SPIE.

Development of Near-Infrared Scanning Fabry-Perot Spectrometer for 3D spectroscopy : Design concept and basic performance evaluation

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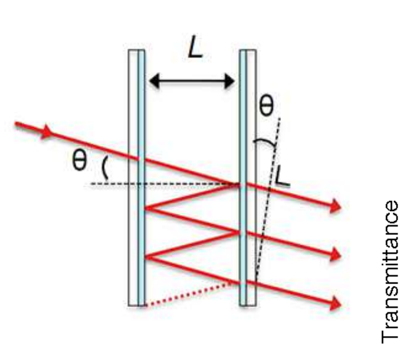
We are developing a Fabry-Perot spectrometer for 3D spectroscopic observation to elucidate the physical condition of large scale starforming regions. By varying the interference conditions, images at arbitrary wavelengths can be obtained. Since the observed wavelengths are in the near-infrared, the module must be operated under vacuum and low temperature. The development items are optical element (Fabry-Perot etalon), a drive actuator and ranging system to control the etalon gap, as well as feed-back system to actively control these elements and maintain spectroscopic performance at any operate conditions. The basic performance as a spectrometer will achieve R=5,000 for finesse=50 and order=100.

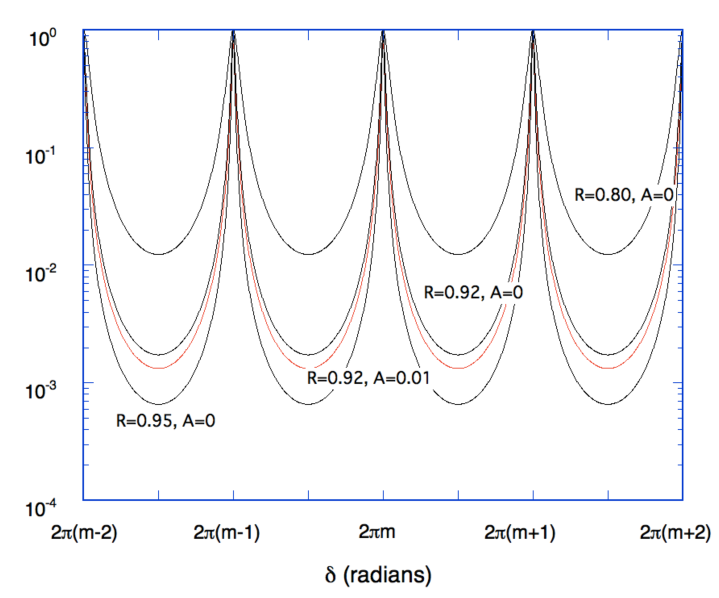
About Fabry-Perot Interferometer

A Fabry–Pérot interferometer (FPI) or etalon is an optical cavity made from two parallel reflecting surfaces (etalons). Optical waves can pass through the optical cavity only when they are in resonance with it.

Principle



▲Fig.1 Principle of Fabry-interferometer



▶Fig.2 Transmittance profile (Airy function)

Interference Condition

$$\lambda_{peak} = \frac{2nd\cos\theta}{m}$$

Airy function

$$T(\delta) = \frac{\left(1-\frac{A}{1-R}\right)^2}{1+\left(\frac{2\sqrt{R}}{1-R}\right)^2\cdot\sin^2\left(\frac{\delta(\lambda)}{2}\right)}$$

Parameters

Interference Condition $2nd\cos\vartheta = m\lambda$

n : Refractive index, d : gap pf etalon, θ : incident angle, m : order, λ : wavelength

Resolving power $R = \lambda/\Delta\lambda = mF$

R ~ Resolving power, m : order, F : Finesse

Free Spectral Range $FSR = F\Delta\lambda_{FWHM} = \lambda^2/2d = \lambda/m$

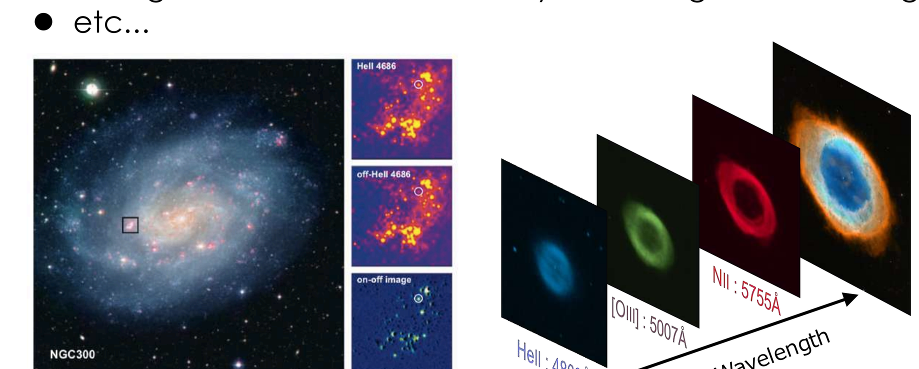
Finesse $F = F_R = 2\pi/\delta_{FWHM} \sim \pi\sqrt{R}/(1-R) = \lambda^2/(2d\cdot\Delta\lambda_{FWHM})$

