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Ultra-compact machined slicer IFU

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ABSTRACT

Canon has the world's most advanced cutting machine and has provided the world's first CdZnTe[1] and InP[2] immersion gratings to the market. Cutting gratings on brittle materials is very delicate, and nm-accurate processing can be achieved by cutting alone. Using this technology, we have fabricated the machined image slicer integral field unit (MISI) for the Diffraction-Limited near-IR Spectropolarimeter (DL-NIRSP)[3] of the Daniel K. Inouye Solar Telescope (DKIST)[4]. The MISI-36 we produced is consists of 112 36μm×1.3mm micro slicer mirrors, a parabolic collimator, a monolithic flat mirror array consists of 112-fold mirrors, and a monolithic spherical mirror array consists of 112 spherical mirrors. This paper presents the latest high precision machined and fabricated ultra-compact IFU/ MISI-36.

Keywords: Image Slicer, Integral Field Unit, machining, Spectrograph, monolithic, Solar, Spectroscopy

INTRODUCTION

High Precision Marching in Canon

Canon's products are supported by its superior processing technology, and especially in precision cutting, the company has always achieved the world's most advanced precision through its own research and development of cutting machines. Figure 1 shows our original machine[5] which is a 5-axis machine with 3 linear axes and 2 rotary axes. The processing methods are the shaper and fly cut shown in Figure 2. Typical product accuracies for this equipment are < 1 nm RMS for surface roughness, < 2 nm RMS for positioning stability, and < 10 nm RMS for scale stability. What these values mean is that the stability of the machining point is extremely excellent, allowing not only general metal cutting, but also cutting of crystalline materials that are easily destroyed by the slightest vibration.

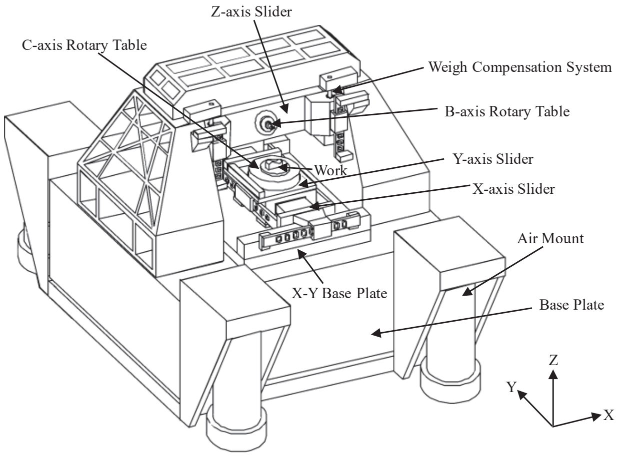

Figure 1. Canon original free-form cutting machine (A-Former)

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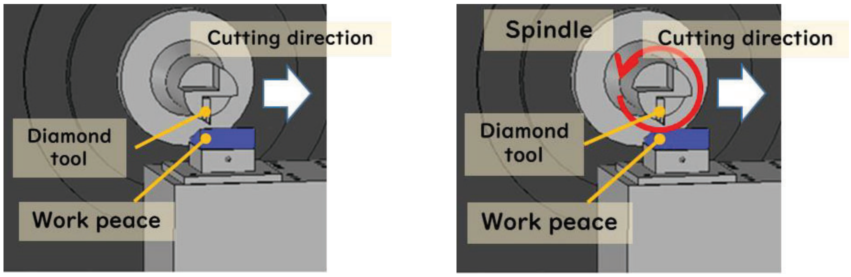

Figure 2. Typical processing methods: Shaper (left), fly cut (right) Shaper is processed with a fixed tool, while fly cut is processed with a rotating tool. Select the method best suited to the workpiece.

Gratings are one of the products that simply demonstrate the accuracy of a machining center. Grating machining has always required the best of the best in terms of machining. Furthermore, the performance of the machine becomes even clearer when grating processing is performed on brittle materials. IFU devices are fabricated by shaper, and the results of grating processing of ZnS[6] are shown in Figure 3 as an example of the potential of our machine by shapers. In polycrystalline, which is more difficult to cut stably than single crystal, a surface roughness of 1.1 nm RMS is achieved by cutting alone. The enlarged SEM image of grooves (center) shows that the grain boundary has been successfully cut.

