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

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ABSTRACT

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.

Keywords: imaging spectrograph, 3D spectroscopy, Fabry-Perot interferometer, tunable filter, near-infrared, starformation

1. INTRODUCTION

Fabry-Perot interferometry (FPI) is a device that extracts only light of a specific wavelength by multiple reflection and interference of incident light between two parallel optical elements with highly reflective surfaces, called etalons. It is named after Charles Fabry and Alfred Perot, who developed the instrument in 1899.[1,2] The multiple reflections between the etalons, whose mirrored surfaces face each other, cause optical interference between the reflecting surfaces, and only light with wavelengths that satisfy the interference conditions described below is transmitted through the etalons. Light with wavelengths that do not satisfy the interference conditions is reflected back to the incident side. The interference condition is obtained from the fact that an integer multiple of the wavelength of light is equal to the optical path difference due to light reflection on the two reflective surfaces. Assuming that the spacing between the reflective surfaces is d, the refractive index of the material enclosed between the reflective surfaces (usually air or vacuum) is n, and the incident angle of the light relative to the normal direction of the reflective surfaces is θ, the interference condition can be written as in Eq.1.

$$\lambda_{peak} = \frac{2ndcos\theta}{m}, \tag{1}$$

where m is an order. By changing the spacing d between the reflecting surfaces, the wavelength of transmitted light can be changed. Because of this property, they are used as interference filters (tunable filters) with variable transmission wavelengths.

As can be seen from the interference conditions above, the transmission profile of the Fabry-Perot interferometer is periodic according to order. This is expressed as an Airy function (Eq.2).

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

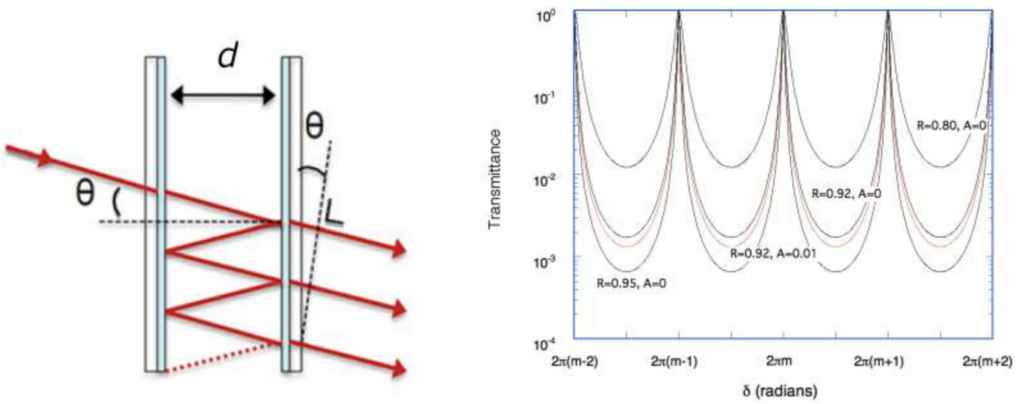

Figure 1. (left) Principle of Fabry-Perot interferometory. (right) Transmittance profile of Fabry-Perot interferometer (Airy function).

The interval between adjacent transmission peaks is called the free spectral range (FSR). When the wavelength range to be observed exceeds this range, light from neighboring transmittance peaks will be mixed in. Therefore, the observed wavelength range must be separated by a narrow band filter or the like (called an order-selective filter = order sorter), which is usually narrower than the free spectral range. The width of the transmittance peak and the transmittance between the peaks vary depending on the reflectivity of the reflective surface. This is because a low reflectivity allows light that does not satisfy the interference condition to be transmitted. The higher the reflectivity, the narrower the transmittance peaks and the lower the peak-to-peak transmittance. In other words, monochromatic light with higher purity can be obtained. The ratio FSR/$\Delta\lambda$ of the half width of the transmittance peak (FWHM) $\Delta\lambda$ to the free spectral range is called finesse. The larger the finesse, the sharper and more pointed the transmission profile.

