Optical device for diffraction limited observations and novel gratings

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NAOJ研究集会「将来装置による地球型系外惑星直接検出および撮像」24-25 Jan. 2013,

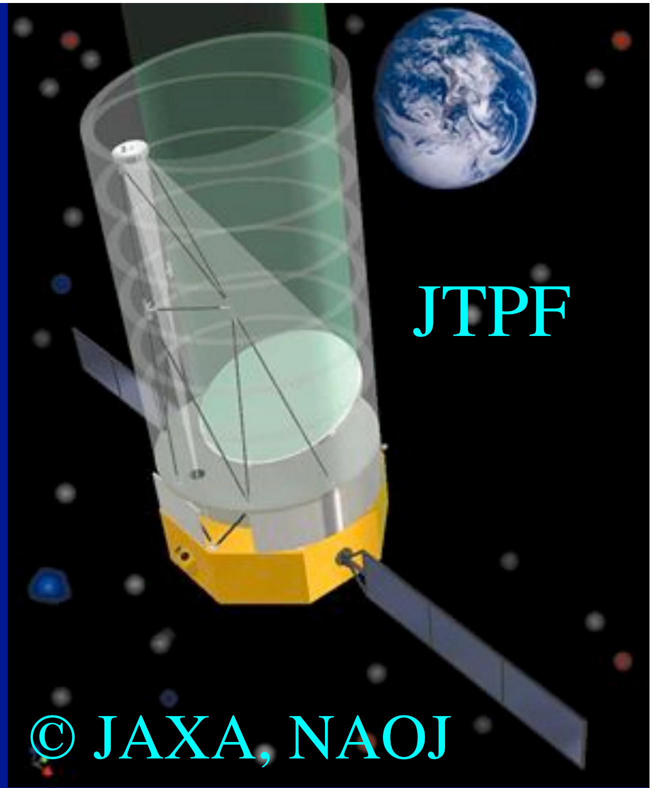
Next Generation Huge Telescopes

Grand based

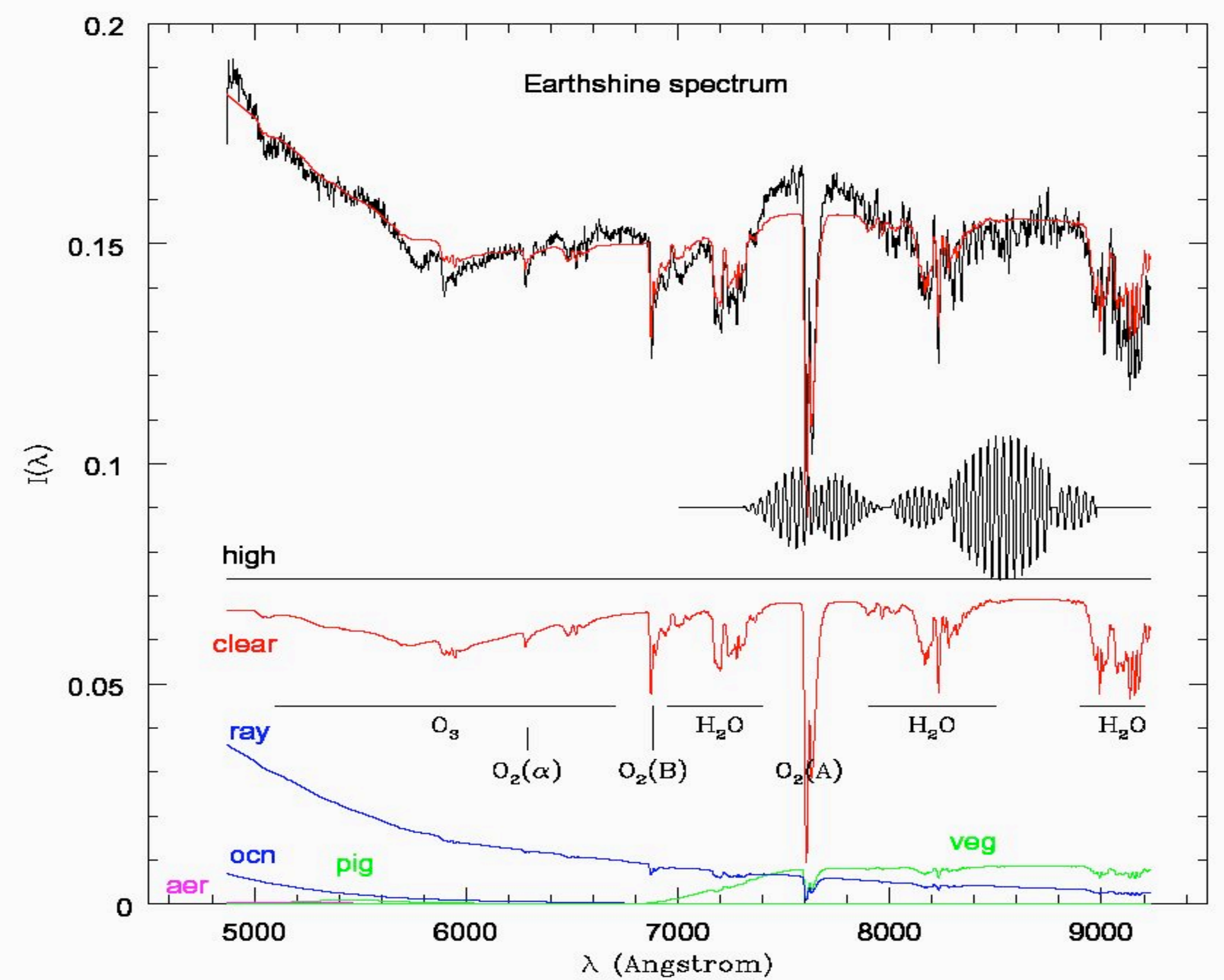
- TMT: D=30m (USA, Canada, Japan, …)
- E-ELT: D~ 40m (EU, …)

Space

- TPF: D~10 m or D~ 4m×N: Interferometer (NASA, CALTEC, ESA, …)
- SPICA, JTPF: D~ 4m (Japan, …)

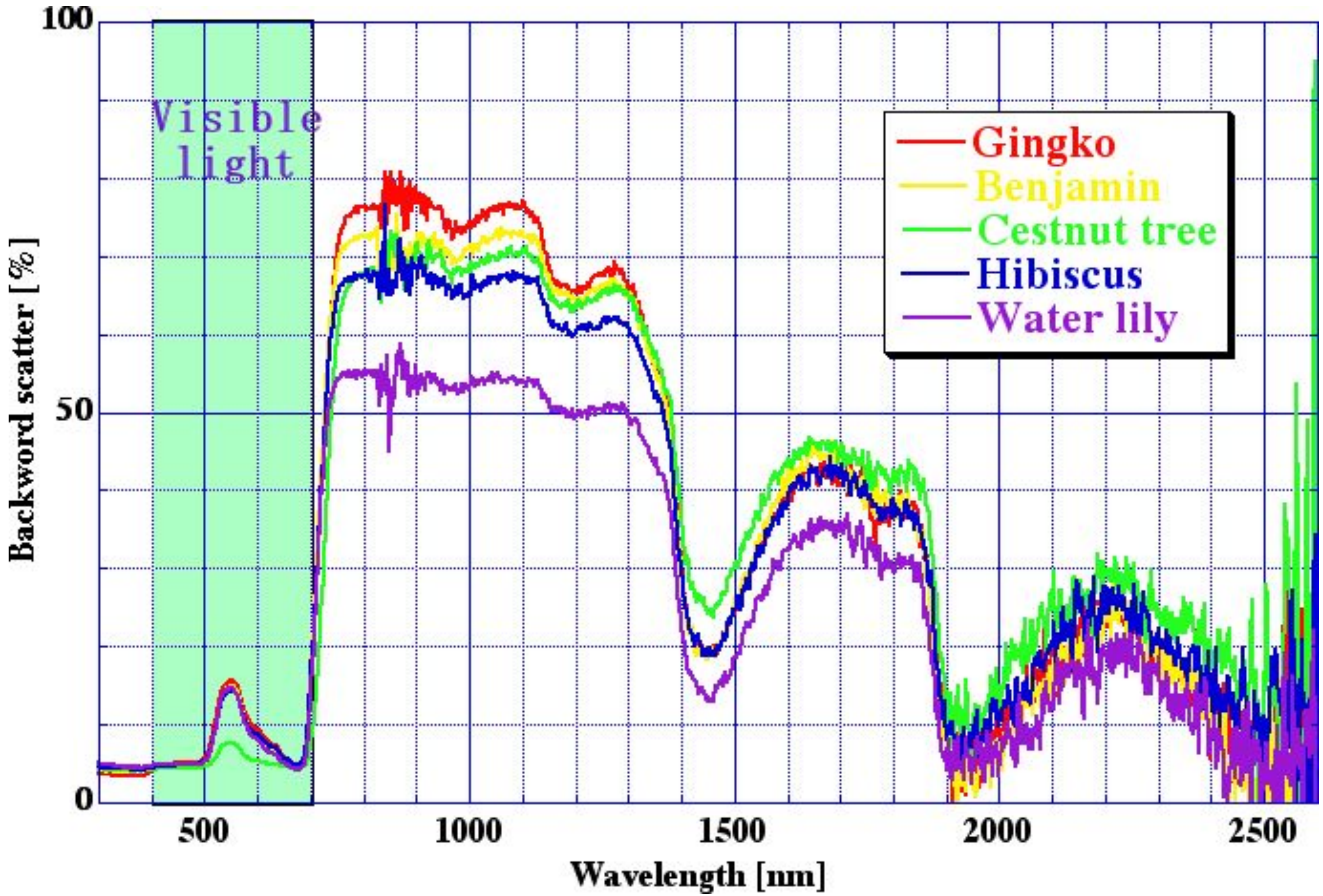


Earth Shine Spectrum

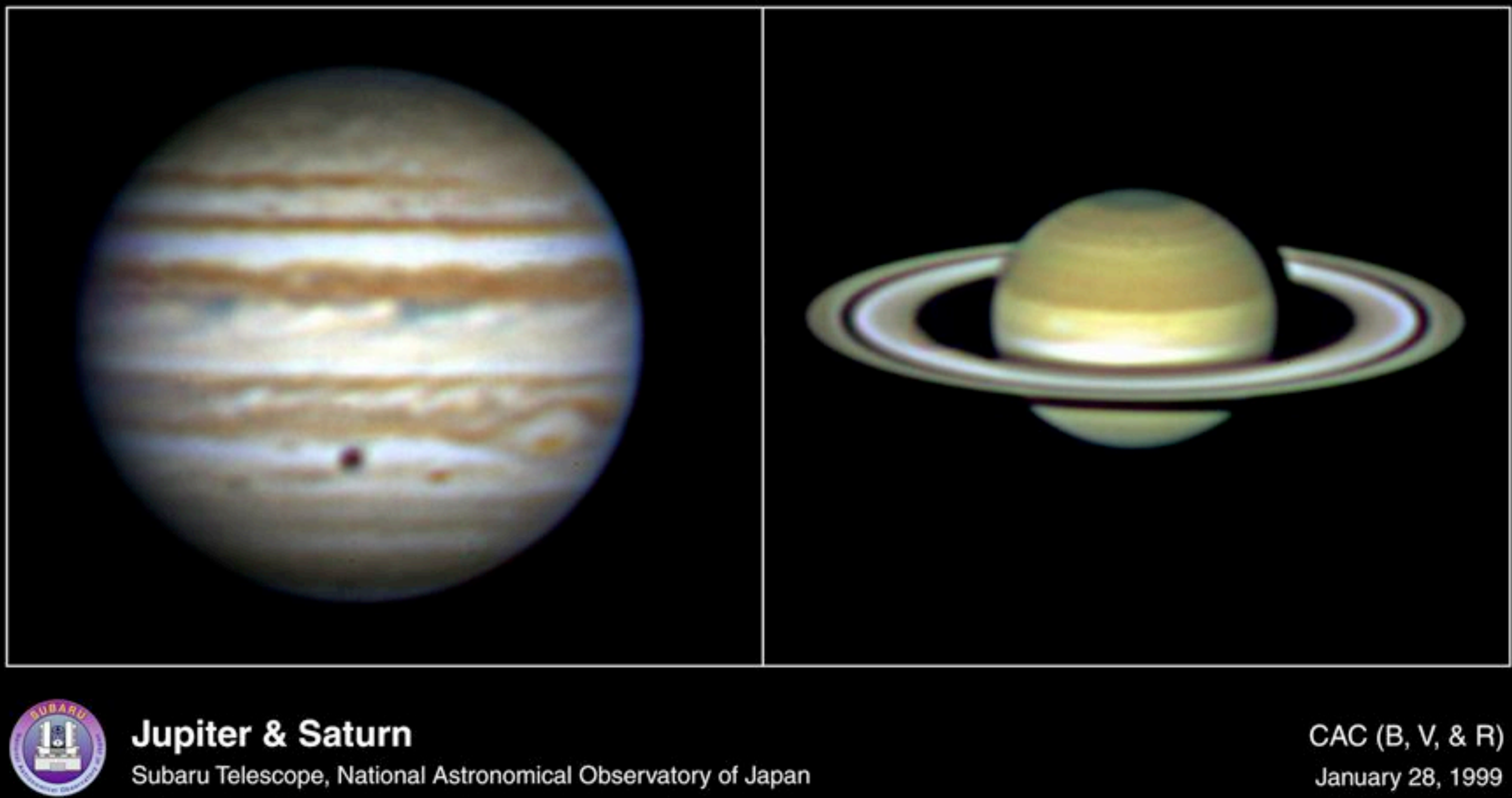


N.J. Woolf and P.S. Smith, Hervard-Smithsonian Center for Astrophysics

Reflection Spectra of Plants



Direct Vision Prism



Spectroscopy with Wide Wavelength

Diffraction grating

- Linear dispersion for wavelength.
- Decrease of diffraction efficiency without blazed wavelength.
- Overlap of higher diffraction orders.

