel, Whistler B.C. Canada

November 2-6 2015

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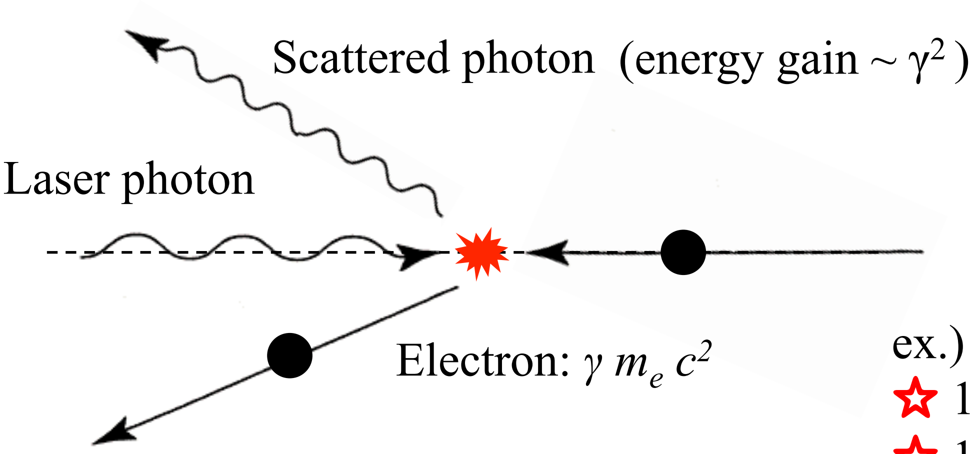
KEK



ex.)
☆ 10 MeV electron → 10 keV X-ray
☆ 1 GeV electron → 10 MeV gamma-ray

Laser-Compton scattering sources

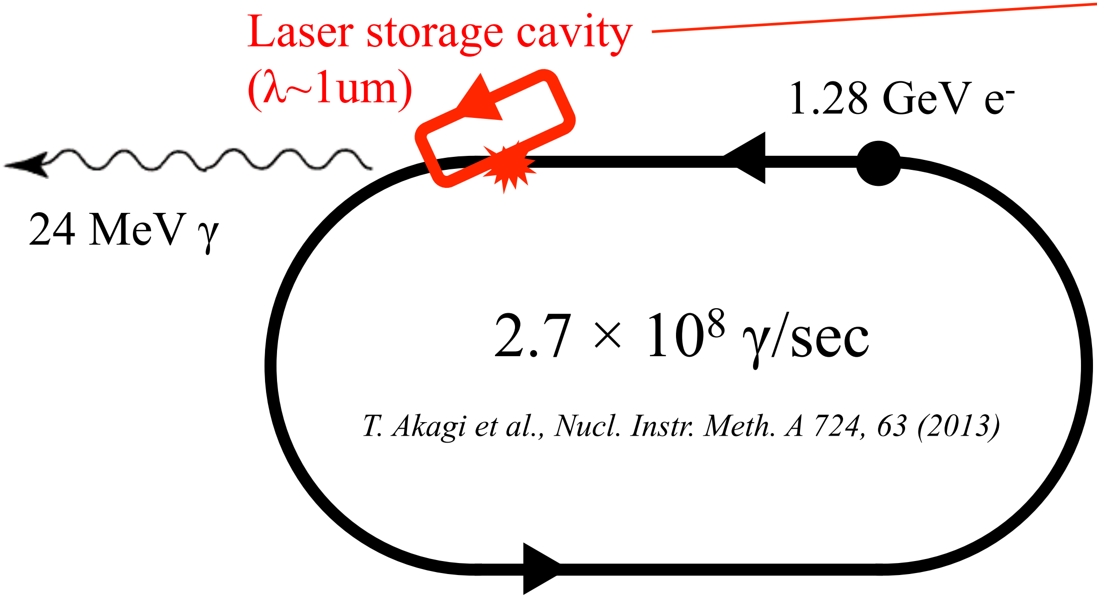
- Photon sources by the inverse-Compton scattering of laser photons from relativistic electrons

Applications

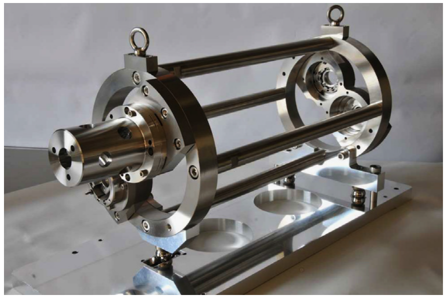
- Compact X-ray sources for a wide field of material science, industrial, medical applications etc.
- A gamma-ray driven polarized positron source for the ILC

ILC Technical Design Report: Volume 3, Part I, p.p. 137

Gamma-ray generation at KEK-ATF (2013)



Laser storage cavity



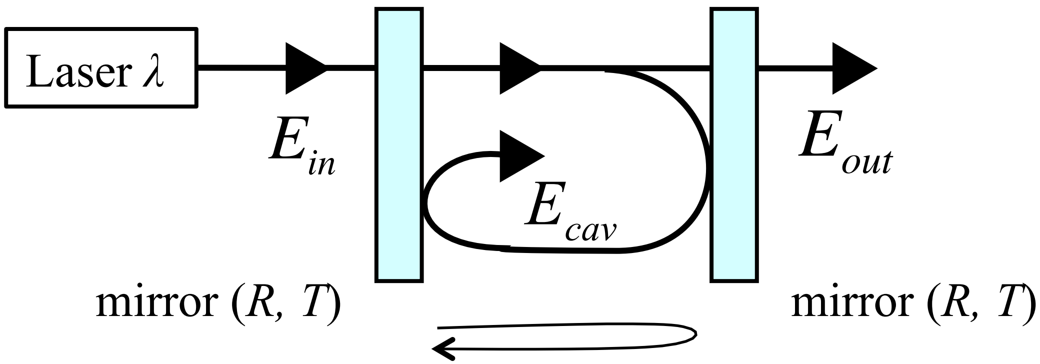
Input laser power	2.2 W avg.
Power enhancement	1,200
↓	
Lasear storage	2.6 kW avg.

Need more gamma-rays (2 to 3 orders of magnitudes)

→ Need more laser power storage (~ 1 MW)

→ Need more power enhancement of the cavity! (10k to 100k)

Fabry-Perot cavity (2-mirror cavity)



Intra-cavity field

$$E_{cav} = \frac{1}{1 - R\exp\left(-i2\pi\frac{L}{\lambda}\right)} E_{in}$$

Phase factor of the resonance condition

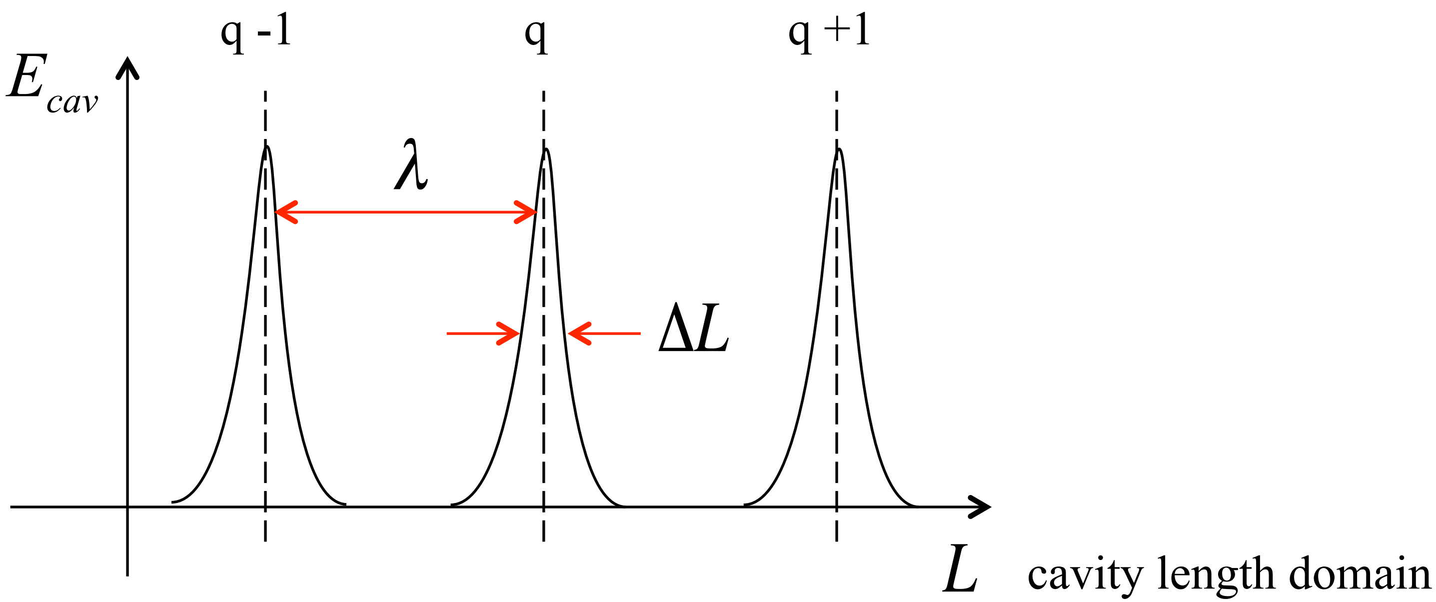
Transmitted field

$$E_{out} = T \times E_{cav}$$

☆ Resonance condition $L = \lambda \times q$

(L: round-trip path length, λ: wavelength of light, q: integer, R: reflectance, T: transmittance)

Optical resonant cavity



- Mode separation equals λ
- Resonance peaks have the "resonance width" written as ΔL (FWHM)
- "Finesse" is defined as the ratio of λ and ΔL,

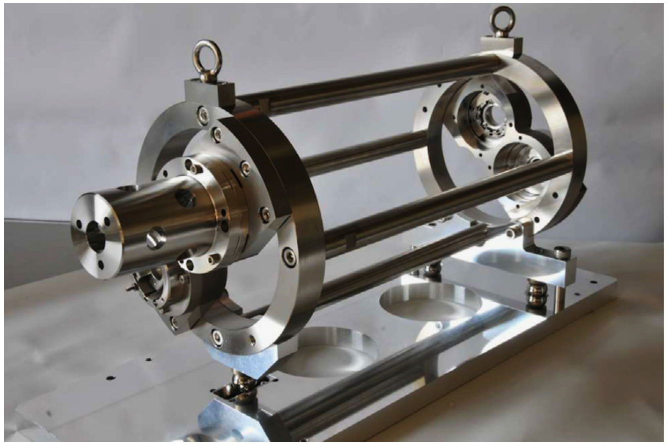
$$F = \frac{\lambda}{\Delta L}$$

- The finesse is almost same as the quality factor, Q-value

☆ Finesse $\propto$ power enhancement factor!

An example of the cavity: at KEK-ATF

- Wavelength $\lambda = 1064$ nm
- Finesse $F = 4{,}040$
- Resonance width $\Delta L = 260$ pm
- Enhancement factor 1,200



Ring cavity at KEK-ATF

T. Akagi et al., Nucl. Instr. Meth. A 724, 63 (2013)

Achieved laser power storage

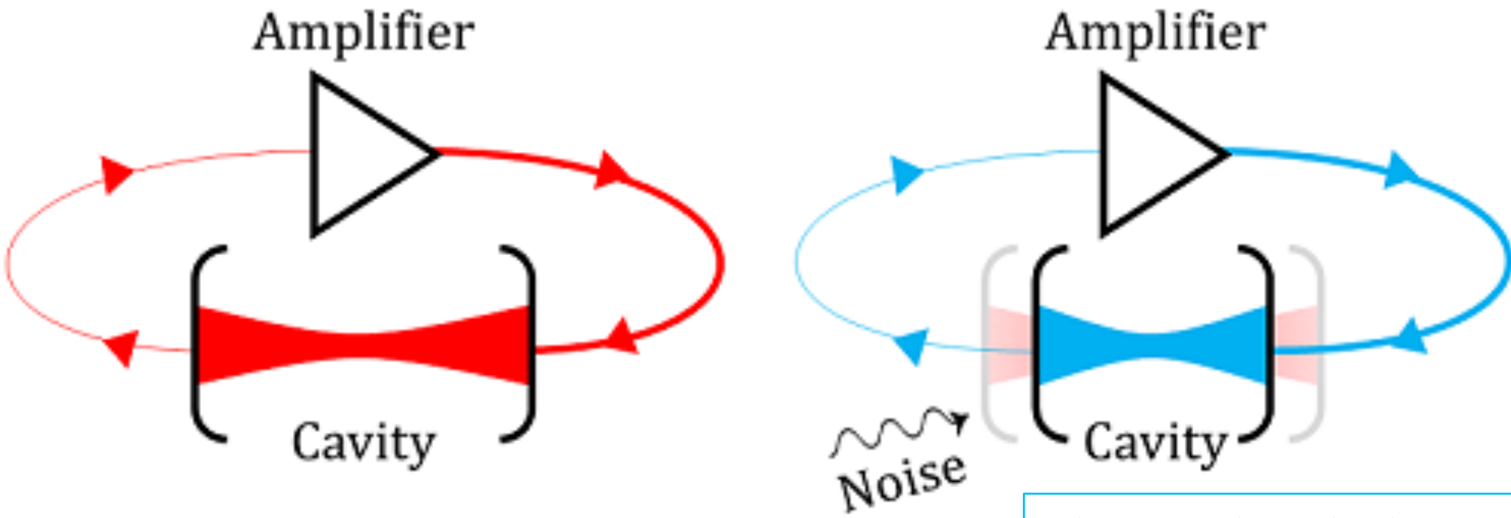
- Input laser power 2.2 W avg.
- laser power storage 2.6 kW avg.
- Power fluctuation 37 W

  → This fluctuation came from accuracy of the feedback system

  → It corresponds to deviation of the cavity length of 16 pm

- The enhancement increases ten times → ΔL of 26 pm ≈ feedback accuracy of 16 pm
- Precise feedback control will be a major technical difficulty for high finesse cavity

New idea: self-resonating mechanism



The wavelength always follows the resonant condition of the cavity

Principle of the self-resonating mechanism

1. An optical amplifier emits seed (noise) light
2. A part of seed light, which is satisfied the resonance condition, transmits the cavity
3. That light doesn't feel the optical loss → reaches the laser oscillation

