ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

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International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105620S · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296205

COMPACT INTEGRAL FIELD UNIT FOR OPTICAL TELESCOPE OF THE SOLAR-C MISSION

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I. INTRODUCTION

A Japan-led international solar mission “SOLAR-C” is being proposed for mid-2020s launch. It designed to investigate the magnetic activities of the Sun [1], focusing on the study of heating and dynamical phenomena of the solar chromosphere and corona, and to advance algorithms for predicting short and long term solar magnetic activities. For these purposes, SOLAR-C carries three dedicated instruments; the Solar UV-Vis-IR Telescope (SUVIT), the EUV Spectroscopic Telescope (EUVST) and the High Resolution Coronal Imager (HCI), to jointly observe the entire visible solar atmosphere with essentially the same high spatial resolution (0.1"--0.3"), performing high resolution spectroscopic measurements over all atmospheric regions and spectro-polarimetric measurements from the photosphere through the upper chromosphere.

The main science requirement of SUVIT is to obtain chromospheric velocity, temperature, density and magnetic field over as wide a range of heights as possible, by high cadence full spectral line profiles and polarimetry. This is done by a proper choice of chromospheric spectral lines such as Ca II 854 nm and He I 1083 nm. The SUVIT is a meter-class telescope in order to attain sufficient spatial resolution and S/N ratios. With this diameter, well-sampled spectral line profiles can be obtained within 20 seconds, with a polarimetric sensitivity of $3x10^{-4}$ for 0.2"--0.3" pixels, which is sufficient to obtain chromospheric magnetic field measurements above the plasma-beta unity layer. The spatial and temporal samplings are dictated by latest space observations of chromospheric dynamic events that have demonstrated intensity changes on timescales of order 20 s. The SUVIT spectro-polarimeter should be equipped with a powerful integral field unit (IFU) to grasp the rapidly changing chromospheric phenomena with about 10" x 10" field-of-view, whereas a conventional slit-scan spectro-polarimeter is necessary for chromospheric magnetic field measurements at high spatial resolution over a field-of-view large enough to cover a medium-sized active region.

So far, there exist many applications of integral field spectroscopy for ground-based solar observations [2]-[6]. There are three techniques to realize the IFS depending on image slicing devices such as a micro-lenslet array, an optical fiber bundle and a narrow rectangular image slicer array. From the view point of a high efficiency spectroscopy, a wide wavelength coverage, a precision spectro-polarimetry and space application, most of which are mandatory for SOLAR-C, the image slicer consisting of all reflective optics is the best option among the three. In addition, space application requests a small-sized and light-weight IFU. The image slicers are presently limited either by their risk in the case of classical glass polishing techniques or by their optical performances when constituted by metallic mirrors. The optical design of IFU for SOLAR-C demands that width of each mirror of slicer array is as narrow as an optimal slit width (< 100 micron) of spectrograph which is usually hard to manufacture with glass polishing techniques [7]. To solve this difficulty, we can apply a high precision free form cutting machine developed by Canon to manufacture high optical performance metallic mirrors of small dimensions [8]-[11].

For a spectrograph of SUVIT, we designed the IFU made of a micro image slicer of 45 arrayed 30-micron-thick metal mirrors and a pseudo-pupil metal mirror array re-formatting three pseudo-slits; the design is feasible for optical configuration sharing the spectrograph of a conventional slit without any movable elements. According to the optical design and specifications for mirrors of IFU, Canon manufactured a prototype IFU for evaluation, demonstrating high performances of micro image slicer and pupil mirrors; enough small micro roughness for visible light spectrographs, sharp edges for efficient image slices, surface figure for high image quality, etc. In the following, we review the optical design of IFU feasible for the space-borne spectrograph, presenting a progress in designing an additional field lens at slit plane which makes the beams from pseudo-pupil mirrors telecentric configuration We also give results of a second prototype light-weight IFU on whose mirrors a protected silver coating is deposited, together with the method and result of space qualification of the coating on the metal mirror.

