次世代観測装置用の新しい回折格子の開発状況

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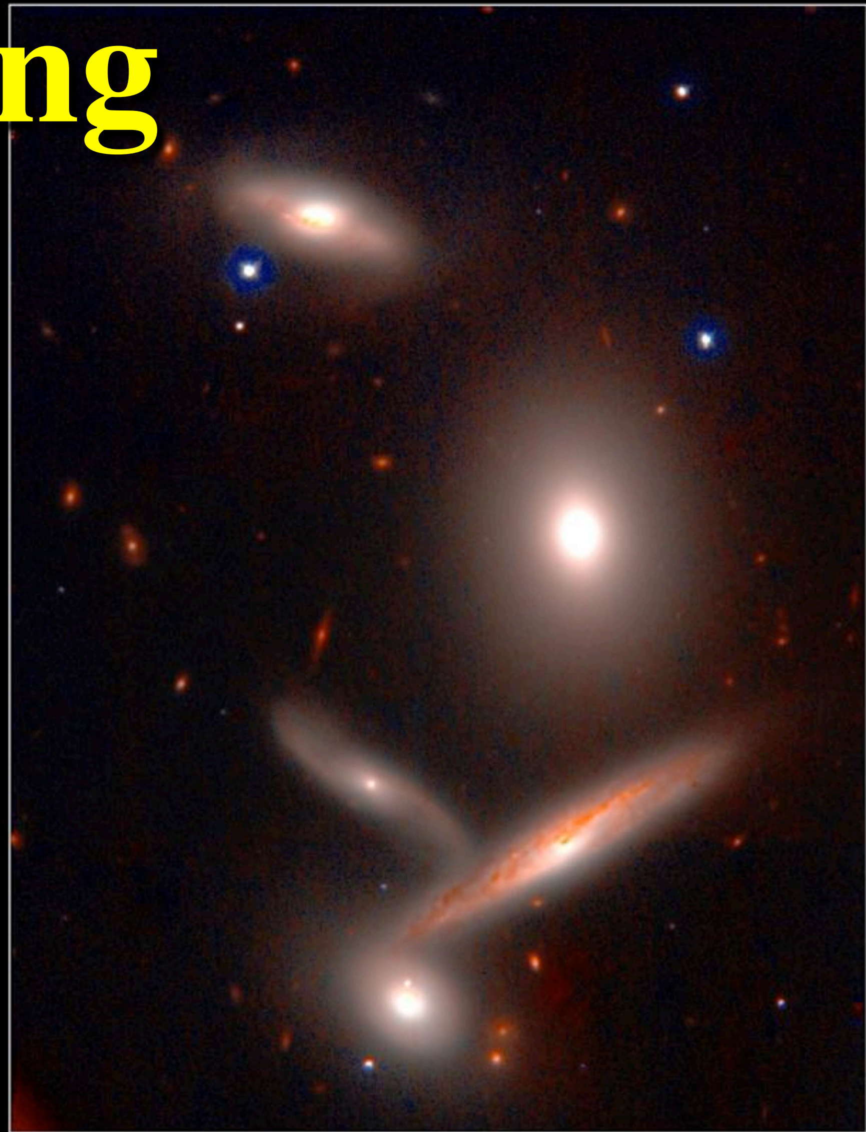
第3回 可視赤外線観測装置技術ワークショップ　2013年12月17-18日

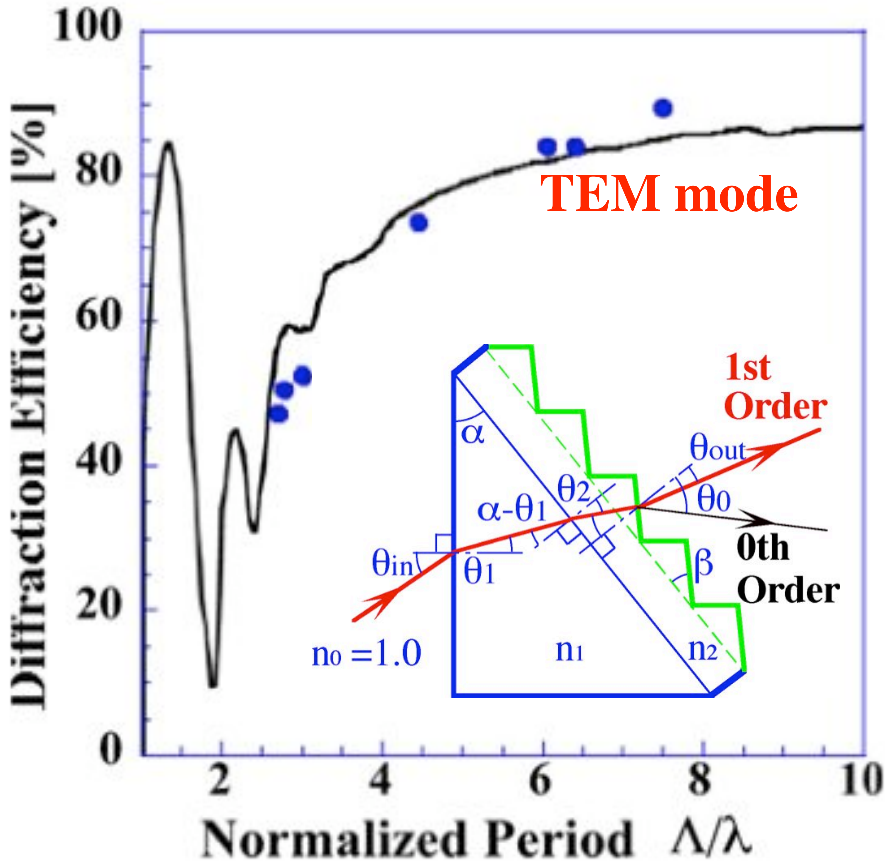
Volume Phase Holographic Grating

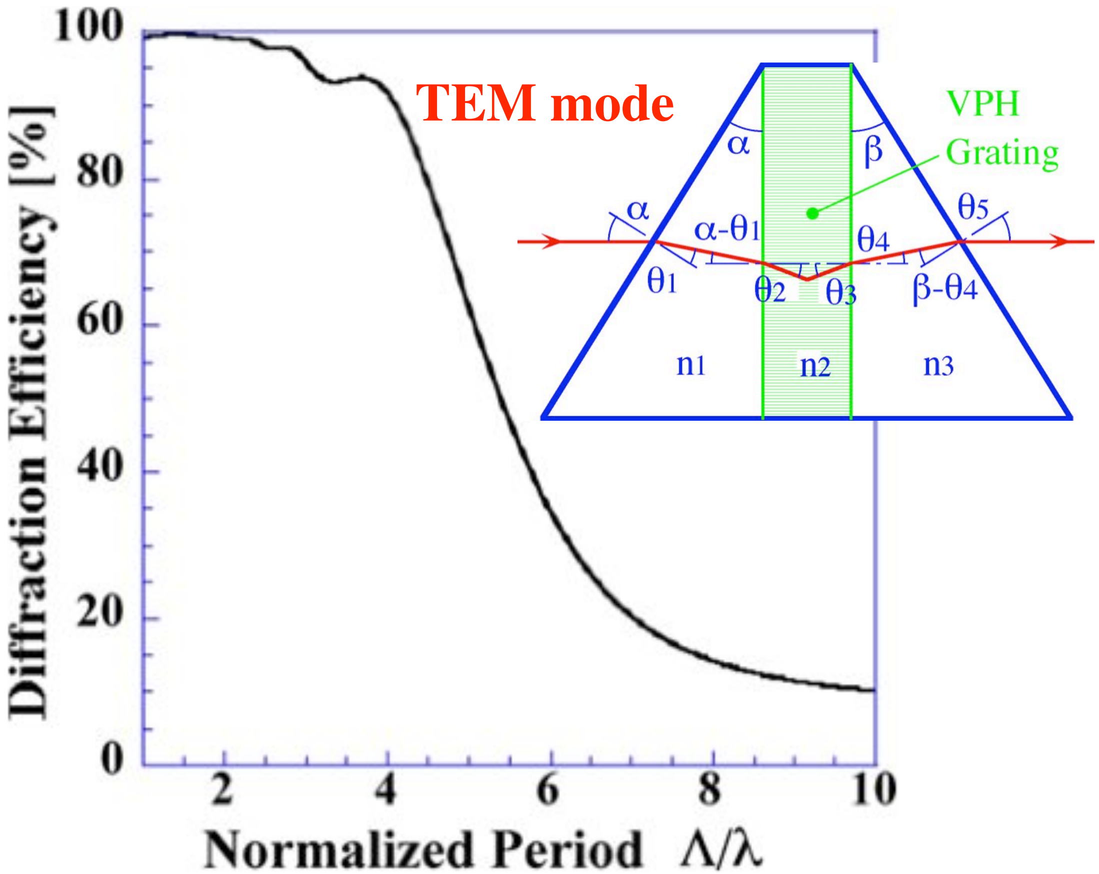
M 82 (NGC 3034) FOCAS (B, V, Hα)
Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000



Hickson Compact Group 40 CISCO (J & K′)
Subaru Telescope, National Astronomical Observatory of Japan January 28, 1999

Efficiencies of Transmission Gratings

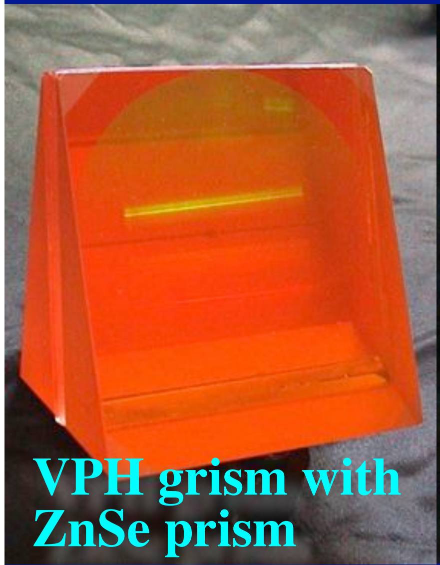


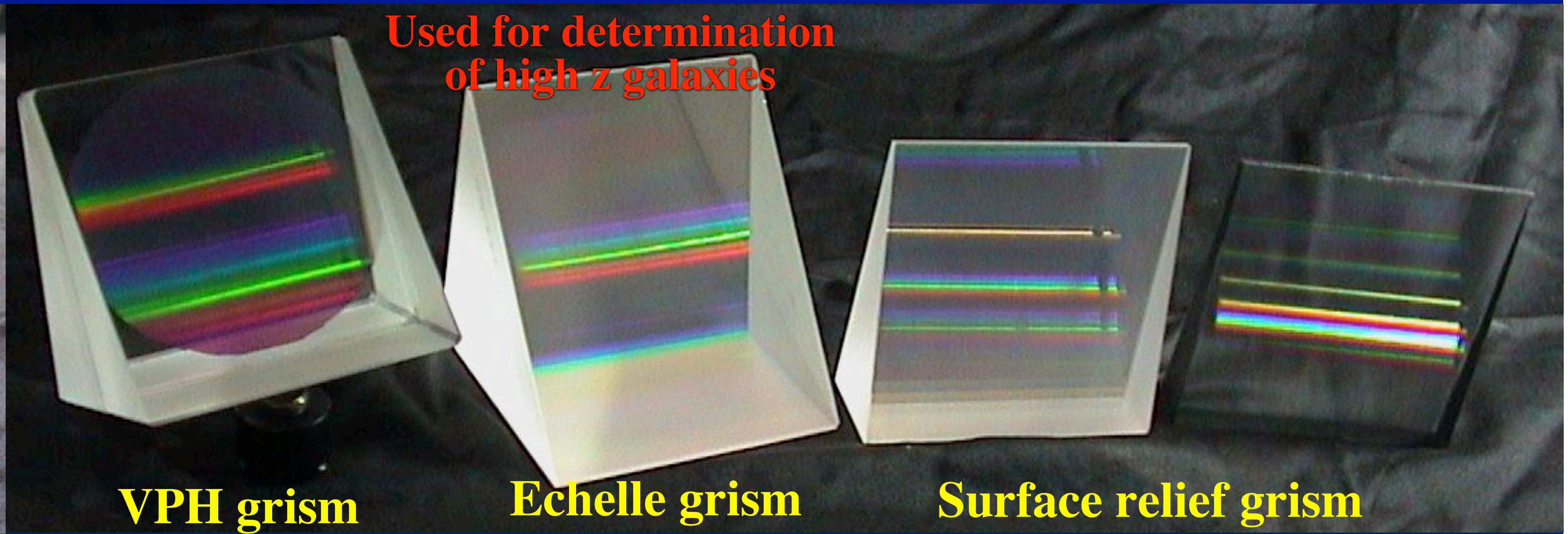


Surface relief grating: Efficiency decreases steeply below 4 *Λ/λ*.

VPH (Volume Phase Holographic) grating (*Δn* ~ 0.02): Efficiency increases up to 100% below 4 *Λ/λ*.

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





FOCAS Grisms

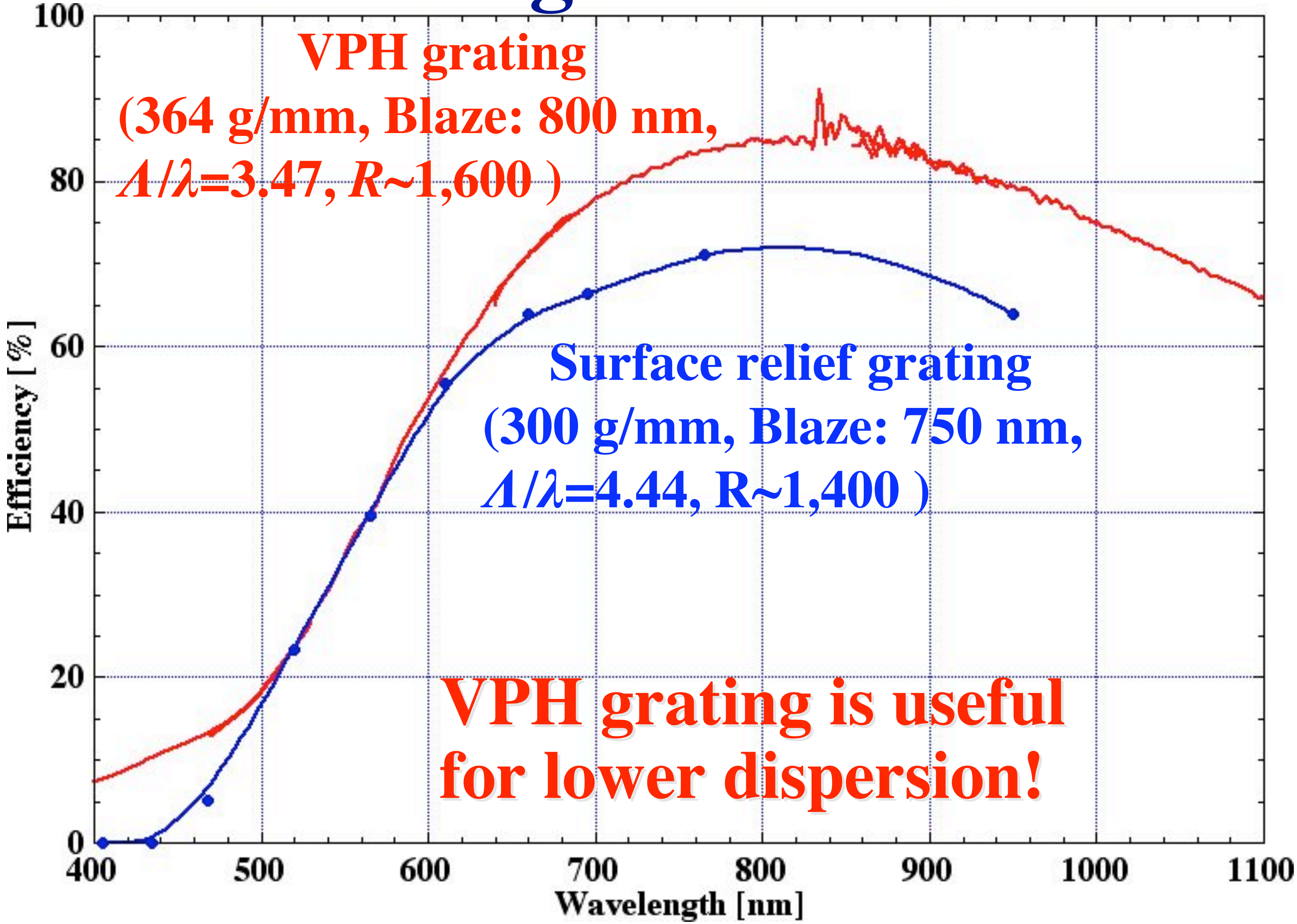
(Ebizuka et. al. PASJ, **63**, 2011a)

Size: 110 × 106 × 106 (max).

