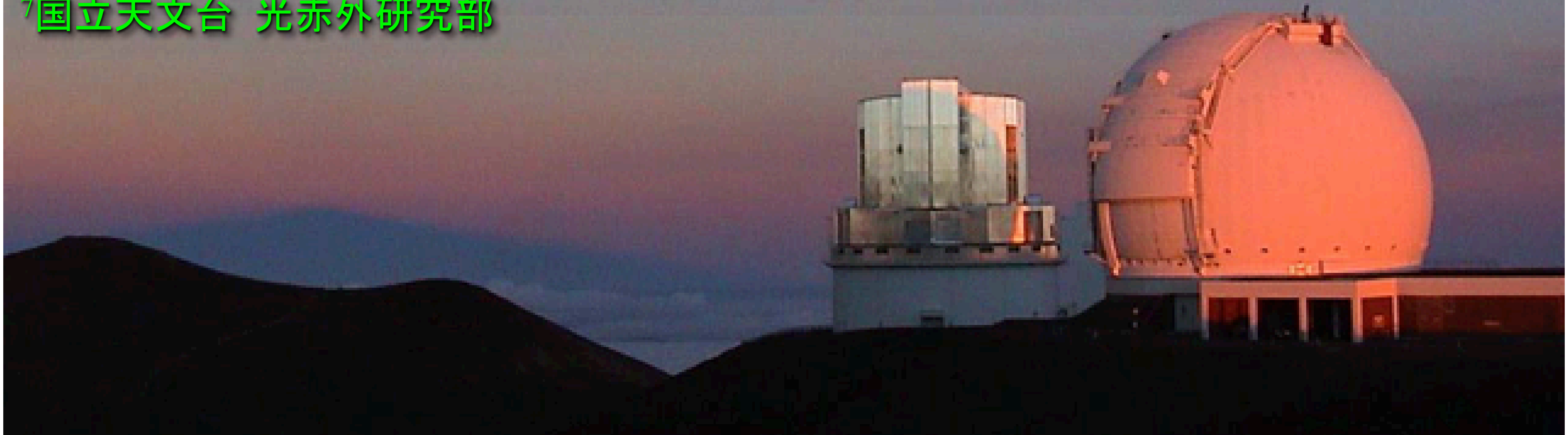
次世代観測装置用の新しい回折格子の開発状況 II

海老塚 昇[1], 細畠 拓也[1], 山形 豊[1], 岡本隆之[2], 佐藤 慎也[3], 田辺 綾乃[3], 橋本 信幸[3], 佐々木 実[4], 魚本 幸[5], 島津 武仁[5], 桐野 宙治[6], 尾崎 忍夫[7], 青木 和光[7], 高見 英樹[7]

[1]理研 先端光学素子開発チーム, [2]理研 石橋極微デバイス工学研究室, [3]シチズンホールディングス (株) 開発部, [4]豊田工業大学 ナノテクプラットフォーム, [5]東北大学 学際科学フロンティア研究所, [6](株) クリスタル光学 開発部, [7]国立天文台 光赤外研究部



第5回可視赤外線観測装置技術ワークショップ 2015年12月7-9日 東北大学

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

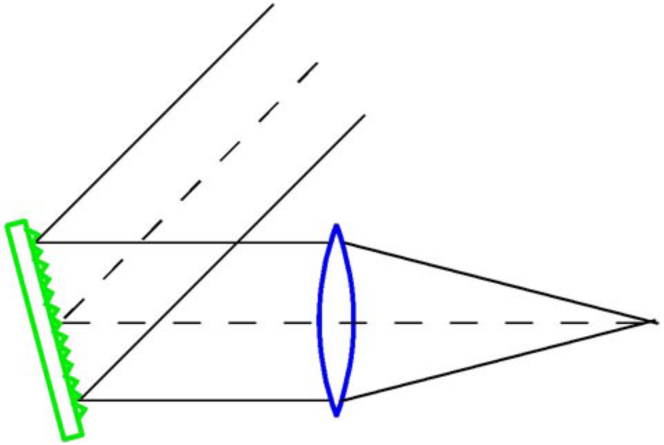
	Natural seeing: 0.5”	Diffraction limit: 0.0084”	Remarks
Slit width	727μm	12.2μm	F/10
Dcol	3 m	0.05 m	$\alpha = 26.7°$, ~ 900g/mm
Fcol	30 m	0.5 m	F/10
Size of spectrograph	36 × 9 × 4.5 [m]	0.6 × 0.15 × 0.075 [m]	Littrow mount
Camera F	F/0.62	F/37	15μm × 3 pix.
Precision of optical elements	~ 3λ	< λ/20	r.m.s.

A high dispersion grating is necessary!

Novel Gratings under Development

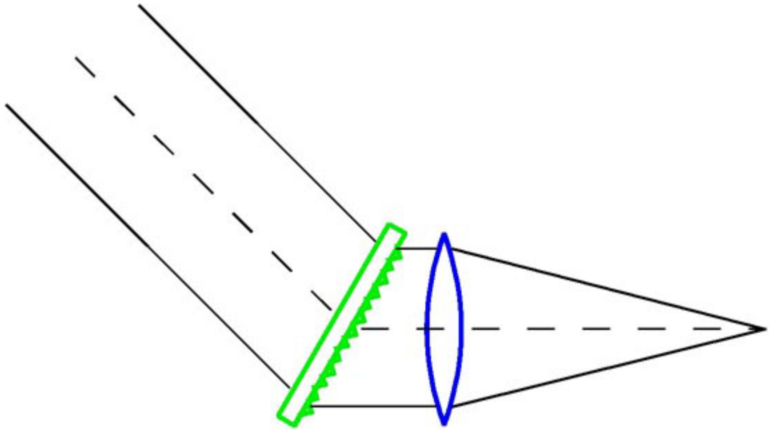
- Volume phase holographic (VPH) grating (All most finished for SUBARU)
  Thick grating of sinusoidal index modulation for the 1st order diffraction.
- Birefringence VPH grating
  VPH grating of which spectral efficiency is coincide with S and P polarization by using birefringent media.
- Birefringence Bragg binary (3B) grating
  Thick rectangular grating of which spectral efficiency is coincide with S and P polarization by using birefringent media. Available for the 1st and several diffraction order.
- Surface relief grating with acute angle grooves
  Replicated grism for MOIRCS with high index prism. (3rd ~6th diffraction order).
- Quasi-Bragg grating
  Transmission grating for high diffraction order fabricated by lamination of mirror plates. Having the imaging capability.
- Immersion grating (Already developed in 10μm band, under development for the near-infrared)
  High dispersion echelle grating of which optical path is filled up a high index media.
- Quasi-Bragg immersion grating

Reflection and Transmission Grating



Reflection grating

- Utilize wide range electromagnetic wave from X ray to THz.
- Relatively inexpensive.

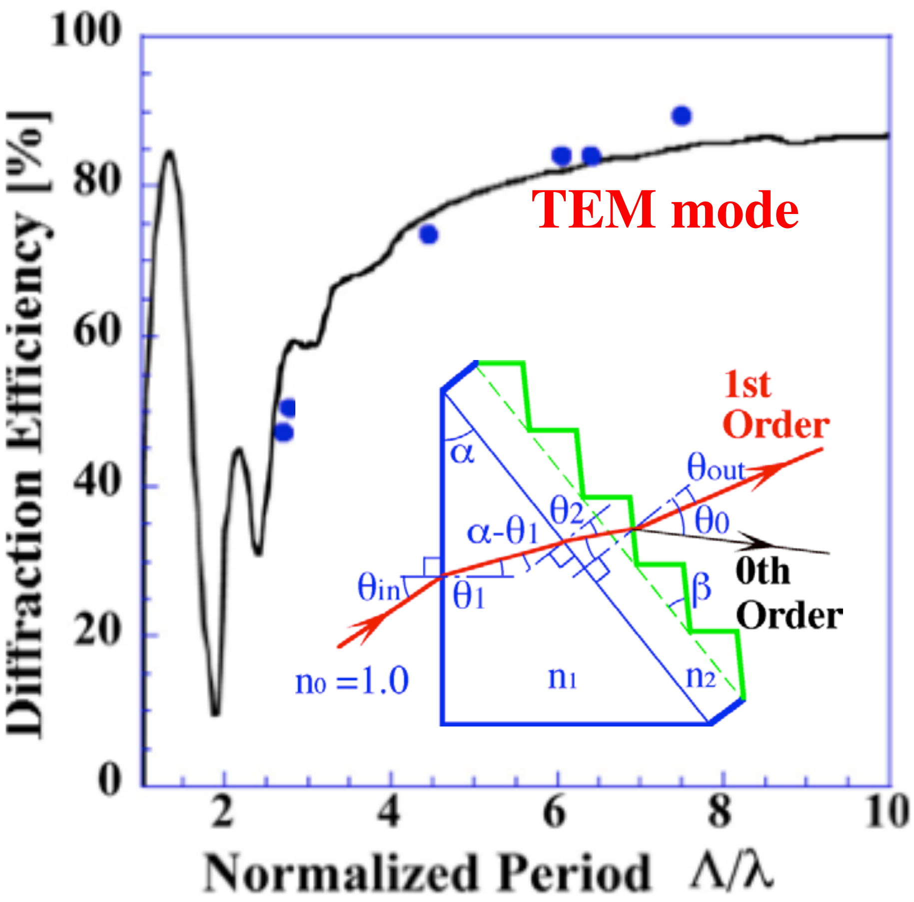


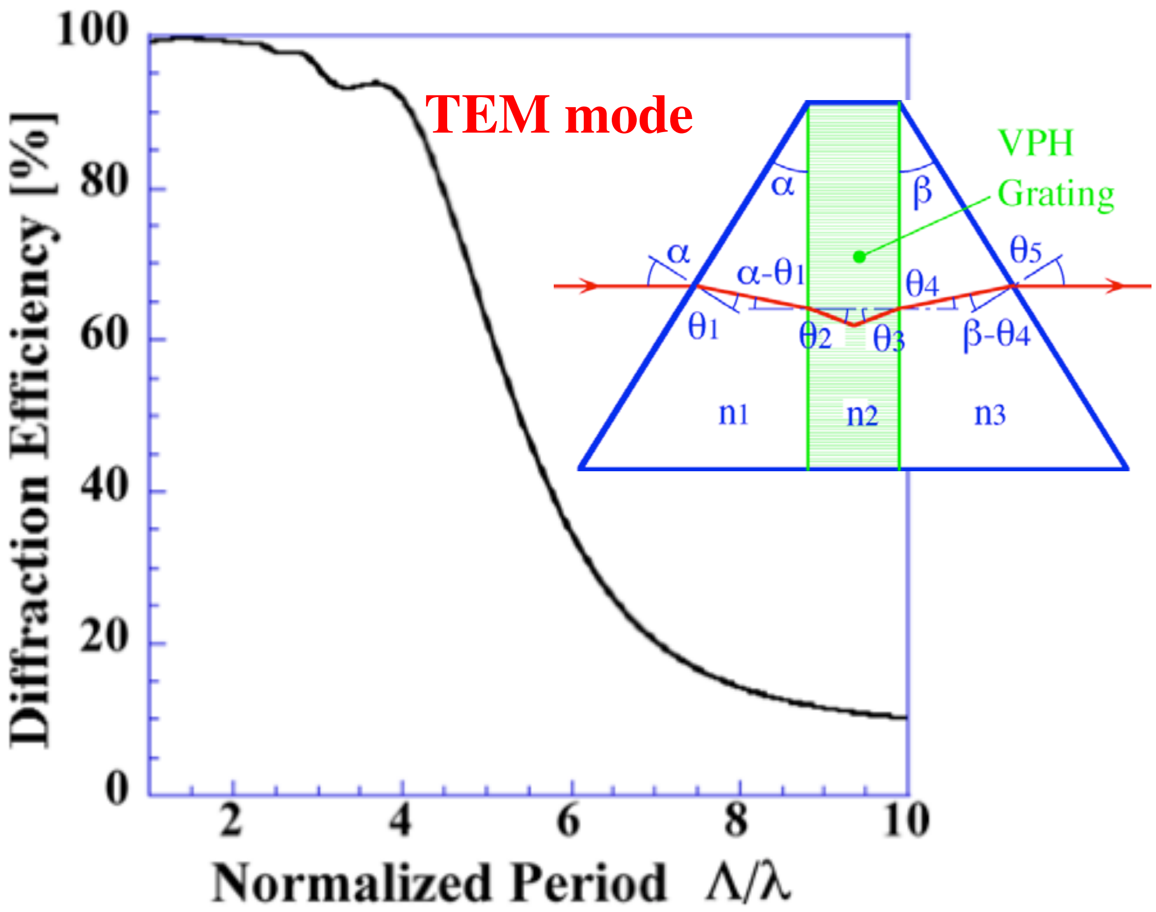
Transmission grating

- Collimator and camera optics could place nearby the grating.
- It is able to reduce size of the spectro-meter.