II. OPTICAL DESIGN OF INTEGRAL FIELD UNIT

The spectrograph of SUVIT/SOLAR-C is designed to achieve scientific requirements on the spatial (better than 0.2 arcsec) and spectral resolution (resolving power of 10^5) for chromospheric lines at Ca II 854 nm or He I 1083nm. The IFU needs to be designed to share with a conventional slit spectrograph for large field-of-view observations and be placed around the slit plane with a reasonably small physical dimension. This requests four-slit configuration; one from real slit and three from IFU pseudo-slits.

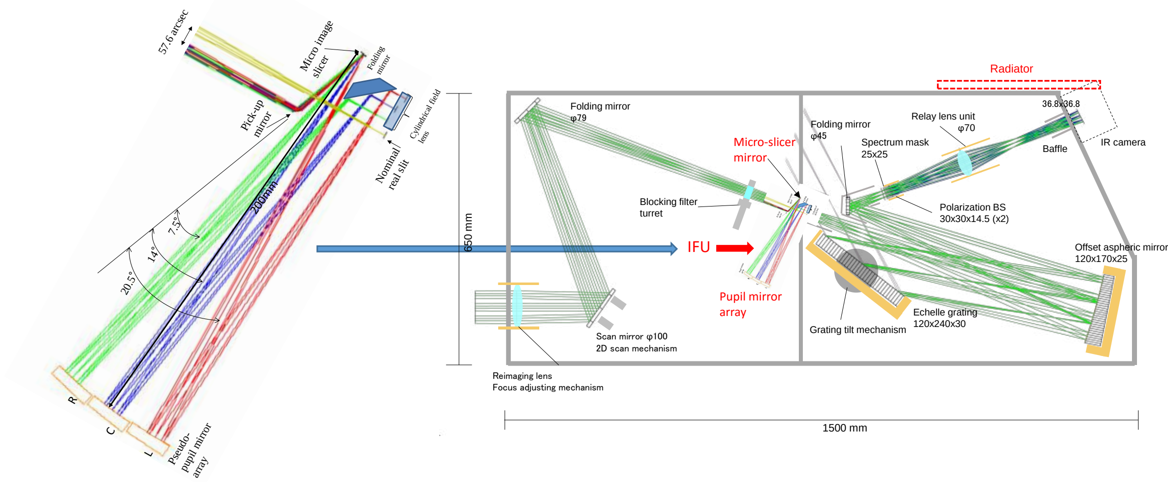

Figure 1.The mirror slicer IFU (left) to be placed around the slit plane of SUVIT spectrograph (right).

The solar image formed on the slit plane by the telescope of beam F/24 with image scale of 0.18 arcsec per 30 µm. Then, we tried to design the IFU in which a slicing mirror is 30 µm wide and a pupil mirror refocus the slicer without changing the image scale. The real slit is 24 mm (143 arcec) high which corresponds to a stack of 15 slicers of 1.58 mm (9.5 arcsec) long. As a result, we come to a stack of 45 narrow slicers of 30µm wide and 1.56 mm long; each 15 set of slicers is re-focused as three set of pseudo-slits. Each flat mirror slicer is set at a different angle so that the diverging beam from each slice exits in three columns of pupil mirror array. Each beam is then reflected by pupil mirror which is offset in the direction parallel to the long axis of each slice. The overall effect is to rearrange the rectangular field of 9.5 x 8.1 arcsec^2 into three sets of a long thin field made up of all the slices arranged end to end, which forms three entrance slits of the spectrograph.

Figure. 1 gives the optical layout of IFU for SUVIT. Note that the ratio of the distances pupil-mirror-to-slicing mirror (200 mm) and pupil-mirror-to-image-of-slice (200 mm) set unity so that the slicer and the image-of-slicer have the same size and that the pupil mirrors are oversized in the direction of diffraction to pick up a main lobe of diffracted beam in the longest observation wavelength of 1083 nm, reducing amount of the light vignetted by the pupil-mirrors. The distance between the pupil mirror and the slicing mirror was determined so that each 15 pupil mirror in a column can have the same off-axis conic asphere. The tilts of pupil mirrors are set so that the re-arranged slicer images make a line with an accuracy of 30 µm and with a gap of 30 µm each other. The pupil images do not need to be exactly on the pupil mirrors, as long as the beam size is sufficiently small on them and this is why we here call them pseudo-pupil mirrors. The optical parameters of IFU is given in [7]. To have a telecentric beam into the spectrograph, a field lens at the slit plane is necessary as explained in subsection 2.4. The field lens causes unwanted defocus. Therefore, the focus positions by the pseudo-pupil mirrors, that is, the distance between the slicer and pupil mirror, need to be optimized according to the defocuses given in Figure 7.