Prism

- Wide wavelength coverage with high efficiency.
- Non-linear dispersion for wavelength and wave number.
- Small dispersion.

Fourier transform spectrograph

- Wide wavelength coverage.
- Linear dispersion for wave number.
- Vanishment of multiplex advantage for continuum.
- Loss of optical throughput advantage for point sauce.

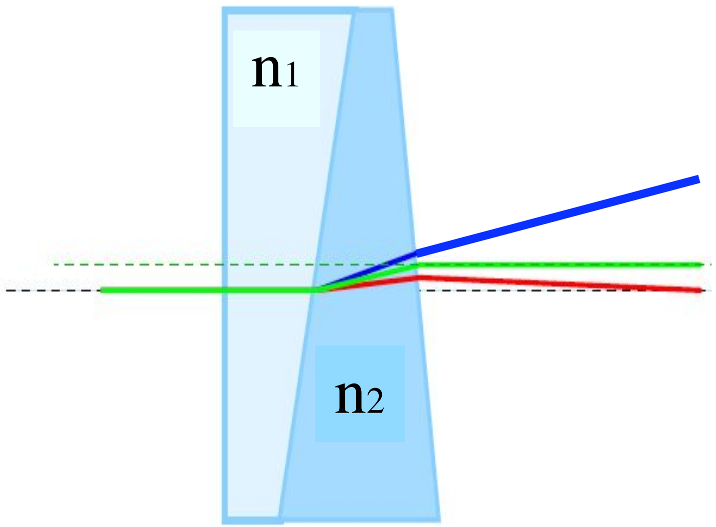
Direct Vision Prism

10m telescope@0.5 μm : 0.0126”

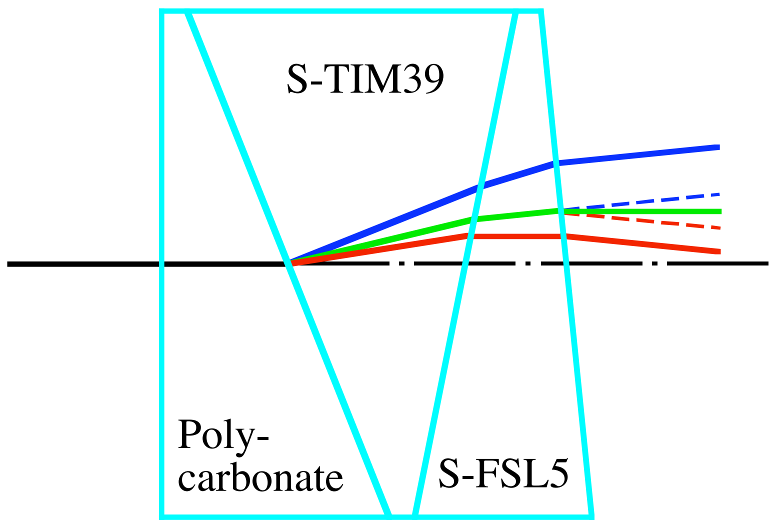
→ Slit width : 1/40 (vs. Seeing: 0.5”)

→ Resolving power : × 40

*** Required small wave front error: < λ/20**



Conventional Direct vision Prism



Novel Direct vision Prism

Dispersion of Refractive Index

Refractive index $n(\lambda)$ of a dielectric is given by

$$n(\lambda)=A_0+A_1\lambda^2+A_2\lambda^{-2}+A_3\lambda^{-4}+A_4\lambda^{-6}+A_5\lambda^{-8}...,\quad (1)$$

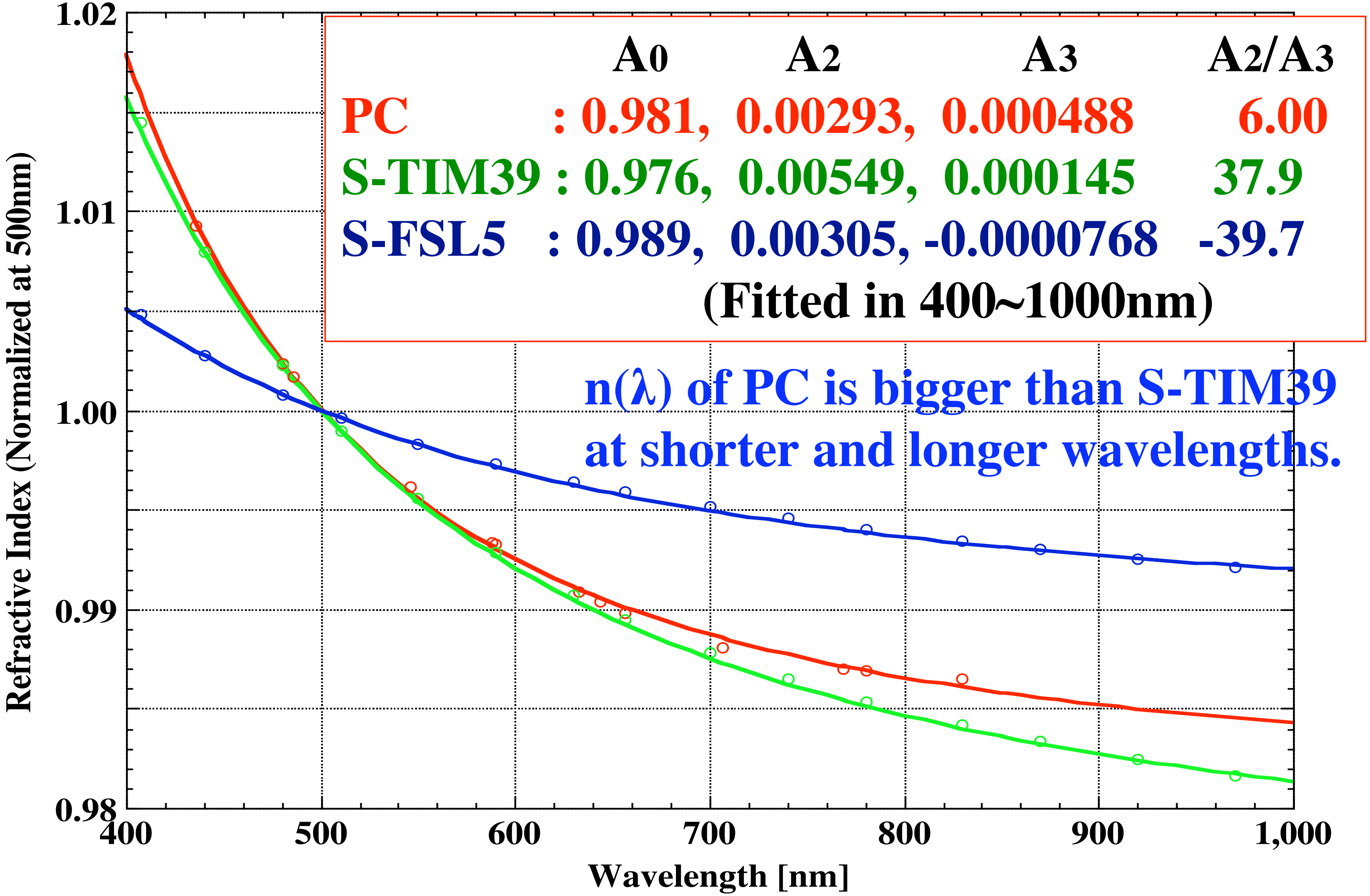
where λ is wavelength. $n(\lambda)$ is practically obtained by

$$n(\lambda) = A_0+A_2\lambda^{-2}+A_3\lambda^{-4}. \quad (2)$$

A linear angular dispersion with wavelength is obtained by combination of prisms with different A_2 and A_3 ratios.

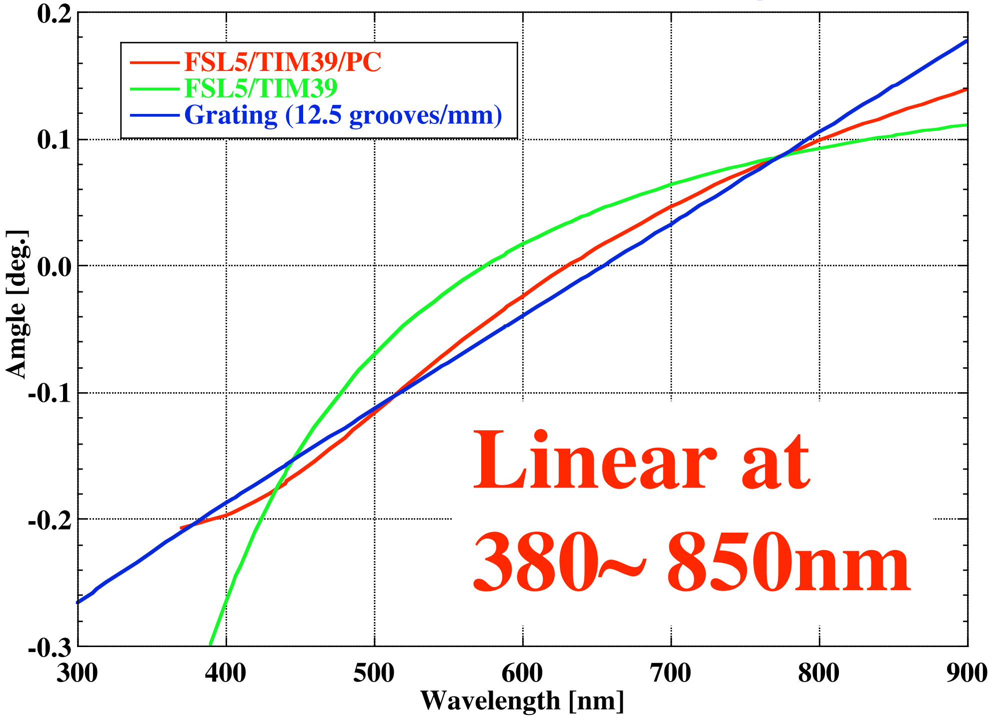
Thickness of a prism block is reduced by using a resin, since some resin has small absolute value of A_2/A_3, compared with a glass or crystal.

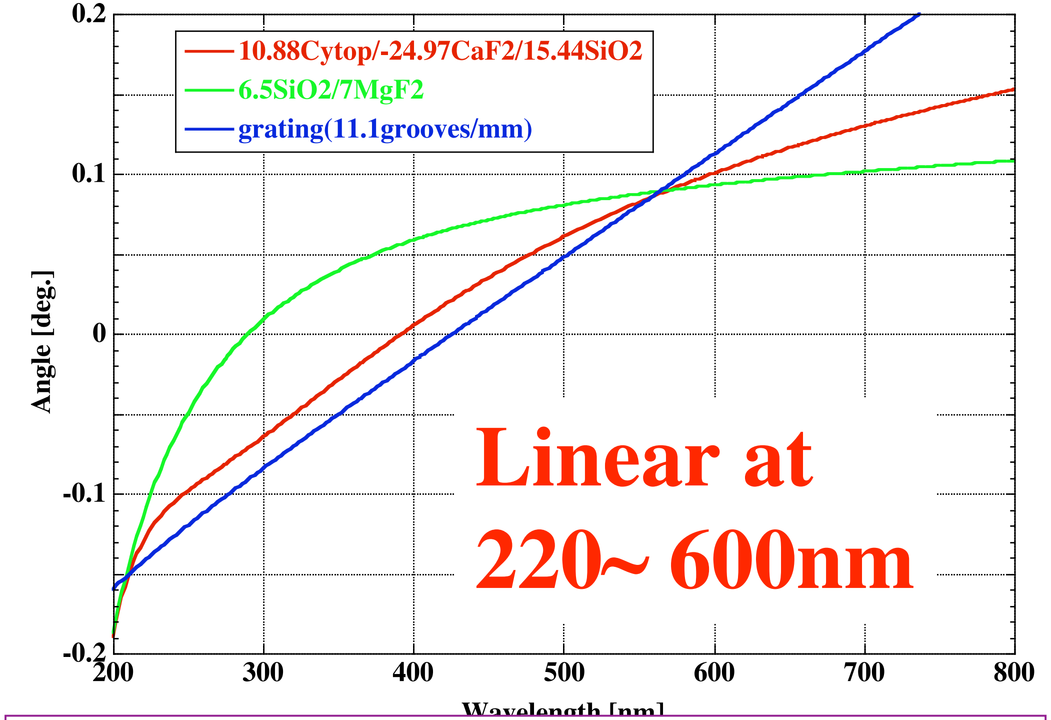
Refractive Indices of Optical Glasses and Resin



Marker: Polycarbonate (PC) : Measured,
S-TIM39 and S-FSL5: Sellmeier's dispersion formula.

Linear Angular Dispersion Prism





Visible

S-FSL5 (OHARA) : 7.75°,
S-TIM39 (OHARA) : -27.28°,
Polycabonate : 22.71°.

S-FSL5 : 12°,
S-TIM39 : -10.688°.

