# The machined immersion grating

## for the absolute and simple solution of the downsizing concept in the high-precision infrared Spectroscopy

Takashi. Sukegawa

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# Outline

- Introduction
  - ✓ First History in Canon
  - ✓ Original Machine capability
  - ✓ Conventional grating for IR
  - ✓ Image slicer
- Immersion grating
  - ✓ InP
  - ✓ Germanium
  - ✓ CdZnTe
- Conclusions

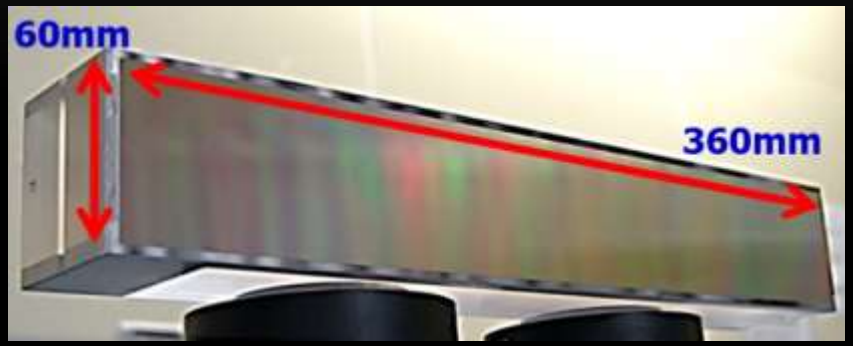
# Introduction

# What is first motivation in Canon?



**There is the Key Device for our semiconductor business.**


**Echelle Grating with the length of 360mm**




There was only one vendor for this device in 2010. We thought this situation was one of the restrictions for our business cost.

General Requirement

| | |
|---|---|
| Grooved pitch | : FSR > 1nm @193.4nm |
| Grooved area | : Length > 350mm Width > 55mm |
| Wavefront Error | : **< 30nmRMS 100nmPV** (Flat or Concave) |
| **Absolute Diffraction Efficiency** | : **> 60%@193.4nm** Required robustness against 193nm |

Although we started the difficulty at not knowing first, at the end, it succeeded.
We learned and experienced a lot from this development.



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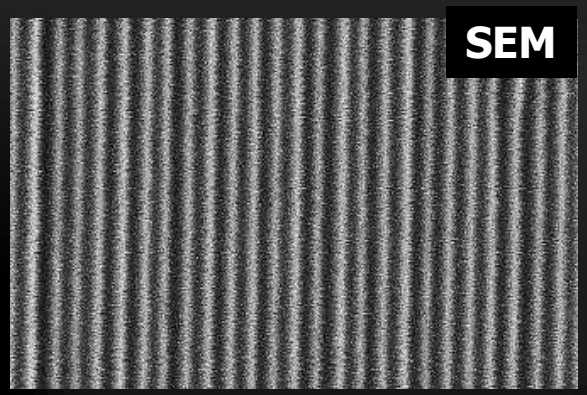
# Original Machine potential

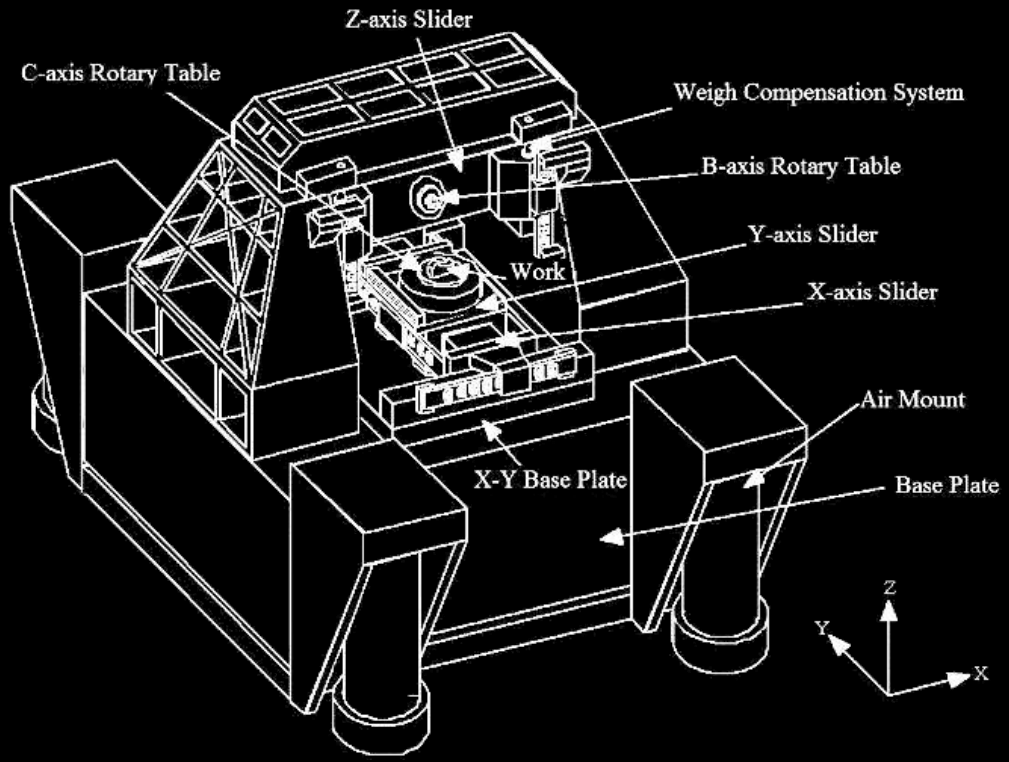


## Free Form Mechanical Cutting tool

- **High precision**
  - Placement Error : < **2nm(RMS)**
  - Surface roughness : < **1nm(RMS)**




**50,000 grooves/mm**
**20nm/pitch**




**Machined Area**
**300mm x 200mm x 300mm**

A machining with the accuracy of UV grating is possible in 3D.



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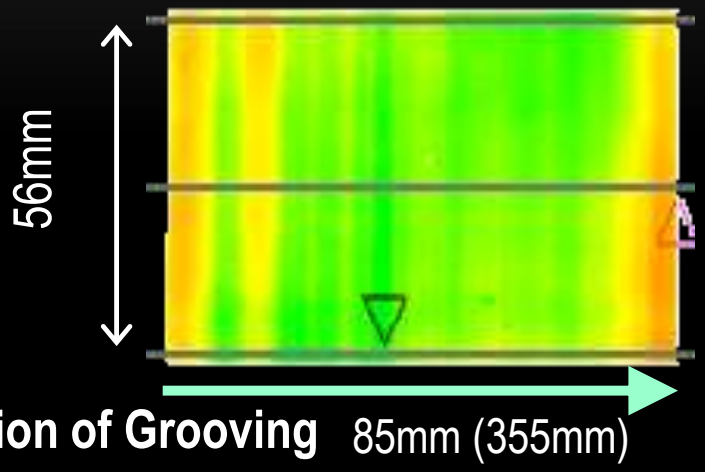
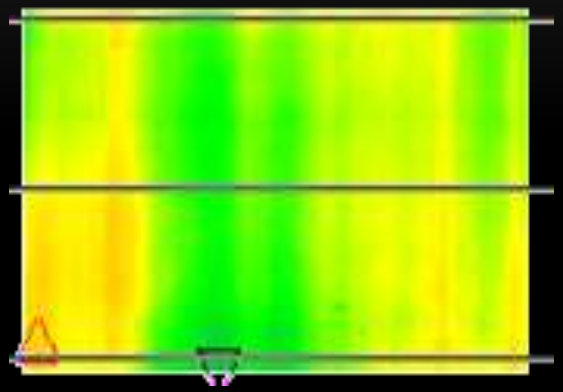
# Performances of UV grating by 3D machining