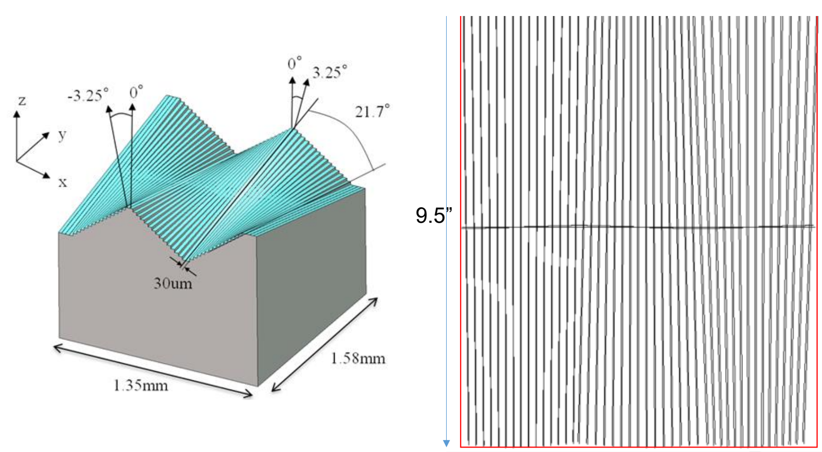

Figure 2. Close up of micro-image slicer unit (left) and its sliced images in arcsec unit projected on the plane perpendicular to the axis of feeding opics.

A. Micro-slicer mirrors

By using the cutting method instead of polishing, it is possible to make the micro slicer mirrors as monolithic module. In contrast to polishing, the cutting can make a flexible shape, and decrease geometrical figure error by making units together. In addition, the cutting has advantages of making micro planes of 30 µm width which have different directions, and ensuring a shape which has sharp edge. However, there is generally a drawback in cutting method: It is difficult to obtain low surface roughness. To overcome this drawback, Canon developed a high precision free form cutting machine and ultra-precision cutting process technology. Canon's high precision free form cutting machine has three liner axes (X-axis, Y-axis, and Z-axis) and two rotation axes (B-axis, C-axis) on a highly rigid frame with air mount to suppress vibration and has a high quality control system which enables positioning resolutions of control axes which is less than 1nm [8]. Moreover, Canon has ultra-precision cutting technology which can control and optimize cutting conditions such as feed speed, cutting depth, rake angle, etc. and other conditions such as crystal orientation, cutting force, temperature, etc. [9]

The micro-image slicer consist of three units, each unit consists of 15 plane mirrors as shown in Figure 2. Each mirror is 1.58mm in length and 30µm in width. Each mirror tilts 1.55 degrees toward θ_x in a unit. Two outside units tilt 3.25 degrees compared to the center unit. This metal mirrors were cut using a high precision free form cutting machine developed by Canon. A rectangular diamond tool whose width is 30µm was set on the B-axis of the Canon's cutting machine, the work of the micro slicer mirrors was set on the C-axis table, and shaper cutting was conducted using single point of diamond tool by controlling XYZBC-axes.

Figure 3 shows the scanning electron microscope (SEM) images of the micro slicer mirrors. It was found that the micro slicer mirrors of flip grating shape were cut as expected. The surface roughness of one of the micro slicer mirrors measured by Zygo NewView 3D Optical Surface Profiler; the surface roughness is about 1 nm rms on average. By using Canon's high precision cutting machine and cutting process technology, it is confirmed that cutting can obtain low surface roughness equivalent to polishing. The width of this micro slicer mirrors is 30 µm, it is too small to be constructed from separated mirrors and also reduce tilt errors. However, the cutting does not require re-configuration because it can make monolithic module and is able to satisfy strict requirement of tilt error (10 arcsec). The edge quality is less than 0.1 µm. A sharp figure of diamond tool used makes a sharp edge by cutting. Tilts of each mirror's surface were measured from profiles by Zygo NewView 3D Optical Surface Profiler. Tilt errors were calculated by subtracting tilts between two consecutive mirrors from design values. It was shown that tilt errors in both axes are less than 6 arcsec. Finally, the slicer mirror was deposited with a space qualified protected silver coating by Canon.