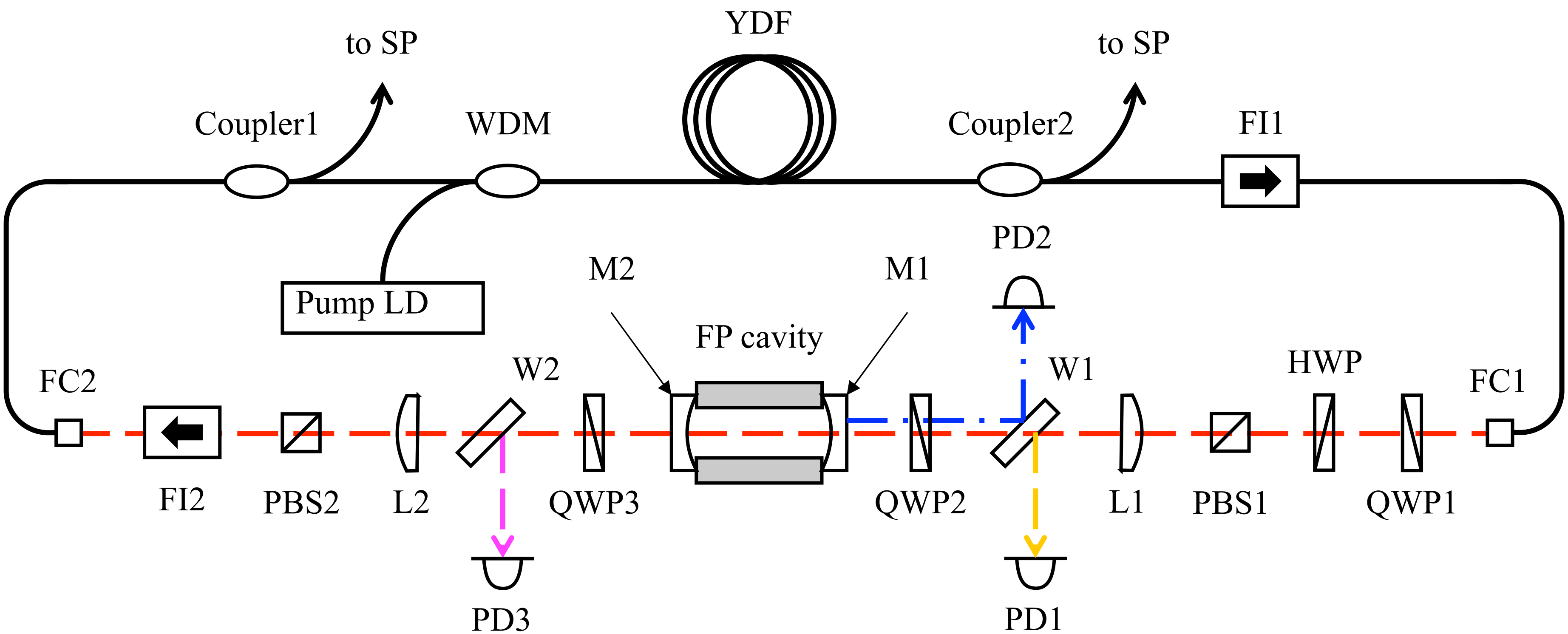
☆ Laser oscillation condition: (gain – losses) > 1

☆ Laser oscillation ⇔ laser storage

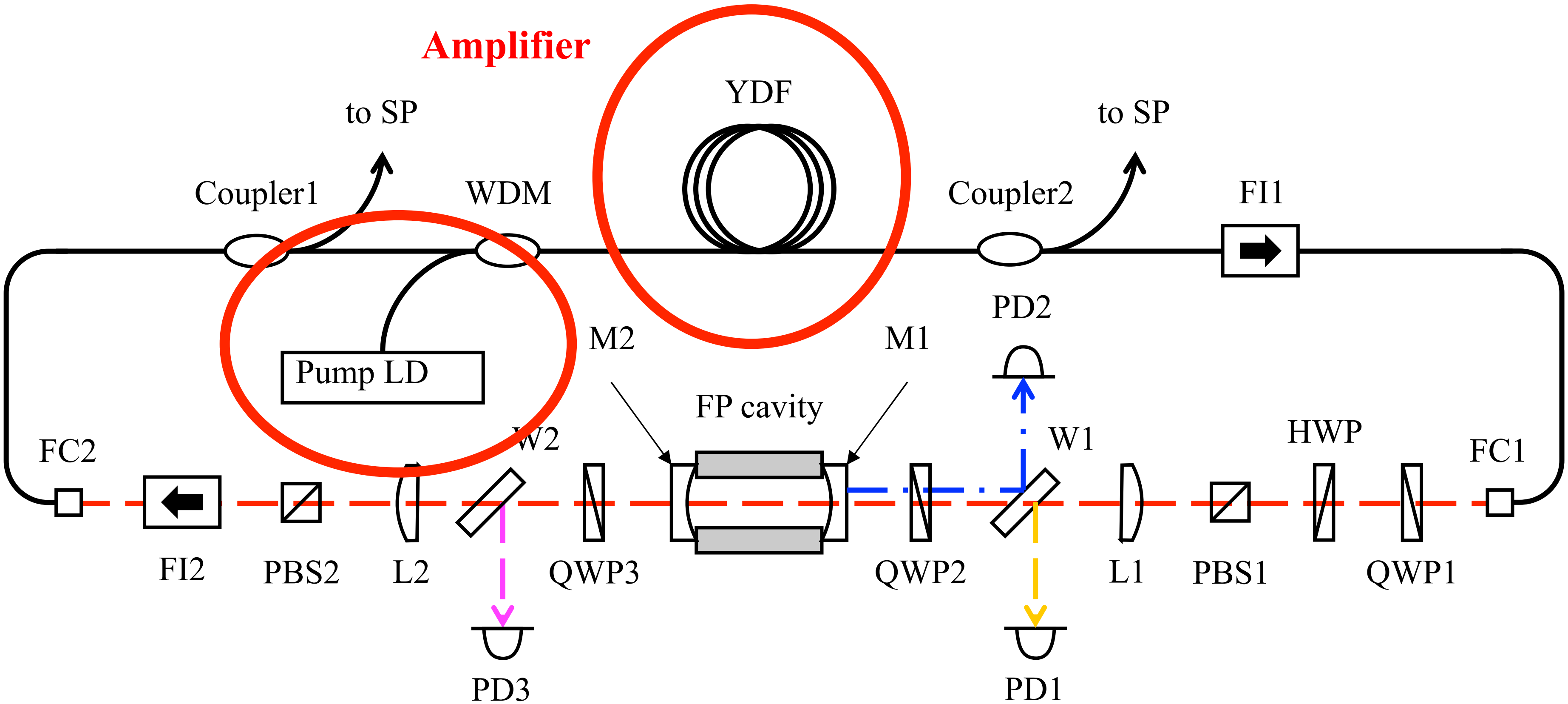
The laser oscillation continues without the feedback system to maintain the cavity length!

Y. Honda, et al., Proc. 7th Annual Meeting of PASJ, 1102 (2010)

Setup of the feedback-free cavity

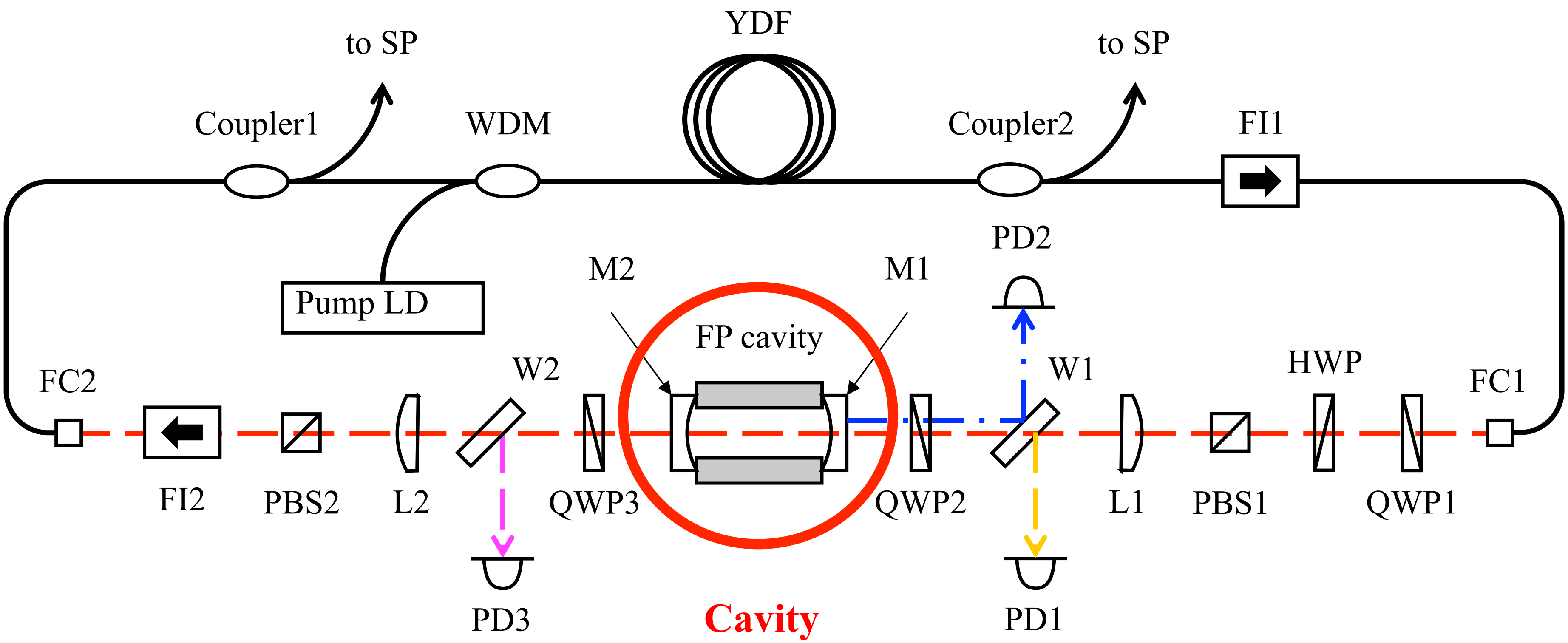


Setup of the feedback-free cavity



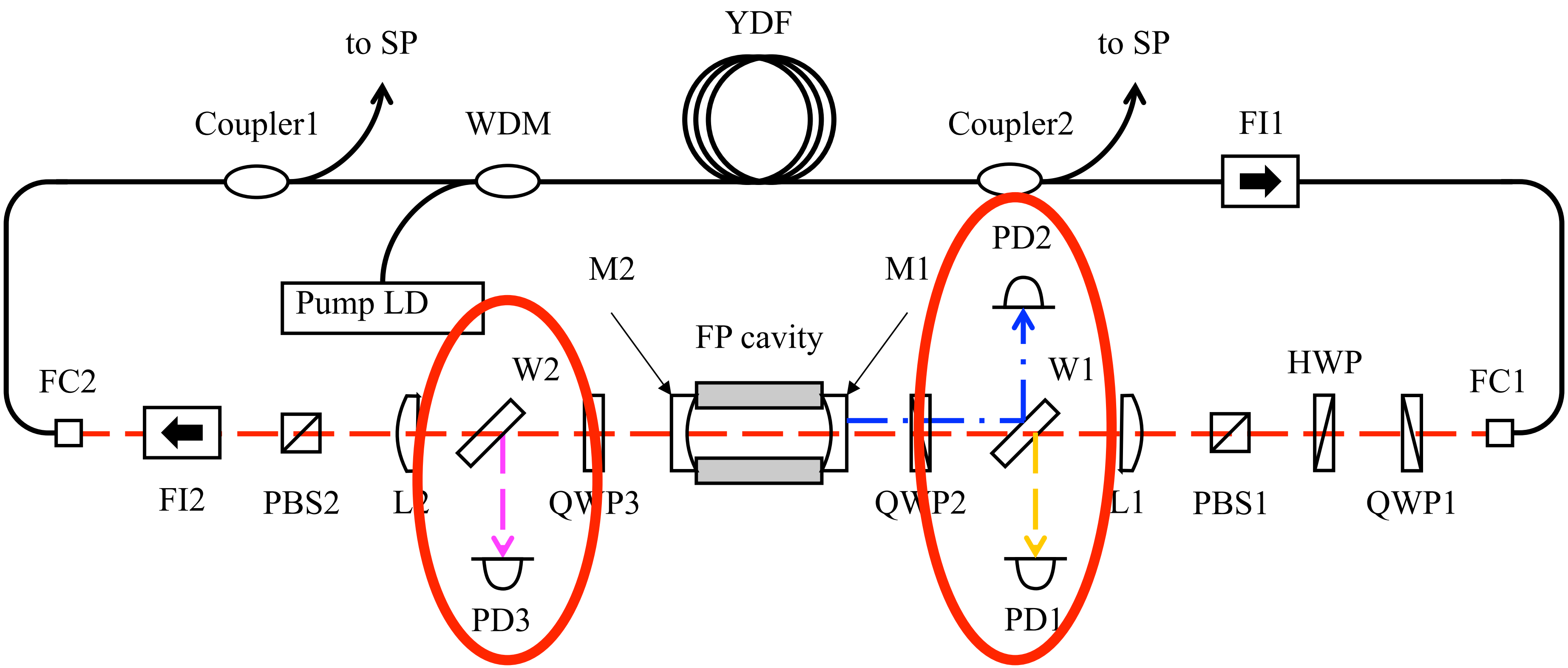
- The optical amplifier consists of a laser medium, the Ytterbium-doped fiber (YDF), and a pumping light sources, the laser-diode (Pump LD)