Development of the transmission grating for higher-order diffraction with high dispersion has been demanded.

Efficiencies of Transmission Gratings



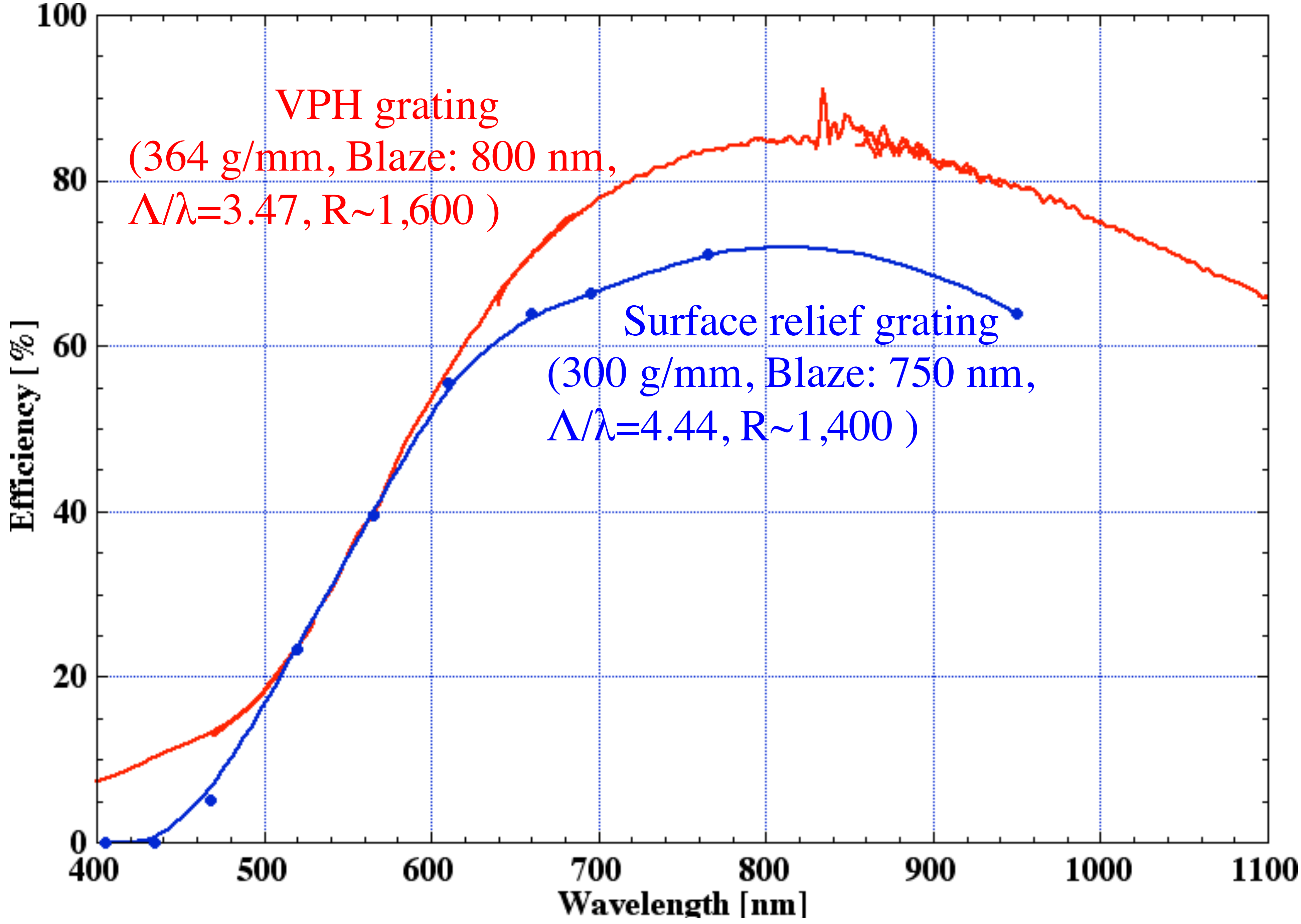


Surface relief grating: Efficiency decreases steeply below 4 Λ/λ

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

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

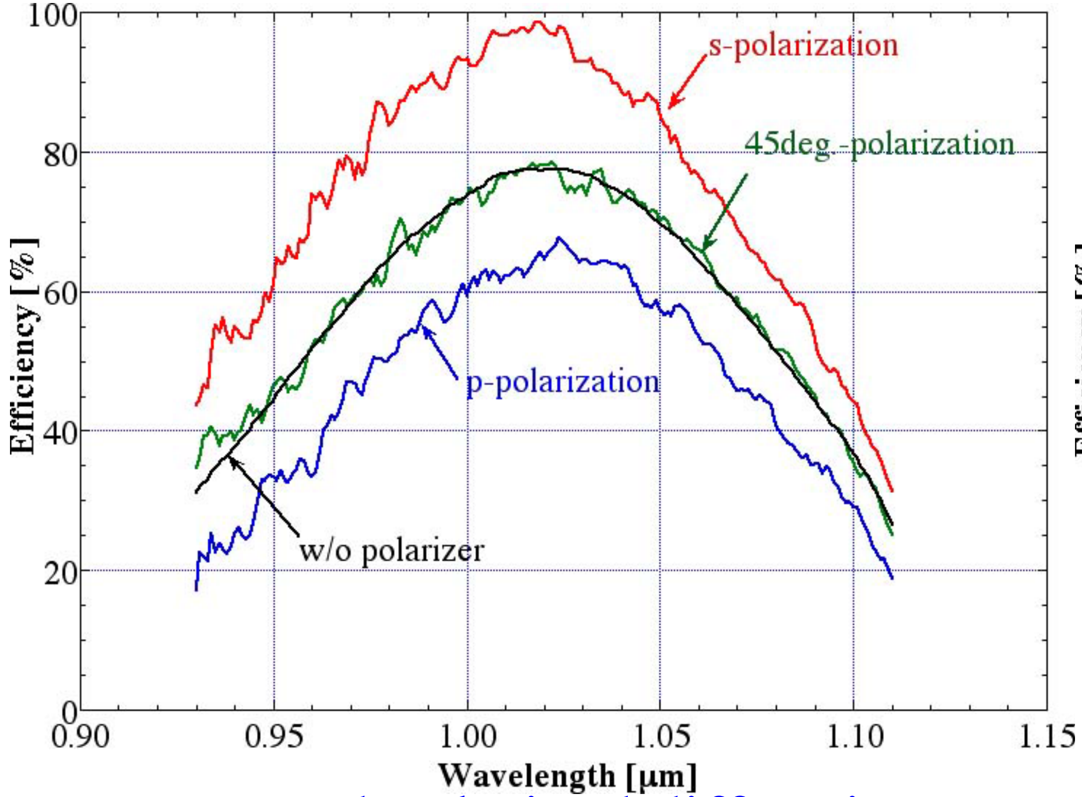
Diffraction Efficiencies of VPH Grism for FOCAS



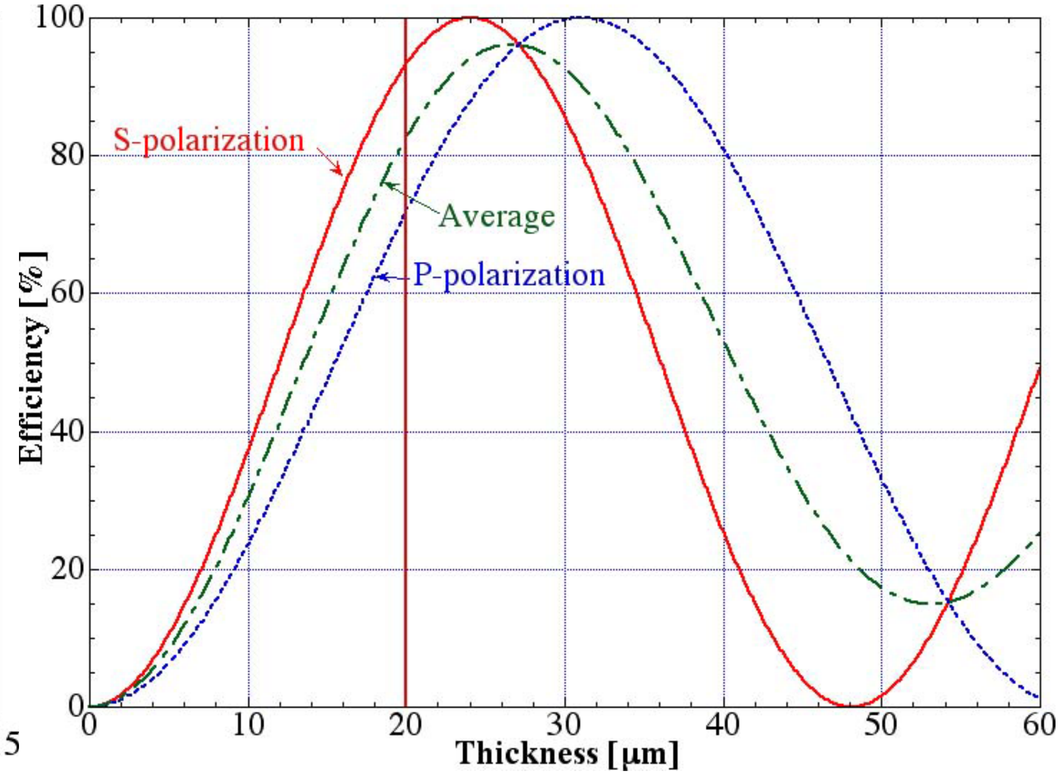
Polarized Diffraction Efficiency of VPH Grating

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

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



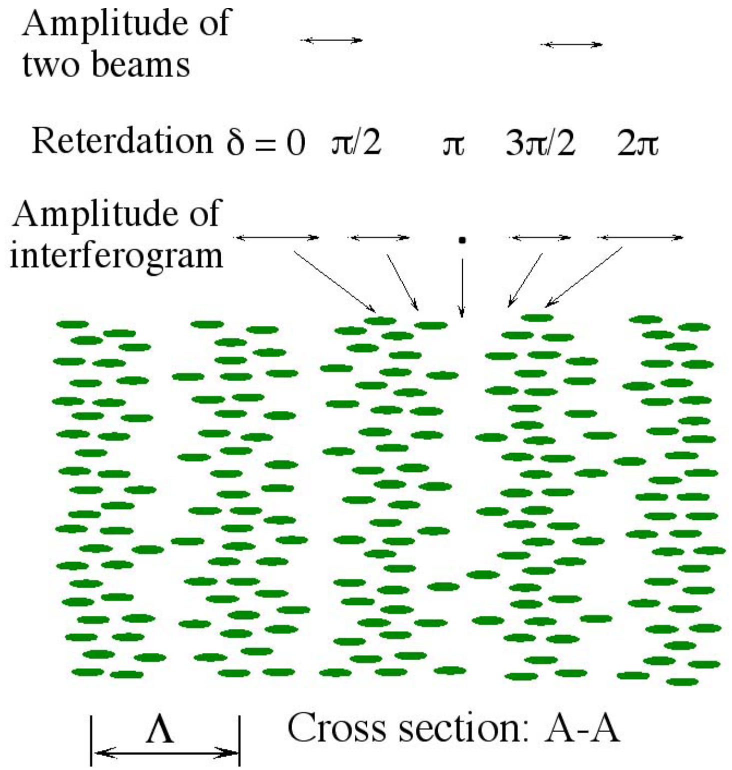
Measured polarized diffraction efficiencies of a prototype VPH grating for a MOIRCS grism. n_{ave}=1.53, Λ=0.984 μm t = 20 μm, θ=19.8°@λ=1.02 μm.