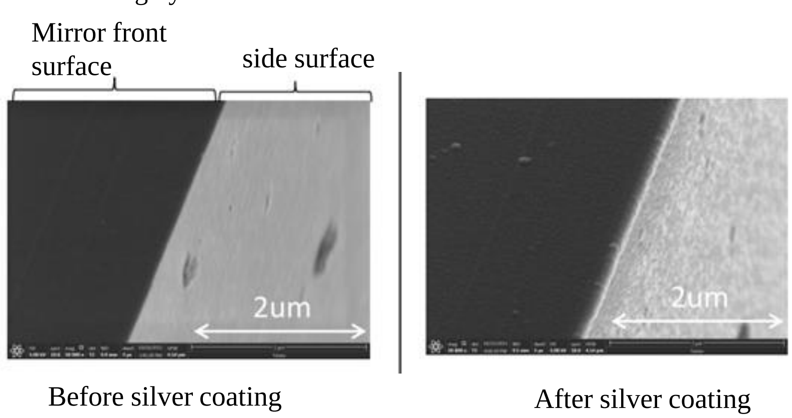

Figure 3. SEM image (X50) showing an edge quality of the micro slicer mirrors before (right) and after (right) the protected silver coating.

B. Pseudo-pupil mirrors

The pseudo-pupil mirror also consists of three units and each unit has 15 mirrors. All mirrors are off-axis conic aspheres. For light-weighting (850 g), the substrate of the mirror was designed with an aluminum alloy and its mirror surface was plated with different metal before cutting for small micro-roughness. The metal pseudo-pupil mirror was cut using the high precision free form cutting machine of Canon. The pseudo-pupil mirror also has tight requirement in tilt error (7.7 arcsec) so that cutting which does not need re-alignments of separated mirrors is very useful compared to polishing which needs alignments of separated mirrors and control tilt of each mirror's surface.

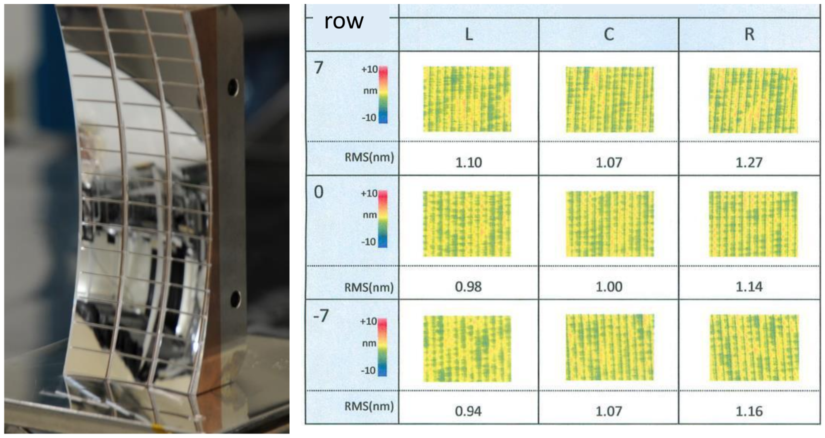

Figure 4. Aluminum alloy made pseudo-pupil mirror unit deposited by the protected silver coating (left) and the surface roughness measured at six selected mirrors of the mirror unit.

