A trial production of a large format image slicer unit for a possible future mid-infrared instrument on the TMT

Itsuki Sakon*[a], Yuji Ikeda[b], Hiroyuki Nakagawa[c], Hitoshi Tokoro[d], Mitsuhiko Honda[e],
Yoshiko K. Okamoto[f], Hirokazu Kataza[g], Takashi Onaka[a],
Mark R. Chun[h], Matthew J. Richter[i], Christopher Packham[j]

[a]Department of Astronomy, Graduate School of Science, University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[b]Photocoding, Inc., 61 Ikeda-cho, Iwakura, Sakyo-ku, Kyoto 606-0004, Japan
[c]Crystal Optics, 3-4-25 Imakatata, Otsu, Shiga 520-0241, Japan
[d]Astro-Aerospace, Inc., 1333-1 Atobe, Mugegawa-Cho, Seki, Gifu 501-2697, Japan
[e]Department of Physics, School of Medicine, Kurume University,
67 Asahi-machi, Kurume, Fukuoka 830-0011, Japan
[f]Institute of Astrophysics and Planetary Sciences, Ibaraki University,
2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan
[g]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency,
3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
[h]Institute for Astronomy, University of Hawaii,
640 N. A'ohoku Place, Hilo, HI 96720 USA
[i]Department of Physics University of California, Davis,
1 Shields Ave. Davis, CA 95616, USA
[j]Department of Physics and Astronomy, The University of Texas at San Antonio,
1 UTSA Circle, San Antonio, Texas 78249, USA

*isakon@astron.s.u-tokyo.ac.jp; phone +81-3-5841-4276/ fax +81-5841-7644

ABSTRACT

We have carried out a trial production of the large-format (n=11) image slicer unit for a possible future mid-infrared instrument on the TMT aiming to verify its technical feasibility. The key elements in our trial production are the monolithic large-format slice mirrors and the monolithic large-format pupil mirrors. The results of our trial production of those key elements based on the ultra high-precision cutting techniques and the assembly of the large-format image slicer unit are presented in this paper.

Keywords: Integral Field Unit, infrared, image slicer

1. INTRODUCTION

While the future infrared space-based telescopes such as JWST (Clampin 2014) and SPICA (Nakagawa et al. 2014) achieve the highest sensitivity in the mid- to far-infrared and provide us opportunity to detect the faintest ever emission from the interstellar medium (ISM) of remote galaxies, the future mid-infrared instrument on thirty meter telescope (TMT) with the mid-infrared adoptive optics provides us, for the first time, a capability to investigate the variations in the infrared spectra of dust and gas on a

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spatial scale better than 0.1 arcsec. For example, Galactic nearby (< a few kpc) stellar sources of various main sequence masses at various stellar evolutionary stages offer unique laboratories to investigate the life cycle of dust and gas in circumstellar environments. Those targets will be much more efficiently observed by mean of the Integral Field Unit (IFU) spectroscopy with the FOV size of a few arcseconds by a few arcseconds rather than the long slit spectroscopy with a few tens arcseconds' slit length. Facing on the growing science requests to have IFU spectroscopic capability in the mid-infrared for the TMT, we have carried out a trial production of the large-format image slicer unit for a possible future mid-infrared instrument on the TMT aiming to verify its technical feasibility and to demonstrate its overwhelming spectral mapping efficiency rather than the case of a long slit spectroscopy. This paper reports the results of the trial production of the large format (n=11) image slicer unit designed based on the specification of TMT/MICHI (Packham et al. 2012).

2. SCIENCE REQUEST FOR THE IFU SPECTROSCOPIC CAPABILITY IN THE MID INFRARED INSTRUMENT ON THE TMT

2.1 Image Slicer

Figure 1 shows the configuration drawing of the image slicer unit. The beam from the telescope is focused on the slice mirrors and the field of view on the slice mirrors are divided into *n* of slitlets. The neighboring slice mirrors have an offset angle and their pupil images are produced on the spherical pupil mirrors, which are placed independently on the output pupil positions. Finally, the images of slitlets refocused by the spherical pupil mirrors are aligned on the pseudo slit mirrors, forming in a pseudo slit image (see Fig. 1). This geometric reconfiguration of the FOV area into a pseudo long slit using the image slicer unit enables us to carry out the two-dimensional spectroscopy of extended objects efficiently.