## Wavefront Error ( 31th-order at 632.8nm by Zygo interferometer)

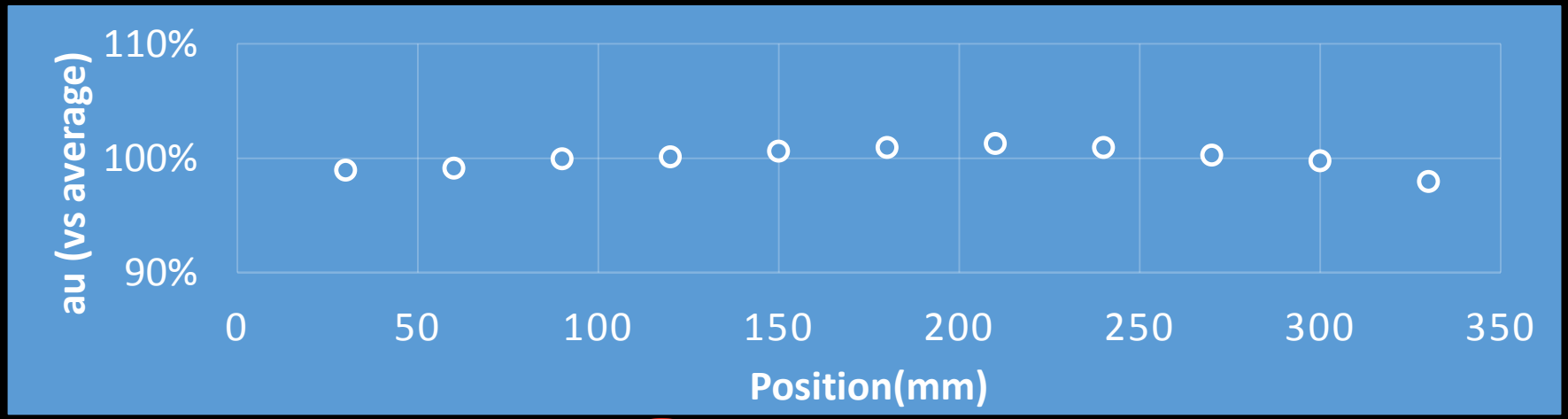
**Master #1** 6nm RMS 32nm PV




**Master #2** 6nm RMS 33nm PV



## Flatness of Diffraction Efficiency



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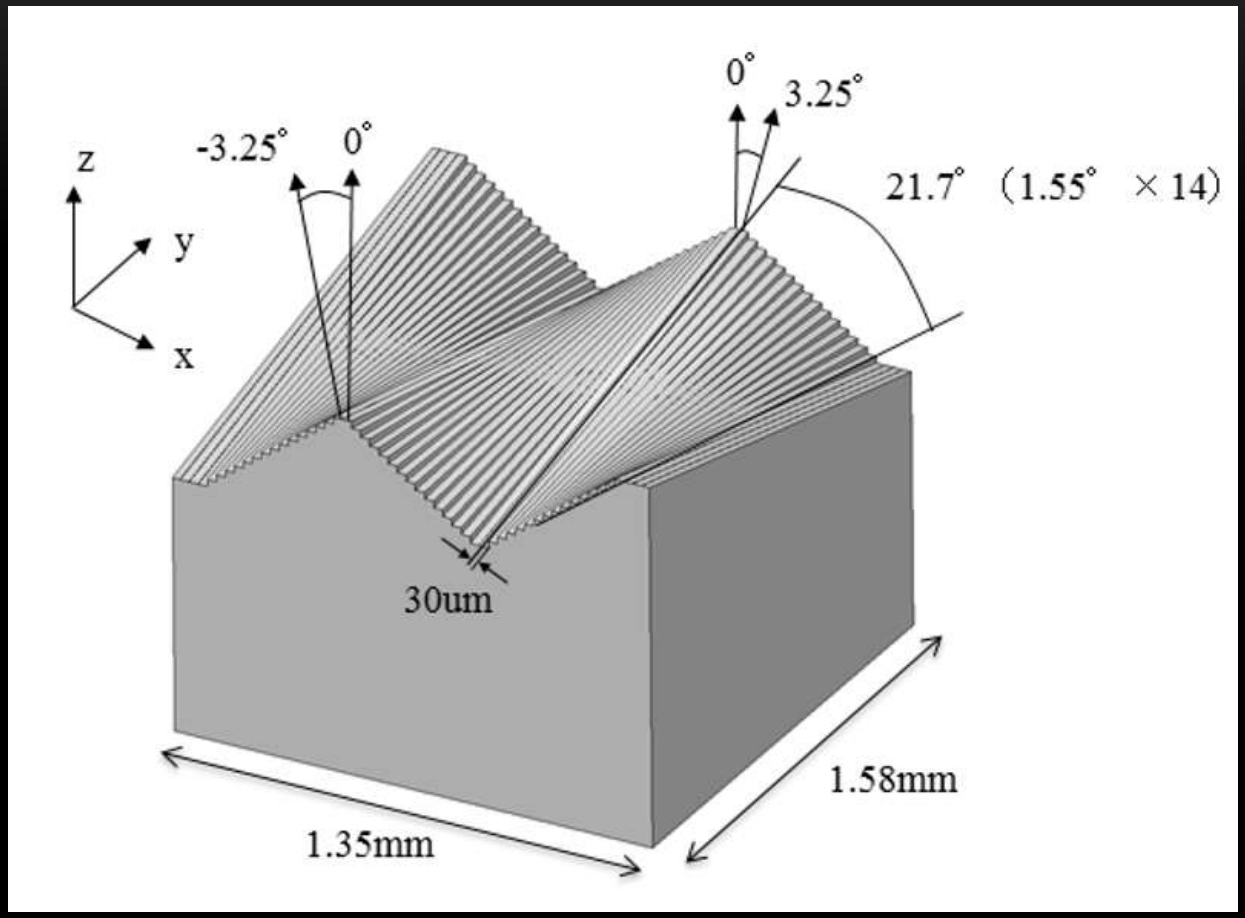
# Micro Slicer for 2D spectrograph in SPACE

**Designed by Suematsu-san (NAOJ)**




Suematsu, et al. “Development of compact metal-mirror image slicer unit for optical telescope of the SOLAR-C mission” SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, 990411 (29 July 2016);



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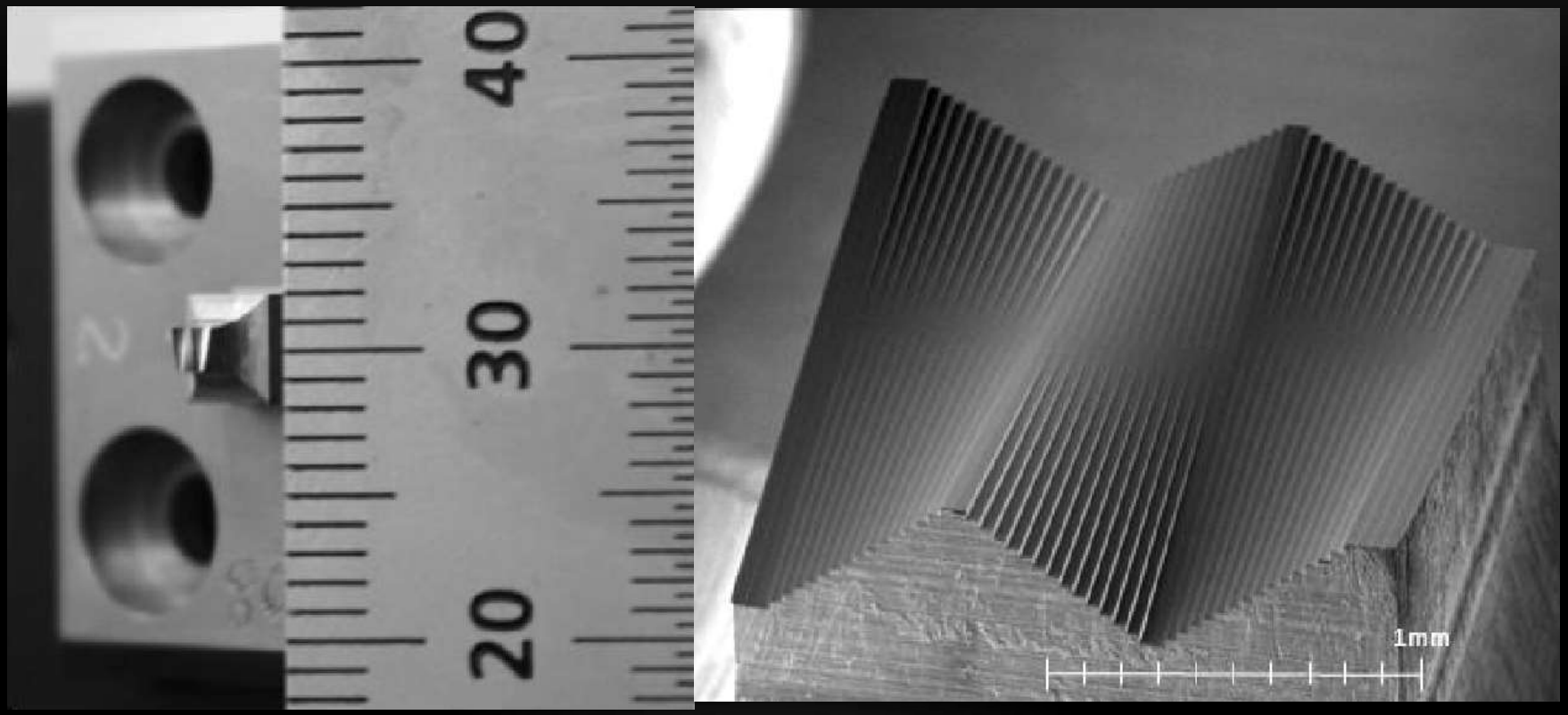
# Micro Slicer for 2D spectrograph in SPACE






