新しい回折格子
Novel gratings

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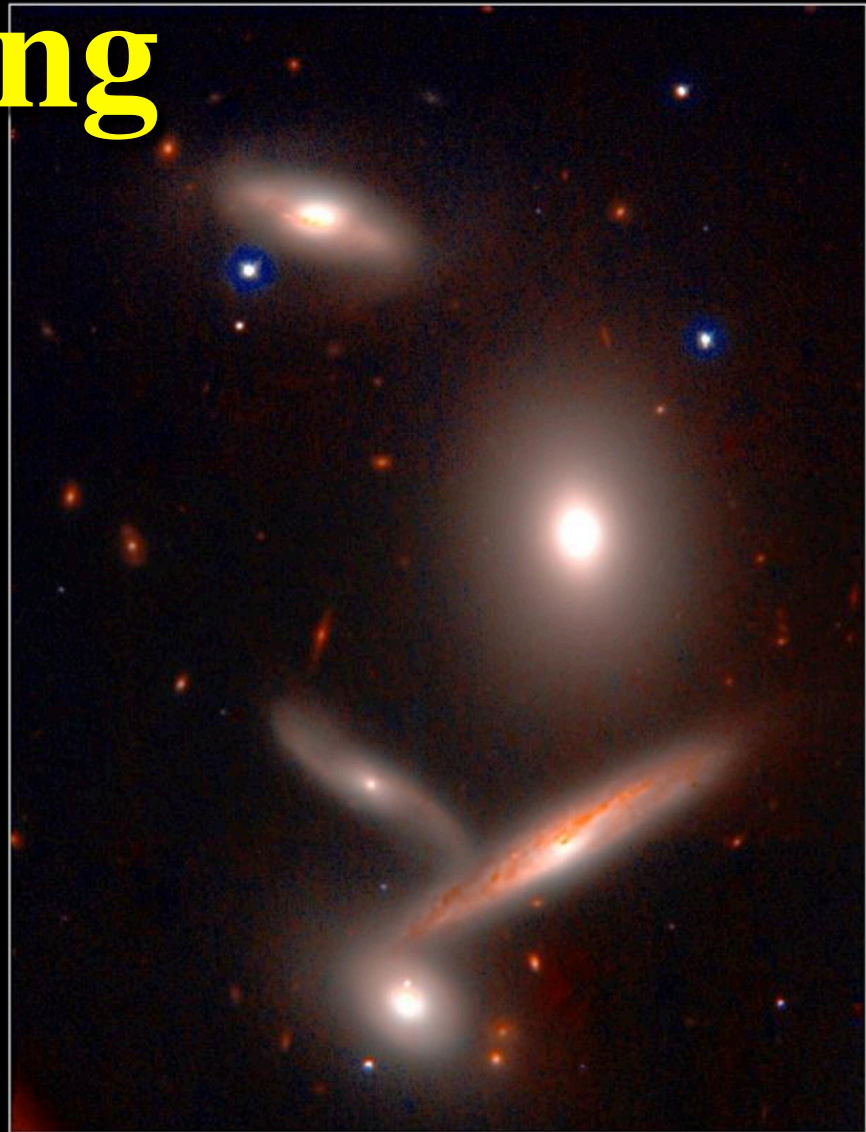
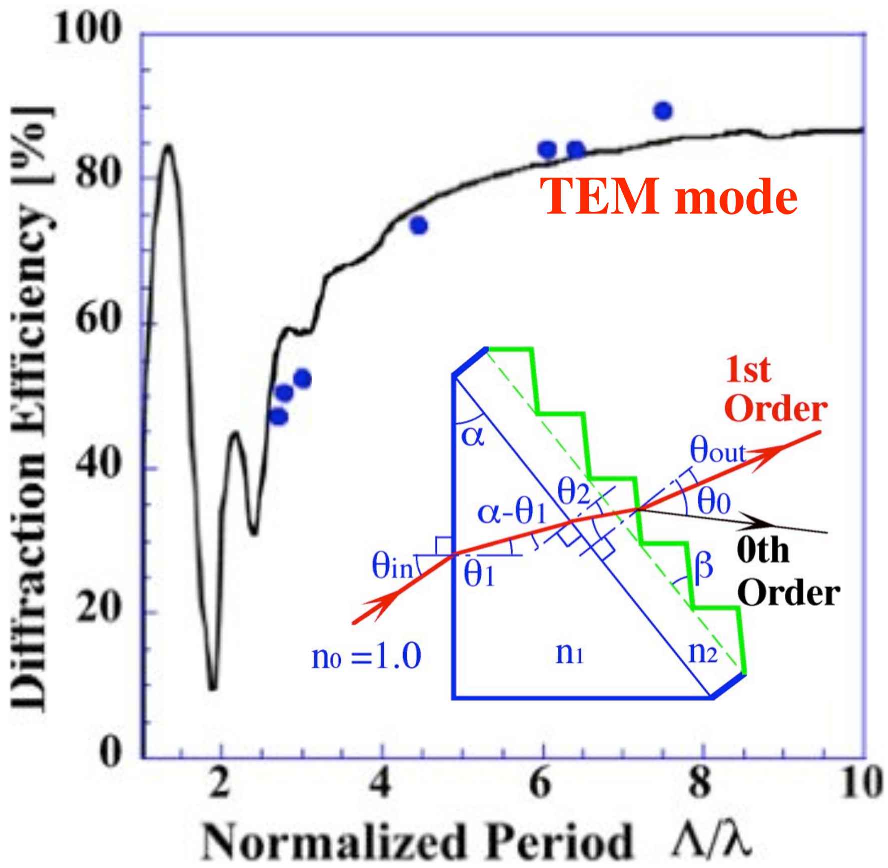
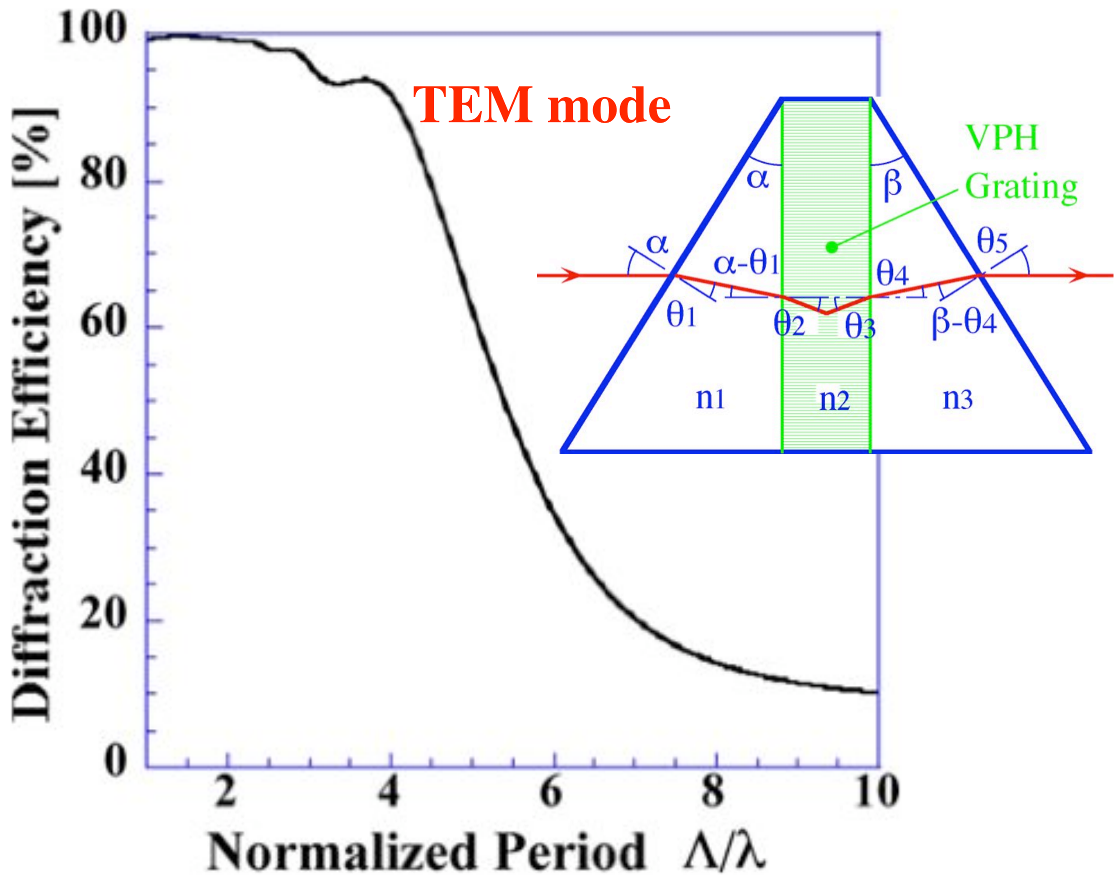
第二回可視赤外線観測装置技術ワークショップ　2012年12月17, 18日

Volume Phase Holographic Grating



Efficiencies of gratings

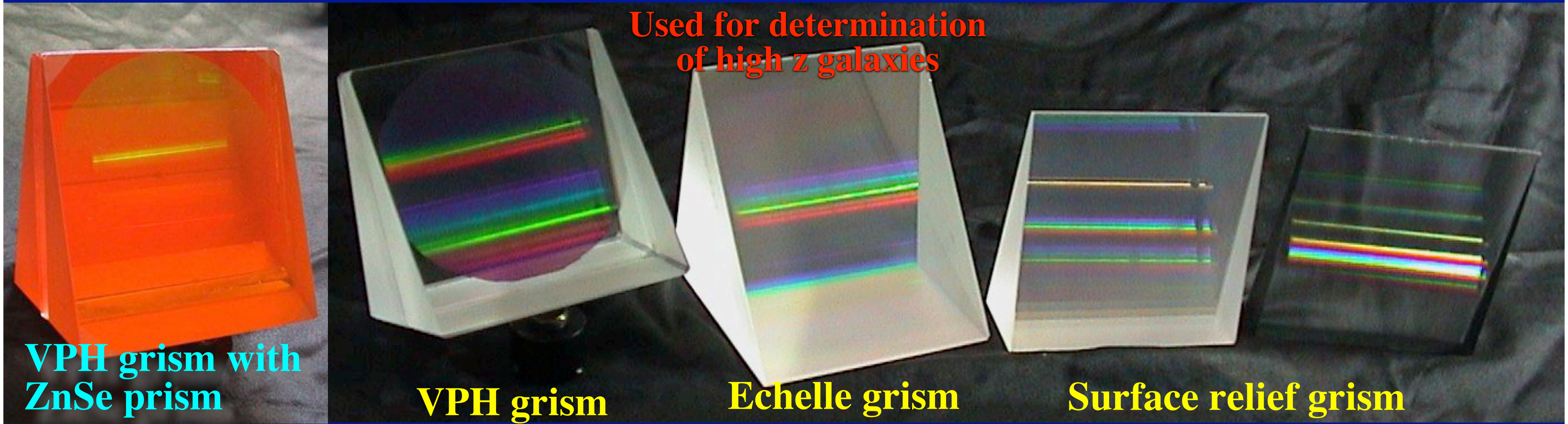




Surface relief grating: Efficiency decreases steeply below 4 Λ/λ.

VPH (Volume Phase Holographic) grating ($\Delta n \sim 0.02$): Efficiency achieves up to 100% below 4 Λ/λ.

(Oka et. al., SPIE, **5005**, 2003)



Grisms for FOCAS

Size: 110 × 106 × 106 (max).

4 SR grisms: 300 < *R* < 1,400.

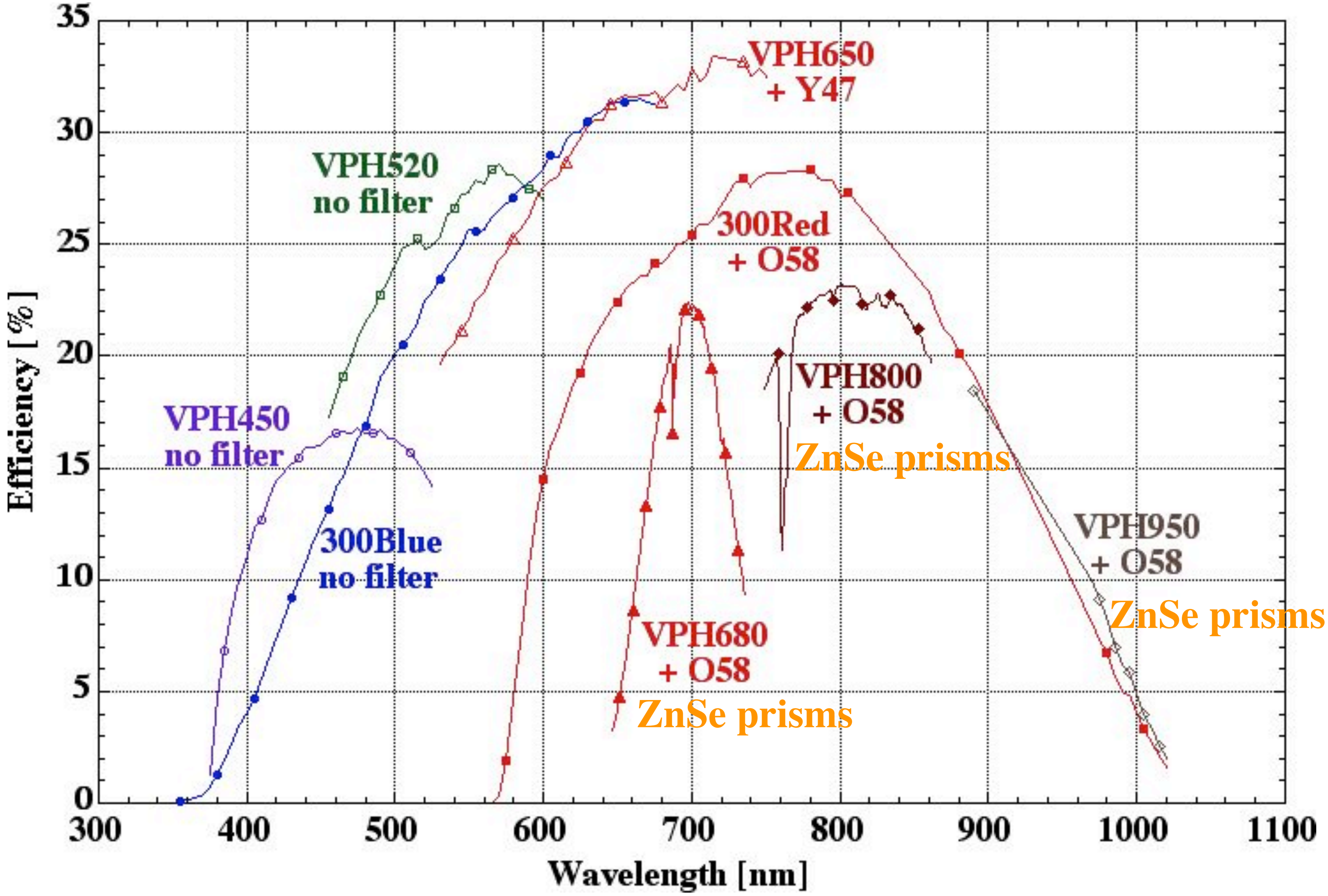
1 Echelle grism: *R*~2,500.