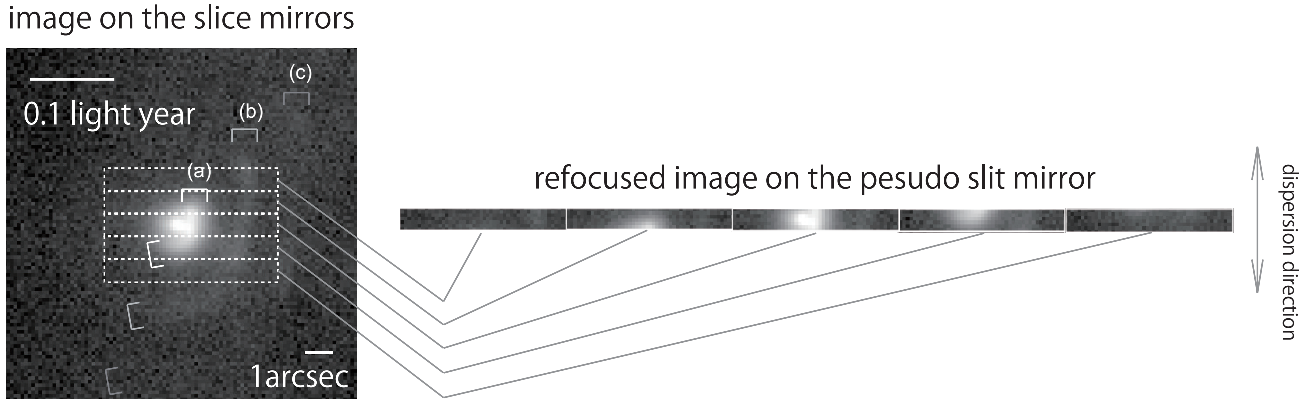


Figure 1. A configuration drawing of the image slicer unit. The left panel shows, as an example, the 11.7μm image of a massive binary (Wolf-Rayet star + O-type star) system WR140 at d~1.7kpc taken with Subaru/COMICS on July 2011. The binary period of WR140 is 7.93y and dust is formed in the two-winds collision zone whenever the O-type companion star passes though the periastron point of the Wolf-Rayet primary star. The last periastron event was in 2009. The expanding dust clouds formed during the past periastron events in 2009, 2001 and 1993 are recognized at positions (a), (b) and (c), respectively. The field of view of MIRSIS (Okamoto et al. 2008), which employs a small format (n=5) image slicer, is shown assuming the case of being mounted on the IRTF. The field of view is divided into five slitlets by means of the slice mirrors. The beams reflected by each slice mirror toward different directions are geometrically rearranged and refocused on the pseudo slit mirrors place in a straight line by the pupil mirrors.

Our initial attempt to develop an image slicer for mid-infrared instruments was for MIRSIS (Okamoto et al. 2008), where the small format (n=5) image slicer was employed. In the case of MIRSIS, the slice mirrors were designed and produced by piling up five thin (300μm thickness) aluminum plates with a constant angle offset. One side edge of each thin aluminum plate was polished as a mirror surface. With this design, however, the optical alignment process to make the refocused images by the pupil mirrors

produced straightly in a line on the pseudo slit mirrors was not easy. It was predominantly due to the warpage of the thin aluminum plate assembled as the slice mirrors.
Then we have started the examinations to develop an image slicer that adopts monolithic slicing mirrors, monolithic pupil mirrors and monolithic pseudo slit mirrors. The trial production of the small format (n=5) image slicer unit based on the specification designed for SPICA/MCS (Kataza et al. 2012) were made by means of the super precision cutting techniques (Sakon et al. 2012). The major goal of this trial production was to have a technical verification to create each of the major components of the image slicer unit (e.g., the slice mirrors, pupil mirrors and pseudo slit mirrors) in a monolithic piece by means of the latest ultra precision cutting technologies so that the optical alignment of these components becomes as simple as possible. As for the slice mirrors, the width of each slice mirror was designed as 184μm. In order to achieve the mirror surface roughness of Ra<20nm, the trial production of a monolithic piece of slice mirrors was made from a single RSA6061 T6 aluminum block using nano-center N2C-53U-S5N5 ultra high-precision machine with a single crystal diamond bite of a thickness of 187μm at NAGASE INTEGREX Co., Ltd. As for the pupil mirrors, in order to achieve the mirror surface roughness of Ra<20nm, the five spherical mirrors with different mirror axes was produced from a single RSA6061 T6 aluminum block using Nanoform 250 Ultra at Crystal Optics Ltd (Sakon et al. 2013; Sakon et al. 2014). Based on the trial production, we found that the processing accuracy in controlling the axis angles of different spherical mirrors greatly improved with Adaptive Control Technology (ACT).