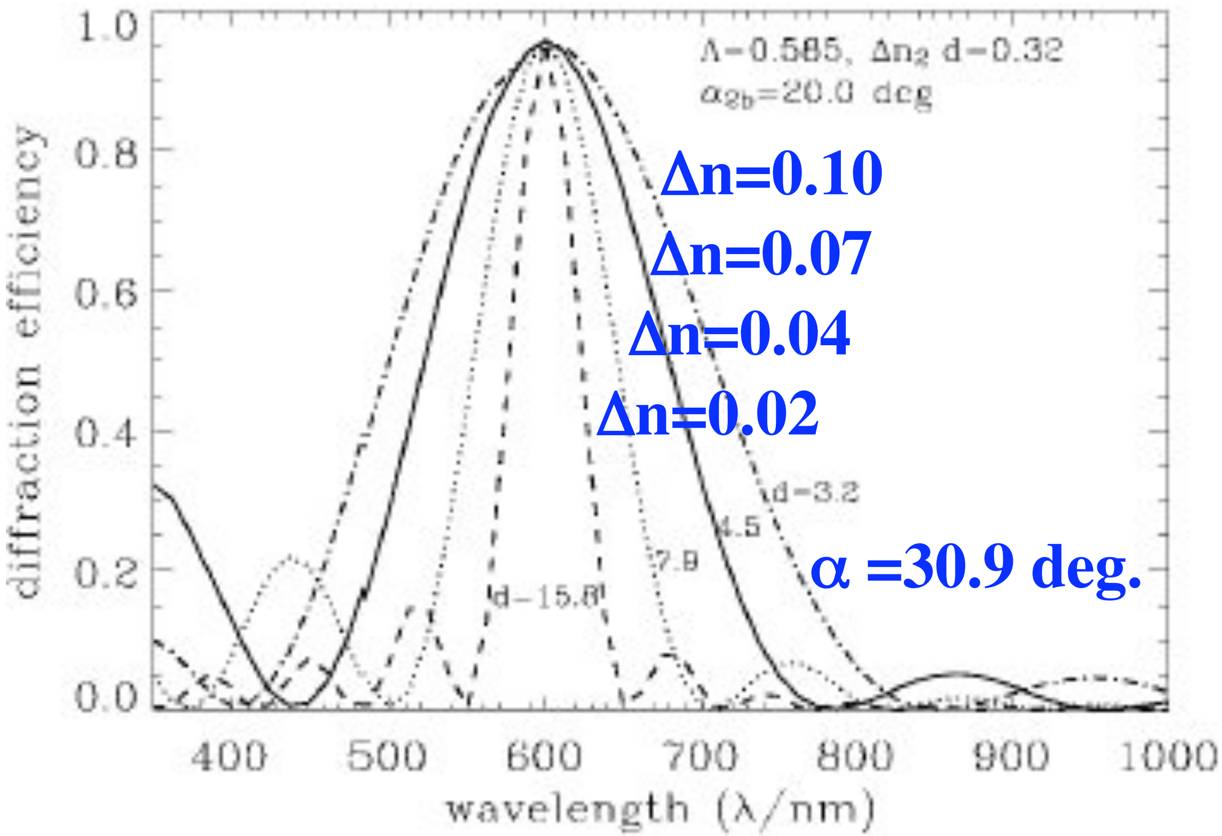
4 SR grisms: 300 < *R* < 1,400.
1 Echelle grism: *R*~2,500.

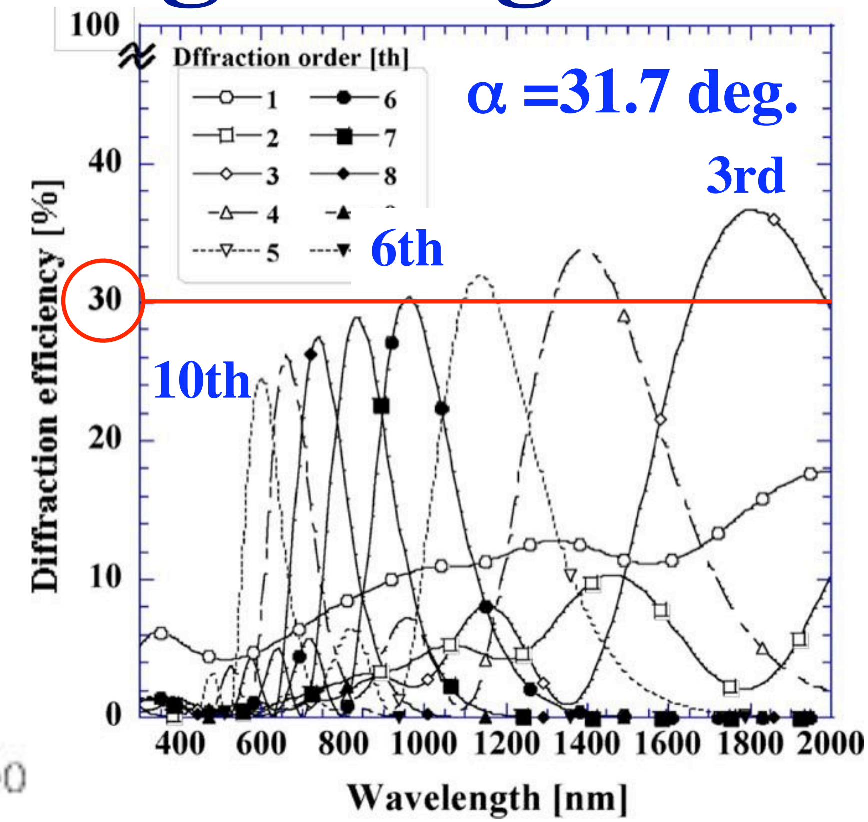
8 VPH grisms (3 grisms with ZnSe prisms): 1,600 < *R* < 7,000, Collaboration of JWU (Japan Wemen's Univ.) and NAOJ.

New VPH grisms for FOCAS



Limitation 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 *Δn* < 0.15.

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

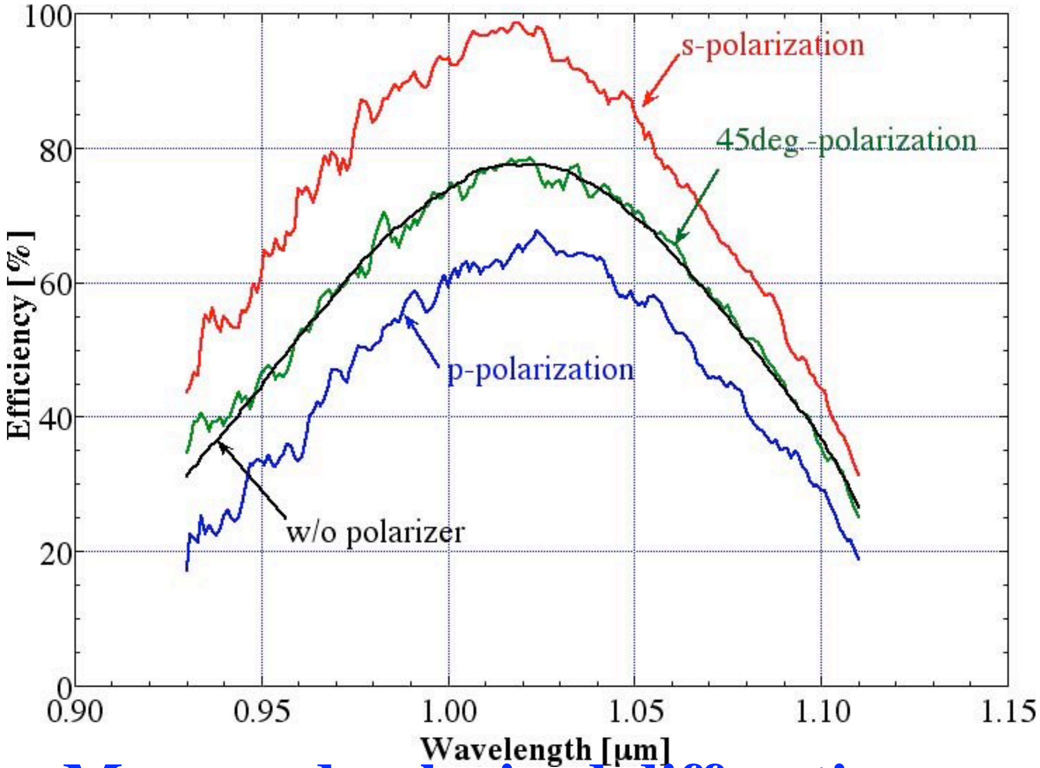
Diffraction efficiency of VPH grating decrease toward higher orders.

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

Polarized Diffraction Efficiency of VPH Grating

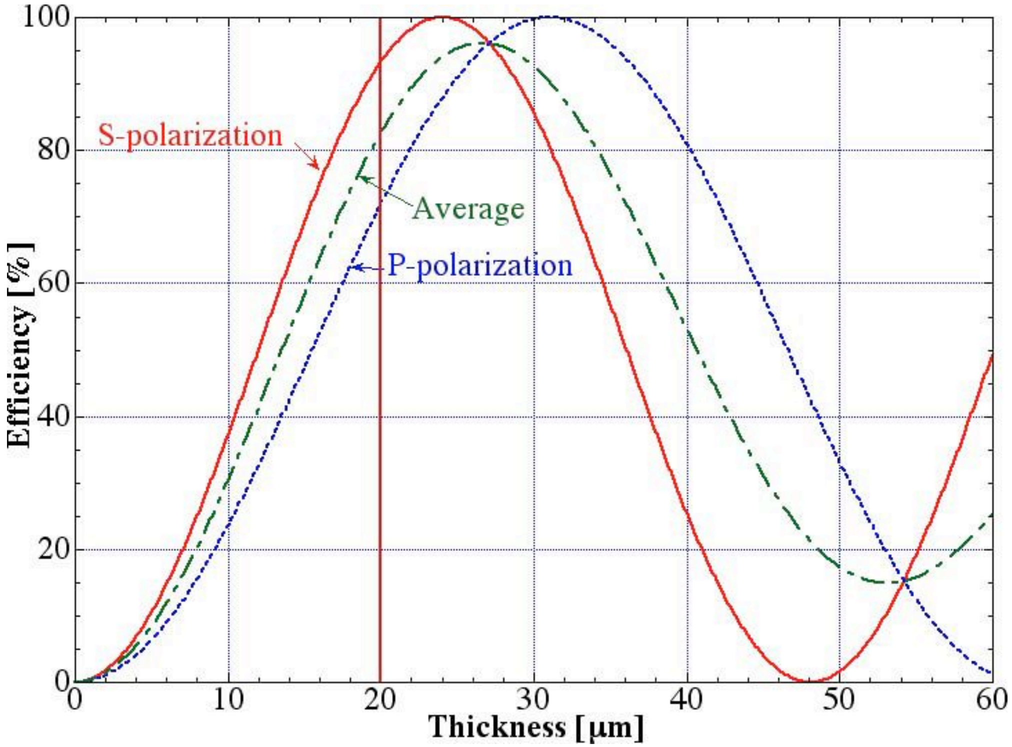
$$\eta_S = \sin^2\left\{\frac{\pi(n_{max} - n_{min})t}{\Lambda(n_{max} + n_{min})\sin 2\theta}\right\}$$

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



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)

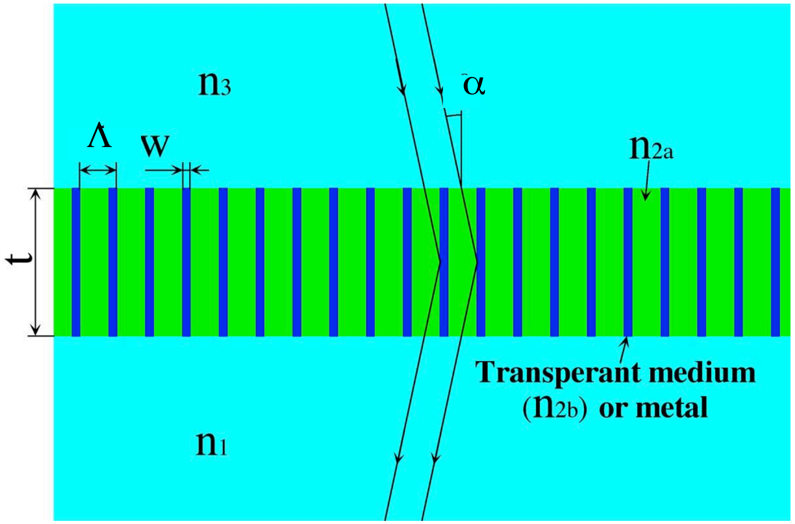
Volume Binary Grating

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

Volume Binary Grating



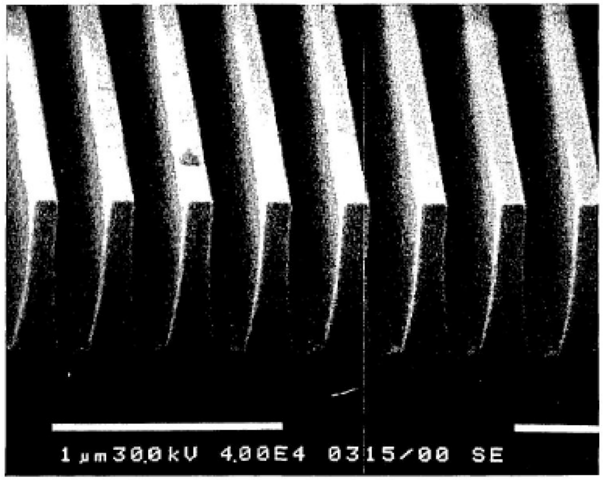


Fig. 1. Scanning electron micrograph of grating lines etched into quartz substrate (n_s = 1.46).

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

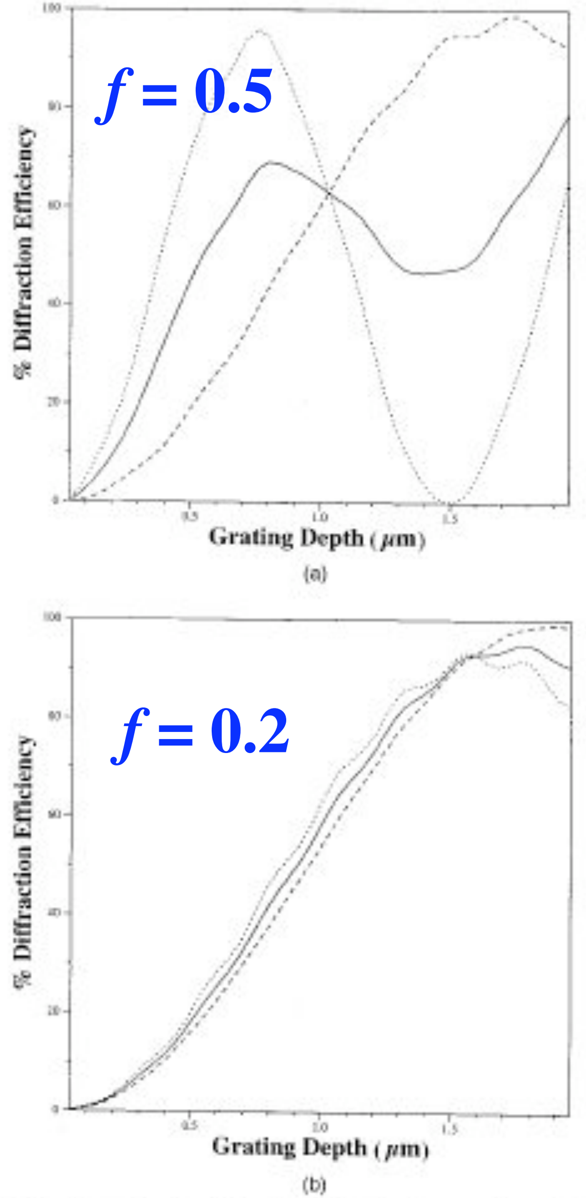


Fig. 5. (a) First-order diffraction efficiencies for a grating with λ = 0.55 μm, Λ = 0.3889 μm, θ_B = 45°, n = 1.50, and f = 0.50. (b) First-order diffraction efficiencies for a grating with λ = 0.55 μm, Λ = 0.3889 μm, θ_B = 45°, n = 1.50, and f = 0.80.