Setup of the feedback-free cavity



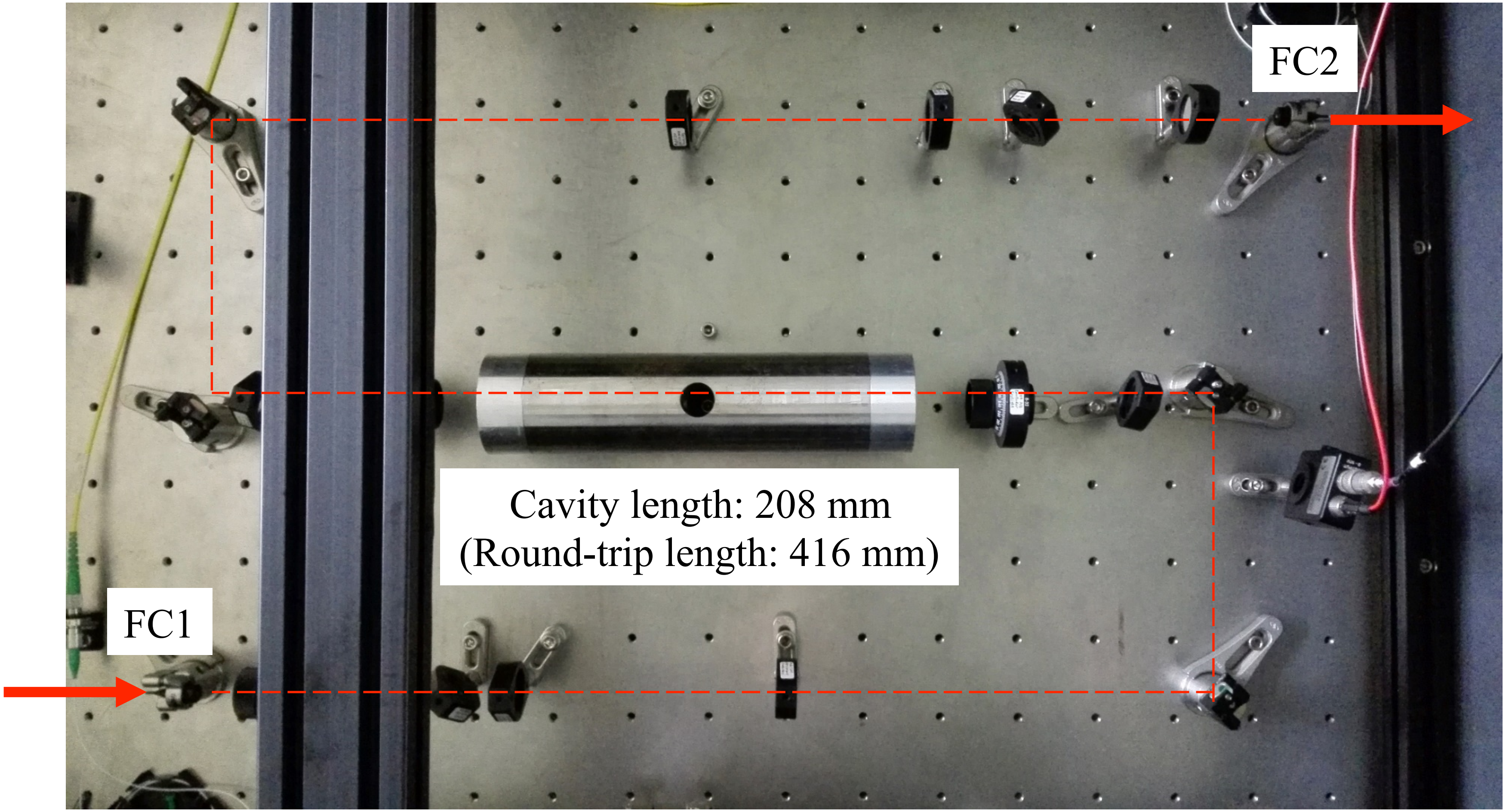
- The optical cavity consists of two concave mirrors with R > 99.999%

Setup of the feedback-free cavity



- The intra-loop laser power around the cavity is monitored by wedge plates (W1, 2) and photo-diode detectors (PD1, 2, 3)

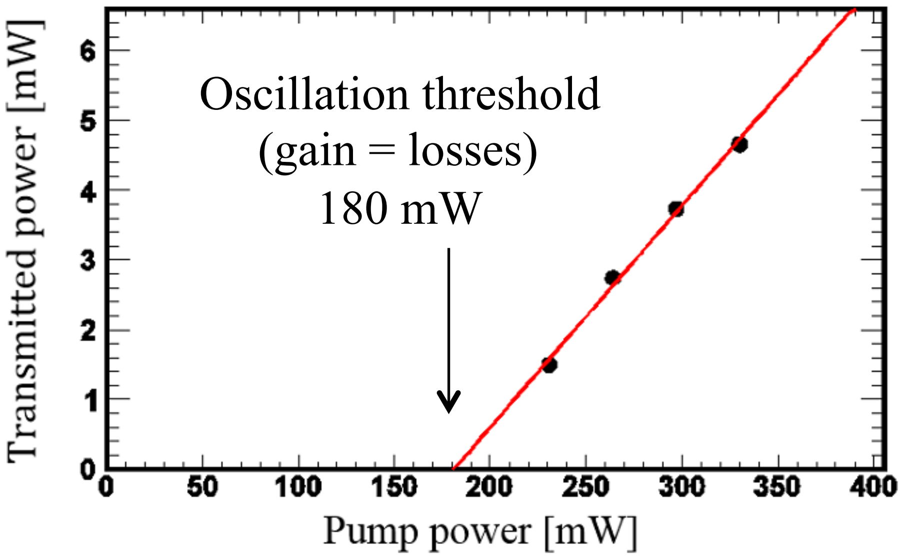
Setup of the feedback-free cavity



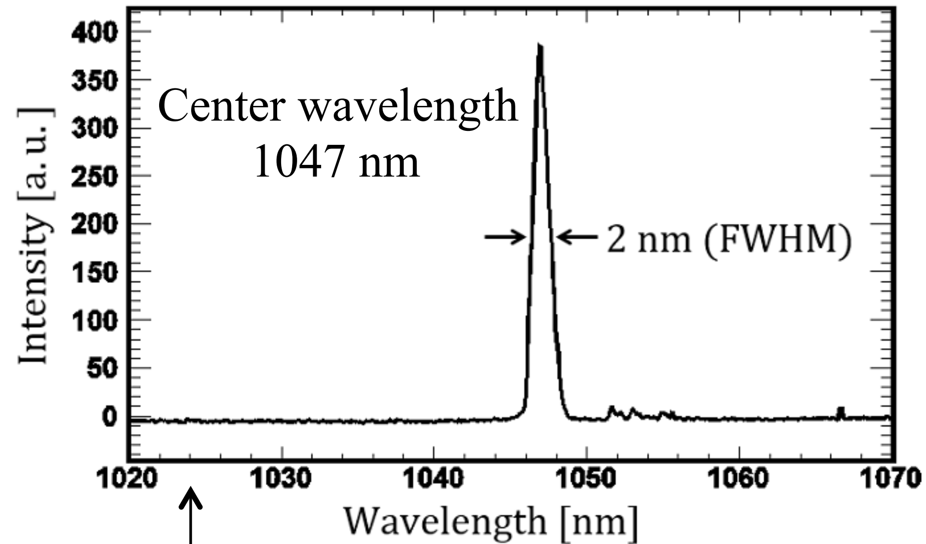
- Mirrors are mounted on a super-invar alloy tube by aluminum holders
- All component are in the air with the room temperature

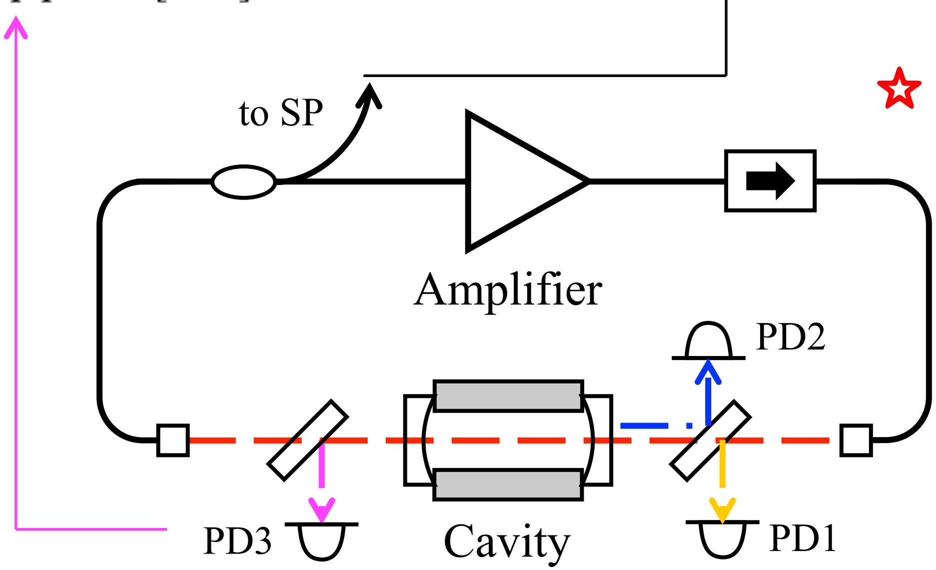
Laser oscillation and laser power storage