2.2 Science cases for TMT/MICHI's IFU

Understanding of the chemical enrichment history of the universe is one of the most important topics of today's astronomy. Mass ejection from the evolved stars is a fundamental step to supply nucleo-synthesized heavy elements into the interstellar space. A fraction of the ejected gas condenses into dust particles as the gas expands and is cooled down to the condensation temperature. Interstellar dust is an important ingredient of the ISM but its formation, evolution and destruction processes have not been fully understood. Observational attempts to detect any differences in infrared spectral properties between the freshly formed dust in the circumstellar medium and the interstellar dust should be a valid approach to understand the evolution of dust from the epoch of its formation until it travels further away from the progenitor. In order to understand what determines the compositional, size and mass evolution of dust in the circumstellar environment, spatially resolved infrared spectral mapping observations of circumstellar medium of Galactic stellar sources of various main sequence masses at various stellar evolutional stages are crucial.

For example, observations of one of the nearest Galactic nova, V1280Sco, with mid-infrared instruments on 8—10 m class telescopes have successfully recognized the bipolar shape of the dust structures (Chesneau et al. 2012; Sakon et al. 2016) and have demonstrated the composition, size and mass of dust formed in the nova ejecta over two thousands' days from the outburst (Sakon et al. 2016; see Fig. 2). However, due to the lack of spatial resolution, the variations in spectral properties of dust emission in the bipolar lobes as a function of the distance from the white dwarf have not yet been studied. Near- and Mid-infrared interferometric observations with VLT/AMBER and MIDI have succeeded in demonstrating the properties of dust shells at just after the dust nucleation epoch (Chesneau et al. 2008), but the sensitivity was not sufficient to trace the evolution of dust shells beyond six months from its outburst. Therefore, our knowledge on the process of the condensation in the stellar ejecta and the mass and size evolution is still limited even with the capabilities of any available instruments to date. If the stellar ejecta gas travels with a constant velocity of 500km/s for one year, it reaches the distance of ~100AU away from its progenitor. For Galactic objects located at the distance of 1 kpc, the angular distance of 0.1 arcsec on the sky corresponds to ~100AU. In the case of V1280Sco, silicate dust and carbon dust distribute over 200—600 AU from the white dwarf at Day 1947 from the outburst. Therefore, spectral mapping observations with TMT/MICHI+MIRAO (Chun et al. 2006), for the first time, will allow us to spatially resolve the structures of dust formed by nearby (< a few kpc) novae at several years from the outburst and to demonstrate the variations in the properties of dust located at different distance from the white dwarf. Wide spectral coverage from 3 to 25μm (L, M, N, Q bands) is indispensable to study the evolution of dust located at a different distance from the heating source and to perform SED analyses decomposing multiple dust emission components. In particular, UIR features at 3.3—3.5μm, 7.7—8.3μm, 8.6μm, 11.3μm and 12.7μm help us to understand the formation and evolution of aliphatic- and aromatic-hydrocarbon dust species (Allamandola et al. 1989; Tielens 2008), which are often seen in novae and PNe, and silicate absorption/emission features at 9—13μm and 16—20μm help us to constrain the composition, size and crystallinity of silicate dust and minerals (e.g., Molster & Kemper 2005; Min et al. 2007).