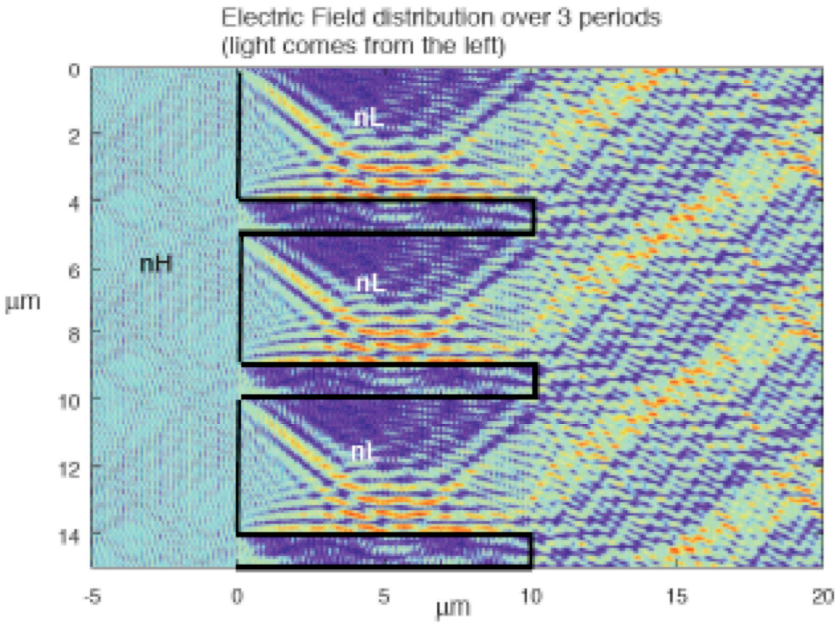
- **$\Delta n = (n_{max}-n_{min})/2 \sim 0.5$.**
- **Polarized diffraction efficiencies of S and P polarization coincide with each other by tuning of *f* and *t*. While aspect ratio becomes *t* : *w* = 1:20 ~ 100.**

Filling factor: $f=w/\Lambda$

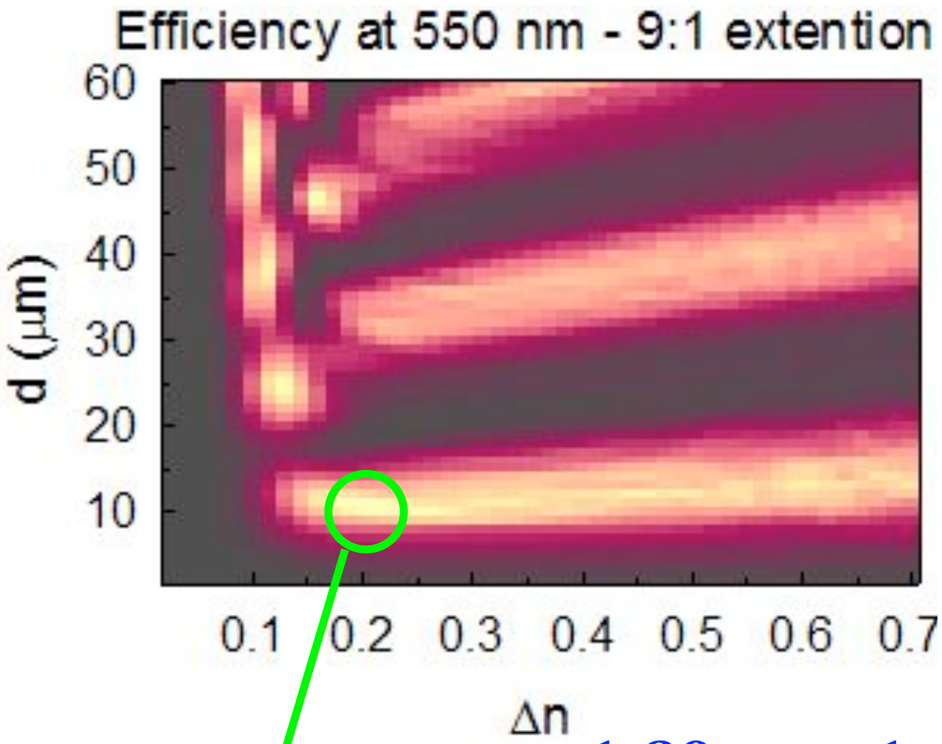
n_H=1.46, n_L=1.0, α =45 deg.

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

Volume Binary Grating for Higher Diffraction Orders

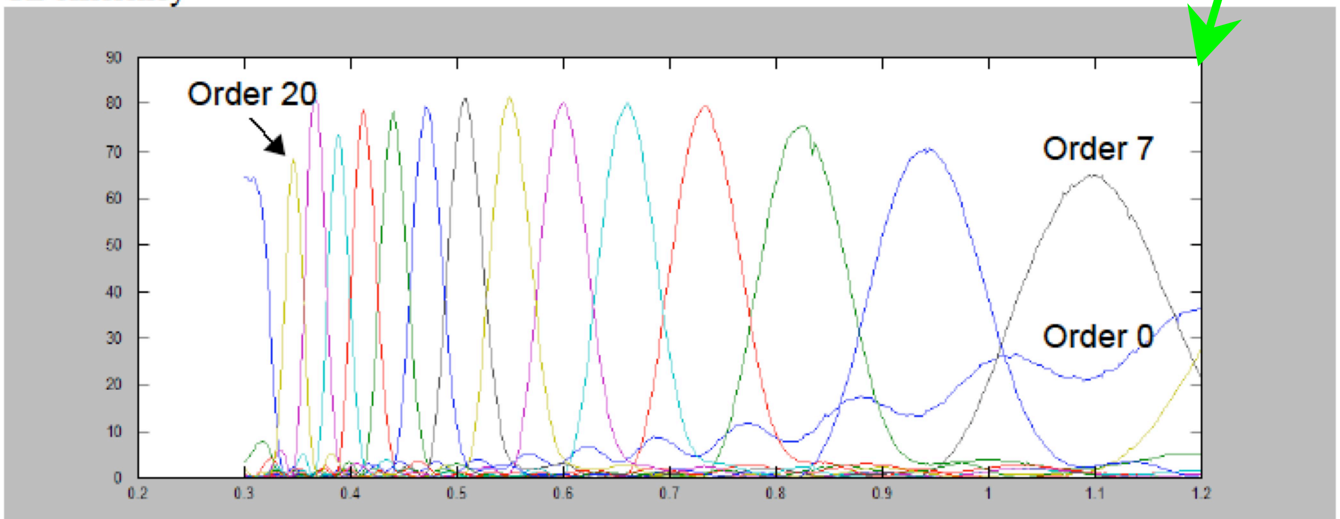


λ = 0.55 µm, α = 20.44° (= 41.3° in air), nH = 1.89, nL = 1.46, d = 10 µm



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

TE efficiency



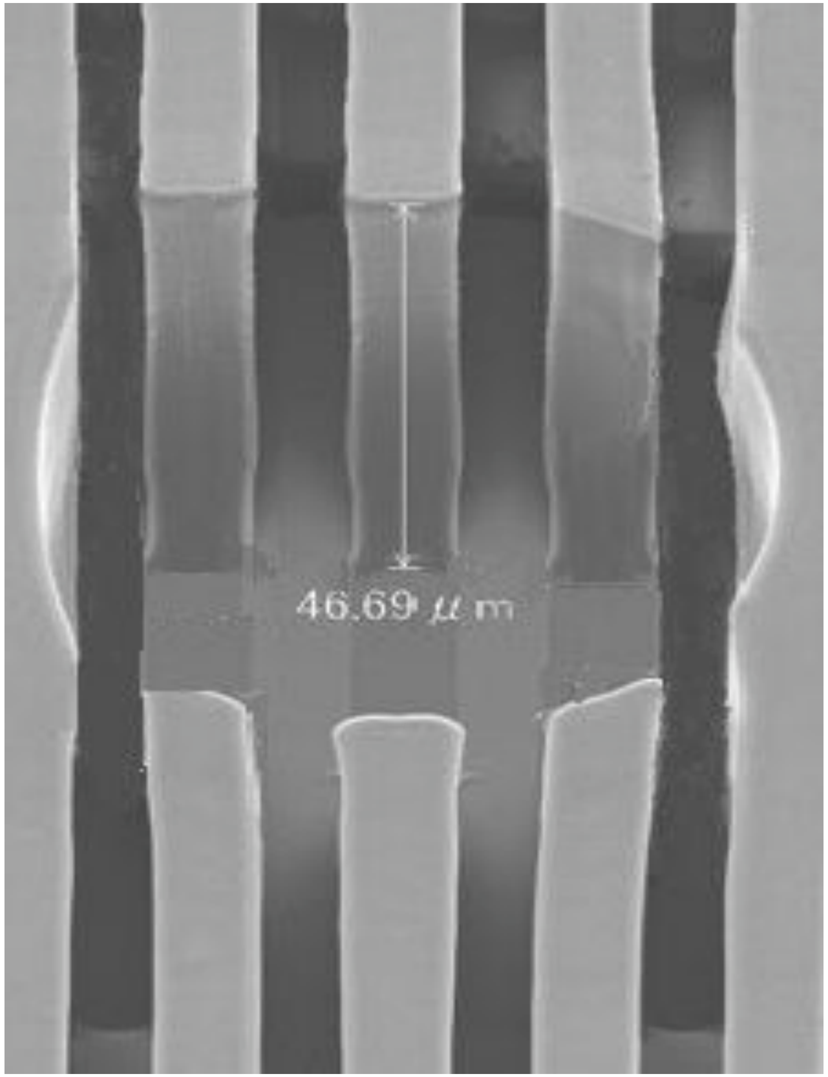
INAF Osservatorio Astronomico di Brera, Italy

n_H=1.89, n_L=1.46, α =41.3°, f = 0.1

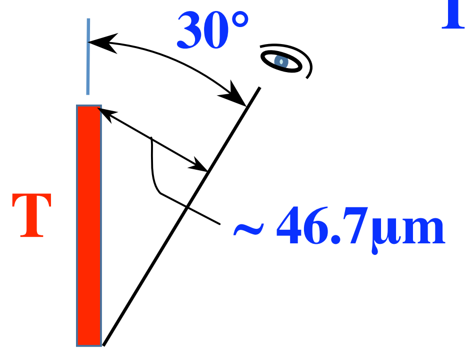
t:w (Aspect ratio) = 1:22

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

Photo Resist Grooves with High Aspect Ratio



SEM image of grooves (L&S: 10μm), tilting with 30°. Photo resist: KMPR1000.

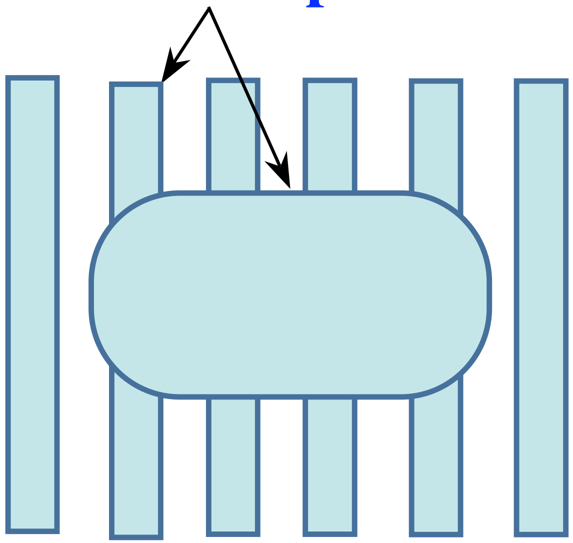


Thickness of Grooves

$$T = \frac{46.7\ [\mu m]}{\sin 30^\circ}$$

$$\fallingdotseq 93\ [\mu m]$$

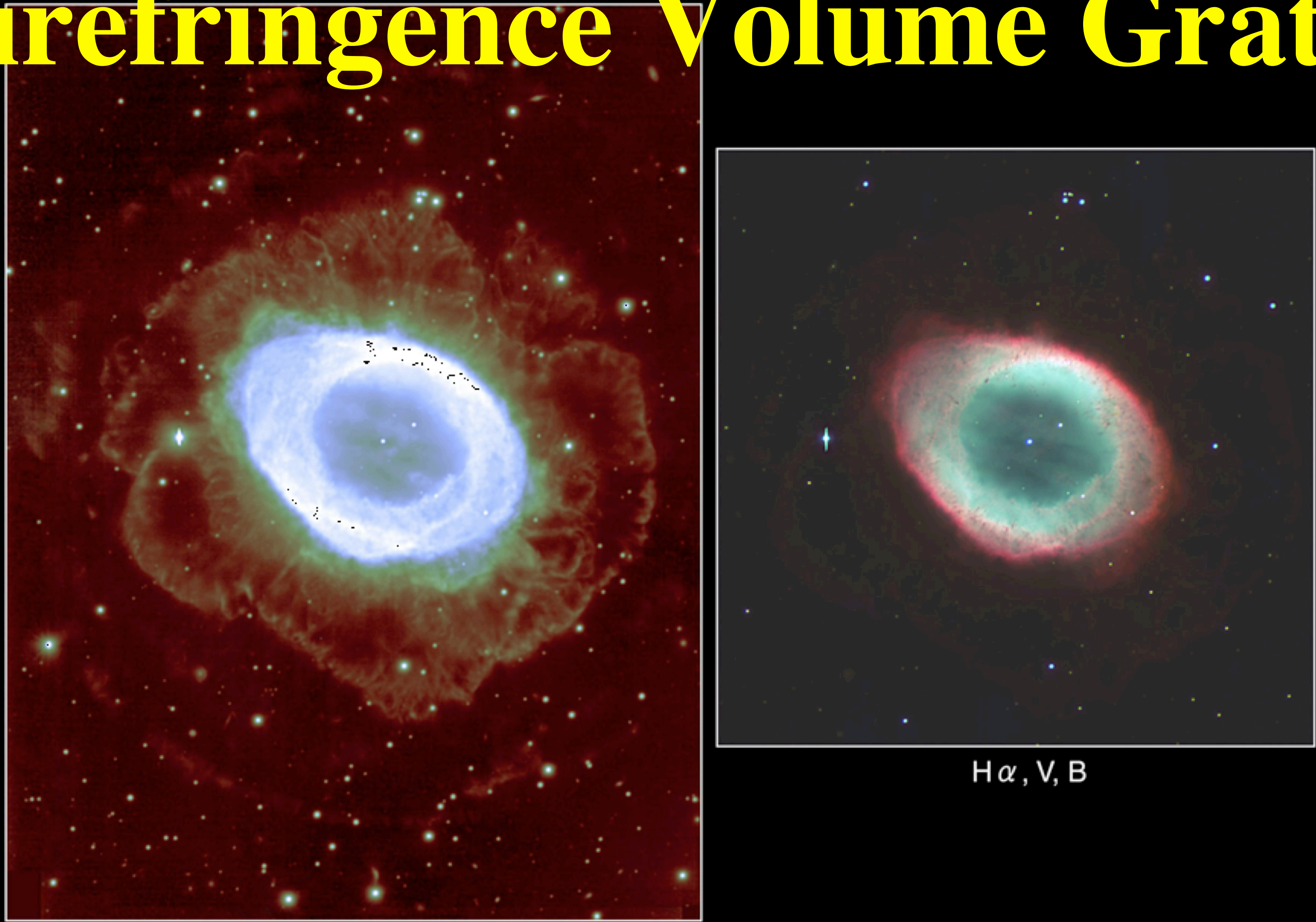
Cr mask pattern



L&S: 10μm → 1μm : 9μm

豊田工業大学ナノテクプラットフォーム

Birefringence Volume Grating



$H\alpha$

$H\alpha$, V, B

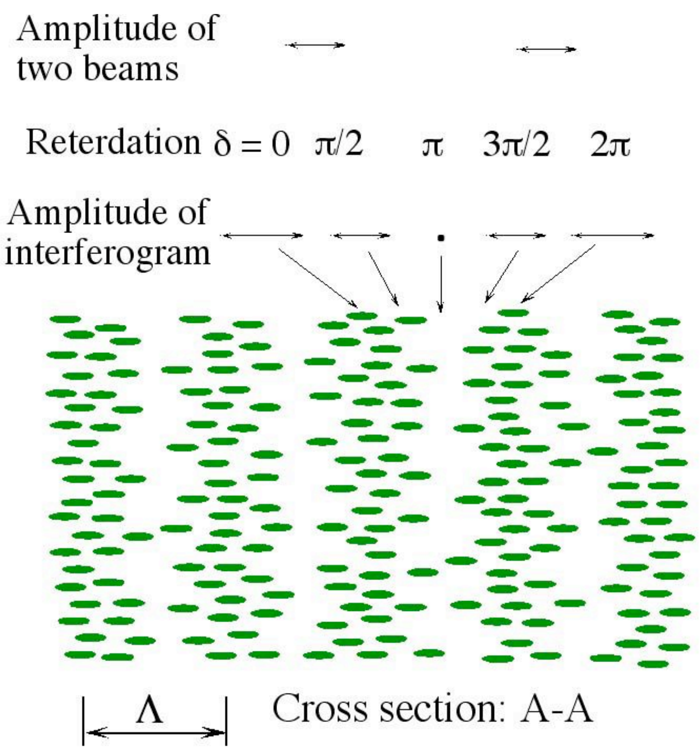
Ring Nebula (M 57 / NGC 6720)

