新しい偏光・分光光学素子

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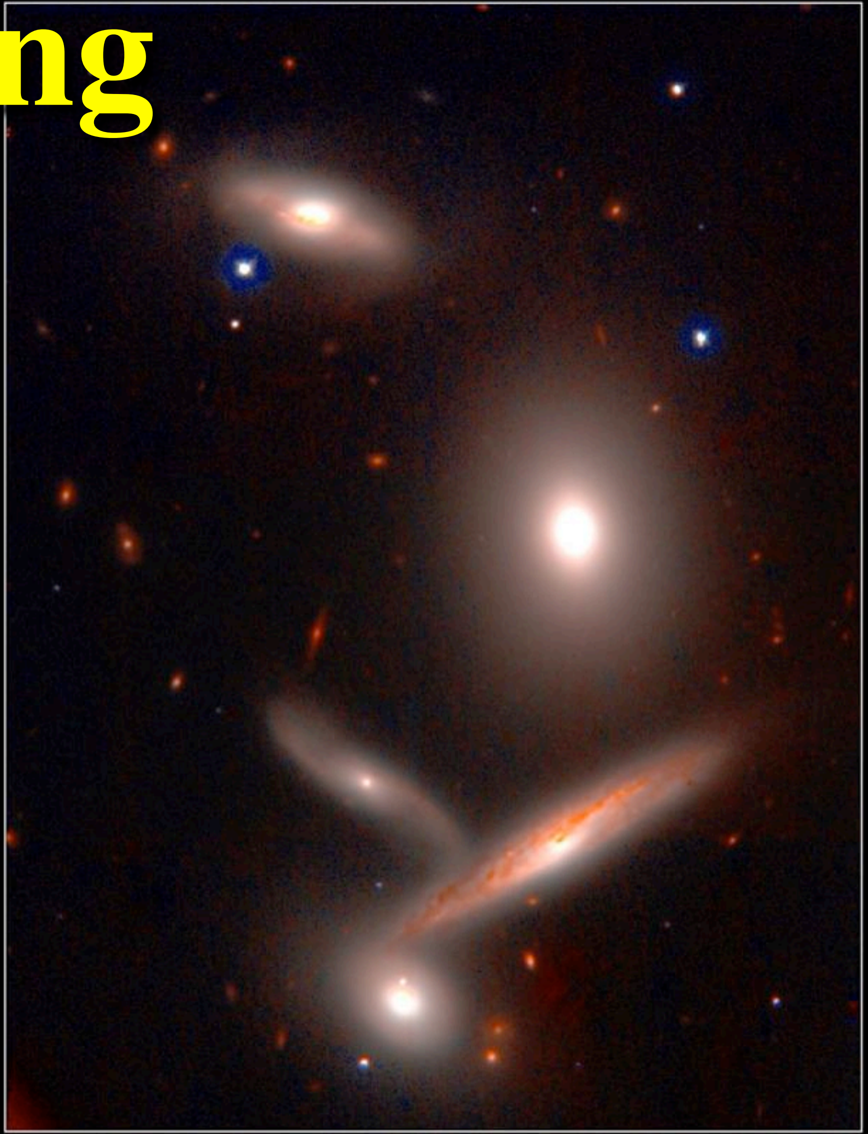
研究会「光赤外偏光天文学の軌跡と今後」

2013年 3月17, 18日

Volume Phase Holographic Grating

M 82 (NGC 3034) FOCAS (B, V, Hα)

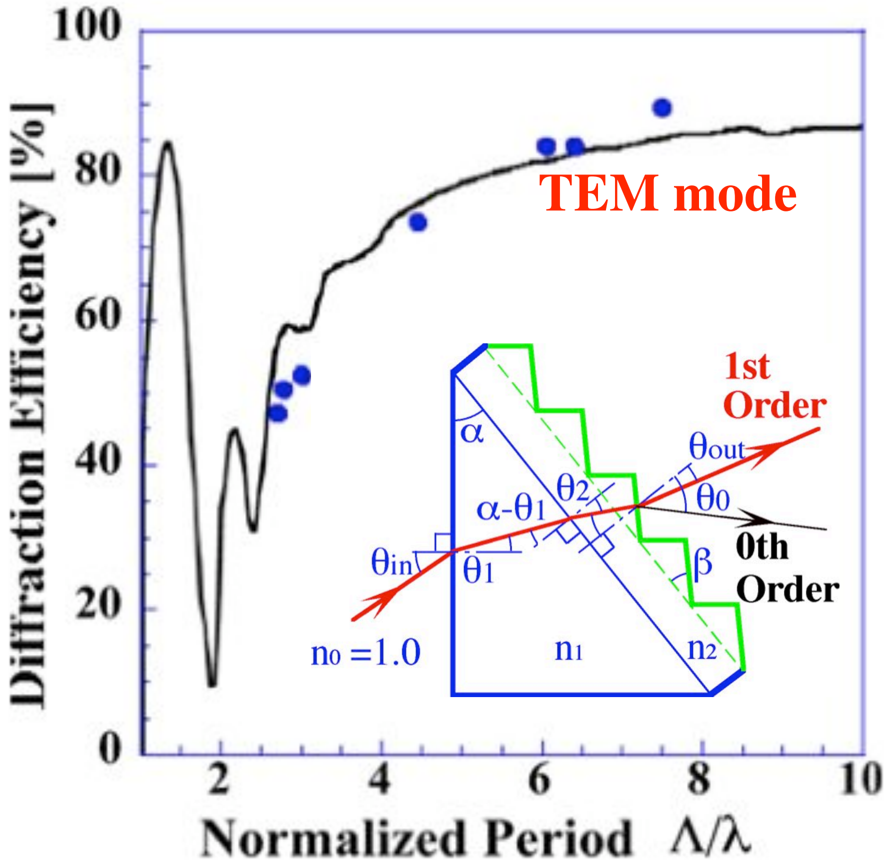
Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000



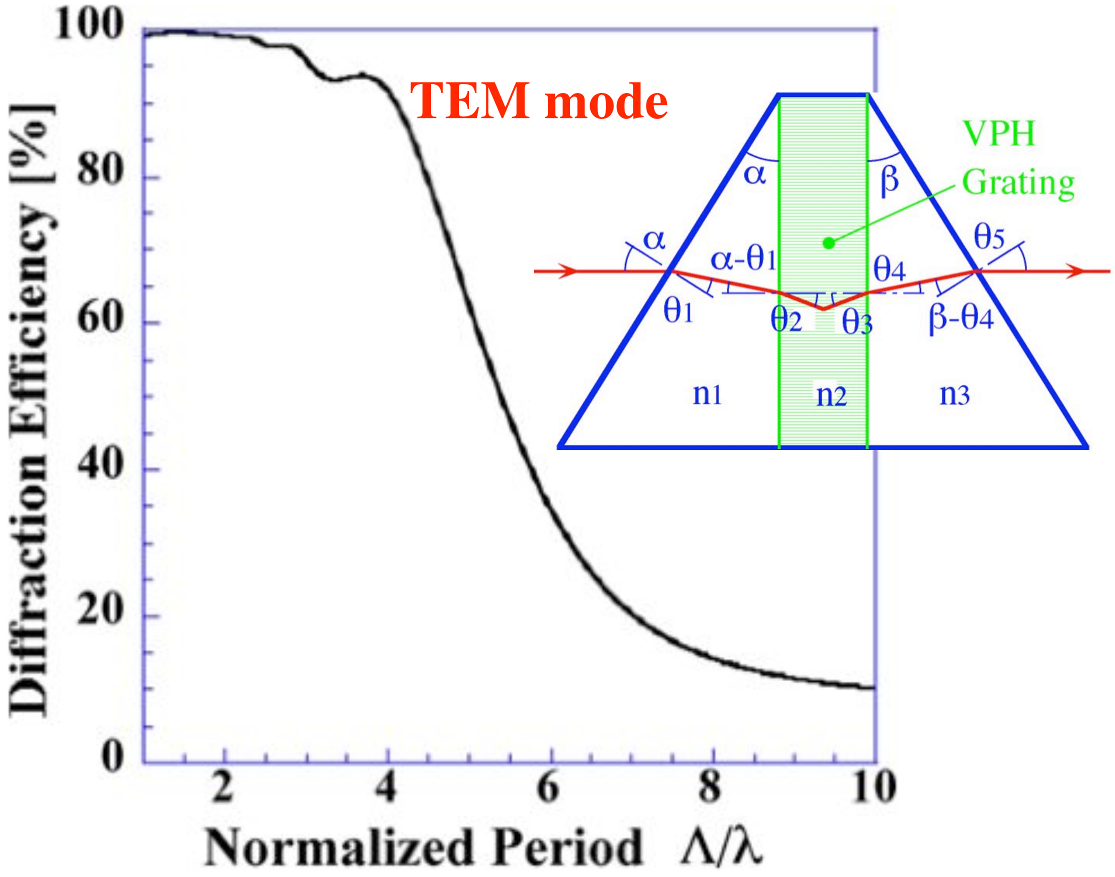
Hickson Compact Group 40 CISCO (J & K′)

Subaru Telescope, National Astronomical Observatory of Japan January 28, 1999

Efficiencies of gratings

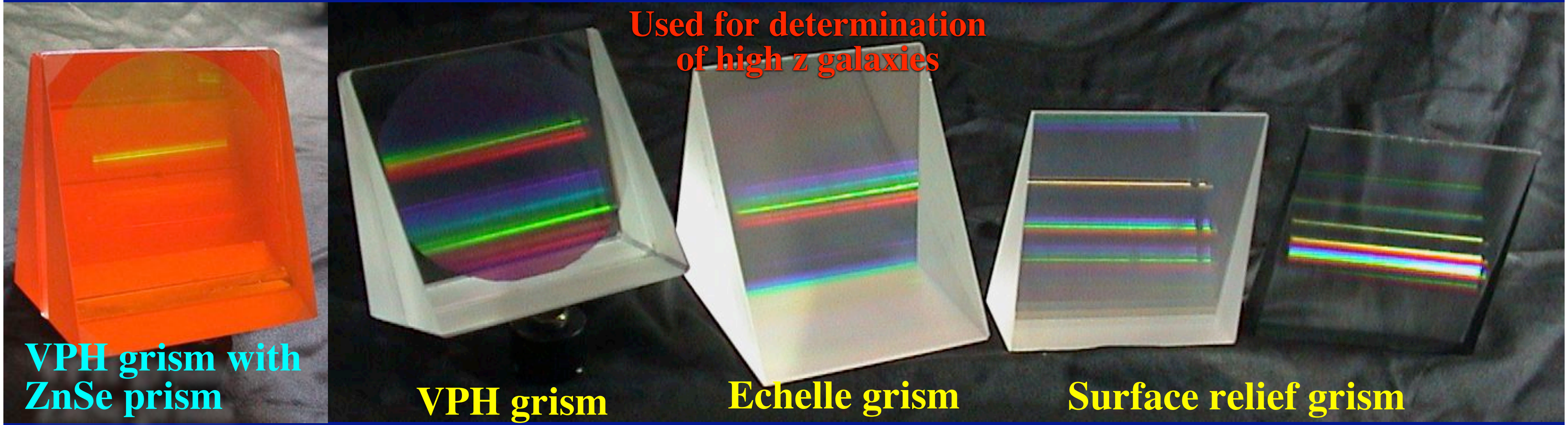


Surface relief grating: Efficiency decreases steeply below 4 Λ/λ.



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)


Used for determination of high z galaxies

Grisms for FOCAS

Size: 110 × 106 × 106 (max).

4 SR grisms: $300 < R < 1{,}400$.

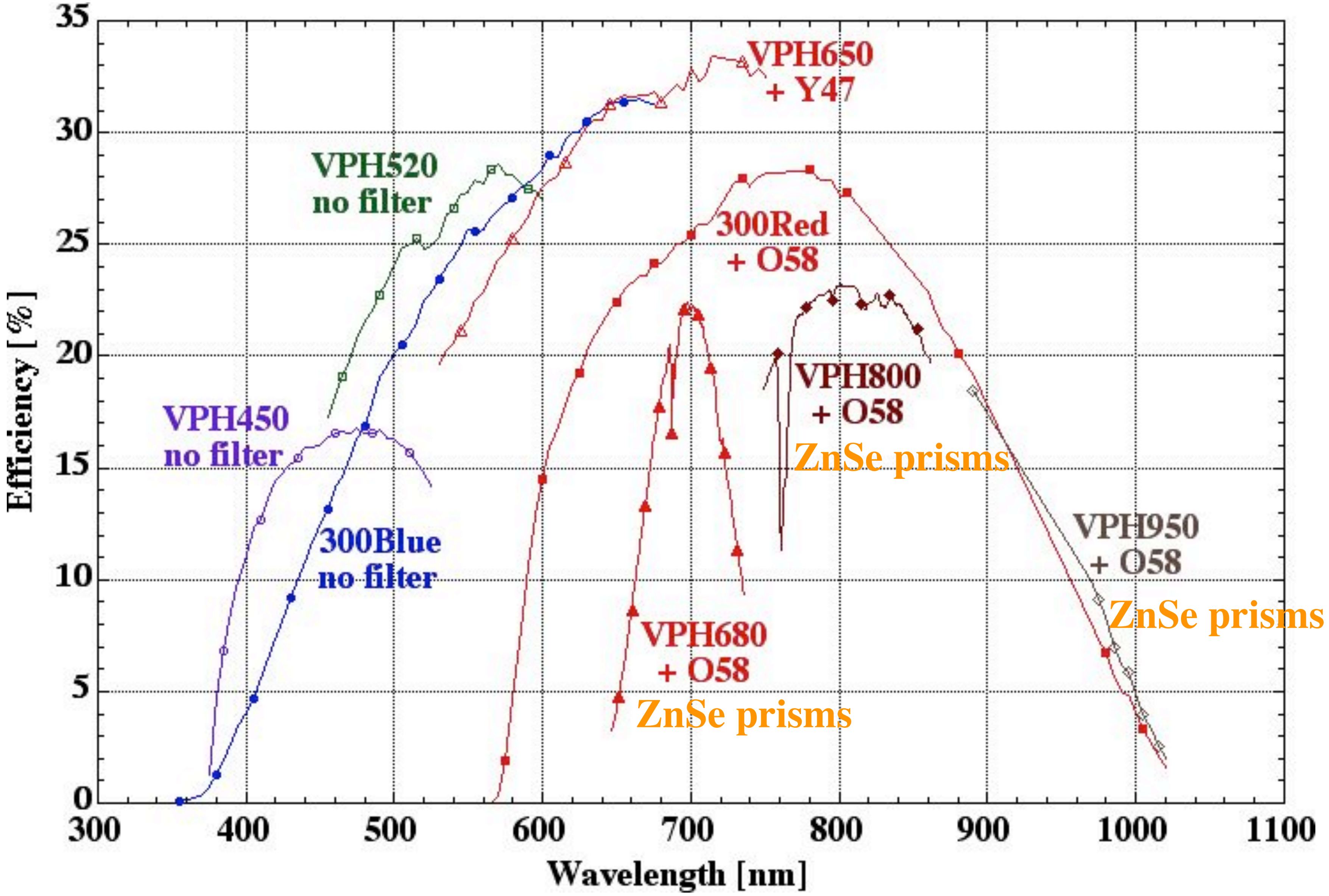
1 Echelle grism: $R \sim 2{,}500$.