Spectral mapping observations of nearby dusty novae, dusty Wolf-Rayet stars, AGB stars and planetary nebulae (PNe) with TMT/MICHI+MIRAO provide us unique opportunity to examine the composition, size and mass evolution of dust on different time scales and at different physical and chemical conditions. For those objects, the geometry of circumstellar medium is often asymmetric and IFU capability is crucial to efficiently study the 2-dimensional spatial variations in the properties of circumstellar gas and dust.

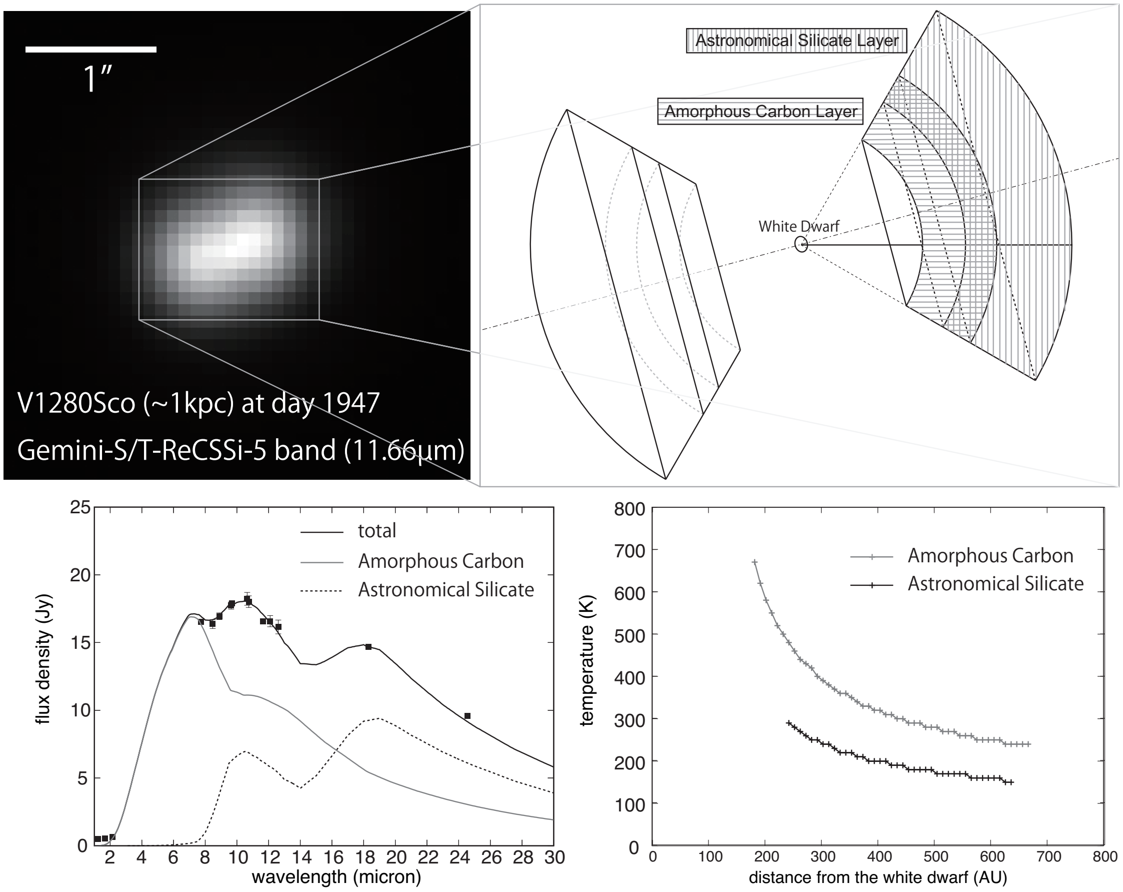


Figure 2. (Top-left): The 11.66μm image of V1280Sco at Day 1947 from the outburst obtained with Gemini-S/TReCS. (Top-right): The schematic view of the distributions of amorphous carbon and astronomical silicate around V1280 Sco. (Bottom-left): The observed near to mid-infrared spectral energy distribution of V1280Sco at Day 1947. The SED was reproduced by the amorphous carbon dust of mass $6.6—8.7\times10^{-8}M_{\odot}$ with a representative grain size of 0.01μm and astronomical silicate dust of mass $3.4—4.3\times10^{-7}M_{\odot}$ with a representative grain size of 0.3—0.5μm. (Bottom-right): The temperature distributions of amorphous carbon and astronomical silicate as a function of the distance from the white dwarf (see Sakon et al. 2016 for details).