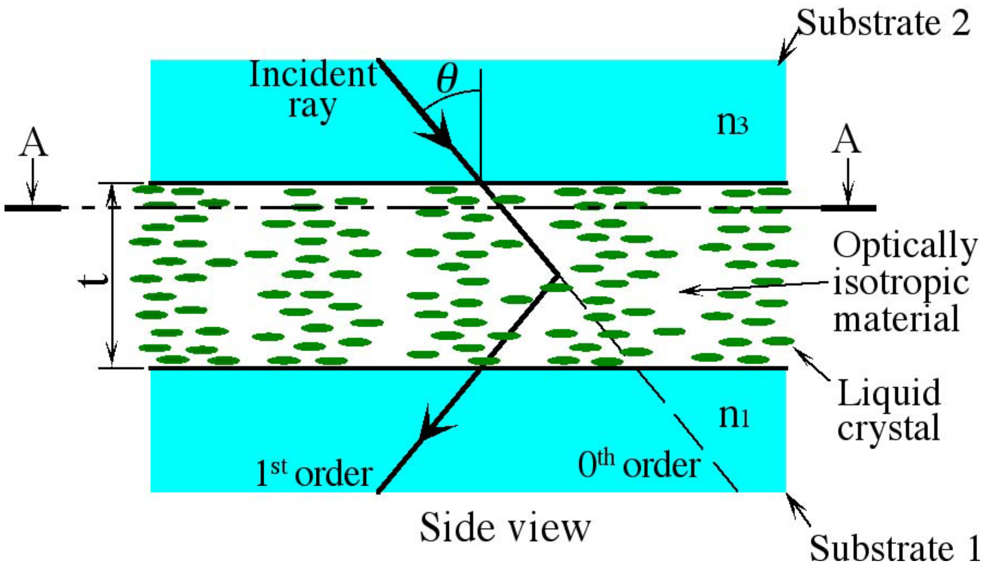


Calculated polarization diffraction efficiencies versus thickness of a VPH grating with refractive index modulation: Δn=0.017.

[Ebizuka et al., PASJ, **63**, 2011b]

Birefringence VPH Grating



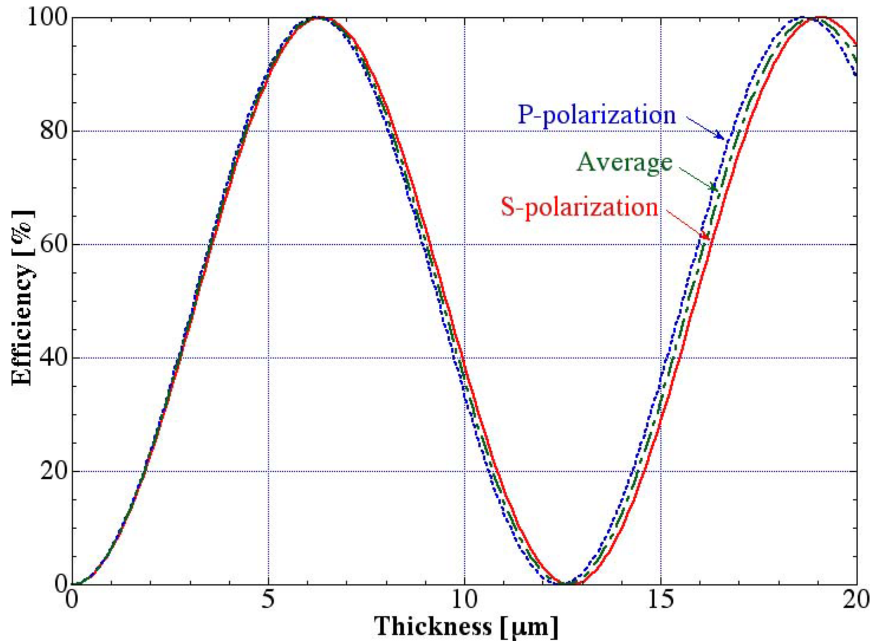


$$\frac{n_{S\max} - n_{S\min}}{(n_{S\max} + n_{S\min})\sin 2\theta_S} = \frac{(n_{P\max} - n_{P\min})\boxed{\cos 2\theta_P}}{(n_{P\max} + n_{P\min})\sin 2\theta_P}$$

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

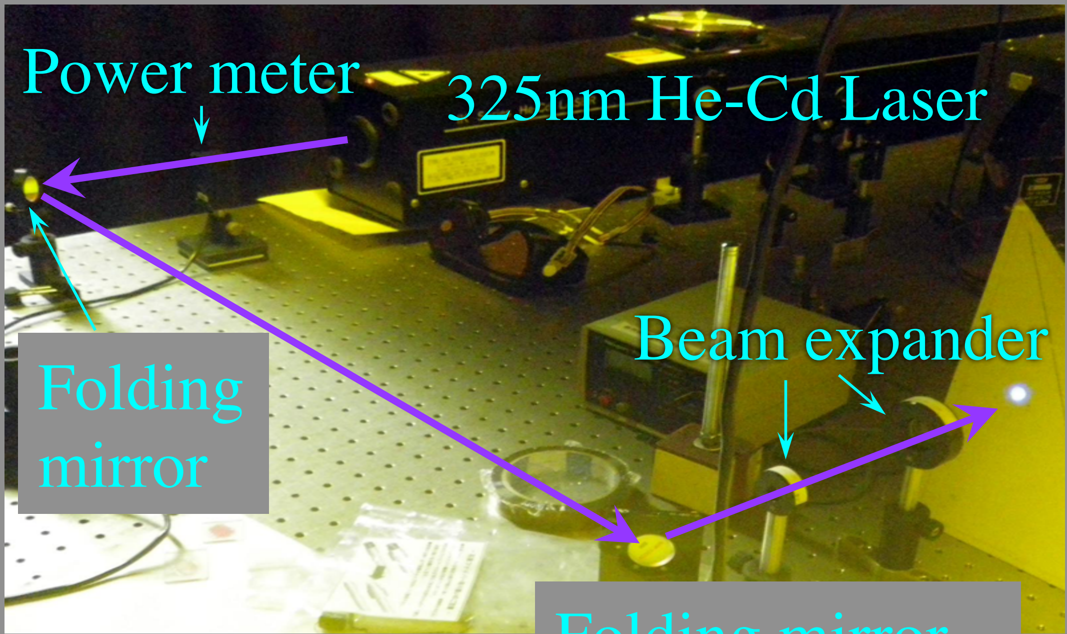
Snell's low

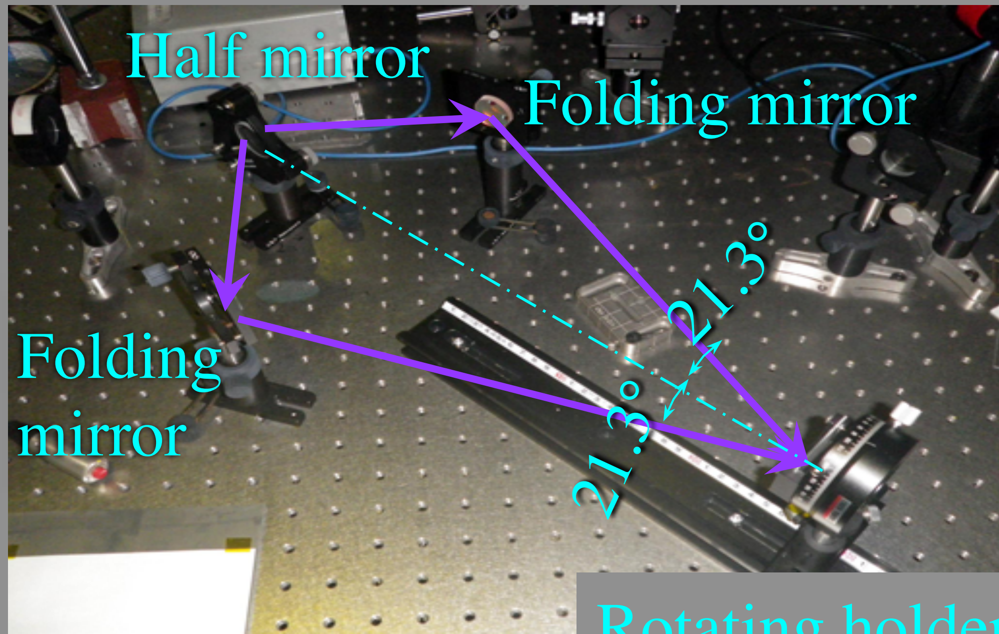
$$\frac{n_{S\max} - n_{S\min}}{\cos\theta_S} \cong \frac{(n_{P\max} - n_{P\min})\boxed{\cos 2\theta_P}}{\cos\theta_P}$$



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

Fabrication for Liquid Crystal Grating



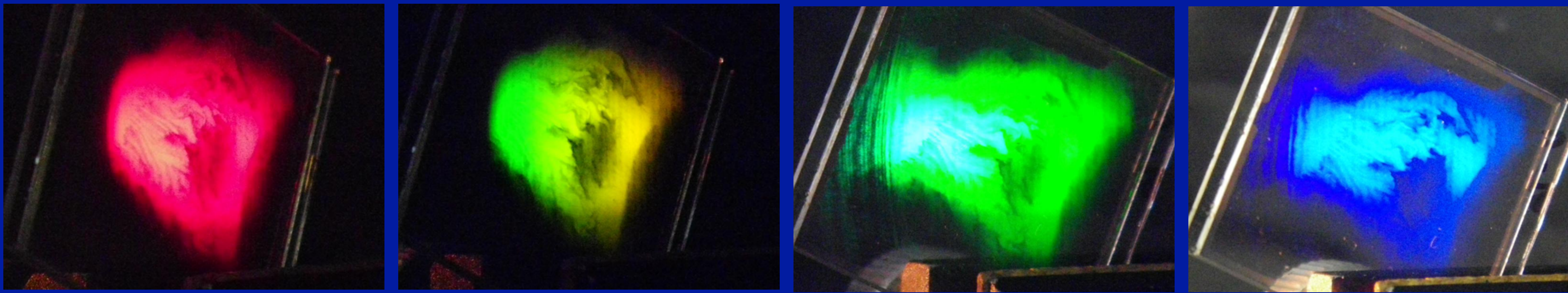


Two beam interference exposure optics

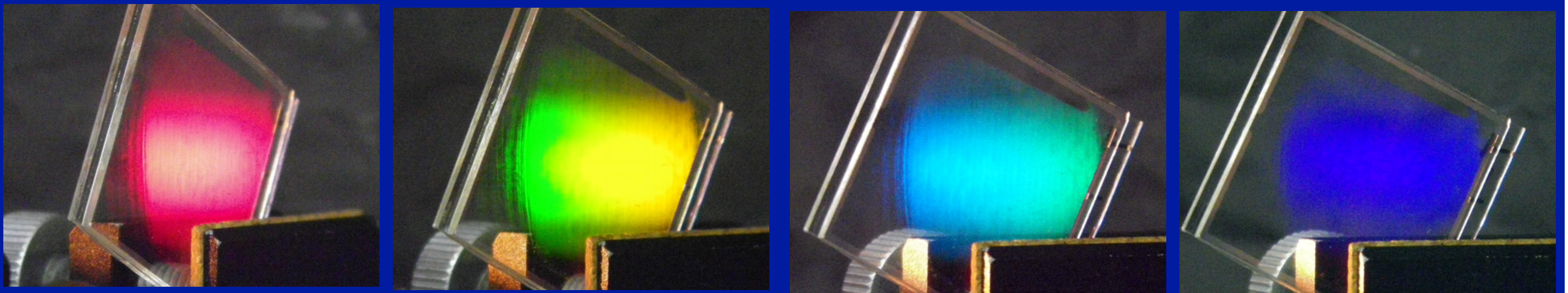
$$\Lambda = m\lambda/2\sin\theta_B = 0.325/2\sin 21.3° = 0.447\ [\mu m]$$