The surface roughness measured by Zygo NewView 3D Optical Surface Profiler, being less than 1.27 nm rms as a result (Figure 4). The requirement of 1.5 nm rms was achieved and it is confirmed that cutting can obtain low surface roughness even if a work is freeform surface. In order to measure a surface accuracy, A-Ruler developed by Canon was used [10][11]. After measuring all surfaces' shape, surface accuracy was calculated using best fitting for all the surfaces together. It was found that the surface figure accuracy is 59 nm PV and it is enough excellent compared with the requirement (80 nm PV). A-Ruler was also used for measuring tilt errors. Tilt errors between designed values and tilts around X-axis and Y-axis were calculated after all the surfaces simultaneous best fitting. Tilt errors around X-axis of all surfaces are less than 4.6 arcsec and tilt errors around Y-axis of all surfaces are less than 2.3 arcsec which are less than requirement (7.7 arcsec). This means that by using cutting method, tilt errors can be reduced even if a surface is freeform. The pseudo-pupil mirror was also deposited with a space qualified protected silver coating by Canon.

C. Optical performance of combined pseudo-pupil mirror with micro-slicer mirror

To optically evaluate the image slicer IFU, the prototype micro image slicer and pseudo pupil mirror array was set up as designed, using a halogen lamp focused on the micro slicer with focal ratio of F/24. We confirmed that the pseudo pupils are projected as designed and re-arranged slicer images are focused by the pseudo pupil mirrors as three pseudo slits at the distance 200 mm away (Figure 5).

We also simulated a spectrograph configuration with the IFU, simply using a collimator lens and a camera lens, to re-focus the pseudo slits on a camera and evaluate their optical quality. The collimator was not large enough to catch all the beams from the pseudo-pupil mirror, Other than this, we confirmed very sharp slicer images and low level of scattered light, that is, very small errors in the surface figure of pseudo-pupil mirrors and very small micro roughness of both mirrors as mentioned above.

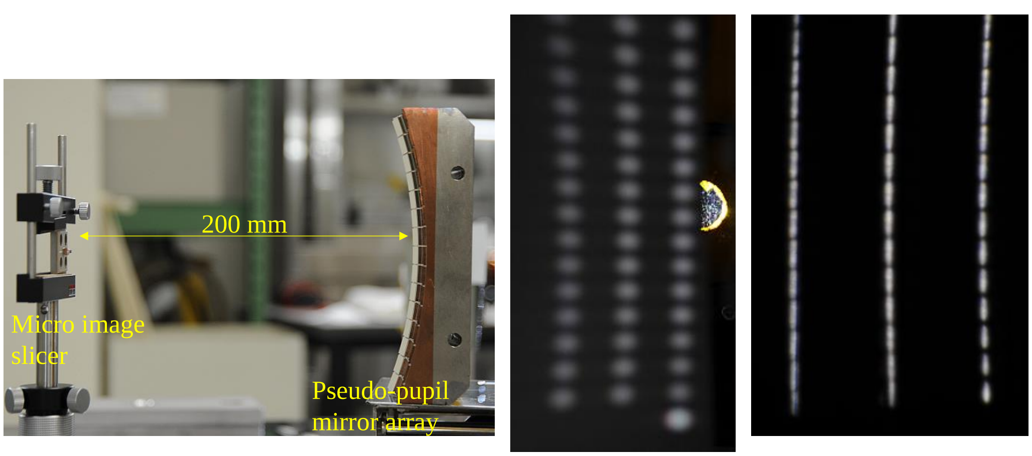

Figure 5. Set up of IFU (left), footprint at pseudo pupil mirror array of F/24 beams from micro image slicer (middle) and image on screen of re-arranged slicers (right).

D. Design of Field Lens

To have a telecentric beam into the spectrograph, a field lens at the slit plane is necessary (Figure 6). The role of the field lens is to change diverging (F/1.4) principle beams to parallel ones without much degrading image quality. The change of beam angle is realized by a wedge plate. Therefore, the field lens can be designed as a stack of plates of different wedge angles, which is determined by incident angles and refractive index of the plate. At the wedge, focus shifts take place according to the relation $d(1-1/n)$,where the d is thickness of wedge and the n is a refractive index. These defocus partly compensated by the focus position of pupil mirror. However, differential focus shift along a wedge remains. To have smaller defocus change over a whole slit length, the field lens need be made of material of higher index like ZnS or ZnSe. We found a satisfactory design of cylindrical field lens with lens material of ZnS or ZnSe (Figure 7); Strehl ratio changes from 0.96 to 0.99 at the steepest wedge for 854 nm. The figure of this cylindrical lens is close to a parabola whose radius of curvature is -111.1 mm and conic constant -1. As a first step, a preliminary off-the-shelf ZnSe spherical cylindrical lens whose radius of curvature (-101.56 mm) is close to the design was used to examine the validity of the optical design (Figure 8).