2. FEATURES OF FABRY-PEROT SPECTROMETER

There are several types of spectrographs used in astronomy (prism/grism/grating spectrometer, Fourier interferometer, etc...). Among them, Fabry-Perot spectrographs can treat the light flux from a telescope as a plane light source, so it can be constructed a bright optical system and enable integral field spectroscopy observations simply by inserting a optical module in the collimated beam. In other words, a compact spectrometer module can be constructed. In addition, by changing the gap of etalon, wavelength scanning can be performed (any wavelength can be selected), and in principle, wavelength resolution can also be increased. Observationally, the off-band of a specific wavelength can be obtained, and the intensity of emission/absorption line can be easily estimated by subtracting the off-band from the on-band. Furthermore, by narrowing the transmitted wavelength, background can be reduced, and Fabry-Perot spectrometers can be used for ground-based observations under relatively large background emitted condition.

On the other hand, there are some disadvantages. Since transmitted light according to each order appears periodically, a mechanism for order selection system is required for monochromatic observation. For mechanically, a driving mechanism for the optical elements for wavelength scanning and a device for measuring the interval of etalons are necessary. In order to cover a wide wavelength range, the requirements for the optical elements become more demanding. In addition, matching with the detector system is also necessary as a observational instrument.

3. DEVELOPMENT OF FABRY-PEROT SPECTROMETER

As describe before, the key points necessary to increase and maintain the performance of a Fabry-Perot spectrometer are mechanically to maintain the parallelism of the two etalons and optically to achieve a high degree of finesse. Here we report on the development of a wavelength-scanning Fabry-Perot spectroscopic module for astronomical observations used in the near-infrared wavelength range, including its conceptual design and performance evaluation tests of a prototype model.

3.1 Scientific motivation of development

We have developed an infrared wavelength-scanning filter (tunable filter: Fabry-Perot integral field spectrograph), which has been strongly requested by various astronomical research fields, and aim to demonstrate its practical feasibility by installing it as a pre-optics module for medium-large aperture telescope instruments. Astronomically, this spectroscopic module will be used to perform continuous high-spatial-resolution integral field spectroscopic observations of the physical state of large-scale star-forming regions over the entire near-infrared wavelength range with a wide spatial dynamic range from the cluster level in the Milky Way to nearby and distant galaxies. The goal is to investigate the physical processes of star formation activity and to elucidate the evolution of massive stars and galaxies.

In the past, we have developed a mid-infrared Fabry-Perot spectroscopic imager.[3] The nature of buried massive stars has been revealed through observations of the Ultracompact H II region in our Galaxy using this instrument.[4,5] The ultimate goal is to further develop such studies to search for a wide variety of massive stars and to expand the scope of observations to the galactic level.

3.2 Development elements

As elements of the development of a spectroscopy module, it is essential to optical design and fabricate the etalon optimized for the near-infrared wavelength range and to develop a driving mechanism for wavelength scanning and a gap measurement mechanism. The key points in this development are as follows. (1) Optical design of a Fabry-Perot etalon and fabrication of an element with a large-diameter multilayer film that achieves flat reflection characteristics over almost the entire near-infrared wavelength range at low temperatures, (2) selection and acquisition of a driving element to scan a small distance while maintaining the parallelism of the two parallel etalons, (3) selection and acquisition of a gap-measuring sensor to measure the gap between the optical elements and provide feedback to the optical element spacing adjustment, and (4) fabrication of a prototype aluminum model enclosure to install these components. Furthermore, (5) design of a real-time control system and circuit board fabrication that keeps etalon gap and parallelism while scanning wavelengths through closed-loop control of driving actuator and ranging by the gap sensor is also essential.