(2,235 grooves/mm)

Liquid Crystal VPH grating

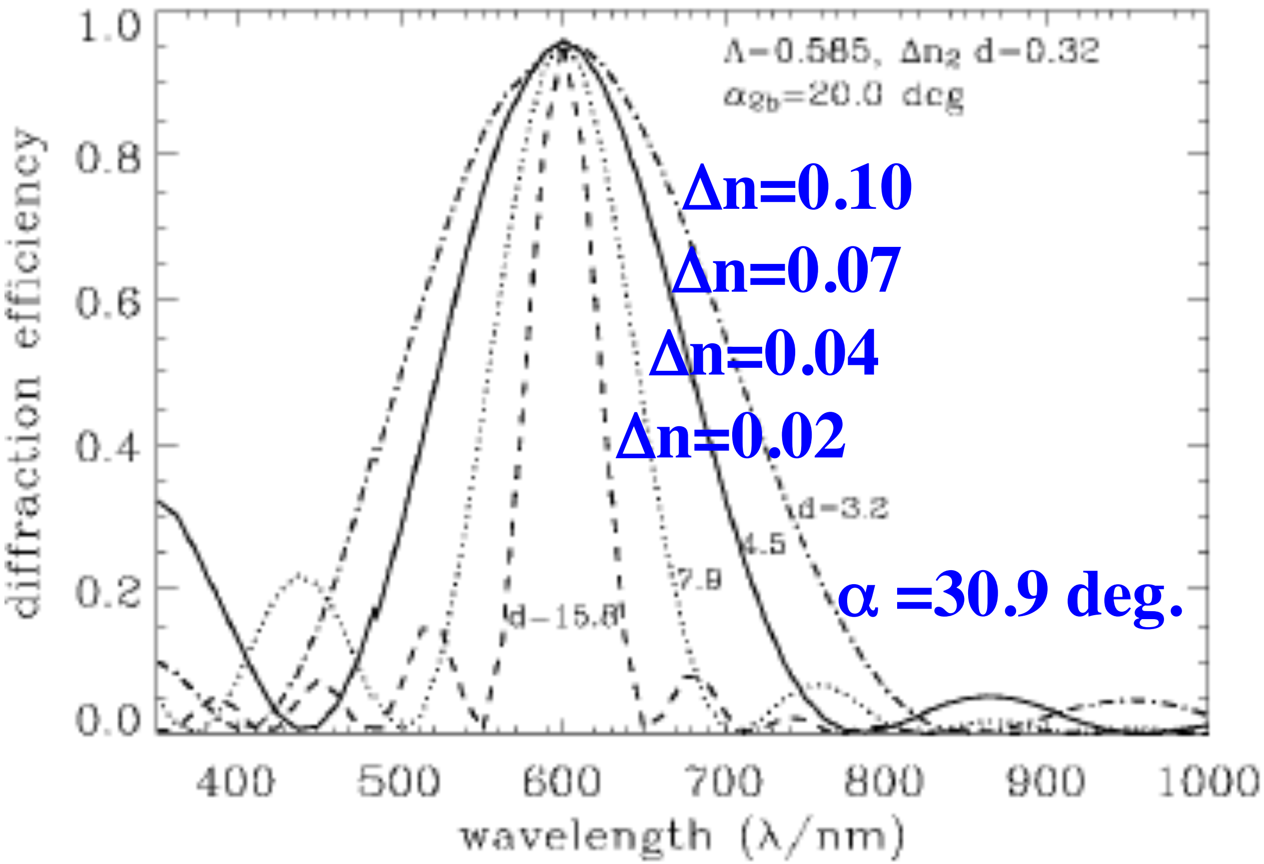


DIC ULC17A+Merck MJ041609, UV: 11mW, 180sec.



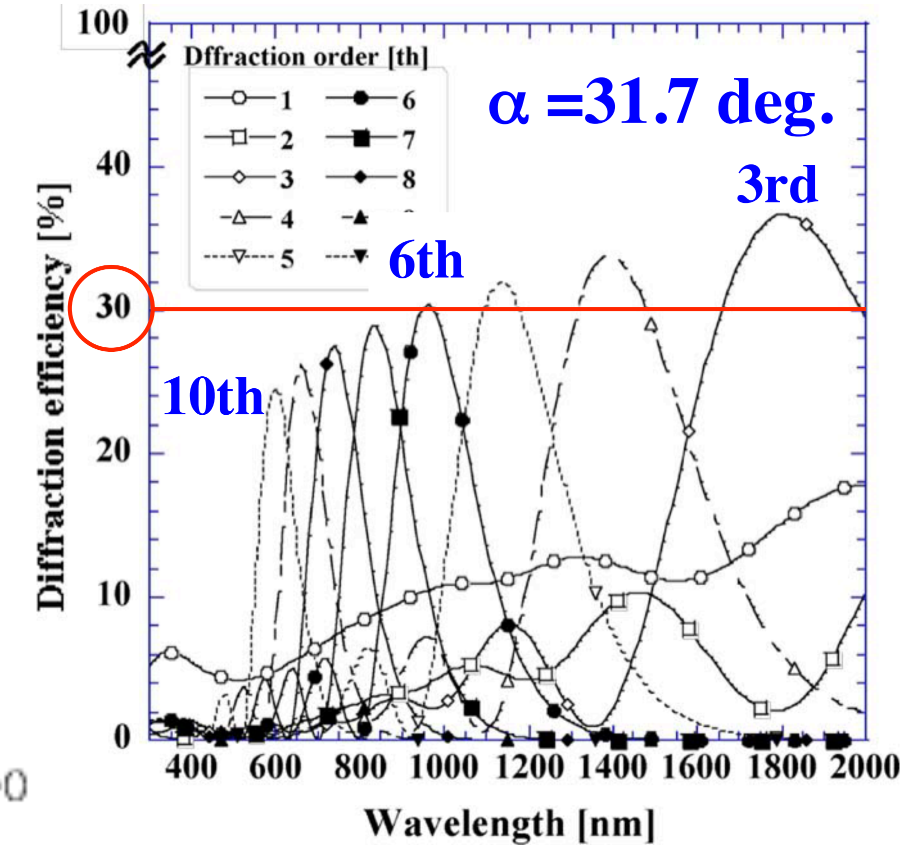
DIC TKN+MerckMJ041609, UV: 12.4 mW, 180sec.

Limitation of VPH Grating



Band width of VPH grating becomes narrow in diffraction angle: α increase because semi-amplitude of index modulation (Δn) of dichromated gelatin (DCG) is up to 0.15.

[Baldry et al., PASP, 116, 2004]

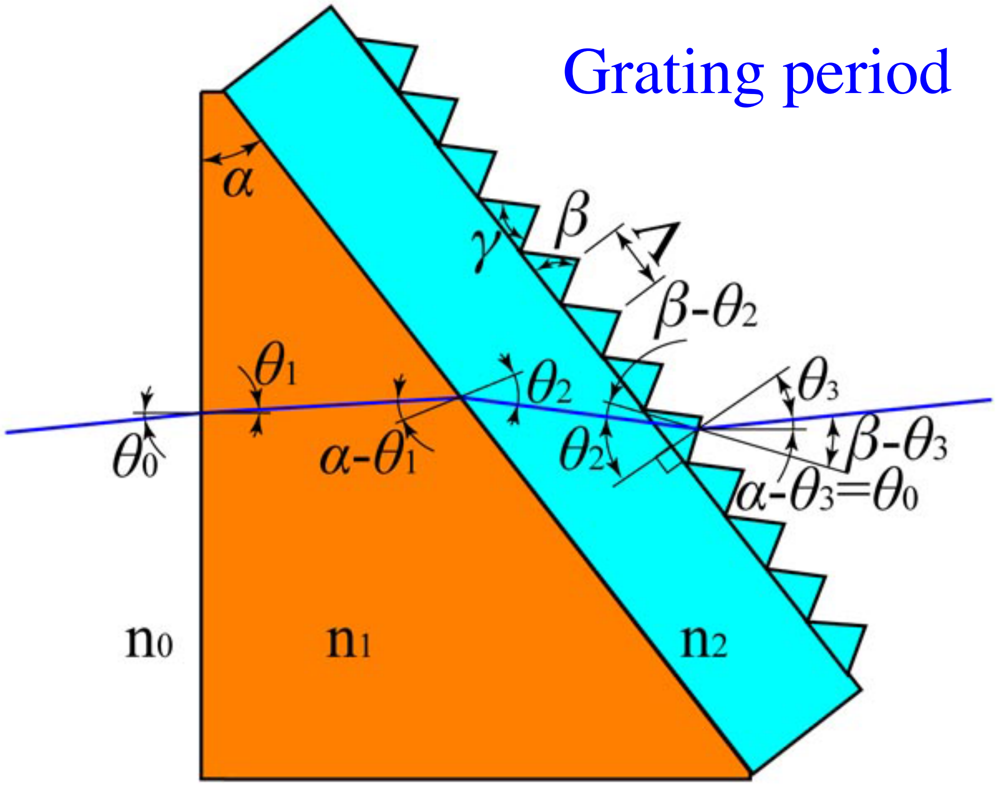


Diffraction efficiency of VPH grating decrease toward higher orders.

[Oka et. al., SPIE, 5290, 2004]

MOIRCS SR Grism

Prism material 1	: ZnSe (n_1= 2.4529@1.65 μm)
Plate	: S-FPM3 (n_2= 1.5240@1.65 μm)
Prism vertex angle	: $\alpha = 23.8°$
Incident angle	: $\theta_0 = 5°$
Groove blaze angle	: $\beta = 64.8°$
Groove vertex angle	: $\gamma = 61.8°$
Grating period	: Λ= 10.79μm (92.68 grooves/mm)



7th, R= 1,487@0.88 μm (z band)

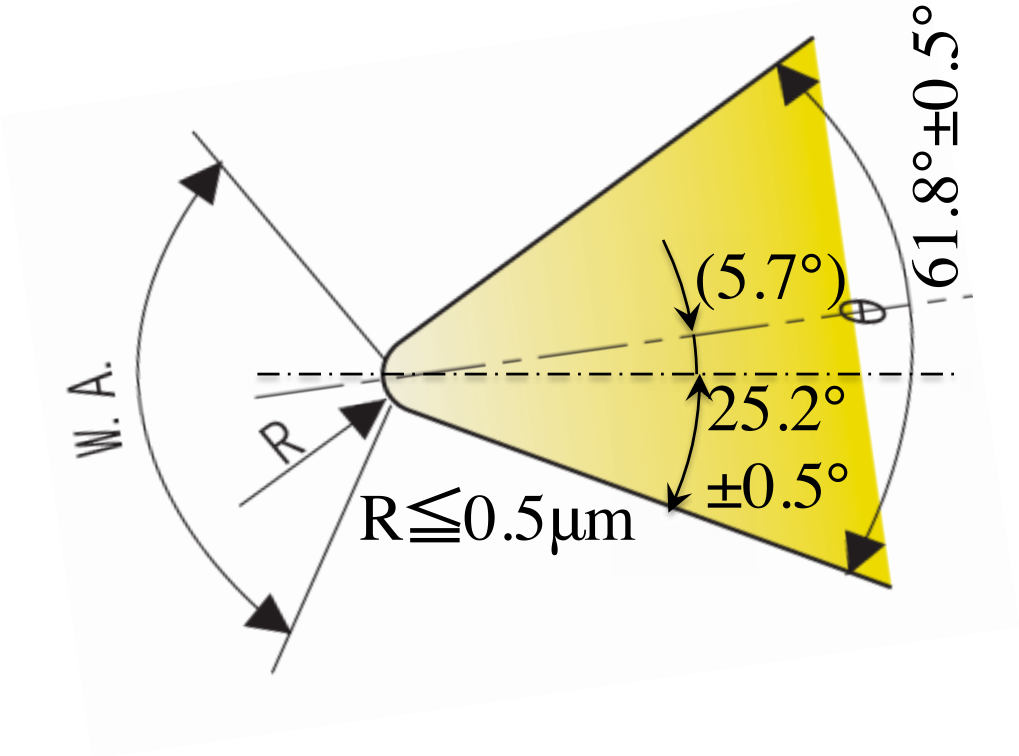
6th, R= 1,431@1.02 μm (Y band)