8 VPH grisms (3 grisms with ZnSe prisms): 1,600 < *R* < 7,000,

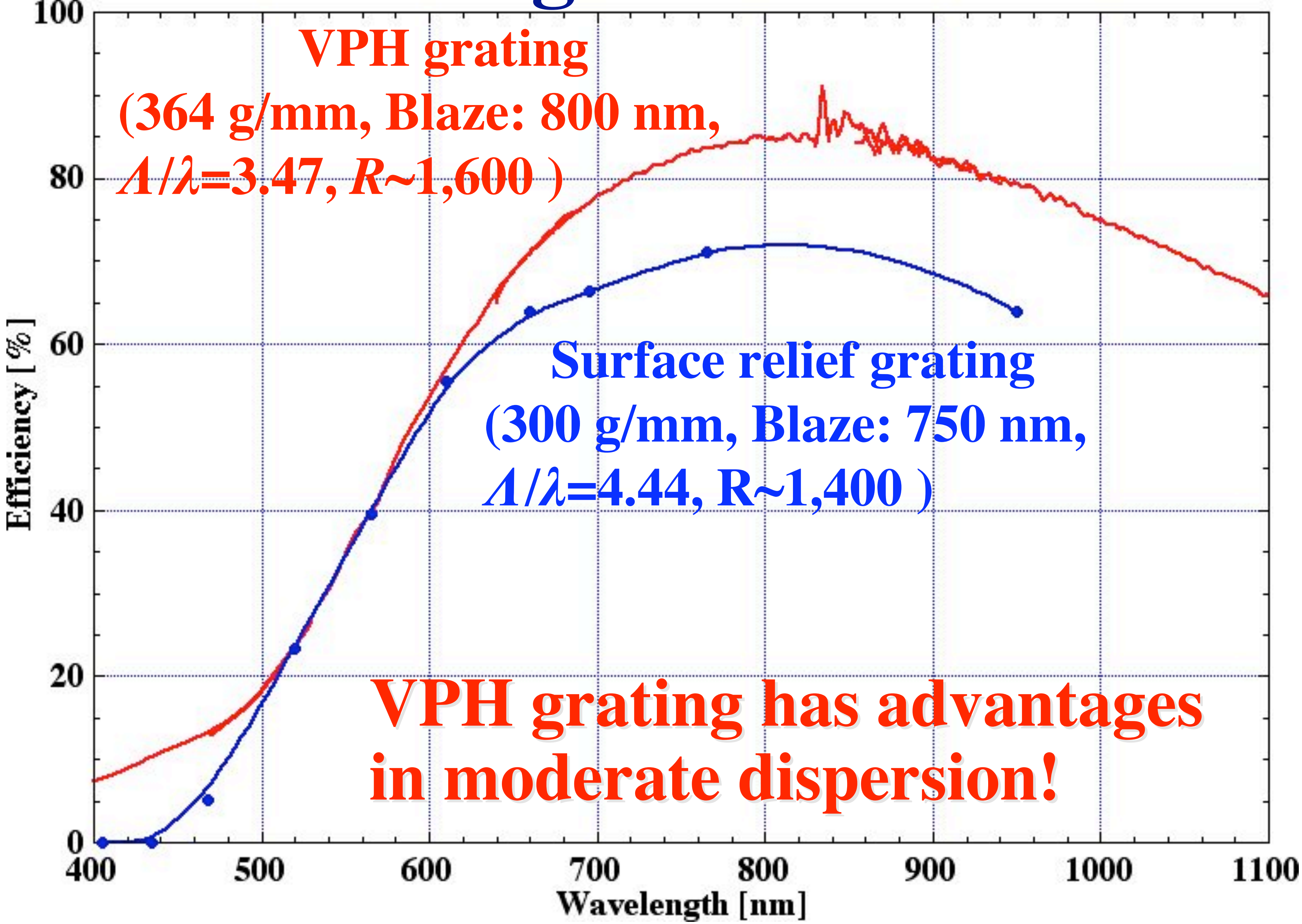
Developed by in collaboration with Japan Wemen's Univ., NAOJ and RIKEN.

(Ebizuka et. al. PASJ, **63**, 2011a)

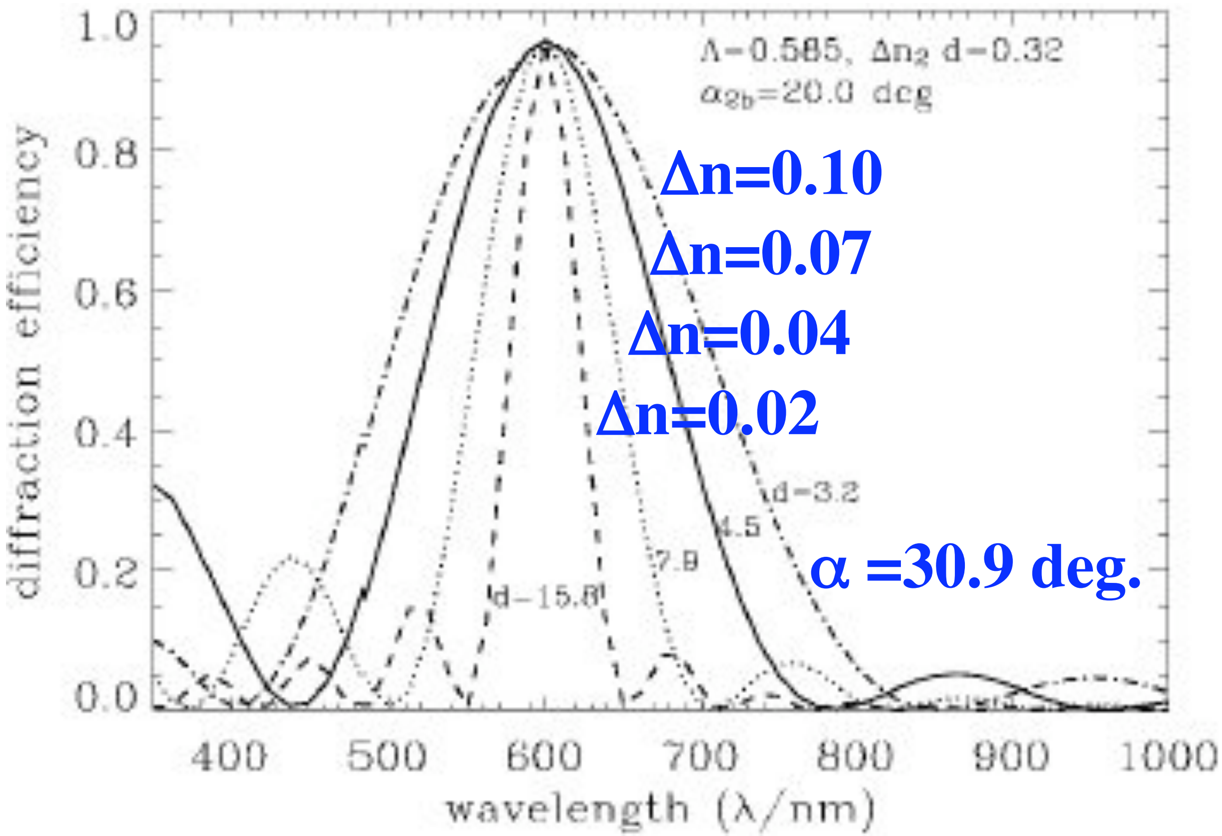
Relative efficiencies of grisms within Subaru Telescope and FOCAS

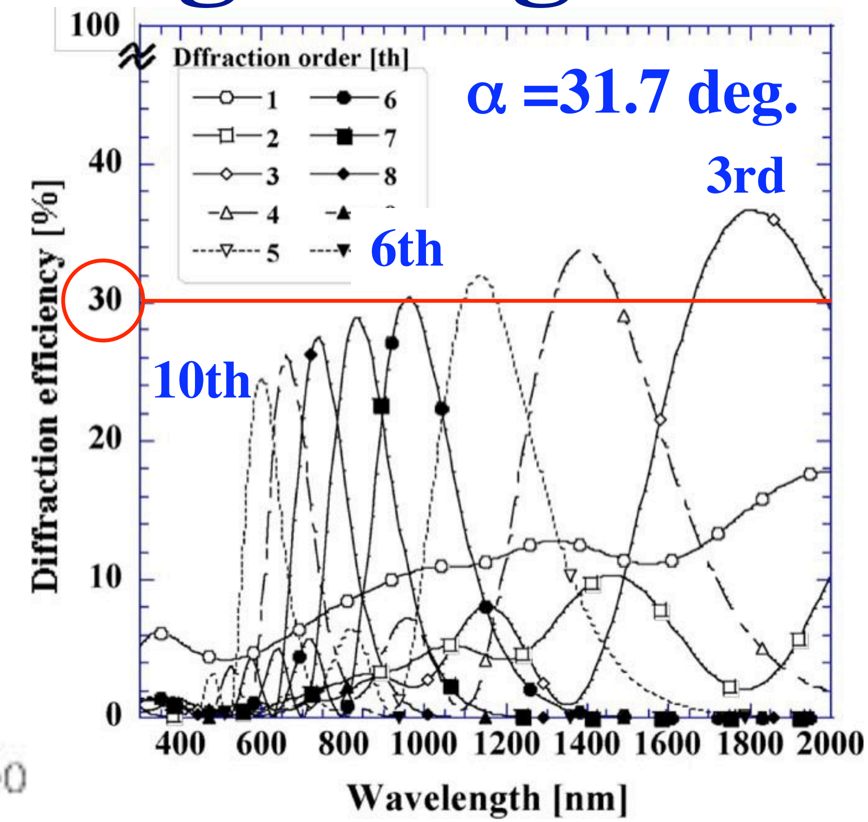


New VPH grisms for FOCAS



Limitations of VPH grating





Band width of VPH grating becomes narrow in diffraction angle: *α* increase because semi-amplitude of index modulation of dichromated gelatin (DCG) is $\Delta n < 0.15$.

(Baldry et al., PASP, **116**, 2004)

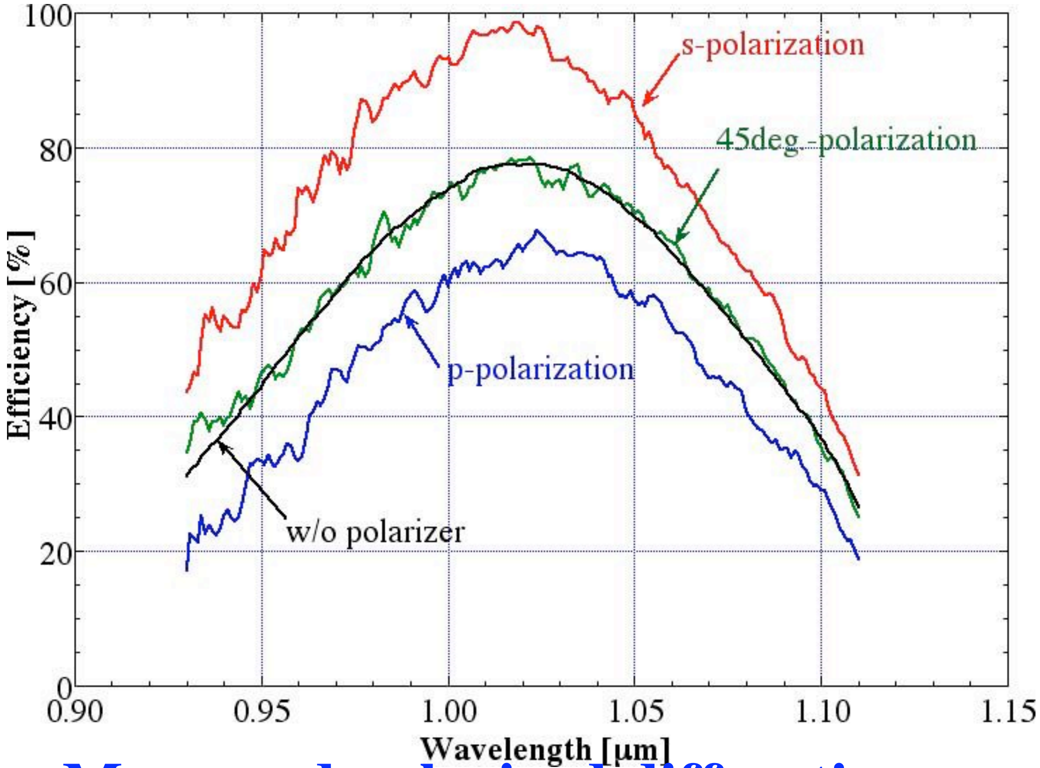
Diffraction efficiency of VPH grating decrease toward higher orders.