Laser power vs Pump power



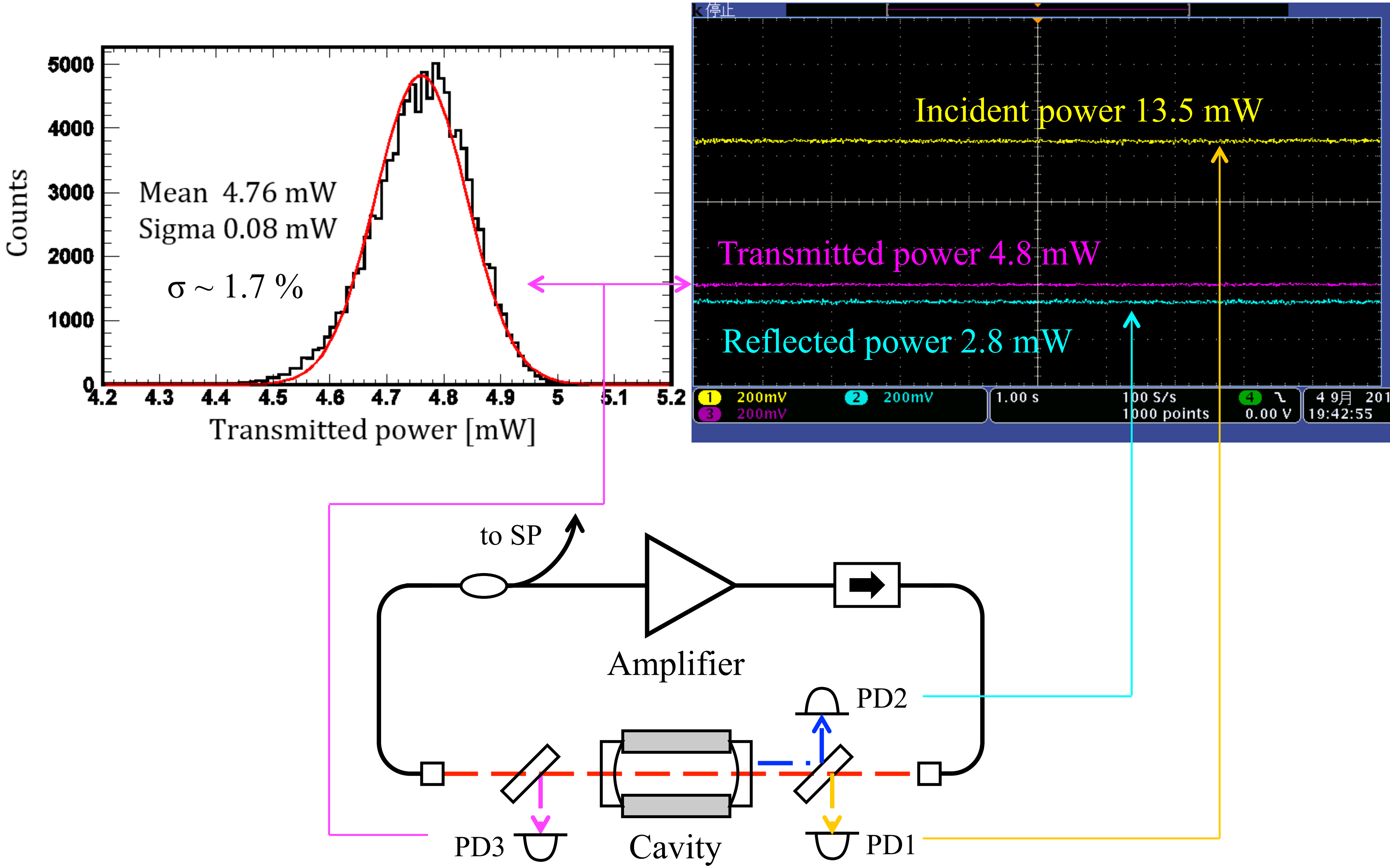
Laser spectrum

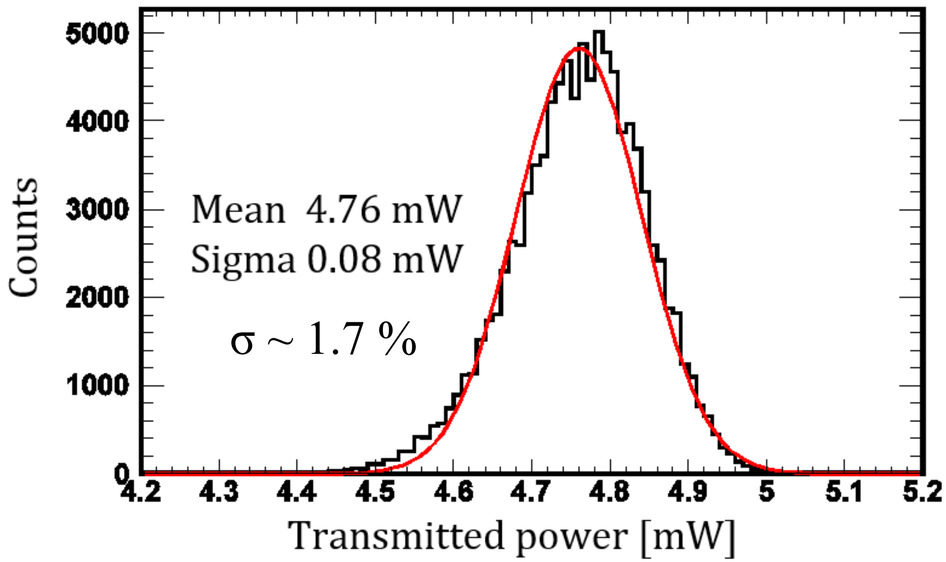




☆ Multi-mode oscillation

Laser oscillation and laser power storage



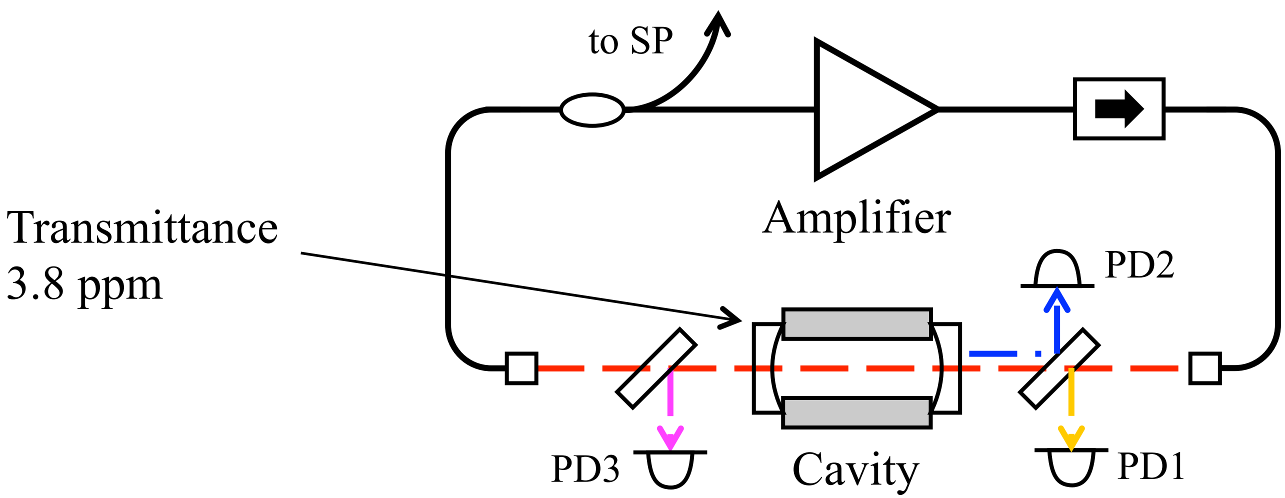


- Stored laser power = Transmitted power / Transmittance

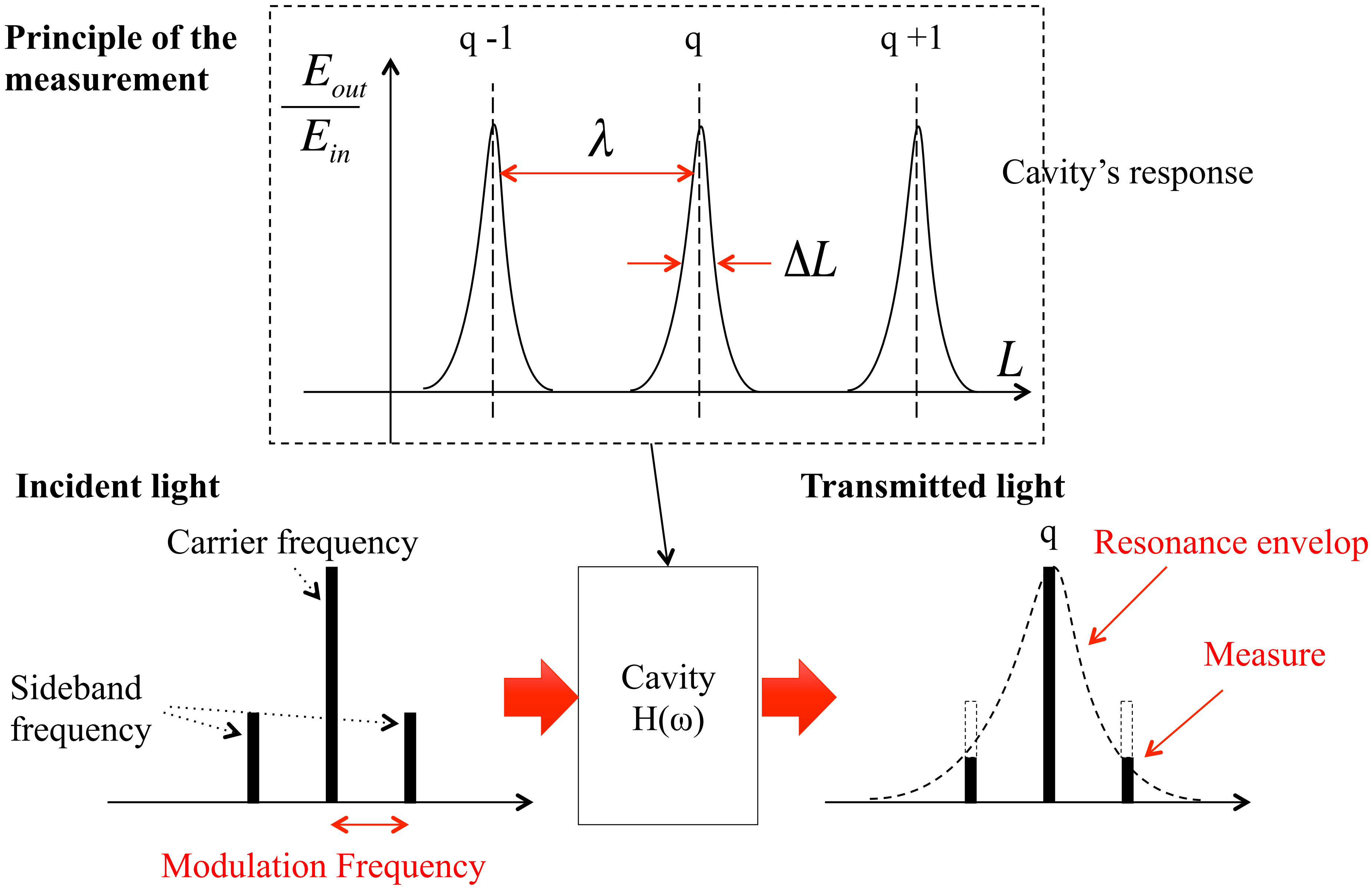
☆ Laser storage → 2.5 kW

- Enhancement factor = Stored power / Incident power

☆ Power enhancement → 187,000



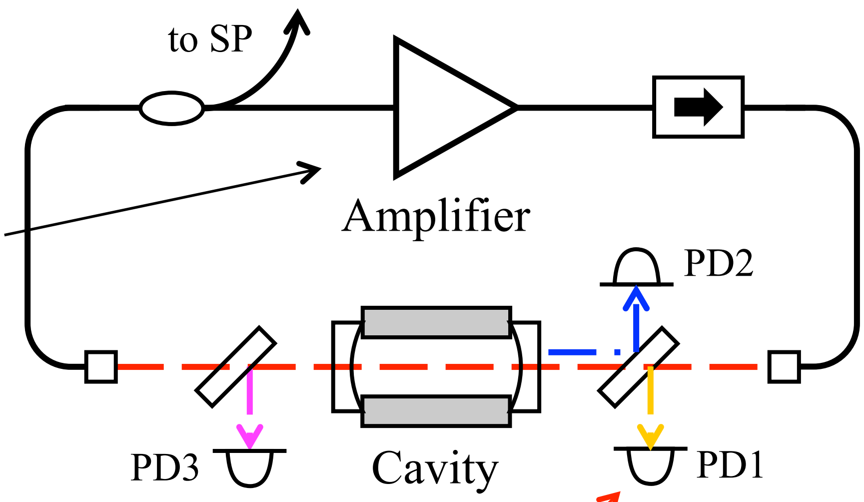
Finesse measurement by a frequency response function of the cavity



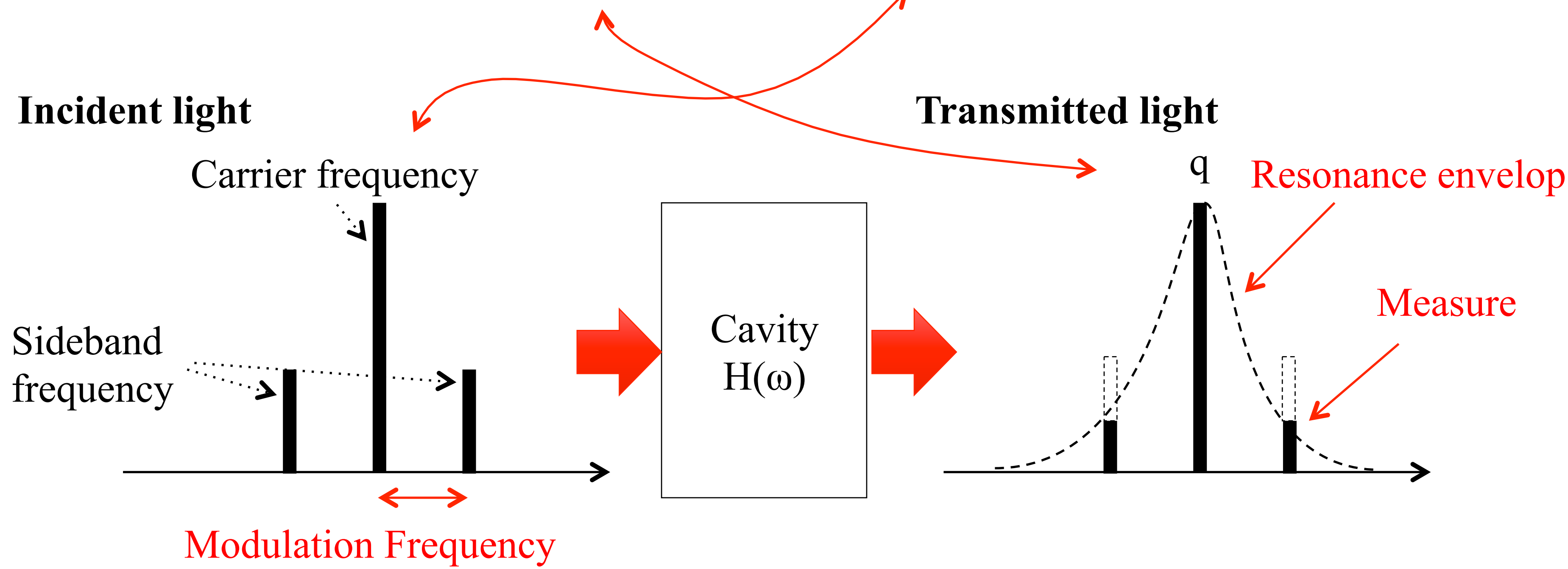
See, e.g., N. Uehara, K. Ueda, Appl. Phys. B 61, 9 (1995)

Finesse measurement by a frequency response function of the cavity

- Modulated the laser frequency with the depth of 1%

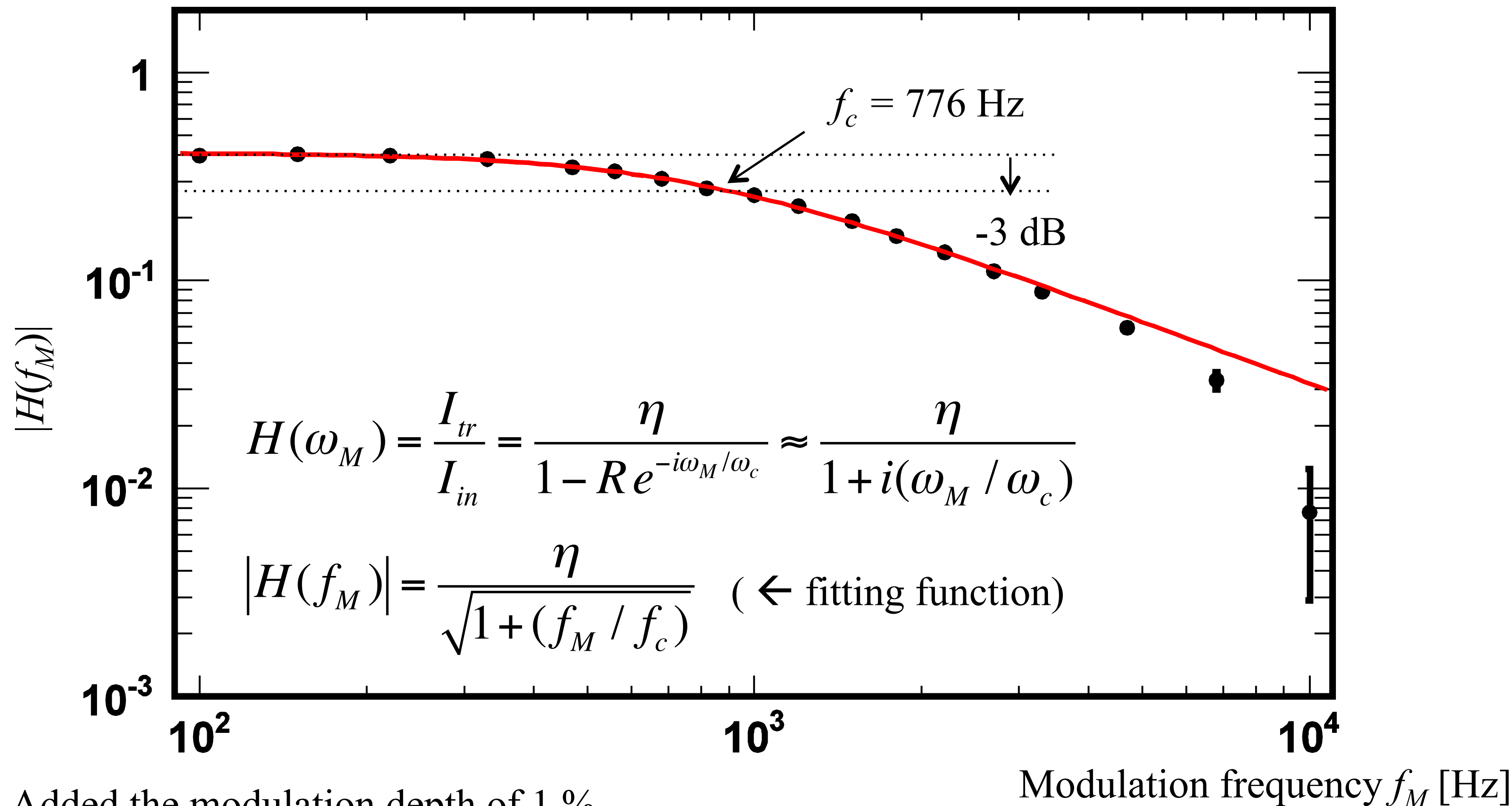


- Measured the response of the intensity of the sideband light



See, e.g., N. Uehara, K. Ueda, Appl. Phys. B 61, 9 (1995)