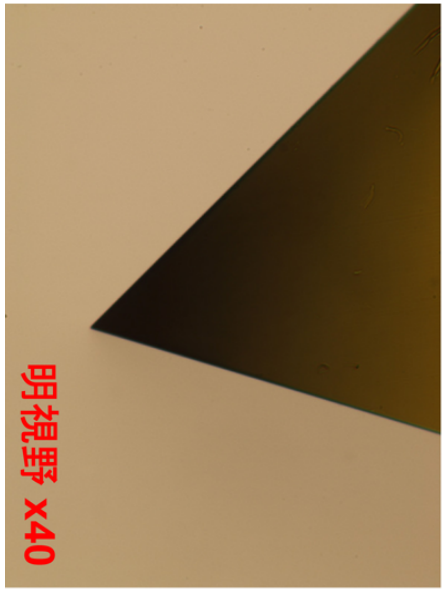
5th, R= 1,408@1.25 μm (J band)

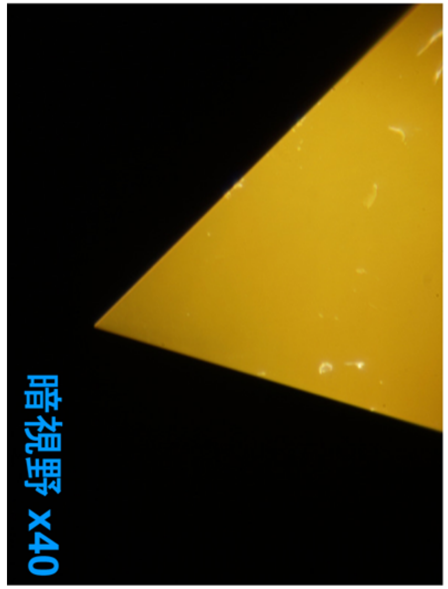
4th, R= 1,434@1.65 μm (H band)

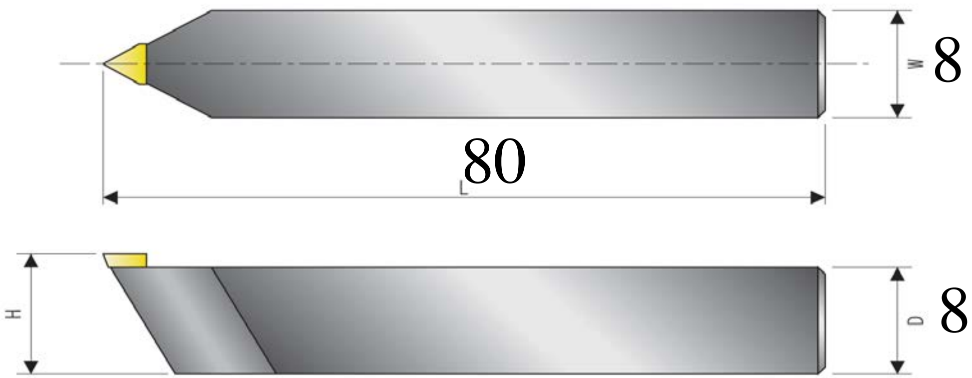
3rd, R= 1,419@2.20 μm (K band)

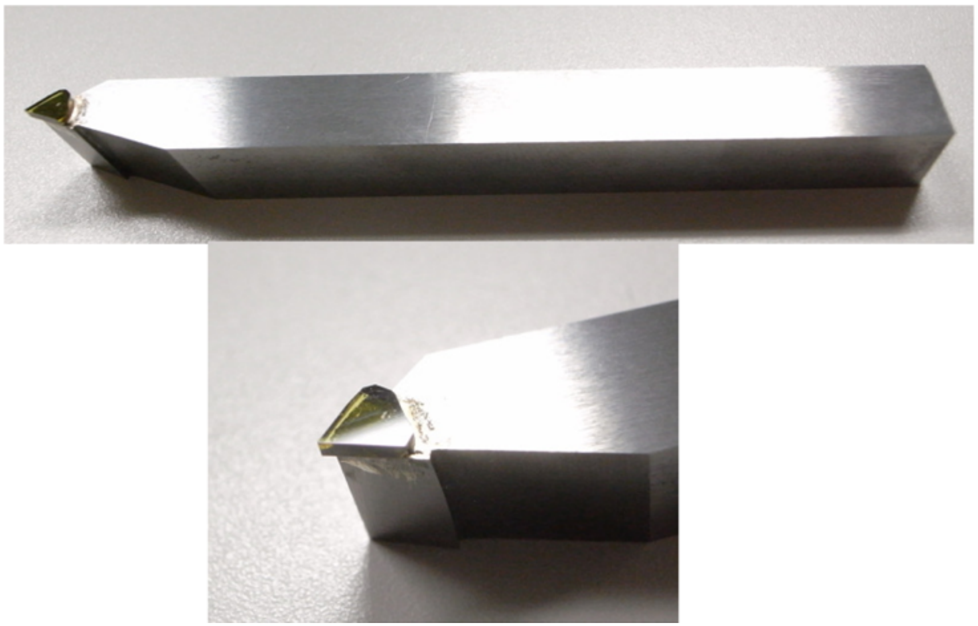
Diamond Bite for Master Grating



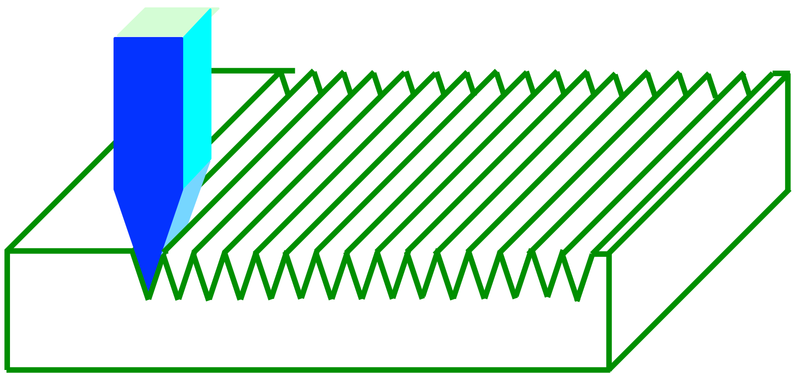








Fabrication Method for MOIRCS SR Grating



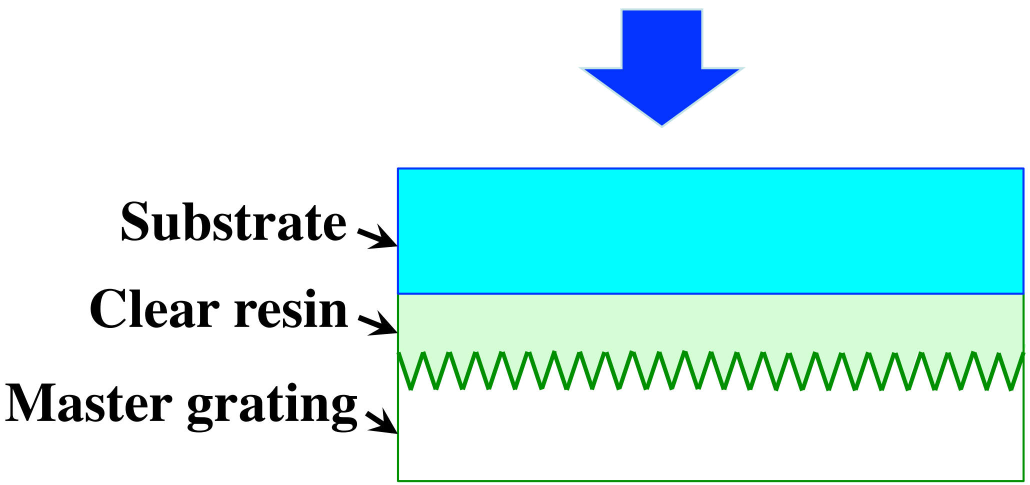
Shaper cutting of master grating

Work : Ni-P alloy of Non-electrolytic plating

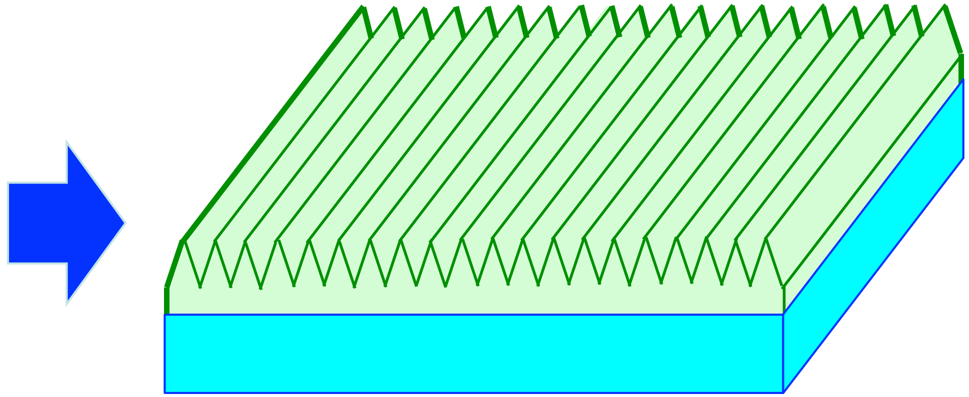
Blaze angle : $\beta = 64.8°$

Vertex angle : $\gamma = 61.8°$

Grating period : $\Lambda = 10.79\mu m$



Replication



Finish

Limitation of Surface Relief Grating

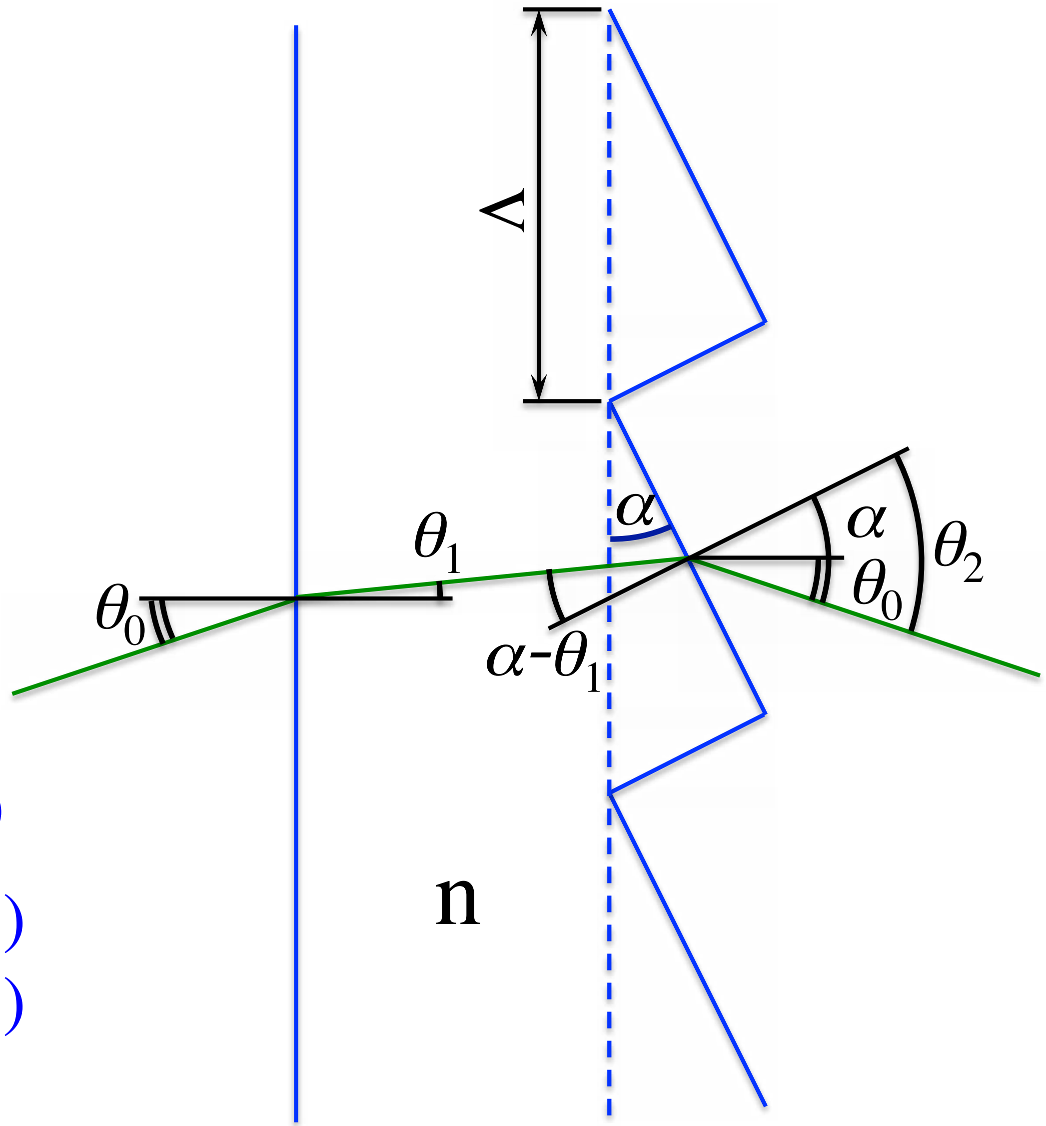
$$\sin\theta_0 = n \sin\theta_1$$
$$n \sin(\alpha - \theta_1) = \sin\theta_2$$
$$\theta_2 = \alpha + \theta_0$$