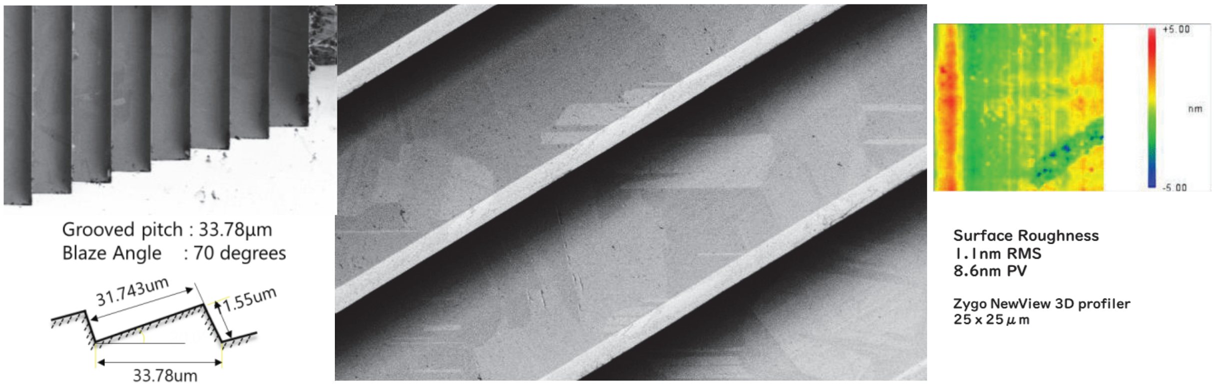

Figure 3. ZnS polycrystalline cutting grating by shaper

Machined image slicer for IFU

2D spectroscopy is widely used in many observations and is positioned as a very important function. A typical image slicer integral field unit divides the two-dimensional field of view into n elongated subfields, which are optically rearranged into an elongated field to form the entrance slit. The key to this is an image slicer, a collection of n rows of small mirrors arranged to fit the field of view, each row oriented in a different direction to spatially separate them for rearrangement. One method of fabrication is to precisely divide the polished mirrors into sections, which are then shifted to the desired angle and stacked on top of each other. In contrast, we have provided a machined image slicer that cuts the desired mirror into a single metal block. This method is much simpler than dividing mirrors, but all mirrors are one piece (monolithic structure) and the relationship of each mirror does not change over time. This structure is extremely important for the stability of the equipment and is especially advantageous in cases such as space observation, where readjustment after operation is impossible. In addition, the machining method can easily produce mirrors with very narrow widths by selecting the tool width.

Our first practical machined image slicer[7,8], offered in 2013, has a mirror width of 30µm and 45 mirrors in Figure 4. The field of view is 1.35mm x 1.35mm with 45 flat mirrors, each mirror being 1.35mm long and 30µm wide. In the case of such a flat mirror, the mirror can be fabricated by simply cutting it in a straight line at the desired angle using a tool that is normally the width of the mirror. Although a tool width of 10µm is possible, the length of the tool is necessary for the mirror to be formed three-dimensionally due to its angle, and in some cases, the length is limited by the strength of the tool. Figure 5 shows an integrated machined image slicer consisting of 84 mirrors with a 20µm width[9].

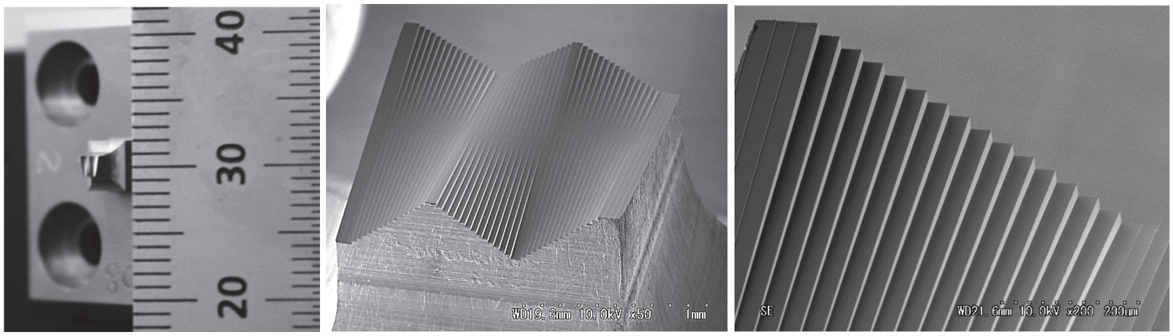

Figure 4. Picture and the scanning electron microscope (SEM) images (x50, x200) of the machined image slicer.