The most important point for improving spectrometer performance are

- **Parallelism** of etalons (mechanical)
- **High Finesse** (optical)

Advantages

- Spectroscopic Imaging
- High spectral resolution
- Compact optical system
- Arbitrary wavelength selection
- Wide wavelength band observation
- Easy to obtain velocity information
- Background can be reduced by narrowing the wavelength
- etc...



Crowther 2007, ARAA,45,177

Fig.3 Examples of expected observations with FP (left: velocity structure, right: emission line image)

- Arbitrary wavelength image can be obtained by wavelength scanning.
- Easy to subtract continuum image -> image of emission lines

Design Concept

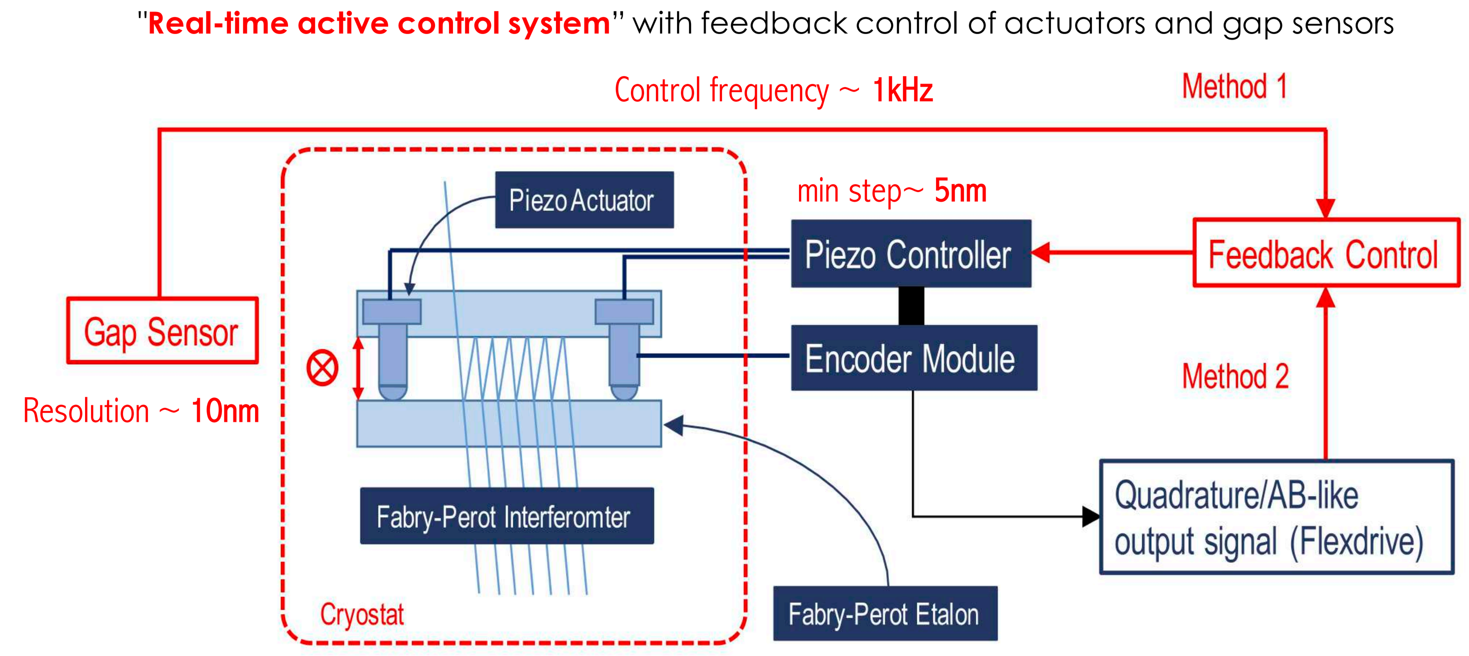
Key points in development are (1) Optical elements + Scanning drive mechanism + Gap measurement mechanism, (2) Optimal mechanical design + precision machining, (3) Control system including feedback control, and (4) Design and fabrication of cooling test vessels. Another situation for us is (5) Cooperation / Collaboration with local companies (consortium).