$$n \sin(\alpha - \theta_1) = \sin(\alpha + \theta_0)$$
$$n (\sin\alpha \cos\theta_1 - \sin\theta_1 \cos\alpha) = \sin\alpha \cos\theta_0 + \sin\theta_0 \cos\alpha$$
$$(n \cos\theta_1 - \cos\theta_0) \sin\alpha = (\sin\theta_0 + n \sin\theta_1) \cos\alpha = 2\sin\theta_0 \cos\alpha$$
$$\tan\alpha = 2\sin\theta_0 / (n \cos\theta_1 - \cos\theta_0)$$

$n = 1.8,\ \theta_0 \le 36° \ (\theta_2 > 90°)$

$n = 3.0,\ \theta_0 \le 54° \ (\theta_2 > 90°)$

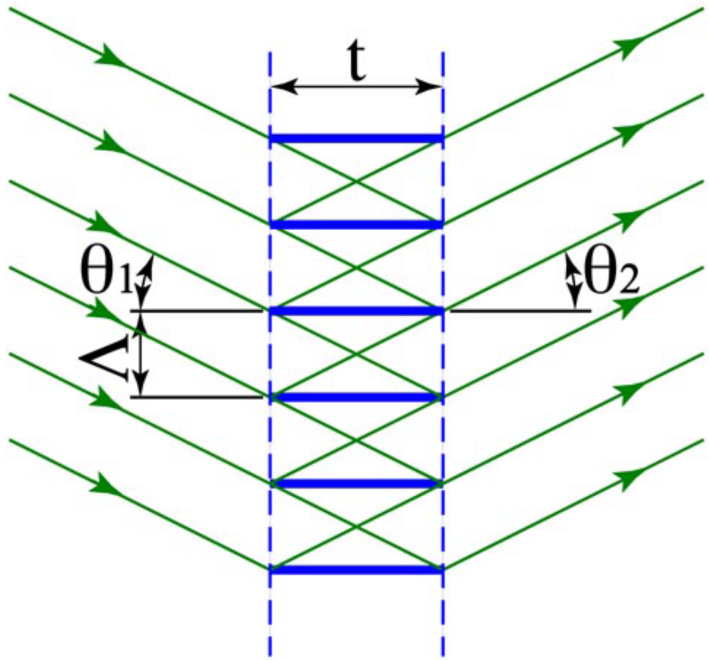
Diamond: $n = 2.46$@400nm



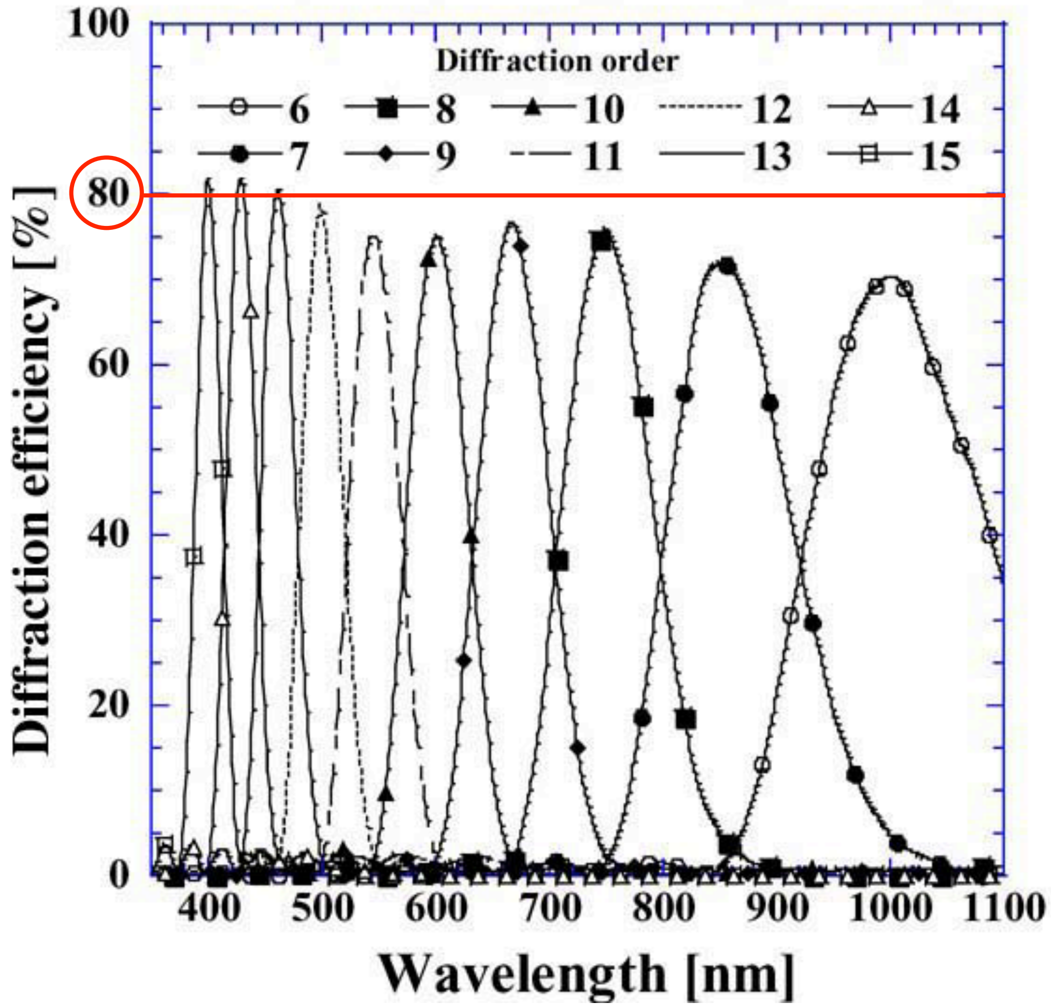
Surface relief grating with saw tooth grooves is not feasible for the medium and high res. gratings.

Quasi-Bragg grating

Quasi-Bragg Grating for Higher Orders



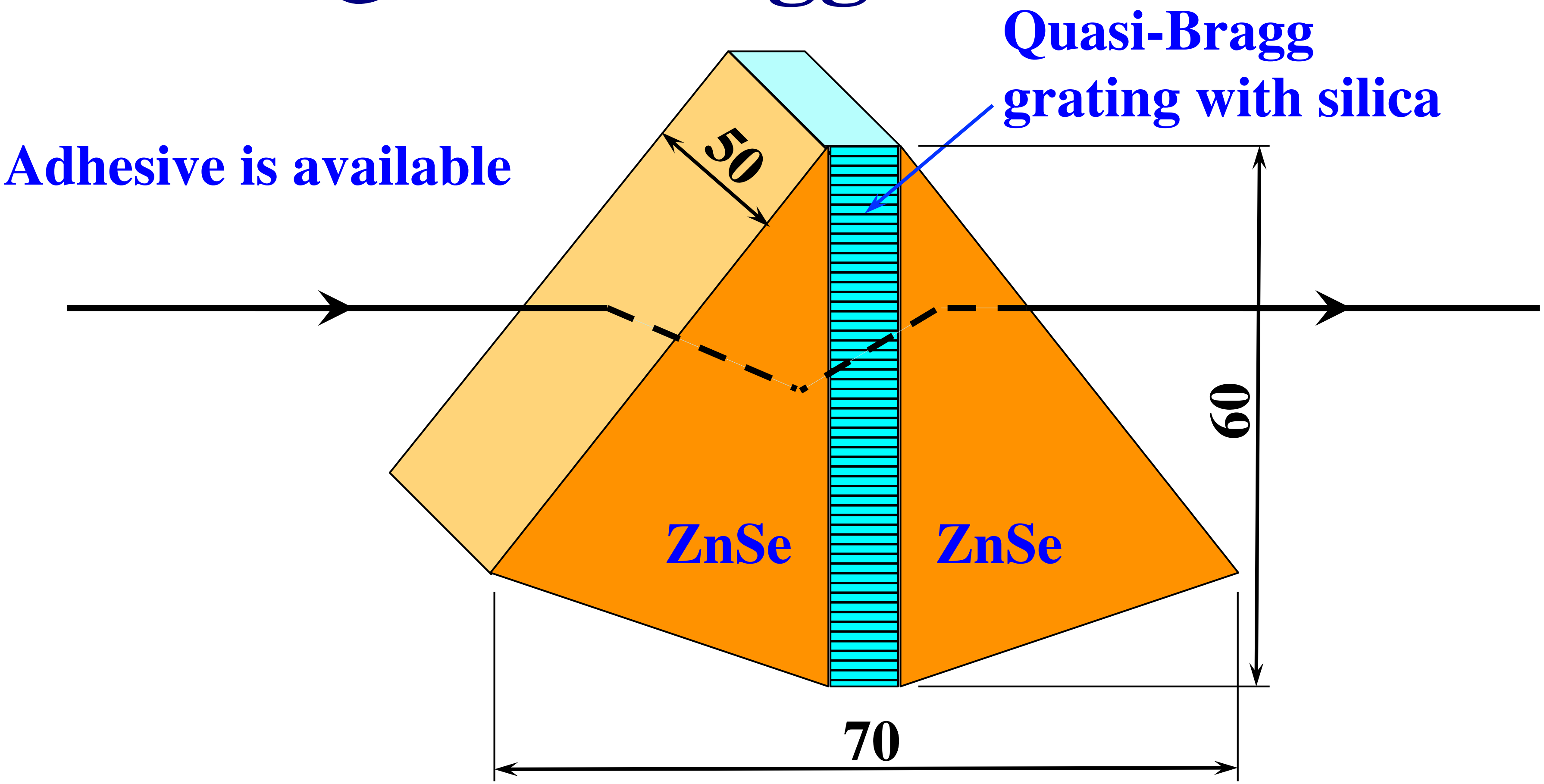
- Quasi-Bragg grating (QBG) achieves high diffraction efficiency toward higher order.
- QBG inherits advantages of VPH grating.
- QBG has the imaging property.



Diffraction Efficiency of quasi-Bragg grating. n = 1.50, Λ = 5.71 μm, t =15.27 μm, $\theta_1 = \theta_2 = 20.51°$.