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

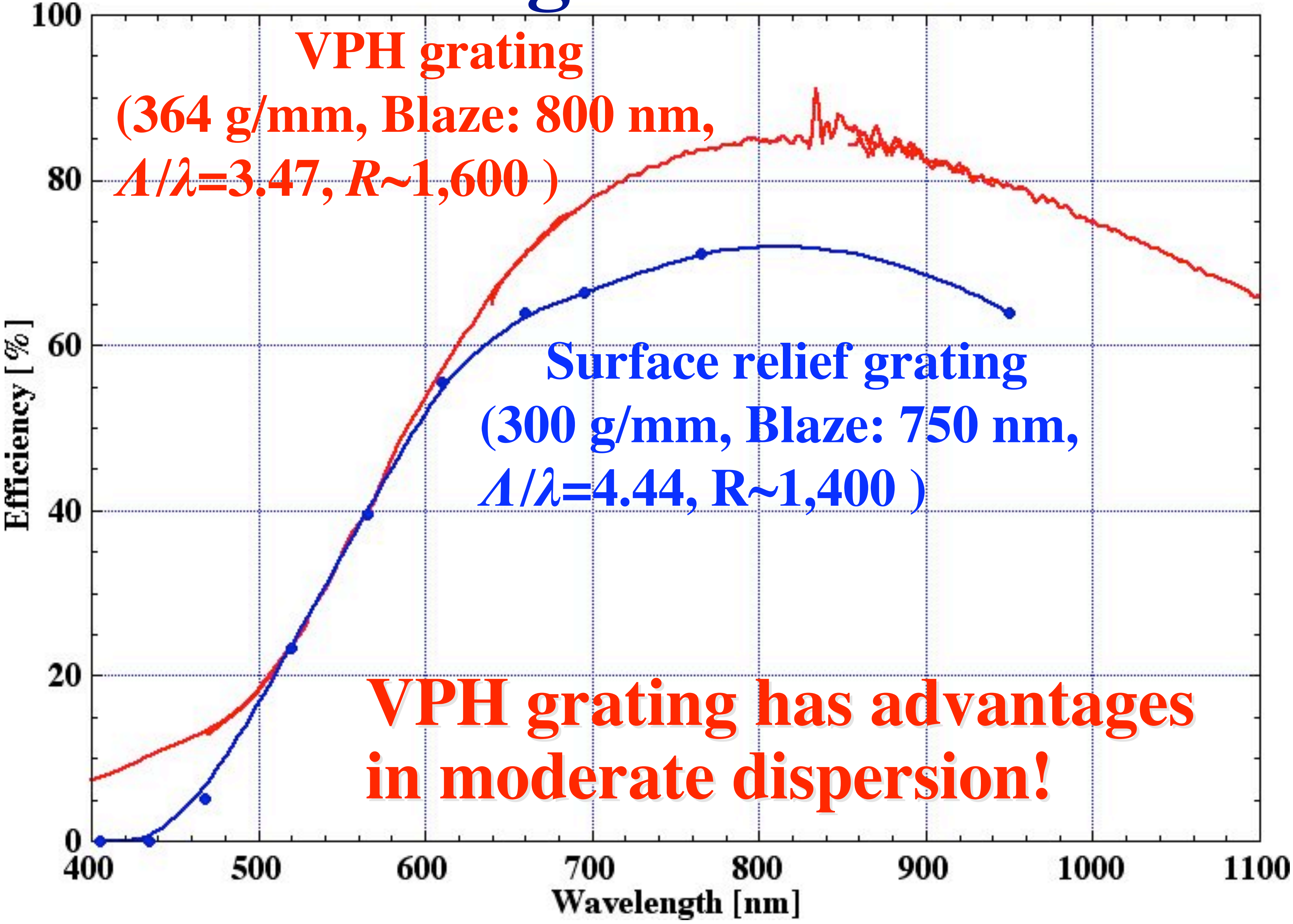
Developed by in collaboration with Japan Wemen’s Univ., NAOJ and RIKEN.

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

Relative efficiencies of grisms within Subaru Telescope and FOCAS

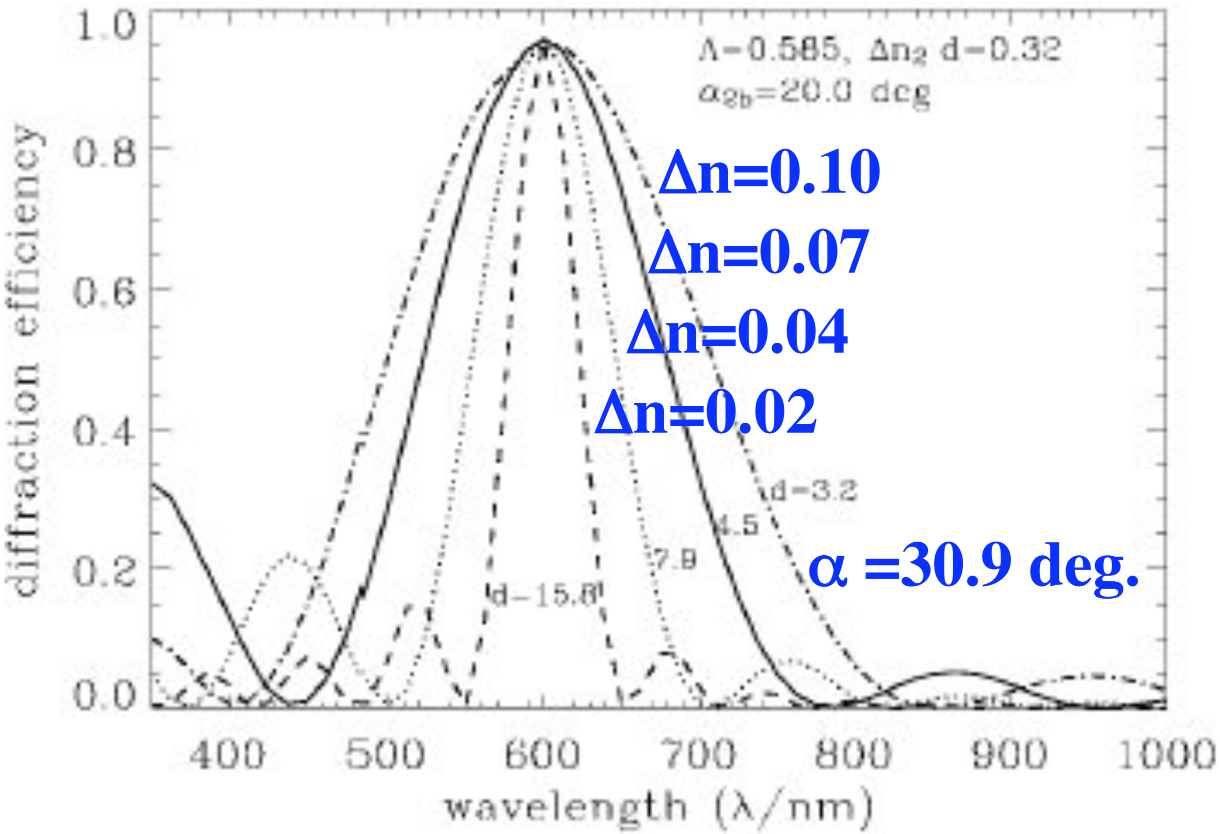


New VPH grisms for FOCAS



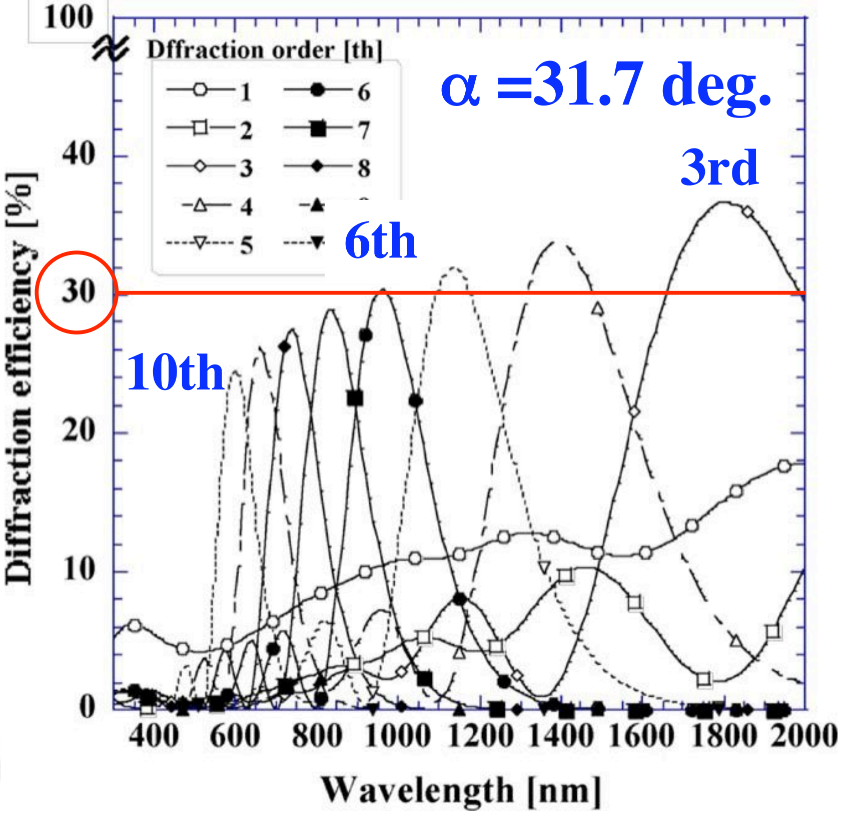
VPH grating has advantages in moderate dispersion!

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)



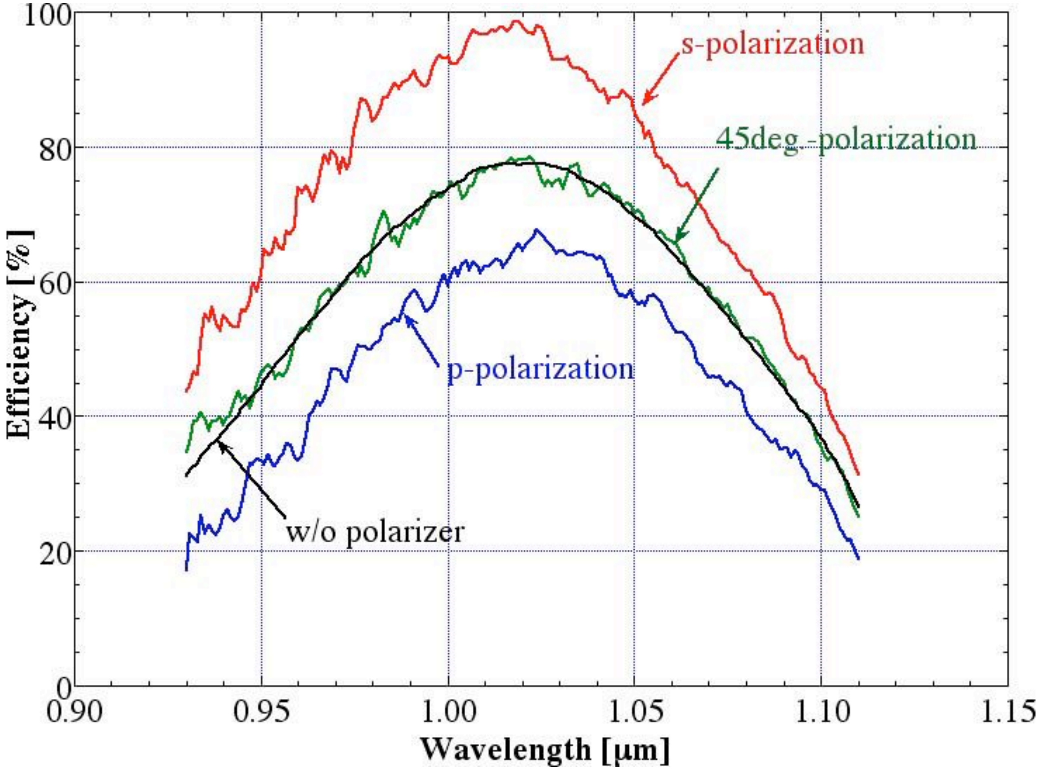
Diffraction efficiency of VPH grating decrease toward higher orders.

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

Polarized diffraction efficiency of VPH grating

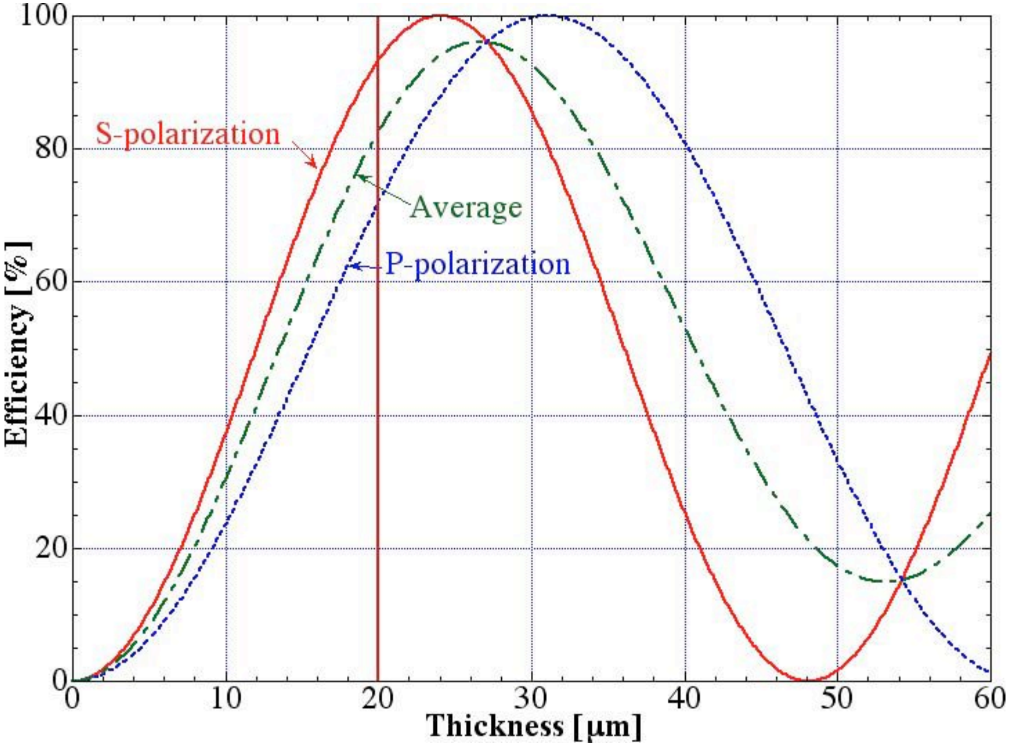
$$\eta_{\mathrm{S}} = \sin^2\left\{\frac{\pi(n_{\max}-n_{\min})t}{\Lambda(n_{\max}+n_{\min})\sin 2\theta}\right\}$$

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



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 thickness of a VPH grating with refractive index modulation: Δn=0.017.

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

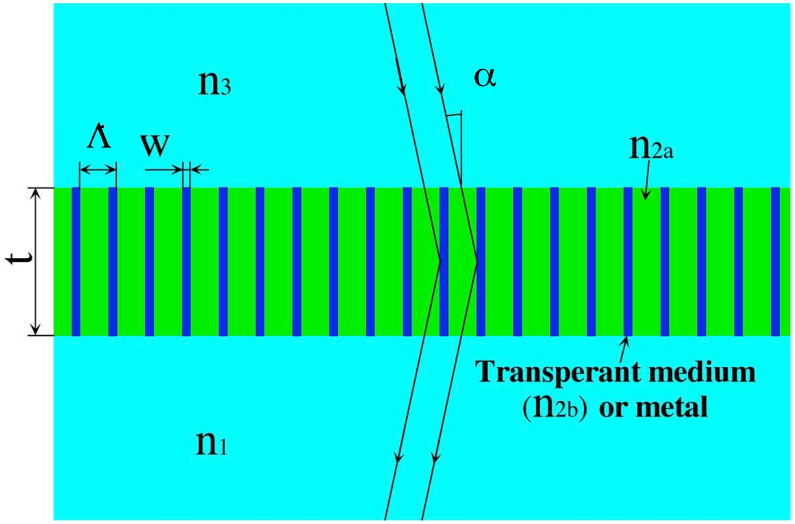
Volume Binary Grating

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

Volume binary grating



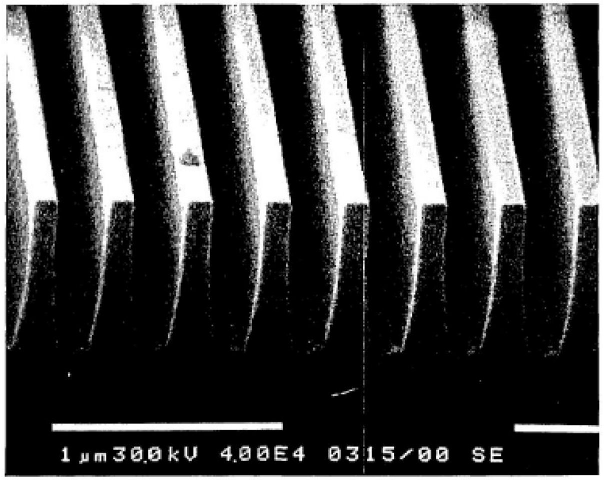


Fig. 1. Scanning electron micrograph of grating lines etched into quartz substrate (n_s = 1.46).