3.3 Conceptual design

The specifications of the spectrometer are given in Table 1. It should be noted that the spectrometer covers the near-infrared range from 1 to 2.5 μm and that it is used under vacuum and cooling. The optical elements are highly reflective to maintain high reflective finesse. In addition, the plane precision of the etalon must be high in order to increase the efficiency of multiple reflections. On the other hand, considering efficiency, it is important to keep the absorption coefficient as low as possible. The substrate of the optical element is Fused Silica, and an optimum multilayer coating is applied to achieve the reflectivity and surface accuracy. When the reflection finesse is $F_R = 78$, the effective finesse is $F_{eff} = 59$, and the effective finesse considering the absorption rate is $F_{eff\_A} = 50$. If the wavelength is 2μm and order for $m = 100$ is selected, the spectral resolution will be R$\sim$5000.

To maintain this value, the parallelism of the two etalons must be less than 2×10^{-5} degrees. As a mechanism to achieve and maintain this value, we constructed a system that combines three sets of actuators and gap-measuring sensors. The gap sensors at three symmetrical locations measure the gaps between etalons, and the actuators are feedback-controlled to set the gap at the same value. In other words, it is a "Real-time Active Control System (RtACS)". A conceptual diagram is shown in Fig.2. Feedback control at $\sim$ 100 Hz is sufficient for our use. The mechanical design is shown in Fig.3. One of the two etalons is fixed, and the holder setting the other etalon is variable, so that the gap between the two etalons can be changed arbitrarily, and the parallelism can be maintained by controlling with the RtACS as described above. By arranging the actuators and ranging

Table 1. Design and specifications of Fabry-Perot spectrometer.

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

sensors in three symmetrical positions, arbitrary surface control becomes possible. That is, the distance between the two etalons can be varied while maintaining parallelism.

3.4 Selection of each element

There are several choices of drive elements (linear motors, electromagnets, micro screws, piezo actuators, and others). The driving element was selected based on the fact that this spectrometer will be used in vacuum and cryogenic condition, and taking into consideration items such as accuracy, heat generation, linearity, hysteresis, and durability, a piezo actuator was selected because it is capable of fine-driving at low temperatures, which is suitable for this purpose. The drive element selected was a piezo actuator (CLA2201-COE) manufactured by JPE. This product has solved the problems of conventional piezoelectric actuators that have been considered an issue when operating at low temperatures, such as damage to the element due to thermal cycling and the need for high drive voltages at low temperatures. It also has the drive distance accuracy to meet the specifications of the spectrometer to be developed in this project. To control this actuator, it is necessary to measure the distance between the optical elements. For the distance-measuring sensor, we selected a capacitive displacement sensor, which is a non-contact type and has a proven track record at low temperatures. (Micro-Epsilon : CSH1FL(20)-CRm1.4).

In actual operation, the actuators are feedback-controlled to commensurate the distance between the etalons at the three measurement points based on the values from this sensor described before. These were mounted on an aluminum holder as shown in Figure 5 to complete the prototype spectrometer model. The effective aperture has 60 mm in diameter and is intended for use in telescopes with relatively large apertures.

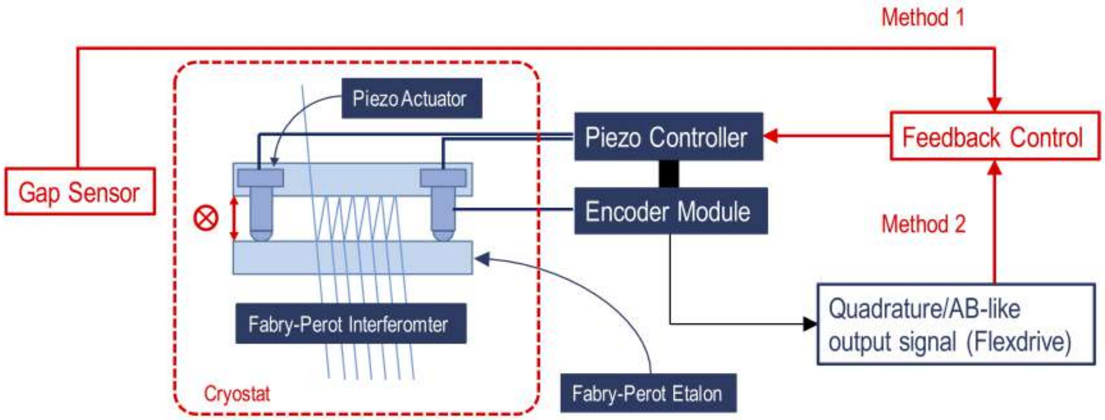

Figure 2. Conceptual design of tunable Fabry-Perot interferometer control system.