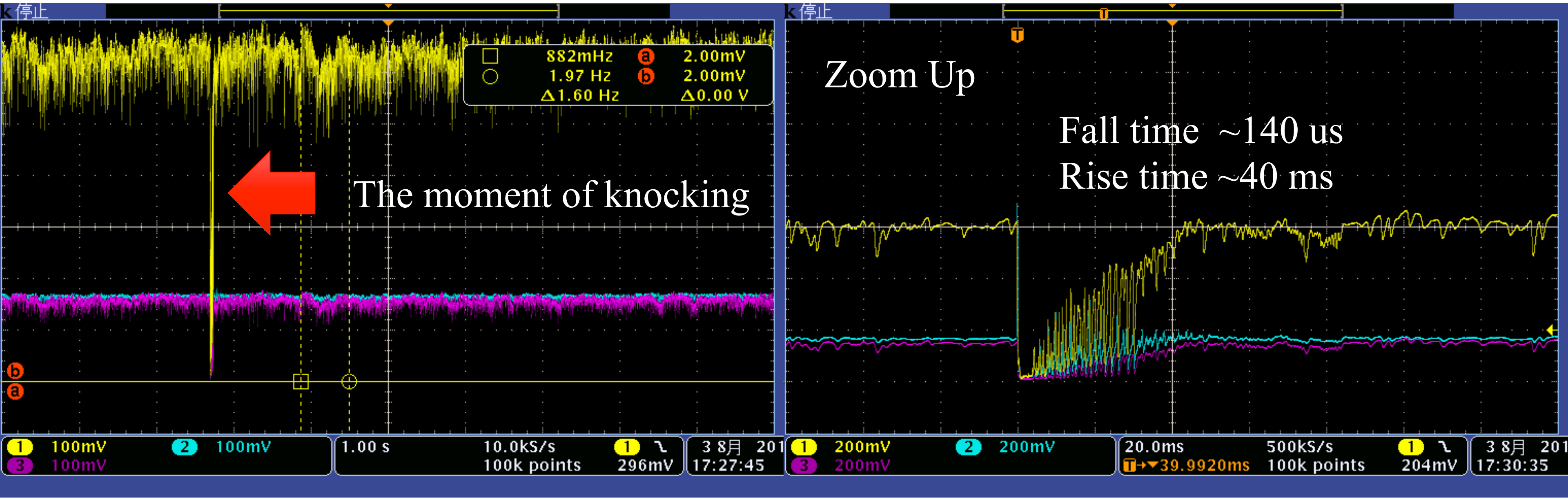
Measured frequency response function of the sideband light



- Added the modulation depth of 1 %
- Measured response function has a low-pass filter shape
- The resonance width was 1.55 kHz which was twice of the cut-off frequency, f_c=776 Hz

☆ Resonance width = 2.3 pm ☆ Finesse = 465,000

Stability of the oscillation



Watched the stability of the resonance condition

- If we added some mechanical noise to the optical table, the laser power and spectrum were not change; the laser oscillation continued
- The oscillation stopped when the cavity was knocked, however, it recovered soon
    - ➢ The fall time of ~140 us → decay time constant of the cavity
    - ➢ The rise time of ~40 ms → maybe, dumping time of the super-invar alloy tube

☆ Very robust system!

Summary

- We are working on a development of the optical resonant cavity for laser-Compton scattering sources
- Developed a new laser storage system which doesn't need a feedback system to maintain the resonance condition
- Succeeded the stable and continuous laser storage in the high finesse cavity with the finesse of 465,000 and the resonance width of 2.3 pm
- Achieved the power enhancement factor of 187,000
- R/D for the high peak-power storage (mode-lock pulse oscillation) → on going!

backups

Introduction

The point of issue in the development

- Increase the brightness of X/gamma-rays
- Need 2 to 3 orders

Requirement

☆ Electron beam → Develop a high current and low emittance accelerator

☆ Laser light → High leaser power and small spot size at the IP

- ➢ Use an optical resonant cavity
- ➢ Store laser light in the cavity
- ➢ Enhance the laser power
- ➢ Forces the laser light about 10 micro meters

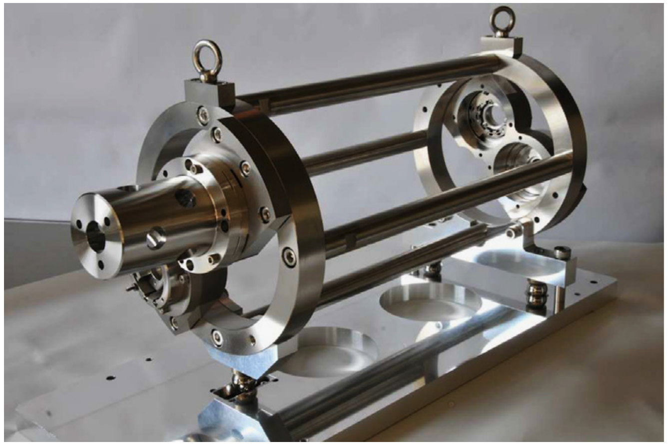
- We are developing the optical cavity
- The target storage power is about 1 MW in average

  e.g.) 100 W incident laser 10,000 enhancement cavity = 1 MW storage

Optical Resonant Cavity

An example of the cavity: at KEK-ATF

- Wavelength $\lambda = 1064$ nm
- Input laser power 2.2 W avg.
- Round-trip path length $L = 1.68$ m
- Finesse $F = 4{,}040$
- Linewidth of the cavity $\Delta L = 260$ pm
- Enhancement factor 1,200



Ring cavity at KEK-ATF

T. Akagi et al., Nucl. Instr. Meth. A 724, 63 (2013)

Achieved storage power

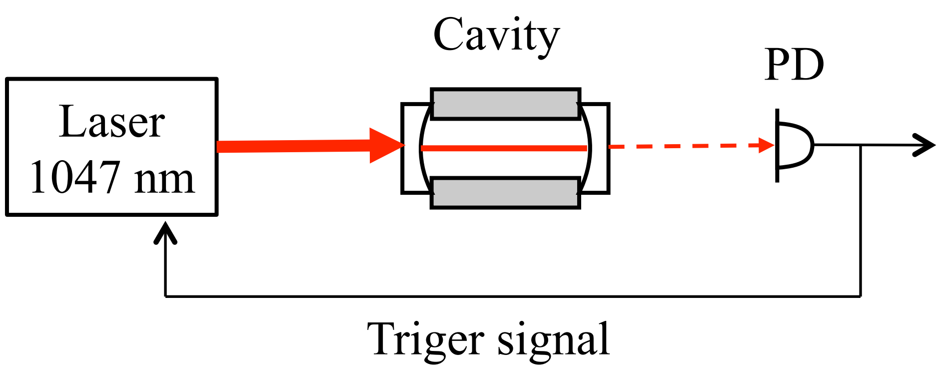
- Power storage 2.6 kW avg.
- Power fluctuation 37 W

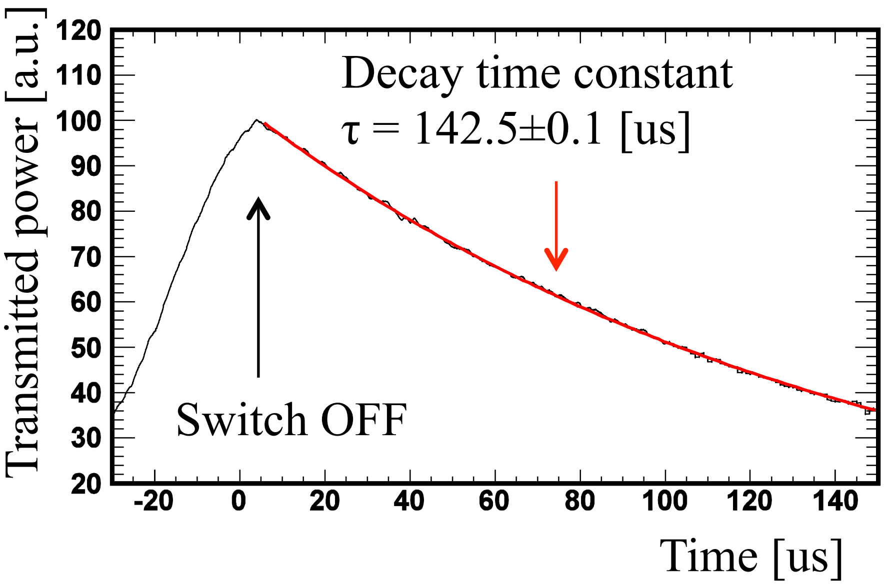
  → This fluctuation came from accuracy of the feedback to maintain the resonance

  → It corresponds to deviation of the cavity length of 16 pm

☆ The enhancement increases ten times → 26 pm linewidth ~ 16 pm feedback accuracy

- Development of a high accuracy feedback system has technical difficulty...



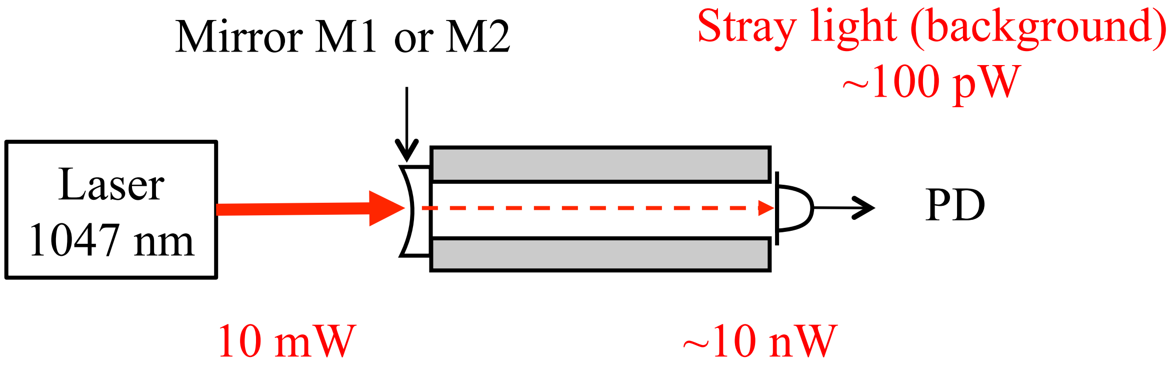


Measured the cavity finesse

- Use an external laser source with 1047 nm wavelength
- Switch off the laser light when the transmitted power increases (the cavity reaches the resonance condition)
- Intra-cavity light goes out with the exponential decay
- Finesse: $F = 2\pi c\tau / L$ (L: cavity length, τ: decay time constant)

☆ Measured finesse: F = 650,000 which corresponds to R = 99.99952 %

☆ Cavity linewidth: ΔL = 1.6 pm



Measured the transmittance of mirrors

- Use an external laser source with 1047 nm wavelength
- The transmittance would be ~1 ppm (10^{-6}) → be careful the SNR in the measurement

☆ M1 4.2 ppm (input-side mirror)

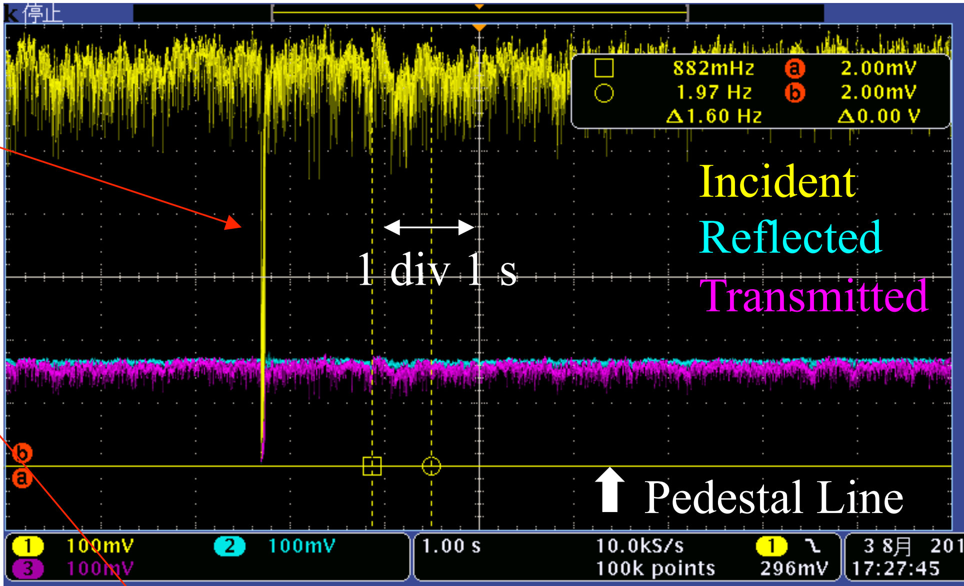
☆ M2 3.8 ppm (output-side mirror)