Thus, the process itself is the same even if the mirror width is narrower and the number of mirrors is significantly increased. However, if the angle of the mirrors is not simple, changing in the direction of the mirror length (tilt), but tilted in the direction of the mirror width, the ideal shape cannot be cut out unless the shape of the tool is the same as the valley between each of the mirrors. Therefore, a very large number of tools are ideally required due to the number of mirrors and the tilt configuration, but the number of tools used is reduced and the mirror angle is machined with priority, resulting in a mirror with a mirror width slightly different from the ideal. Of course, it is possible to produce the ideal shape using the necessary number of tools, but even with a limited number of tools, the optical effect is adjusted within an acceptable range.

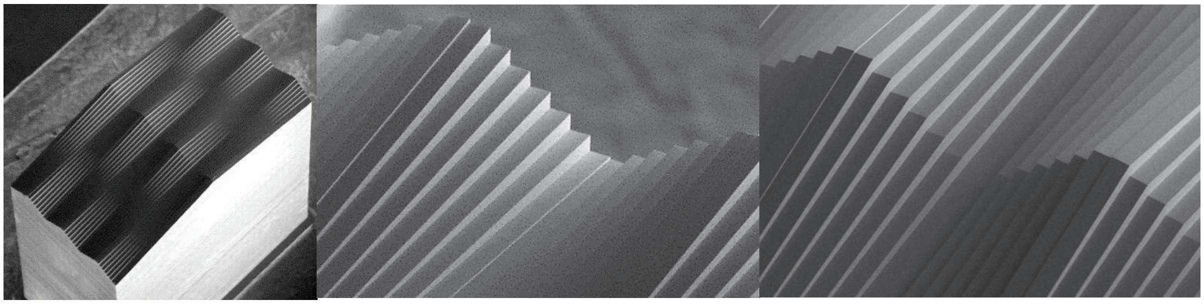

Figure 5. SEM images (x100, x500, x500) of monolithic machined image slicer consisting of 84 mirrors with a 20µm width.

Even when a mirror-width tool is used, the length direction does not have to be straight (flat) to be the processing locus, and it is possible to have any curve in the length direction. If the mirror that constitutes the slicer is a free-form surface, it is possible to form a free-form surface by continuously cutting out a very narrow area using a sharp tool. This is a common method for machining free-form mirrors, and the mirrors that make up the IFUs in this paper were fabricated using this method.

ULTRA COMPACT MACHIEND SLICER IFU MISI-36

Optical Design

For each of the micro slicer mirror, the optical system of MISI-36[10] reimages the micro slicer mirror to a designated position in the exit port using a parabolic collimator mirror to collimates the diverging beam from the slicer mirror, followed by a micro flat folding mirror, and a micro spherical mirror to refocus the image[3]. Figure 6 shows the optical diagram. As can be seen in this dense diagram, the mirrors are very close to each other and are divided into four groups based on their roles, and the actual device is fabricated by integrally constructing the mirrors that make up these four major groups. They are Collimator, Slicer, Spherical Mirror Array and Fold Mirror Array in the order of their physical location along the local Z axis defined by the propagation direction of the chief ray of the incoming beams. In front of the MISI-36 is a relay unit consisting of six mirrors with no magnification to adjust the spatial distance to place this unit.

Except for the six mirrors in the relay unit, this MISI-36 consists of 337 mirrors. It is not common to precisely place this many mirrors, but that will be discussed in the unit design.