Transmisson grating : 12.5 [g/mm]

UV-Visible

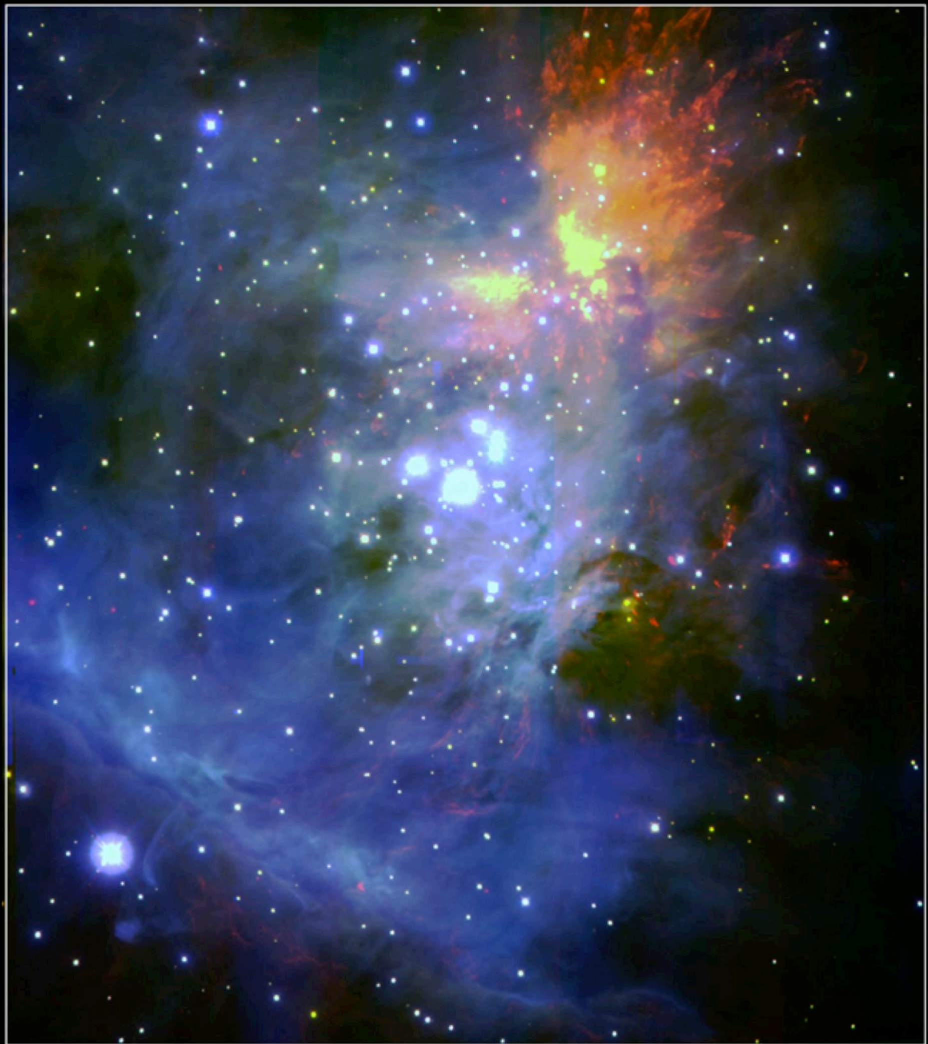
		A_2/A_3
Cytop (ASAHI Glass)	: 10.88°,	-50
CaF_2	: -24.97°,	112
Sillica	: 15.44°.	125

(Fitted in 200~1000nm)

CaF_2 : -7°,
Silica : -6.5°.

Transmisson grating : 11.1[g/mm]

Birefringence prism



Orion Nebula CISCO (J, K′ & H2 (v=1-0 S(1))
Subaru Telescope, National Astronomical Observatory of Japan January 28, 1999

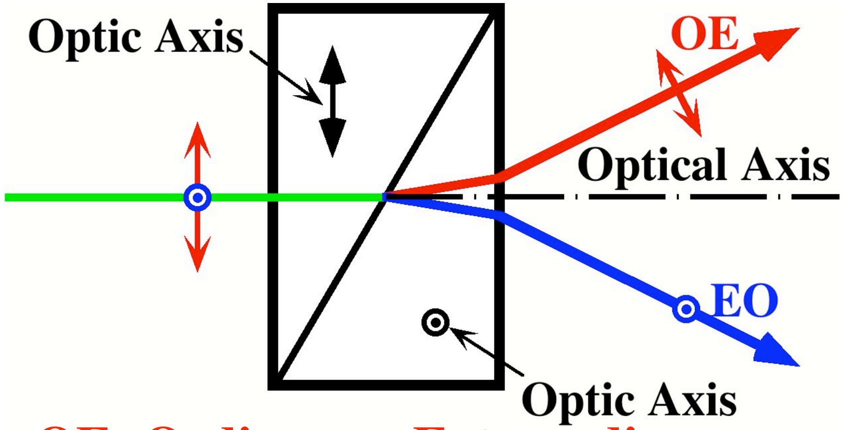
Star-forming Region S106 IRS4 CISCO (J, H, K')
Subaru Telescope, National Astronomical Observatory of Japan February 13, 2001

Applications of Wollaston Prisms

Polarization Spectroscopy

- Angular dispersion is small against a separation angle.

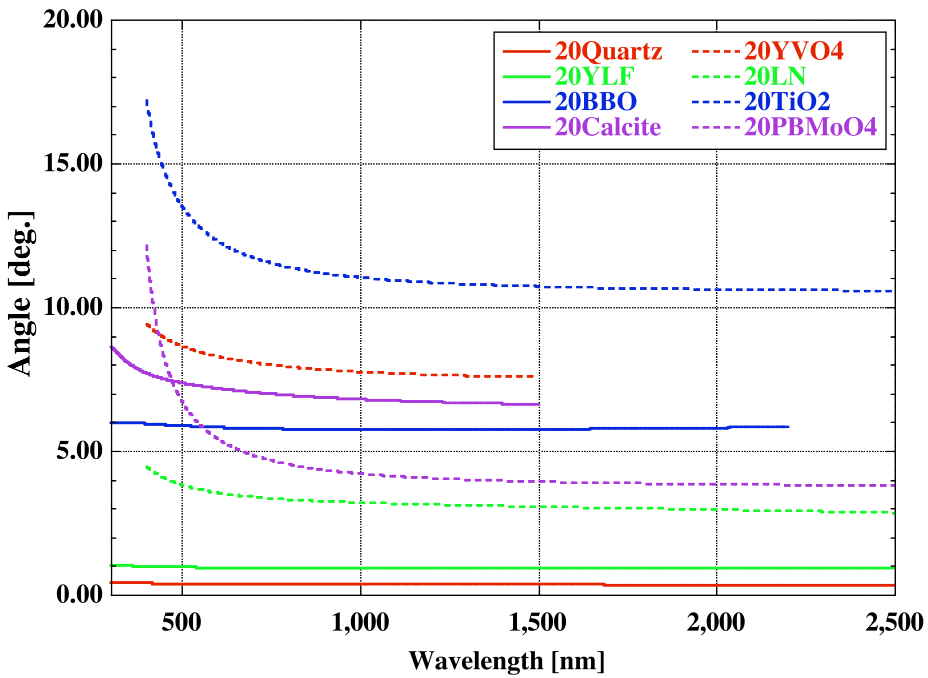
→Combined with another disperser.



OE: Ordinary→Extraordinary
EO: Extraordinary→Ordinary

Polarization Imaging

- Angular dispersion should be small.
- α-BBO (BaB_2O_4) has small angular dispersion, but it is difficult to obtain a large crystal.

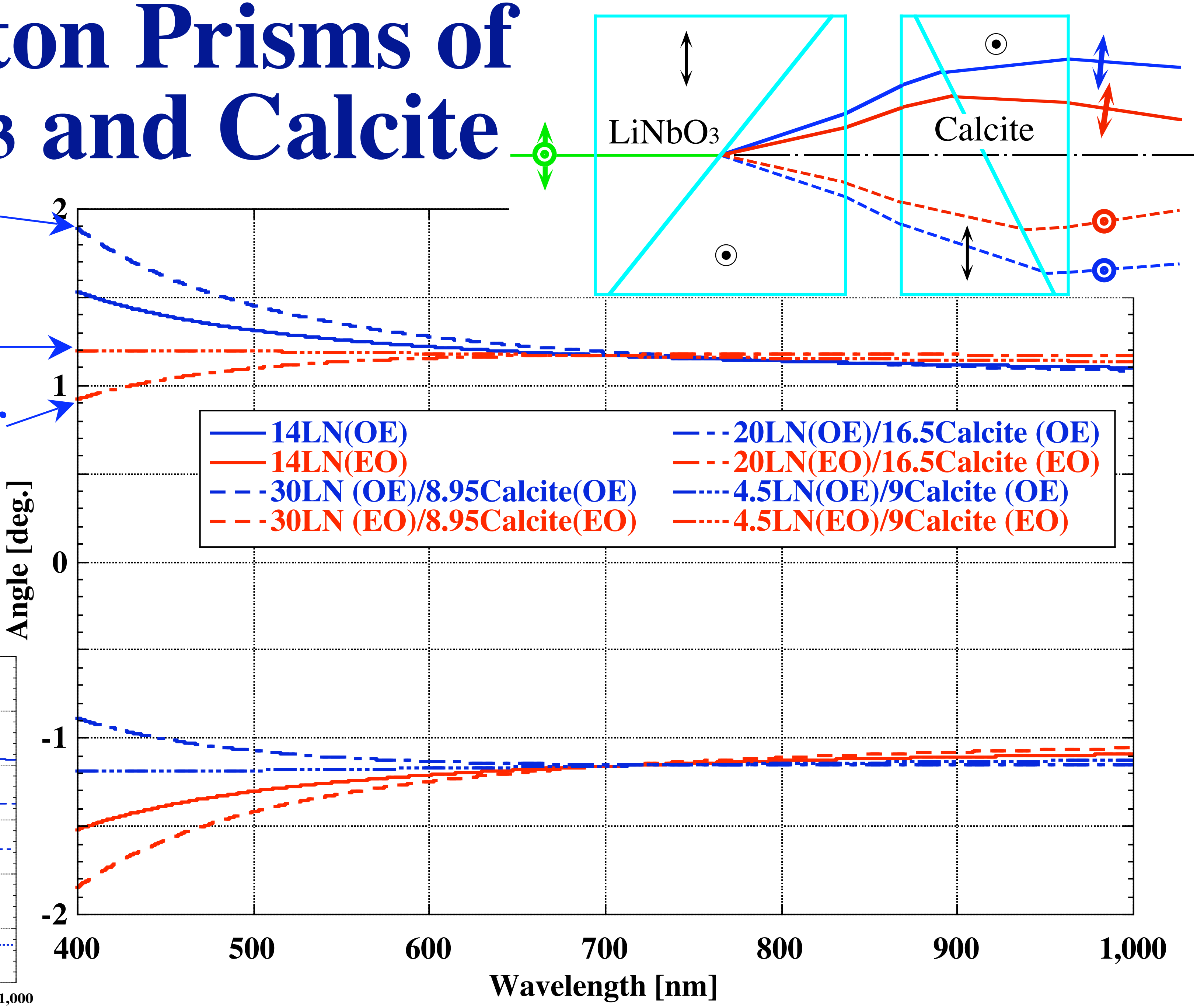


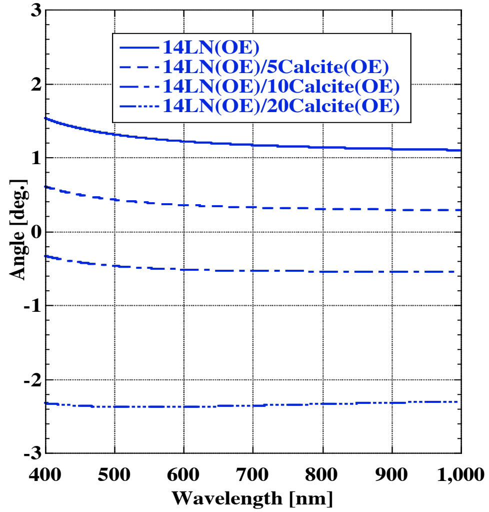
Wollaston Prisms of $LiNbO_3$ and Calcite

Spectroscopy

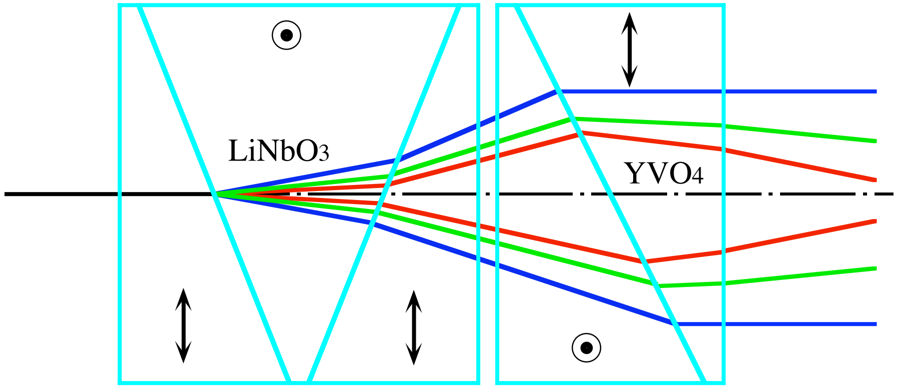
Imaging

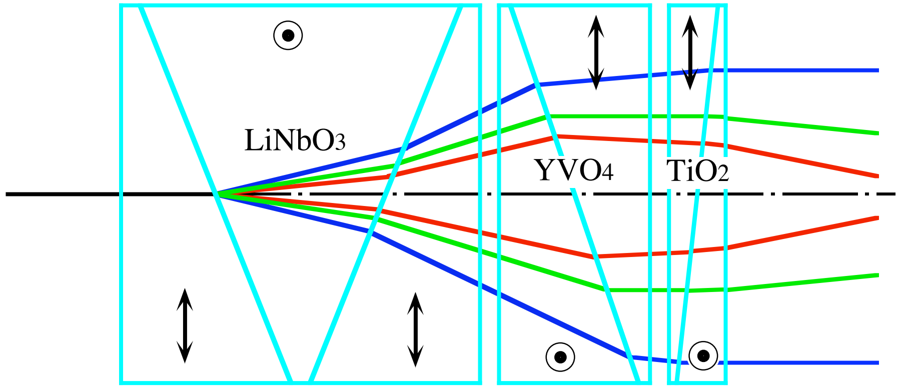
Interferometer of FTS (Linear at 400~1,000nm)