**Machined by CANON**



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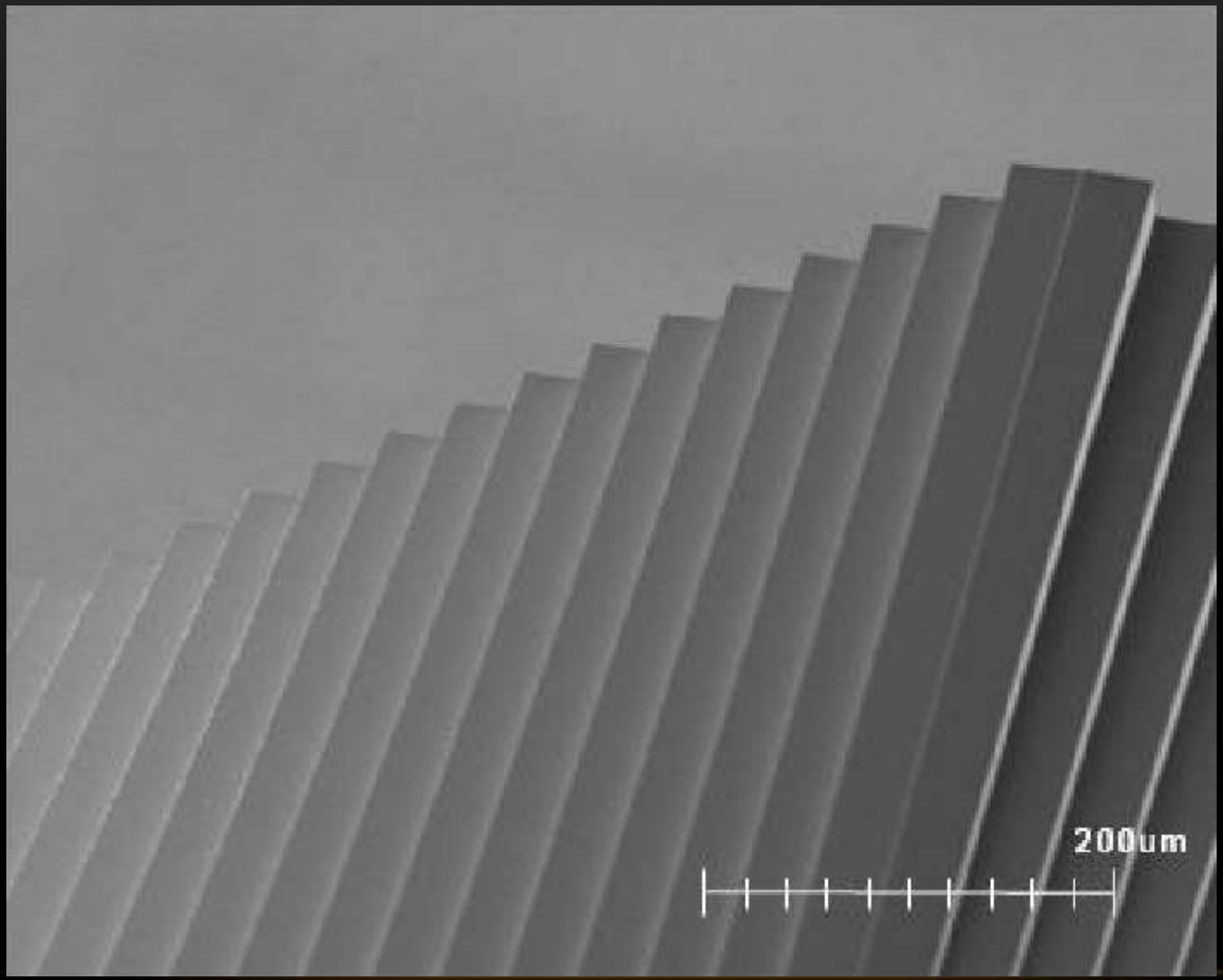
# Micro Slicer for 2D spectrograph in SPACE






**Machined by CANON**



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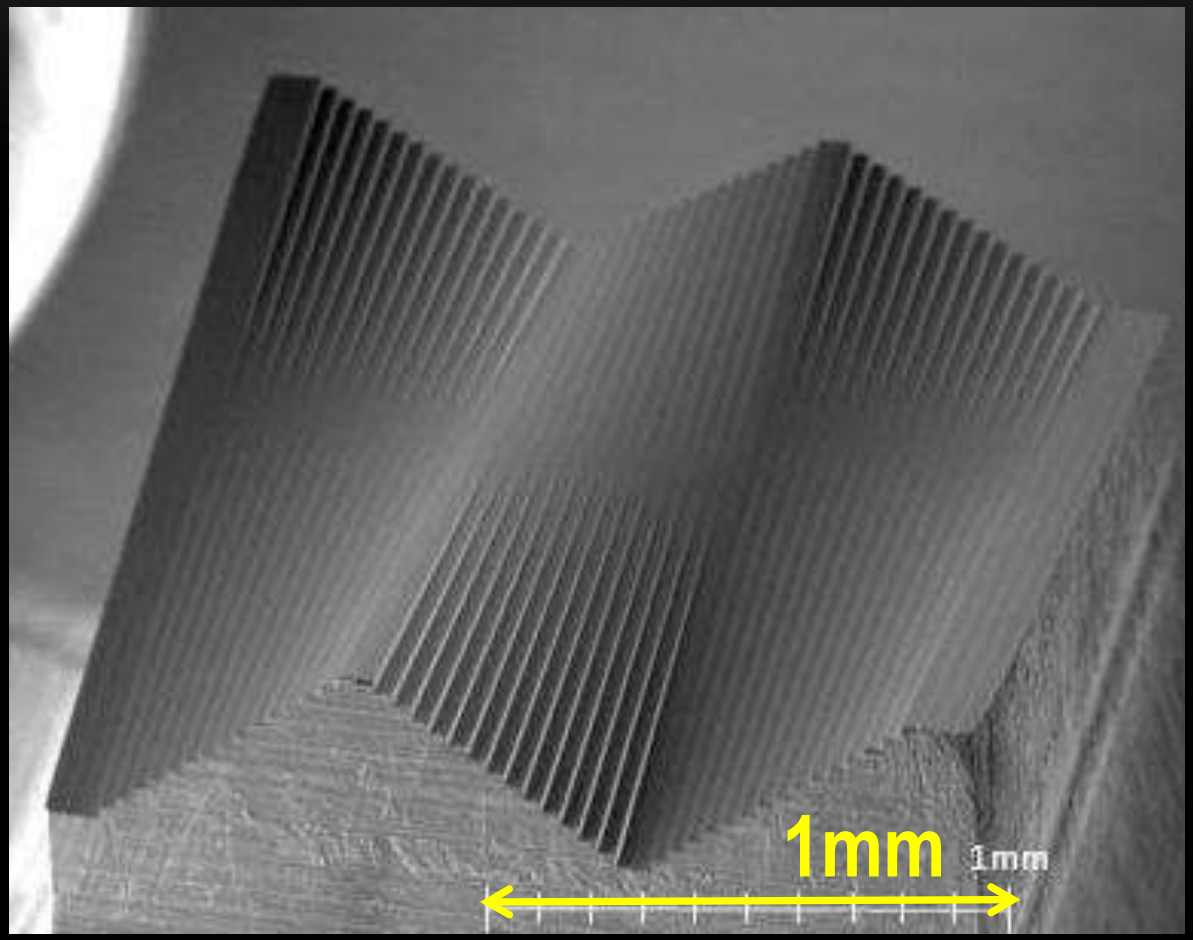
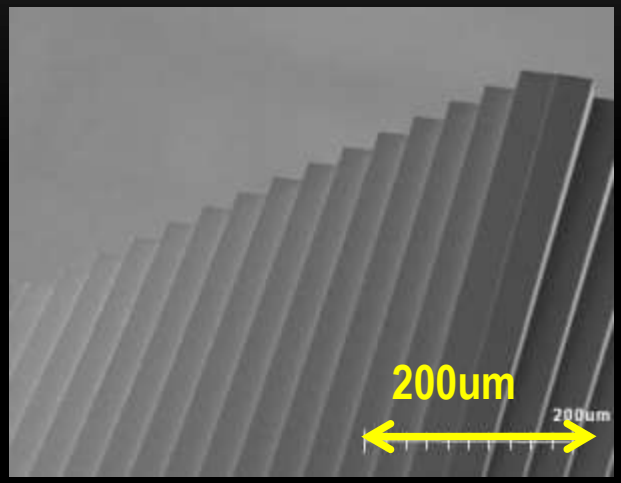
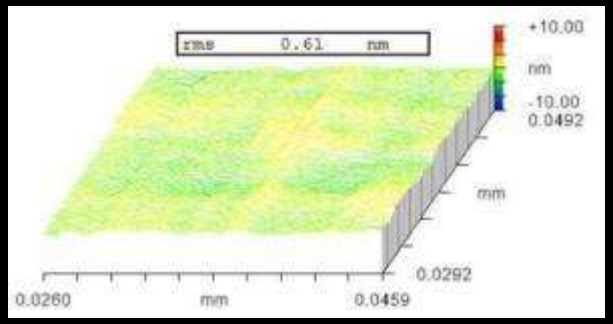
# Machined potential - 3D machining ~ e.g.②






**Surface roughness**
**0.61nm RMS**



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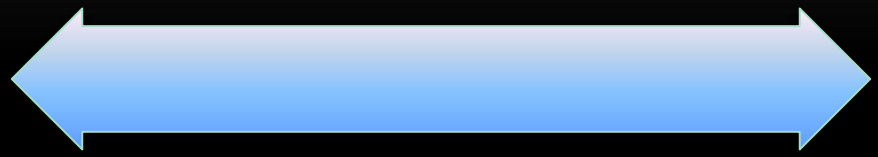
# The types of Grating currently offered by Canon


**Reflective**

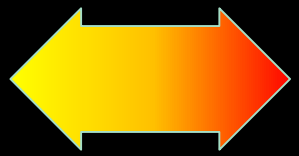
for Astronomy

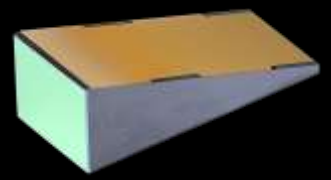


**Transmittance**


**Immersion**

for Astronomy





An Immersed grating is the absolute and simple solution of the downsizing concept in the high-precision infrared Spectroscopy.