Specifications

(1) Operation condition	
Wavelength	**1.1 ~ 2.5 um**
Temperature	**~77K**
(2) Optical element (Etalon)	
Material	Fused Silica
Size	70mmφ, t=10mm
Reflective coat	Dielectric multilayer
Effective diameter	**60mmφ**
Wedge angel	5'
Back surface	AR coating
Reflectivity	**R ~ 96 +/- 1 %** (1.1~2.5um)
Absorptivity	**A < 0.5%** (1.1~2.5um)
Surface roughness	**λ/150** @2μm (λ/47 @633nm)
(3) Performances as a spectrometer	
Wavelength	@2μm
Order	m = 100
Gap of Etalons	d = 100μm
Free Spectral Range	FSR = 0.02μm
Finesse (reflective)	F_R = 78 (R = 96%)
Finesse (surface roughness)	F_s = 90
Finesse (effective)	F_{eff_0} = 59
Finesse (effective w/absorption)	**$F_{eff\ w/A}$ = 50**
Resolving power	**R = 5000**

Diagram of Control System

"**Real-time active control system**" with feedback control of actuators and gap sensors



Requirement of parallelism ~ 2 x 10^{-5} deg. → 25nm (Φ70mm)

Fig.4 Conceptual design of FP control system.

Mechanical System

- Fine precision machining
- Compact and lightweight
- Designed for low temperature use

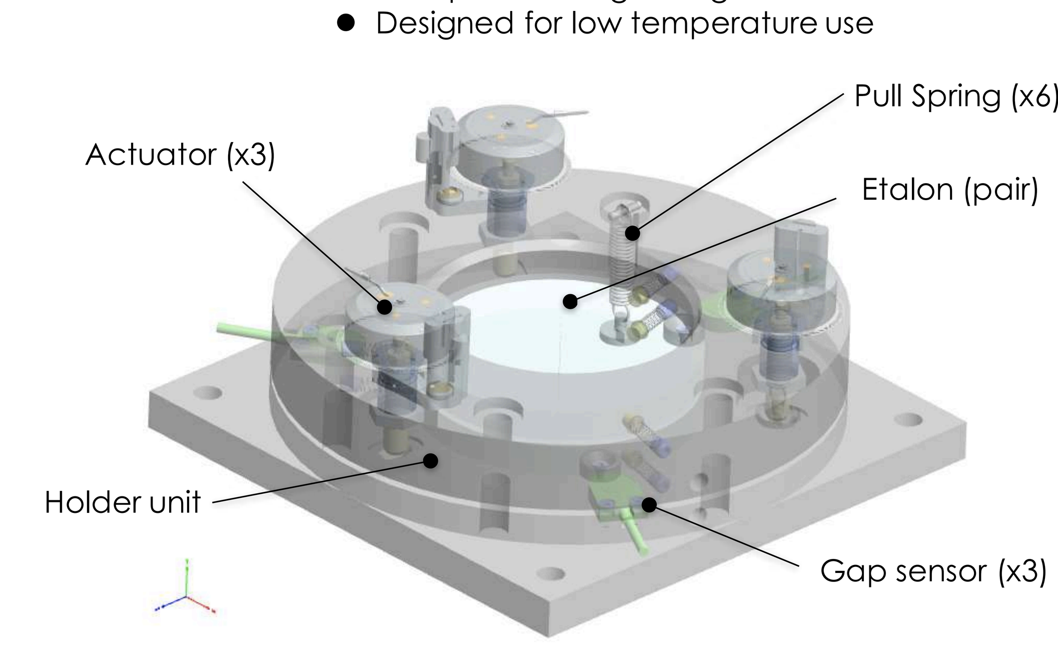


Fig.5 Conceptual design of FP module and layout of each component.

Fabrication and Test

Considering the characteristics of Fabry-Perot interferometer, components that satisfied the specifications were adapted based on the conceptual design. A prototype model combining these components was tested for drive and found to be controllable at the nano-level.

Components

Optical component

Koshin Kogaku Co., Ltd.