III. SPACE QUALIFICATION OF PROTECTED SILVER COATING ON METAL MIRROR

From a view point of reflectivity in visible wavelength, particularly in the band at 854 nm, a silver coating is the most preferable. To have robust silver coating of high reflectivity (>95 % in visible wavelengths, Figure 9) on metal mirrors, an adhesive layer is necessary between the substrate and silver layer. Moreover, the surface of small roughness metal mirrors of the IFU in this study has additional surface layer of different metal for small micro-roughness. To qualify space application of the silver coating to be deposited on the metal mirrors of IFU, tests explained below which were used for qualification of an enhanced silver coating of aluminum alloy made heat dump mirrors of Hinode Solar Optical Telescope [12] were performed (Table 1). Note that to qualify the coating on the micro image slicer, it was thermal cycled and inspected with SEM to see any degradation on the mirror surface.

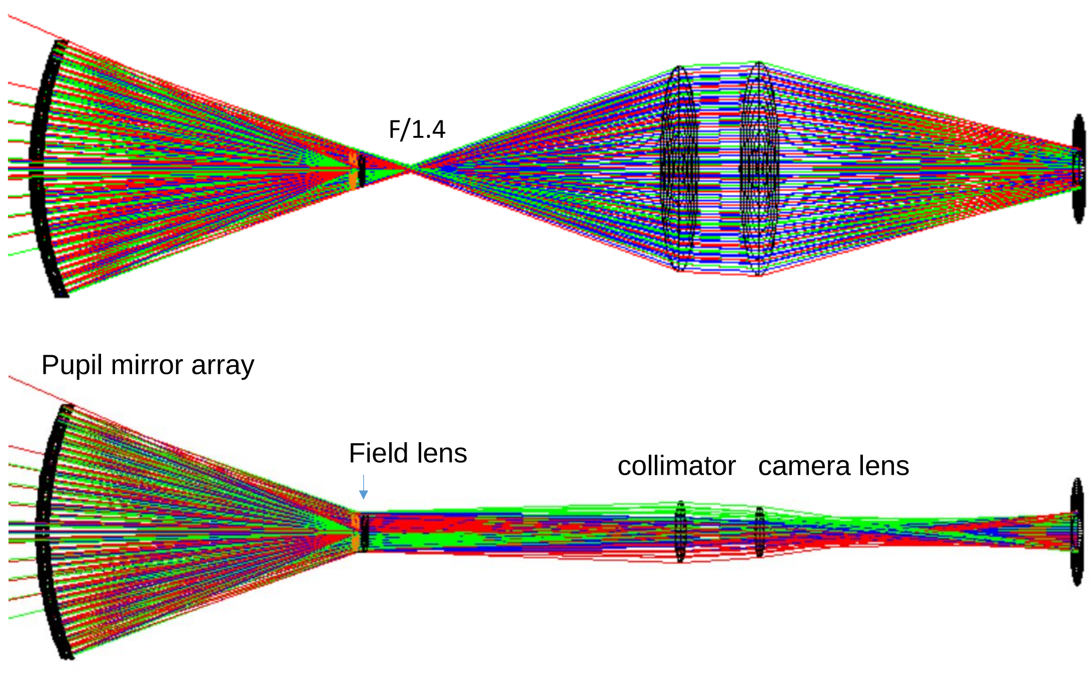

Figure 6. Optical ray path from IFU through spectrograph without a field lens (top) and with a field lens.