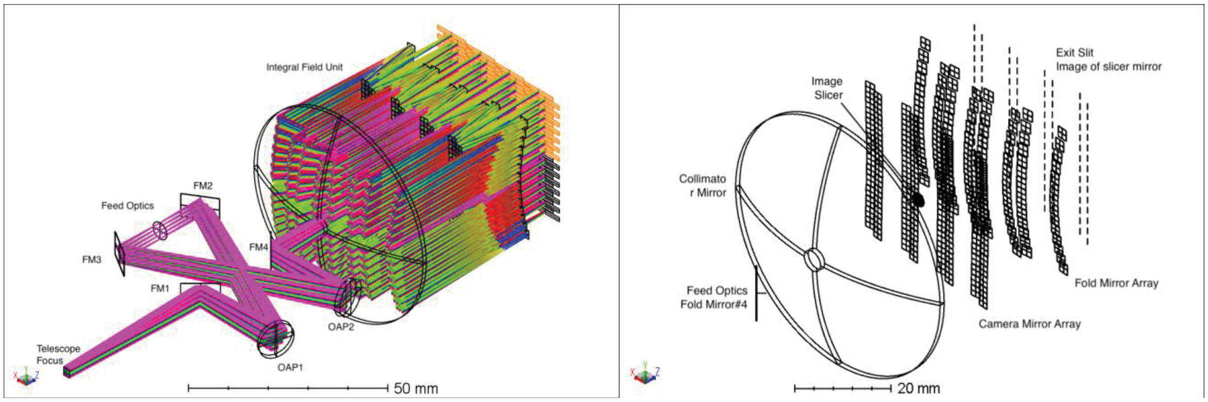

Figure 6. Full Zemax model of MISI-36 with relay unit in front of MISI-36 (left), Optical system of MISI-36 showing all the optical components and their grouping (right)

Unit design

The biggest problem in configuring a good optical design with minimal space into an actual unit is the near impossibility of incorporating structures to adjust individual mirrors. In fact, the distance between the first collimator and the last slit in the optical axis direction of the IFU is only about 70 mm, in which 337 mirrors are placed. We decided to eliminate any adjustment mechanism due to the precision of the fabrication of the structural components and the precision of the mirror placement by using original high precision cutting machining.

Figure 7 shows the unit's configuration[11]. The four groups of mirrors shown in the optical design are integrated devices, and the angular and positional accuracy between each component mirror is ensured by the accuracy of the cutting machine, which is better than the accuracy that could be achieved by an adjustment mechanism. The relative positions and angles with respect to the two reference planes of the device are adjusted in the pre-machining setup. In this way, the accuracy of each optical device is assured with respect to the two reference planes, and the structure is such that they are stacked in a case with two reference planes machined with high accuracy. The optical devices are stacked with spacers fabricated according to the required distance from each other based on the manufacturing results. As shown in the lower right of the figure 7, 10 metal parts are stacked, and an O-ring (elastic material) is inserted between the slit and end plate to hold them in the stacking direction. The parts except the front and end plates are fixed by pressing them with screws from the vertical direction against the two reference planes. This innovative configuration has resulted in ultra-compact overall unit size of only 70mm x 70mm x 80mm.

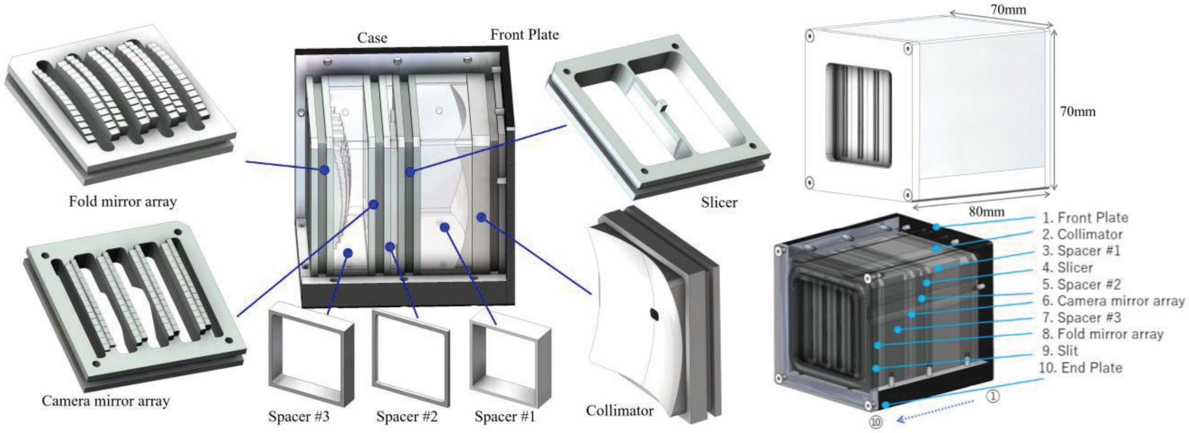

Figure 7. Ultra-Compact machined slicer IFU/MISI-36 Configuration

FABURICATION

Collimator

The collimator has a parabolic mirror within a common 55mmx55mm rectangle for stacking. It has the hole in the center for guiding light to the slicer. This is round mirror, this mirror was fabricated by turning in our original cutting machine as same as others. Figure 8 shows pictures of the workpiece before processing and the collimator after processing. The base material is made of low expansion metal (Invar), and the machined surface is Cu plated with good machinability, just like other devices. Typical surface roughness of each mirror is <1.5nm RMS, and surface profile accuracy is 50 nm PV. Protected Silver is deposited on the mirror surface after cutting.