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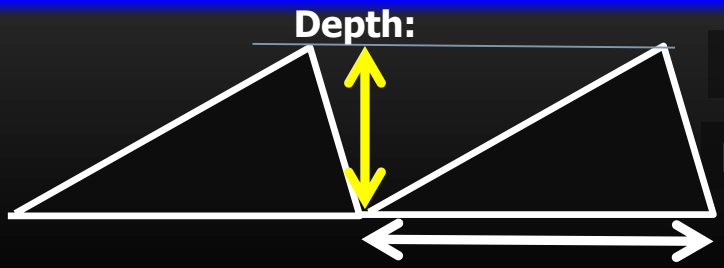
# Reflection Grating for Infrared

# High Blazed echelle Grating for mosaicking



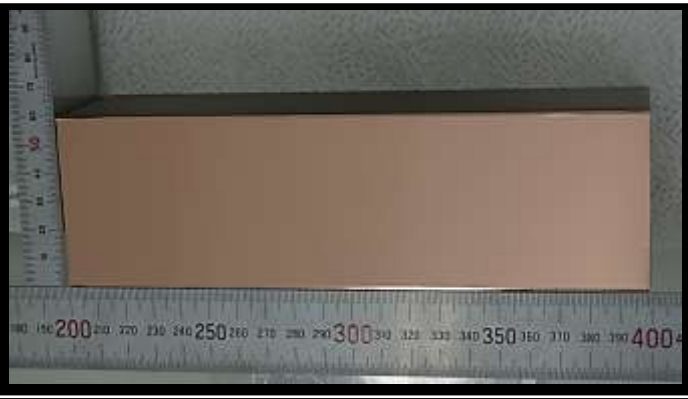
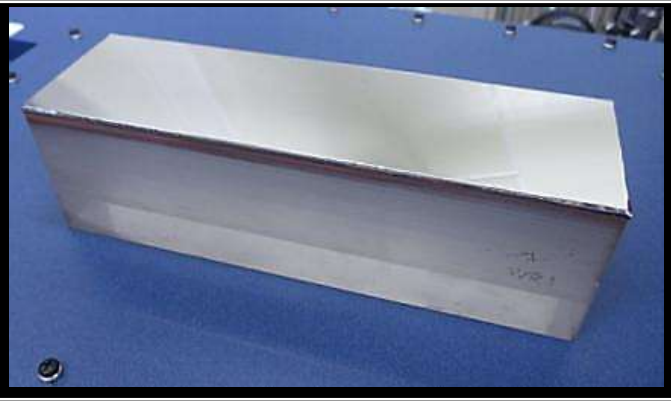
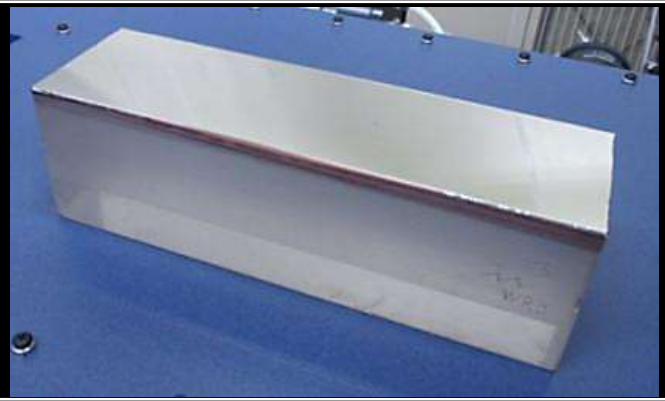
Grooved Length:198mm
Grooved width : 58mm




**Apex angle: 88°**

**Blaze angle: 79.3°**

**Pitch: 90.4um**

| | A | B |
|---|---|---|
| **Before Coating** |  |  |
| **After Ag Coating** |  |  |



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# High Blazed echelle Grating for IR



These performances are very close in manufactured individually.

| | | Polarization | A | B |
|---|---|---|---|---|
| Absolute Maximum Diffraction Efficiency | Average | TM | 60.9% | 61.3% |
| | | TE | 76.2% | 76.2% |
| | Variation (3 points ±65mm) | TM | 1.9% | 1.1% |
| | | TE | 1.1% | 1.2% |
| Surface Flatness Area of 90% | | PV | 54.1nm | 45.4nm |
| | | RMS | 5.6nm | 6.0nm |

Please refer to the following paper about the spectrograph (WINERED) which mounted the reflection gratings by Canon.

Otsubo et al, “First high-efficiency and high-resolution (R=80,000) NIR spectroscopy with high-blazed Echelle grating: WINERED HIRES modes” Volume 9908, Ground-based and Airborne Instrumentation for Astronomy VI; 990879 (2016)



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# Immersion Grating

# Characteristics of three materials for immersion



| | InP | Ge | CdZnTe |
|---|---|---|---|
| Refractive index | 3.2 | 4.0 | 2.7 |
| **Practical Wavelength** (Attenuation coefficient (α) $<0.1/cm^{-1}$) | 1.4μm~8μm | 2μm~11μm | 5μm~20μm |
| Low temperature operation | ☺ | ☺ | not yet |
| Size availability at the Blaze angle 75 | ~120mm (85mm) | ~200mm | ~85mm |



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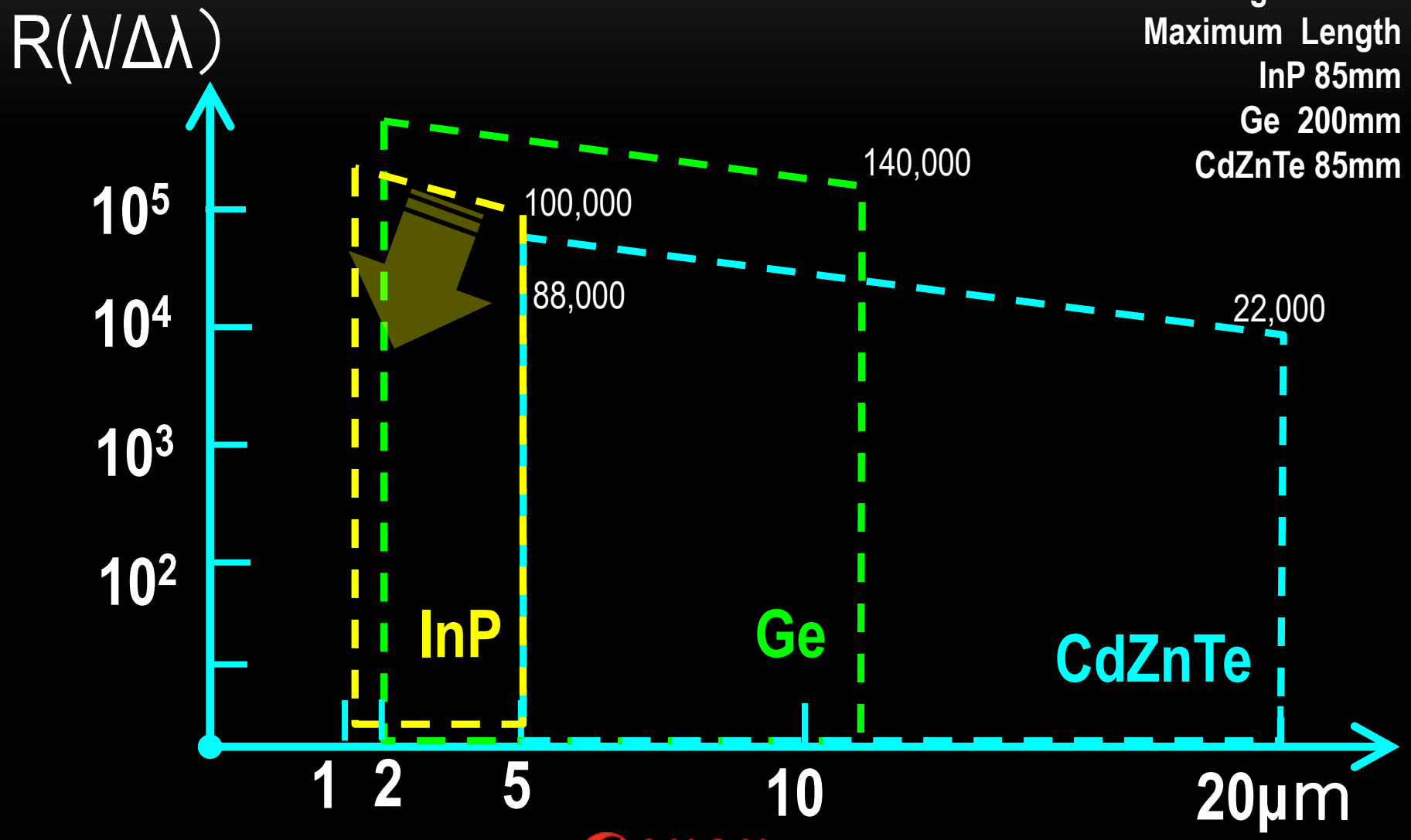
# Potential of three materials for immersion