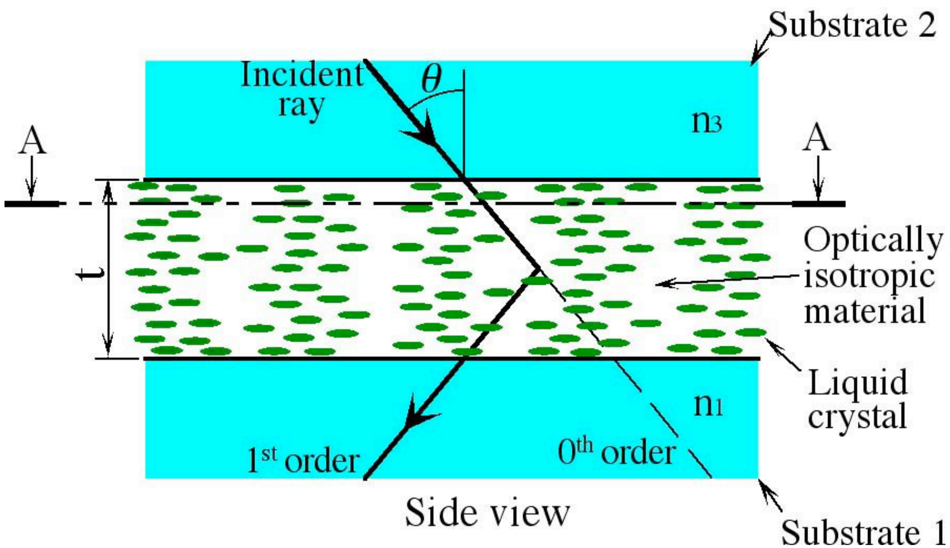
Subaru Telescope, National Astronomical Observatory of Japan

Suprime-Cam ($H\alpha$, V, B)

September 16, 1999

Birefringence VPH Grating



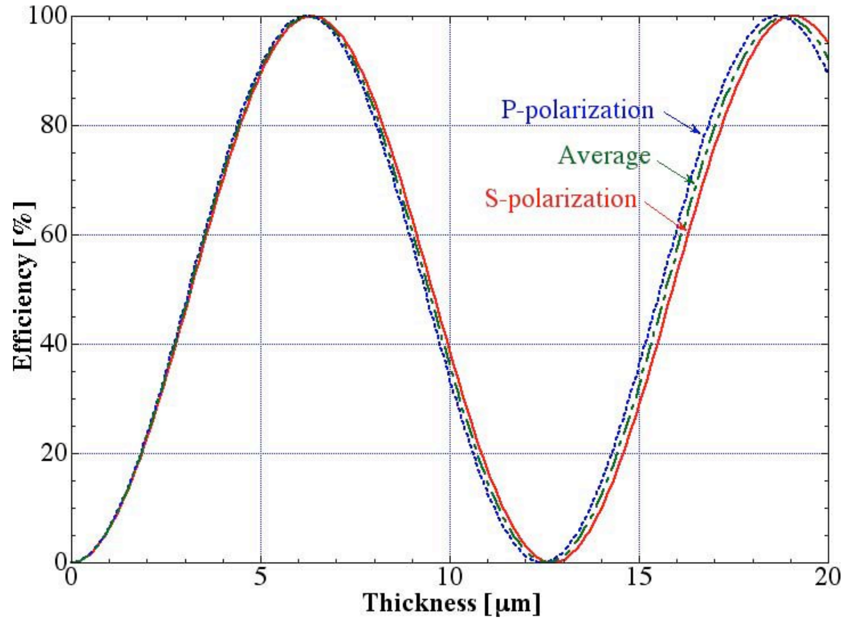


$$\frac{n_{S\max} - n_{S\min}}{(n_{S\max} + n_{S\min})\sin 2\theta_S} = \frac{(n_{P\max} - n_{P\min})\cos 2\theta_P}{(n_{P\max} + n_{P\min})\sin 2\theta_P}$$

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

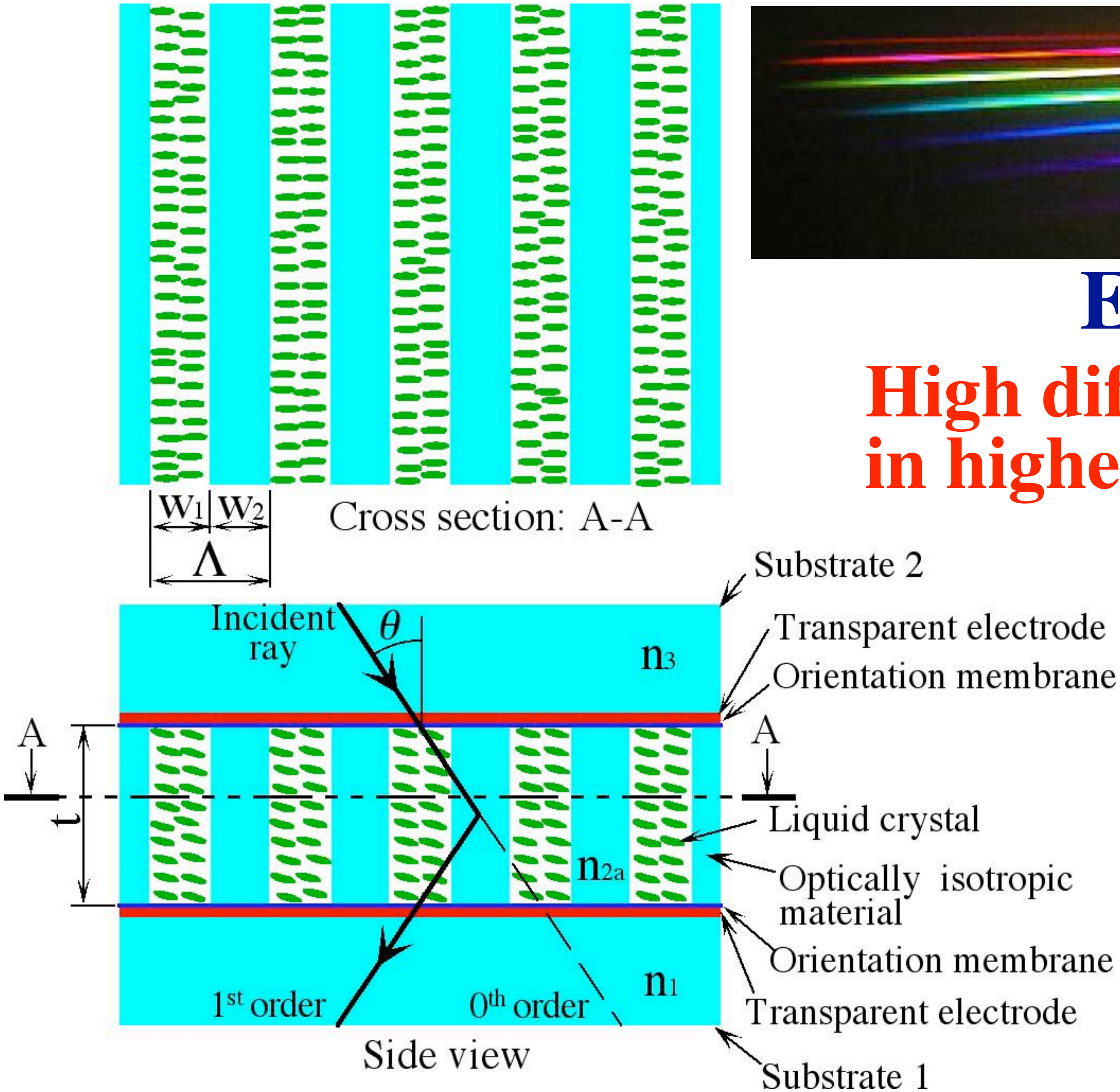
Snell's low

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



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

Birefringence Binary Bragg (3B) Grating

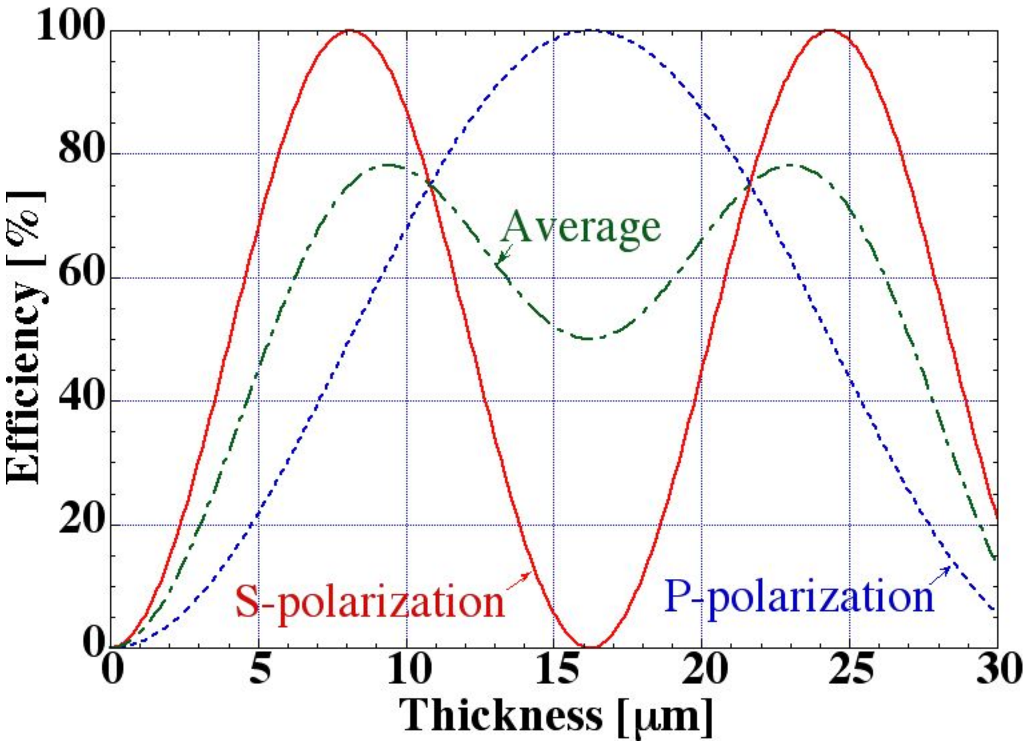


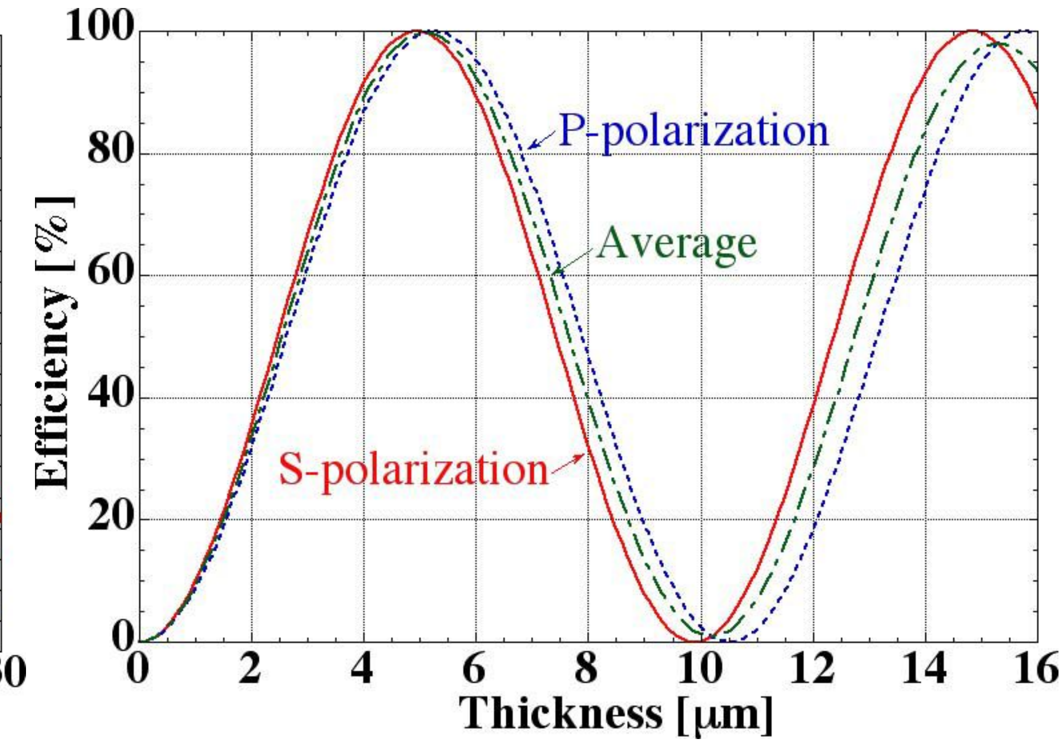
Echellegram

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 Grating and 3B Grating





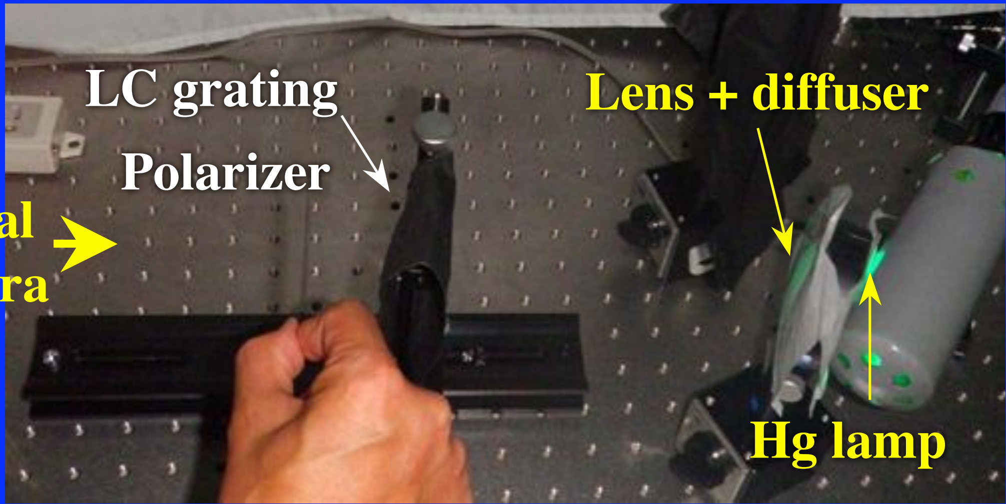
Dicson's VPH grating (Polarizer) calculated by Kogelnik method.
n_L= 1.46, n_H=1.54, θ_B =48.5°.