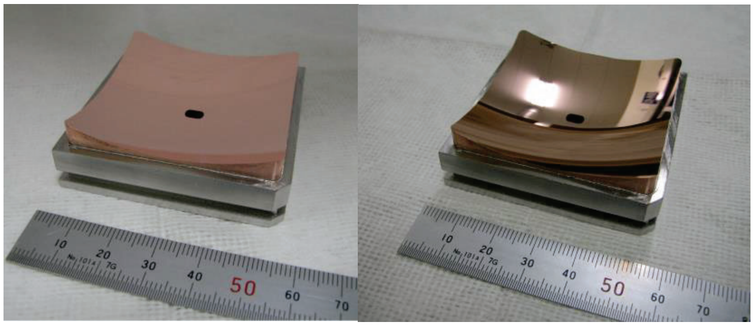

Figure 8. Pictures of the Collimator before finishing(left) after finishing(right)

Slicer

The Image slicer consists of 56×2 slicer mirrors, each with a dimension of 0.036mm(36μm) ×2.664mm. The slicer was configured into a 55mmx55mm frame shape common to stacked structures by shaper machining using a 36μm tool and machined into the base surface of the entire slicer size. Figure 9 shows pictures after processing. The base material is a low expansion metal (Invar), and the area to be machined is Cu plated with good machinability. Figure 10 shows SEM images. They are formed in one piece in a staircase-like shape. Typical surface roughness of each mirror is <1.5nm RMS, and the arrangement relative accuracy of the mirror is 0.05μm in position and about 1 second in angle. Protected Silver is deposited on the mirror surface after cutting.

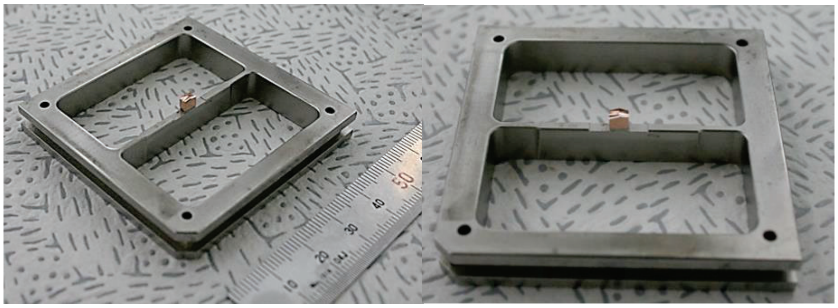

Figure 9. Pictures of machined image slicer

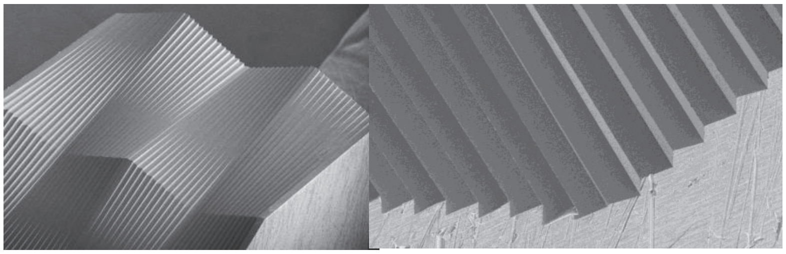

Figure 10. SEM images of machined image slicer, x80(left) x500(right)

Camera mirror array

The camera mirror array consists of 112 spherical mirrors, each approximately 2 mm x 2 mm, with a focal length of 30 mm. Same as other devices, the structure has two reference surfaces of 55mmx55mm low expansion metal (Invar) with apertures for light to pass through and the surface where the mirror is processed is Cu plated. Figure 11 shows pictures of the camera mirror array after cutting. The light reflection shows that each mirror is not flat, and since they are positioned directly opposite the slits, the arrangement is flat and has eight rows of mirrors corresponding to the number of slits.