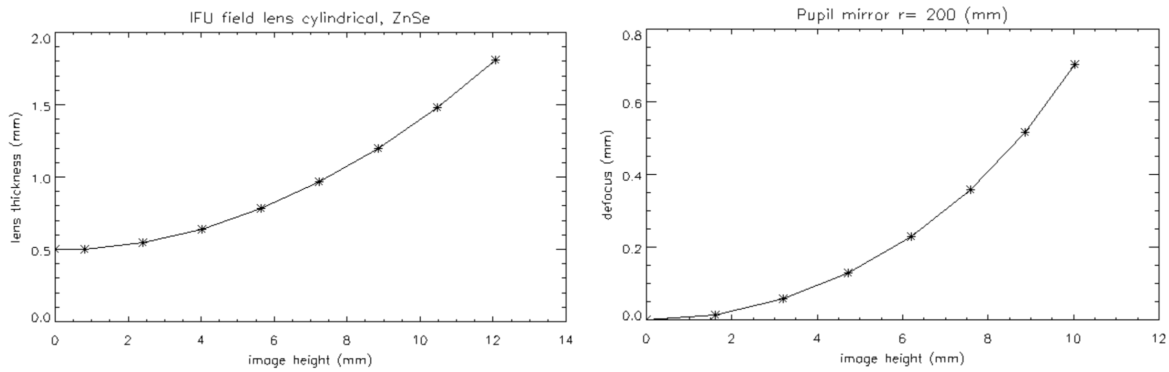

Figure 7. Half cross-section of ZnSe cylindrical lens (left) and defocus shifts do be compensated at each wedge center. The figure of this cylindrical lens is close to a parabola whose radius of curvature is 111.1 mm and conic constant -1.

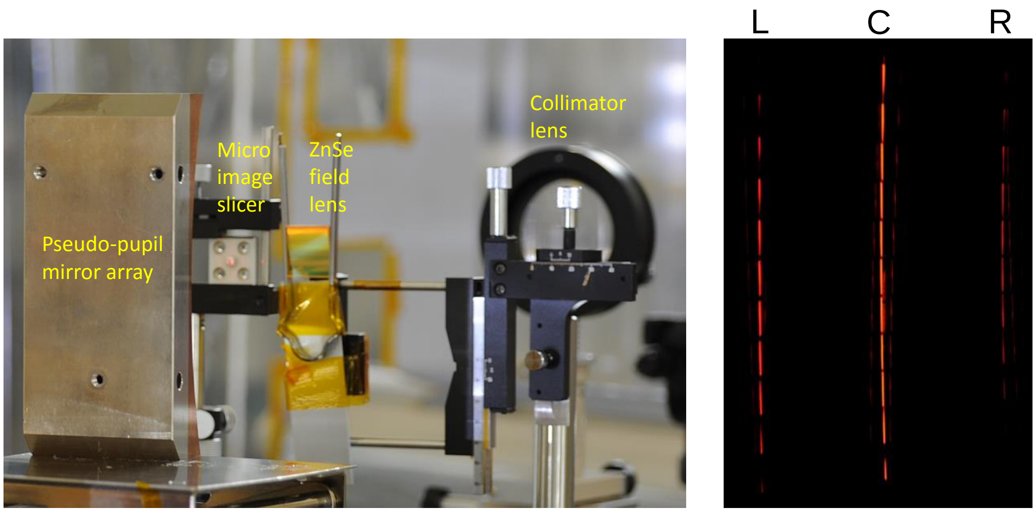

Figure 8. Optical configuration to simulate a spectrograph, refocusing the rearranged slicer mirror images onto a camera (left) and re-focused three-slit configured slicer image (right). Note that a red-band (600nm) interference filter was put in the beam of a lamp to cancel a chromatic aberration of cylindrical field lens and a collimator lens. The rearranged slice image demonstrate that the optical parameters and tilt angles of pseudo-pupil mirrors are fabricated as designed. However, weak ghost slicer mirror images appear aside of the main slicer image because side lobes of light diffracted by narrow slicer mirrors are also refocused by neighboring pupil mirrors which need to be masked out.

A. Test samples

Test samples which made of aluminum alloy plates (25x25 mm^2) and of the same surface structure as the actual IFU mirrors were deposited with a protected silver coating by Canon.

B. Thermal cycling test

The samples were cycled 50 times through temperatures of: -25 degC to 60 degC in a dry air environment. The heating and cooling rates were 3 degC/min and the samples were held for 20 minutes at the high and low temperature ends.