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

***w*:*t* (Aspect ratio) = 1:20~100 → 1:4~20**

Liquid Crystal Grating (3B Grating)

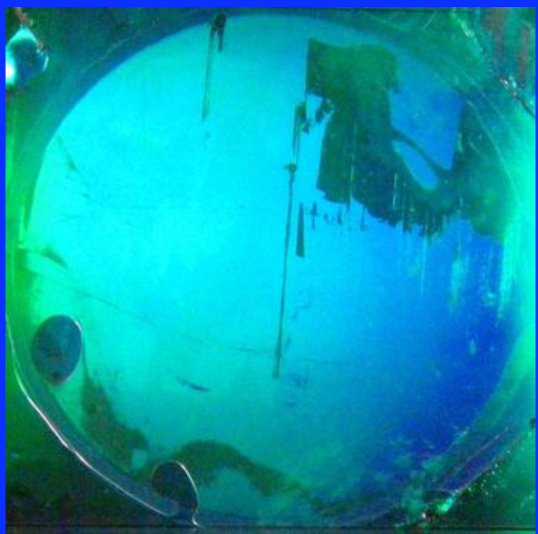
Digital camera



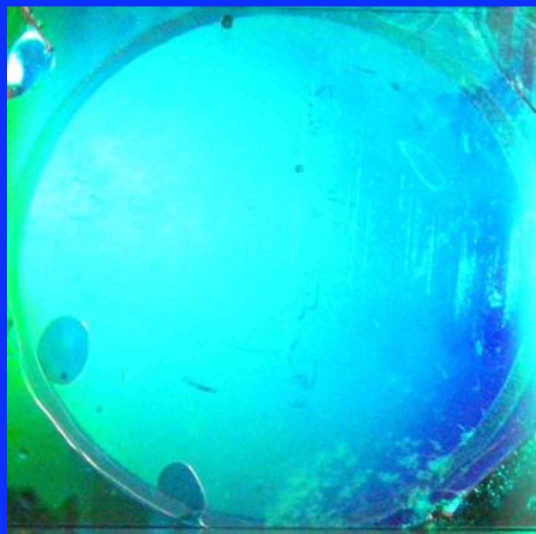
Specifications

Type: replicated grating
Groove period (Λ) : 2 µm
(Line & space : 1 µm)
Groove thickness (t): 1 µm

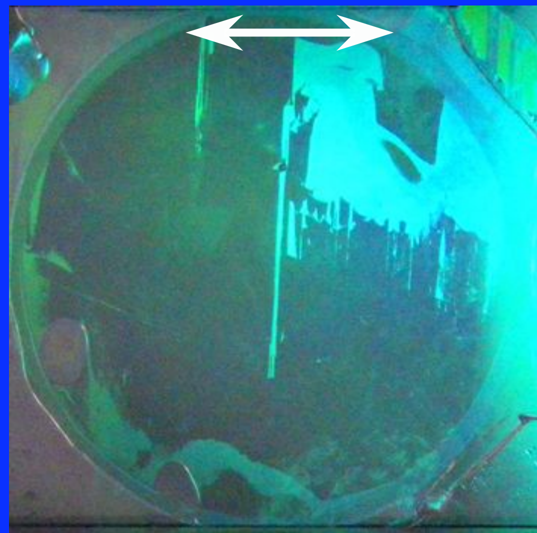
Orientation layer
(Grating vector)



Polarizer angle: 60 ~ 70°



Polarizer angle: 90°

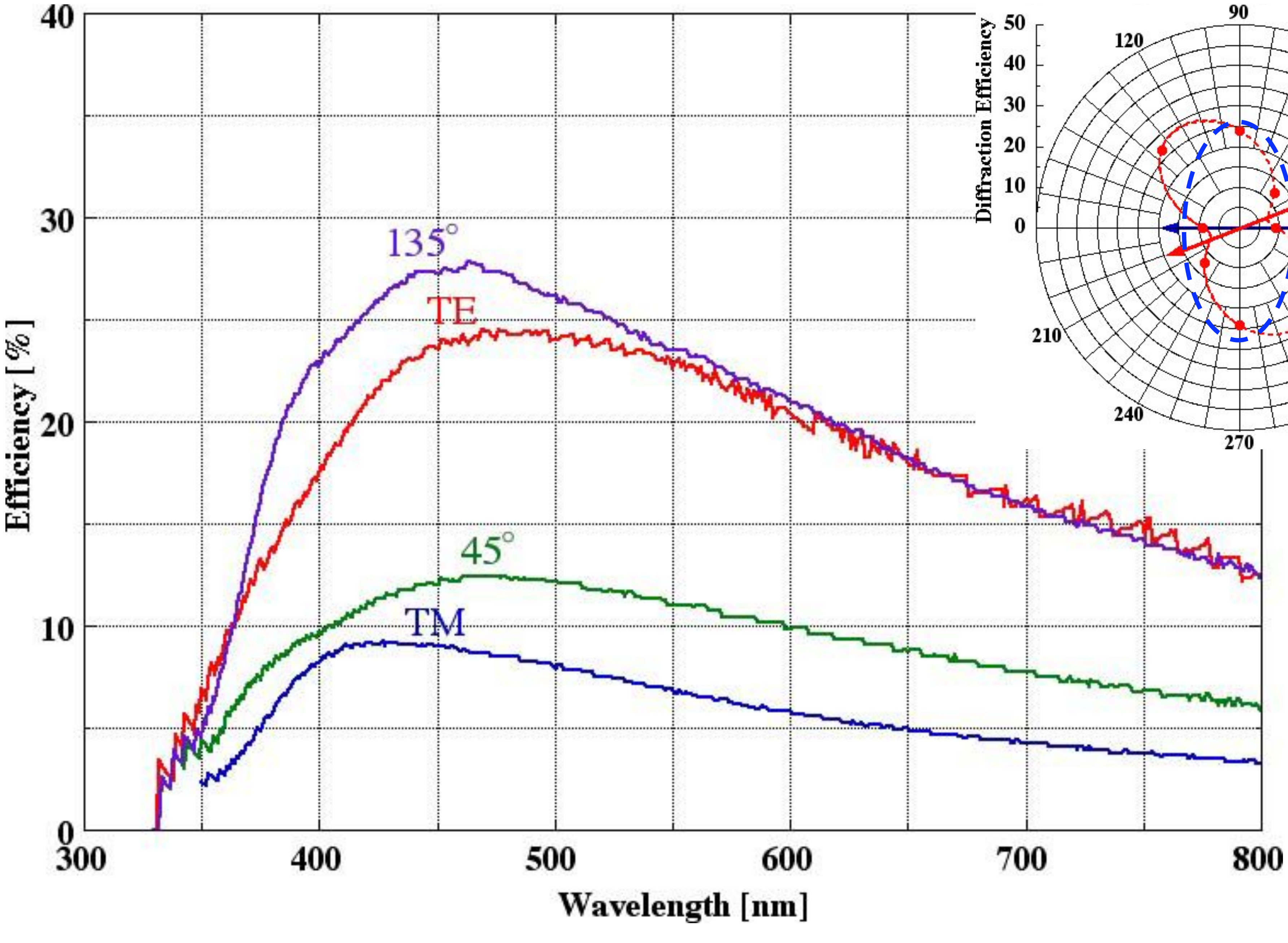


Polarizer angle: -60 ~ -70°

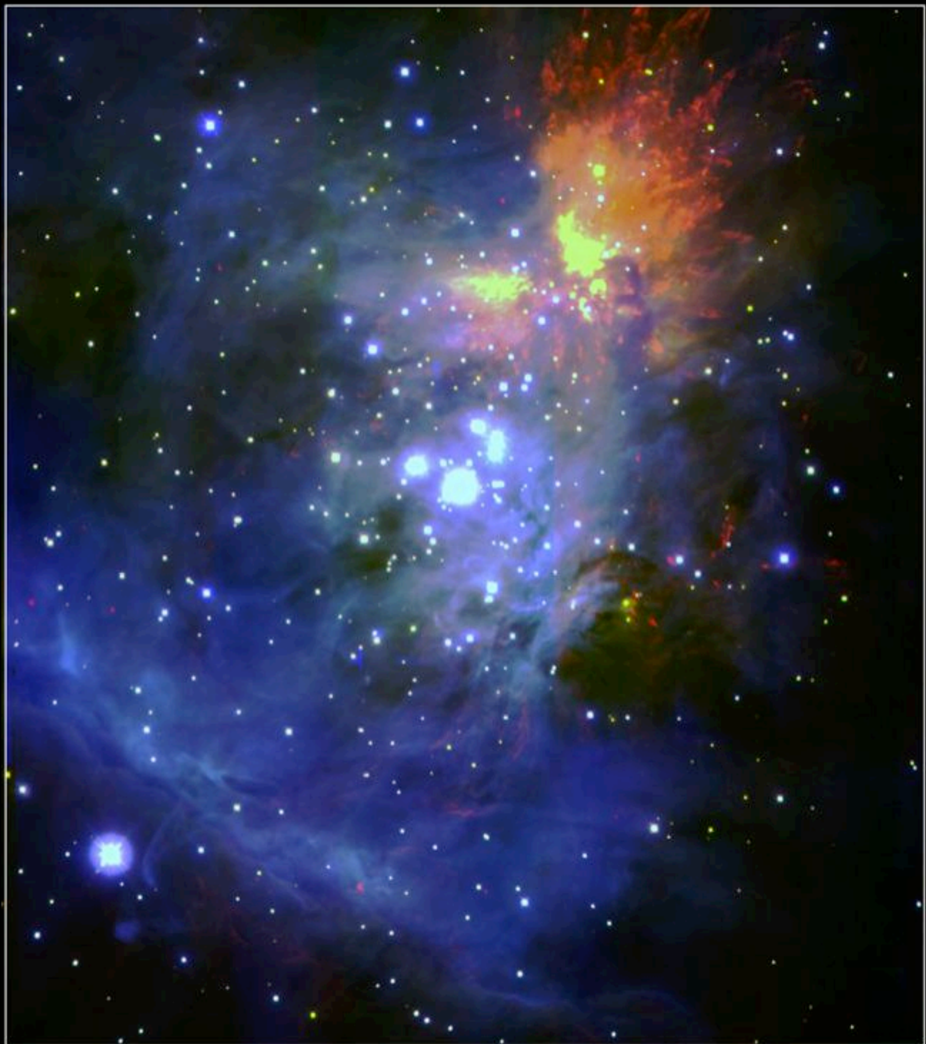
Images of the first order diffraction

シチズンホールディングス（株）開発部

Efficiencies of Liquid Crystal (3B) Grating

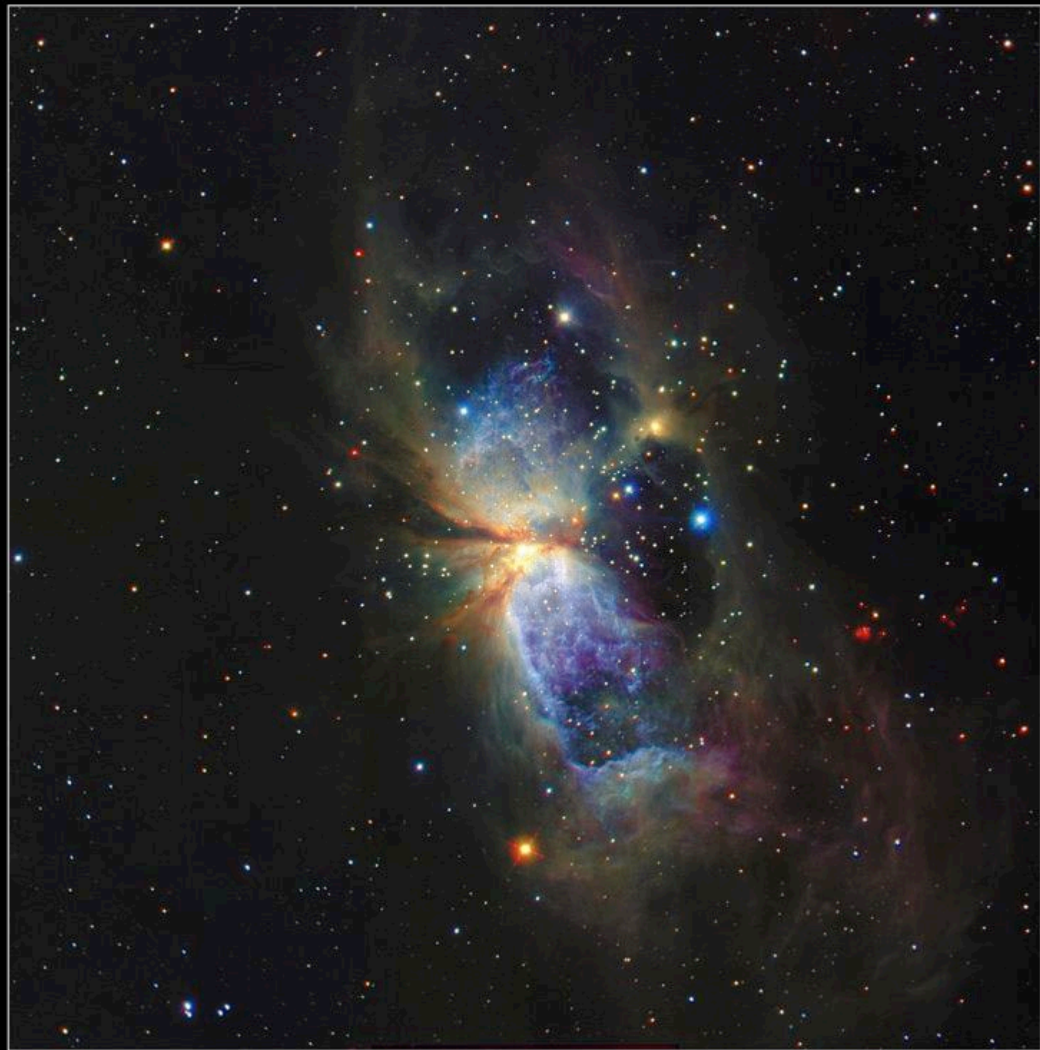


Immersion Grating



Orion Nebula CISCO (J, K′ & H_2 (v=1-0 S(1))

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

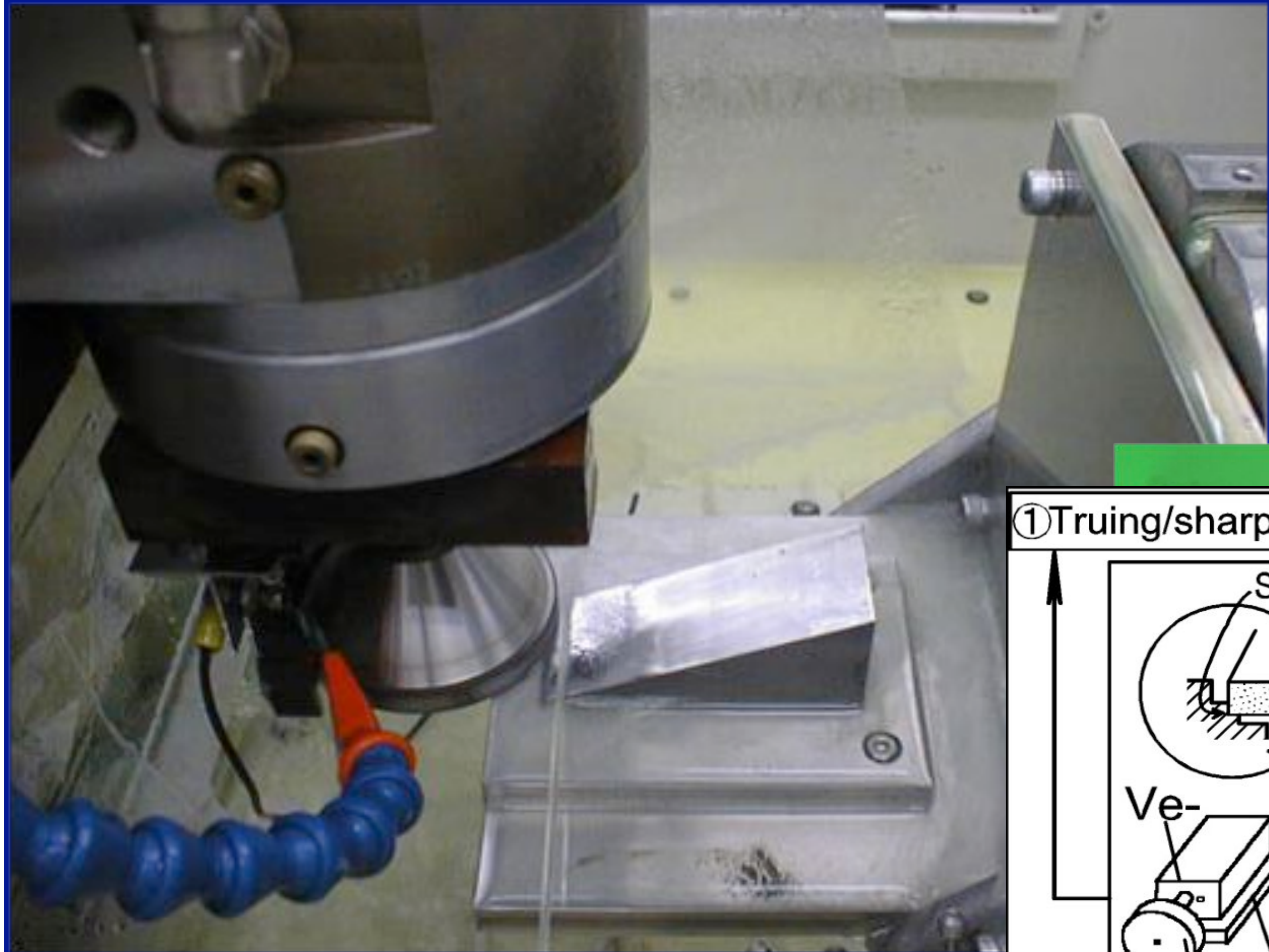


Star-forming Region S106 IRS4 CISCO (J, H, K')

Subaru Telescope, National Astronomical Observatory of Japan February 13, 2001

Ge Immersion Grating for GIGMICS

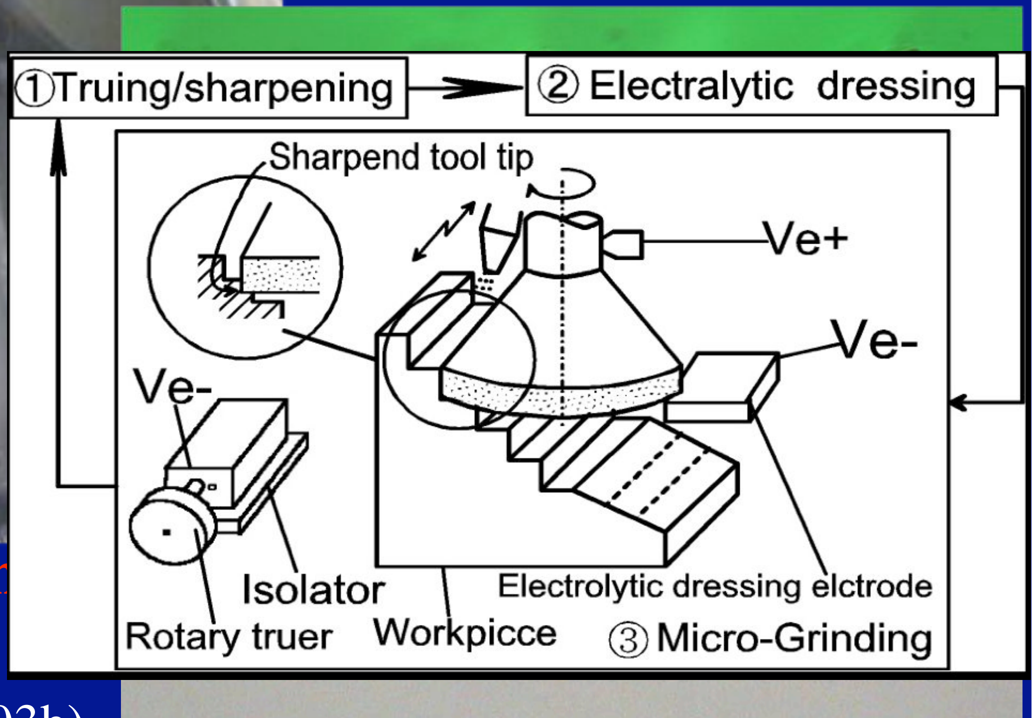
(Germanium Immersion Grating Mid-Infrared Cryogenic Spectrograph)



Nano-precision machine and ELID grinding method.