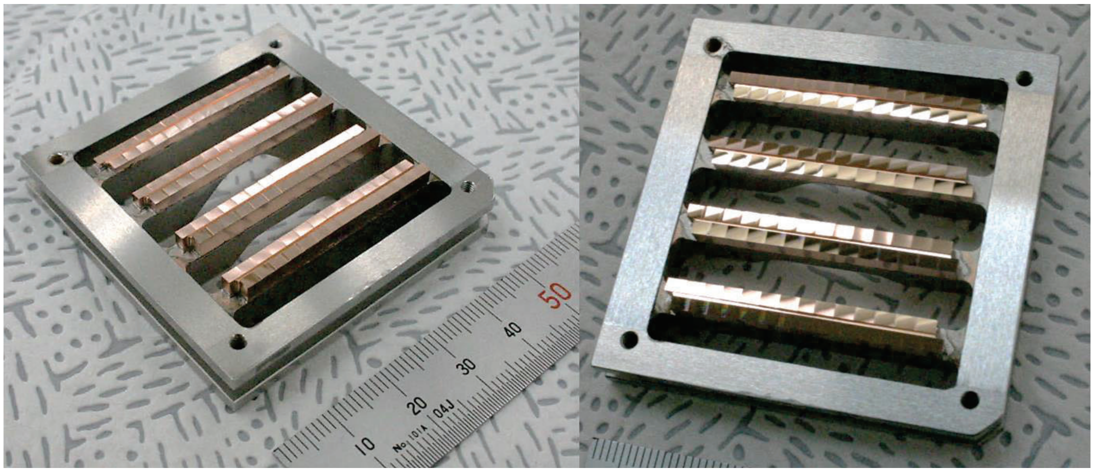

Figure 11. Pictures of the Camera mirror array

Folding mirror array

The Folding mirror array consists of 112 individually oriented mirrors machined in one piece to guide the light, which is divided by the slicer and collimated by the collimator, to the camera mirror. The 112 mirrors are approximately 2 mm x 3 mm in size, arranged in eight rows to match the slit output, and They have a three-dimensional shape with a raised area near the center to match the optical path length of the slicers. Figure 12 shows pictures of the Folding mirror array after mirror processing. As with the other devices, the base material is a low expansion metal (Invar) with 55mm x 55mm in size and the machined areas are Cu plated.

In Figure 12, the area around the mirror is blackened because a blackening process using a laser process is applied to the extent possible to absorb stray light. The narrowest part of the 8-row spacing is only 0.8 mm, and the design considers machining constraints at the optical design stage, such as cutting tool interference. Mirror spacing within a row is similarly considered for the spacing required for processing constraints.