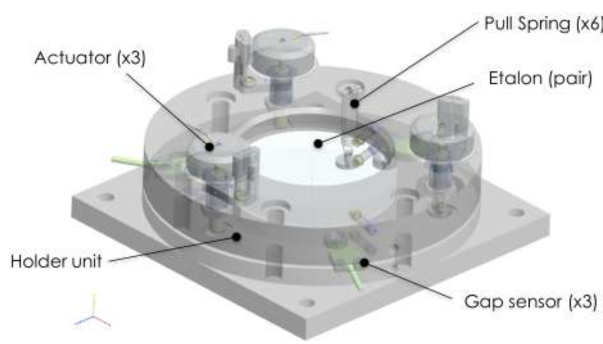

Figure 3. Conceptual design of Fabry-Perot module and layout of each component. This geometry allows the etalon to be freely displaced in three dimensions while at the same time allowing the gap to be measured.

4. PERFORMANCE EVALUATION TESTS

Before evaluating the performance as a spectrometer, a stand-alone test was conducted to see if the actuator and distance-measuring sensor could be driven in combination. The situation is shown in Figure 6. An actuator and a gap-measuring sensor were attached to a test model that is almost equivalent to the final spectrometer, and only one axis was driven to measure the amount of displacement, its accuracy, and repeatability. The gap-measuring sensor outputs a voltage according to the distance between the elements, and by comparing this with the actual gap and reflecting this result in the control parameters of the actuator, it is possible to control any distance. The absolute distance was measured using a Keyence CL-S015 laser ranging system, which is capable of measuring distances at the nano-level. Experiments were conducted in a temperature-controlled room to prevent thermal deformation of the structure due to changes in the environment and the temperature of the spectrometer. The experiments were also performed on an anti-vibration stage to prevent fluctuations in measurements due to vibration.

The results of repeated drive tests at arbitrary intervals (1000 nm = 1 μm) are shown in Figure 7 (left). The minimum drive displacement (1digit) of the actuator in this experiment was set at 25 nm, and the uncertainty in repeated driving is well within that range. Figure 7 (right) shows the results of the minimum displacement drive test. Since the displacement at each 1 digit is highly uncertain, the actuator was first displaced a few digits (to the position of -100 nm) and then driven to the target position in two steps. As a result, it was confirmed that

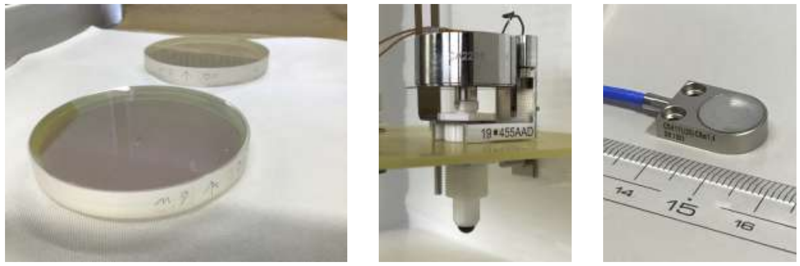

Figure 4. (left) Etalon (center) Piezo actuator (right) Capacitance gap sensor.