**Assumption conditions**
**Blaze angle：75°**
**Maximum Length**
**InP 85mm**
**Ge 200mm**
**CdZnTe 85mm**



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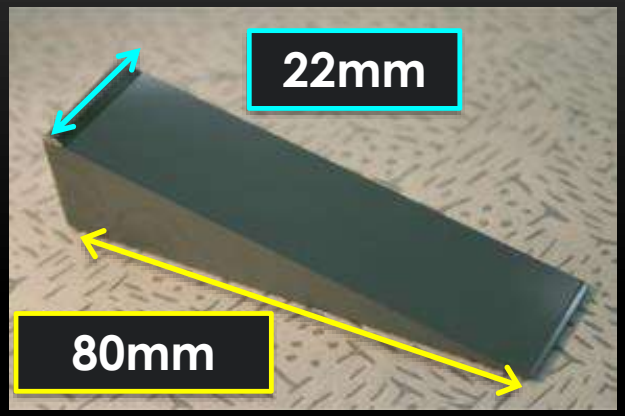
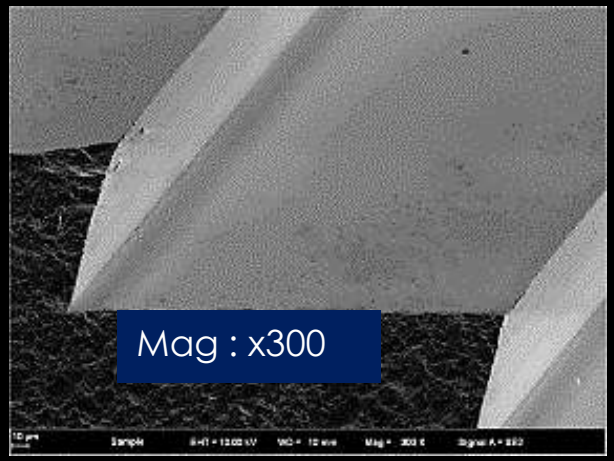
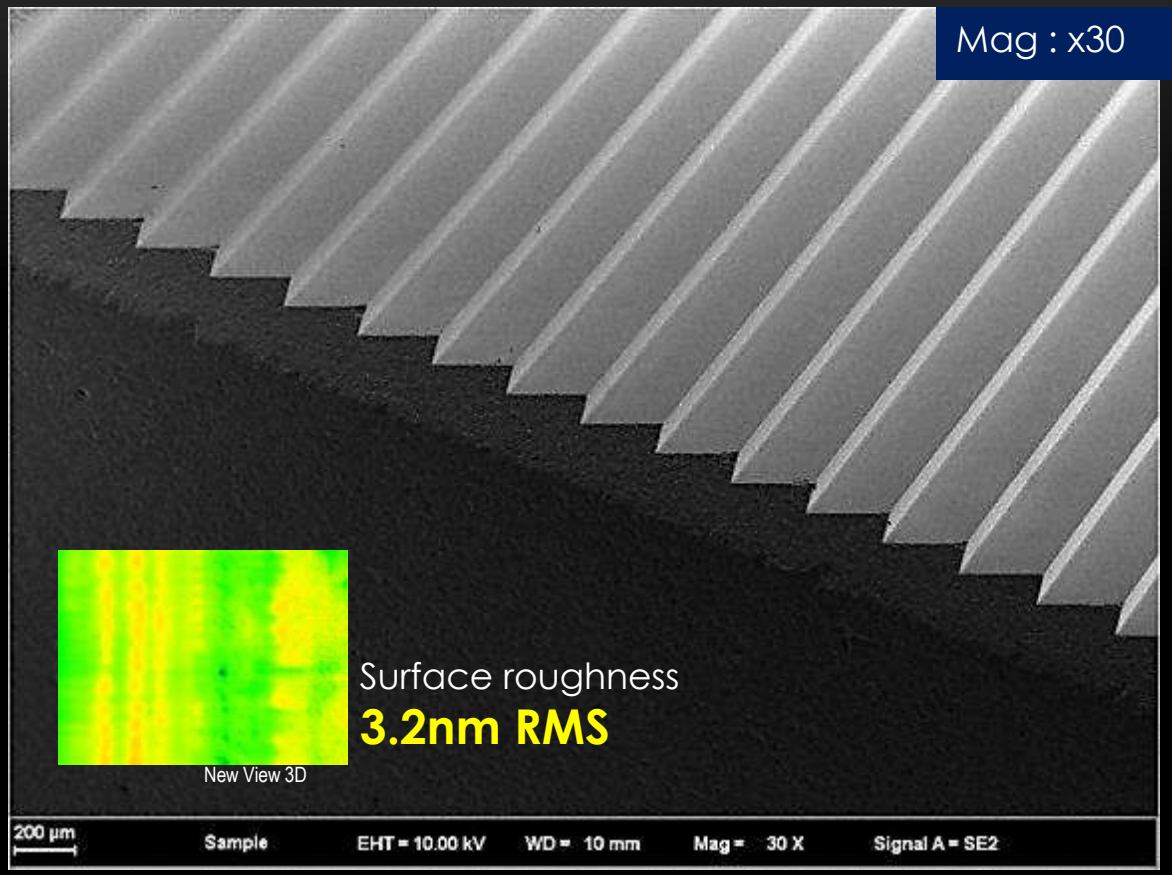
# CdZnTe

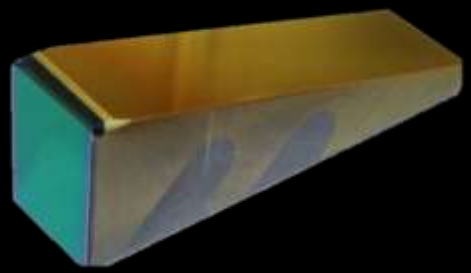
# **CdZnTe** immersion grating




*2012 SPIE Astronomical Telescopes +Instrumentation* *Sukegawa et al*
*Applied Optics 2015 Ikeda et al*





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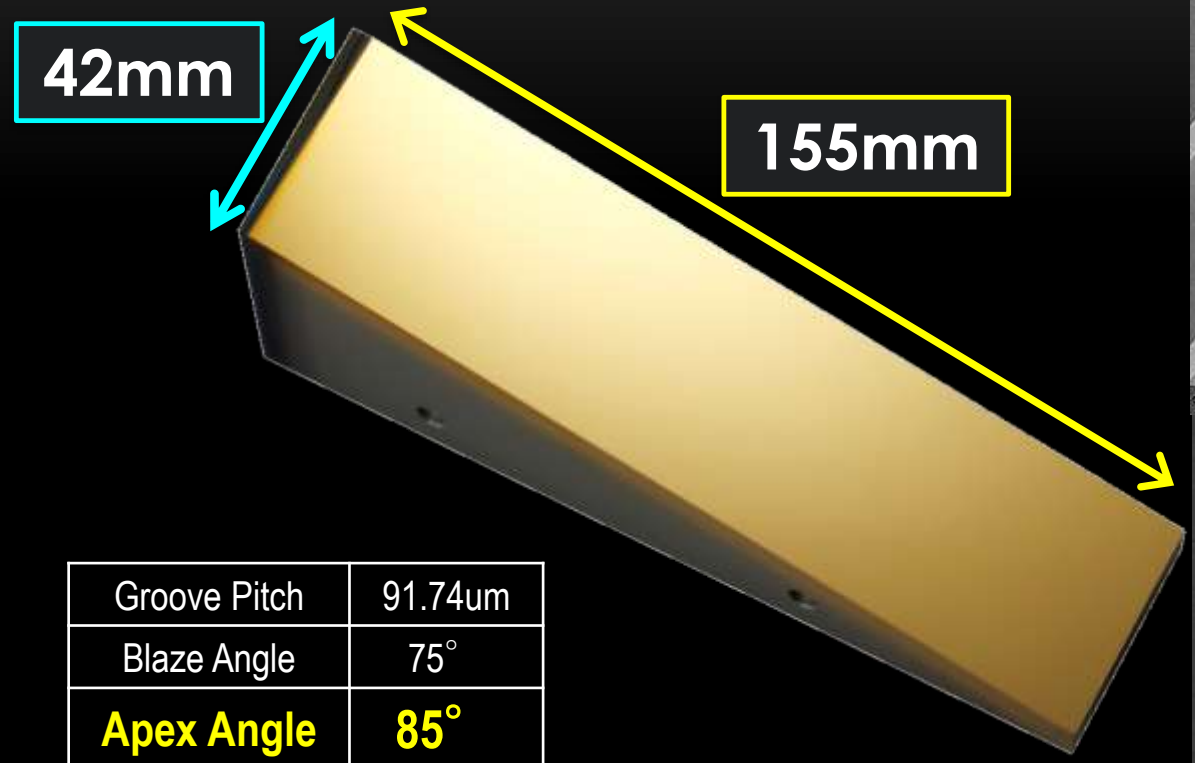
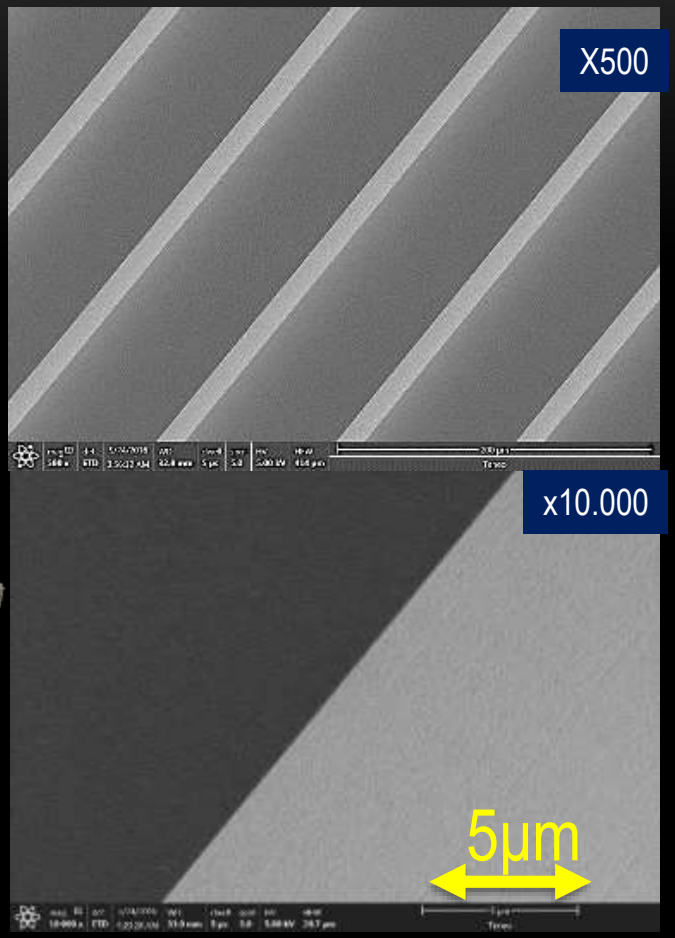
# Germanium