(Oka et. al., SPIE, **5290**, 2004)

Polarized diffraction efficiency of VPH grating

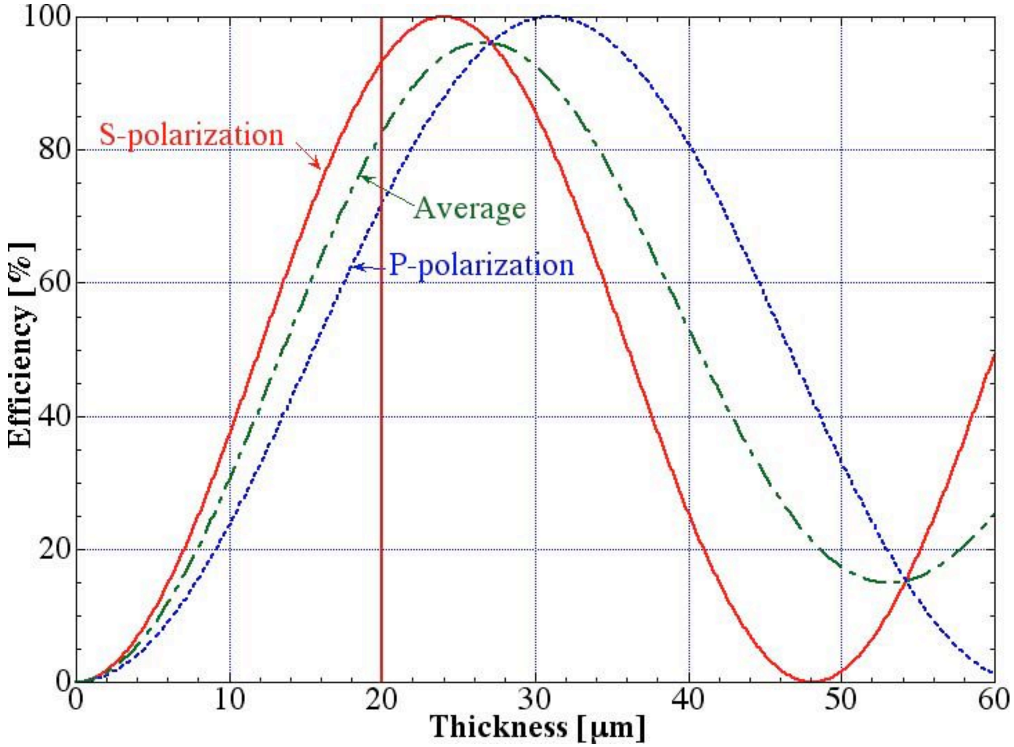
$$\eta_S = \sin^2\left\{\frac{\pi(n_{max} - n_{min})t}{\Lambda(n_{max} + n_{min})\sin 2\theta}\right\}$$

$$\eta_P = \sin^2\left\{\frac{\pi(n_{max} - n_{min})t\cos 2\theta}{\Lambda(n_{max} + n_{min})\sin 2\theta}\right\}$$



Measured polarized diffraction efficiencies of VPH grating.

n_{ave}= (n_{max} - n_{min})/2 = 1.53,
Λ=0.984 μm, t = 20 μm,
θ=19.8° @1.02 μm.



Calculated polarization diffraction efficiencies vs. *t* of a VPH grating.

Δn = (n_{max} - n_{min})/2 = 0.017

(Ebizuka et. al. PASJ, **63**, 2011b)

Volume Binary 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

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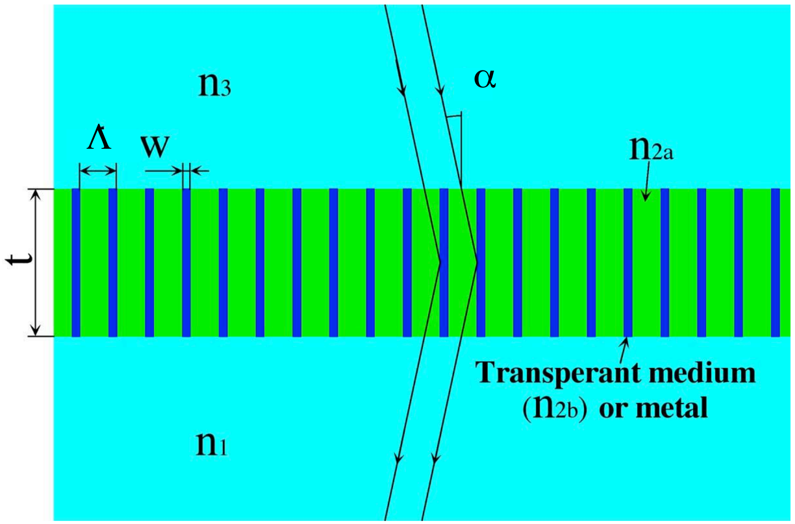
Volume binary grating



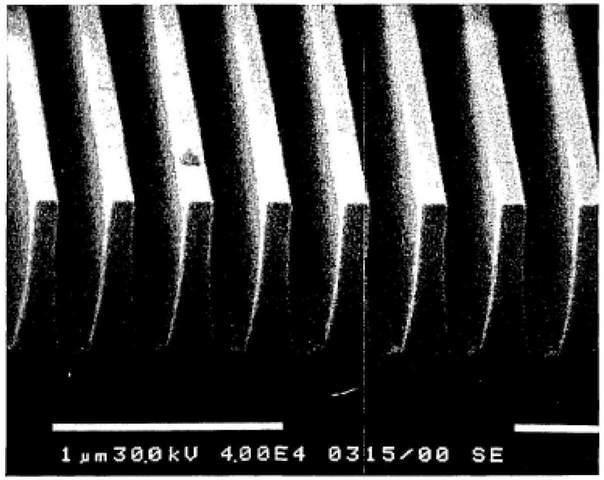
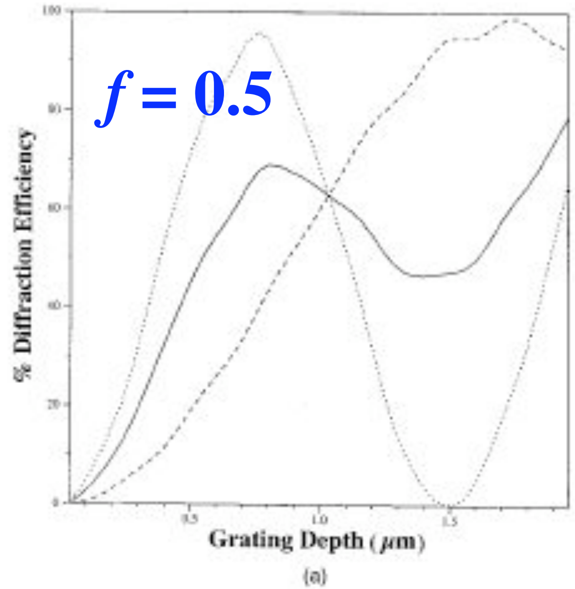


Fig. 1. Scanning electron micrograph of grating lines etched into quartz substrate (n_s = 1.46).

(Gerritsen, Jepsen: Appl. Opt., **37**,1998)



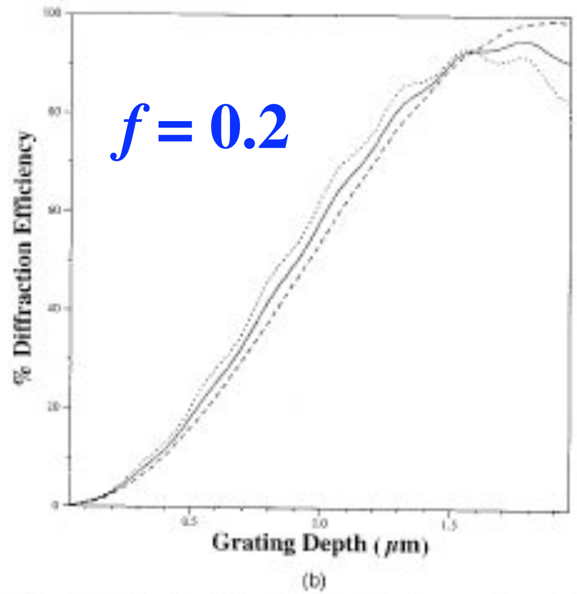


Fig. 5. (a) First-order diffraction efficiencies for a grating with λ = 0.55 μm, Λ = 0.3889 μm, θ_B = 45°, n = 1.50, and f = 0.50. (b) First-order diffraction efficiencies for a grating with λ = 0.55 μm, Λ = 0.3889 μm, θ_B = 45°, n = 1.50, and f = 0.80.

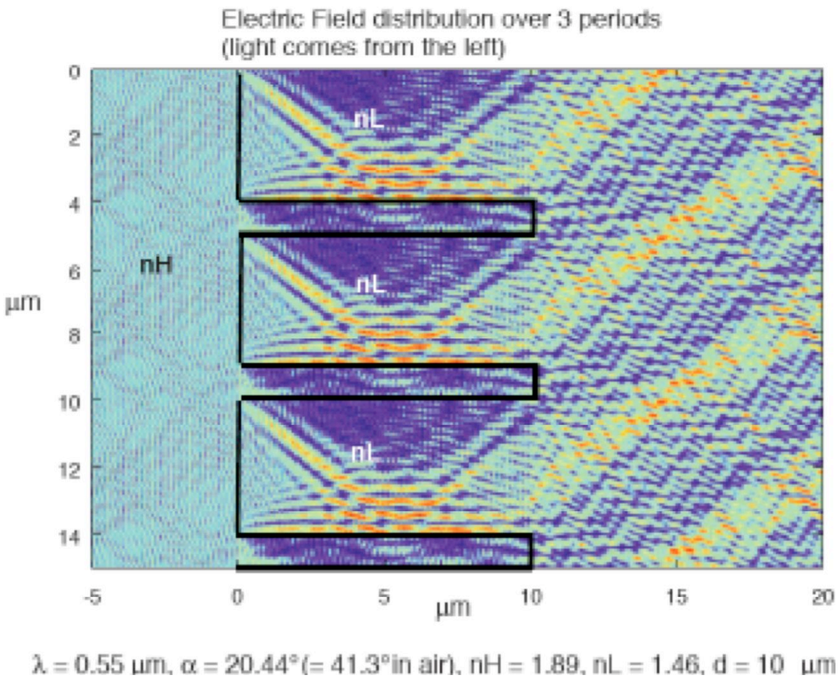
- $\Delta n = (n_{max} - n_{min})/2 \sim 0.5$.
- **Polarized diffraction efficiencies of S and P polarization coincide with each other by tuning of *f* and *t*. While aspect ratio becomes $t : w$ = 1:20 ~ 100.**

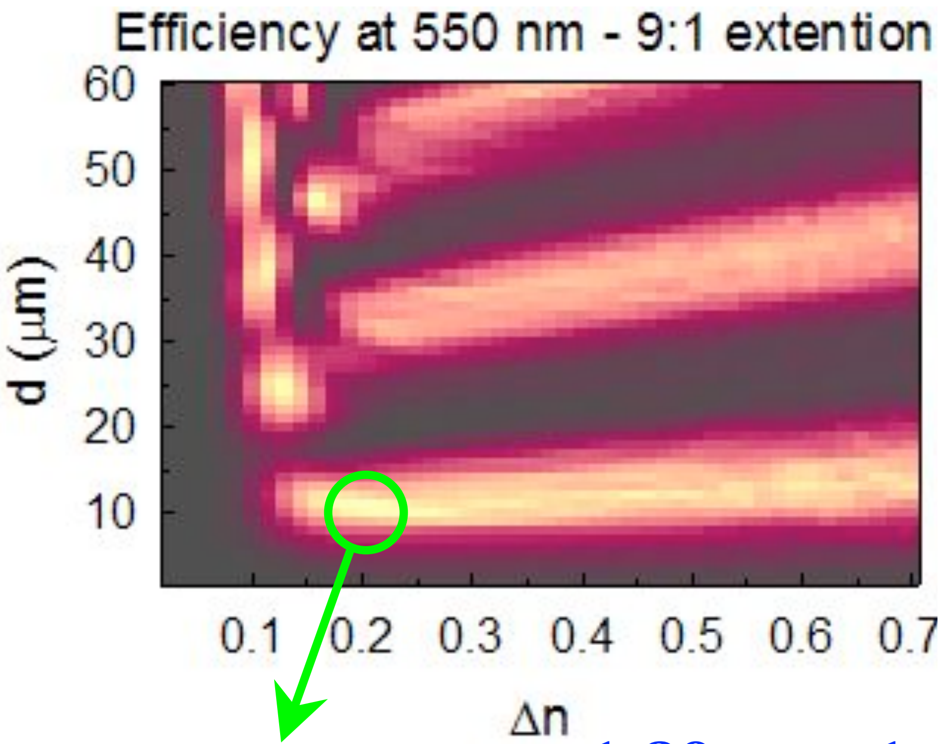
Filling factor: $f = w/\Lambda$

n_H=1.46, n_L=1.0, α =45 deg.

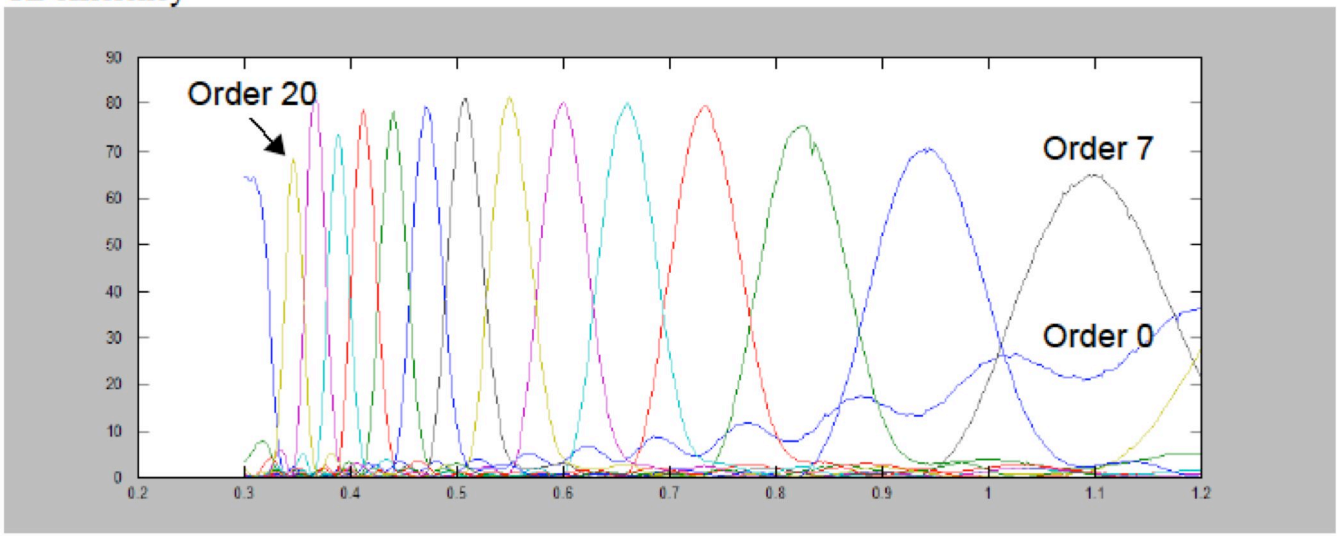
(Gupt & Peng, Appl. Opt., **32**, 1993)