Piezo actuator (JPE/CLA2201-COE)	
Range	6 mm
Min step size	5 nm @ambient
Min step size	1 nm @4K
Max driving force	20 N @4K
Operating frequency	1 – 100 Hz
Operating voltage	-30 ... +120
Operating temperature	0.02 – 375 K
Dissipation	0.59 mJ/step @ambient
Dissipation	0.055 mJ/step @4K

Table 2. Specifications of Piezo actuator

Capacitance sensor (ME/CSH1FL-CRm1.4)	
Range	1 mm
Resolution (stable)	0.75 nm
Resolution (active)	20 nm
Operating temperature	-50 – +200 C
Temperature stability	zero-point 2.4 nm/K
Temperature stability	sensitivity -12 nm/K
Measurement area	ø5.7 mm
Min target area	ø11 mm

Table 3. Specifications of Capacitance sensor

the accuracy of reaching the target point was achieved even at the minimum displacement (25 nm). Linearity of displacement was also measured. The displacement of several round trips was measured, and it was confirmed that there was no hysteresis in the round trip and that the device was driven linearly within the control range.

The temperature control of the device is also severe when it comes to nano-scale drive. If the thickness of the aluminum etalon holder used in this test is ∼15 mm, the thermal expansion coefficient of aluminum is $2{\times}10^{-}6/^{\circ}\mathrm{C}$. Therefore, to keep the thermal deformation within 1 digit= 25 nm, which is the setting in this test, the temperature must be stabilized at $\sim 0.08^{\circ}$C. In actual operation, the spectrometer is cooled in a cryostat to control the temperature to a constant value.

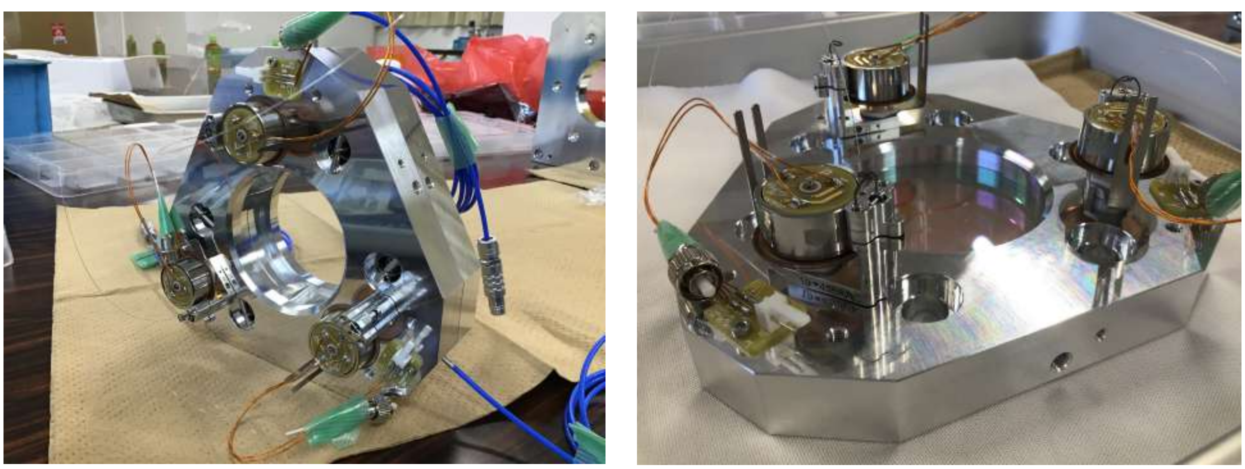

Figure 5. Aluminum housing with each component mounted.