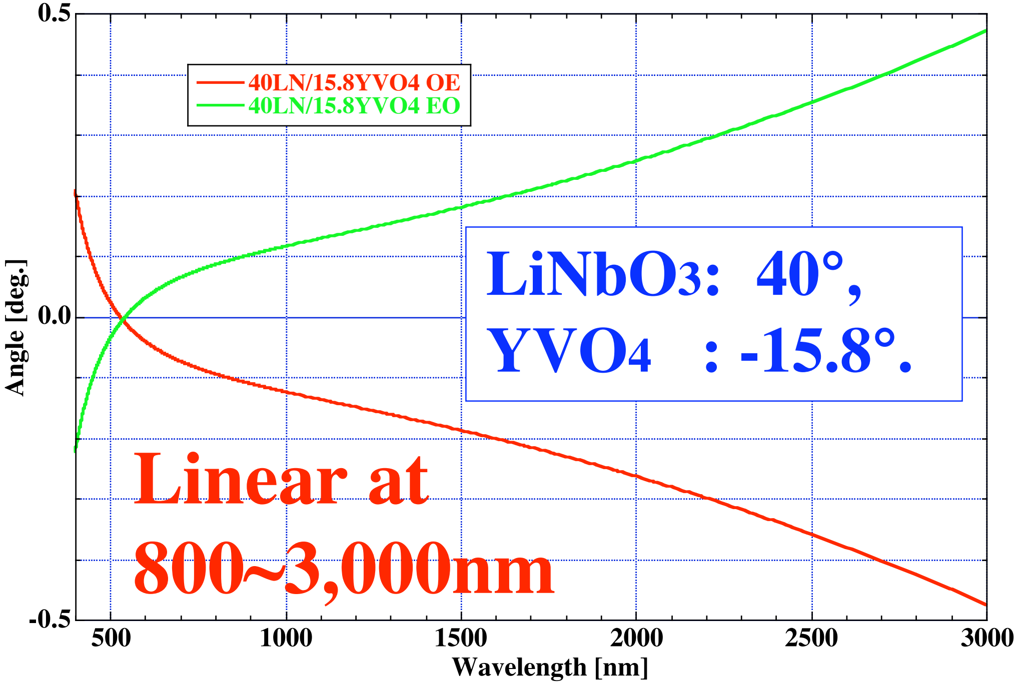


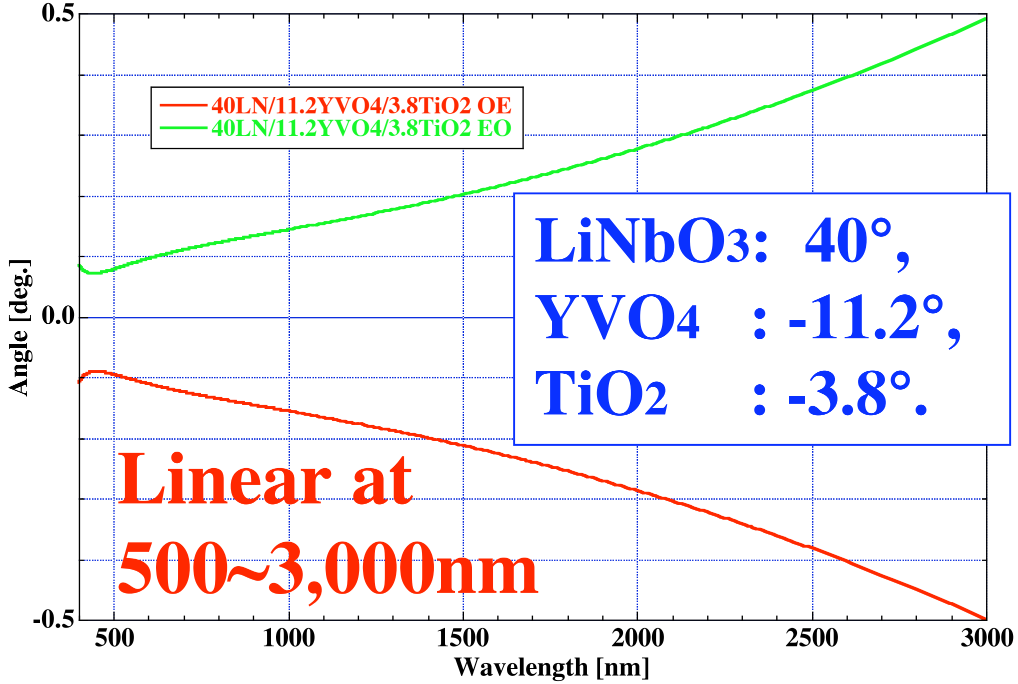


Wollaston Prisms of $LiNbO_3$, YVO_4 and TiO_2

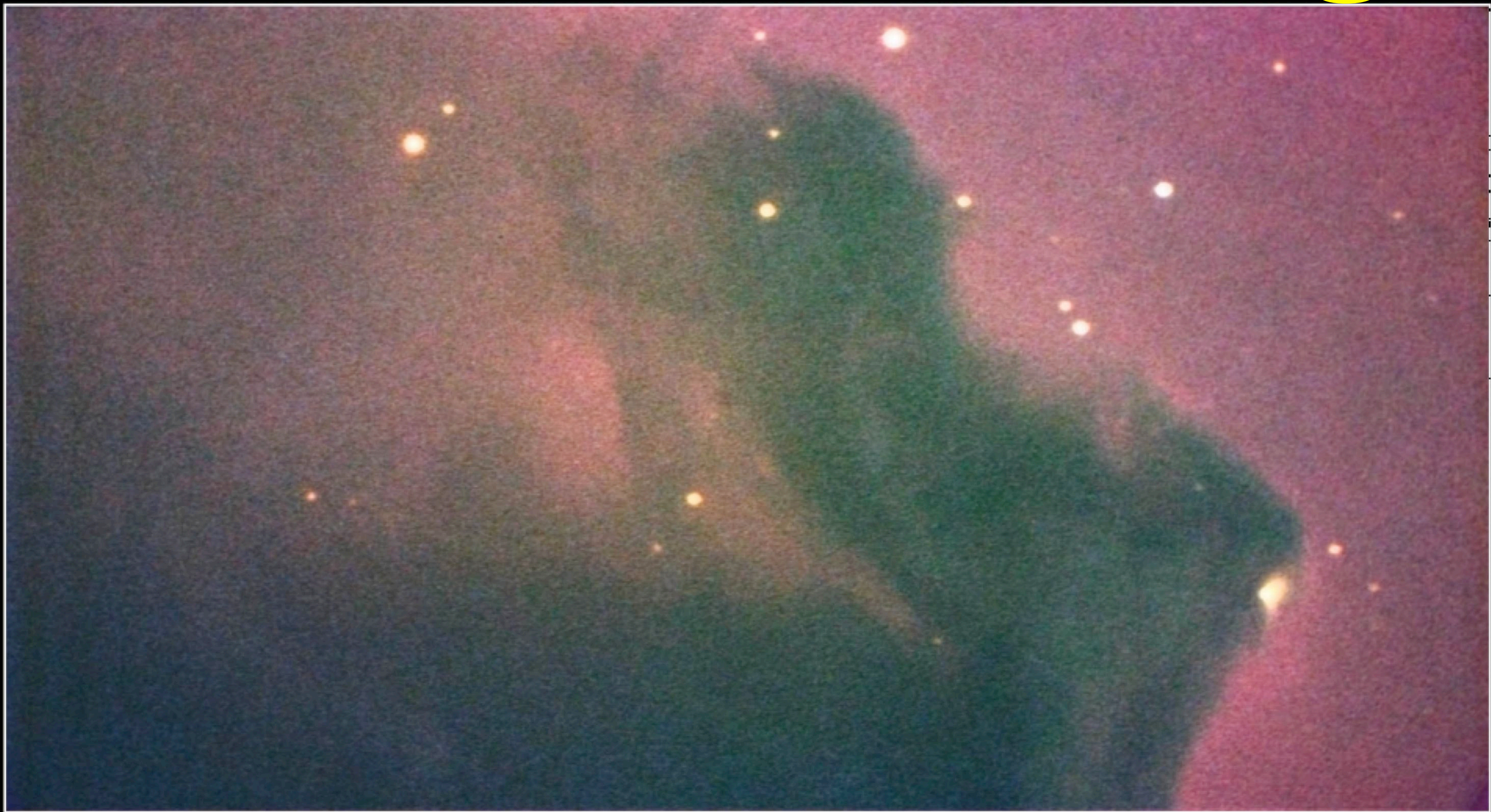








Immersion Grating

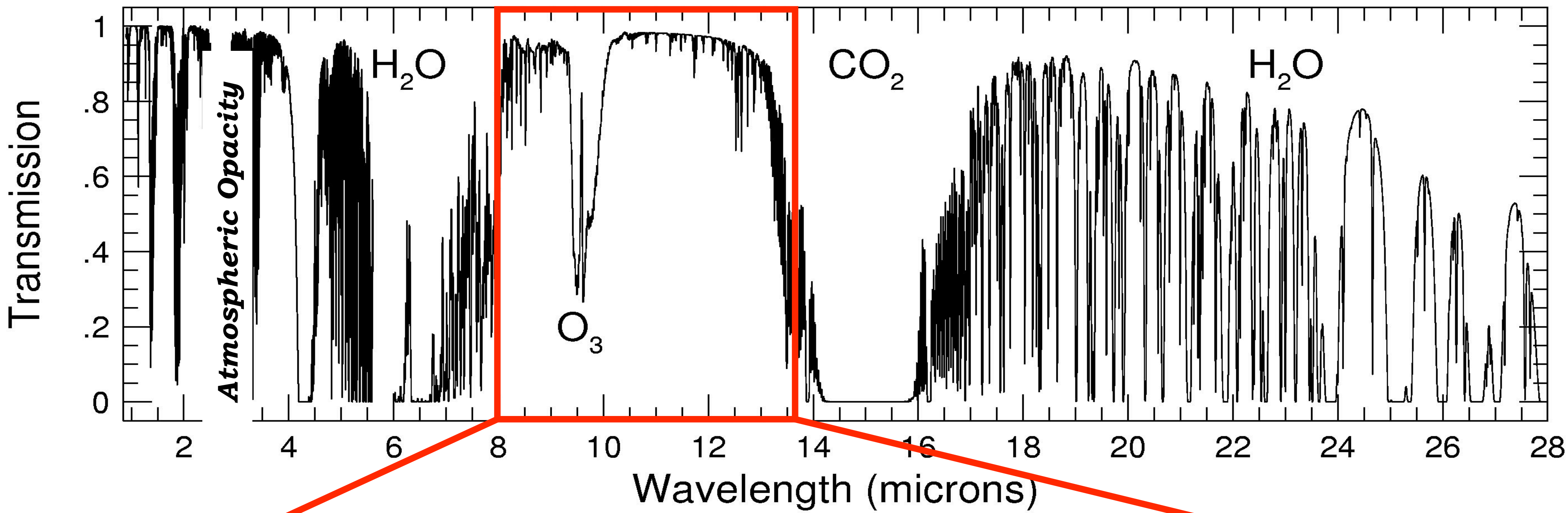


IC 434 (Horse-head Nebula)

Ultra-high-sensitivity HDTV I.I. color camera (NHK)
Exp. 22 sec. (11 frames coadded) January 16, 1999

Subaru Telescope, National Astronomical Observatory of Japan

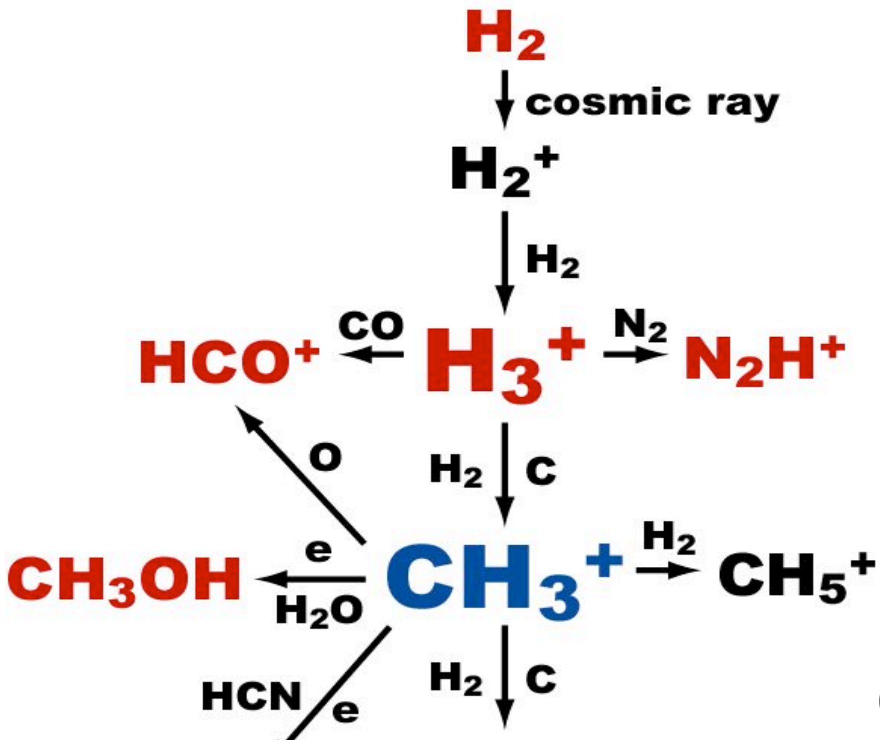
Introduction: 10 μm Wavelength Region



N-Band: 7.5 ~ 13.5 μm

- **CH_4, C_2H_6 , …, Carbon Chain, "PAH"s.**
- ***(SiO)$_x$* ….**
- **Chemistry Related to Star Formation.**
- **"Fingerprint" region (指紋領域) for Complex Organic molecules.**