3. TRIAL PRODUCTION OF THE LARGE-FORMAT IMAGE SLICER UNIT

3.1 Monolithic Slice Mirrors

The test piece of the monolithic large-format slice mirrors is designed to have 11 narrow mirrors (a thickness of 186μm), each of which has an angle offset between the neighboring mirrors by 2.4 degree against the incoming light (see Fig. 3). It was produced from a single RSA6061 T6 aluminum block using nano-center N2C-53U-S5N5 ultra high-precision machine with a single crystal diamond bite at NAGASE INTEGREX Co., Ltd. The width of each slice mirror is designed to be 186μm and the thickness of the single crystal diamond bite used in the cutting was 187μm. Based on the measurements of surface roughness (Ra) with Zygo NewView Optical Profilers, Ra<20nm is achieved at any position of the slice mirrors. Table 1 shows the designed value and the measured value of the offset angle of each slice mirror (SM#1—#11) relative to the SM#6. We confirmed that the good machining accuracy was achieved in this trial production of the monolithic large-format slicer mirrors.

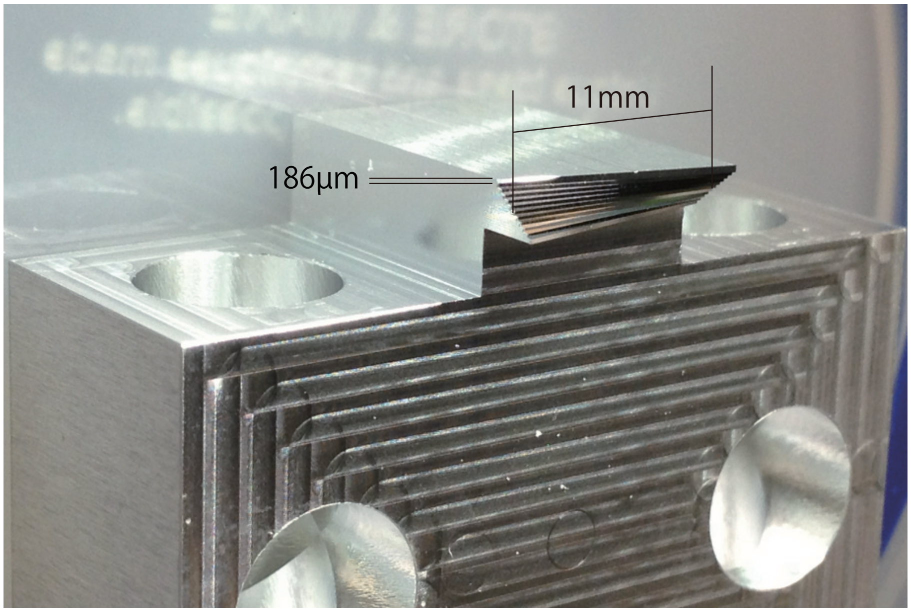


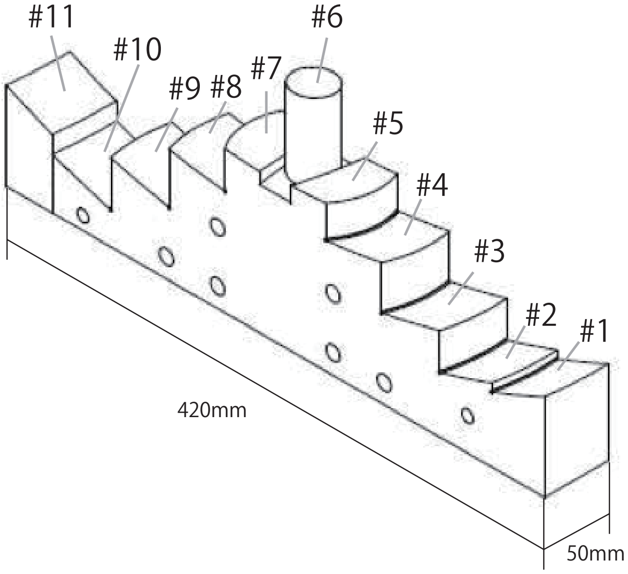
Figure 3. The test piece of monolithic large-format (n=11) slice mirrors