Fig.6 **Etalons**

- Flatness → **λ/150** @2μm
- High Reflectivity → ~**96**+/-1%
- Low absorptivity → <0.5%
- Wide range → **1.35-2.5um**
- Large aperture → D=70mm

Actuator

JPE

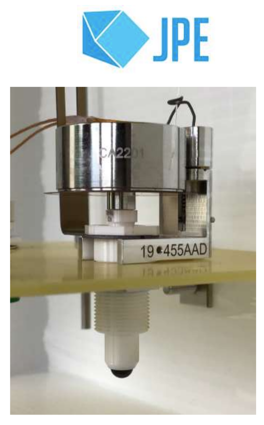


Fig.7 **Piezo actuator**

- Vacuum・cryo → **20mK~**
- High accuracy → **1nm** @4K
- Low heat → 0.055mJ/step
- Rapid response → 600Hz (max)
- High power → 30N (max)

Gap sensor

MICRO-EPSILON

Fig.8 **Capacitance sensor**

- vacuum・cryo → **~20K**
- High accuracy → 0.75/20nm (@2Hz/7.5kHz)

Housing

株式会社 協和精工

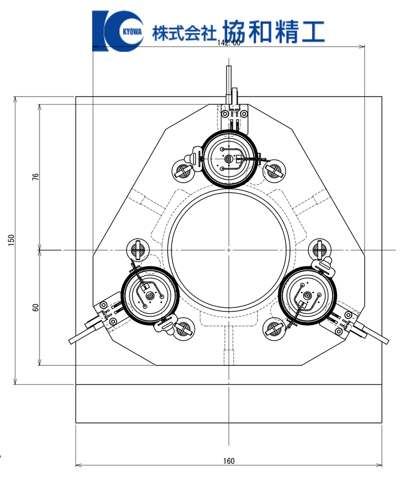


Fig.9 **Housing** (etalon holder)

- Compact → **~140x140x40mm**
- Light weight → **~700g**

Control system

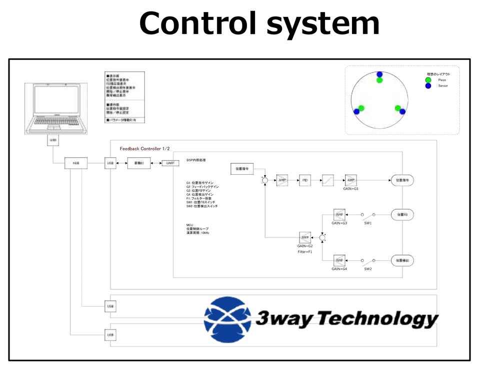


Fig. 10 Basic design of control system and block diagram

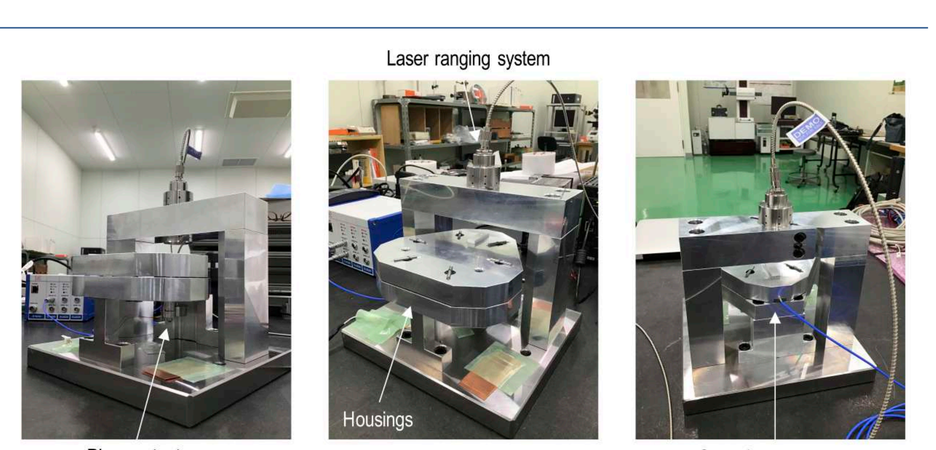


Fig. 11 Measurement setup (1 axis)