C. Humidity test

The samples put in a high humid constant temperature reservoir (humidity of 95% and temperature of 40 degC) for 48 hours.

D. Vacuum test

The samples were exposed in vacuum 10^{-4} Pa for 48 hours without thermal cycling

E. Radiation test

Test samples were exposed in an electron beam of 1 MeV energy for total dose of 5 kGy. The electron beam of this energy stops in a surface layer of the metal samples and

F. UV irradiation test

The test samples were irradiated for 1867 ESH with 2-3 times solar UV light source.

G. Reflectivity

The optical reflectance of the test samples was measured before and after the tests in the visible and NIR range (200-2600nm) using SHIMAZU UV-3100PC spectrophotometer with an integration sphere configuration to see any change in coating quality. Reflection angle was 12 degs.

H. Adhesive tape test

The test is performed after the tests mentioned above by applying a Scotch tape and attempting to lift the coating from the surface by lifting the tape to see any removal of surface layers.

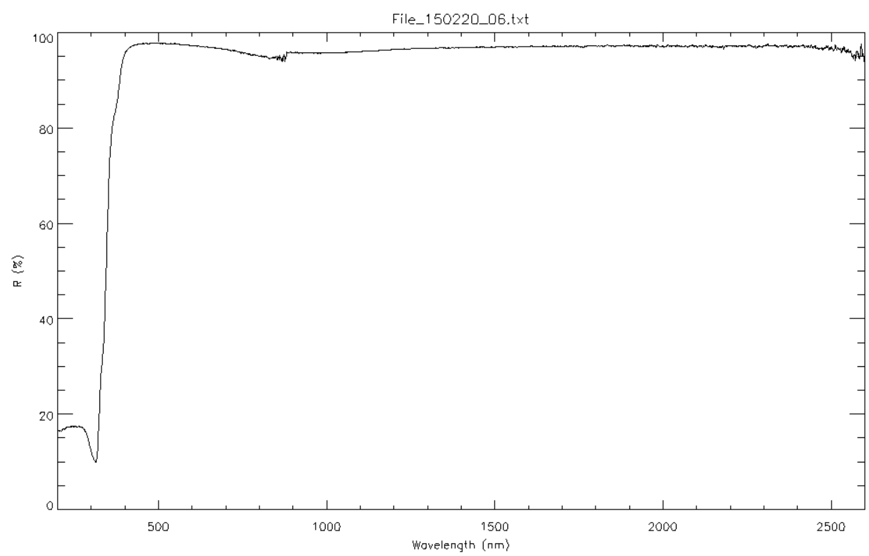

Figure 9. Reflectance of the protected silver coating by Canon.

Table 1. Summary of space qualification tests for the protected silver coating by Canon on metal mirror.

Test Item	Reflectivity	Tape test
Thermal cycling	No change	No removal
Humidity	No change	No removal
Vacuum exposure	No change	No removal
Electron beam radiation	No change	No removal
UV irradiation	No change	No removal

III. SUMMARY

We have presented an optical concepts and manufacturing method for image slicer IFU to attain high performances of micro image slicer; small roughness, sharp edges, surface figures, etc., using a novel technique developed by Canon. Our IFU is small-sized and consists of micro image slicer of 45 arrayed 30-micron-thick metal mirrors and a pseudo pupil mirror array for refocusing three pseudo-slits, providing possible optical configuration for a multi-slit spectrograph: coexistence of a real slit and pseudo slits from the IFU, which is suitable for space-borne spectrograph like that of SOLAR-C. Using a prototype IFU, we confirmed high optical performances of metal-made micro image slicer mirrors and light-weight pseudo pupil mirrors, such as the micro roughness less than 1.3 nm rms, edge sharpness less than 0.2 μm even after reflective coating, mirror tilt errors less than required accuracies, etc. We put a protected silver coating on both of metal mirrors after its successful space qualification tests. We also presented a concept of field lens placed at the slit plane which change the diverging beam from the pseudo-pupil mirrors to a telecentric beam into a spectrograph. The field lens need to have high index of larger than two. Preliminary off-the-shelf ZnSe made cylindrical lens was used to verify the optical concept.

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