Volume binary grating for higher diffraction orders





Configuration 1: ratio 9:1, d = 11 μm, Δn = 0.19
TE efficiency



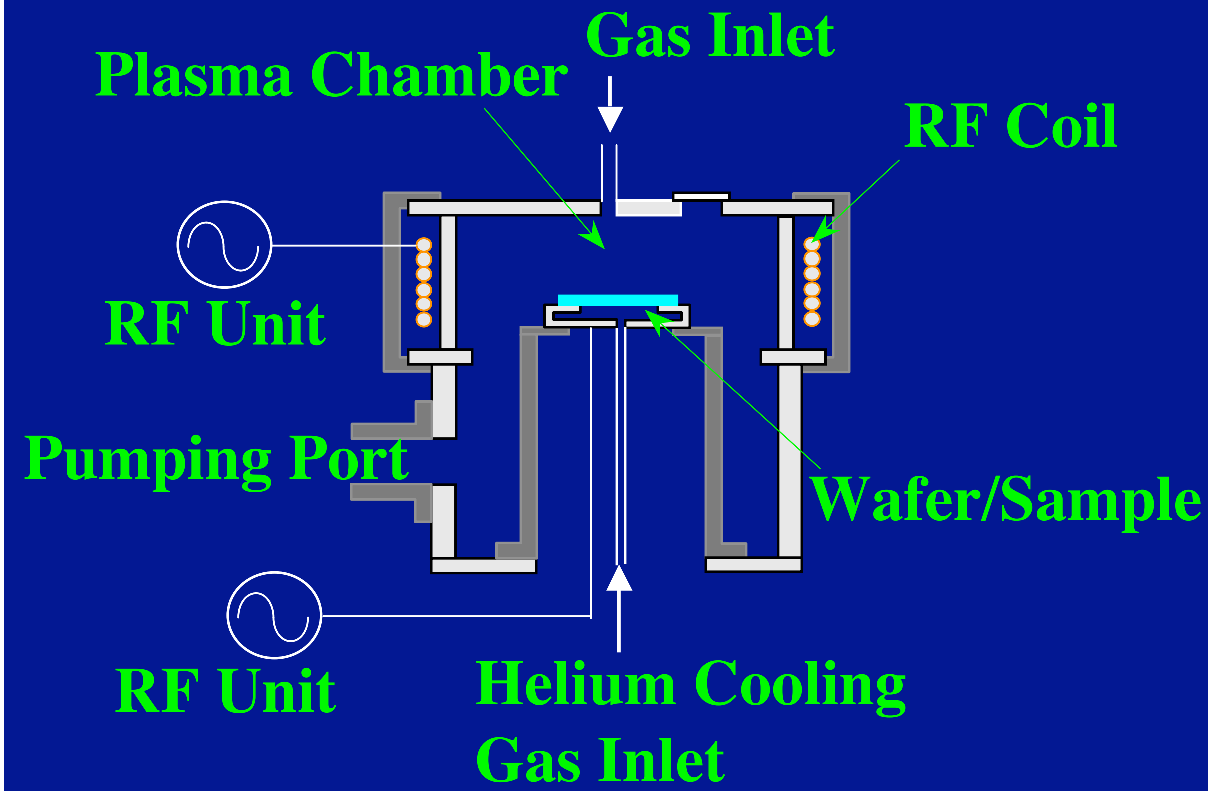
n_H=1.89, n_L=1.46,
α =41.3°, f = 0.1

***t*:*w* = 1:22**

(Bianco & Ebizuka, SPIE, **8450**, 2012)

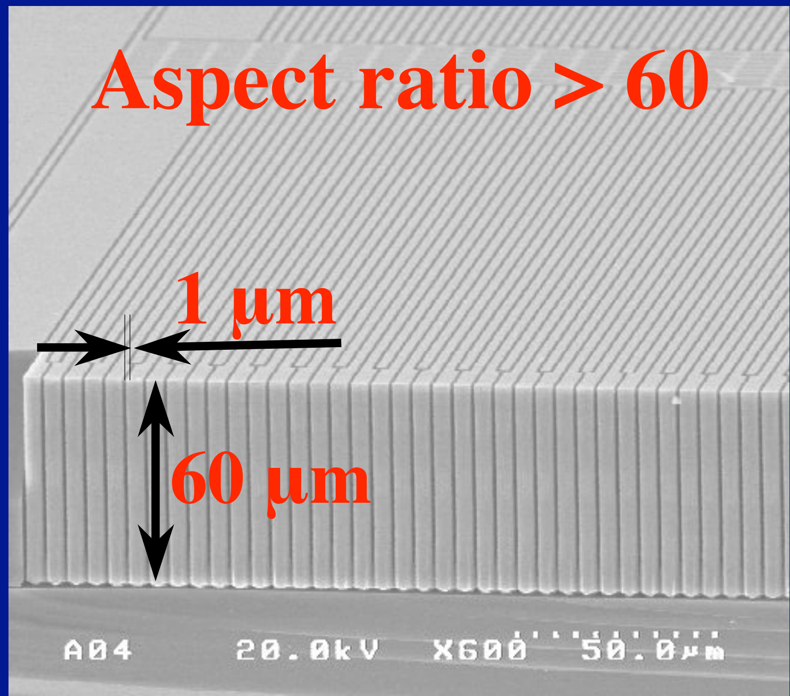
D-RIE (Deep Reactive Ion Etching)

DENSO



ICP Etcher

Inductively Coupled Plasma



G sensor of capacitance type

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Filling dielectric → Volume binary grating,

Oblique etching → Novel immersion grating for vis. – NIR.

Birefringence Volume Grating

M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

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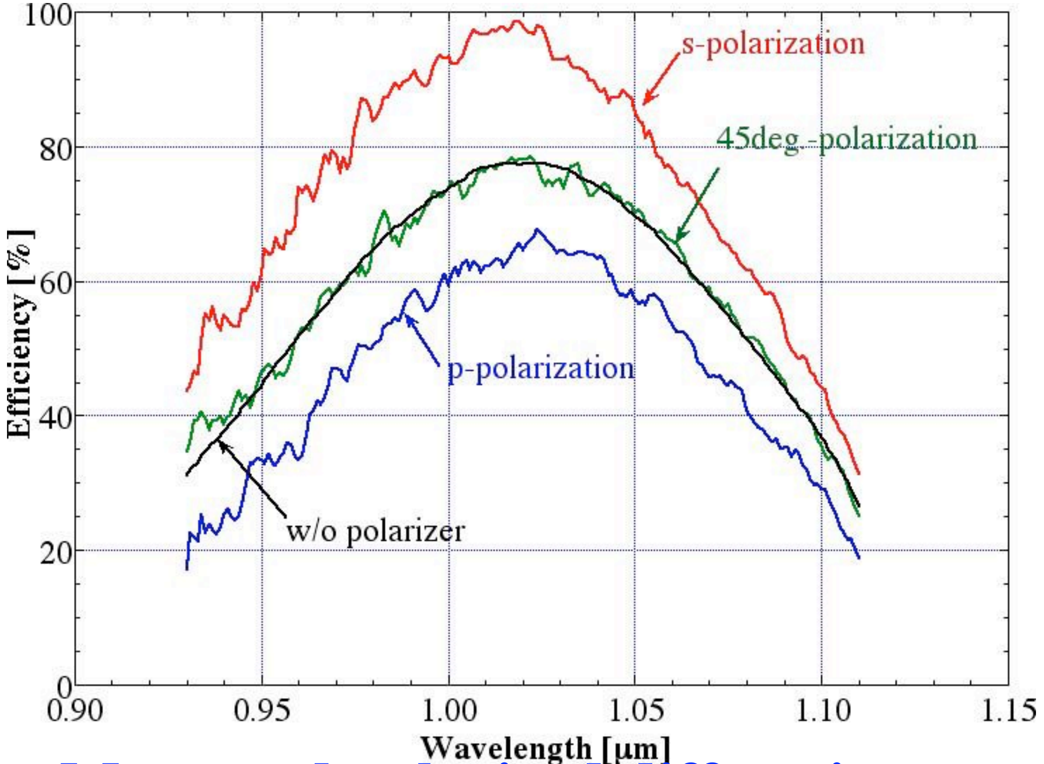
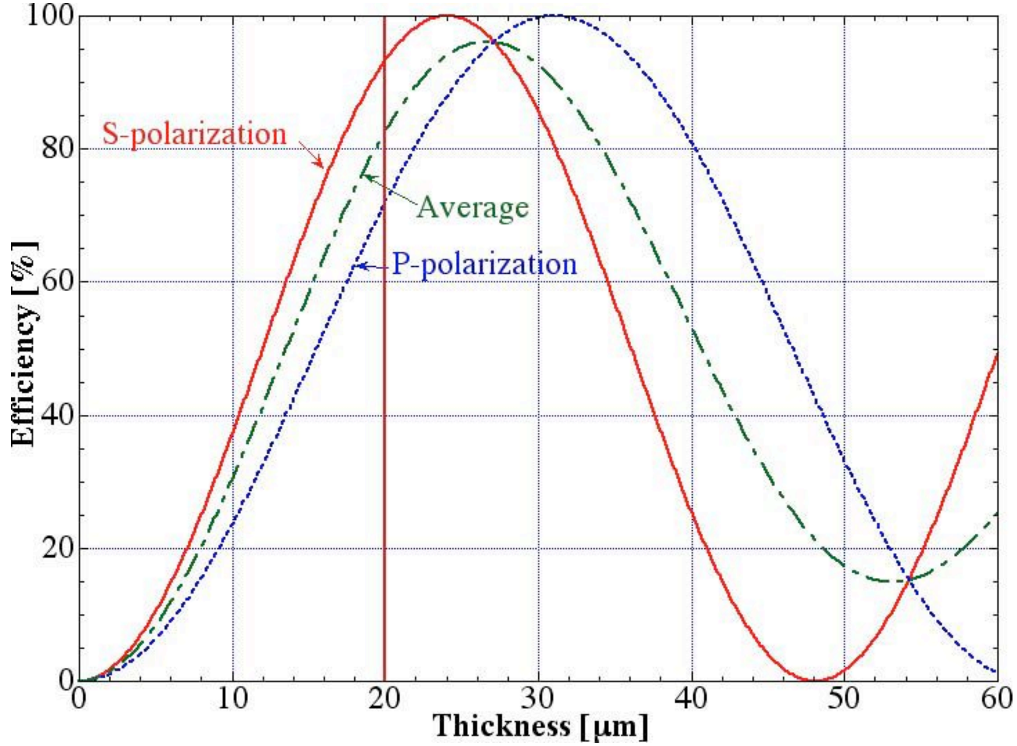
Polarized diffraction efficiency of VPH grating

$$\eta_S = \sin^2\left\{\frac{\pi(n_{max} - n_{min})t}{\Lambda(n_{max} + n_{min})\sin 2\theta}\right\}$$

$$\eta_P = \sin^2\left\{\frac{\pi(n_{max} - n_{min})t\cos 2\theta}{\Lambda(n_{max} + n_{min})\sin 2\theta}\right\}$$



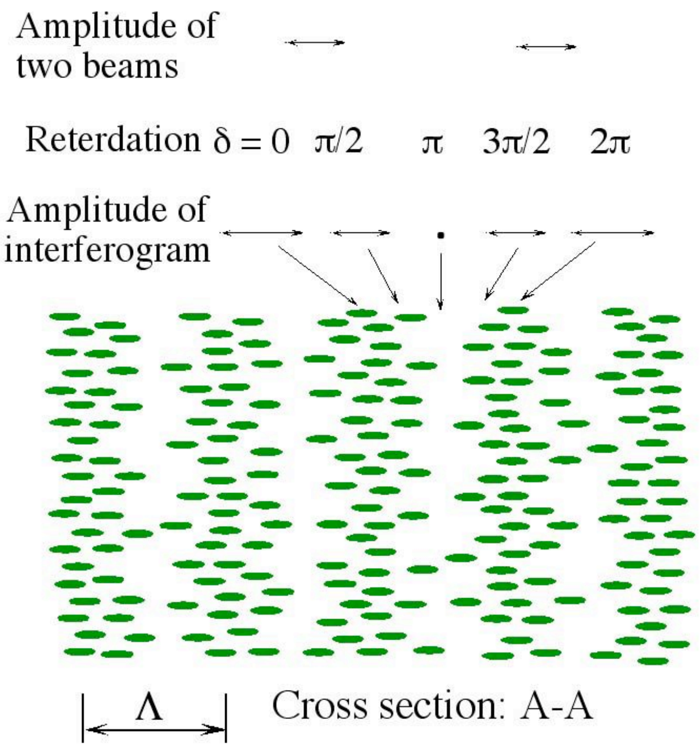
Measured polarized diffraction efficiencies of a prototype VPH grating for a MOIRCS grism.
Average refractive index: n=1.53, grating period: Λ=0.984 mm and thickness: t = 20 μm. Bragg angle: θ =19.8 degree at λ=1.02 μm.

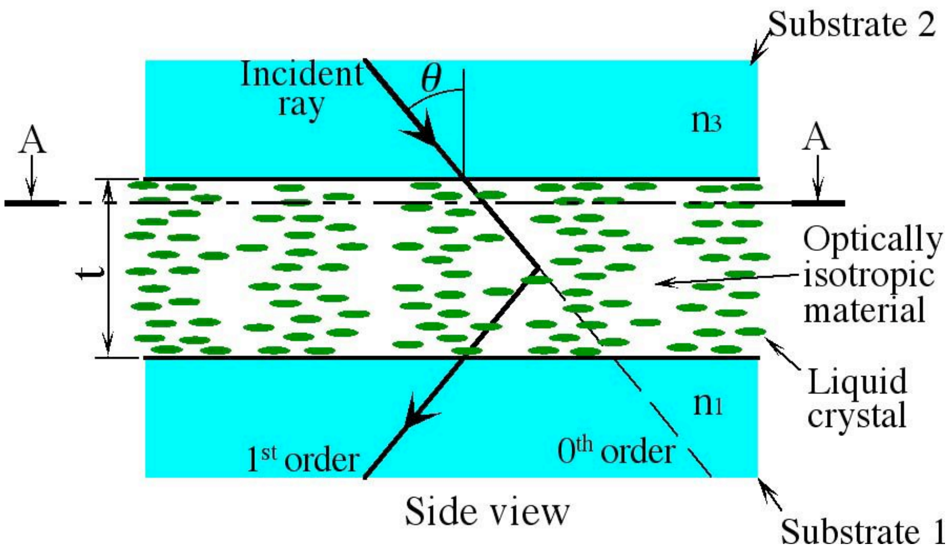


Calculated polarization diffraction efficiencies versus *t* of a VPH grating with refractive index modulation: Δn=0.017.