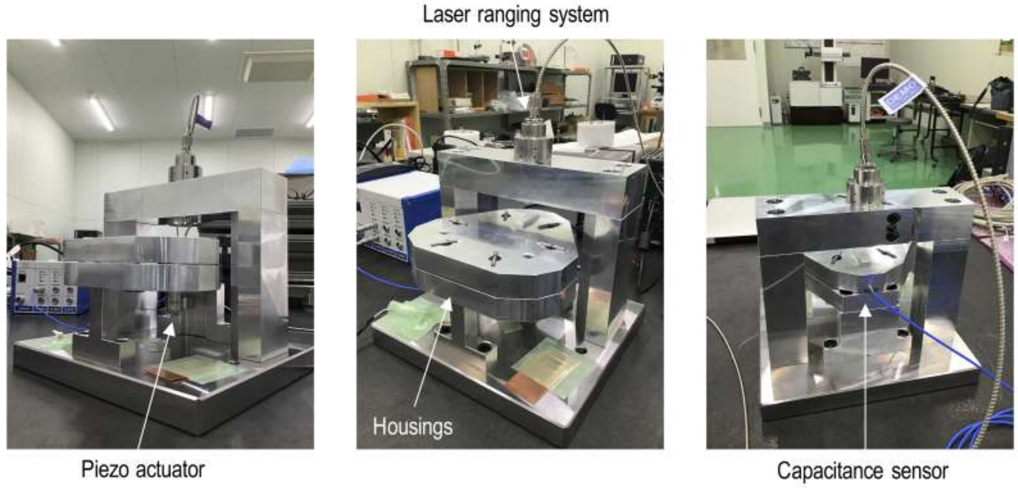

Figure 6.   Measurement setup (1 axis).

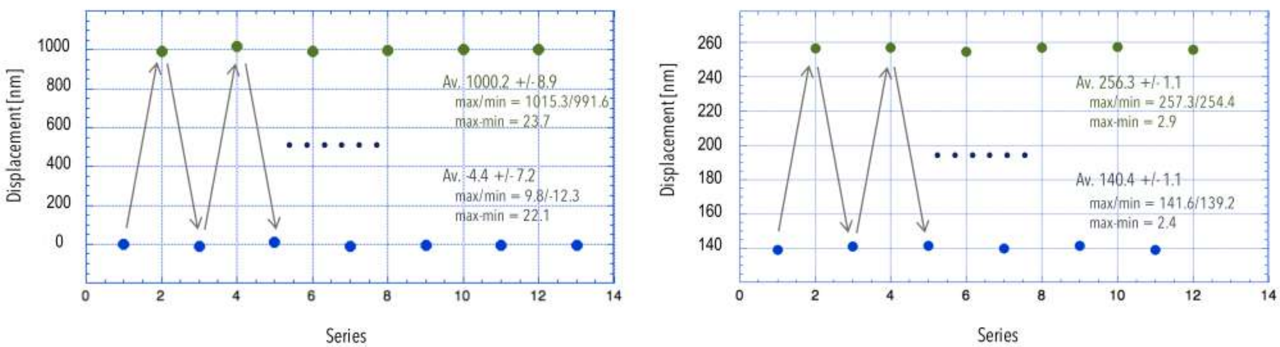

Figure 7.   Results of multiple repetitive test (left : long range, right : short range). Uncertainty (stdv) before and after movement are about (1) 10 nm and (2) 1 nm respectively. Time drift was corrected for each results.

5. FUTURE WORKS

There are many issues to be addressed for future practical use. These include items to be done with the current model, fabrication of new spectroscopic modules toward spectrograph for instruments to be mounted on the telescope, and planning of scientific observations. Specific details are given below.

- Control parameter adjustment
- Operation test with 3-axis independent control
- Optical performance test
- Vacuum cooling test
- Consideration and fabrication of an order sorter
- 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

The spectroscopic module is to be put into practical use within the next few years.

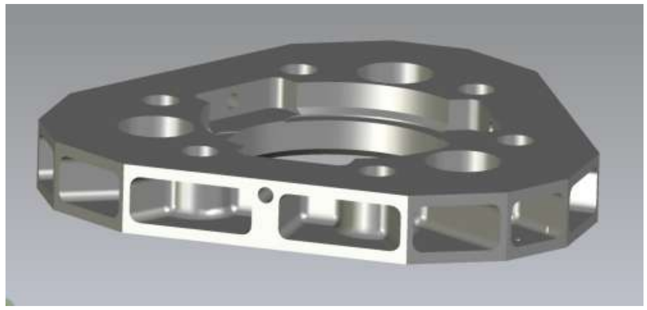

Figure 8. This model was designed to reduce weight while maintaining strength. A prototype made with a 3D printer has successfully reduced weight by approximately 37% compared to the current model.