Interstellar Chemistry in Dense Cloud

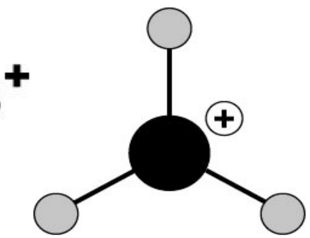


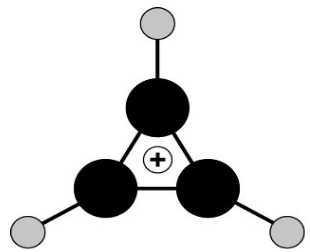
Key ions:

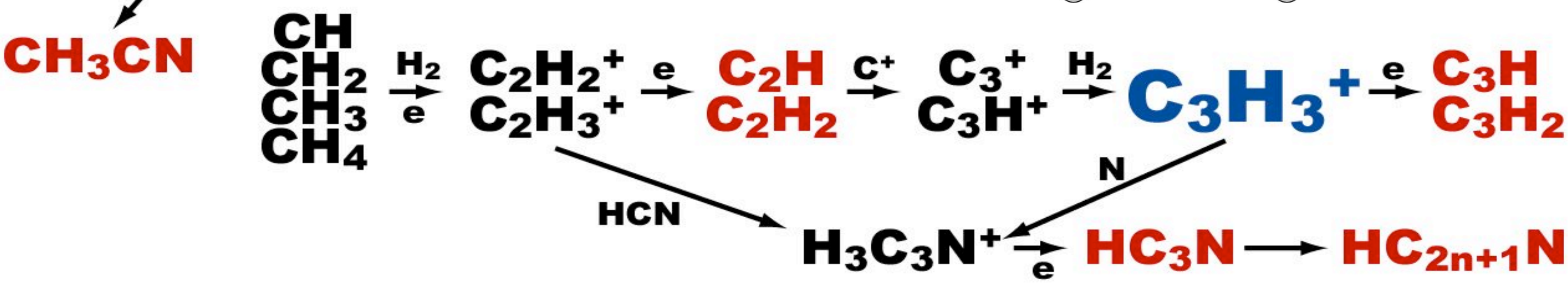
H_3^+, CH_3^+

$C_3H_3^+$: "Smallest Aromatic ion": n(π e^-)=2

Huchel Rule: (4n+2) π







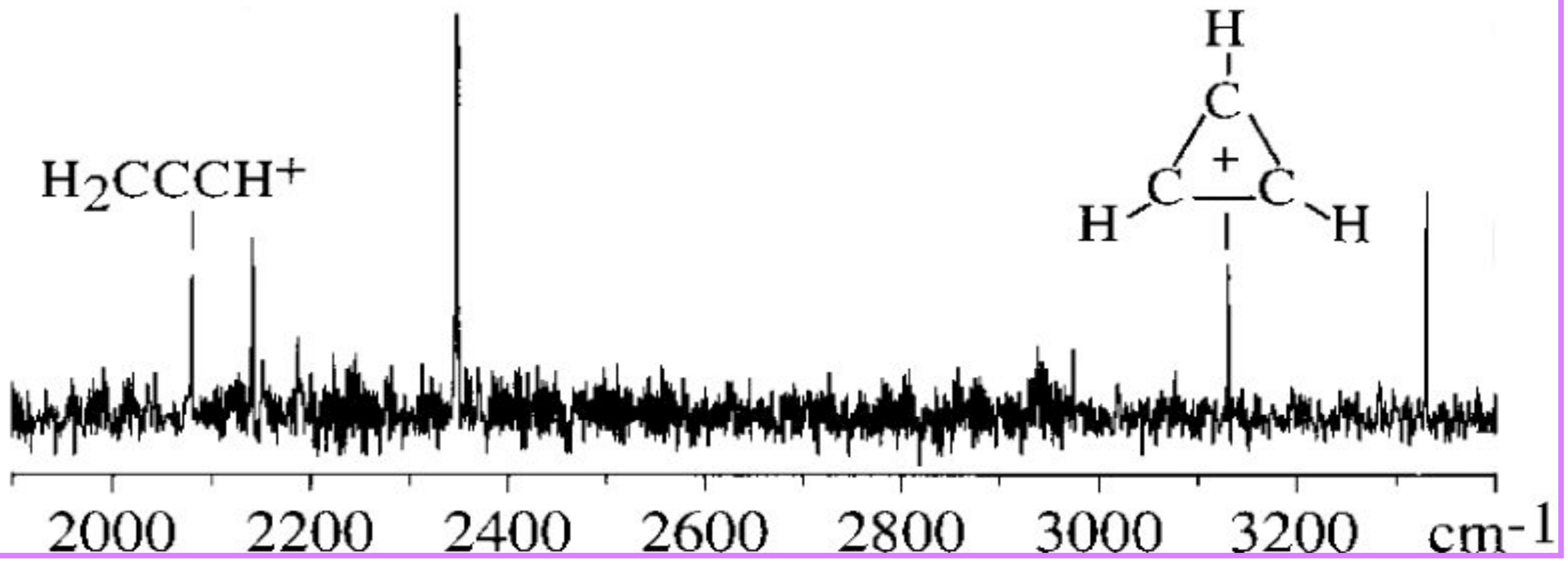
Ion molecule reaction network for Carbon

Laboratory IR Spectroscopy of c-$C_3H_3^+$, CH_3^+

No gas phase data for c-$C_3H_3^+$

c-$C_3H_3^+$					CH_3^+		
n_3	n_4	n_5	n_6	mode (μm)	n_2	n_3	n_4
9.71	3.19	10.74	7.74	calc.	7.26	3.22	7.21
…	$\boxed{3.19}$	…	…	neon	…	…	…
…	**…**	**…**	**…**	**gas phase**	**…**	**3.22**	**…**

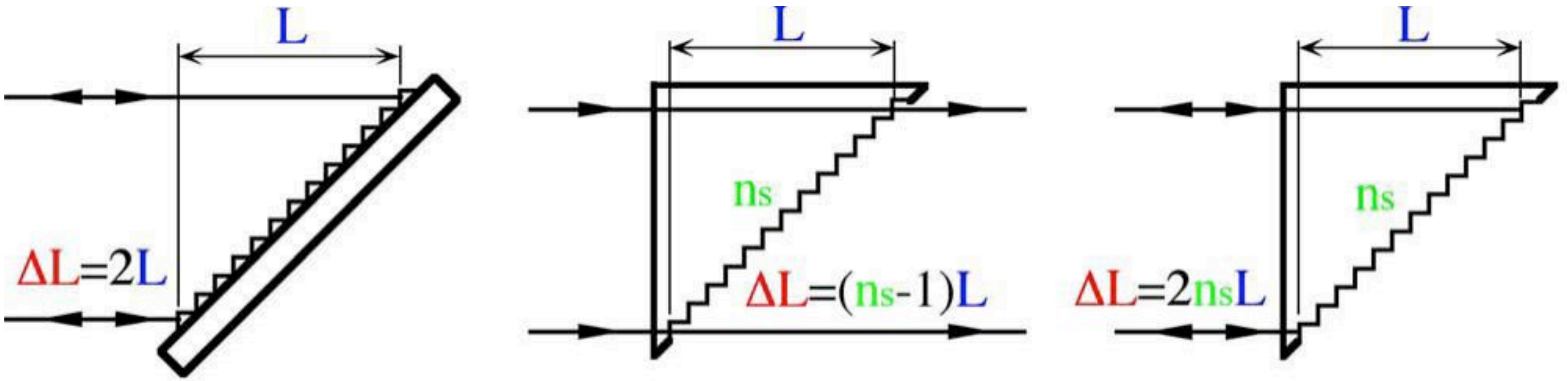
Neon matrix (Wyss et al., 2001)



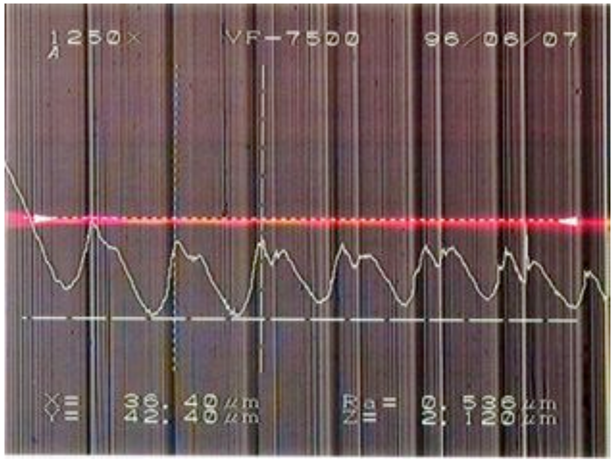
Spectrograph of 30m Telescope
(R~ 50,000@1μm)

	Natural seeing: 0.5”	Diffraction limit: 0.0084”	Remarks
D col = Optical pass difference	3 m	0.05 m	~ 900 g/mm grating (α=26.6°)
Collimator f	30 m	0.50 m	F/10
Size of optics	35 × 10 × 4.5 [m]	0.6 × 0.2 × 0.075 [m]	Conventional spectrograph
Slit width	727μm	12.2μm	F/10
Camera F	F/0.62	F/37	15μm × 3 pix.
Precision of optical elements	~ 3λ (P-V), ~ 0.5λ (rms)	< λ/20 (P-V), < λ/100 (rms)	

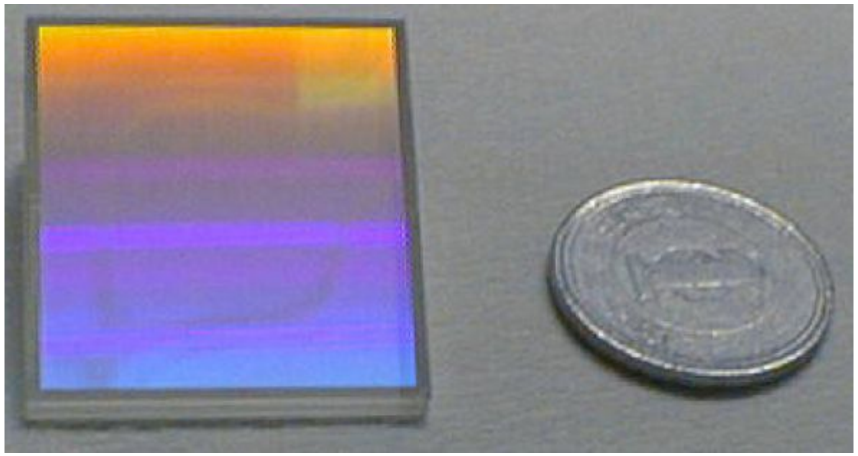
Development of High Dispersion Gratings



(a) Reflection grating (b) Grism (c) Immersion grating

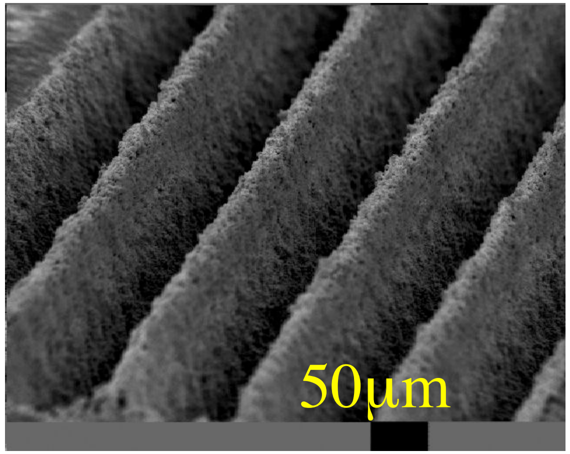


$LiNbO_3$ (n = 2.3) grating, 30 g/mm, Dicing Saw



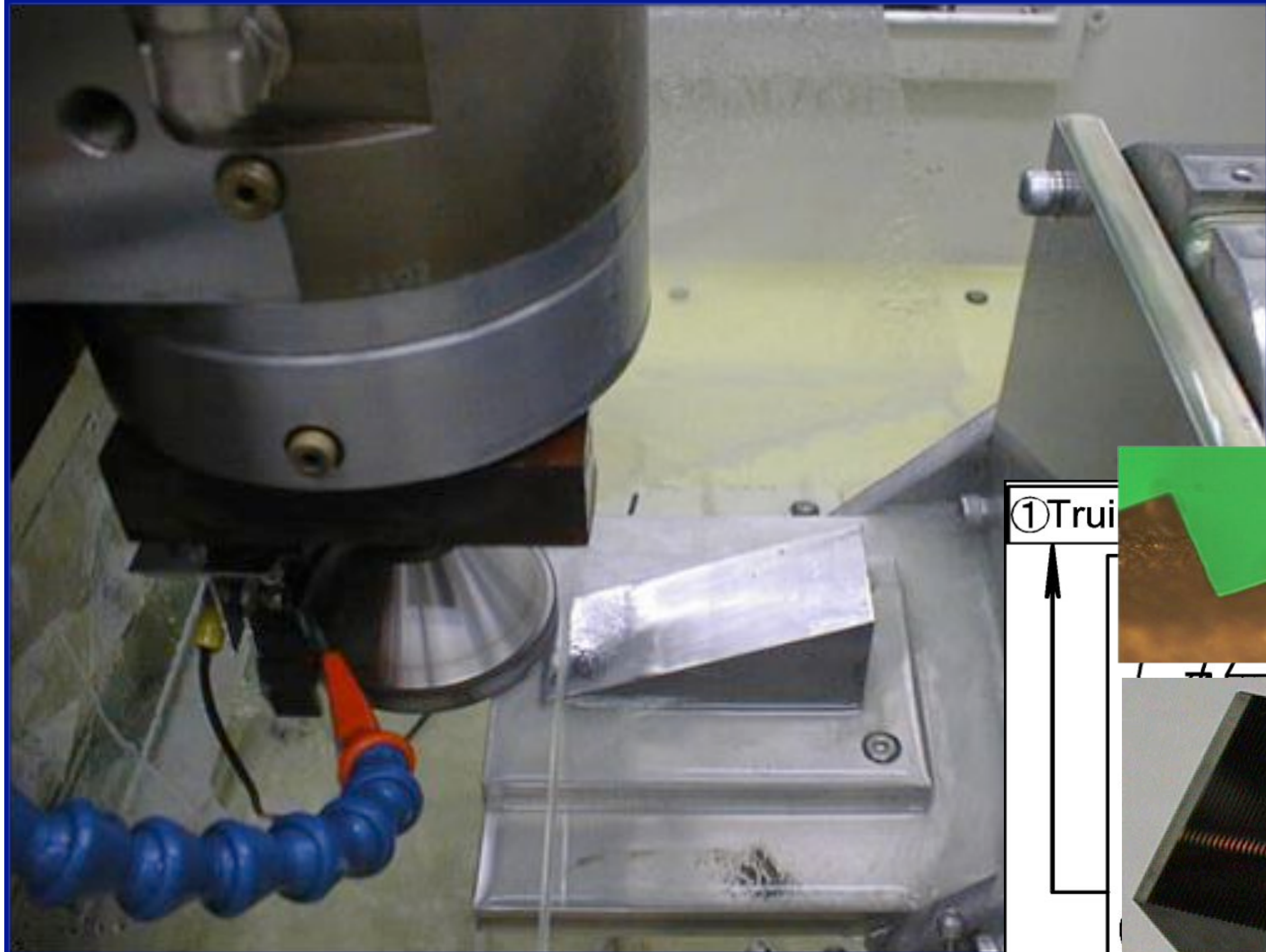
$LiNbO_3$ (n = 2.3) Grism, 444 g/mm, Ion etching