Table 1. The offset angle of each slice mirror relative to the SM#6

Mirror number	Offset angle from SM#6	
	Designed value (deg)	Measured value (deg)
SM#1	12.0	12.05±0.05
SM#2	9.6	9.65±0.04
SM#3	7.2	7.21±0.02
SM#4	4.8	4.81±0.01
SM#5	2.4	2.40±0.01
SM#6	0.0	--
SM#7	-2.4	-2.41±0.01
SM#8	-4.8	-4.81±0.01
SM#9	-7.2	-7.21±0.02
SM#10	-9.6	-9.65±0.04
SM#11	-12.0	-12.03±0.05

3.2 Monolithic Pupil Mirrors

The test piece of the monolithic large-format pupil mirrors is designed to have 11 spherical pupil mirrors. The structural design of the monolithic pupil mirrors is shown in Fig. 4. The pupil mirrors PM#1, PM#2, PM#3, PM#4, PM#5, PM#7, PM#8, PM#9 and PM#10 were produced from a single A6061 aluminum block using Nanoform 700 Ultra (Precitech) with Adaptive Control Technology (ACT) at Crystal Optics Ltd. Due to the mechanical interference between the cutting tool and the pupil mirorrs, the mirrors PM#6 and PM#11 were produced independently but were assembled in a single structure before the final fine machining was made in a single chucking. Based on the measurements with Zygo NewView Optical Profilters, excellent surface roughness Ra<10nm is achieved at any position of the pupil mirrors.



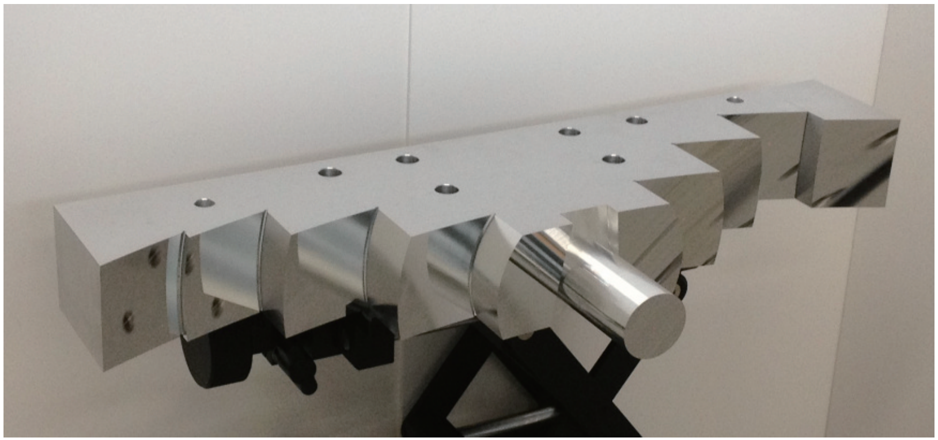


Figure 4. The structural design (top) and the produced piece (bottom) of monolithic large-format pupil mirrors

3.3 Assembly and Optical Alignment

The produced test pieces of the monolithic slice mirrors and the monolithic pupil mirrors were assembled on the optical plate. The alignment of each element was made by adjusting in positions of the datum surfaces defined in each element. The visible laser was lead to the slice mirrors to check the center position of each pseudo slit mirror (see Fig. 5). We have shown that the center positions of the pseudo slit mirrors are perfectly aligned on the screen located at the position of the pseudo slit mirrors. We concluded that good machining accuracy were achieved both for the monolithic large-format slice mirrors and the monolithic large-format pupil mirrors.