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

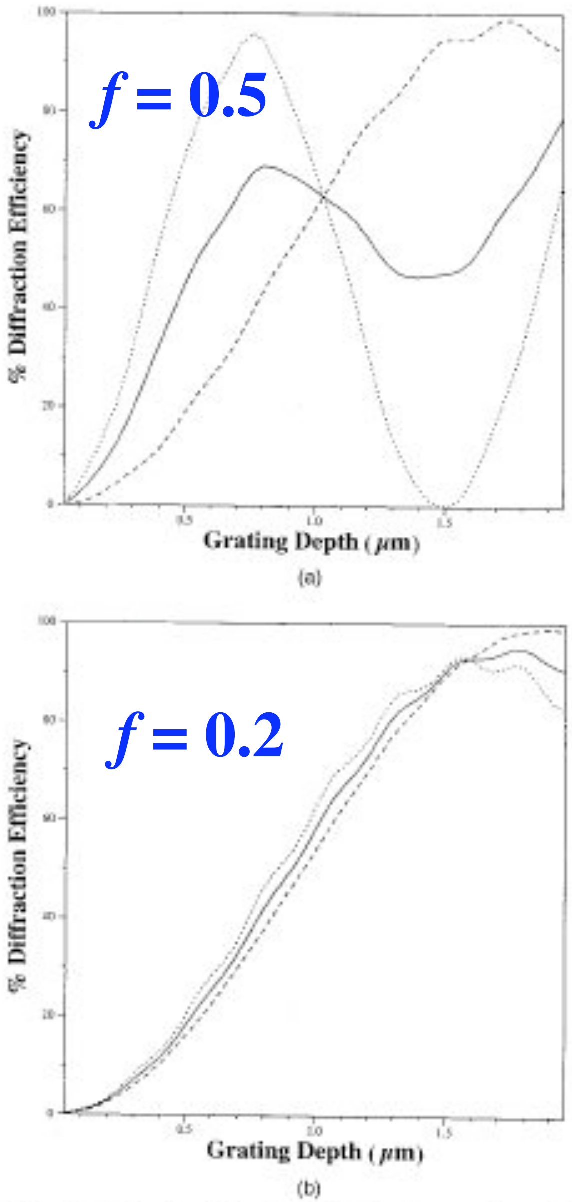


Fig. 5. (a) First-order diffraction efficiencies for a grating with λ = 0.55 μm, Λ = 0.3889 μm, θ_B = 45°, n = 1.50, and f = 0.50. (b) First-order diffraction efficiencies for a grating with λ = 0.55 μm, Λ = 0.3889 μm, θ_B = 45°, n = 1.50, and f = 0.80.

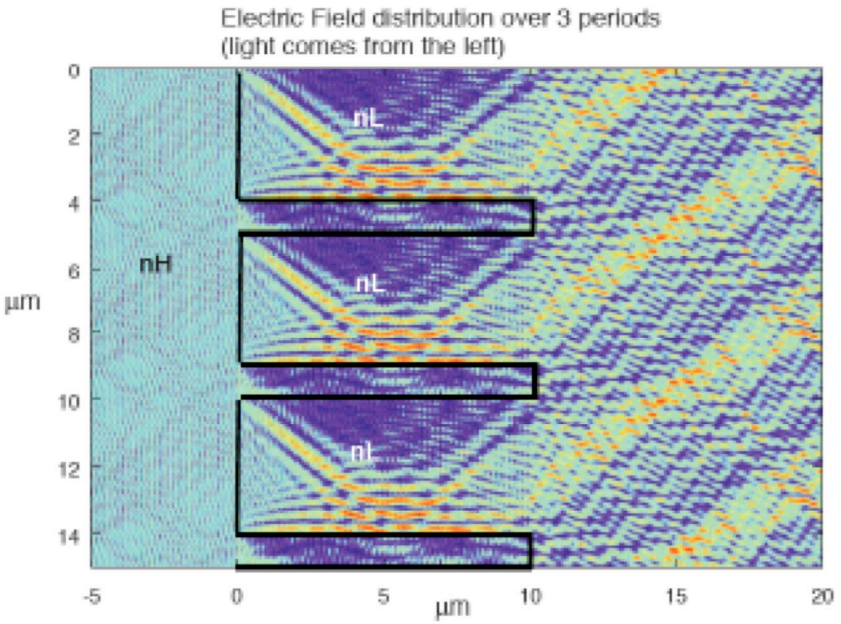
- **$\Delta n = (n_{max} - n_{min})/2 \sim 0.5$.**
- **Polarized diffraction efficiencies of S and P polarization coincide with each other by tuning of *f* and *t*. While aspect ratio becomes *t* : *w* = 1:20 ~ 100.**

Filling factor: $f = w/\Lambda$

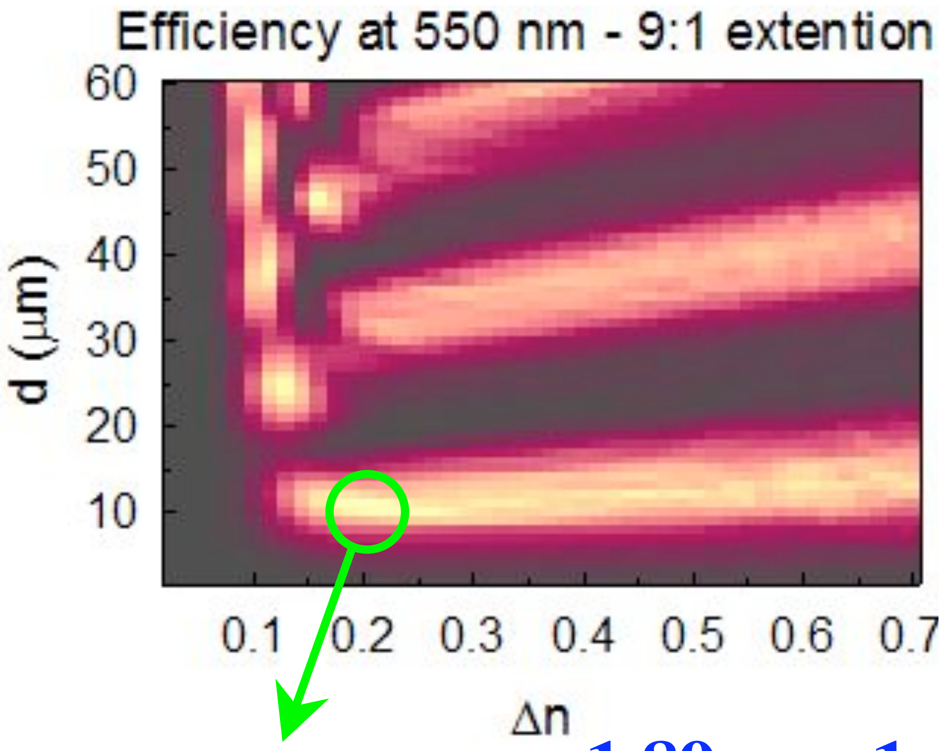
n_H=1.46, n_L=1.0,
α =45 deg.

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

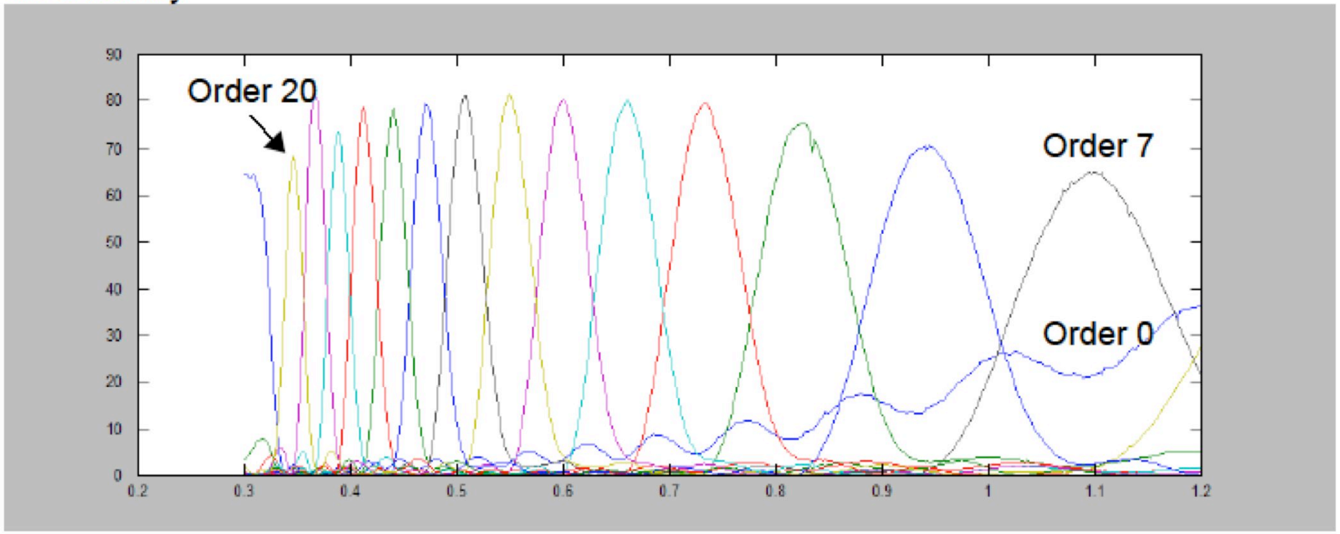
Volume binary grating for higher diffraction orders



λ = 0.55 µm, α = 20.44° (= 41.3° in air), nH = 1.89, nL = 1.46, d = 10 µm



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

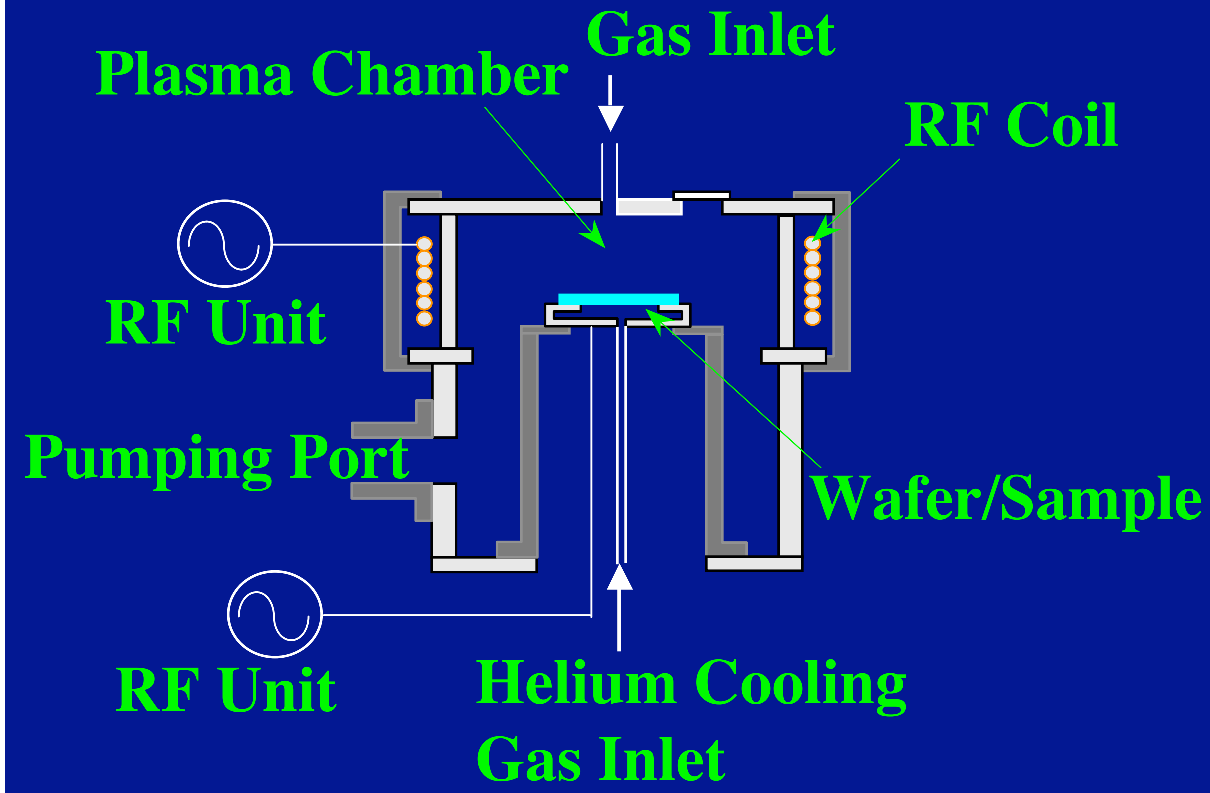


n_H=1.89, n_L=1.46,
α =41.3°, f = 0.1

t:w = 1:22

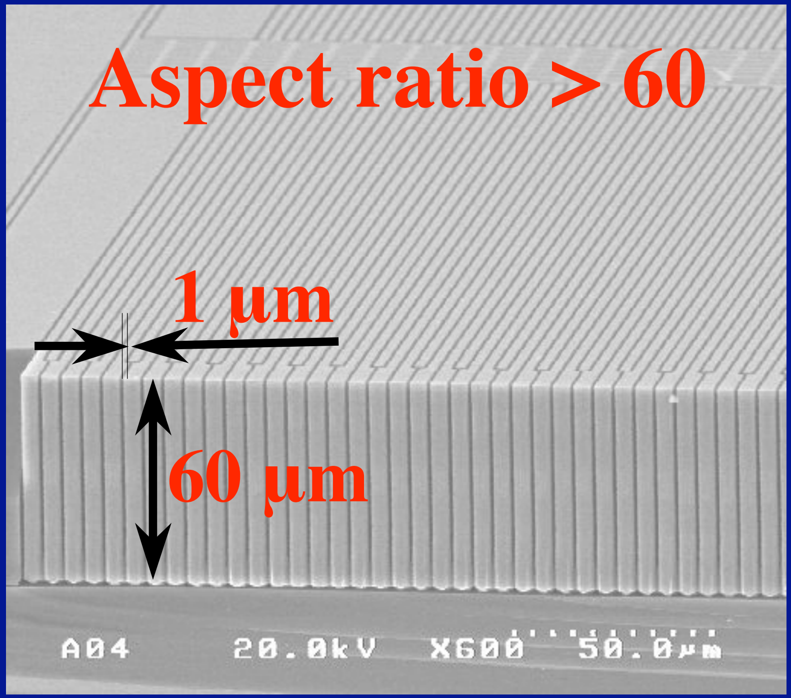
(Bianco & Ebizuka,
SPIE, **8450**, 2012)

D-RIE (Deep Reactive Ion Etching)



ICP Etcher

Inductively Coupled Plasma



G sensor of capacitance type

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

Polarized diffraction efficiency of VPH grating

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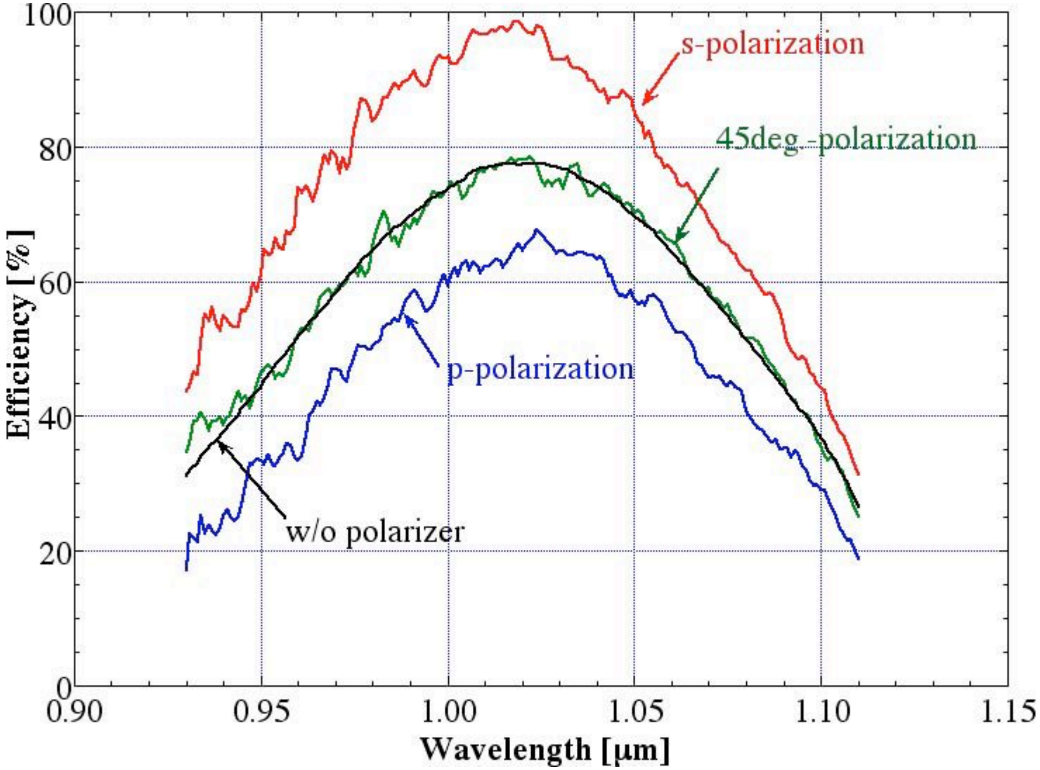
$$\eta_P = \sin^2\left\{\frac{\pi(n_{\max}-n_{\min})t\cos 2\theta}{\Lambda(n_{\max}+n_{\min})\sin 2\theta}\right\}$$