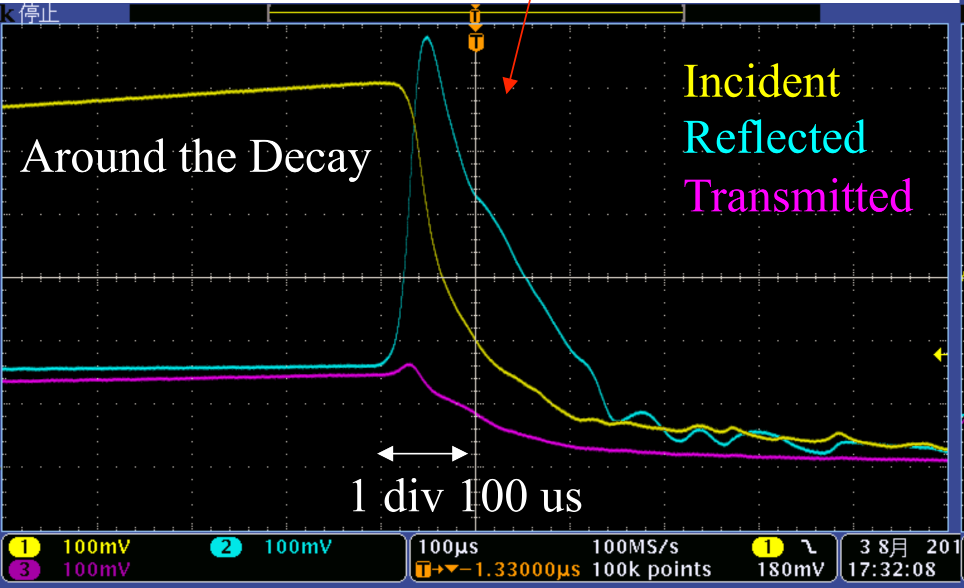
Oscillation with High Finesse

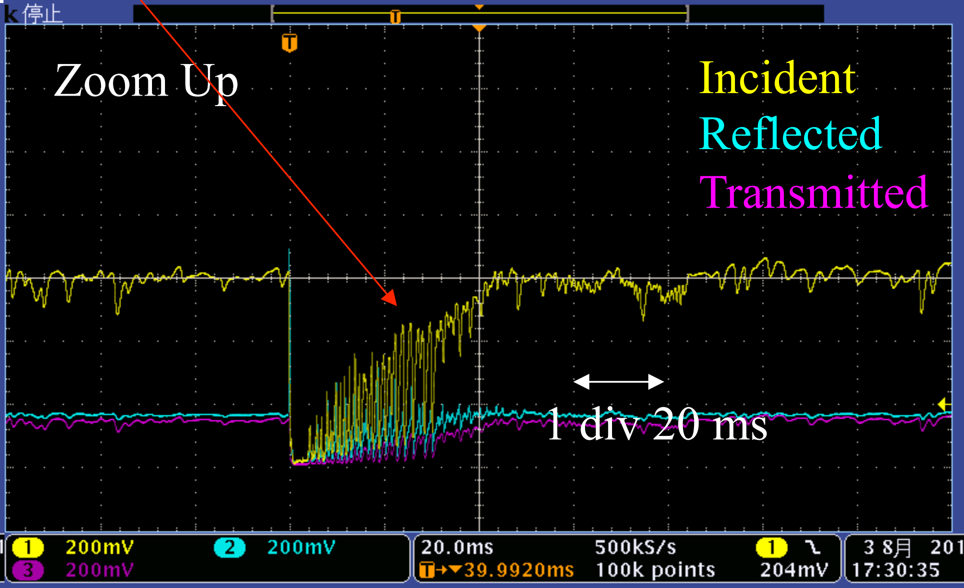
Nocking the cavity, the oscillation is broken in a moment.

The oscillation seems stable when increasing the power at reach some threshold power.

Reflected power increases since the cavity is in the off resonance.



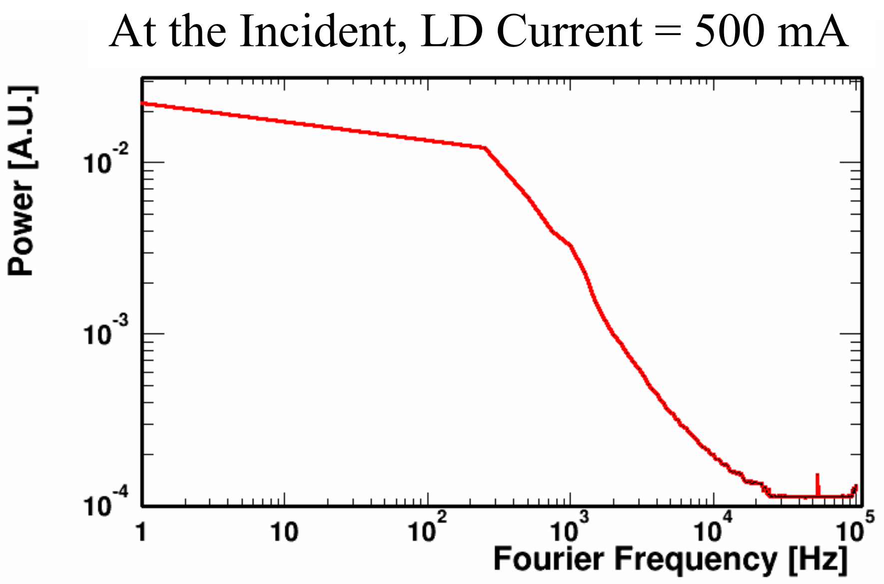


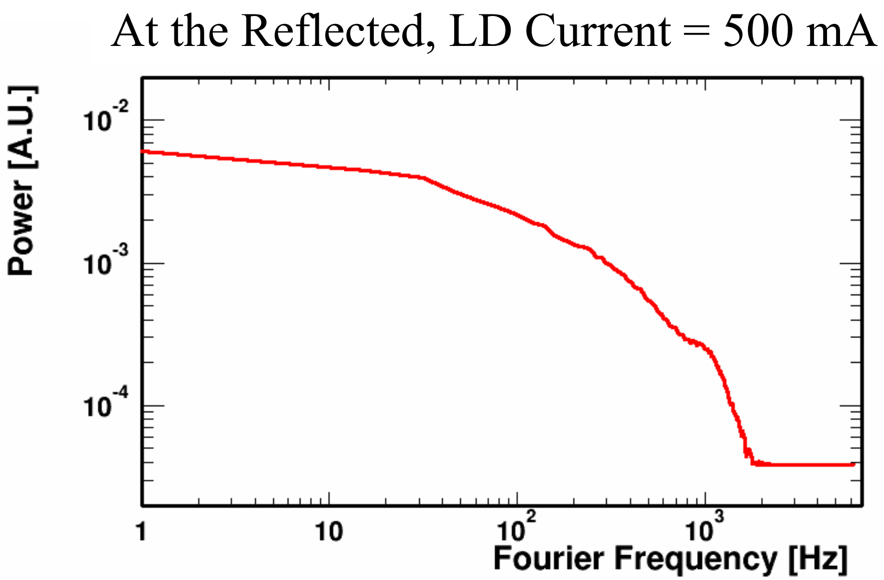


Relaxation Oscillations

In the stable condition, the fluctuation of the laser power didn't have spikes with the ringing like as the case of the low finesse setup.

The power spectrum at the free running condition has a LPF-like shape.



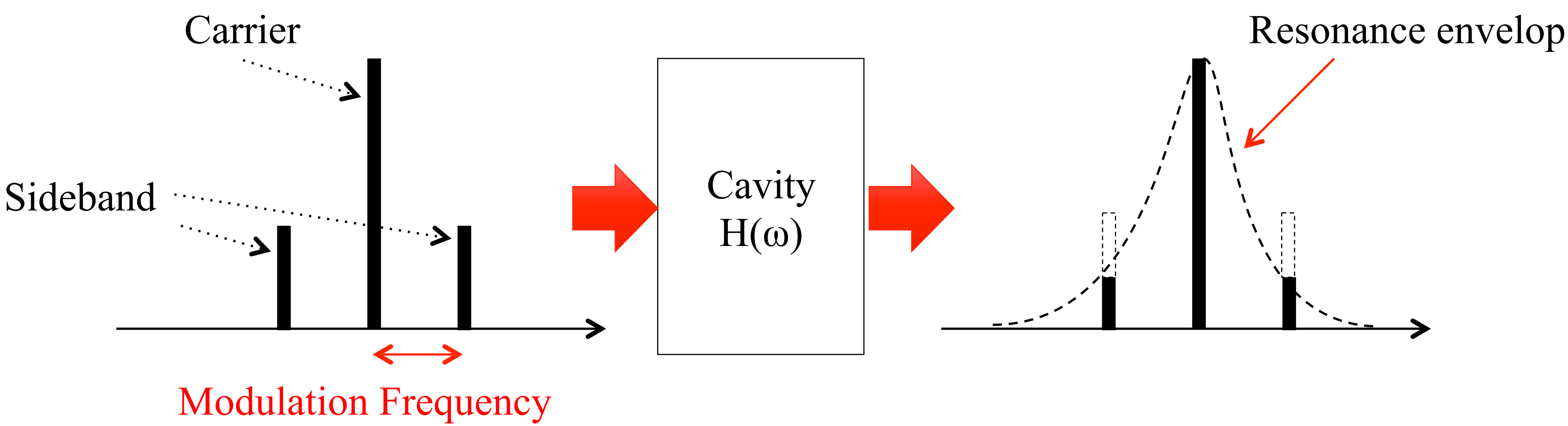


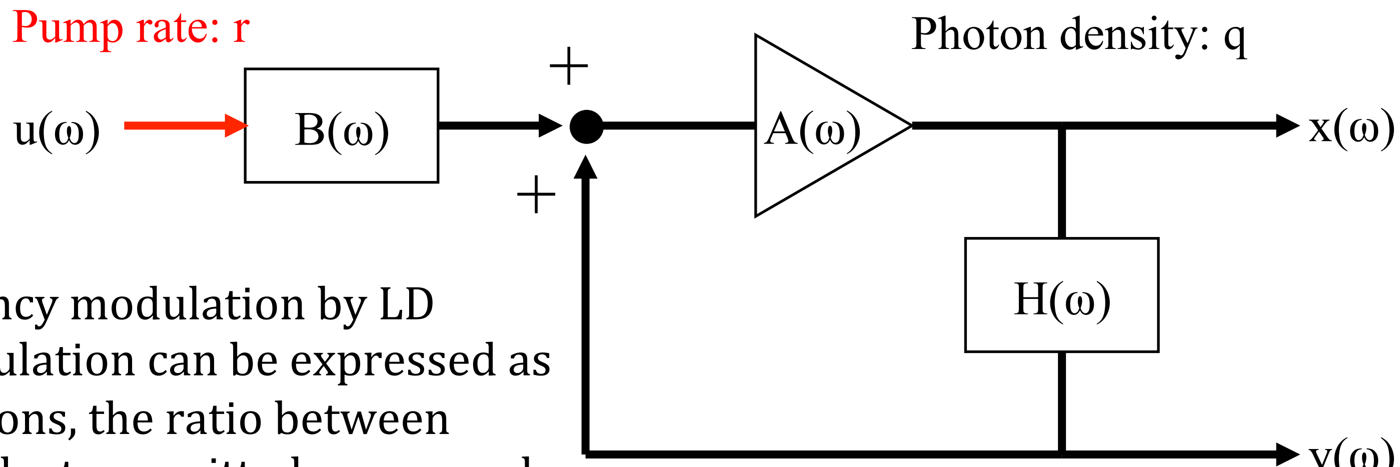
Measure a frequency response function of the cavity

- In a conventional cavity system (laser oscillator + resonant cavity), the frequency response of the cavity is measured by using amplitude modulation

See, e.g., N. Uehara, K. Ueda, Appl. Phys. B 61, 9 (1995)

- Add the sideband frequency to the carrier frequency of the incident laser light
- Measure a frequency response of the intensity of the sideband resonance
- The modulation depth must be small because large modulation depth would break the saturated laser oscillation state





If the frequency modulation by LD current modulation can be expressed as linear equations, the ratio between response of the transmitted power and response of the incident power equals the transfer function of a cavity, H(ω).

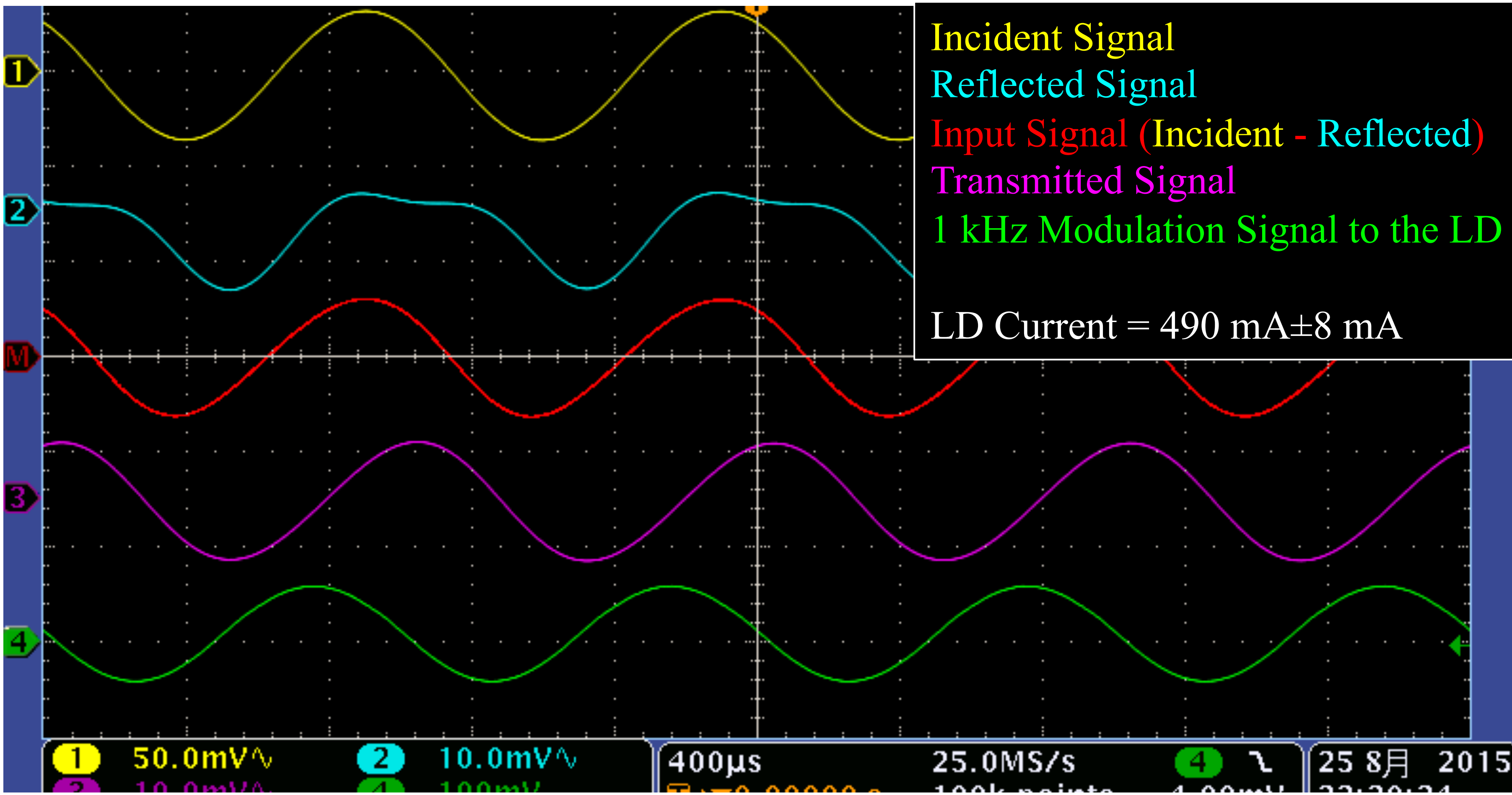
For the photon density *q*, a linear equation is shown as below, (for the 4-level system)