(Ebizuka et. al. SPIE, **3355**, 1998)



Ge (n=4.0) grating, Excimer Laser Ablation

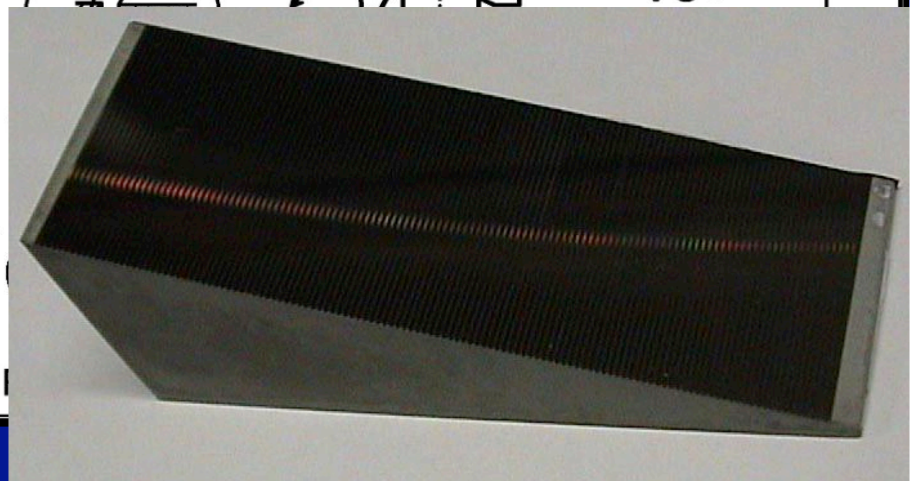
Ge Immersion Grating for GIGMICS



Nano-precision machine and ELID grinding method.

30 × 30 × 72 [mm],

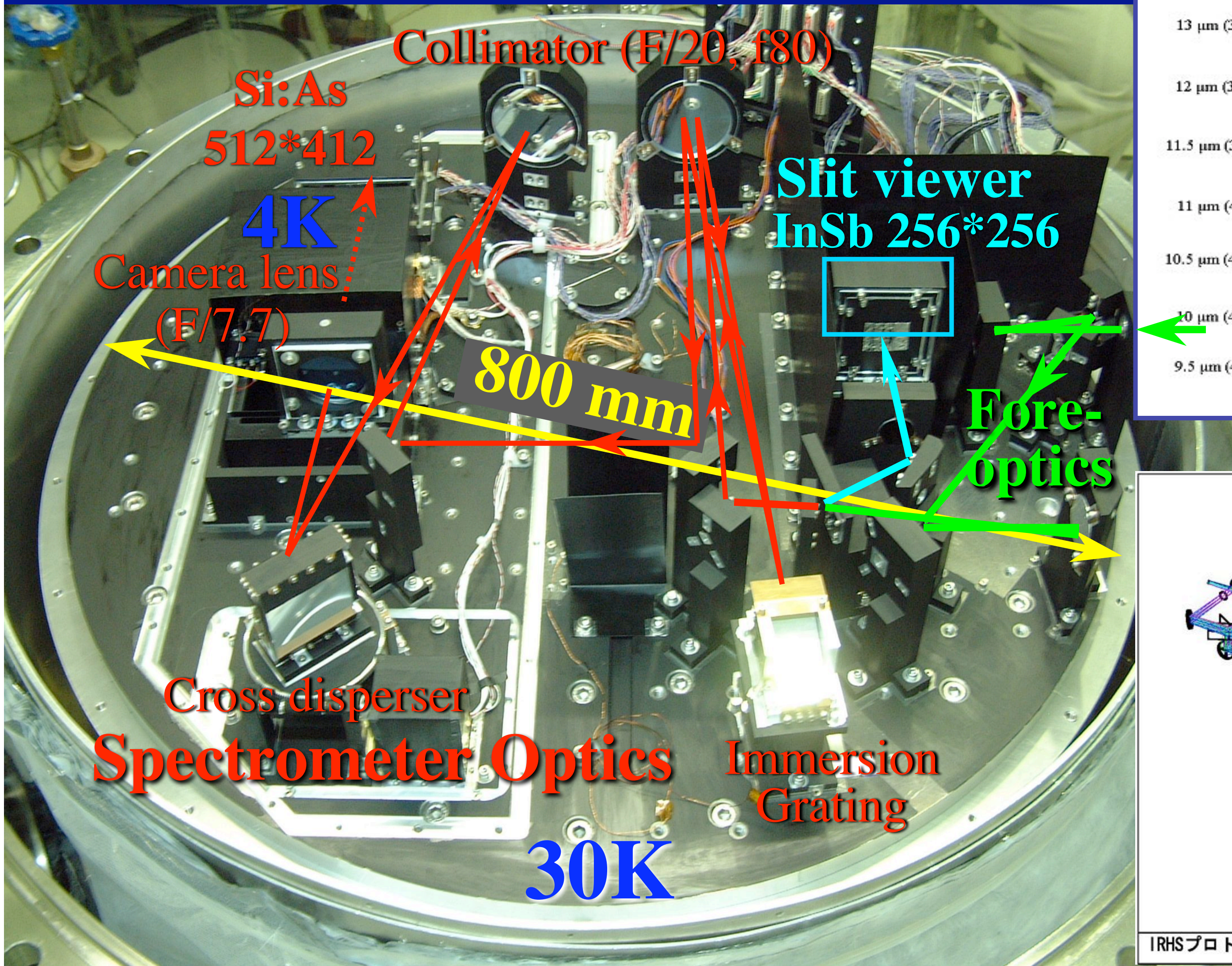
α = 68.75°, Λ=600μm

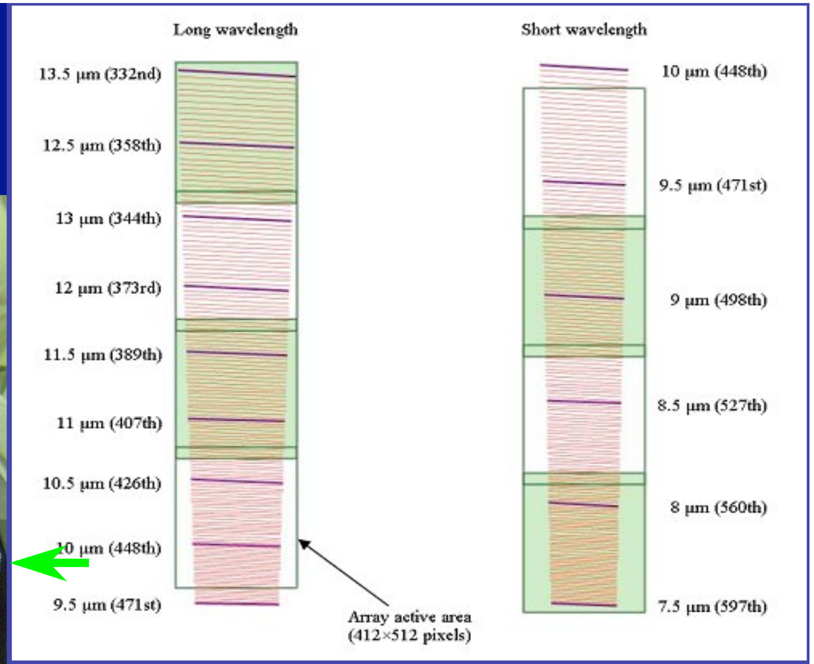


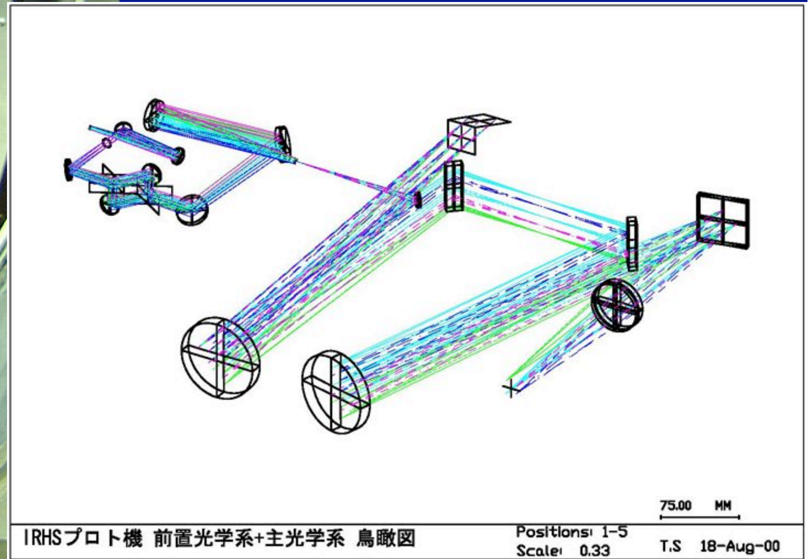
Spent about 400 hours for fabrication

(Ebizuka et. al. SPIE, **4842**, 2003b)

GIGMICS



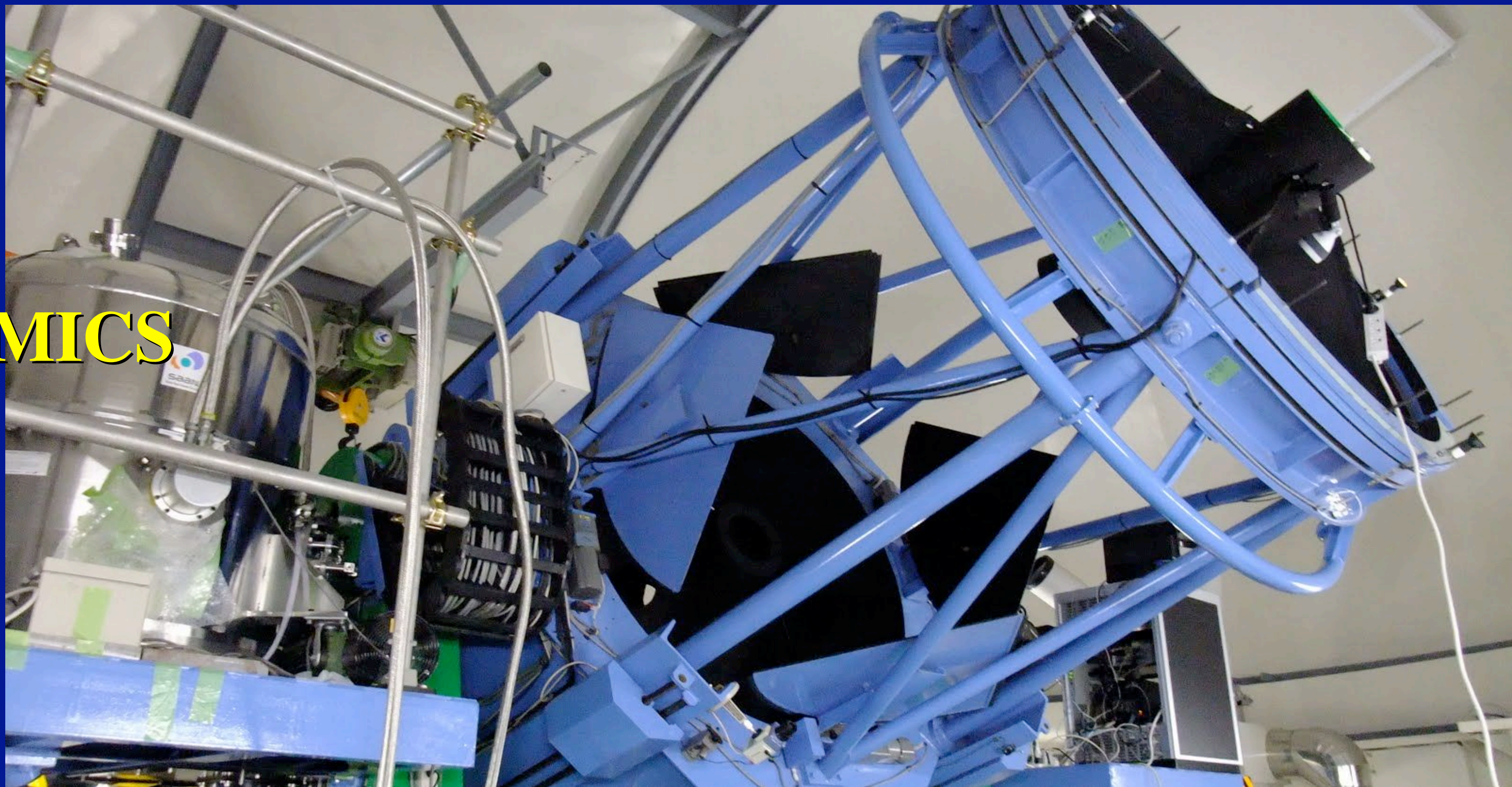




R~ 50,000@10μm, developed by Hirahara lab., Nagoya Univ.