(Ebizuka et. al. PASJ, **63**, 2011b)

Birefringence VPH grating

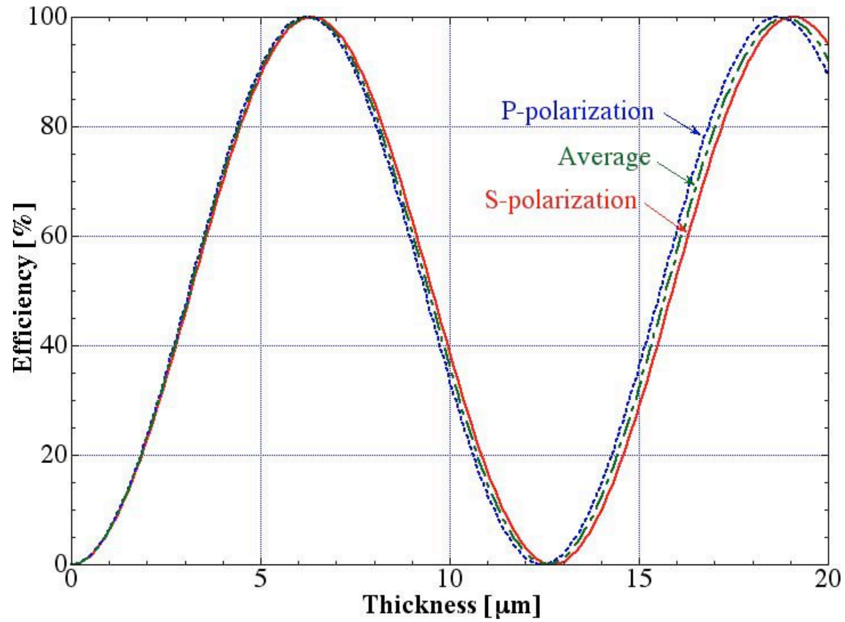




$$\frac{n_{S\max} - n_{S\min}}{(n_{S\max} + n_{S\min})\sin 2\theta_S} = \frac{(n_{P\max} - n_{P\min})\cos 2\theta_P}{(n_{P\max} + n_{P\min})\sin 2\theta_P}$$

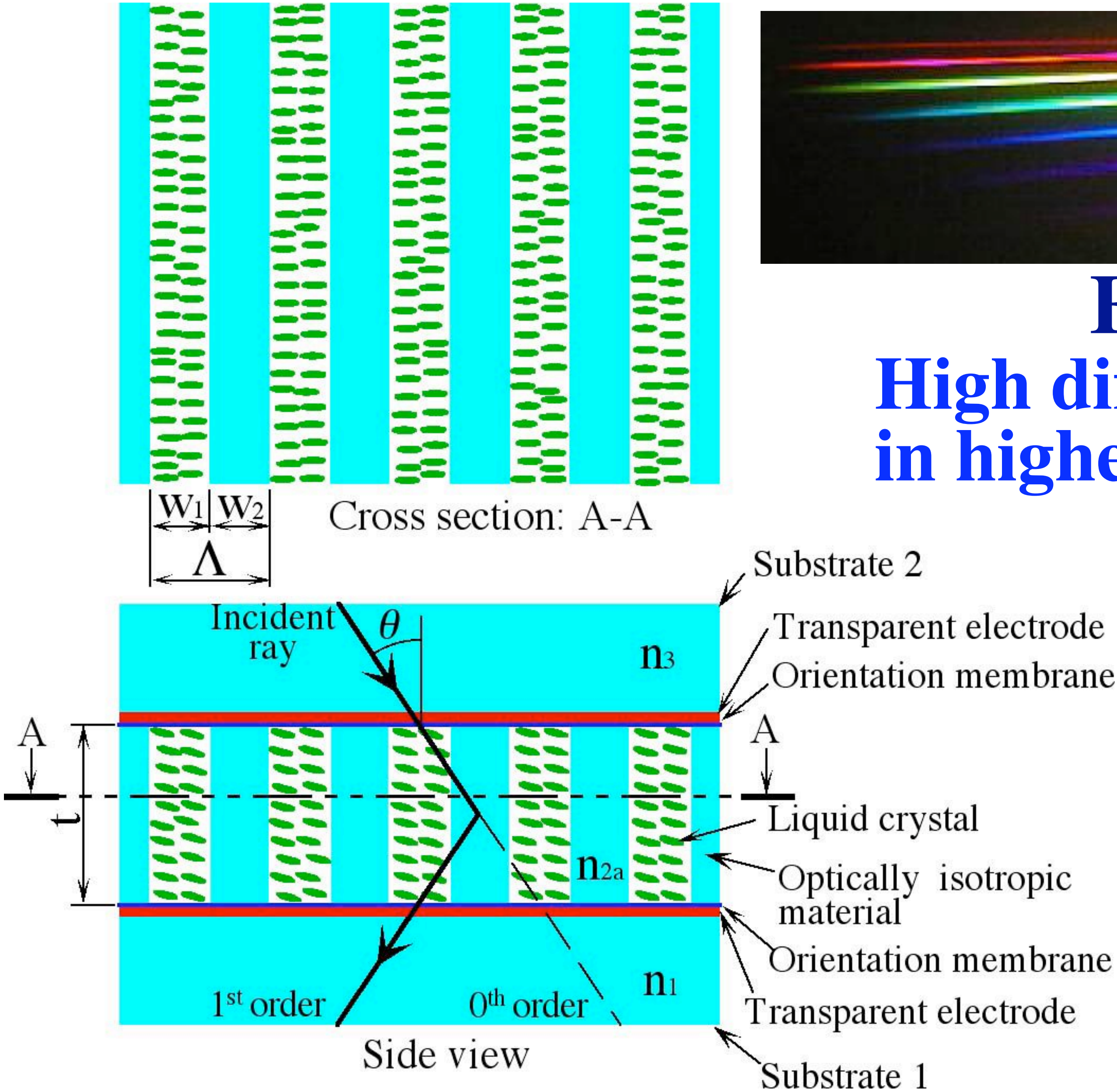
$$\frac{n_{S\max} - n_{S\min}}{(n_{S\max} + n_{S\min})\cdot 2\sin\theta_S\cos\theta_S} = \frac{(n_{P\max} - n_{P\min})\cos 2\theta_P}{(n_{P\max} + n_{P\min})\cdot 2\sin\theta_P\cos\theta_P}$$

$$\frac{n_{S\max} - n_{S\min}}{\cos\theta_S} \cong \frac{(n_{P\max} - n_{P\min})\cos 2\theta_P}{\cos\theta_P}$$



Calculated polarization diffraction efficiencies versus grating thickness *t* of birefringence VPH grating.

Birefringence binary Bragg (3B) grating

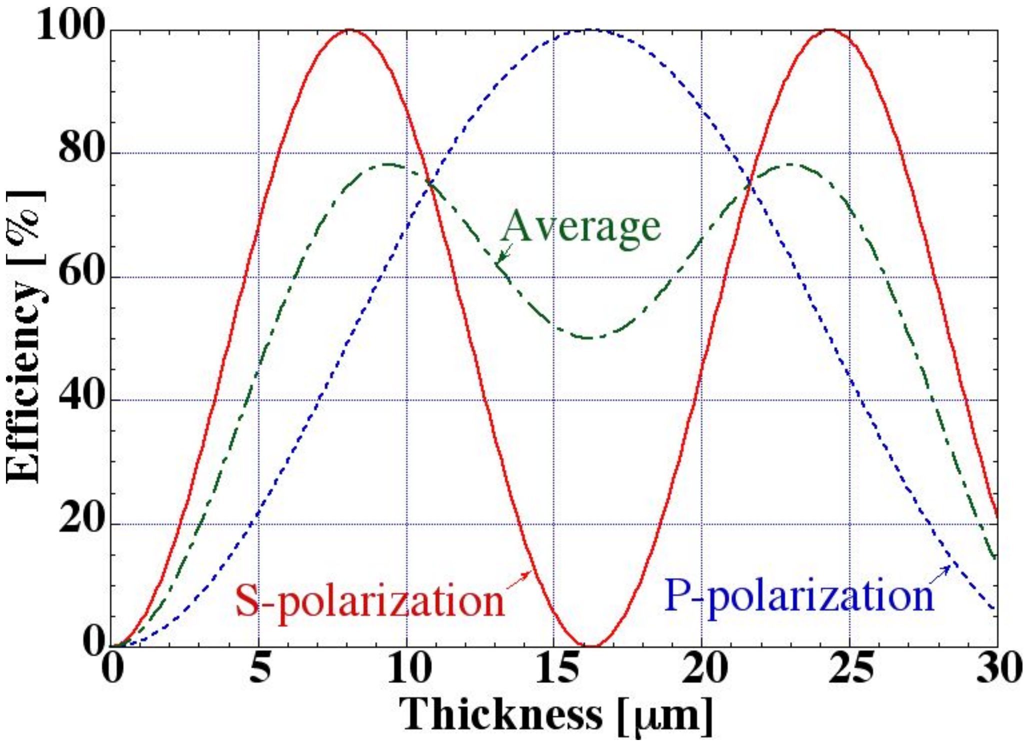


Echellegram

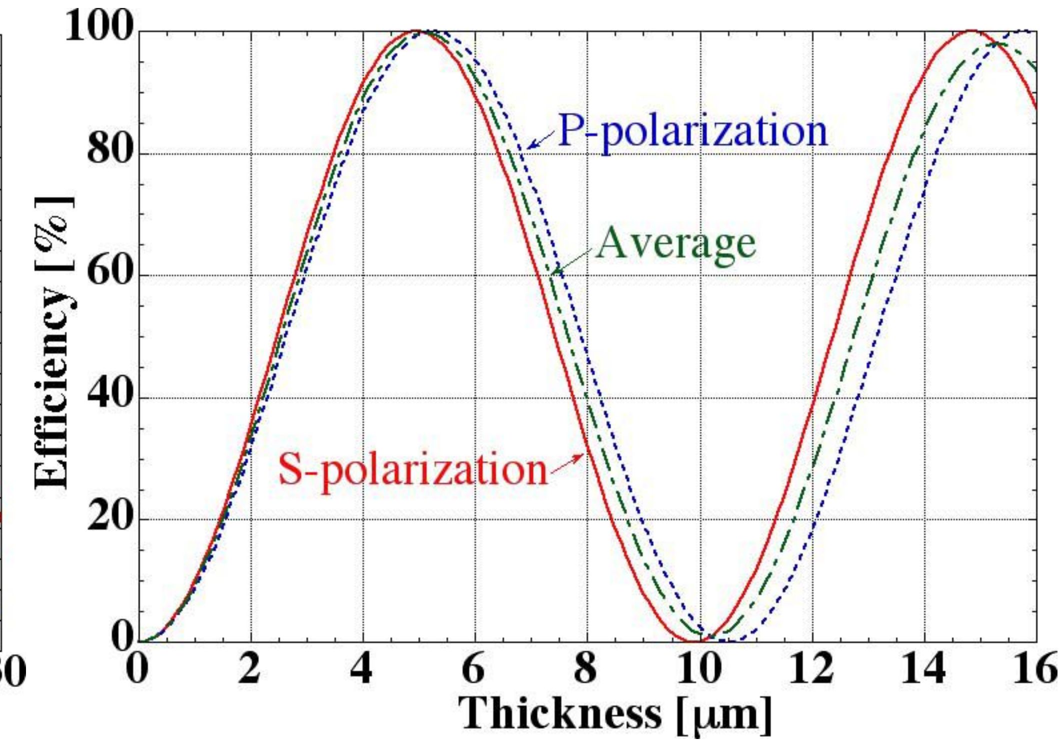
High diffraction efficiency in higher diffraction order.

Active optical element:
Window → Grating,
Grating → Polarizer,
Day lighting, Head-up display, 3D display,
Optical communications & computing, …

Polarized Diffraction Efficiency of VPH and 3B Grating



Dicson's VPH grating (Polarizer) calculated by Kogelnik method.
n_L= 1.46, n_H=1.54, θ_B =48.5°.

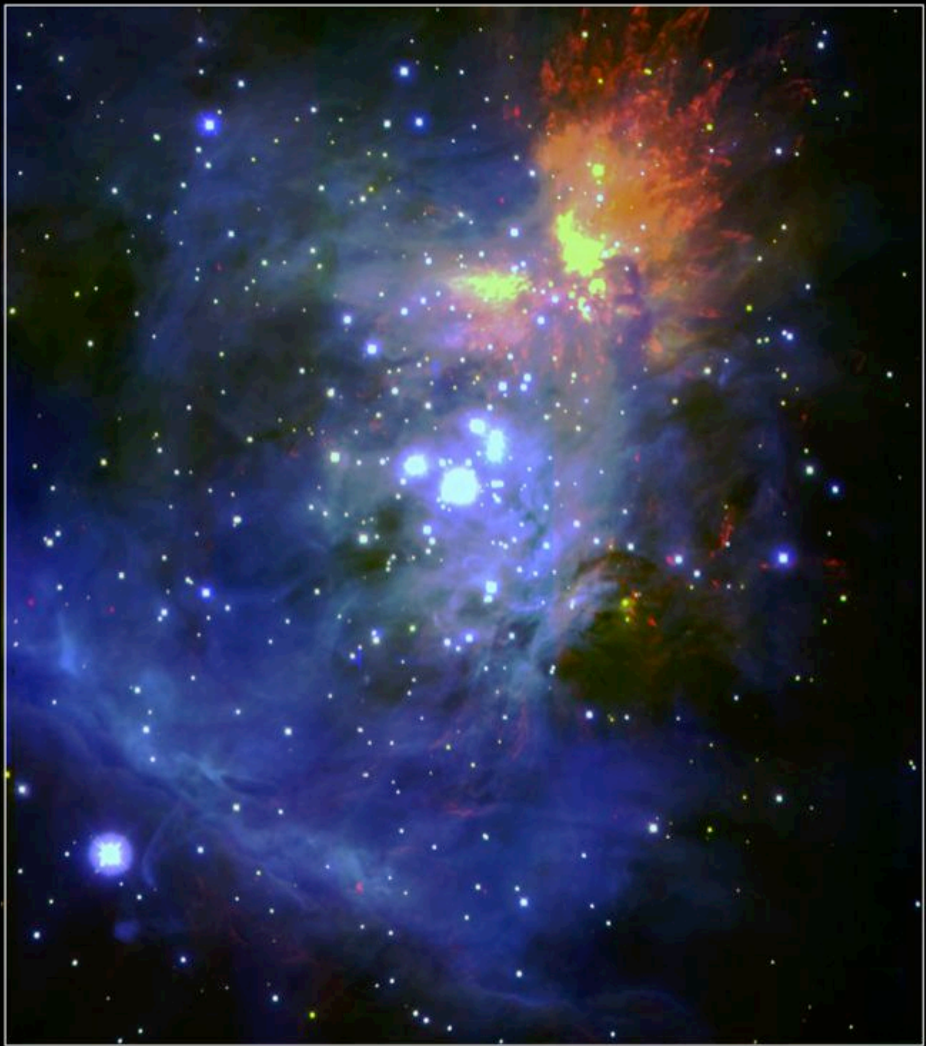


3B grating calculated by RCWA.
n_L=1.46, n_s= 1.544, n_p = 1.60, θ_B =45°.