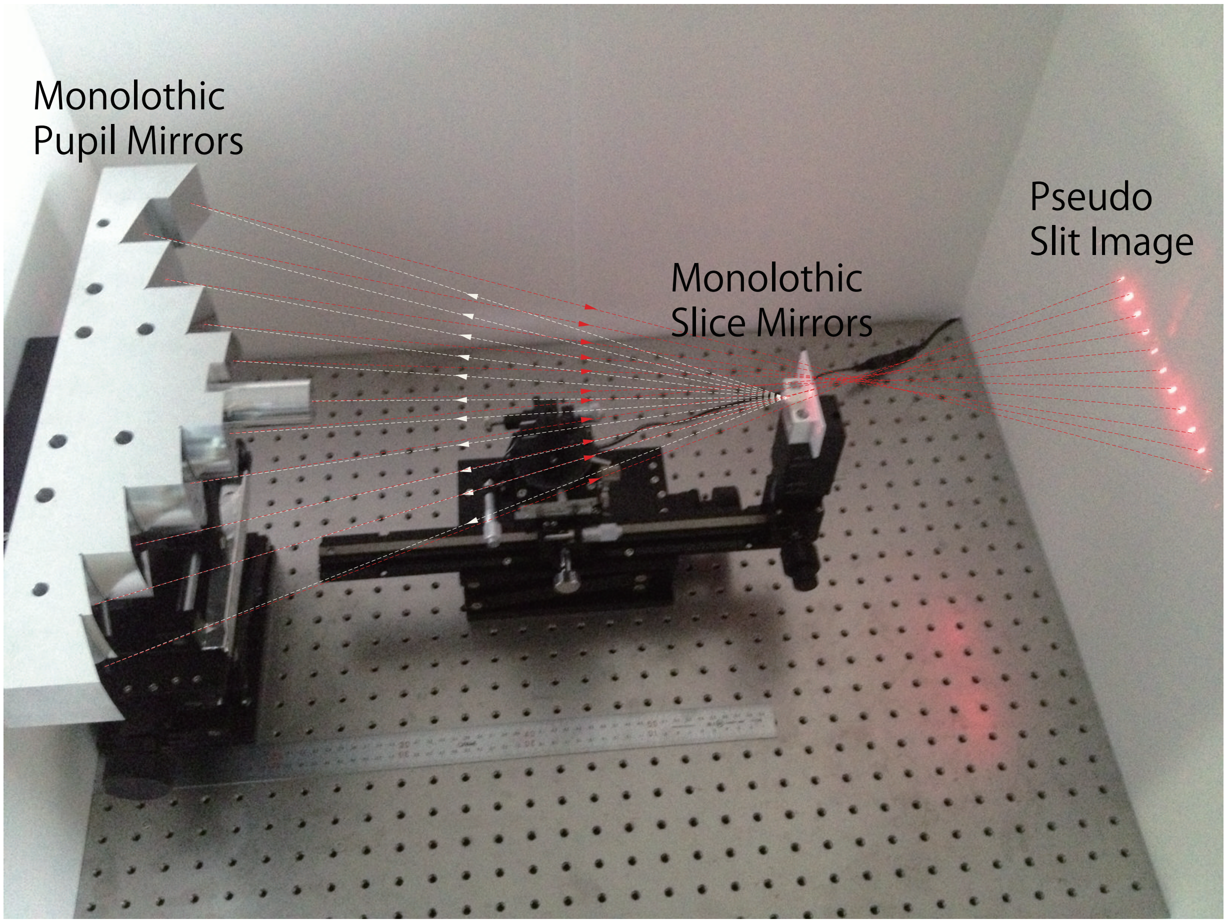


Figure 5. The results of the assembly of the produced test pieces of the monolithic slice mirrors and the monolithic pupil mirrors. The incident optical laser is split into 11 directions and are refocused and aligned on the screen placed at the position of the pseudo slit mirrors by the monolithic pupil mirrors.

4. SUMMARY

The IFU capability is a key function requested for a possible future mid-infrared instrument on TMT, in particular, to demonstrate the spatial variations in the properties of circumstellar gas and dust in Galactic nearby stellar sources of various main sequence masses at various evolutionary stages. We have carried out the trial production of a large format image slicer unit, based on the optical design and specification of the TMT/MICHI. By means of the ultra high-precision cutting techniques, we have verified the technical feasibility to produce the key elements of an image slicer, the monolithic slice mirrors and the monolithic pupil mirrors. We also have confirmed the advantages of producing each of those elements as a monolithic piece in view of the stability for the optical alignment.

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