(Hirahara et. al., SPIE, **7735**, 2010)

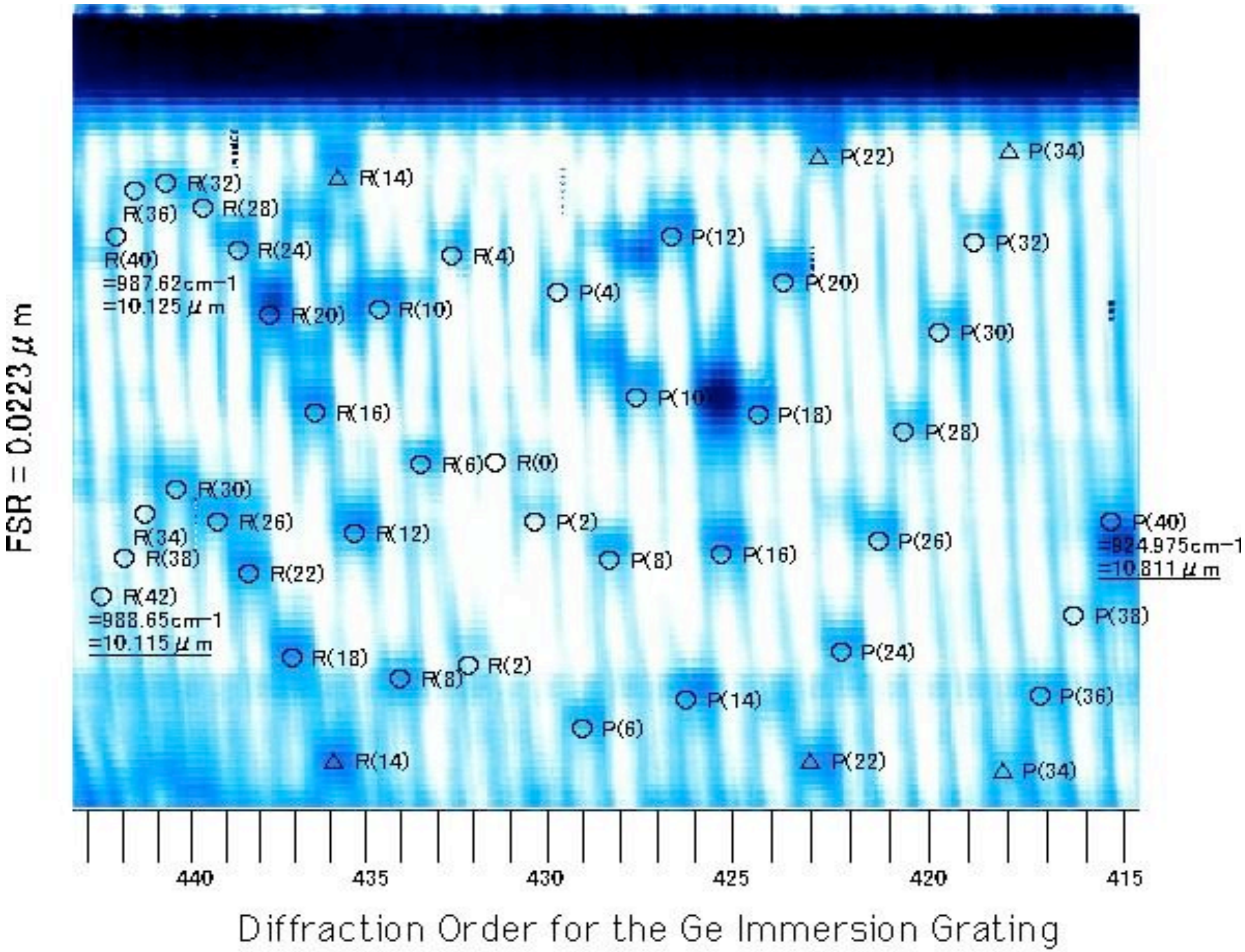
First Light Observation of GIGMICS



KANATA 1.5m telescope, Higashi-Hiroshima Observatory, Space Science Center Hiroshima Univ., Dec. 2010~Apr. 2011.

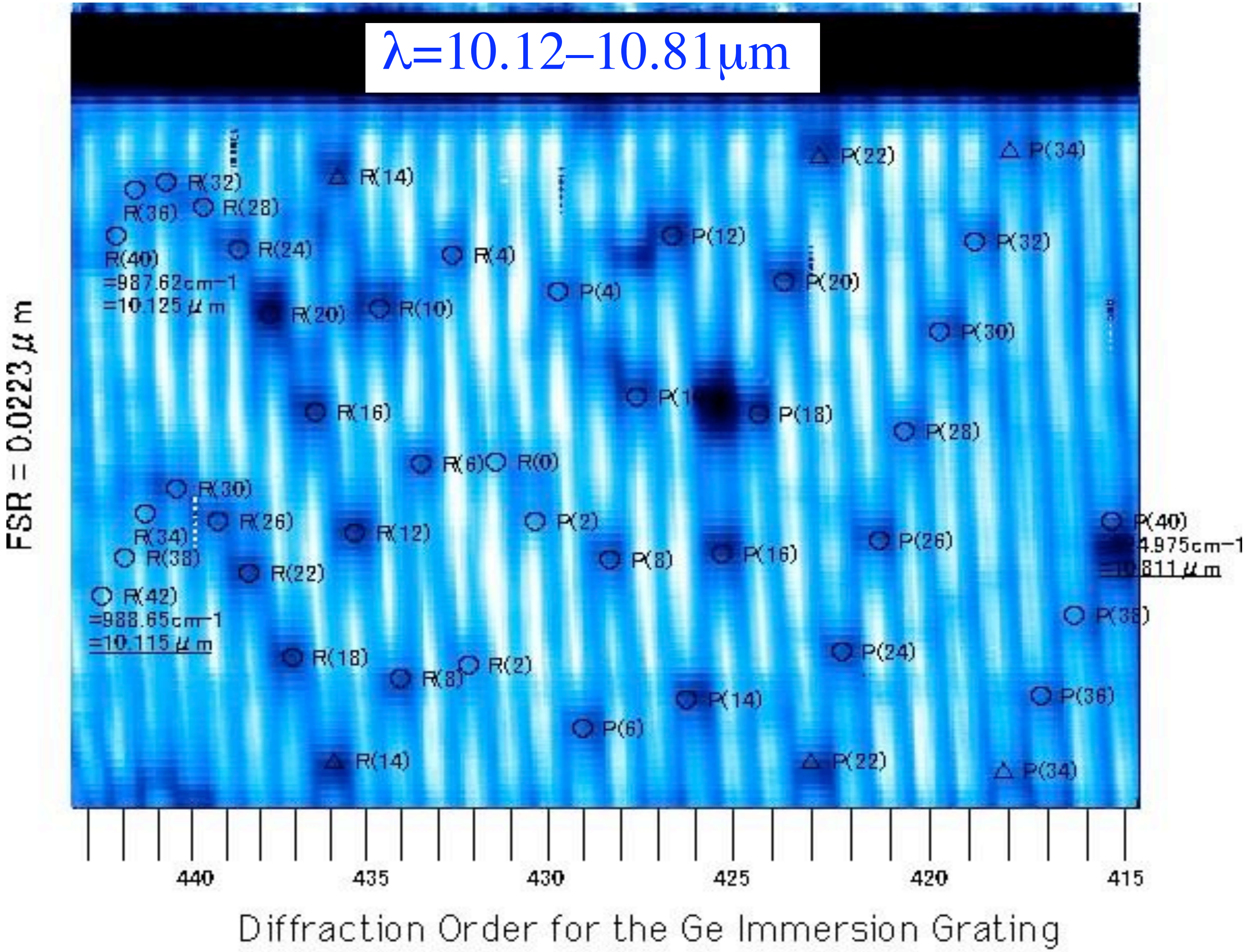
Targets: Vib.-rot. Transitions of Methane, Ethane, Ammonia, N_2O, O_3, SO_2, H_2O, CO_2, SO_2, H_2S, NOx, Halogen Oxides, etc.,in the Planets, Stellar Atmosphere, bright SFRs, CSE of late type stars, and the upper atmosphere of the Earth.

Reference: Earth's atmosphere



10.12~10.81μm

First Scientific Result (1): Venus

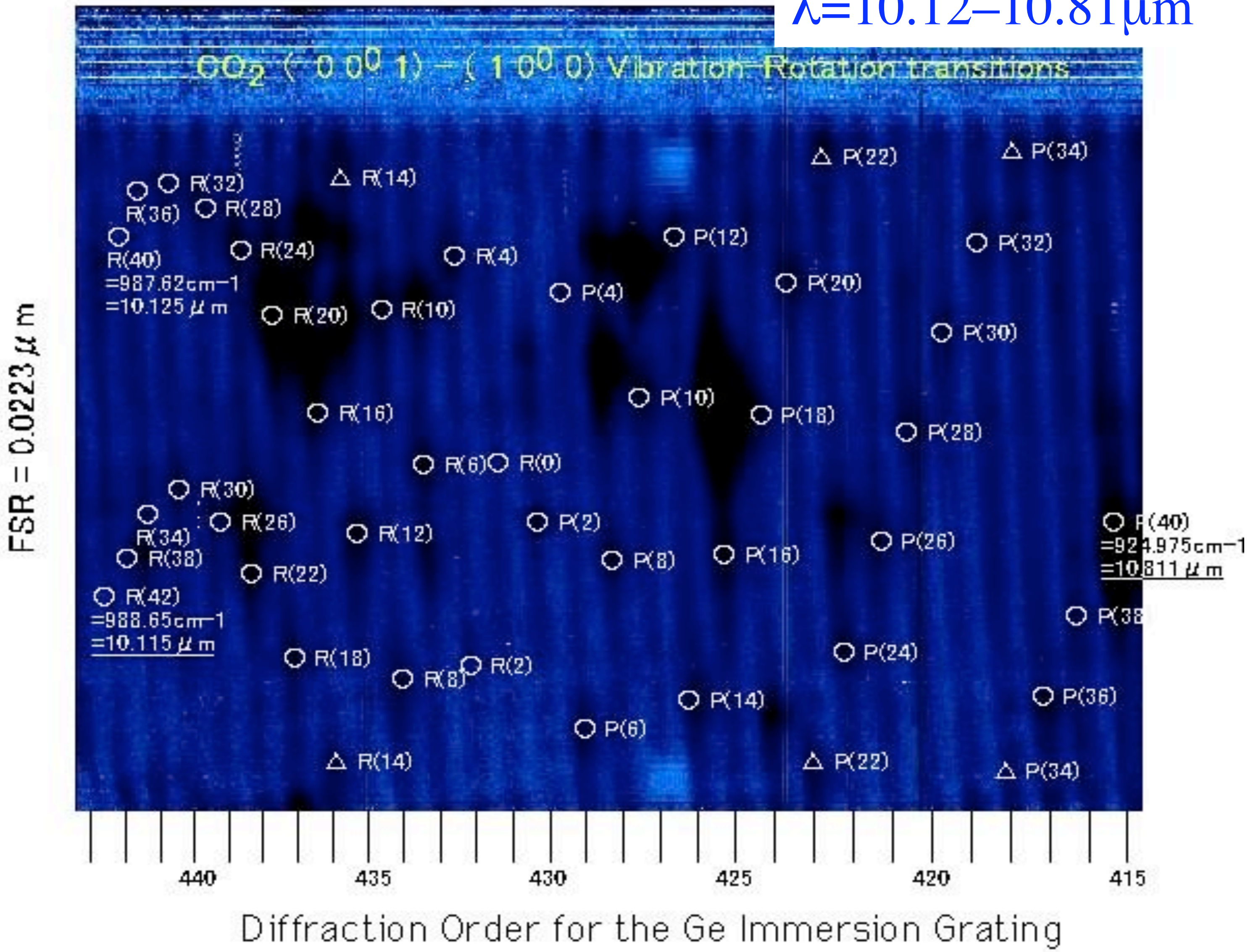


Absorption lines cannot be identified to the “telluric lines”.

→ CO_2 hot-band & isotopes from Venus.