30 × 30 × 72 [mm],

α = 68.75°, Λ=600μm

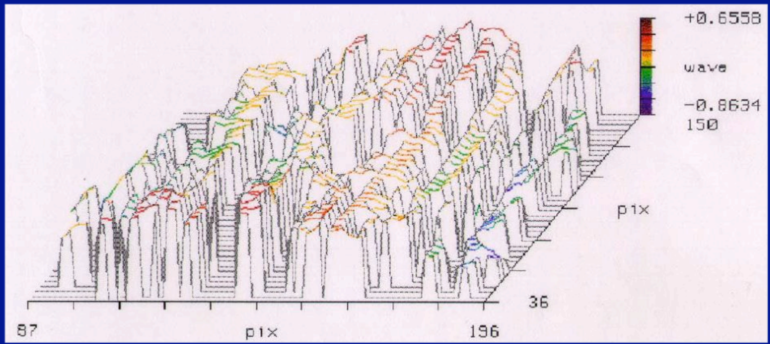


Spent about 400 hours for fabricatio

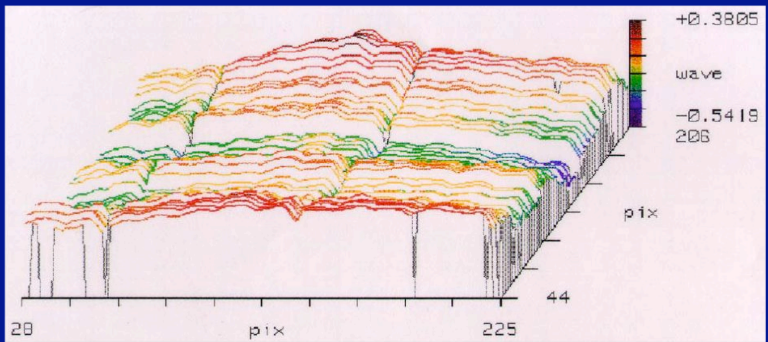
@RIKEN

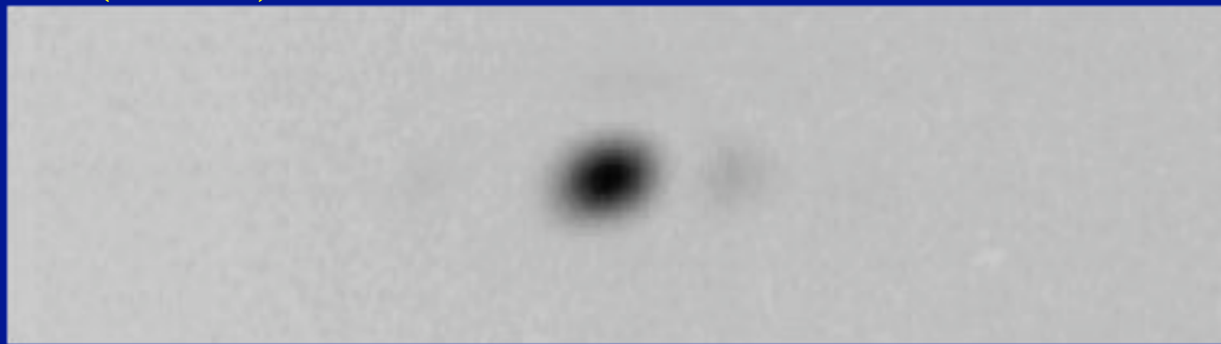
(Ebizuka et. al. SPIE, **4842**, 2003b)

Wave front (633nm, left) and Far Field Images (10.6mm, right) of Immersion Gratings

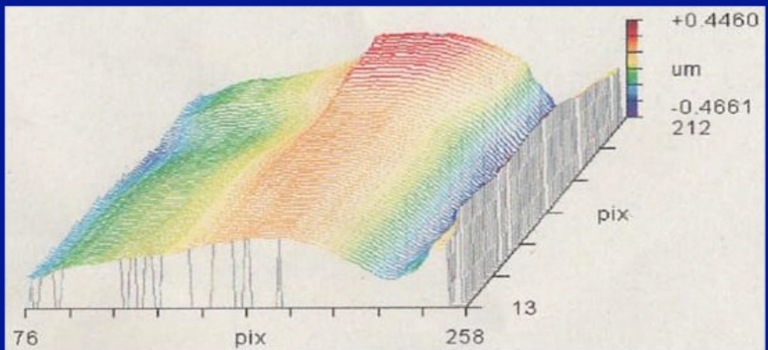


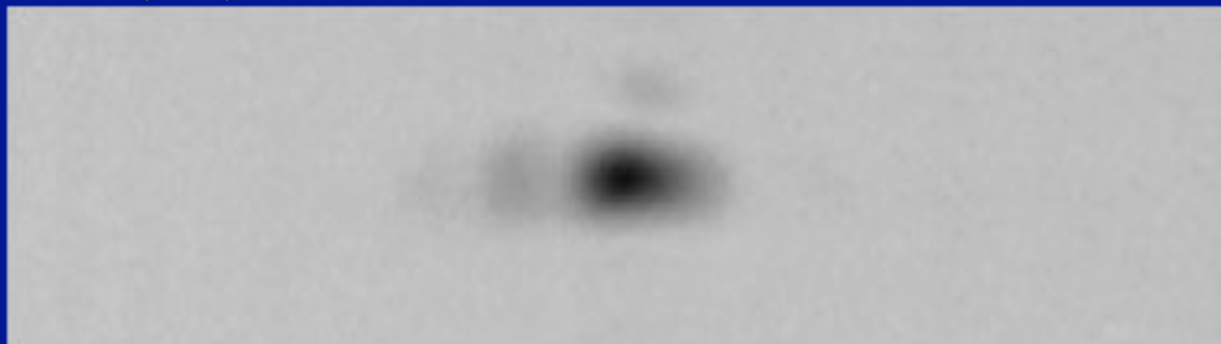
The 3rd trial (GaAs), PV: 961nm, rms: 154nm





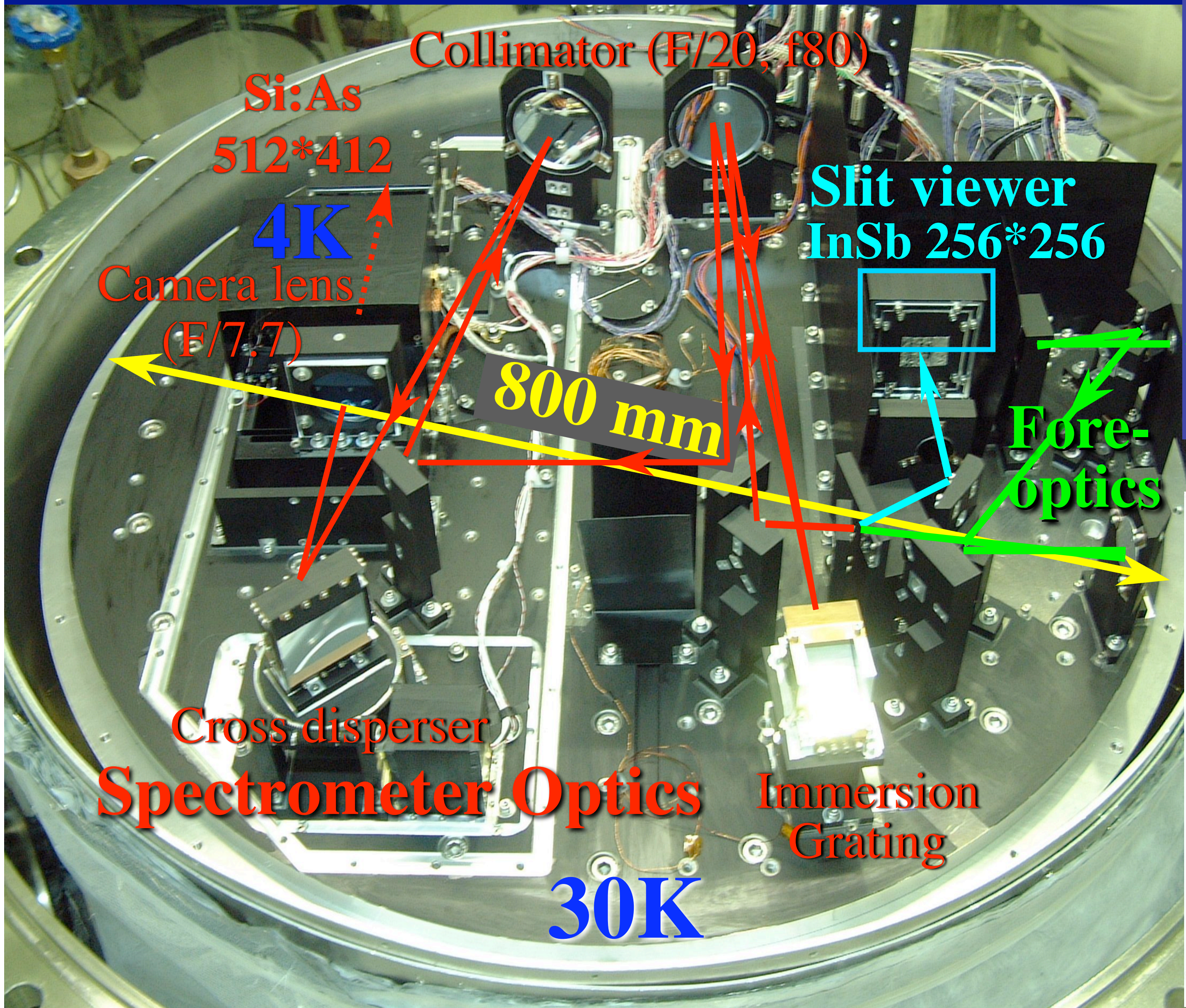
The 4th trial (Ge), PV: 583nm, rms: 87nm

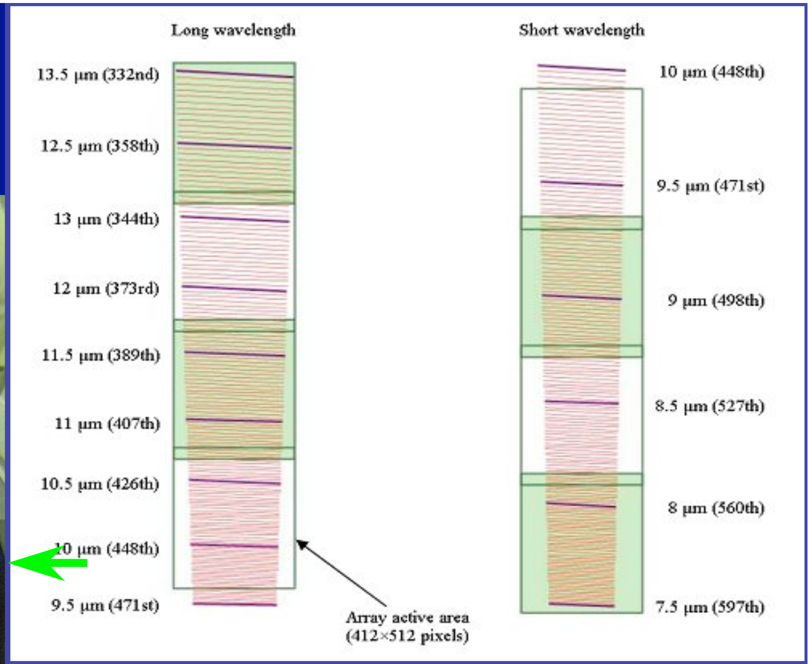


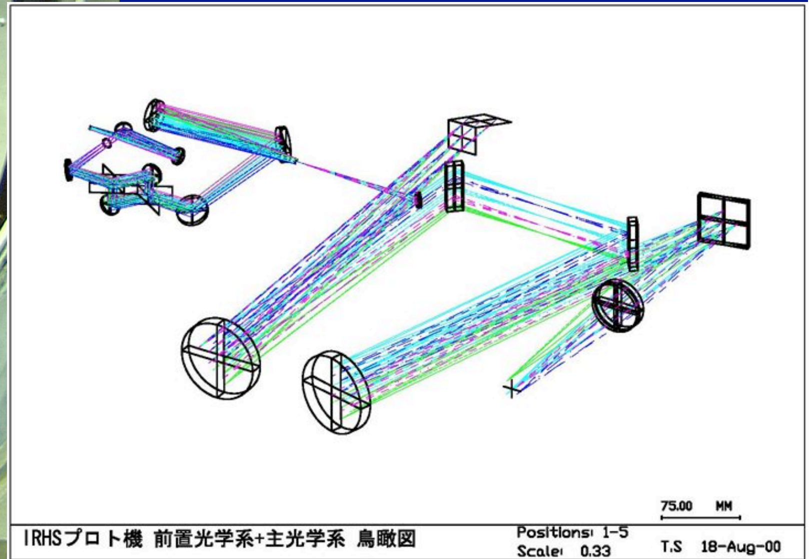


The 5th trial (Ge), PV: 577nm, rms: 107nm

GIGMICS



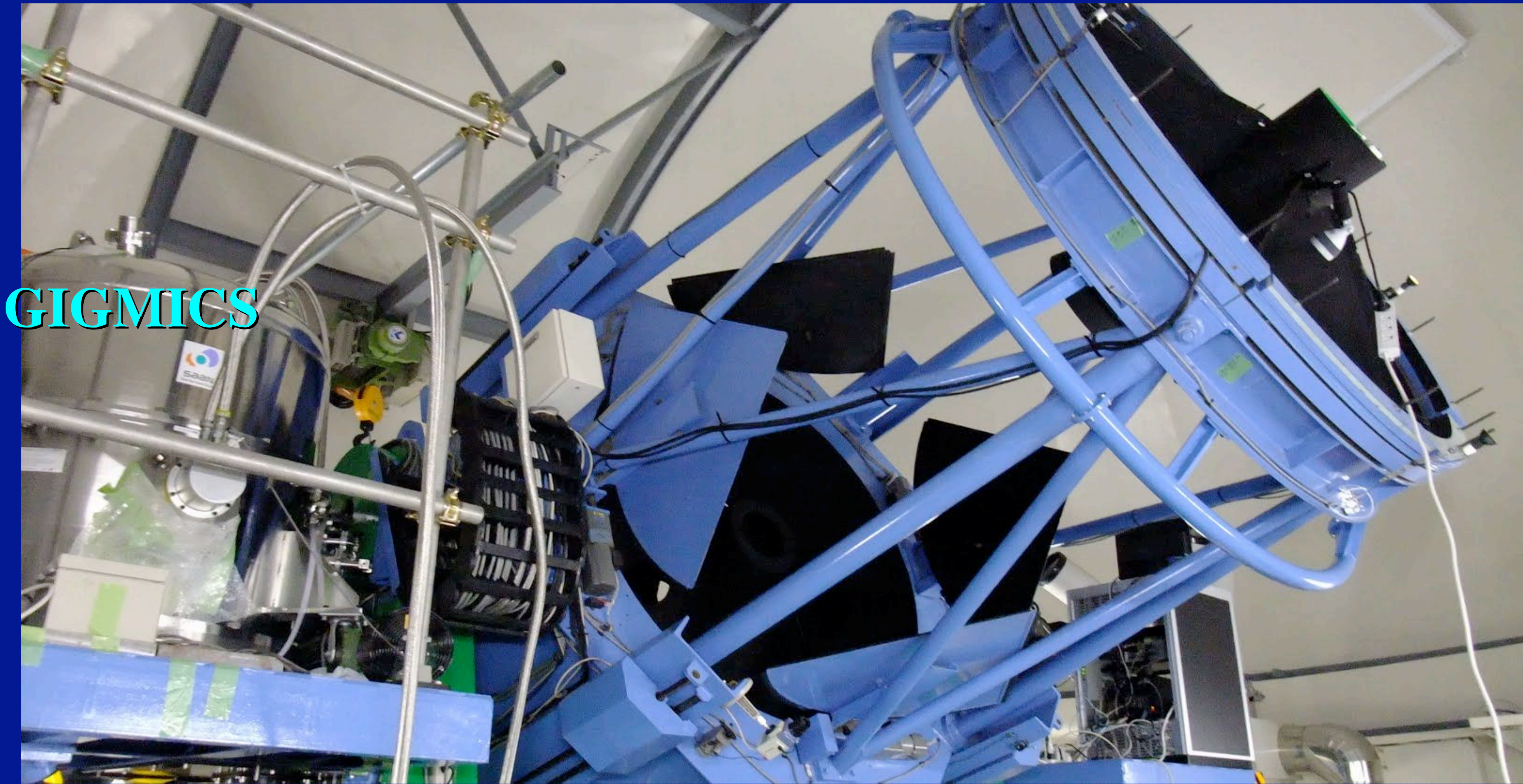




R~ 44,000@10μm, developed by Hirahara lab., Nagoya Univ.