# **Germanium** immersion grating with the length of 155mm






| | |
|---|---|
| Groove Pitch | 91.74um |
| Blaze Angle | 75° |
| **Apex Angle** | **85°** |




Machinability of germanium is the best for us currently. There are also almost no restrictions of material.

⇒ Today, introducing “EGIG” , “GRISM”



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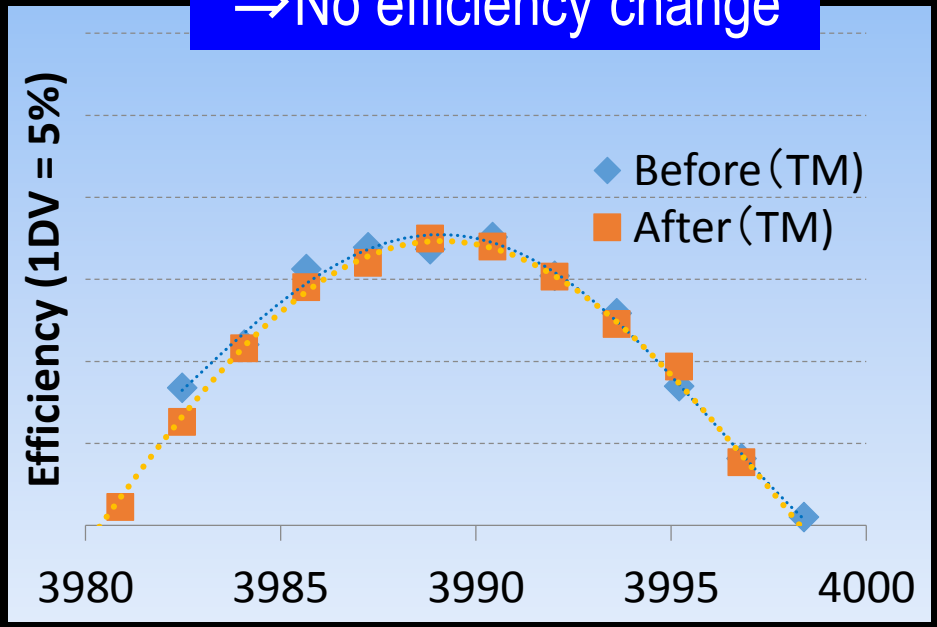
# Test of Low temperature operation

Temperature cycle x 3times
Cooling speed : 250K/9h
Minimum 25K

Ge immersion grating
⇒No efficiency change




**Other Reference**
**Sarugaku et.al,"Cryogenic Performance of High-efficiency Germanium Immersion Grating"**
**SPIE astronomical telescopes and instrumentation(2016)**

We did also a same test for InP immersion grating.
⇒ No change



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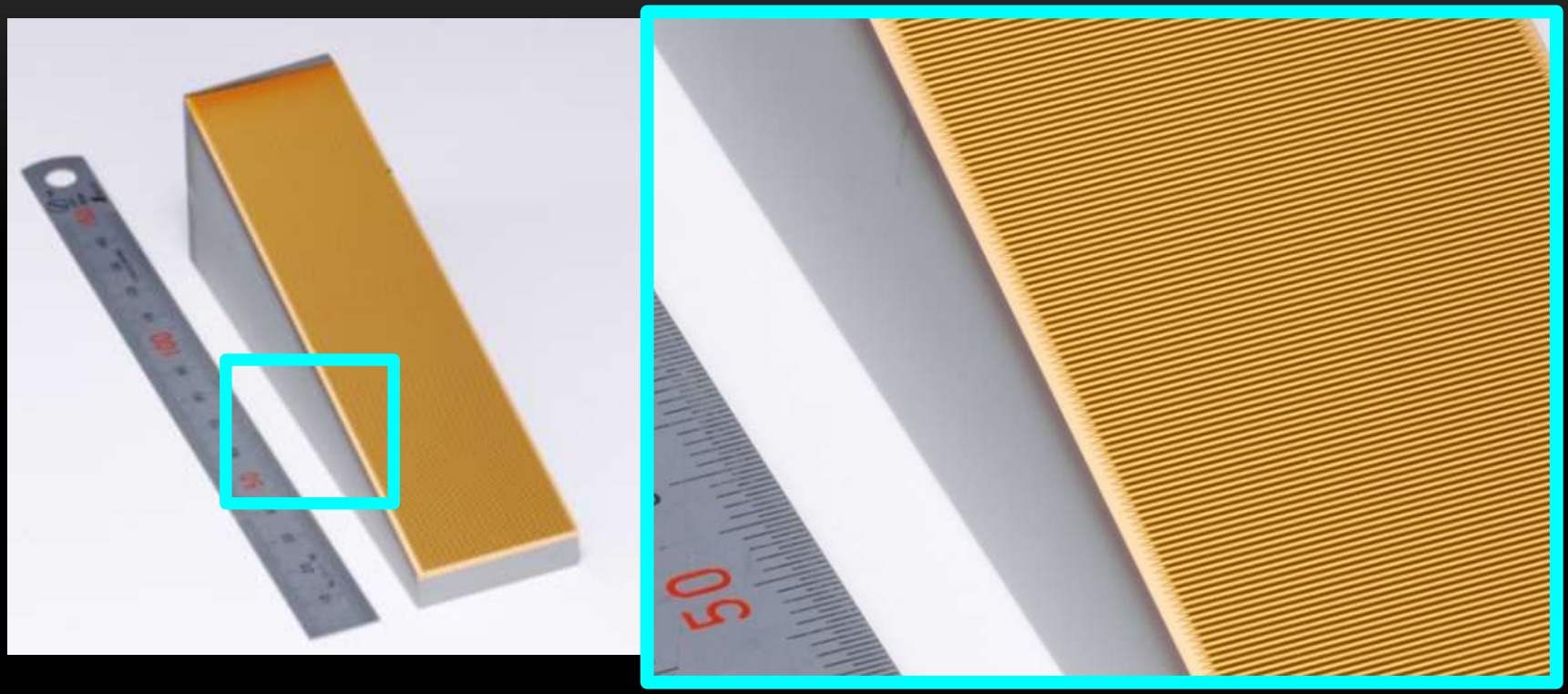
# EGIG : Extremely High-order Germanium Grating



Grooved pitch : **476um for 3-5um** Blaze angle : 75 degrees
Maximum Absolute Diffraction Efficiency : 78%@ 4um

Tani, et al. “Extremely-high-order Ge Immersion Grating-based Spectrometer for Offset-free Precision Spectroscopy in the Mid-infrared Region” CLEO®/Europe-EQEC 2017