[Oka et al., SPIE 5290, 2004]

Quasi-Bragg Grism



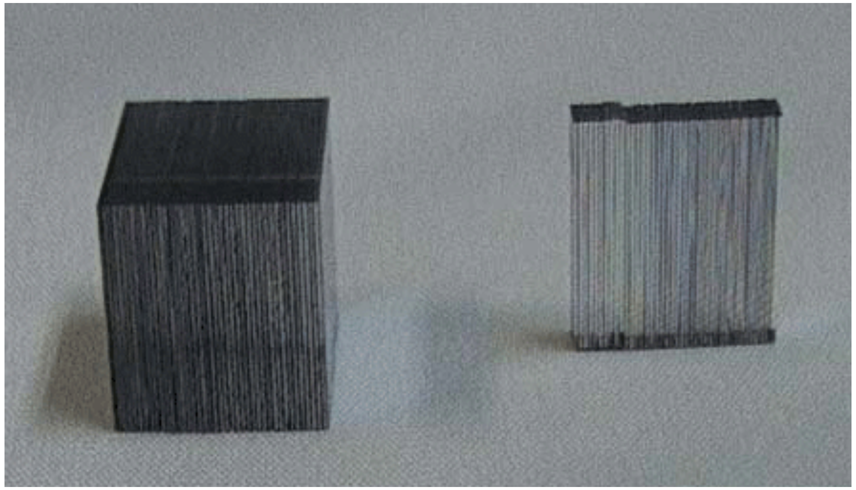
Visible (300~1000nm), Near IR (1.0~2.5μm)

Substrate : Silica, optical glass etc.

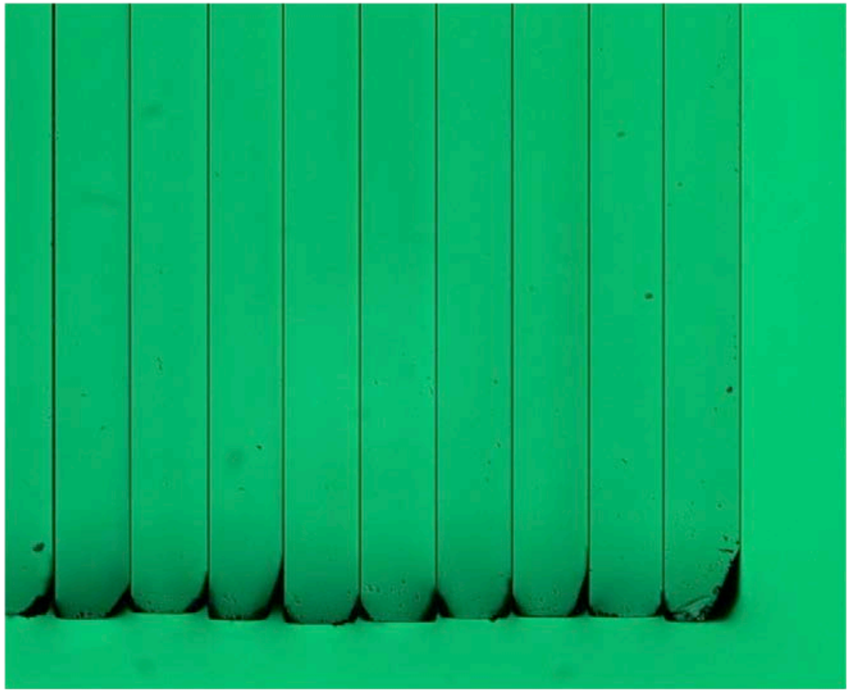
Size × No. of layer: 50 × 0.54 × t0.2 × 350psc.

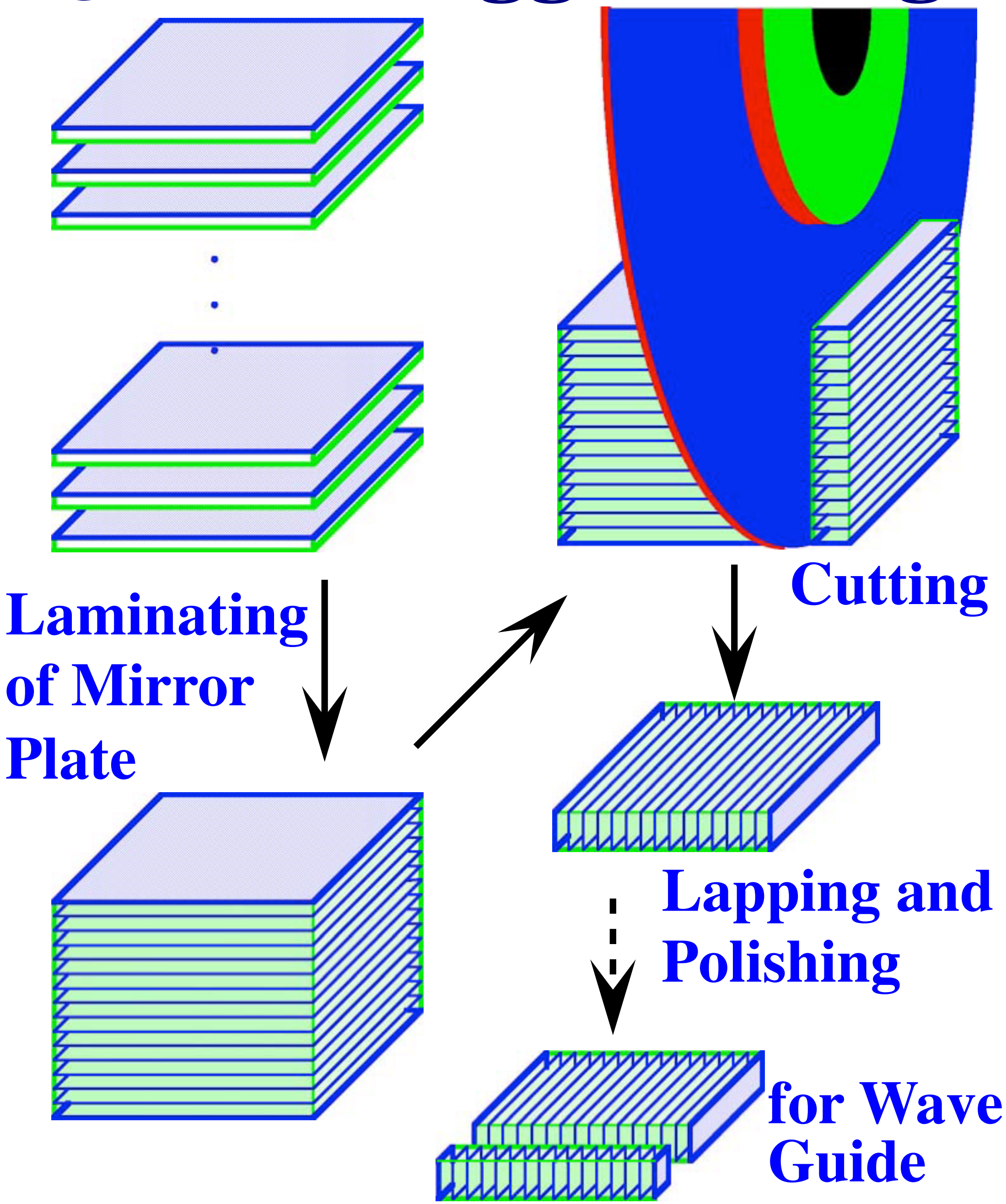
Periodic error : 100~500nm (P-V), 20~100nm (rms)

Trial Fabrication of Quasi-Bragg Grating 1

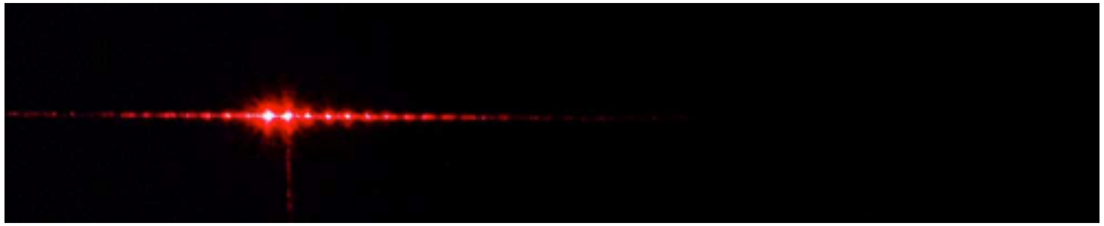


A: 10 x 10 x 0.2 x 40 pcs (left),
B: 1.5 x 10 x 0.2 x 40 pcs (right)