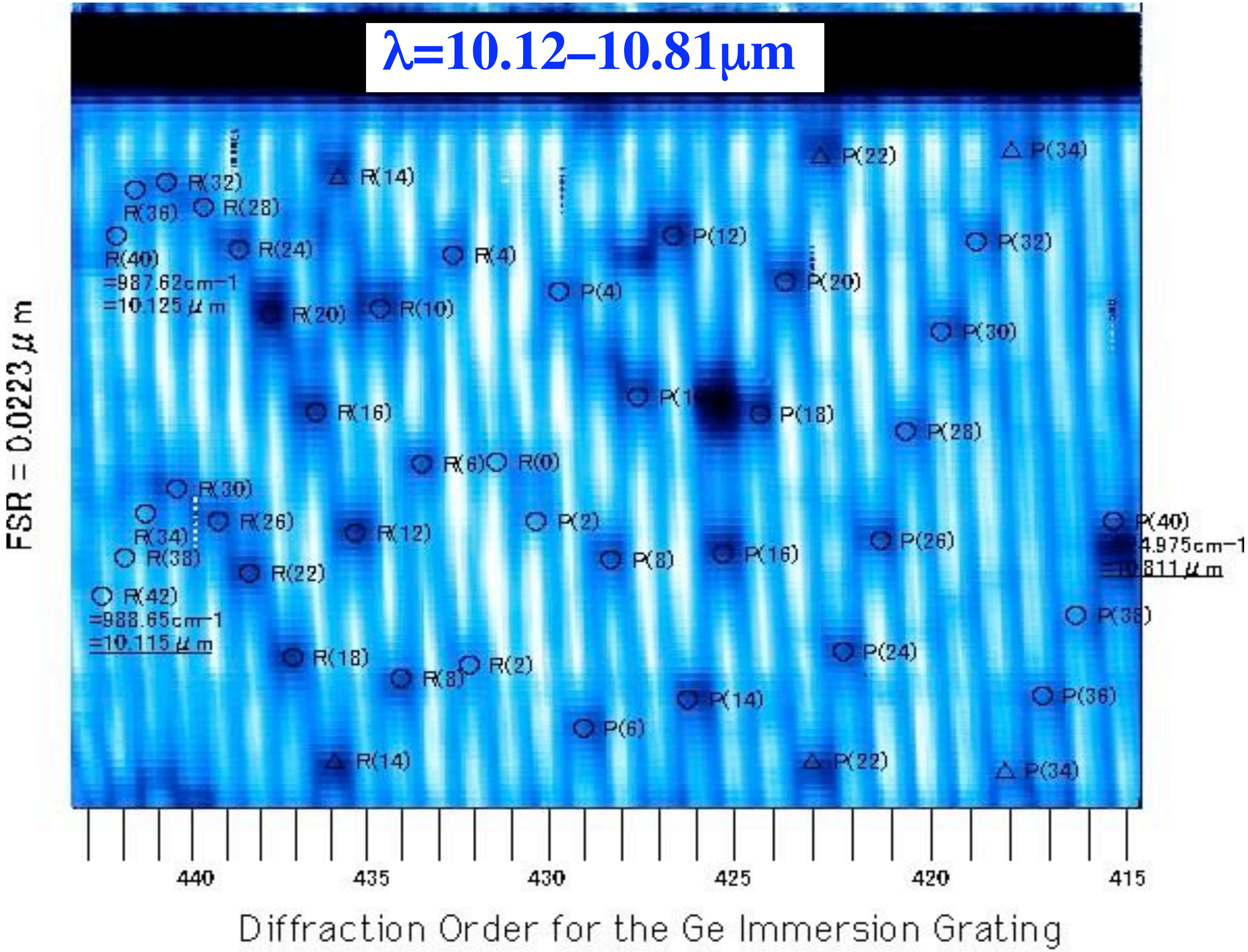
(Hirahara et. al., SPIE, **7735**, 2010)

First Light Observation of GIGMICS



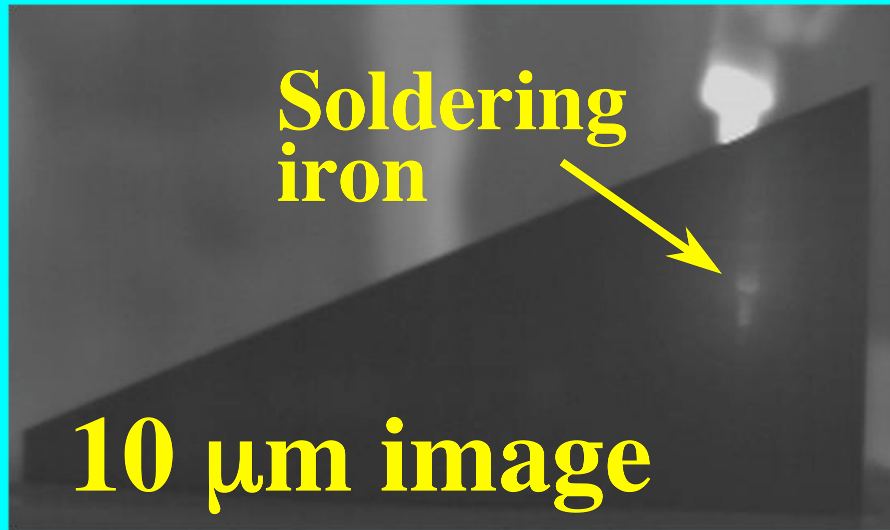
KANATA 1.5m telescope, Higashi-Hiroshima Observatory, Space Science Center Hiroshima Univ., Dec. 2010~Apr. 2011.

First Scientific Result (1): Venus

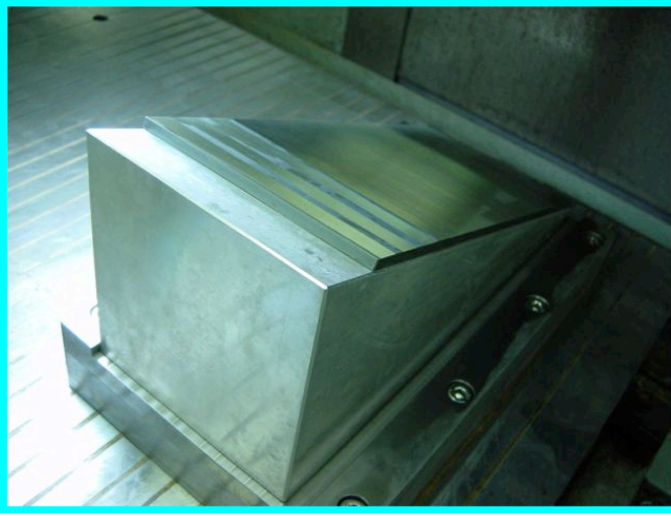


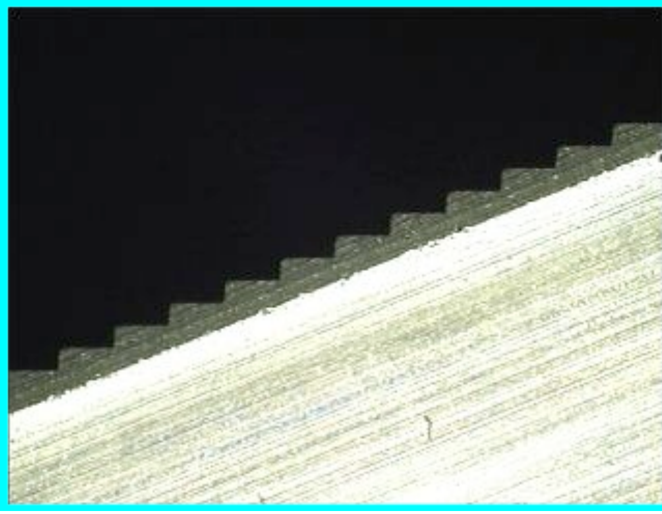
Absorption lines cannot be identified to the "telluric lines".
→ CO_2 hot-band & isotopes from Venus.

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

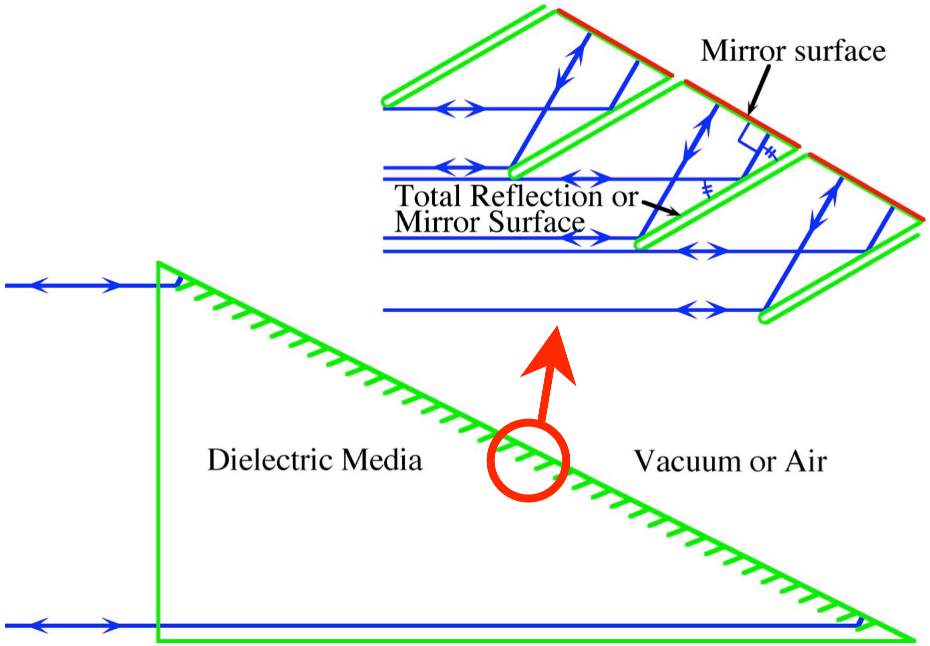


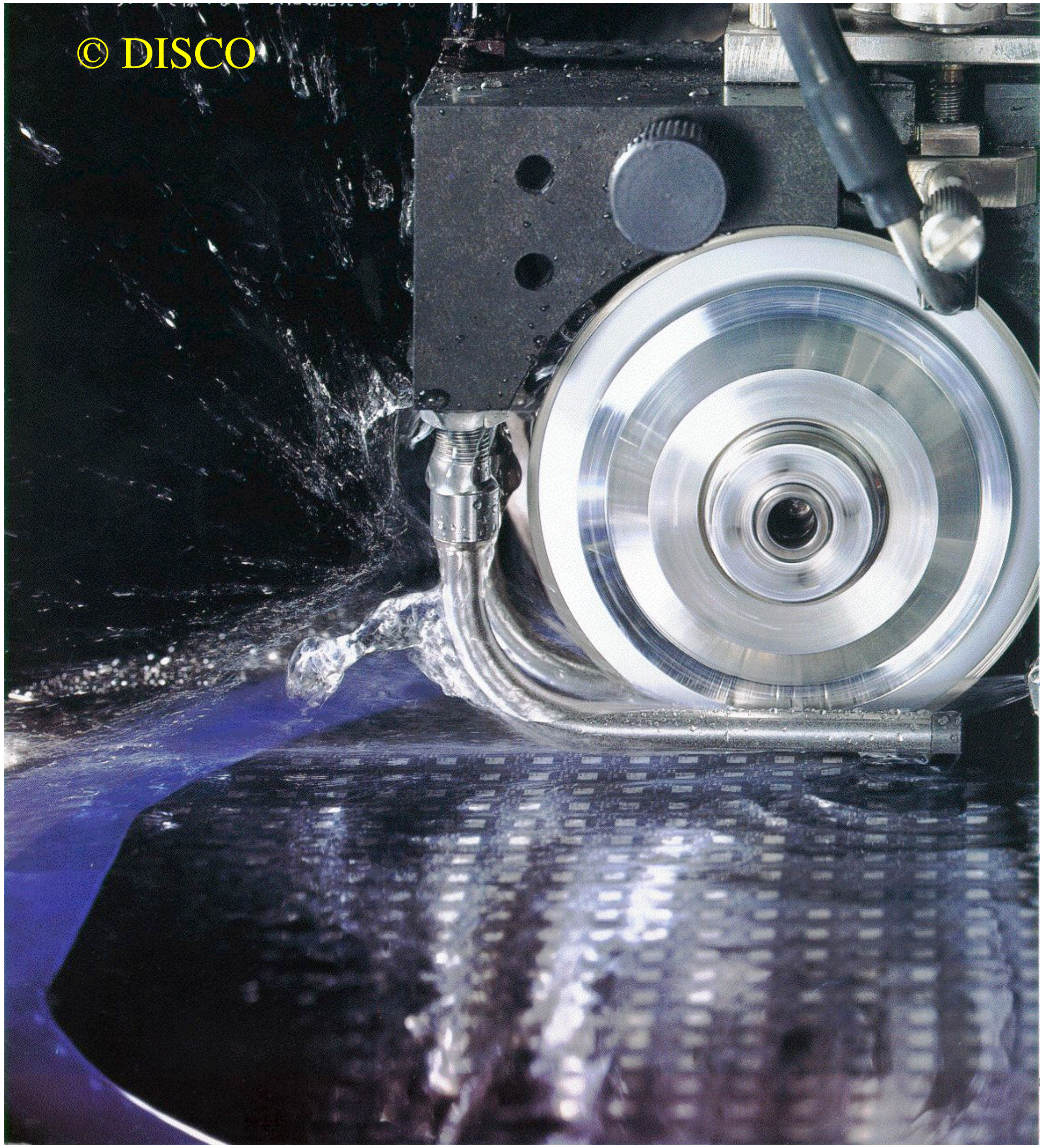
R〜200,000@10μm → Size: 120 x 120 x 270 mm
→ Fabrication time: several 1,000 hours