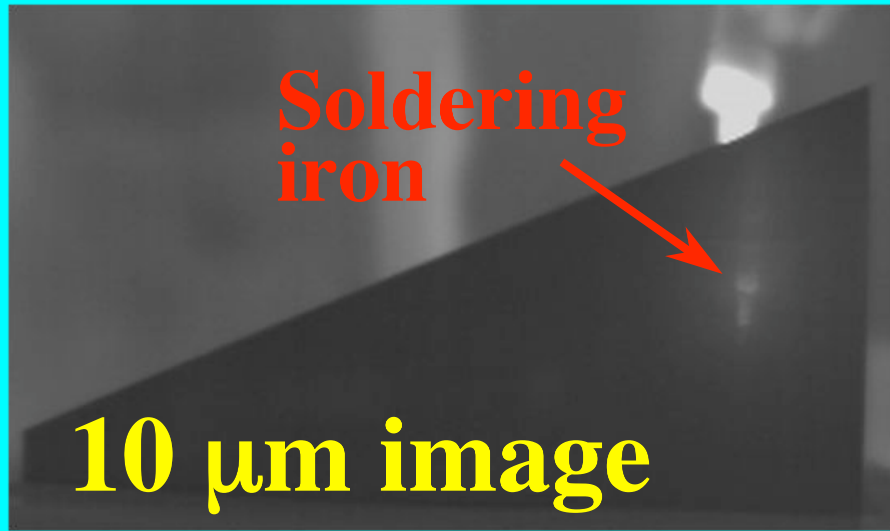
First Scientific results (2): NGC7027

λ=10.12–10.81μm



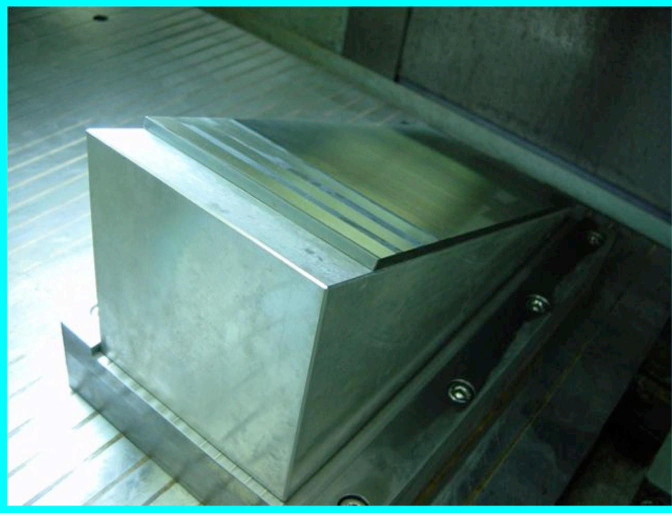
Detection of [S IV] ionic fine-structure emission line toward the planetary nebula.

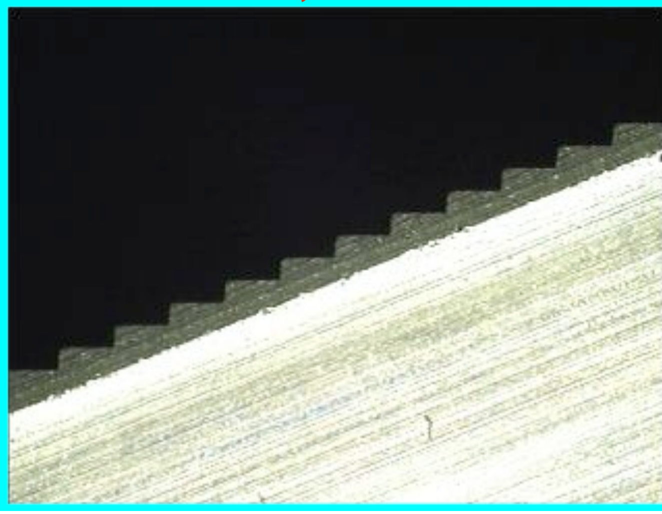
Trial Fabrications of Ge Immersion Grating for R~200,000



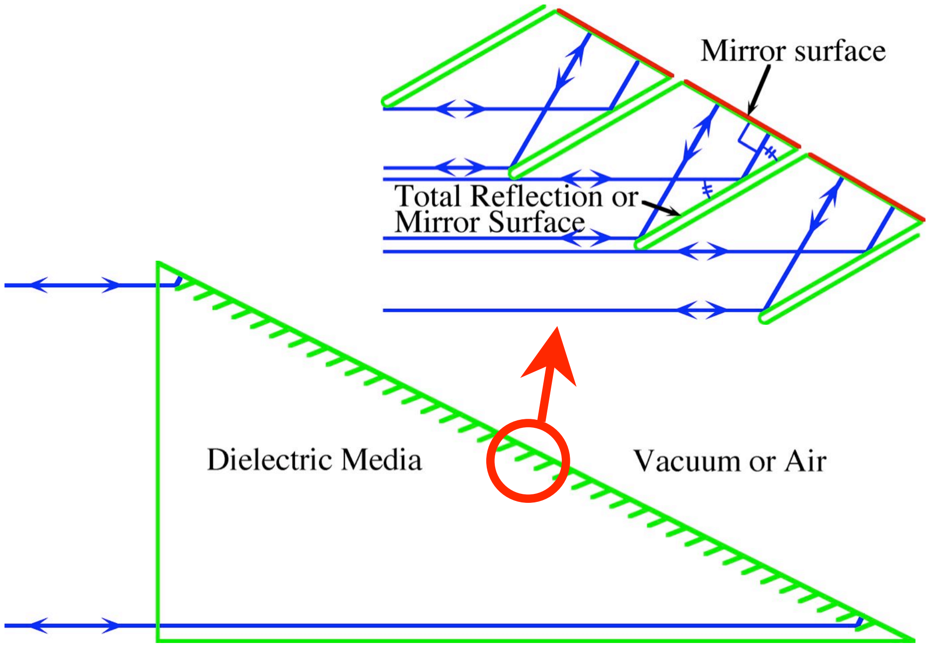
R〜200,000@10μm → Size: 120 x 120 x 270 mm

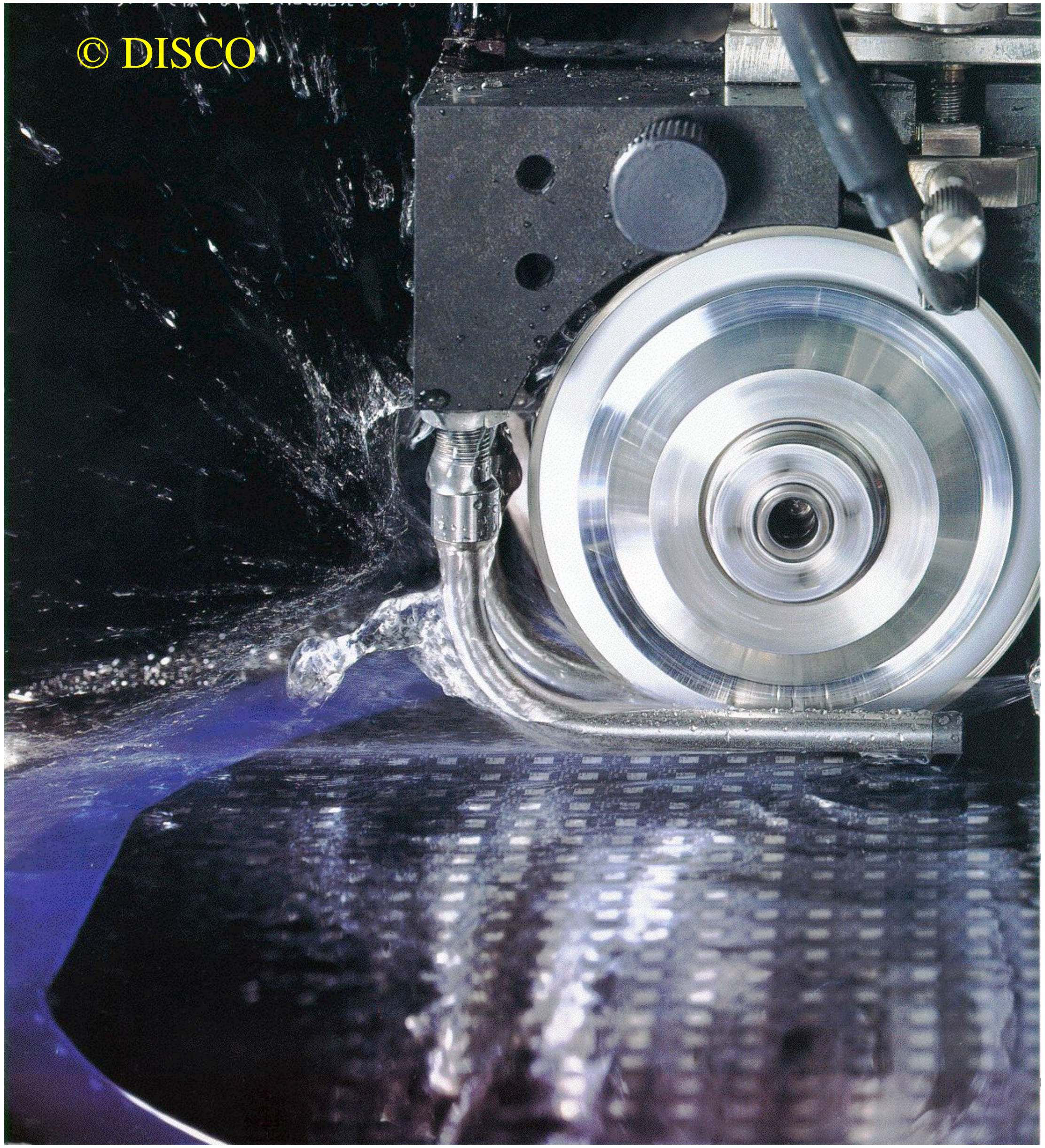
→ Fabrication time: several 1,000 hours





Novel Immersion Grating





- Machining of dicing saw makes smooth surface
- Easy tooling.
- Fabrication time for grating with 120 x 120 x 270 mm →Several 100 hours?

(Ebizuka et. al. SPIE, **6273**, 2006)

Scattering Loss of Immersion Gratings

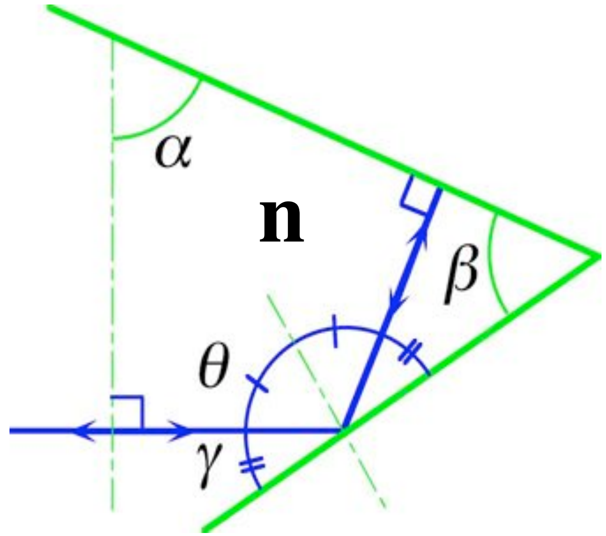
Scattering loss: Ls is given by,

$$Ls = 1-\exp\{-(4\pi n\,\sigma\cos\theta/\lambda)^2\},$$

where σ is surface roughness in rms.

$n = 4.0$, $\sigma = 0.05\mu m$, $\lambda = 10\mu m$

θ [deg.]	Ls[%]	θ [deg.]	Ls[%]
0	6.12	45	3.11
15	5.72	60	1.57
30	4.62	75	0.42



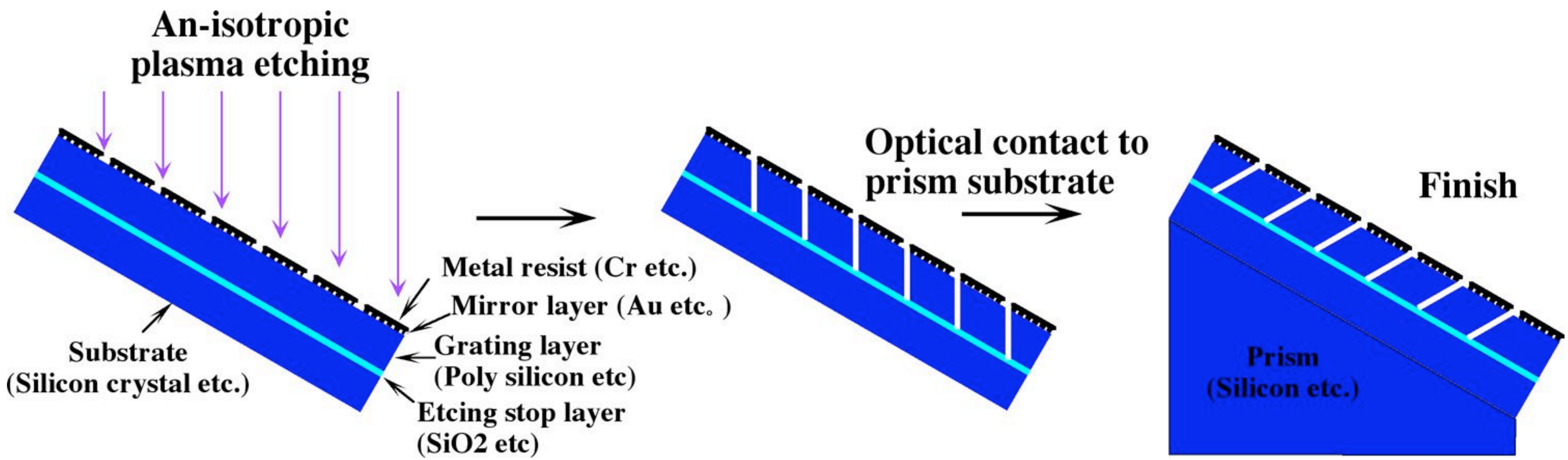
Ordinary immersion grating ($\theta = 0$)

$Ls =$ 6.12 %

Novel immersion grating ($\alpha = 60$, $\theta = 60$)

$Ls = \{1-(1-0.0157)^2\} \times 100 =$ 3.12 %

Fabrication Method of Novel Immersion Grating for Visible and Near IR



Conclusions

- Direct vision prism with glasses and plastic realizes linear dispersion for wavelength or wave number, or constant resolving power.
- Wollaston Prism is able to observe wide wavelength with linear dispersion.
- Novel immersion grating achieves small scattering loss and reduces fabrication cost.