6. SCIENTIFIC OBJECTIVES

The most important features of Fabry-Perot spectrometers are the ability to select arbitrary wavelengths over a wide range and to perform imaging at those wavelengths. By achieving this with a tunable filter, we can develop a wide range of science that could not be achieved with conventional narrow-band filters with fixed wavelengths, such as diagnostics of physical quantities using multiple emission lines from starforming regions and detection of emission lines associated with star formation from galaxies at arbitrary redshifts. Specifically, the following observations are planned with this spectrometer.

(1) Pick up and classify a wide variety of different types of massive stars in clusters, and obtain hints for the formation and evolution processes of massive stars (clusters) from the intensity and multiple emission line ratios of metal ions in the near-infrared wavelength region, which is characteristic of massive stars. Specifically, near-infrared imaging observations of multiple emission lines not only reveal the evolutionary scenario of massive stars, but also provide strong constraints on the age and evolutionary process of clusters by using the characteristics of massive stars with short existence times for each different evolutionary stage.

(2) Explore the star formation activity in the interior of nearby starforming galaxies (starburst galaxies) and their subsequent evolution into passive galaxies. We will use the near-infrared Paα emission lines (wavelength of 1.875 μm in the quiescent system), which are emitted from starforming regions and are the best tool for depicting star formation activity in galaxy interiors.

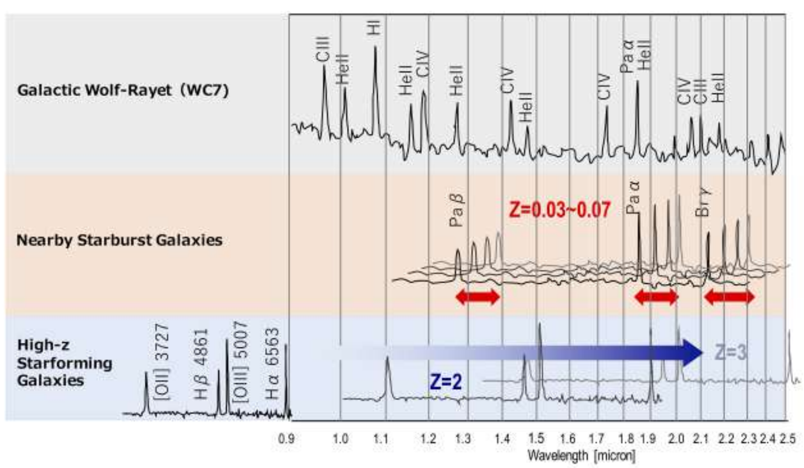

Figure 9. Near-infrared spectra of several objects characterized by starforming activity. Emission lines from a wide variety of metal ions and arbitrarily redshifted emission lines are present over a wide range of wavelengths. Wavelength scanning spectrometers can observe these without any restrictions.

By targeting galaxies at low redshifts (z = 0.03 - 0.07) and using the tunable filter developed in this study, we will realize a systematic Paα emission line survey of starburst galaxies in the nearby universe and map the physical conditions inside starburst galaxies in detail, as well as explore the relationship between the physical processes causing starbursts and their surrounding environment.

(3) It will also enable us to explore the mass-accumulation process of starforming galaxies at the peak of galaxy evolution in the entire Universe. The tunable filter developed here enables narrow-band imaging in the near-infrared at arbitrary wavelengths and is used to observe strong gas emission lines such as Hα emission lines (6563Å in the quiescent system) and [O III] emission lines (5007Å in the quiescent system). Comprehensive observations of starforming galaxies in a wide range of epochs around the peak of galaxy evolution (redshift z = 1 - 3) will enable us to reveal the process of galaxy evolution over time.

7. ACKNOWLEDGMENTS

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