***w*:*t* = 1:20~100 → 1:4~20**

(Ebizuka et. al. SPIE 8450, 2012)

Immersion Grating



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

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

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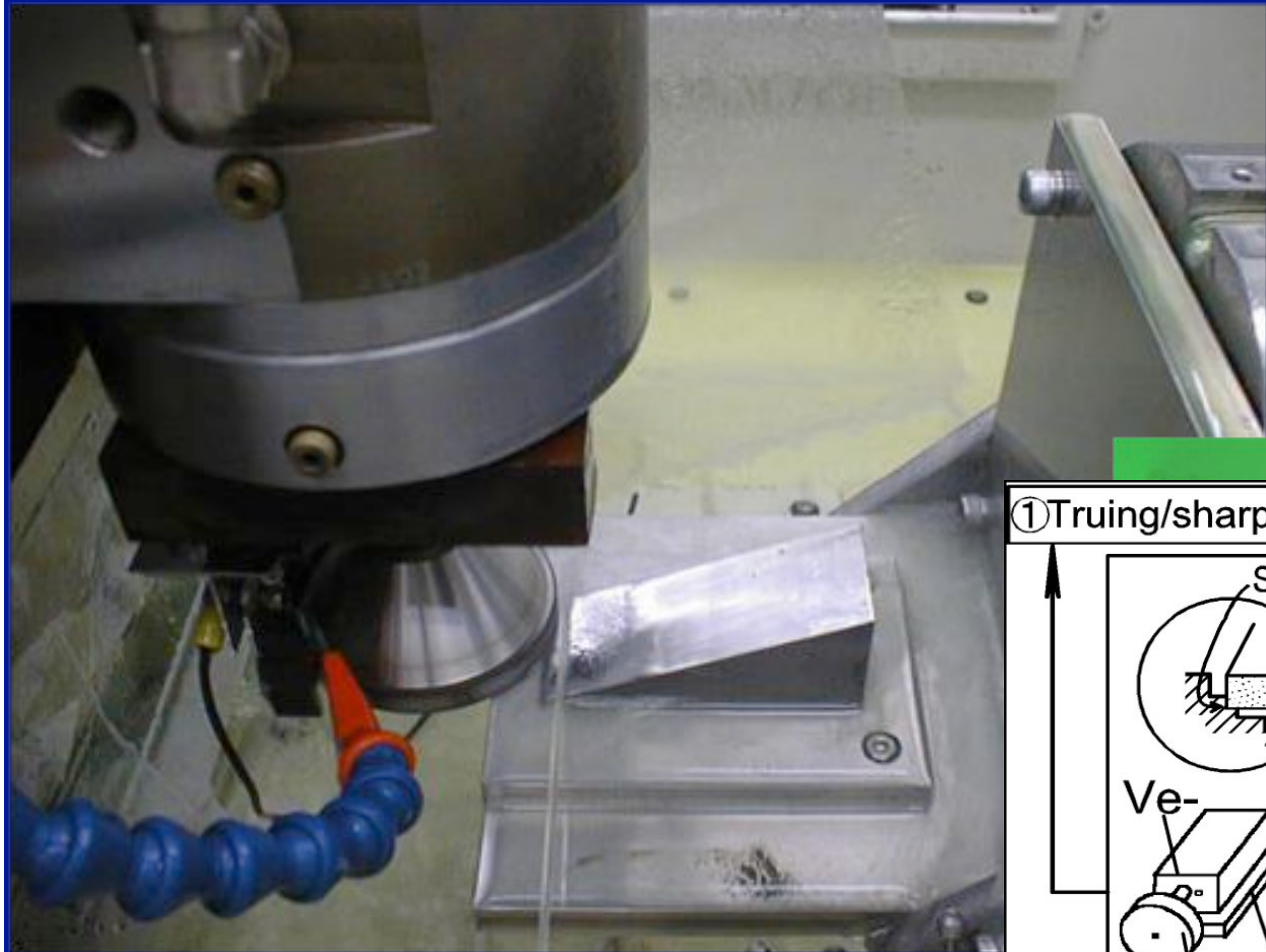
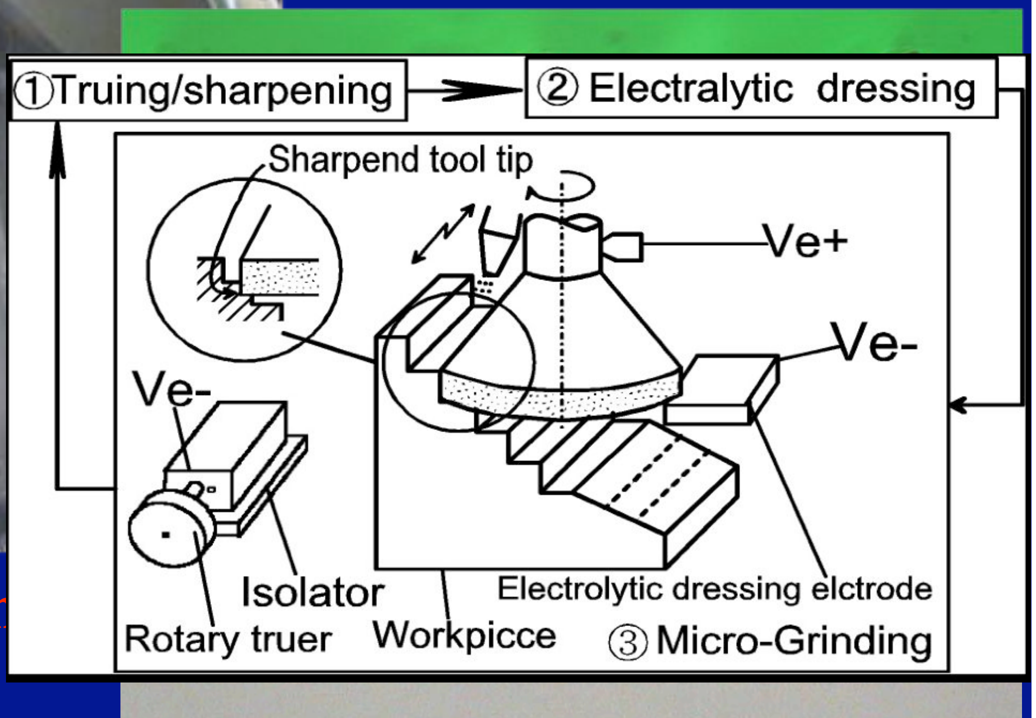
Ge immersion grating for GIGMICS



Nano-precision machine and ELID grinding method.