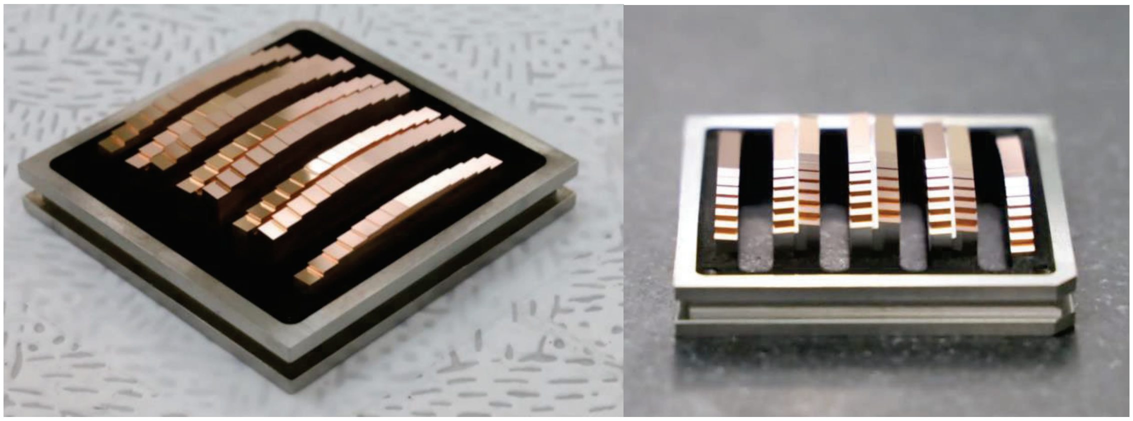

Figure 12. Pictures of the Folding mirror array

Assembly

The structure of each mirror device, which is guaranteed to be orthogonal on the two reference planes and parallel on the 55mmx55mm plane, is constructed by assembling each plane precisely, so that the mirrors that comprise the device are accurately aligned. Figure 13 shows pictures of other devices to be stacked. Each of the three spacers is fabricated with a thickness that allows for accurate spacing between each mirror based on the reference position of the mirror and the post-fabrication position of the base frame (55mmx55mm). The end plate has a groove for an O-ring on the case side, which presses all stacked parallel surfaces together with the deforming pressure of the O-ring during fixation.

Figure 13. Pictures of Front plate, Spacer #3, Slit, End plate (outside of case), End plate (inside of case)

Figure 14 shows pictures of the two cases. Fix the front plate in a case that ensures right angles at three reference planes, each with 55mmx55mm outline, and devices with multi-sided Stack them making sure that the height is less than 3µm. The outer frame is completed by assembling the case for fixing, and then the end plate with O-ring is assembled and each reference plane is fixed closely and completed by tightening each screw on the side of the fixing case.

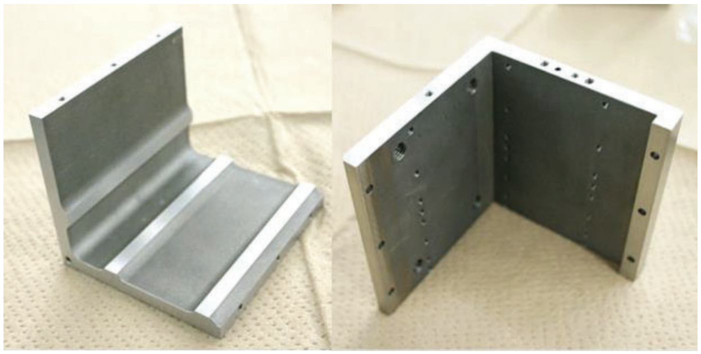

Figure 14. Pictures of Case with 3 reference planes(left), Case with fixing holes(right)

Figure 15 shows the assembled and white-light operating conditions. Assembled with two cases and front and rear plates, MISI-36 is an ultra-compact IFU measuring 70 mm x 70 mm x 80 mm. The innovative IFU consists of 337 mirrors that divide the image into 112 sections and rearrange them into 8 rows, and has no adjustment mechanism of any kind, making it mechanically very reliable.

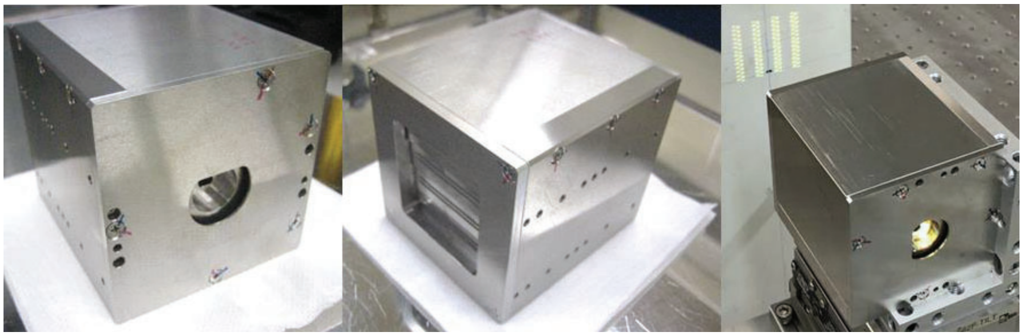

Figure 15. Pictures of assembled MISI-36; Entrance side(left), Exit side(center), Operation check by white light(right)

CONCLUTIONS

This paper describes the fabrication of an ultra-compact machined slicer IFU that fits into a physical space of 70mm x 70mm x 80mm with the function that divides the image into 112 segments composed of 337 mirrors. This unit is also innovative in that it does not require any optical adjustment at all, as the mirrors for each function are manufactured as a single device in a high-precision block, and the necessary placement precision is obtained simply by stacking them in the high-precision case. The stable structure of the IFU is a decisive factor in facilitating its application in space observation and other applications. It is also possible to process multiple gratings in a similar structure, and it is also possible to produce a unit that performs up to spectroscopy in a similar structure.

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