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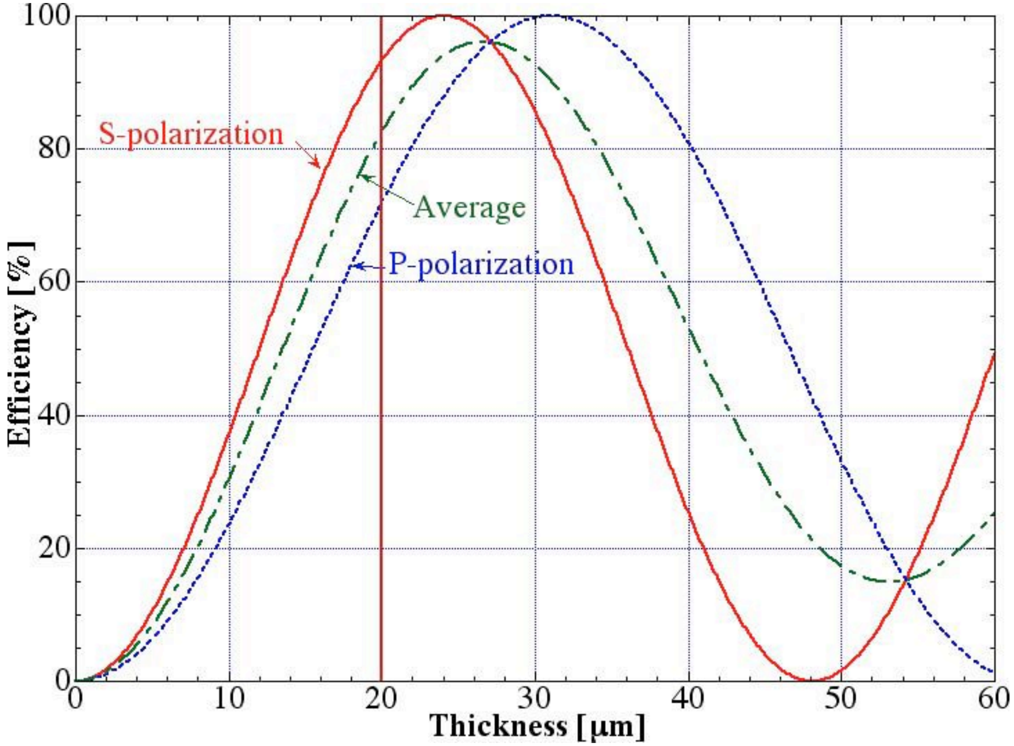
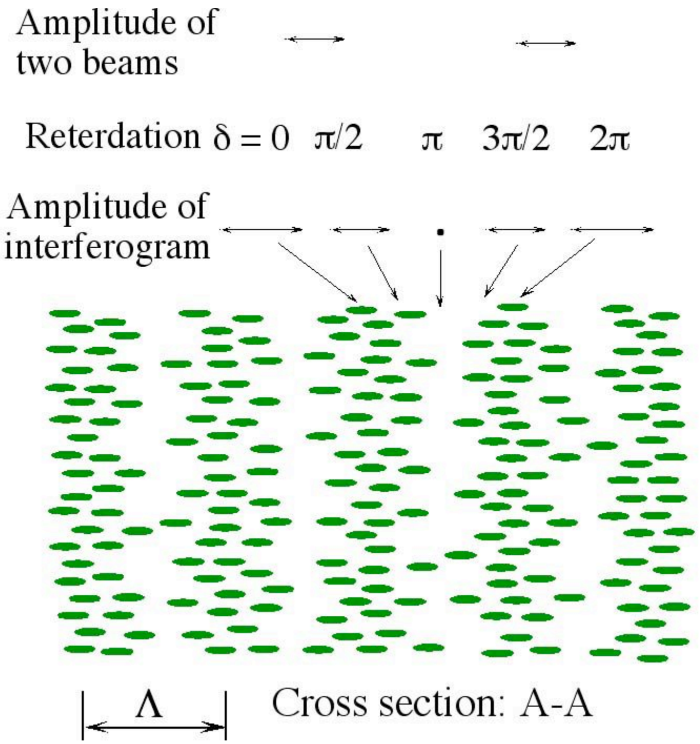
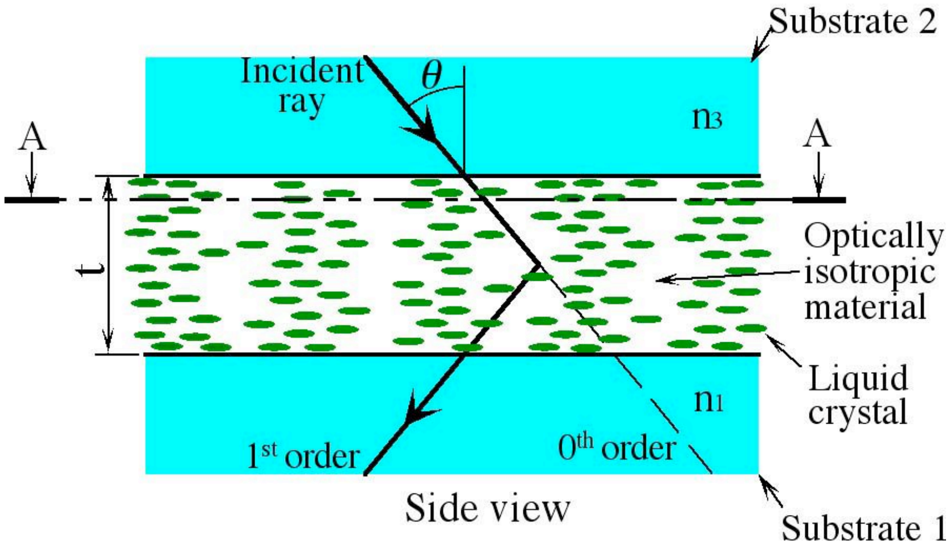


Calculated polarization diffraction efficiencies versus thickness of a VPH grating with refractive index modulation: Δn=0.017.

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

Birefringence VPH grating

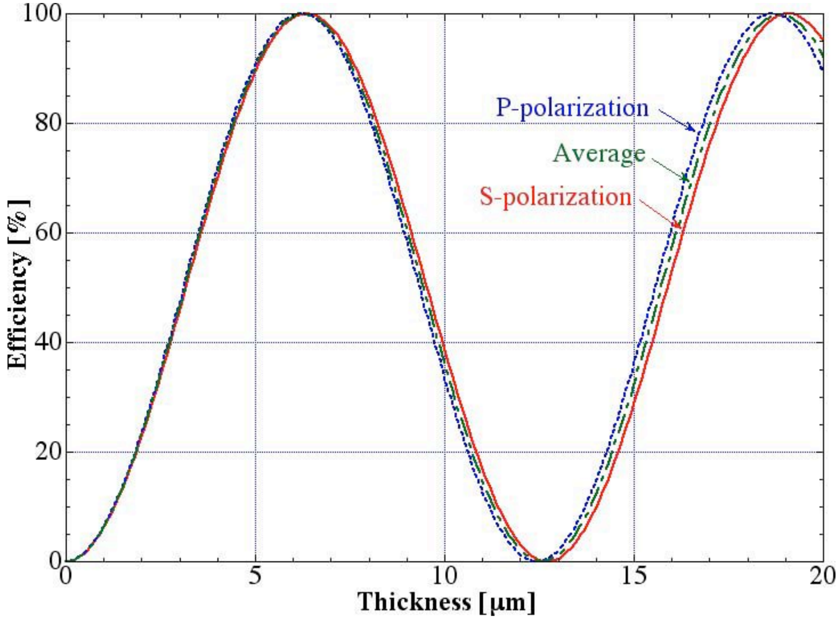




$$\frac{n_{S\max} - n_{S\min}}{(n_{S\max} + n_{S\min})\sin 2\theta_S} = \frac{(n_{P\max} - n_{P\min})\cos 2\theta_P}{(n_{P\max} + n_{P\min})\sin 2\theta_P}$$

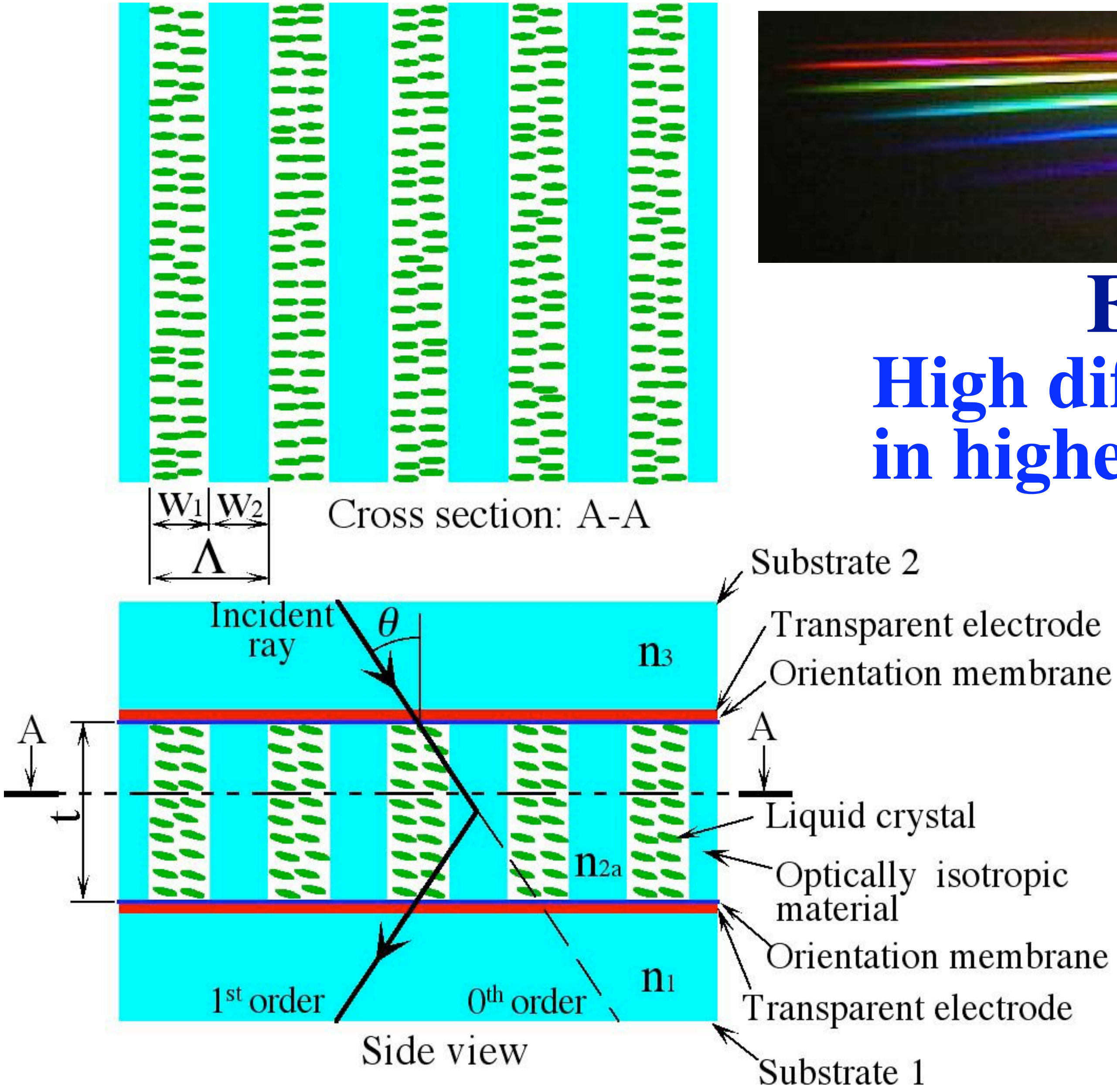
$$\frac{n_{S\max} - n_{S\min}}{(n_{S\max} + n_{S\min})\cdot 2\sin\theta_S\cos\theta_S} = \frac{(n_{P\max} - n_{P\min})\cos 2\theta_P}{(n_{P\max} + n_{P\min})\cdot 2\sin\theta_P\cos\theta_P}$$

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



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

Birefringence binary Bragg (3B) grating



Cross section: A-A

Side view

Echellegram

High diffraction efficiency in higher diffraction order.

Active optical element:

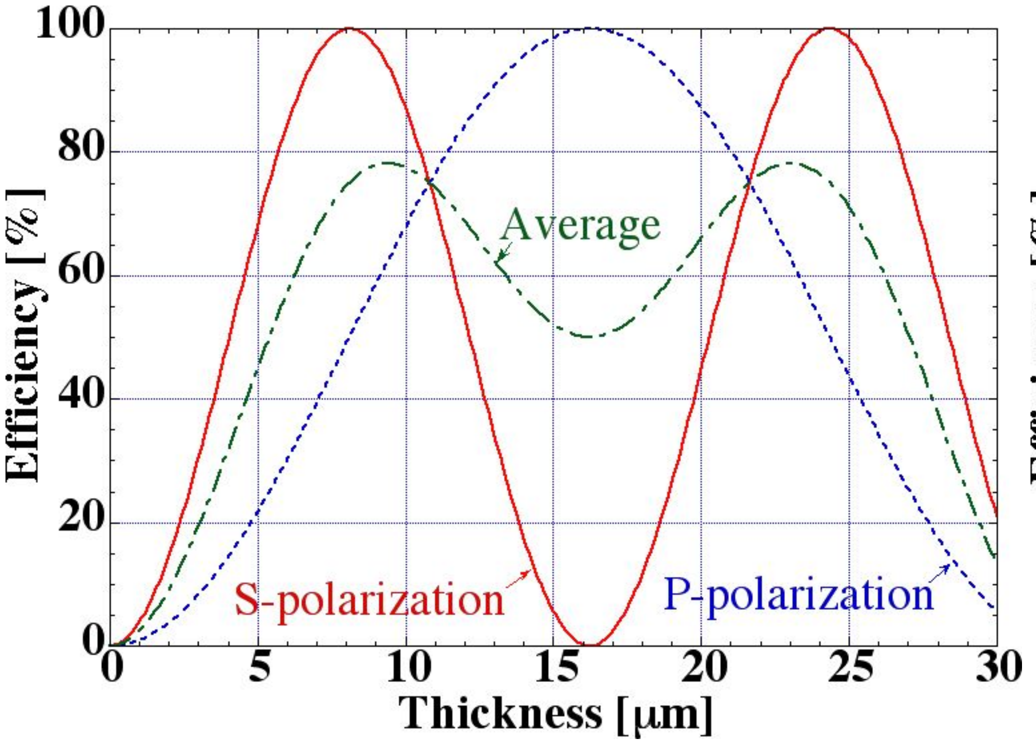
Window → Grating,

Grating → Polarizer,

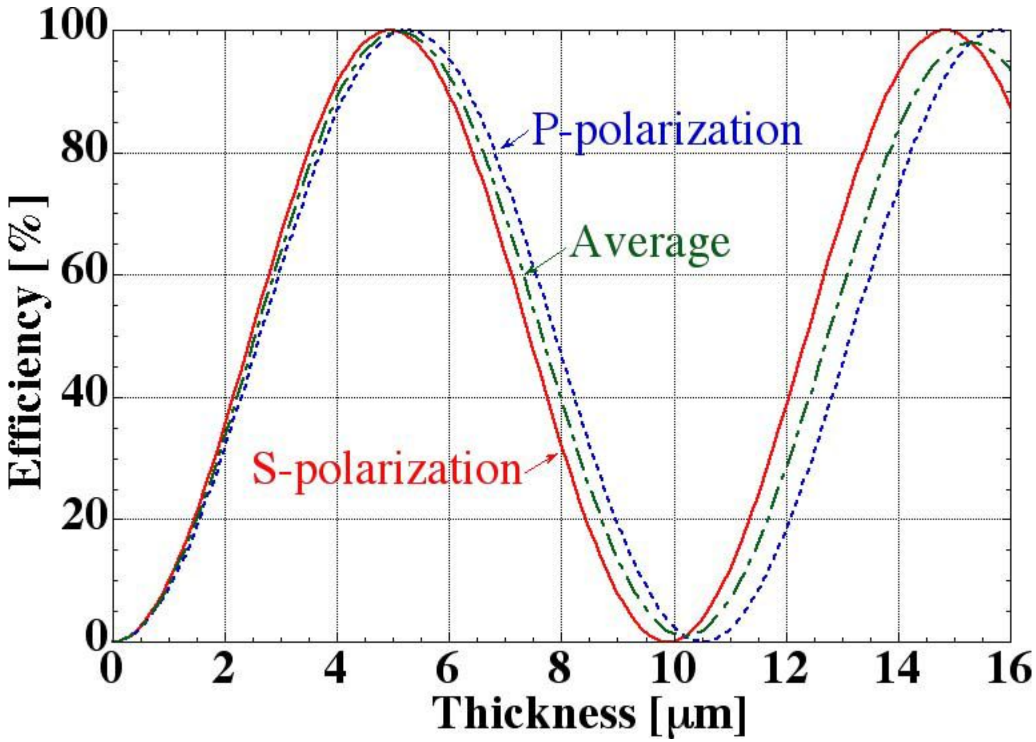
Day lighting, Head-up display, 3D display,