$$\frac{d^2\delta q}{dt^2} + r\gamma_2 \frac{d\delta q}{dt} + (r-1)\gamma_c\gamma_2\delta q = 0$$

$$\frac{x}{u} = BG_1 = \frac{BA}{1-AH}$$

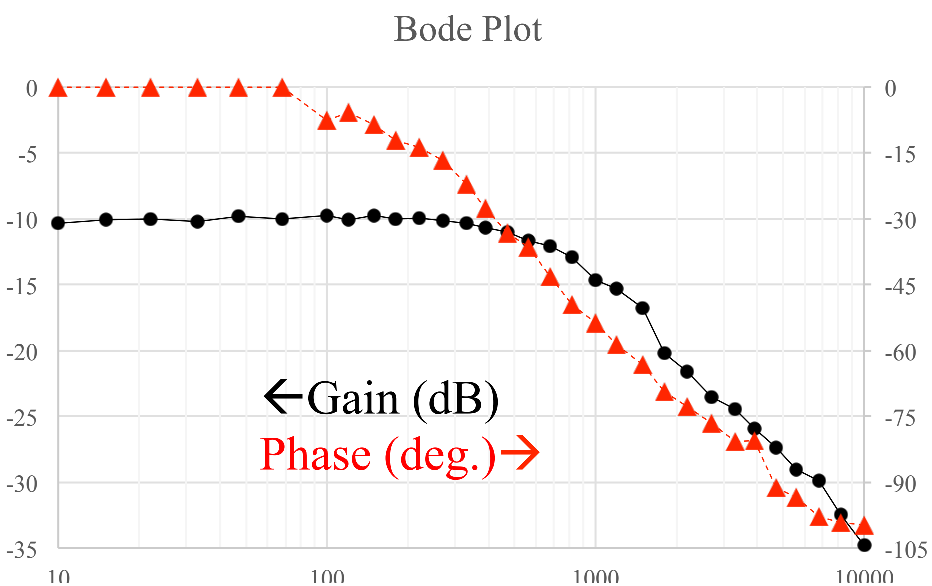
$$\frac{y}{u} = BG_2 = \frac{BAH}{1-AH}$$

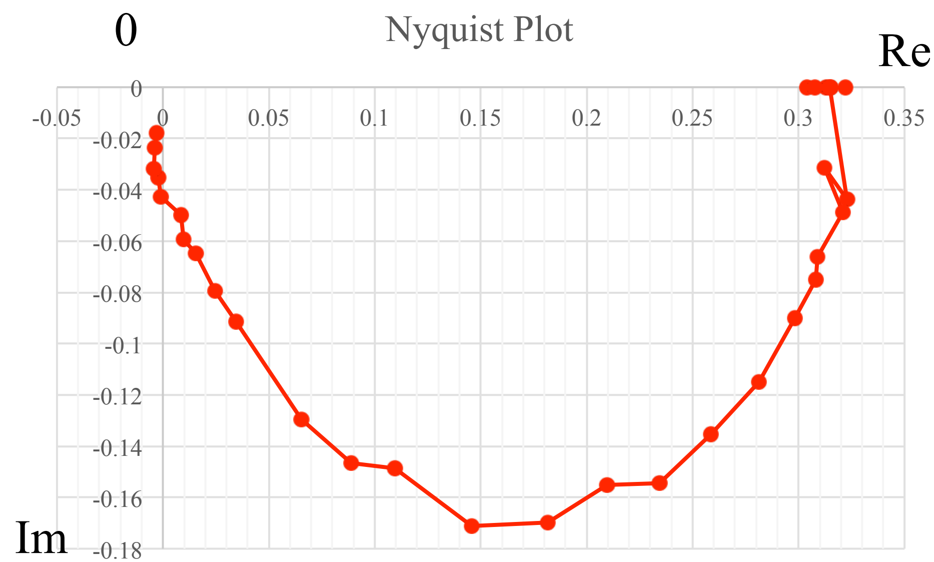
$$\frac{G_2}{G_1} = \frac{x}{y} = H$$



Measured the ratio of the amplitude and the phase difference between the input signal and transmitted signal.

Note that the ration of the amplitude between the input signal and the modulation signal is also changes because they are photon density and the population inversion.

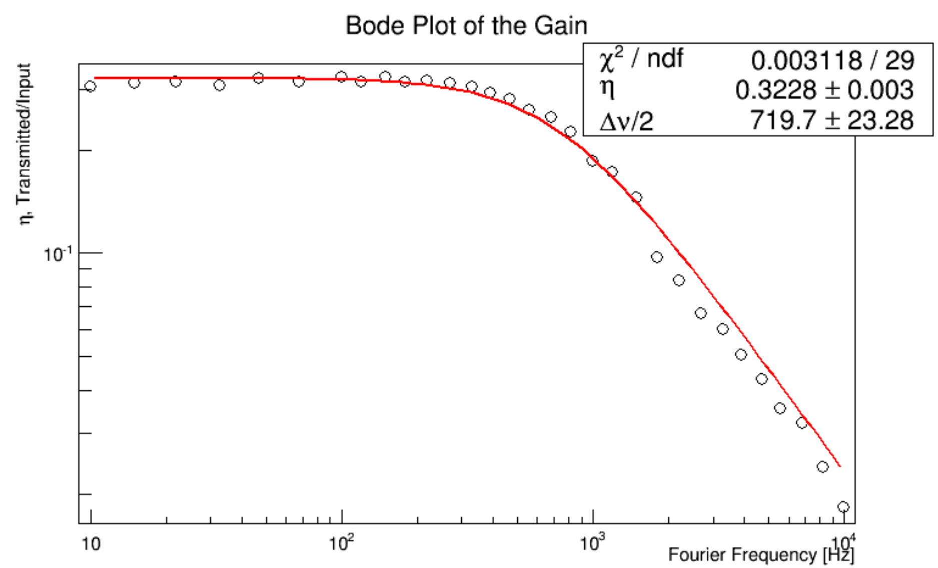




Measured data shows low-pass filter nature.

To get the cut-off frequency, fit a low-pass function to the gain curve.

η=0.3228±0.003
Δf=719.7±23.3 Hz



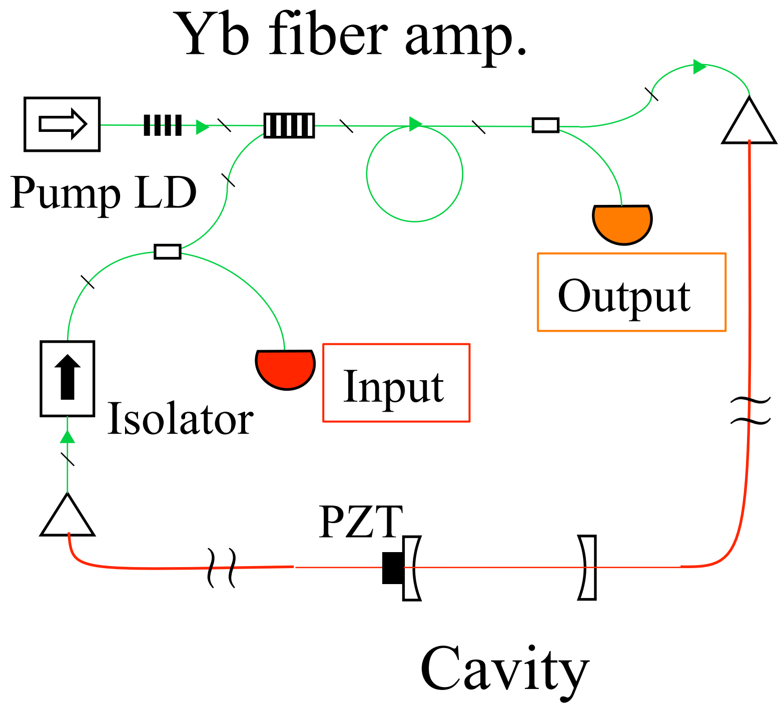
The frequency is consistent with results of the decay time measurement.

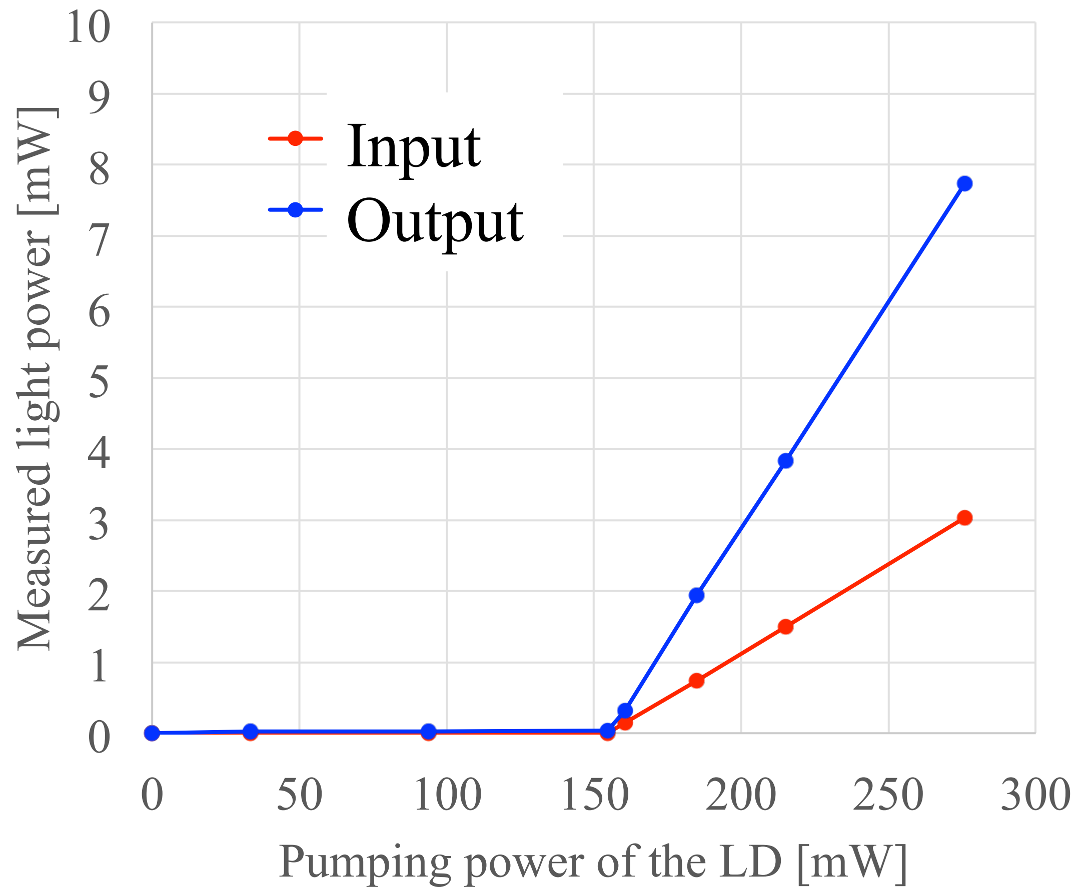
Finesse Measurement Using Intensity Modulation

From the results of the frequency response function measurement

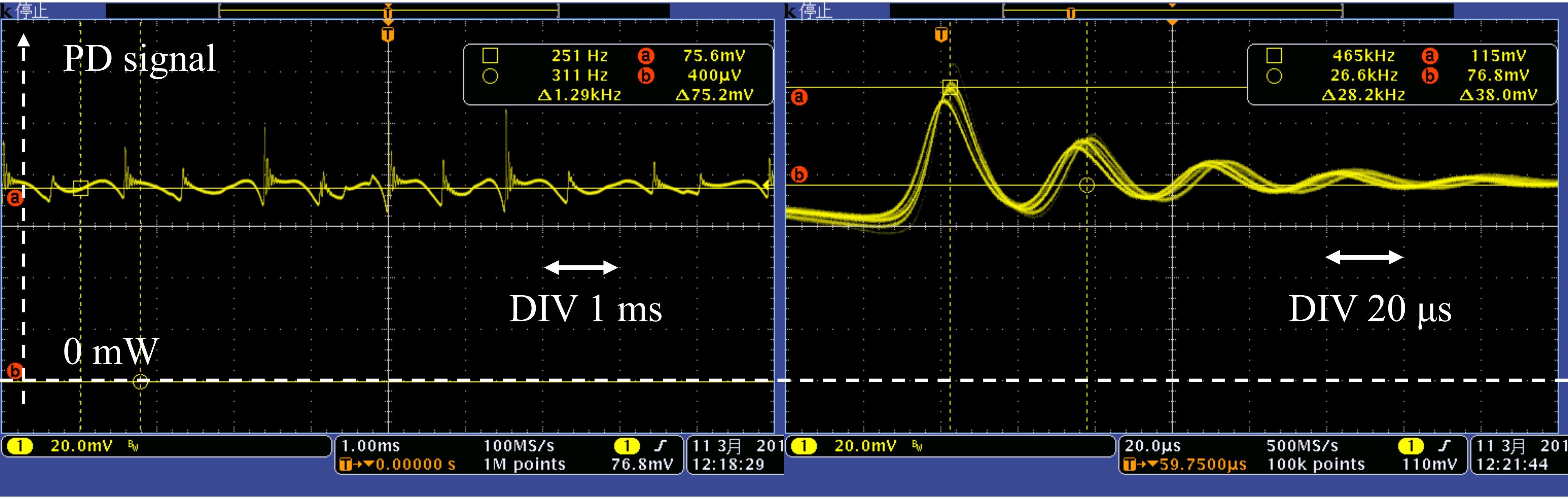
- Cavity linewidth 1.55 kHz
- Finesse 465,000
- Incident / Transmitted ratio $\eta = 0.412$
- Enhancement factor 190,000

*Considering the errors of detectors, which had an error of 0.5 % in its linearity and an error of 5 % in its absolute value, this results is consistent with the above results





- Threshold ∼150 mW (pumping), Gain = 4.8 dB
- Lasing wavelength of 1034 nm with fluctuation ±1 nm



- Lasing power was kept up at 8 mW

✓ Resonance condition was maintained without any cavity−control

- There were spikes in time scale of acoustic noise
- All spikes had a ringing with a time interval of ～30 kHz

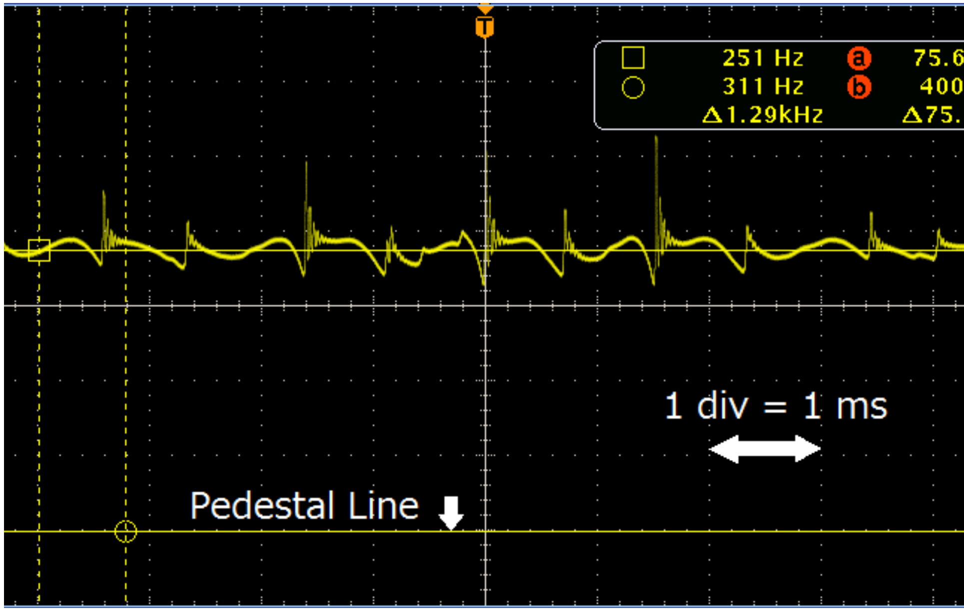
✓ The origin of time scale of this ringing?