Quasi-Bragg Immersion Grating

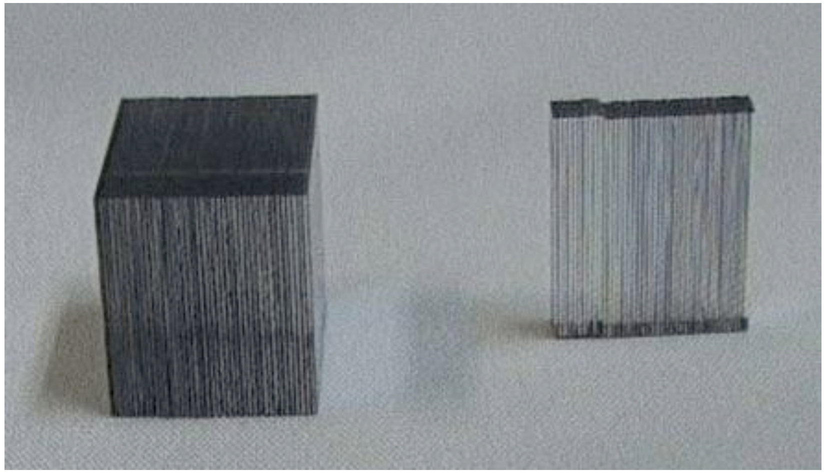




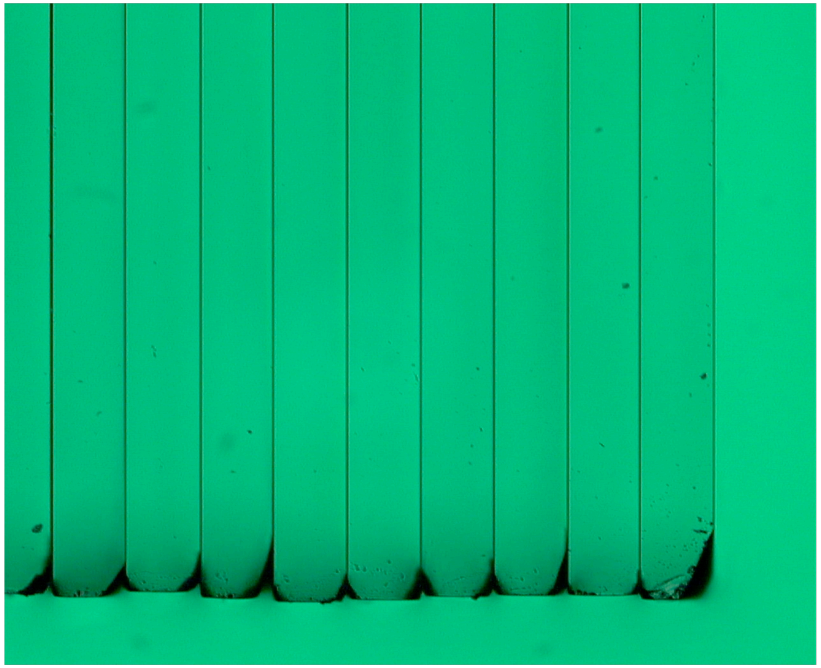
- **Machining of dicing saw makes smooth surface**
- **Easy tooling.**
- **Fabrication time for grating with 120 x 120 x 270 mm → Several 100 hours?**

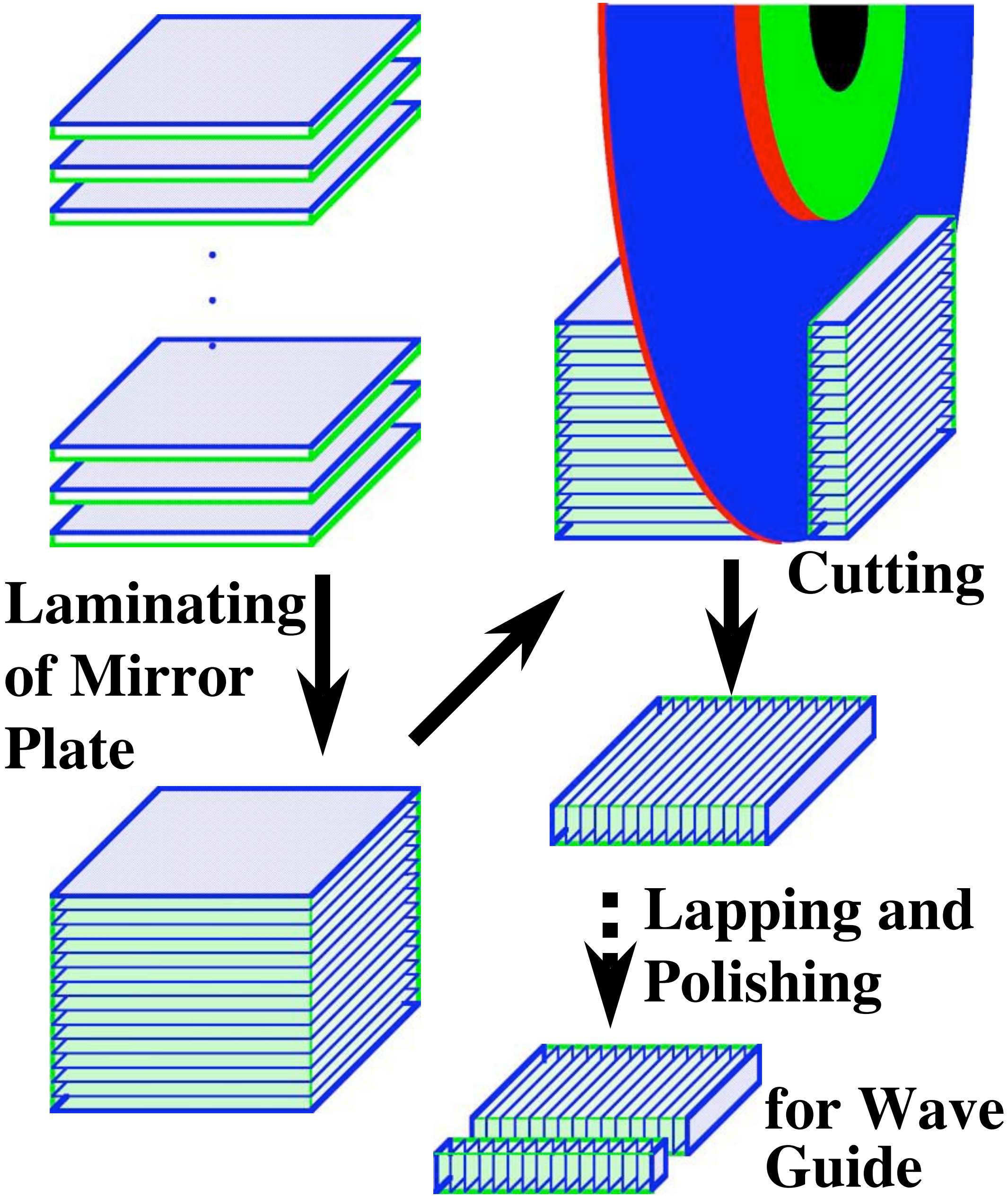
(Ebizuka et. al. SPIE, **6273**, 2006)

Trial Fabrication of Quasi-Bragg Grating

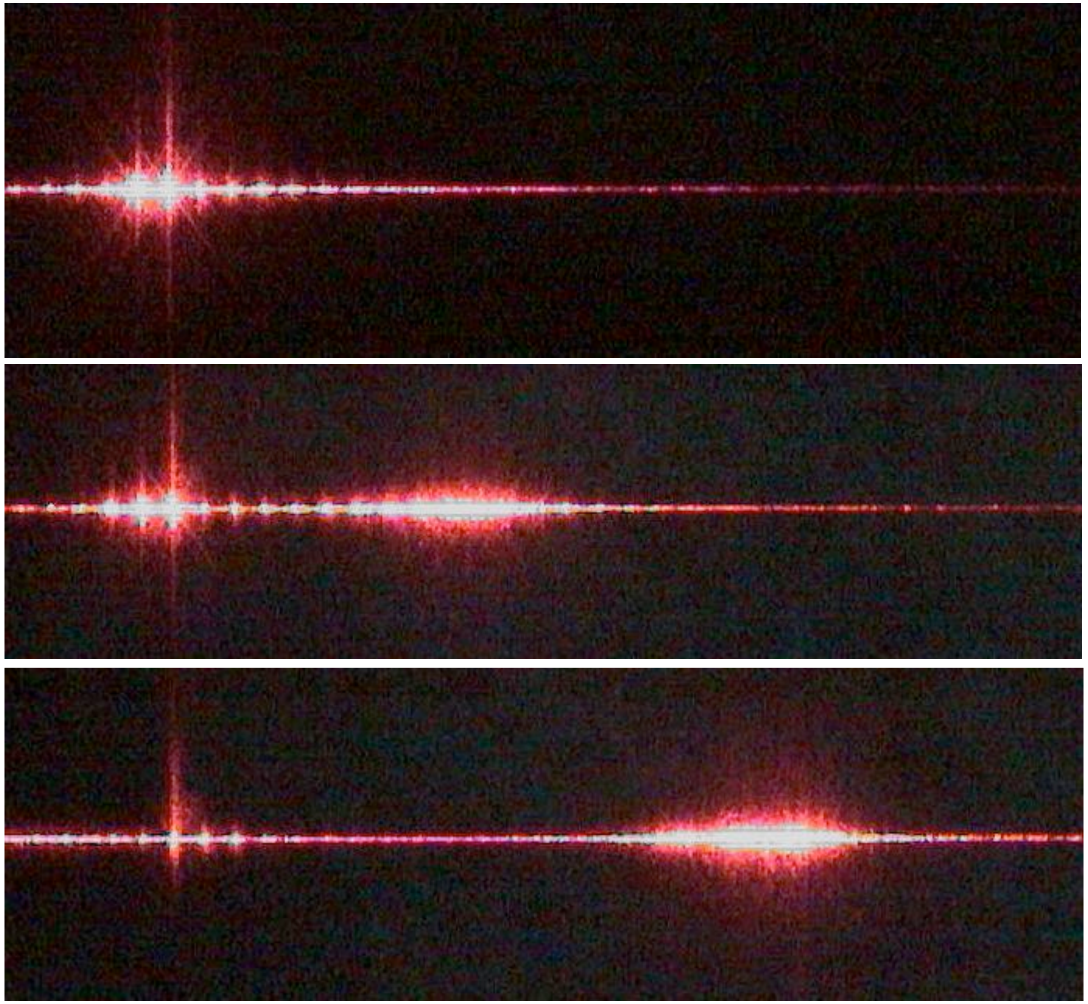


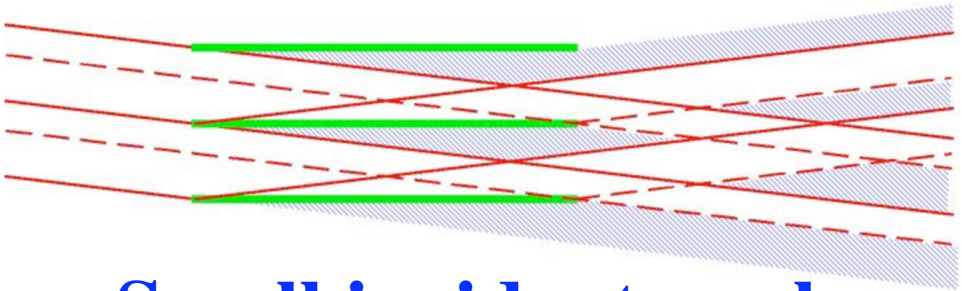
A: 10 x 10 x 0.2 x 40 pcs (left),
B: 1.5 x 10 x 0.2 x 40 pcs (right)



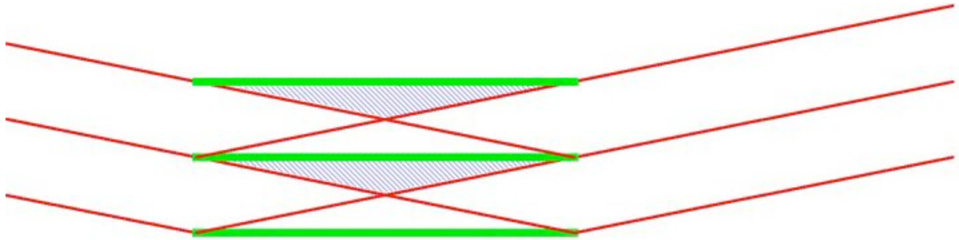


Diffraction of Quasi-Bragg Grating

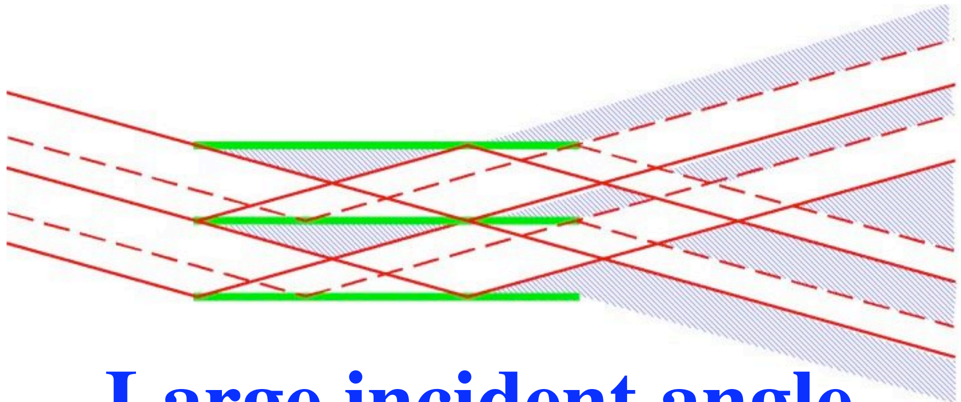




Small incident angle



Ideal incident angle

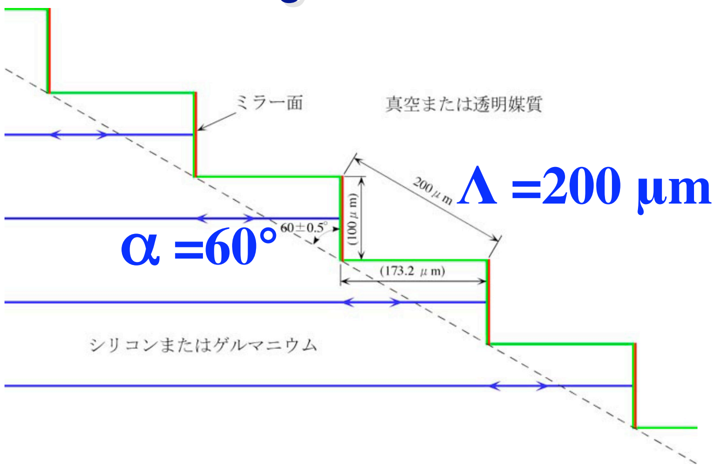


Large incident angle

Diffraction by quasi Bragg grating (A type). $\theta = 0$ (top), $\theta = 0.6$ (middle), $\theta = 1.2$ (bottom).

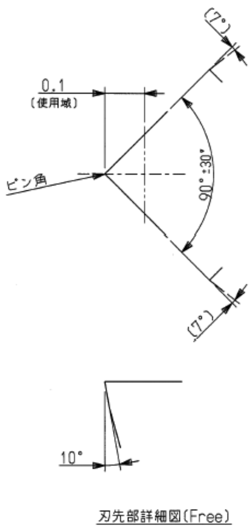
Spacing of mirror plates is imperfect.

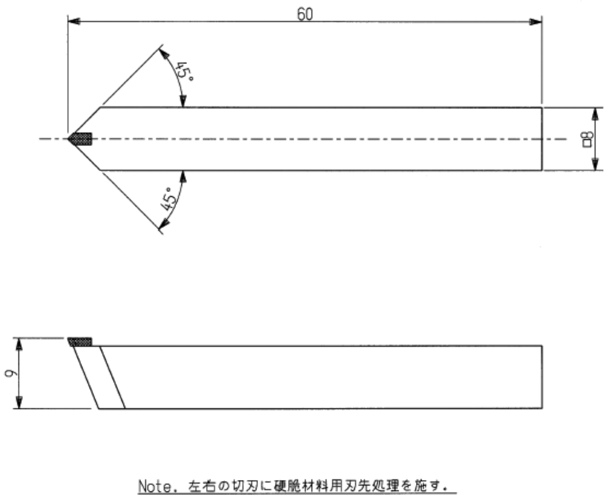
Fabrication of Immersion Grating for Near IR by Means of Diamond Machining

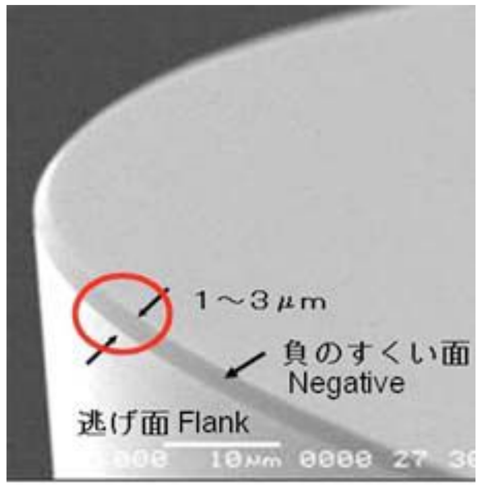


Specifications

Material	: Si, (Ge)
Wavelength range	: 1 ~ 2.5 μm
Groove period (Λ)	: 200 μm
Blaze angle (α)	: 60°







Diamond endmil **Diamond bite**

理化学研究所 光量子工学研究領域 先端光学素子開発チーム

Current and future works

- Trial fabrications of high aspect rectangular grating with duty ratio of 1 : 8~10.
- Trial fabrications of liquid crystal grating with high aspect ratio.
- Trial fabrications of immersion grating for near IR by means of novel diamond turning methods.
- Trial fabrications of quasi-Bragg immersion grating.

謝　辞

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Thank you for your kind attention!