Optical communications & computing, …

Polarized Diffraction Efficiency of VPH and 3B Grating



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

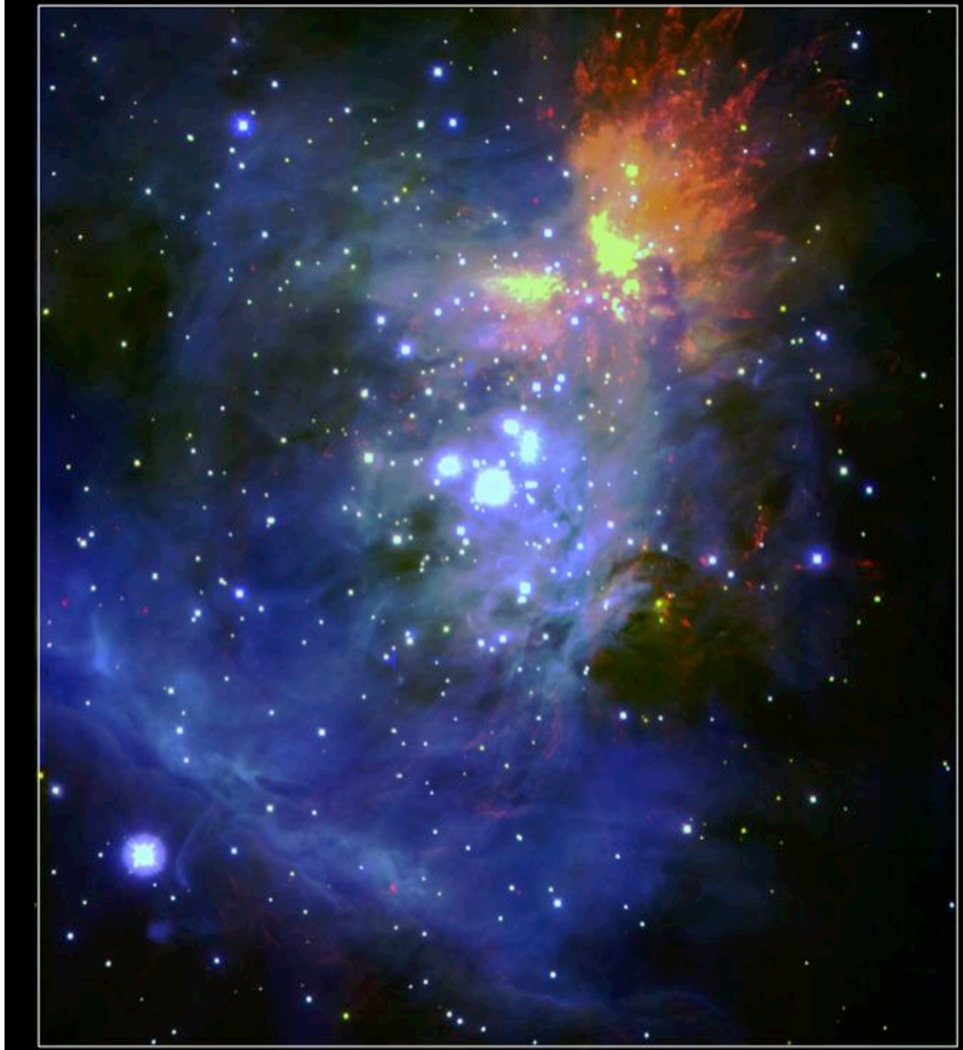


3B grating calculated by RCWA.
$n_L = 1.46$, $n_s = 1.544$, $n_p = 1.60$, $\theta_B = 45°$.

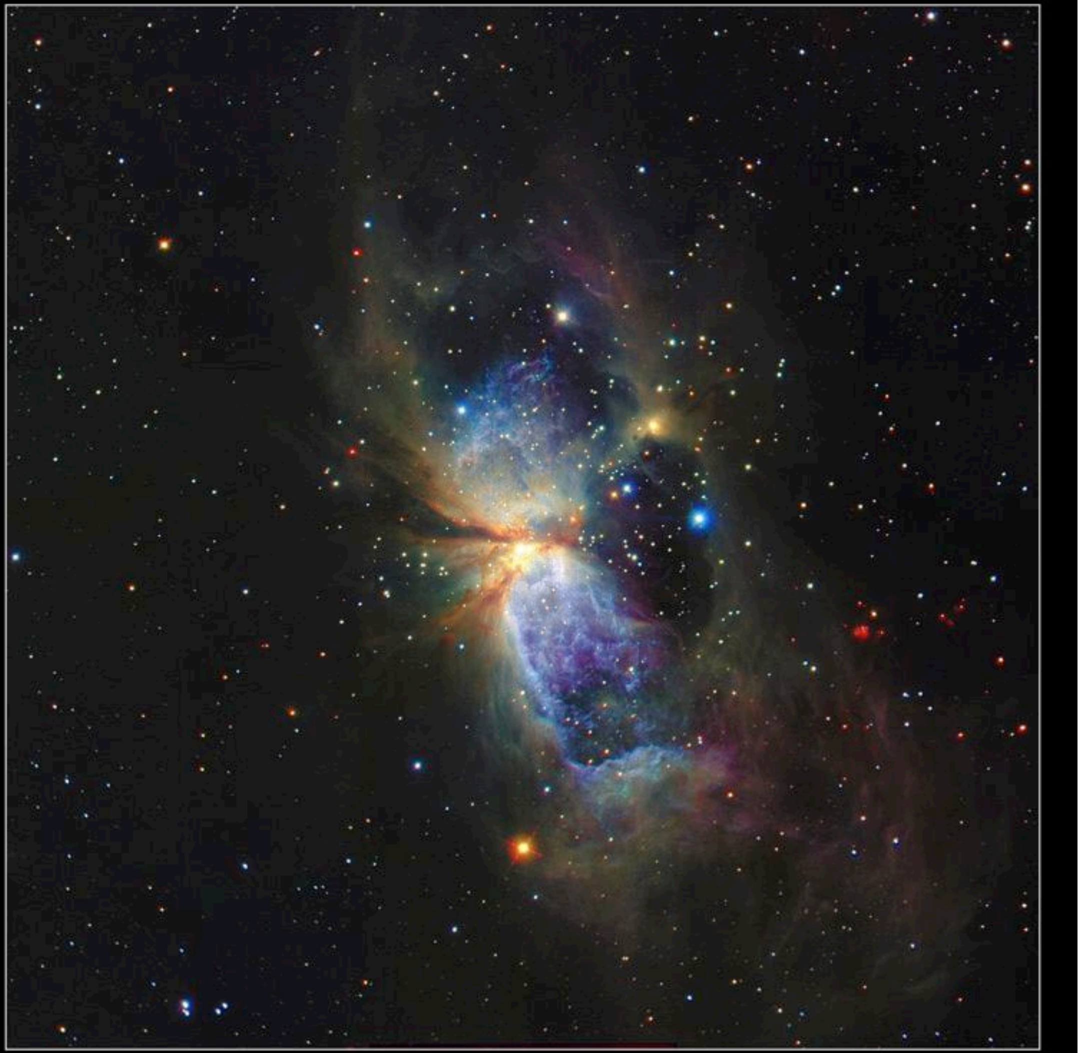
***w*:*t* = 1:20~100 → 1:4~20**

(Ebizuka et. al. SPIE 8450, 2012)

Immersion Grating



Orion Nebula CISCO (J, K′ & H_2 (v=1-0 S(1))
Subaru Telescope, National Astronomical Observatory of Japan January 28, 1999

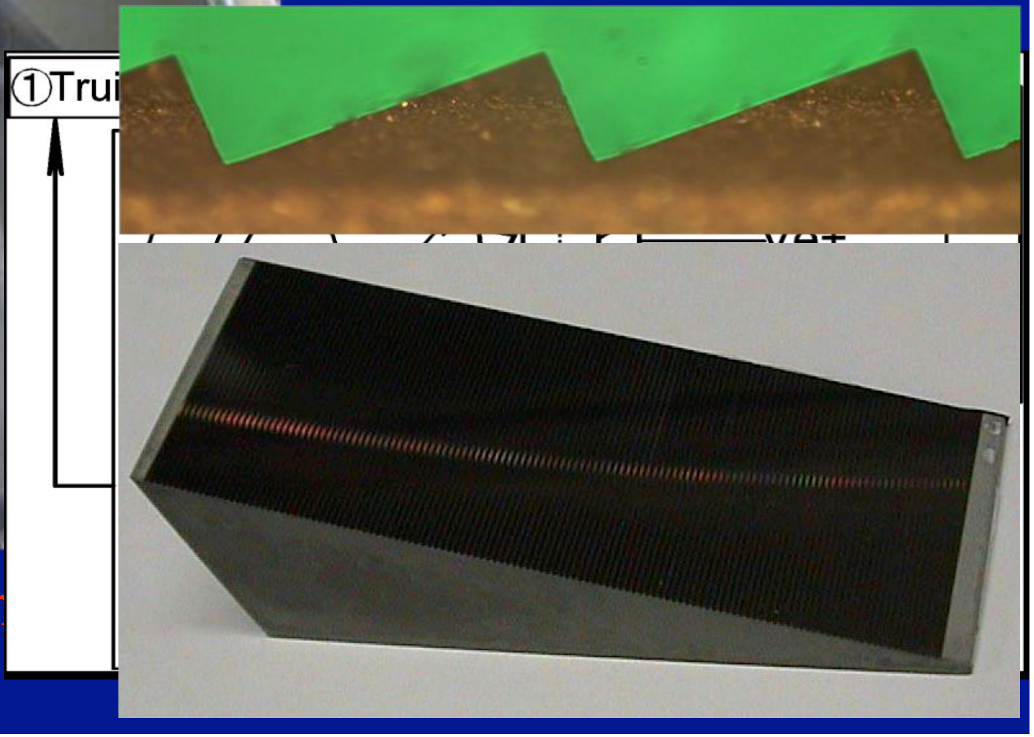


Star-forming Region S106 IRS4 CISCO (J, H, K')
Subaru Telescope, National Astronomical Observatory of Japan February 13, 2001

Ge immersion grating for GIGMICS

Nano-precision machine and ELID grinding method.

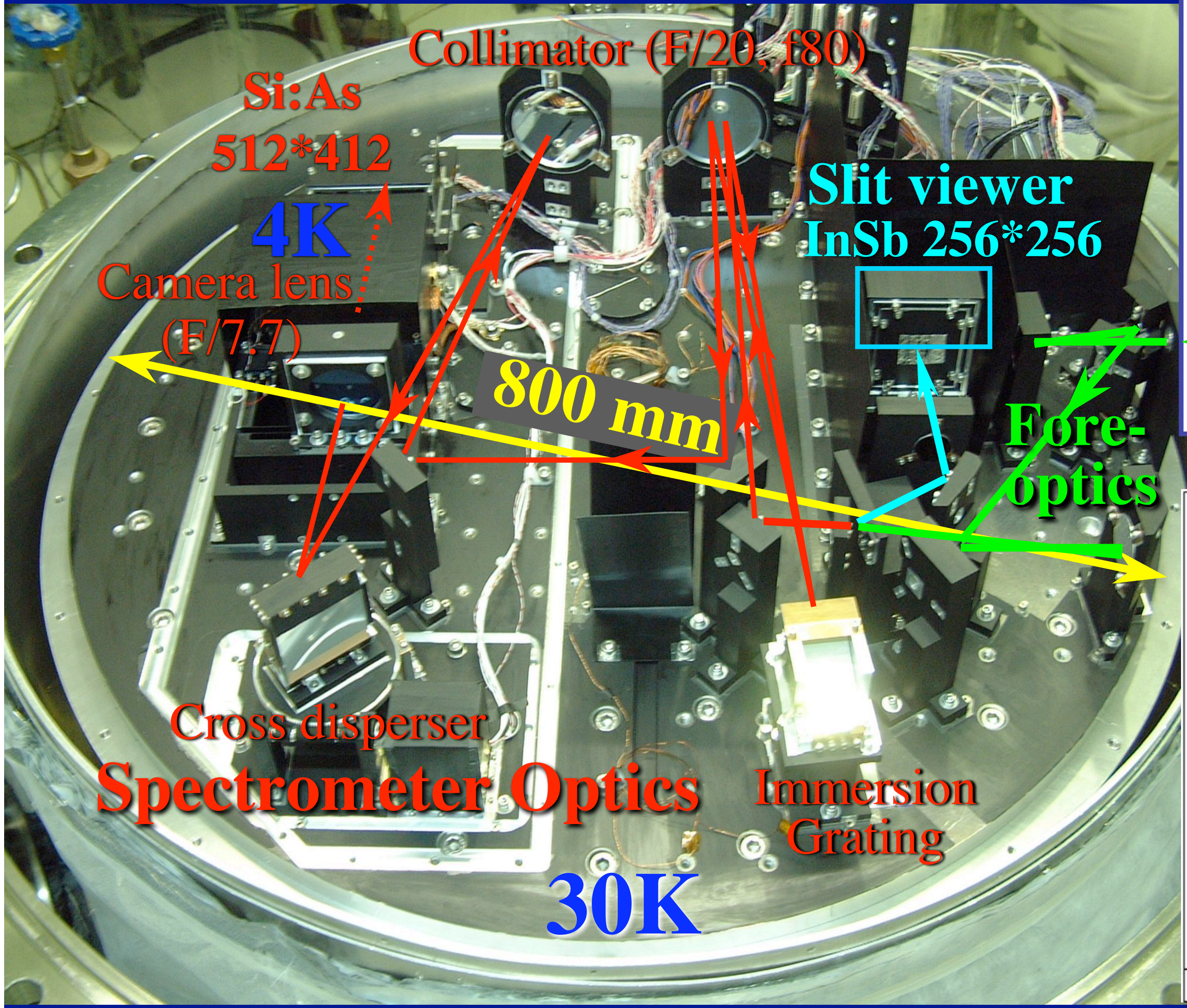
30 × 30 × 72 [mm], $\alpha = 68.75^\circ$, $\Lambda = 600\mu m$