  - ➢ Decay time of the cavity: ～15 MHz
  - ➢ Fluorescence lifetime of a Yb fiber: ～1 ms

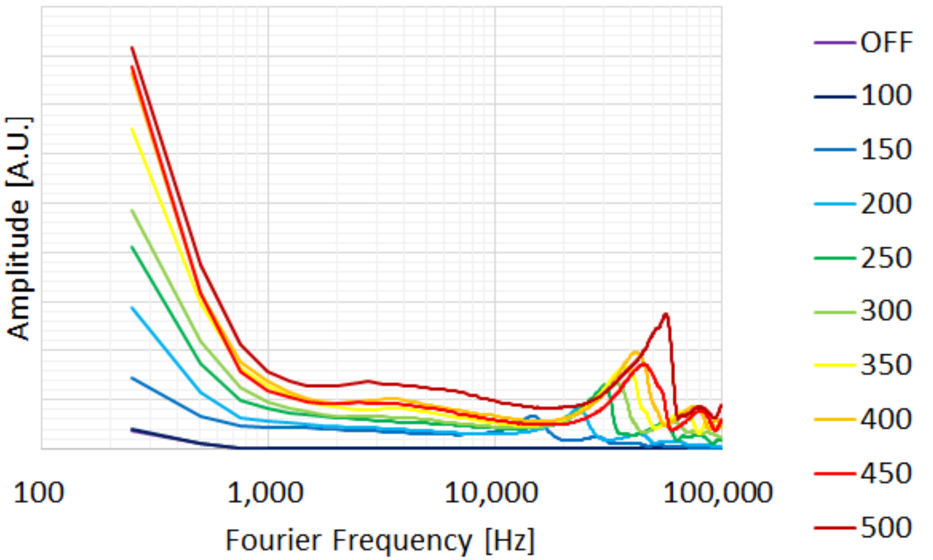
Relaxation Oscillations

Mechanical noise to the cavity

→ a spike with the ringing occurs



The frequency of the ringing increases in proportion to increase the LD current.



Rate Equation（4-level System）

$$\frac{dN_2}{dt} = r_{pump} - \gamma_2 N_2 - KN_2 q$$

$$K = c\sigma_{emiss}^{eff} L^{eff}$$

r_{pump}： 励起効率
γ_2 ： 自然放射 τ_2の逆数
c ： 光速度
σ^{eff}_{emiss}： 誘導の実効反応断面積
L^{eff} ： 実効光路長

Equation of a Photon Density

$$\frac{dq}{dt} = -\gamma_c q + KN_2 q$$

$$\gamma_c = \frac{\ell_c}{\tau_c}$$

τ_c ： 周回光路にかかる時間

Linearized Equation

定常状態からの摂動を考えて線形化する。$(N_2 = N_{ss} + \delta N,\ q = q_{ss} + \delta q)$

$$\frac{d^2\delta q}{dt^2} + r\gamma_2 \frac{d\delta q}{dt} + (r-1)\gamma_c\gamma_2\delta q = 0$$

$$r = \frac{P_{pump}}{P_{th}}$$

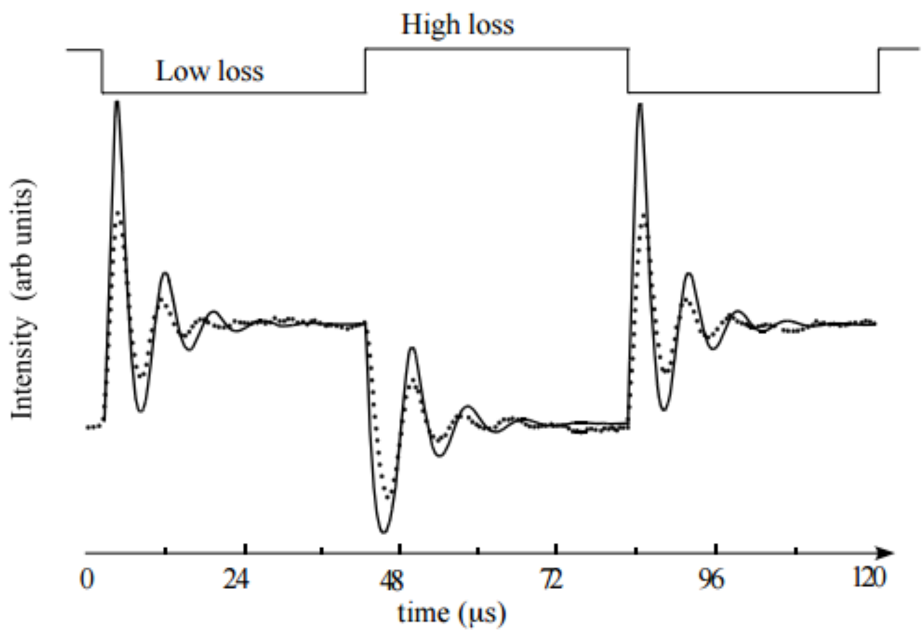
自然角周波数

$$\Omega = \sqrt{(r-1)\gamma_c\gamma_2}$$

減衰の時定数

$$\tau = \frac{2}{r\gamma_2}$$

実験値との比較例



Laser Physics, Lecture text, University of Arkansas Physics, US.

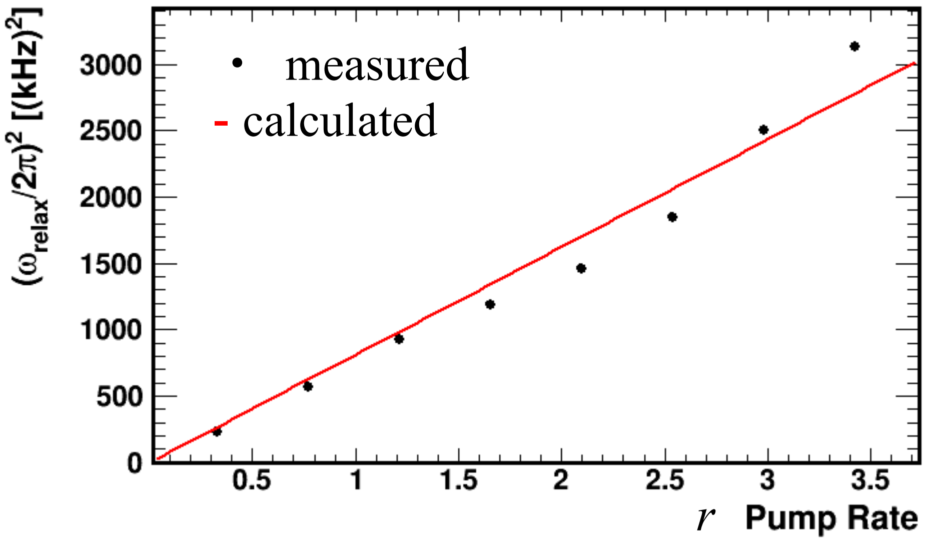
Relaxation Oscillations

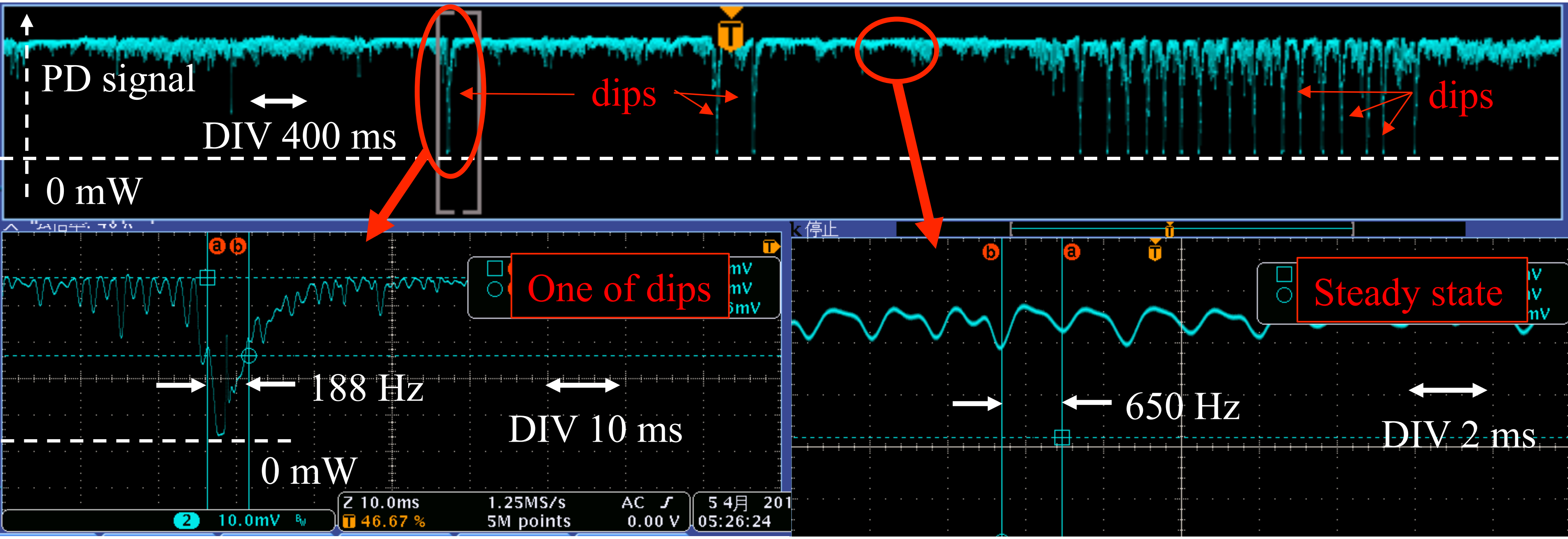
Approximation of the rate equation

$$\frac{d^2\delta q}{dt^2} + r\gamma_2 \frac{d\delta q}{dt} + (r-1)\gamma_c\gamma_2\delta q = 0$$

$$\omega_{relax} \sim \sqrt{(r-1)\gamma_c\gamma_2}$$

δq	Photon Density
r	Pump Ratio
γ_2	1 / Fluorescence Time
γ_c	1 / Light Decay Time in the Optical Loop
ω_{relax}	Angular Frequency of the Ringing





- ✓ Lasing power was kept up at 4 mW
- ✓ Laser oscillating with the high finesse cavity succeeded
- But it was half of the power in case of the low finesse, 8 mW
- Lasing power oscillated with about 600 Hz repetition always
- Sometime lasing power fell to zero, FWHM of a dip was 188 Hz
- ✓ The cause of the 600 Hz oscillate and time scale of the dip?
  - ➡ Now we are looking for mechanisms of these phenomena

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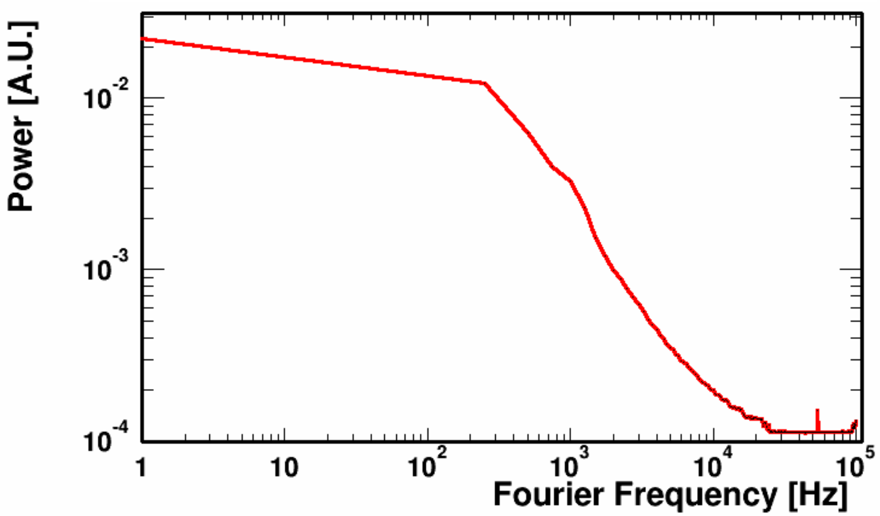
In the stable condition, the fluctuation of the laser power didn't have spikes with the ringing like as the case of the low finesse setup.

The power spectrum at the free running condition has a LPF-like shape.

At the Incident, LD Current = 500 mA



At the Reflected, LD Current = 500 mA