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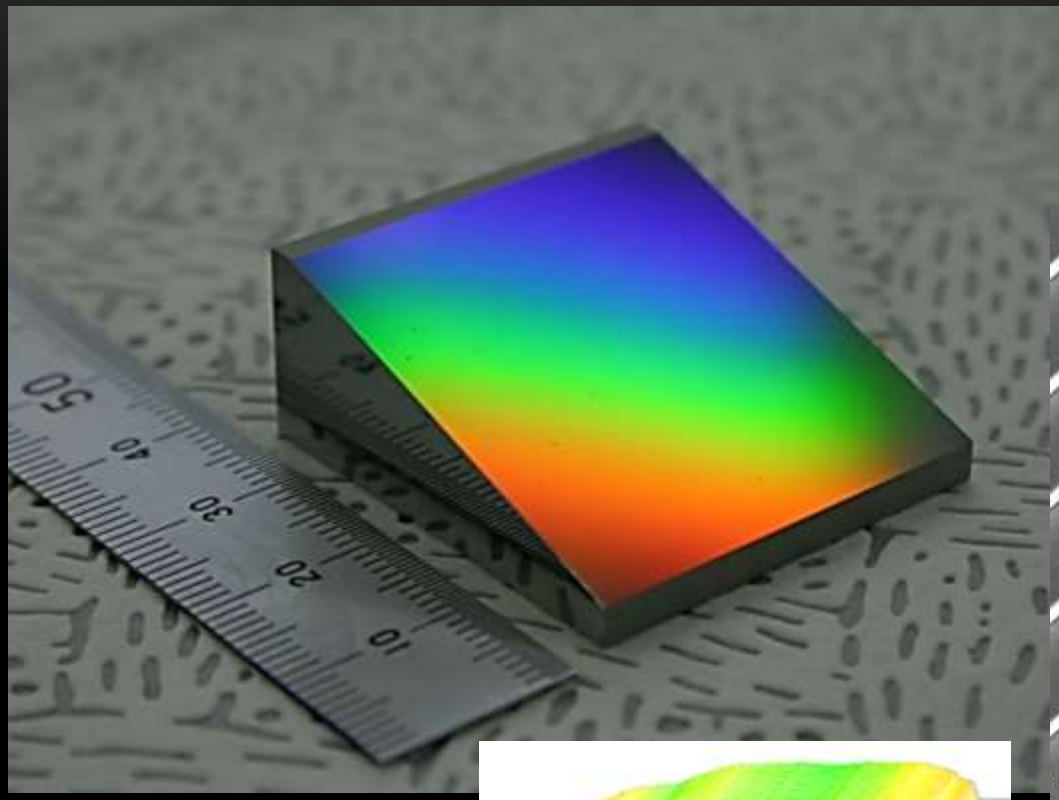
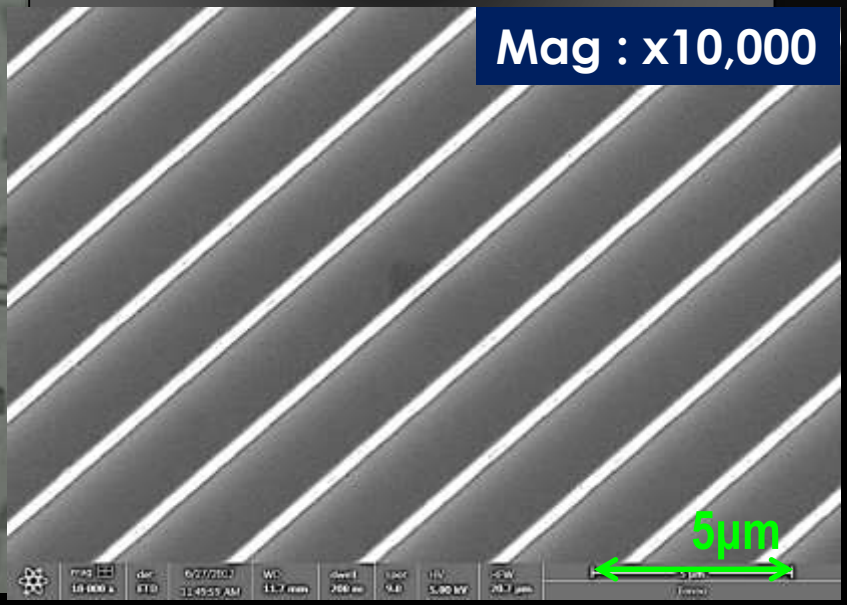
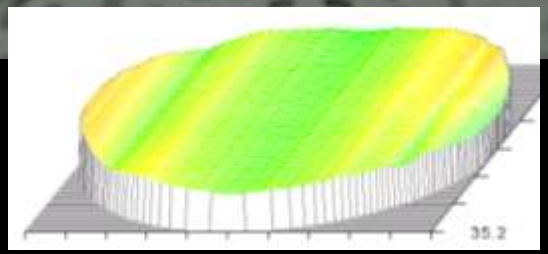
# **Germanium** Grism (GG)





Grooved pitch : 2.174um
Blaze angle : 19.19 degrees
Effective Size : Φ30mm



Wavefront Error : 9nmRMS 47nmPV

Notice !!

Since one groove is machined each by each, an device like grism with a small pitch is extremally high cost.



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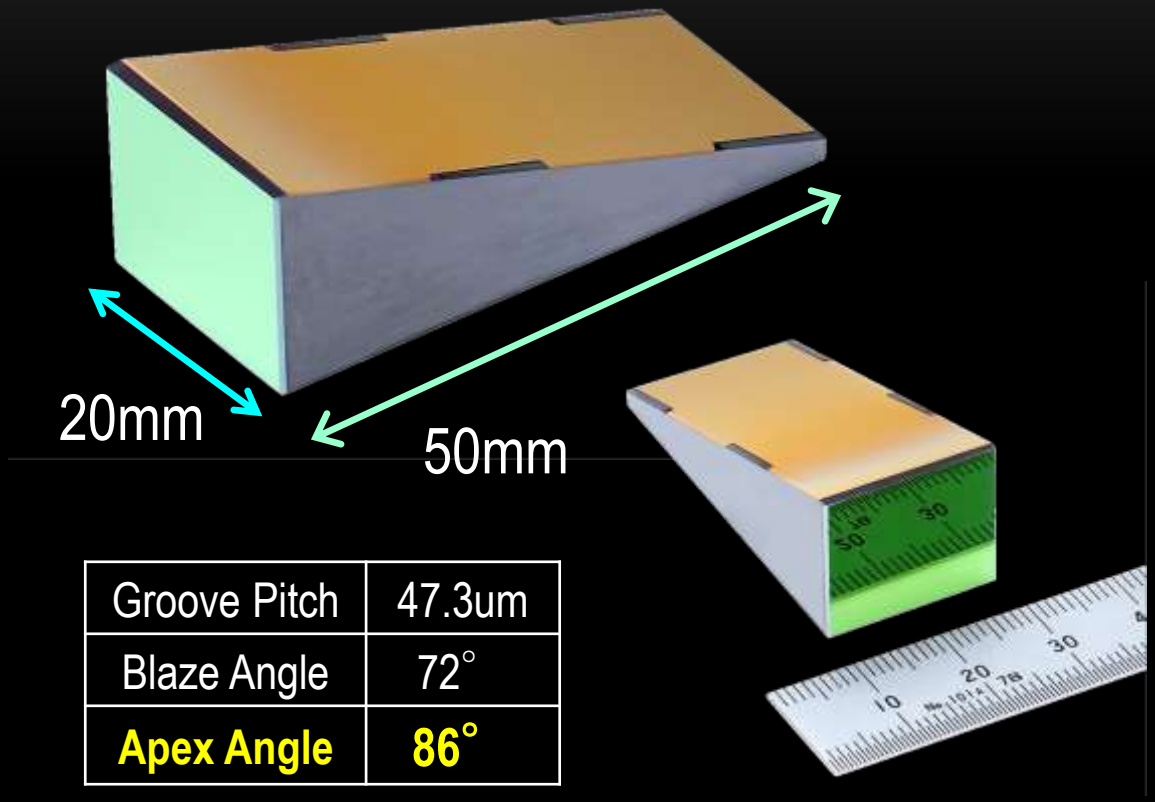
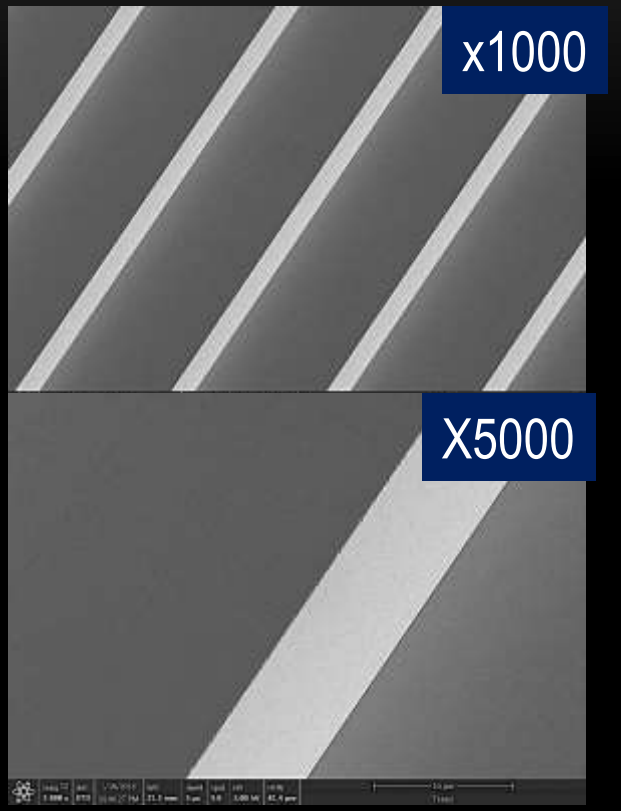
# Indium Phosphide (InP)