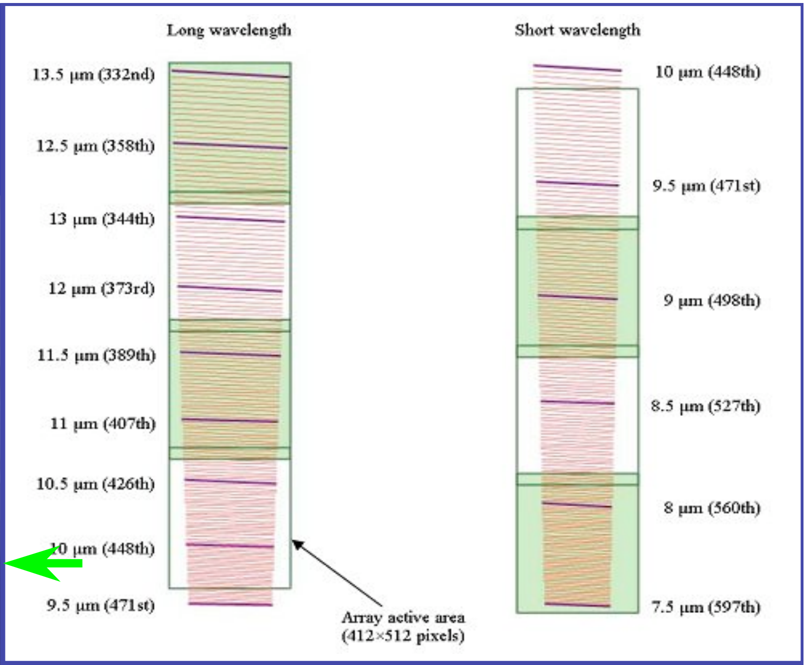


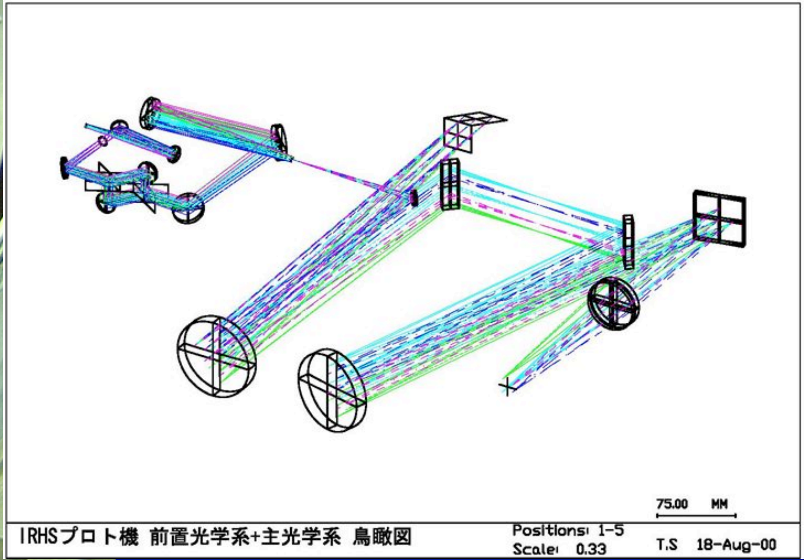
Spent about 400 hours for fabricatio

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

GIGMICS



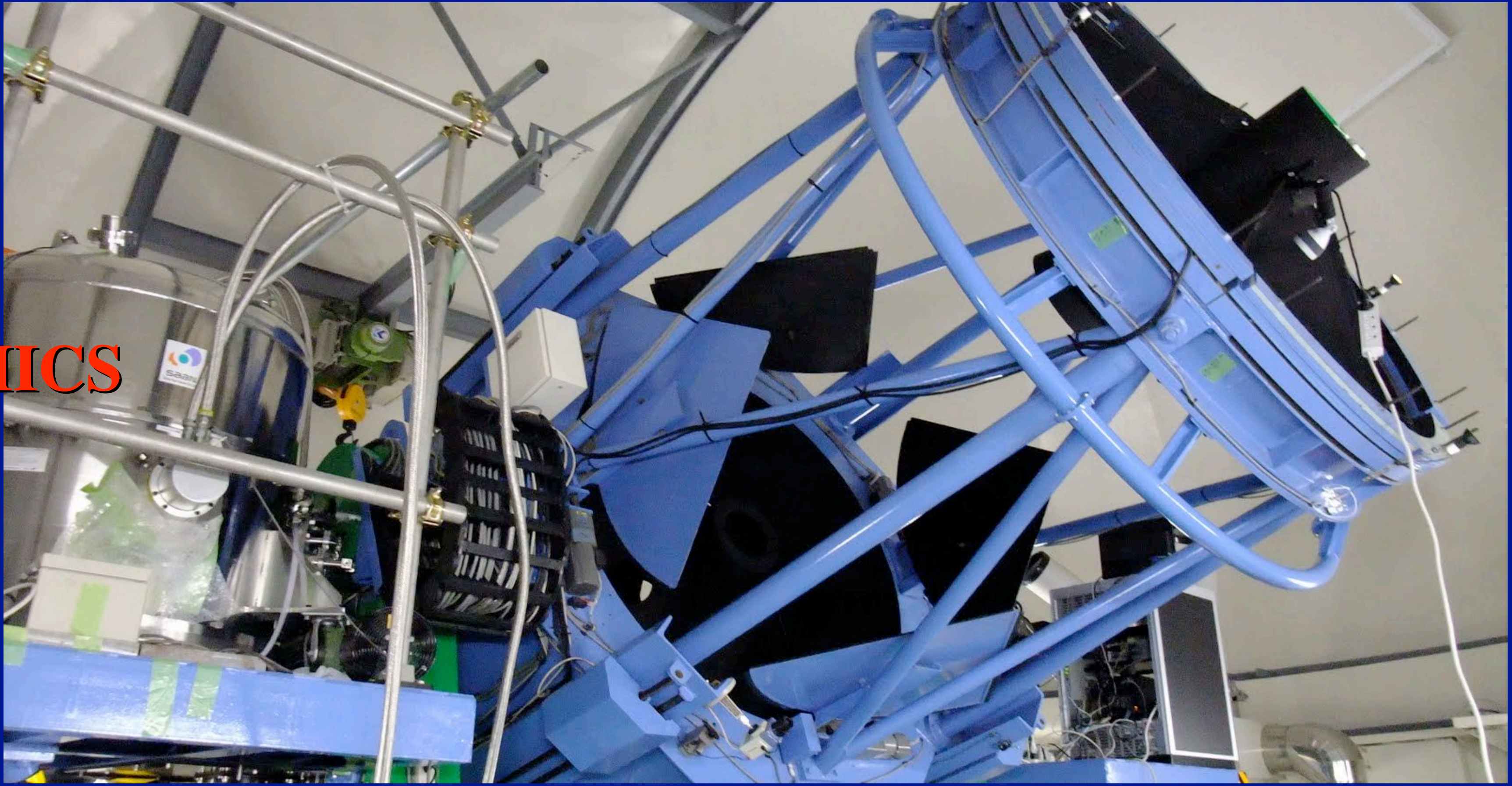




R~ 50,000@10µm, developed by Hirahara lab., Nagoya Univ.

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

First Light Observation of GIGMICS

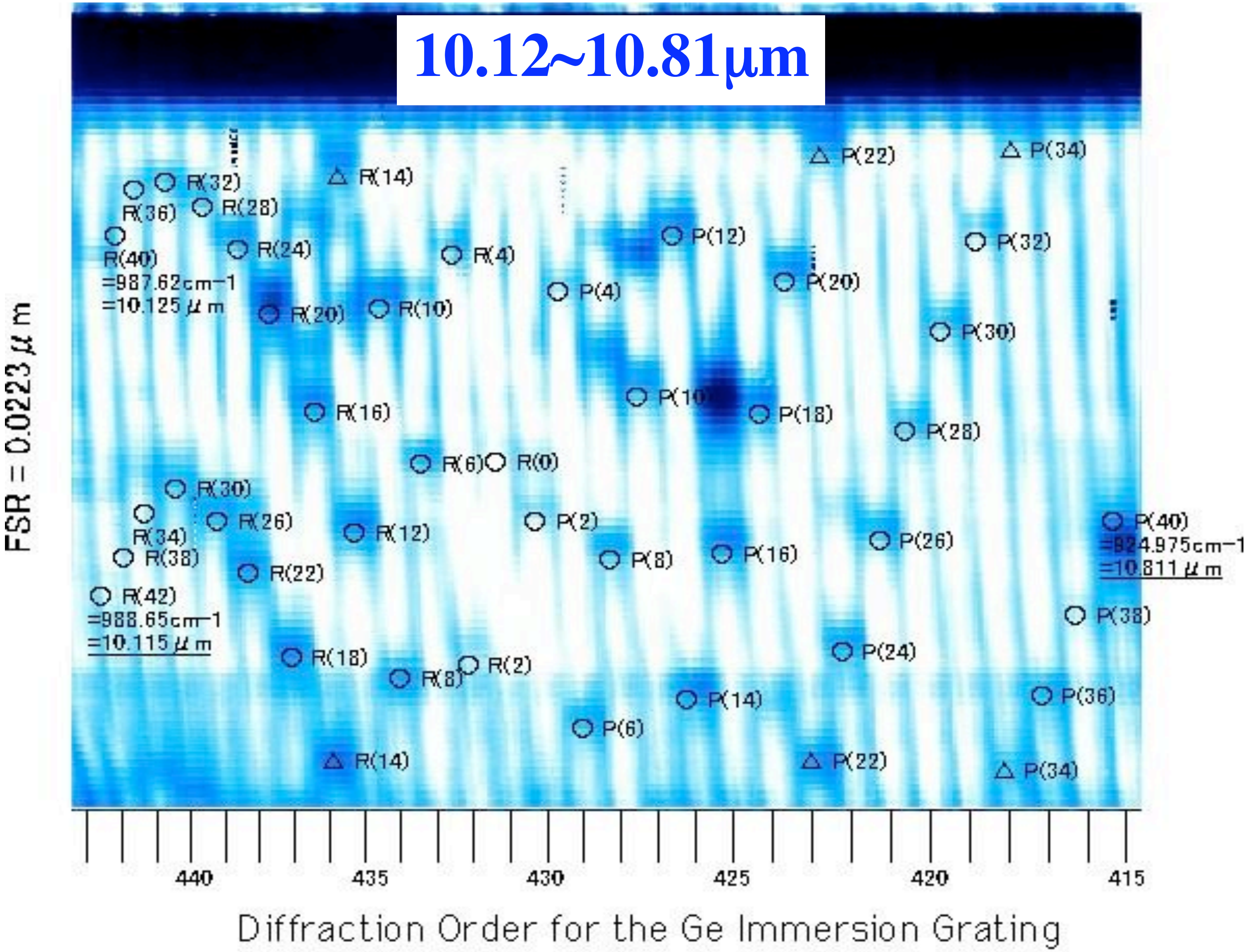


KANATA 1.5m telescope, Higashi-Hiroshima Observatory, Space Science Center Hiroshima Univ., Dec. 2010~Apr. 2011.

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.

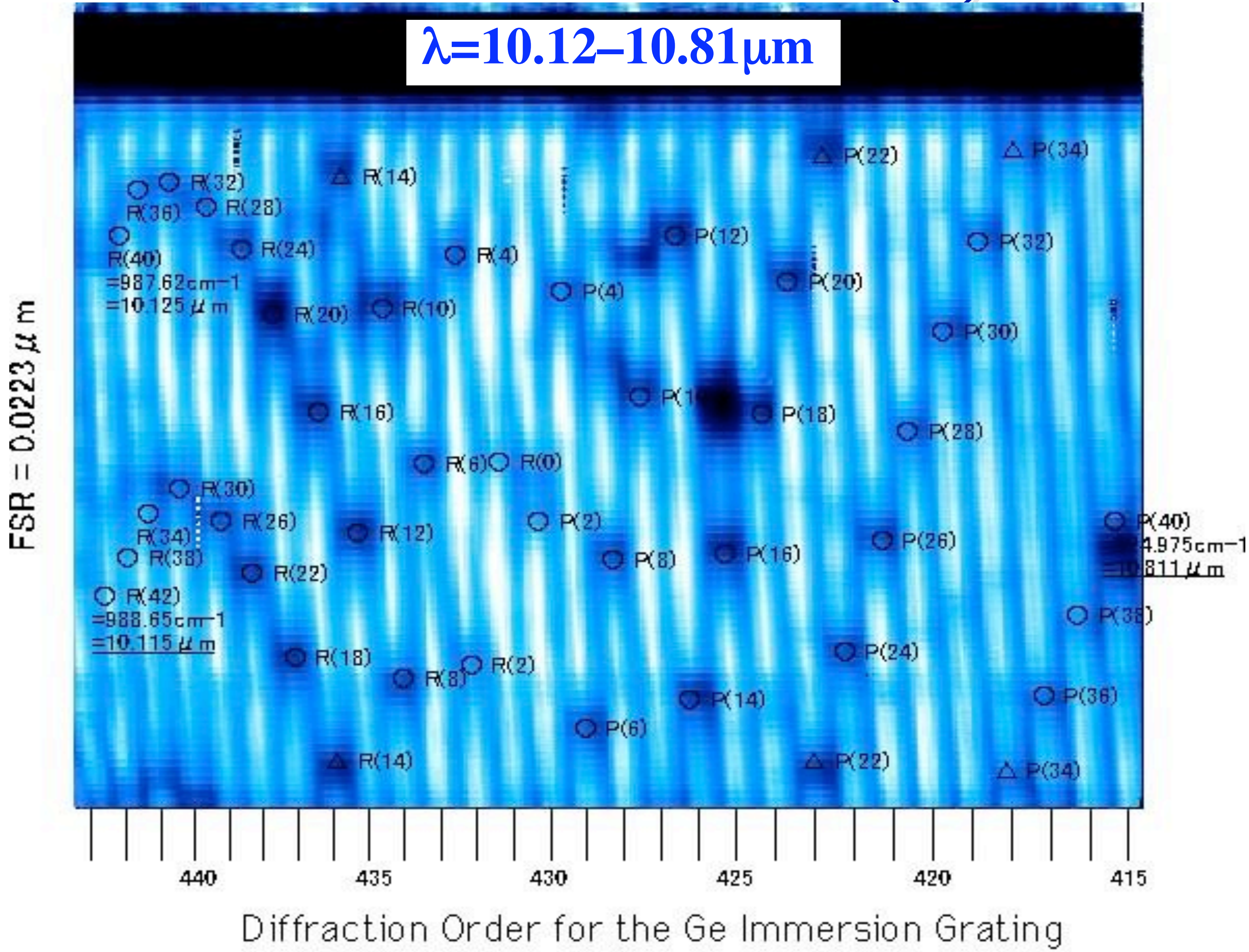
(Hirahara et. al., SPIE, **8446**, 2012)

Reference: Earth’s atmosphere



10.12~10.81μm

First rcientific result (1): Venus

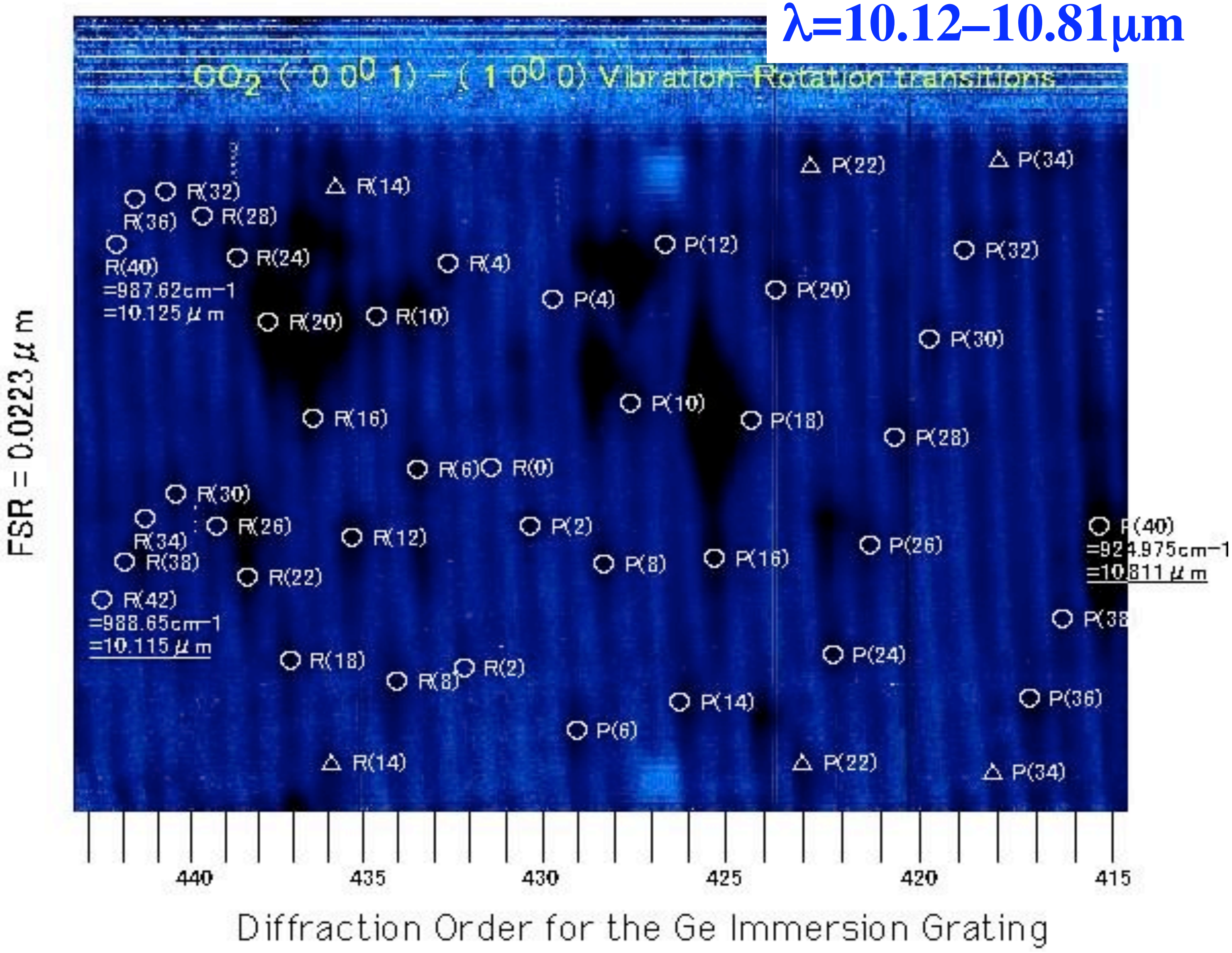


Absorption lines cannot be identified to the "telluric lines".