Proto-type Model

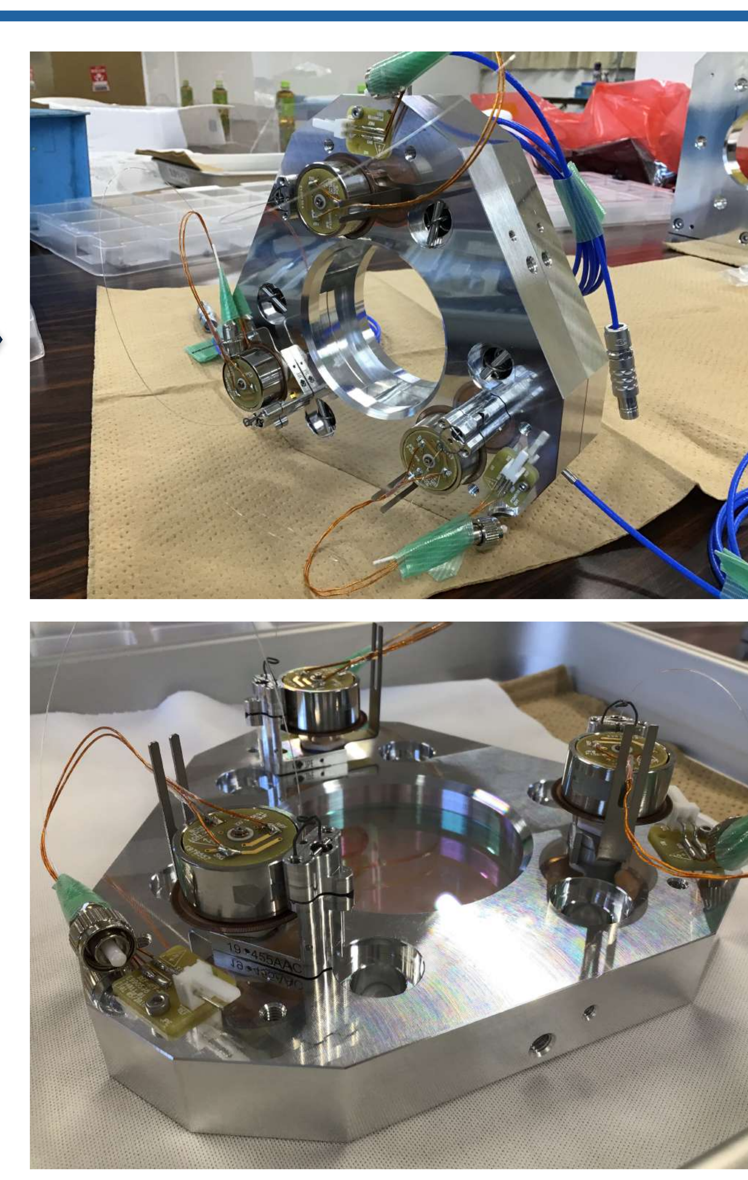


Fig.12 Aluminum housing with each component mounted. 3-dimensional surface control can be done.

Performance Evaluation Tests

- Actuator and gap sensor operation test (1 axis, fig.11).
- Measurement of Nano-scale displacement → Keyence Laser position sensor (CL-S150)
- Evaluation items : Control voltage of piezo actuator vs displacement

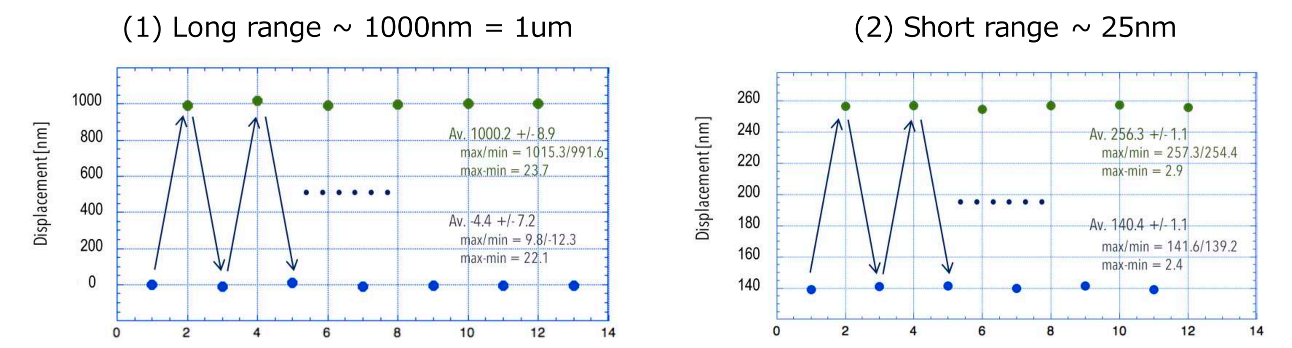


Fig.13 Results of multiple repetitive test (left : long range, right : short range). Uncertainty (stdv) before and after movement are about (1) **<10nm** and (2) **1nm** respectively. Time drift was corrected for each results.

→ Although fine tuning of control parameters is required, it was confirmed that the actuator and gap sensor work as expected (force-gap and distance measurements).

Future Works

- Control parameter adjustment
- Operation test with 3-axis independent control
- Optical performance test
- Vacuum cooling test
- Fabrication of Final model (further weight reduction and downsizing?)
- Development of order selection mechanism (order sorter)
- Design, production, and testing as a spectrometer modules
- Combination with sensor module
- Operational test (onboard telescope)
- Observation planning