# **InP** immersion grating






| | |
|---|---|
| Groove Pitch | 47.3um |
| Blaze Angle | 72° |
| **Apex Angle** | **86°** |



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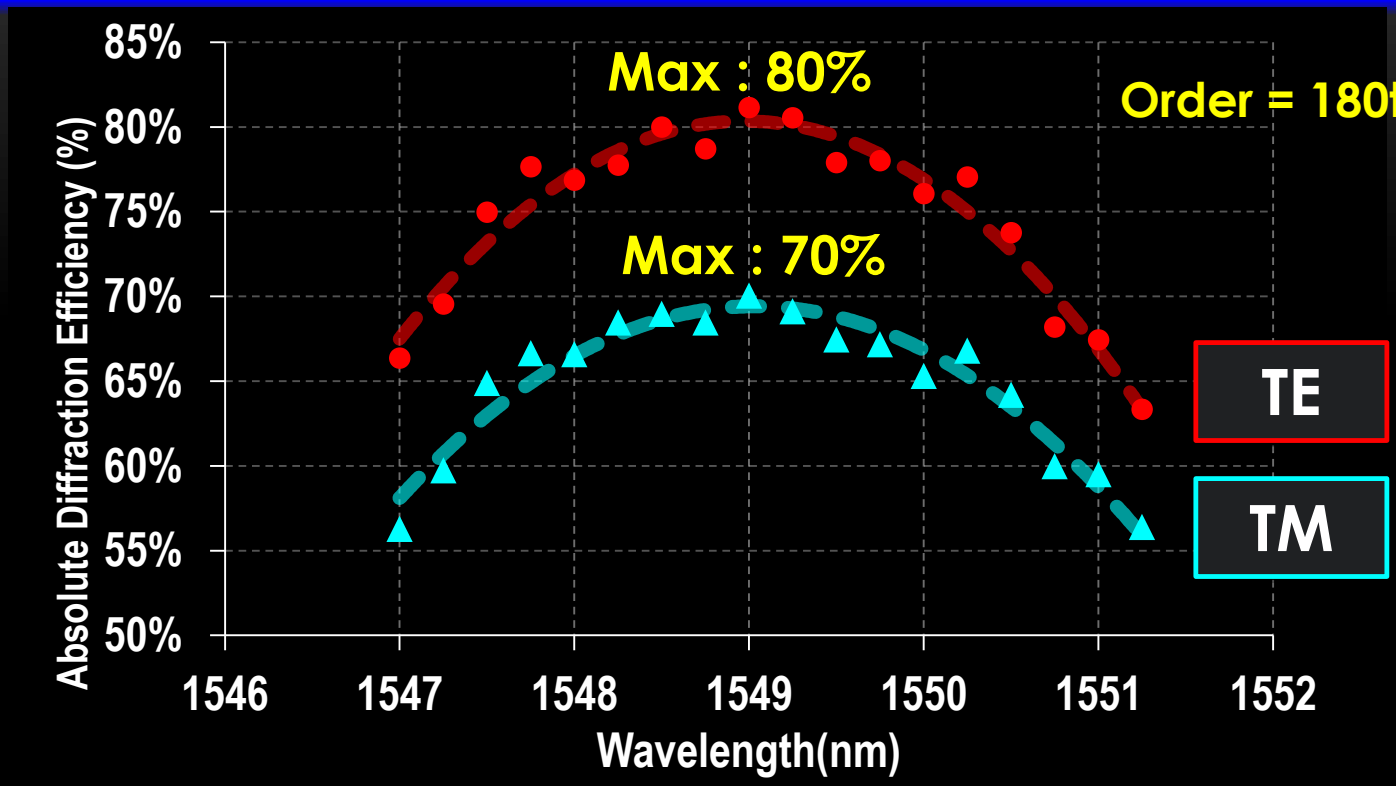
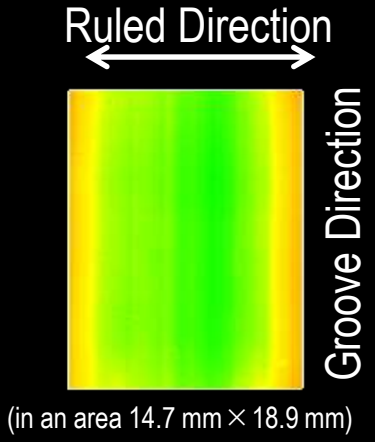
# Performance of InP immersion grating



Absolute Diffraction Efficiency




Wavefront Error




| | |
|---|---|
| RMS | 12.1nm |
| PV | 53.5nm |

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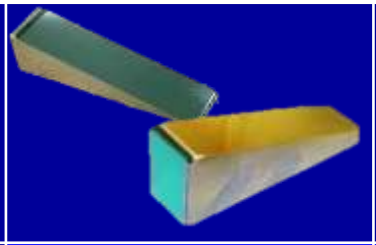
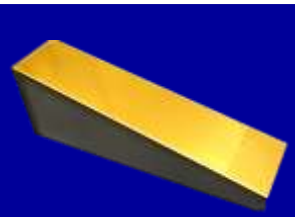
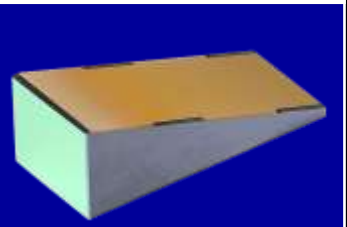
# Conclusions

# Typical Performances of our gratings



| Items | Reflection (L200x60) | CdZnTe (L80x20) | Germanium (L112x32) | InP (L50x20) |
|---|---|---|---|---|
| |  |  |  |  |
| Surface Flatness in grooved area by Littrow condition | 6nm RMS 54nm PV | 6nm RMS 40nm PV | 7nm RMS 54nm PV | 12nm RMS 54nm PV |
| Maximum Absolute Diffraction Efficiency | 76%(TE) 61%(TM) @1.5um | 74%(TE) 74%(TM) @4um (189th) | 80%(TE) 75%(TM) @4um (178th) | 80%(TE) 70%(TM) @1.5um (180th) |



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# Commercial Availability of immersion



| Item | Typical performance | |
|---|---|---|
| Size/Resolution | ~200,000 |  |
| Efficiency | >70% |  |
| Wavefront Error | < 20nm RMS |  |
| Scatter and Ghost | < $10^{-4}$ |  |
| Delivery Time | < 1year |  |
| Cost | Expensive |  |

We consider that it is reasonable enough for its total cost of system miniaturization by immersed effect.



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# Conclusions

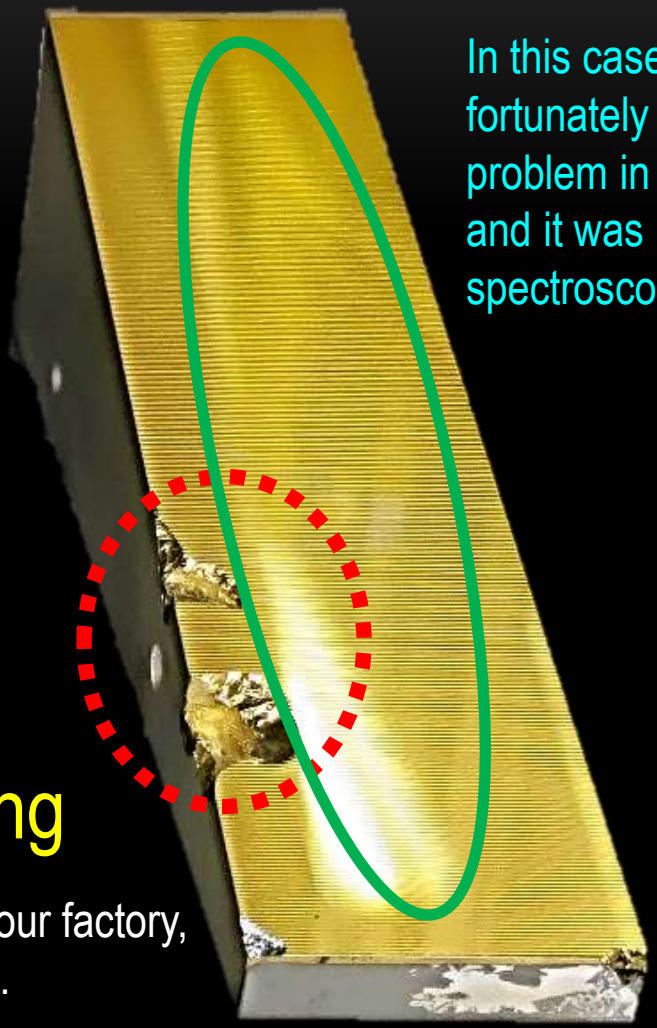


- Canon succeeded in fabricating 3 types of completed immersion echelle grating.

- Canon could also a reflective grating.

**Canon's grating is expected small surface flatness ( <20nm RMS) and high efficiency (60 to 80%).**

# Major risk in " made in JAPAN "



In this case,
fortunately there was no problem in practical use and it was used for actual spectroscopy

## Earthquakes during processing

Although it has several safety counter measures in our factory, it is difficult to respond to the direct type earthquake.



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# Thank you for your attention

## End of Slides

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