30 × 30 × 72 [mm],

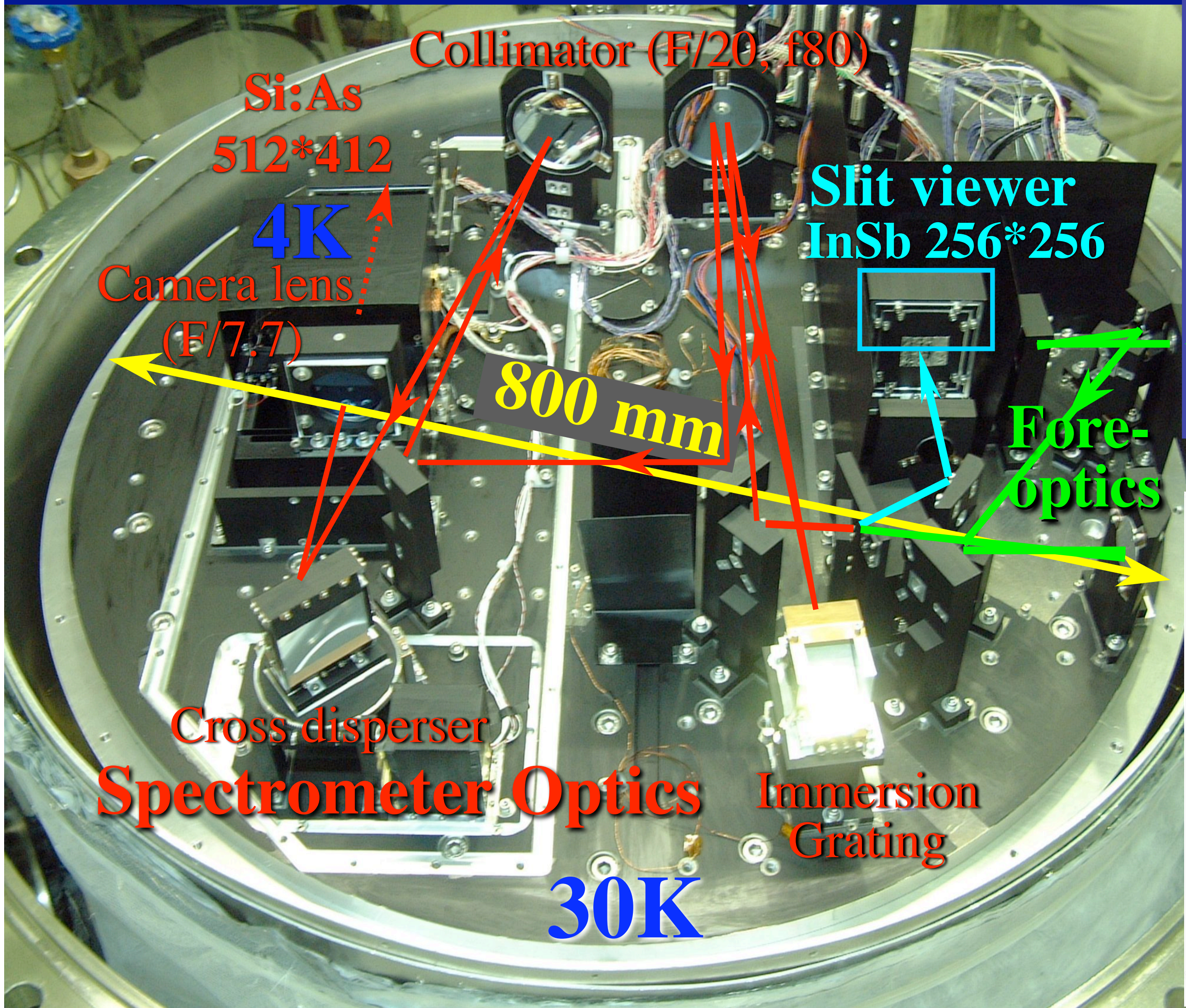
α = 68.75°, Λ=600μm

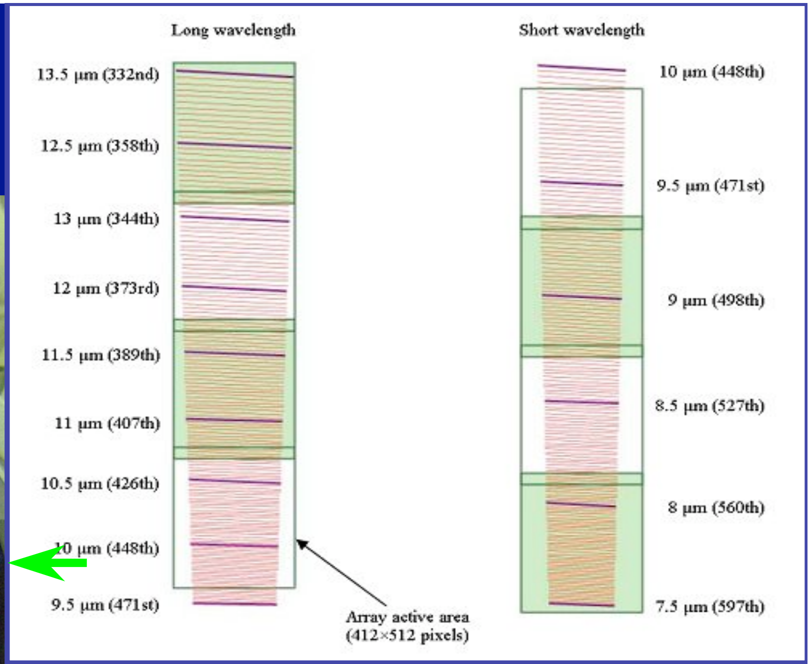


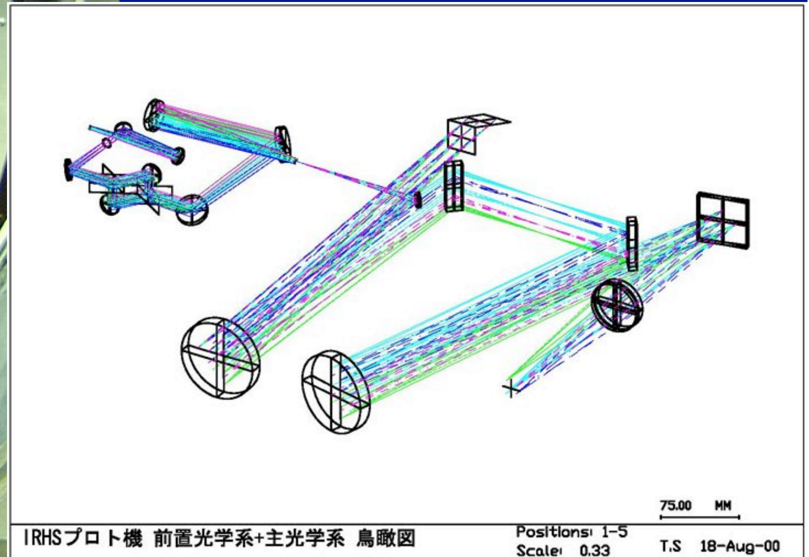
Spent about 400 hours for fabrication

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

GIGMICS





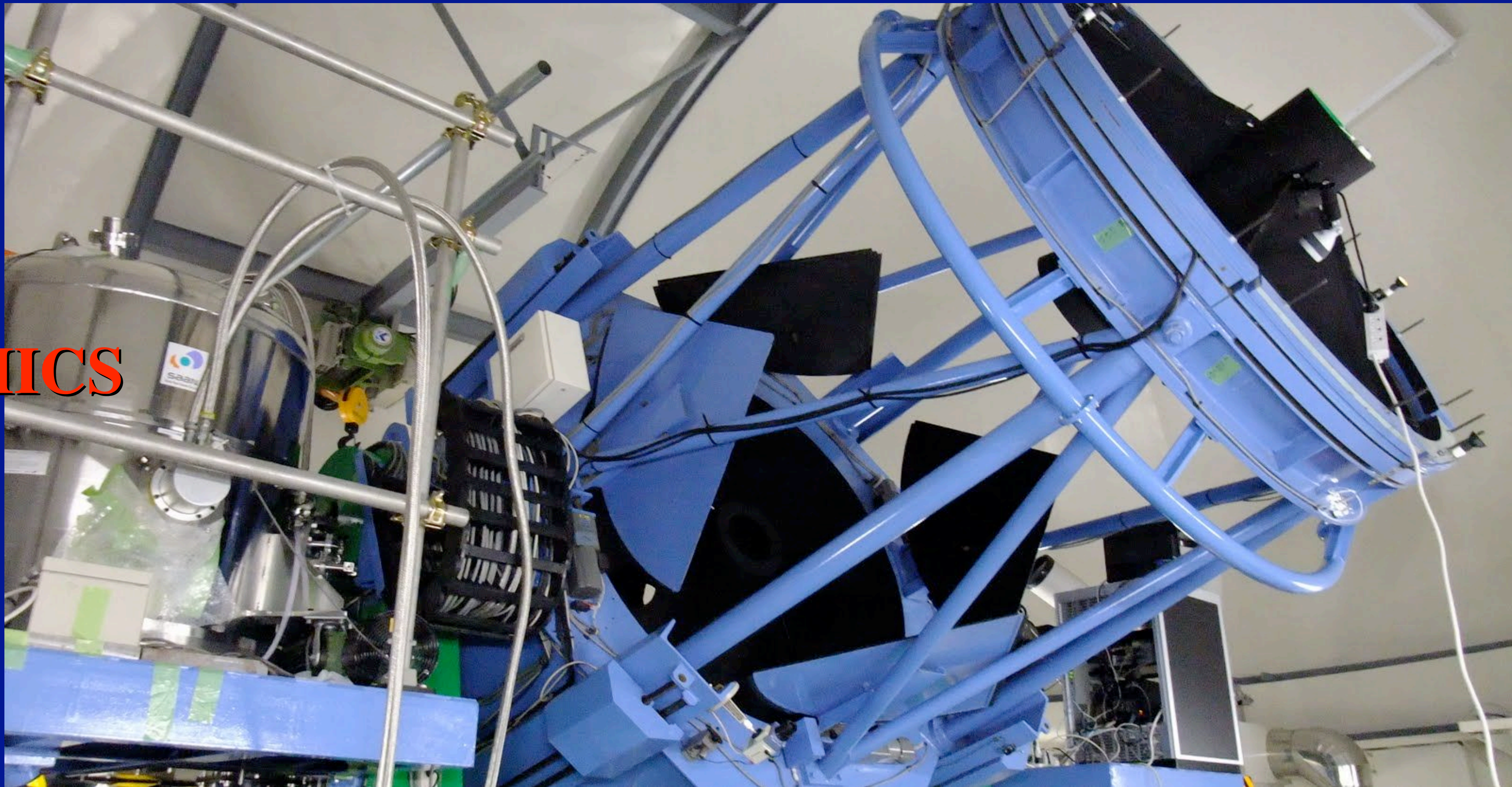


R~ 50,000@10μm, developed by Hirahara lab., Nagoya Univ.

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

First Light Observation of GIGMICS

GIGMICS

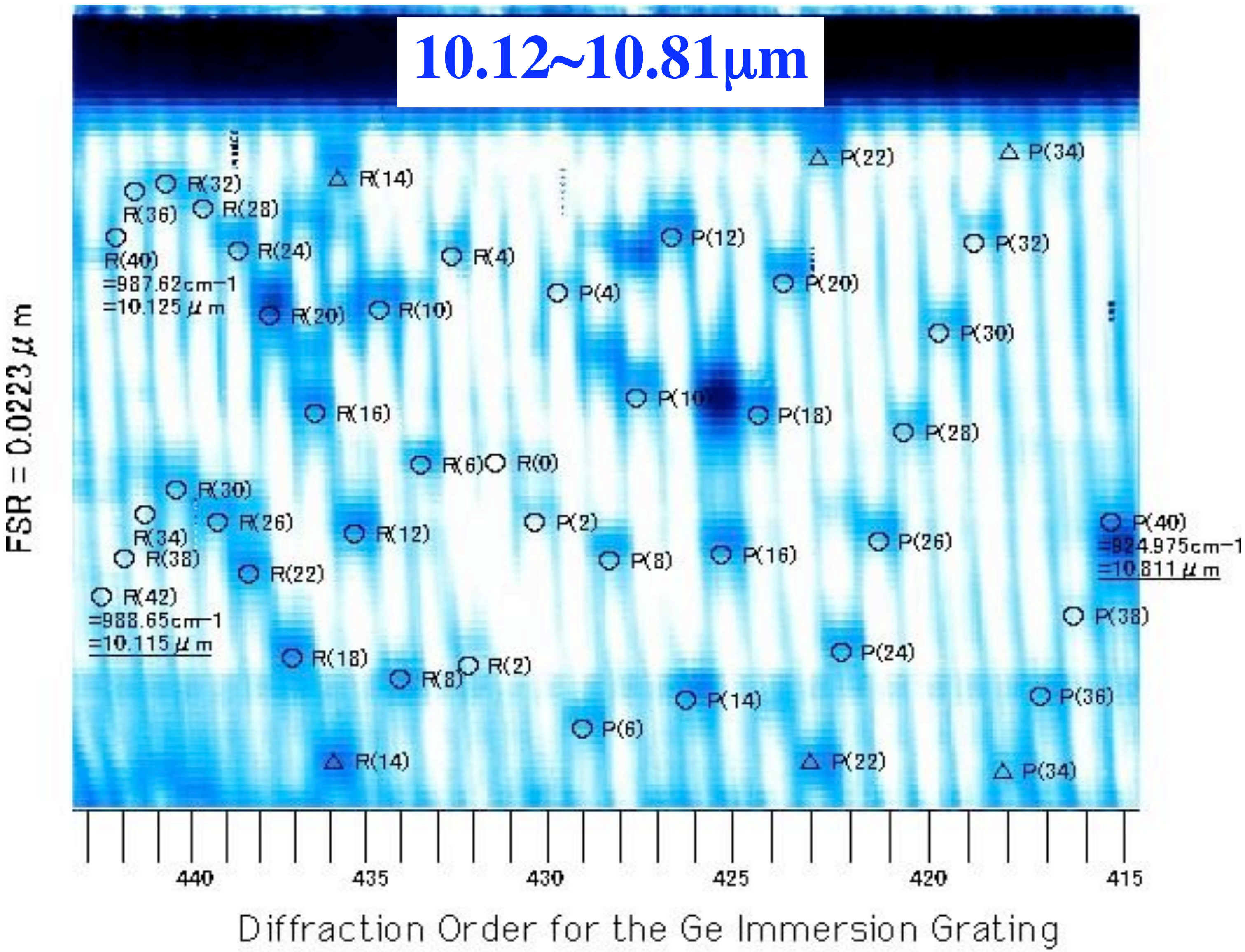


KANATA 1.5m telescope, Higashi-Hiroshima Observatory, Space Science Center Hiroshima Univ., Dec. 2010~Apr. 2011.

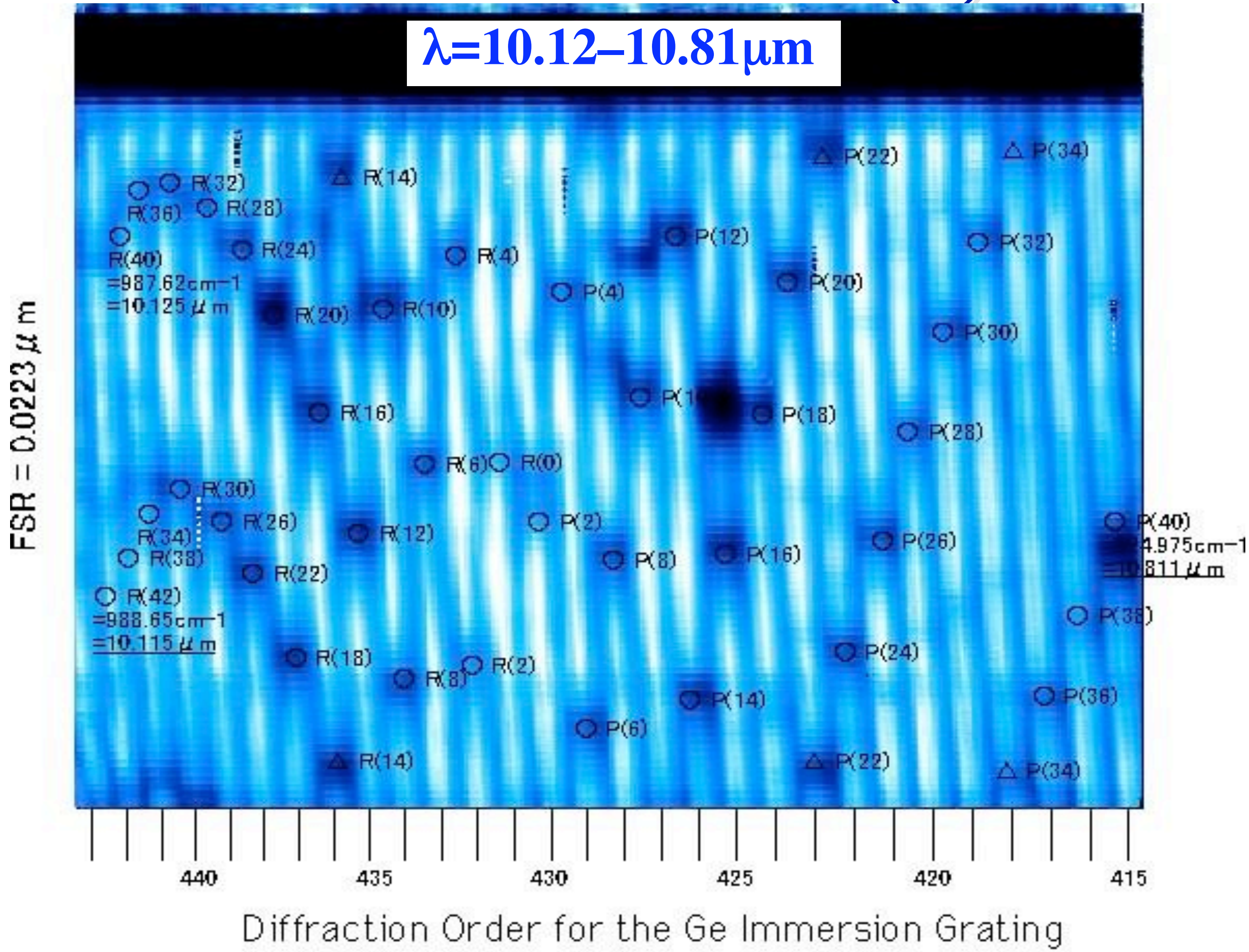
Targets: Vib.-rot. Transitions of Methane, Ethane, Ammonia, N_2O, O_3, SO_2, H_2O, CO_2, SO_2, H_2S, NOx, Halogen Oxides, etc.,in the Planets, Stellar Atmosphere, bright SFRs, CSE of late type stars, and the upper atmosphere of the Earth.

(Hirahara et. al., SPIE, **8446**, 2012)

Reference: Earth's atmosphere



First rcientific result (1): Venus

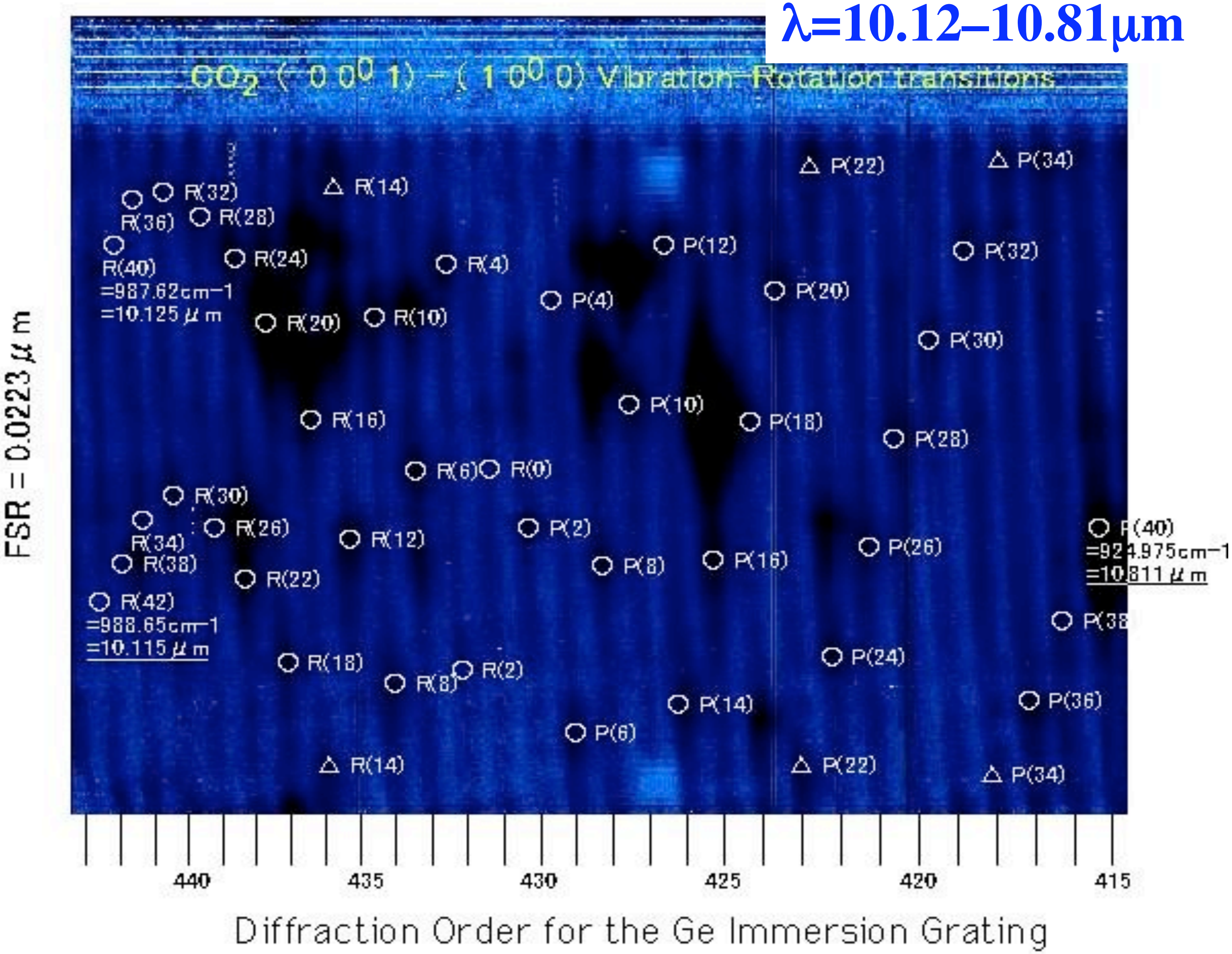


Absorption lines cannot be identified to the "telluric lines".