→ CO_2 hot-band & isotopes from Venus.

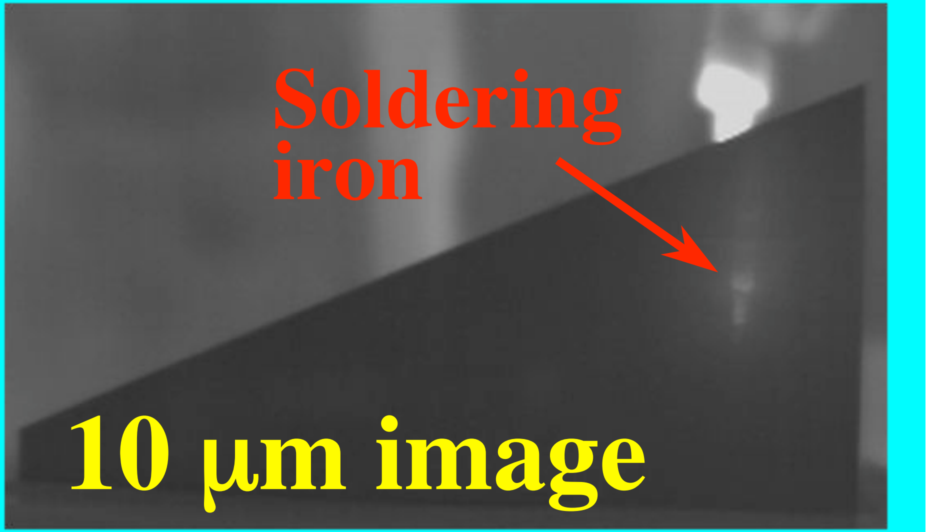
First scientific results (2): NGC7027

λ=10.12–10.81μm

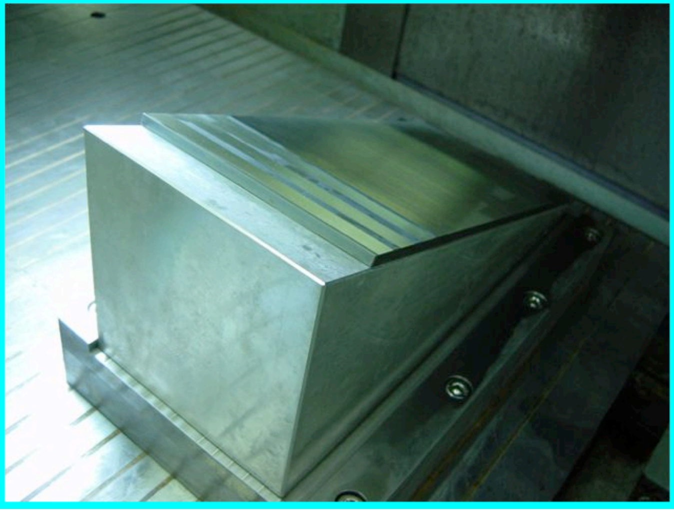


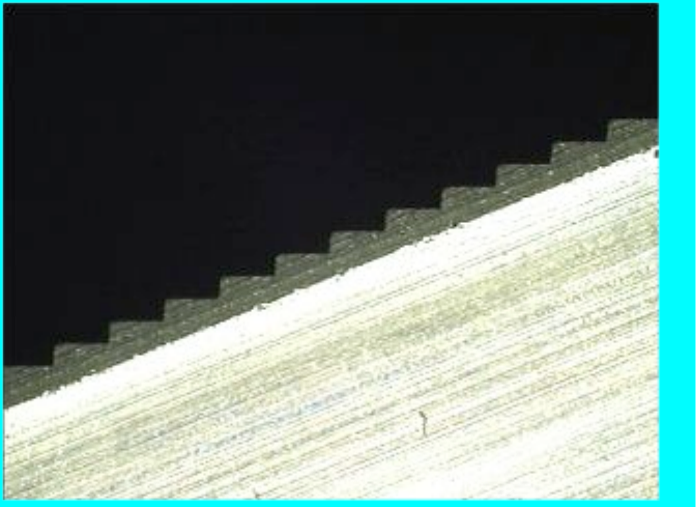
Detection of [S IV] ionic fine-structure emission line toward the planetary nebula.

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

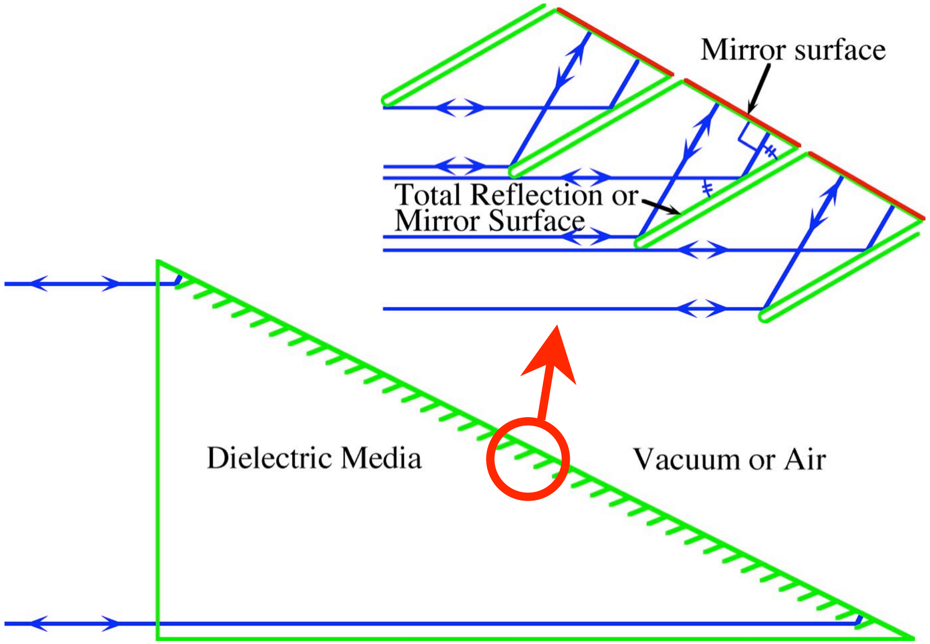


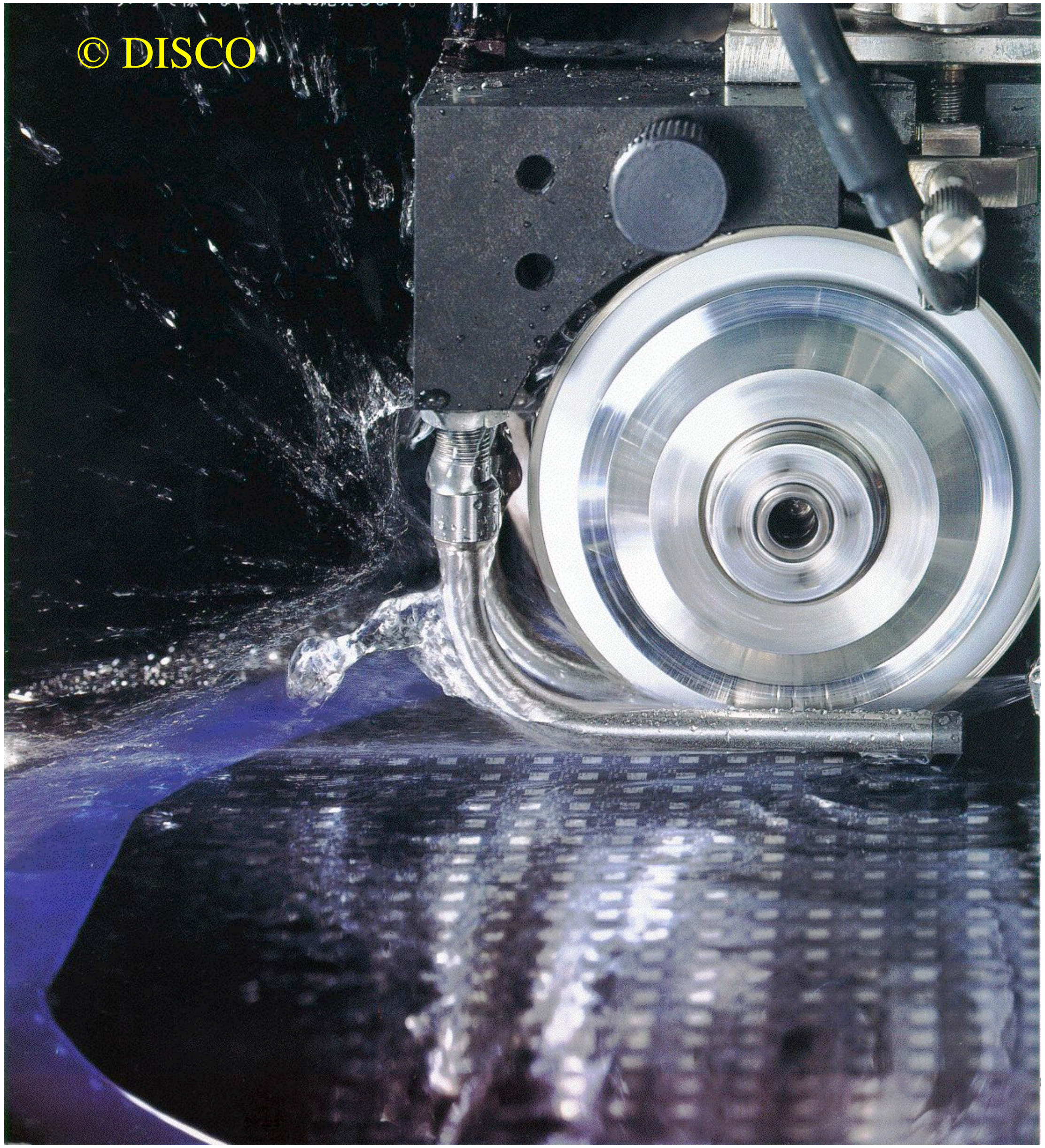
R〜200,000@10μm → Size: 120 x 120 x 270 mm
→ Fabrication time: several 1,000 hours





Novel immersion grating

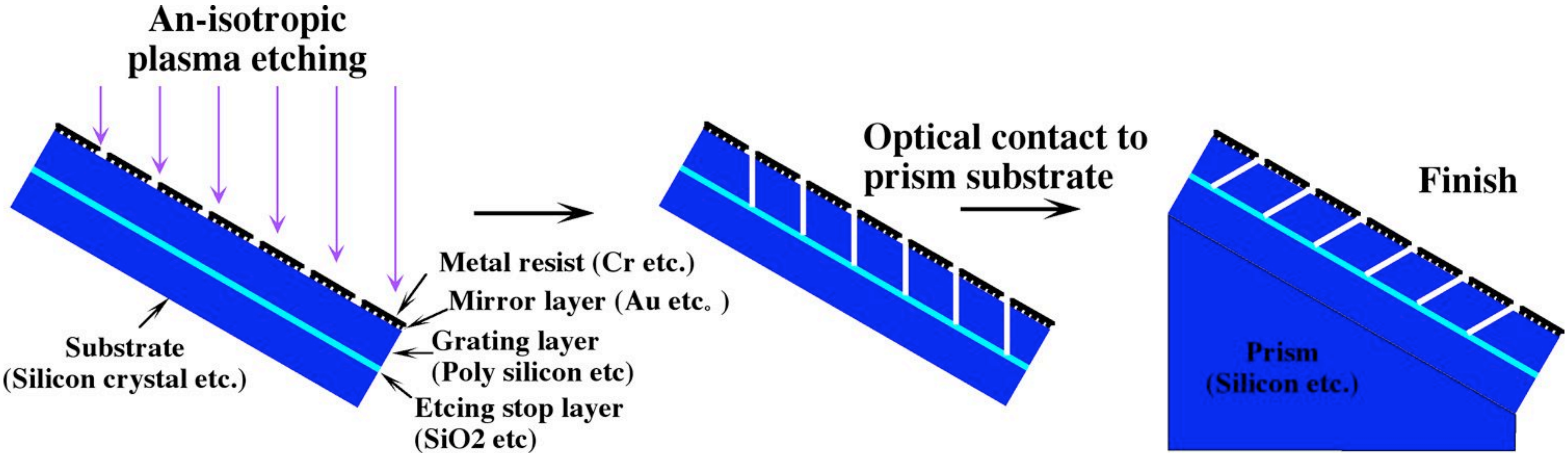




- Machining of dicing saw makes smooth surface
- Easy tooling.
- Fabrication time for grating with 120 x 120 x 270 mm → Several 100 hours?

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

Fabrication method of novel immersion grating for visible and near IR



An-isotropic
plasma etching

Metal resist (Cr etc.)

Mirror layer (Au etc.)

Grating layer
(Poly silicon etc)

Etcing stop layer
(SiO2 etc)

Substrate
(Silicon crystal etc.)

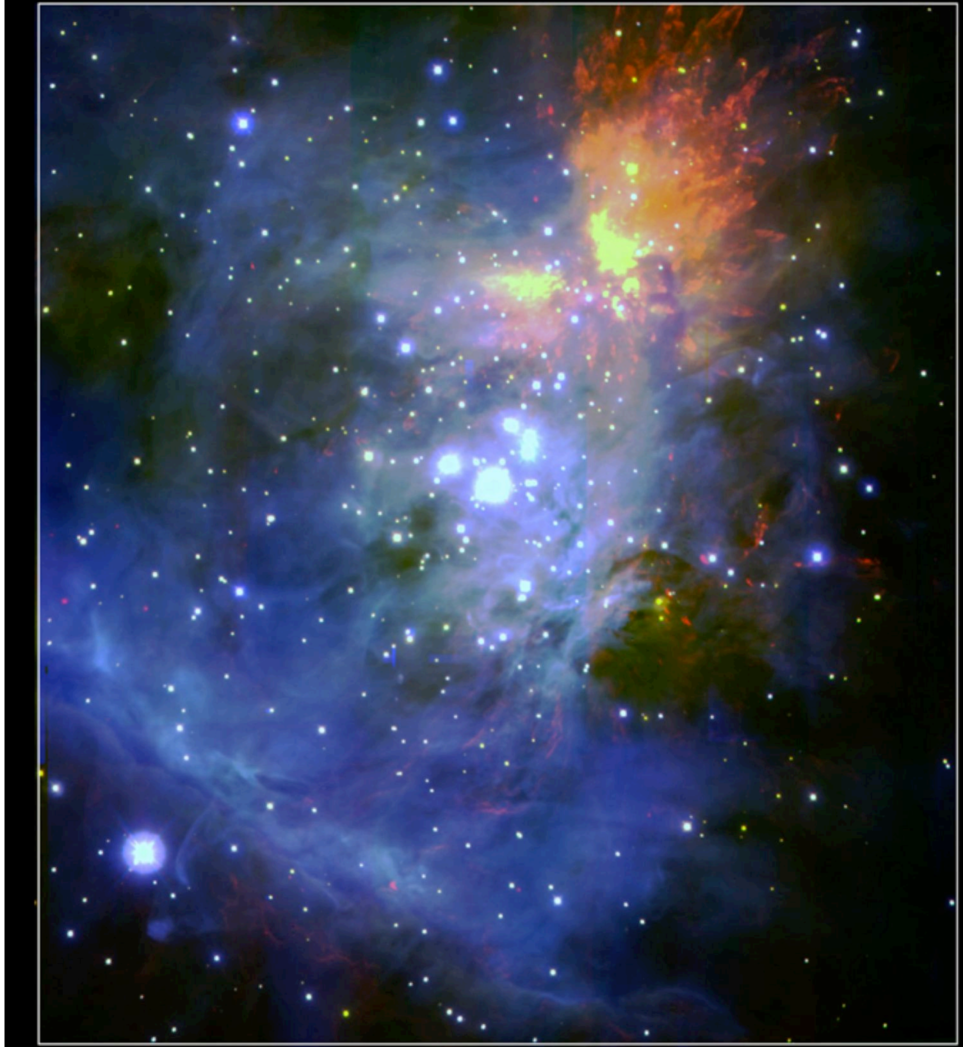
Optical contact to
prism substrate

Finish

Prism
(Silicon etc.)

(Ebizuka et. al. SPIE 8450, 2012)

Birefringence prism



Orion Nebula CISCO (J, K′ & H_2 (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

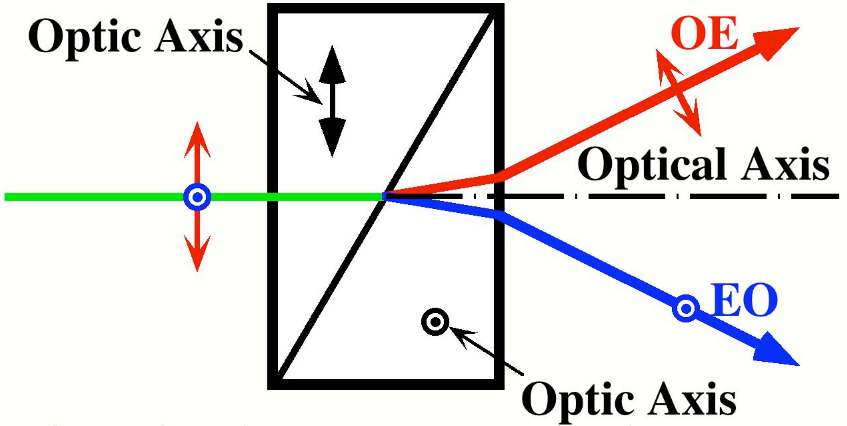
Polarization Spectroscopy

- Angular dispersion is small against a separation angle.

→Combined with another disperser.

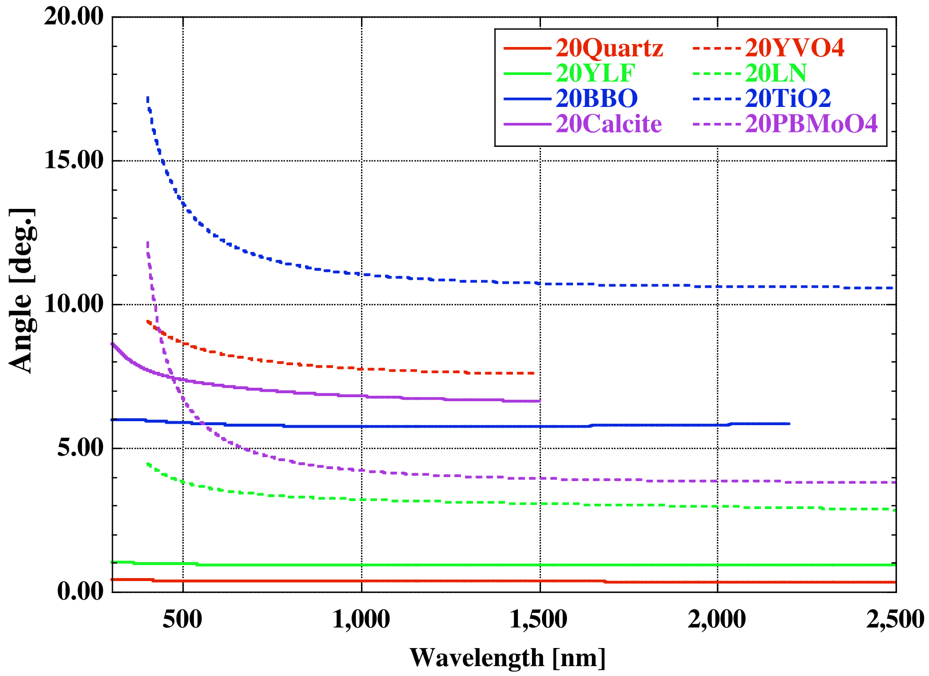
Polarization Imaging

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



OE: Ordinary→Extraordinary

EO: Extraordinary→Ordinary

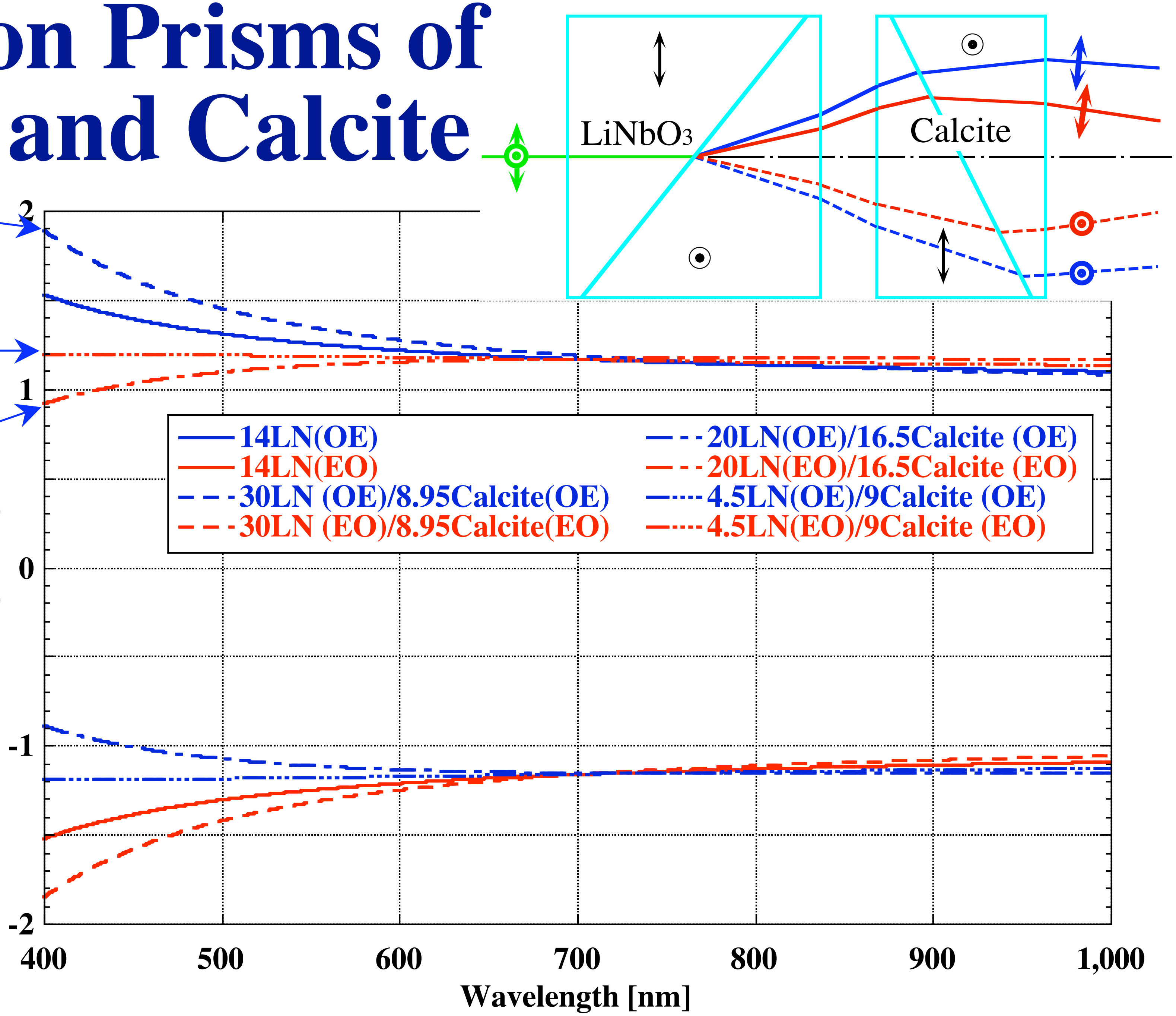


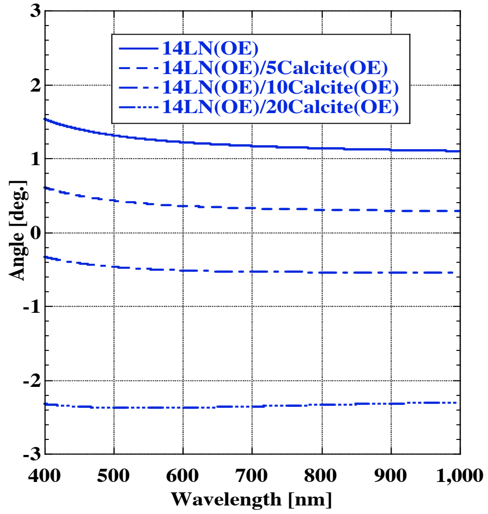
Wollaston Prisms of LiNbO3 and Calcite

Spectroscopy

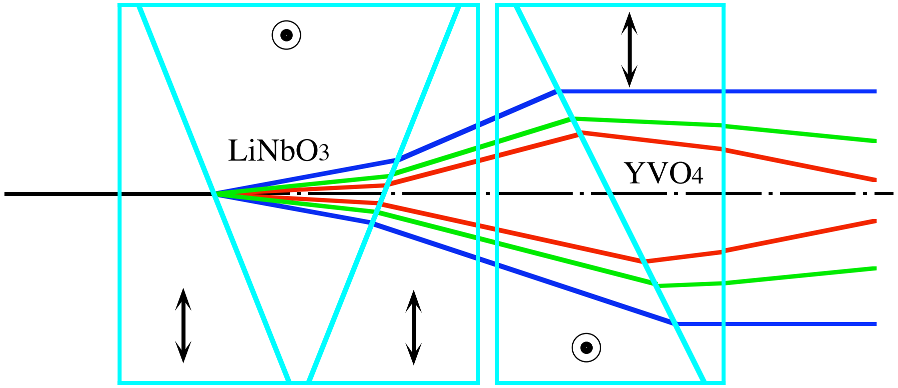
Imaging

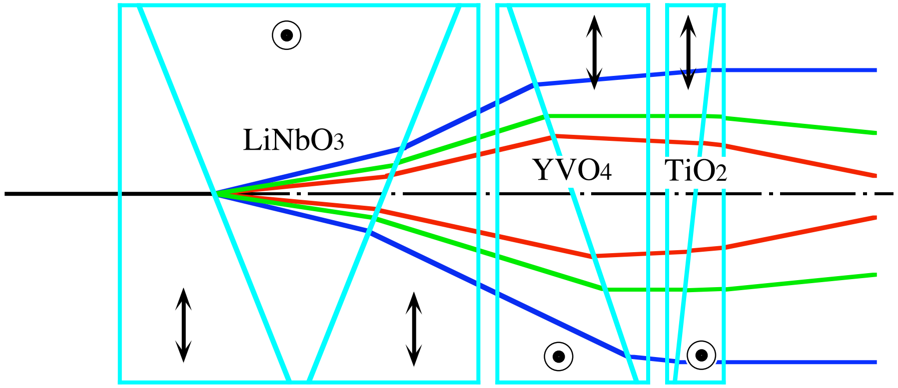
Interferometer of FTS (Linear at 400~1,000nm)

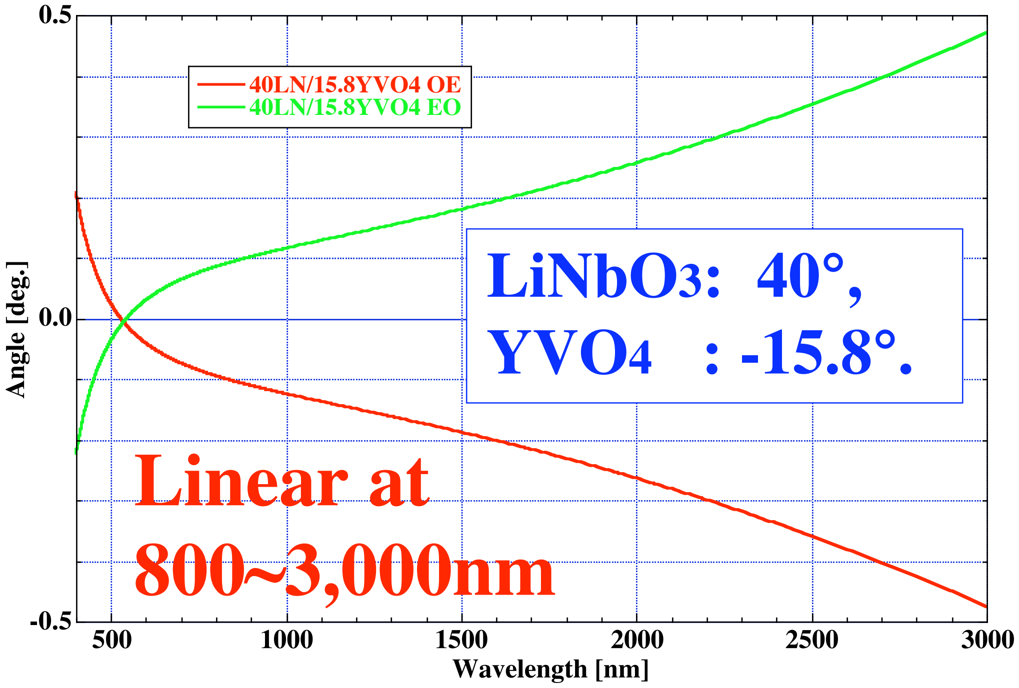




Wollaston Prisms of $LiNbO_3$, YVO_4 and TiO_2

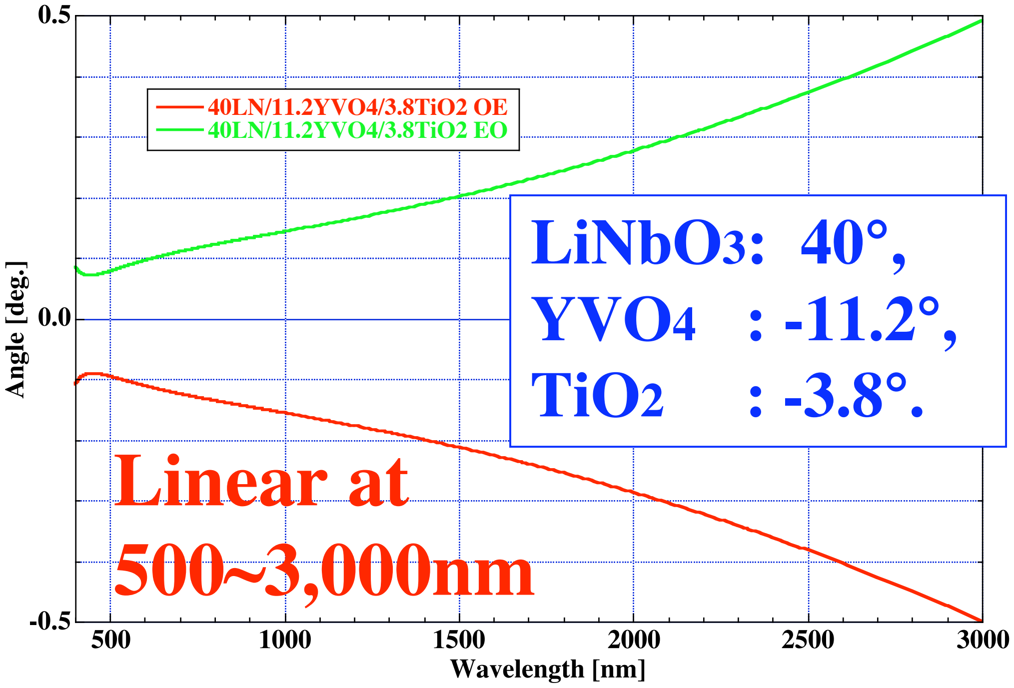






$LiNbO_3$: 40°,
YVO_4 : -15.8°.

Linear at 800~3,000nm



$LiNbO_3$: 40°,
YVO_4 : -11.2°,
TiO_2 : -3.8°.

Linear at 500~3,000nm

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.
- New Wollaston prism is able to observe wide wavelength with linear dispersion.

Thank you for your kind attention!

本研究はJST A-STEP探索タイプの補助によって推進されている。
研究題目：究極的な回折格子の開発

本研究の回折格子の開発は国立天文台先端技術センターの設備を利用させていただいている。