→ CO_2 hot-band & isotopes from Venus.

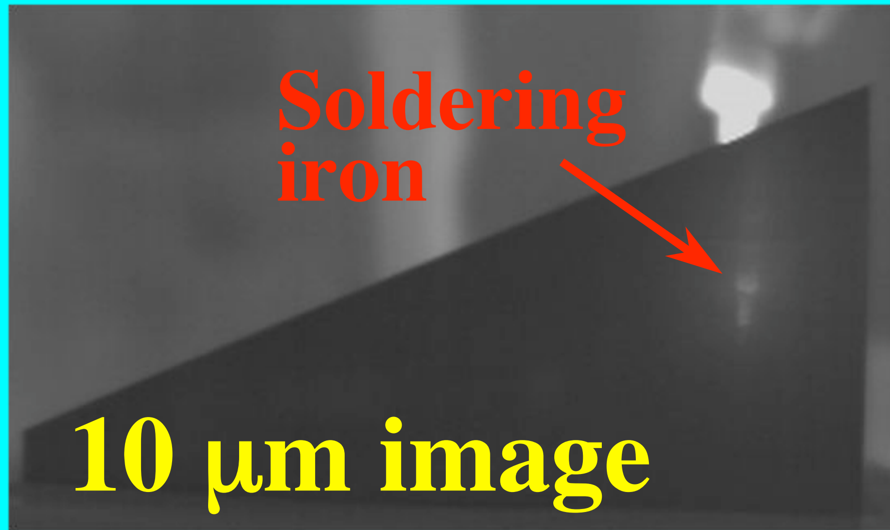
First scientific results (2): NGC7027

λ=10.12–10.81μm



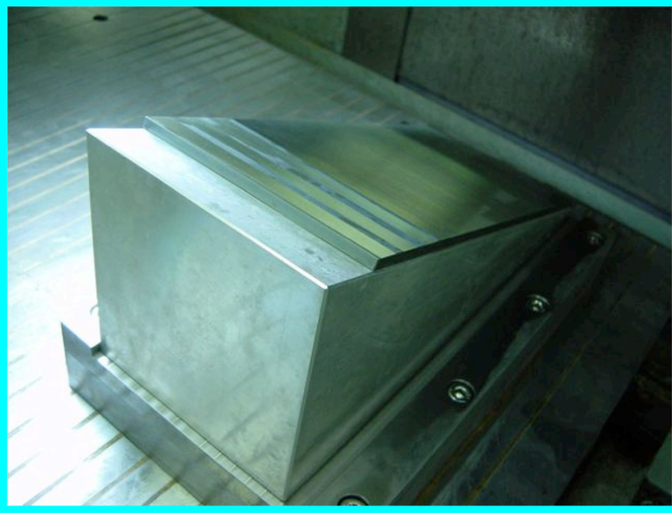
Detection of [S IV] ionic fine-structure emission line toward the planetary nebula.

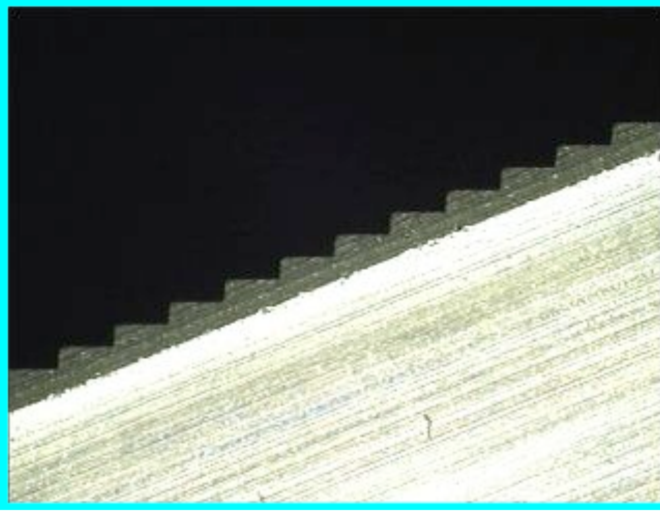
Trial fabrications of Ge immersion grating for R~200,000



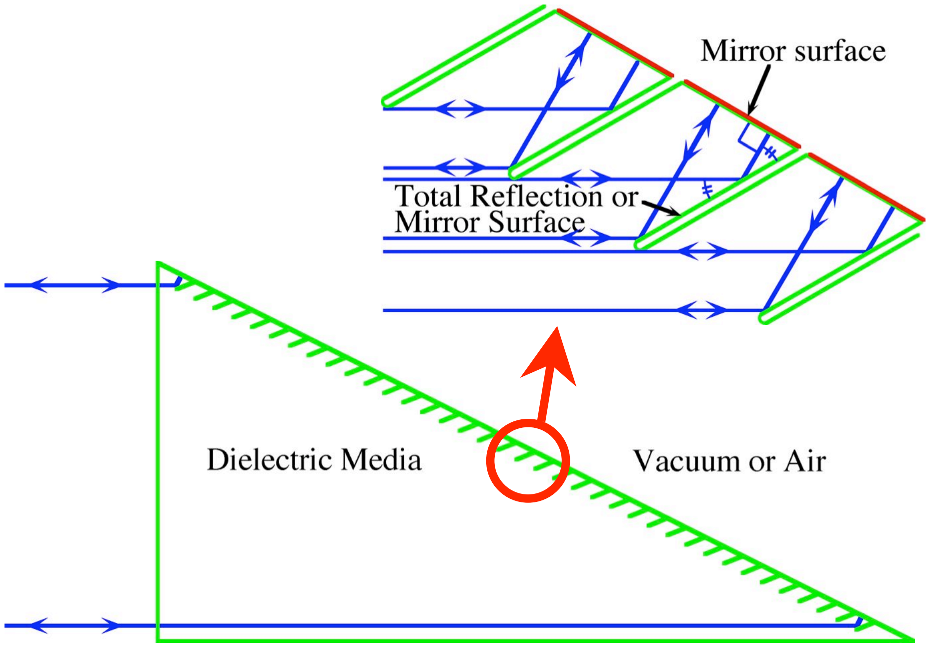
R〜200,000@10μm → Size: 120 x 120 x 270 mm

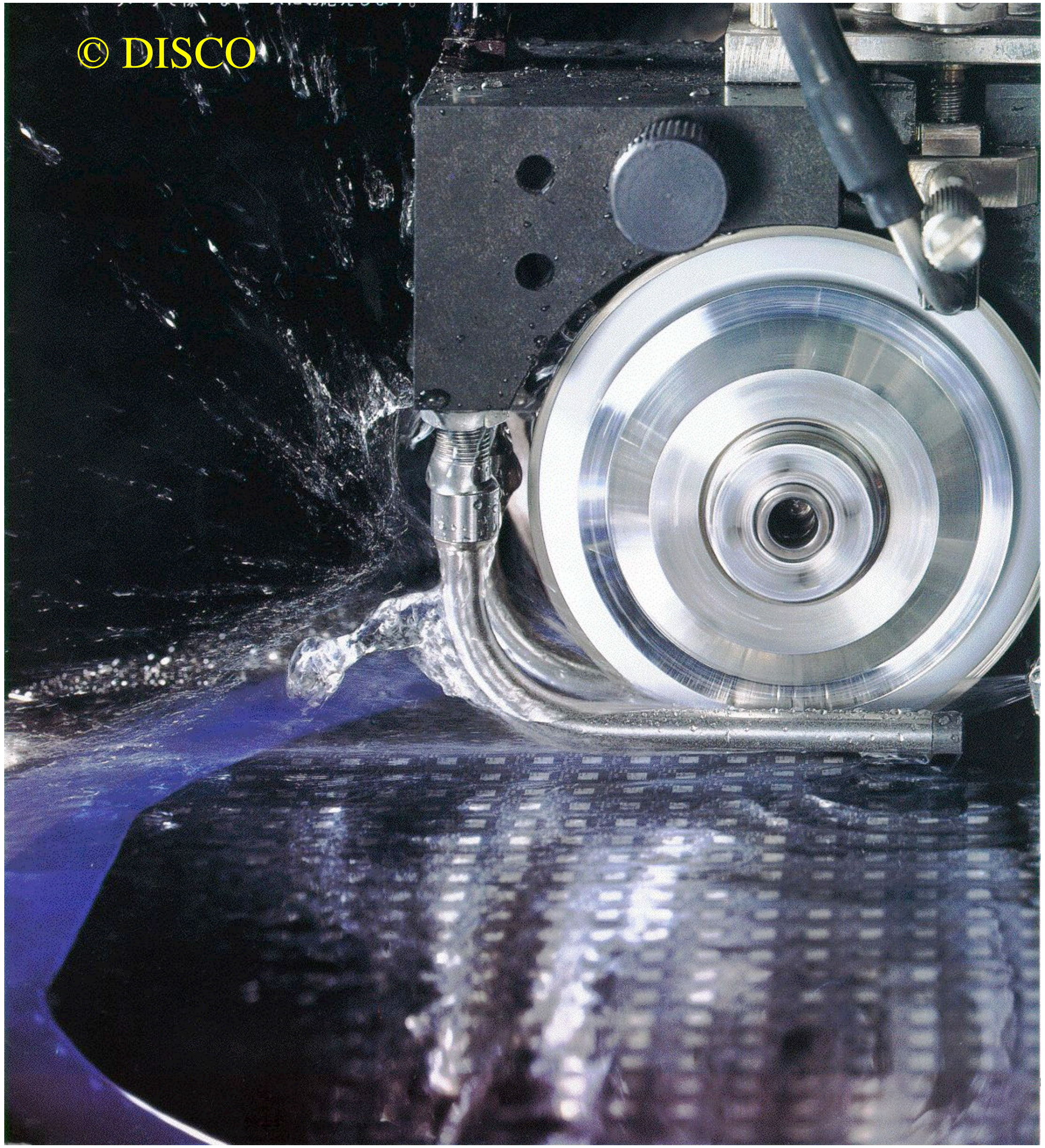
→ Fabrication time: several 1,000 hours





Novel immersion grating

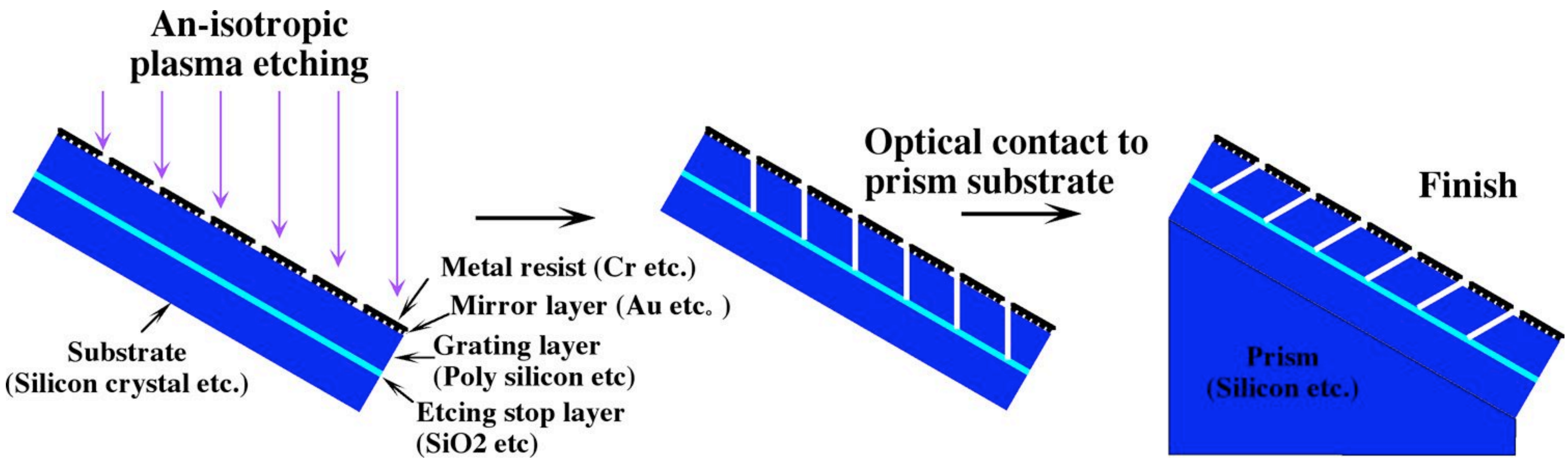




- **Machining of dicing saw makes smooth surface**
- **Easy tooling.**
- **Fabrication time for grating with 120 x 120 x 270 mm → Several 100 hours?**

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

Fabrication method of novel immersion grating for visible and near IR



(Ebizuka et. al. SPIE 8450, 2012)

Conclusions

- **A VPH grating achieves high dispersion and high efficiency, as well as versatile for moderate dispersion.**
- **A volume binary grating achieves wide bandwidth with high efficiency and utilizes for an echelle spectrograph.**
- **A volume birefringence gratings achieve high efficiency up to 100% for non polarized light.**
- **A novel immersion grating achieves smaller scattering loss and able to reduce fabrication cost.**
- **Deep reactive ion etching (D-RIE) is promising methods of fabrications for these high dispersion gratings.**