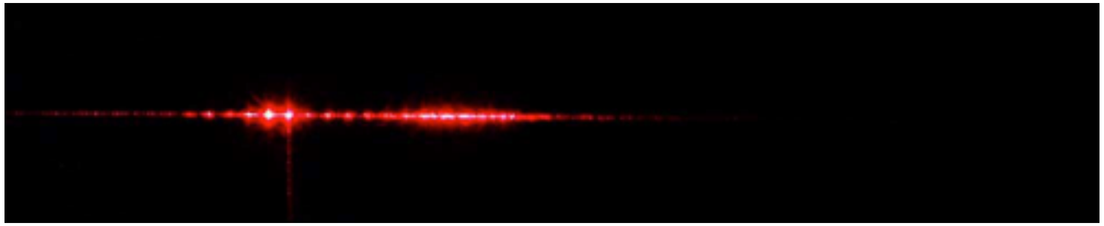


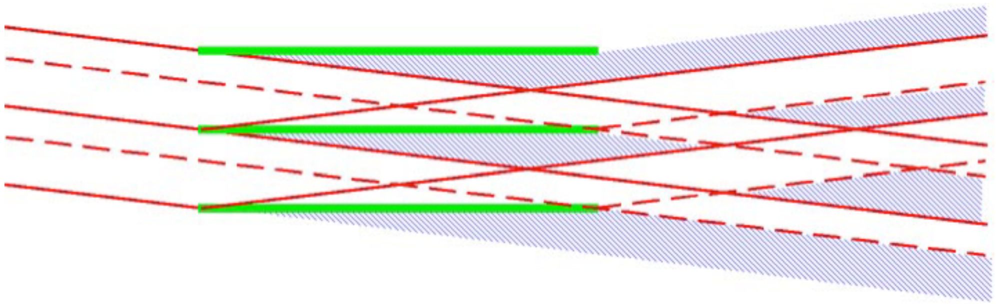


Diffraction by Quasi-Bragg Grating

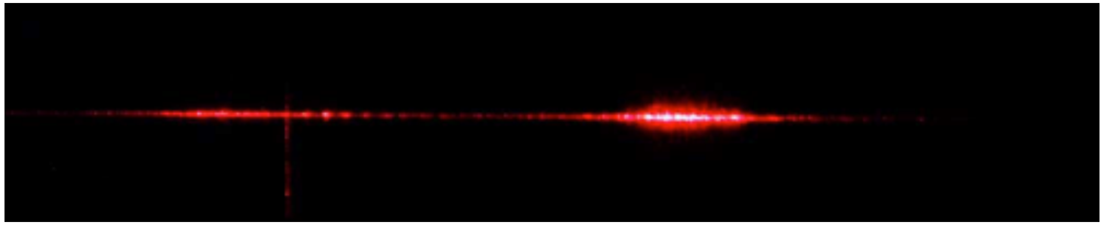


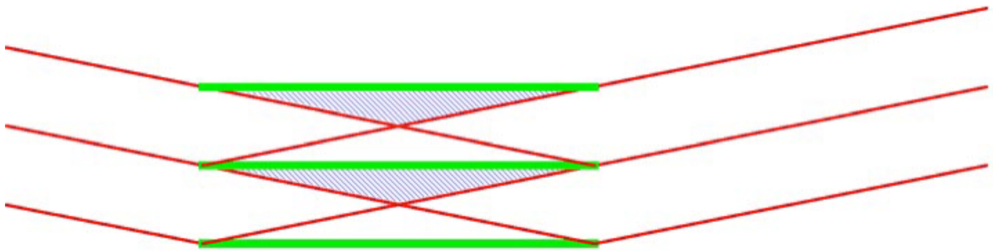
Normal incidence



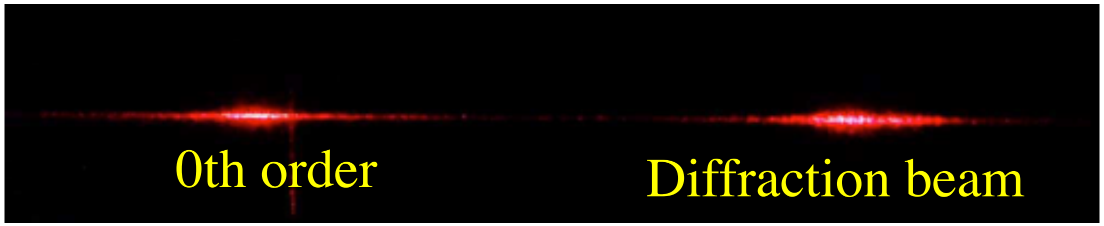


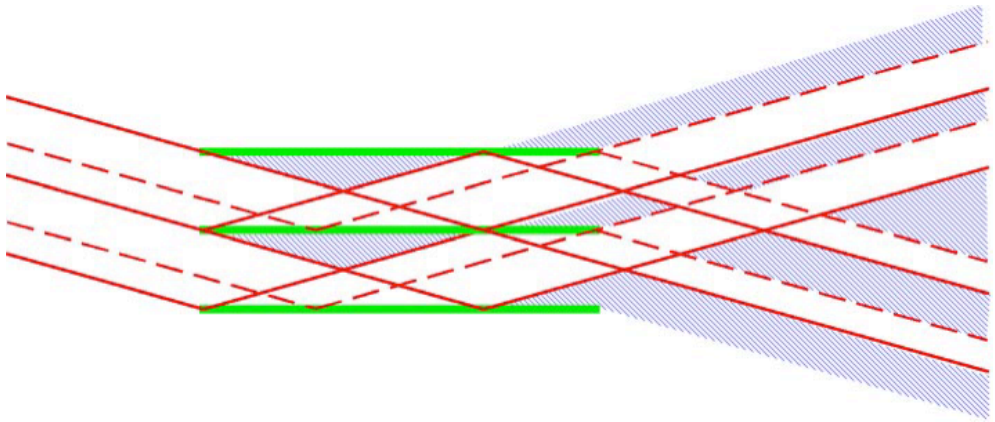
Small incident angle





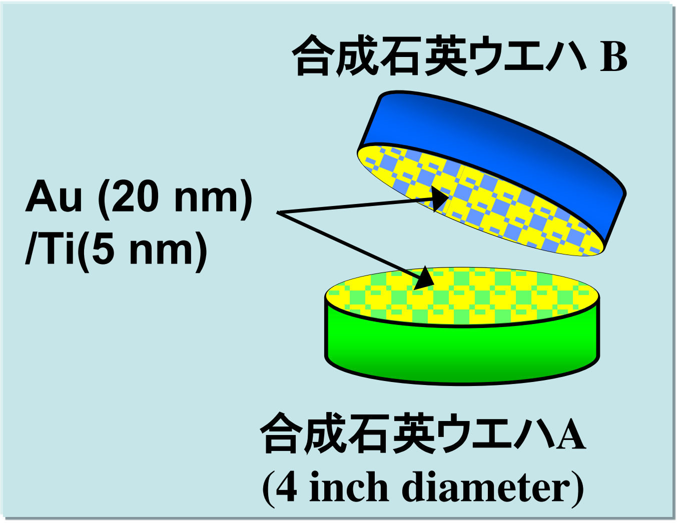
Ideal incident angle

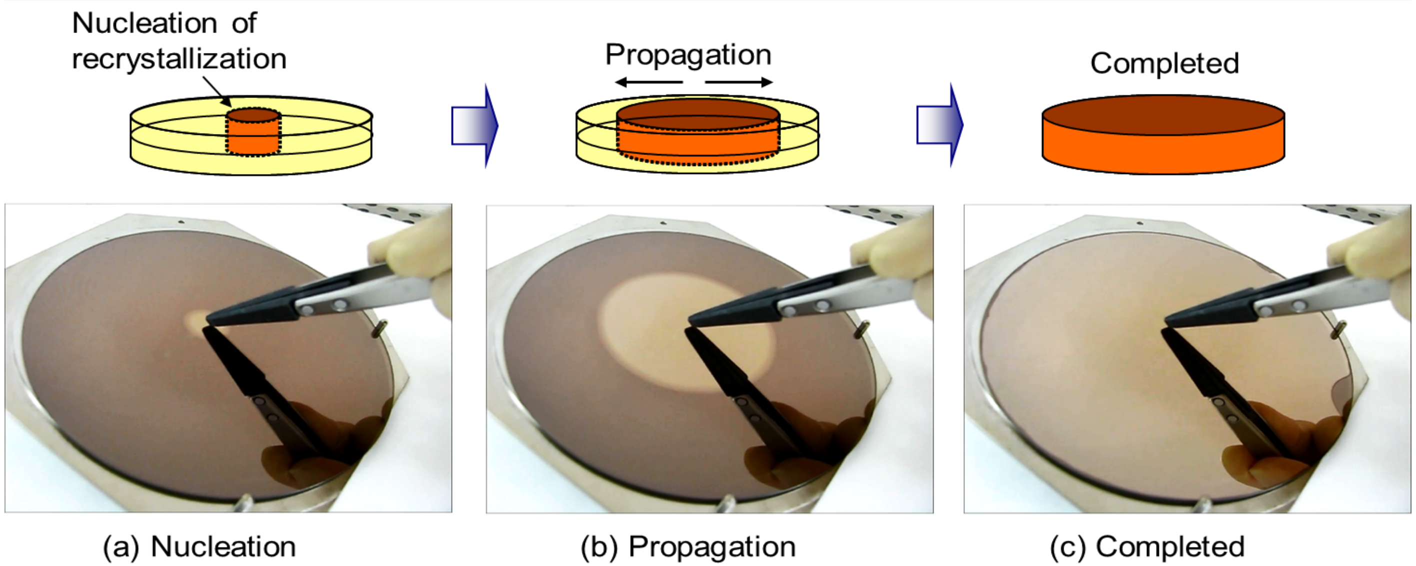




Large incident angle

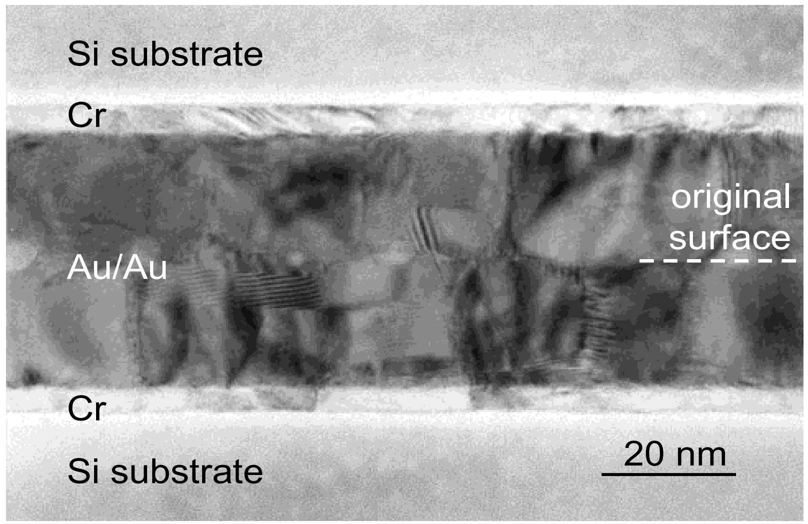
Au膜を用いた大気中の原子拡散接合法





片側あたりAu(20 nm)/Ti(5 nm)の膜厚で合成石英ウエハを接合した際の連続写真

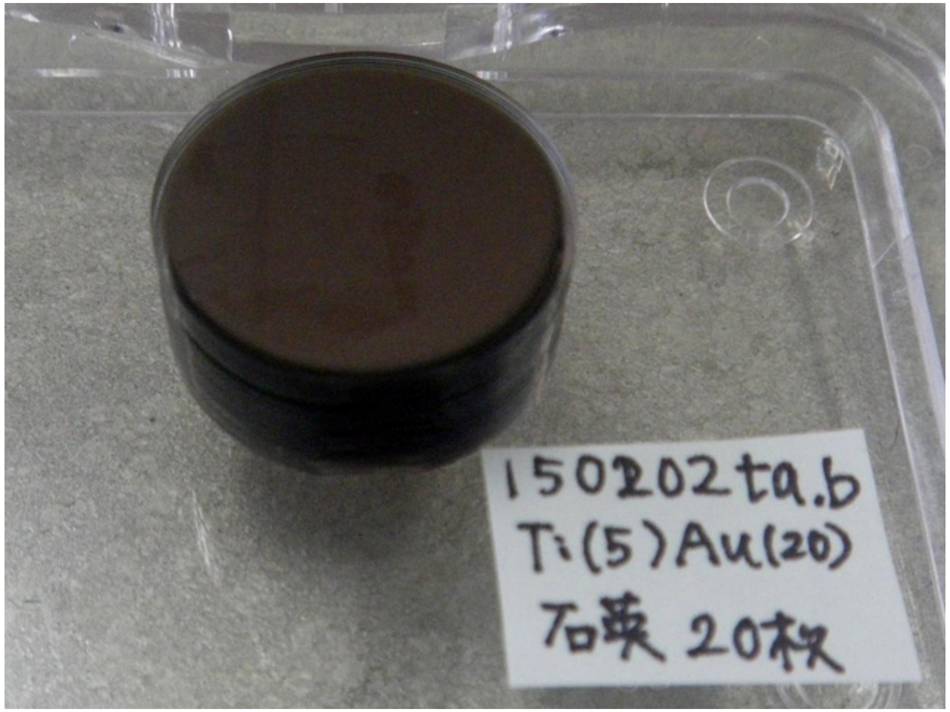
- 重ねたウエハの一部をピンセット等で加圧すると，**Au/Au界面に再結晶の核が形成され，瞬時にウエハ全体に伝搬**.
- 真空中の接合でも同様であると推定.



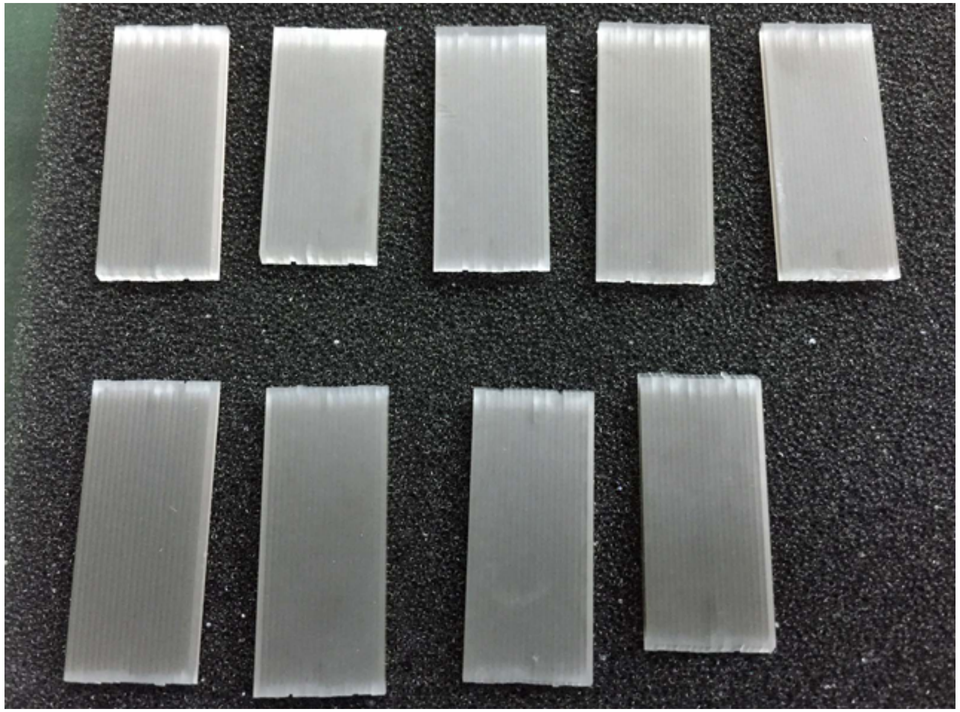
片側あたりAu(20 nm)/Cr(5 nm)の膜厚でSiウエハを接合した際の断面TEM写真

TOHOKU UNIVERSITY

Trial Fabrication of Quasi-Bragg Grating 2



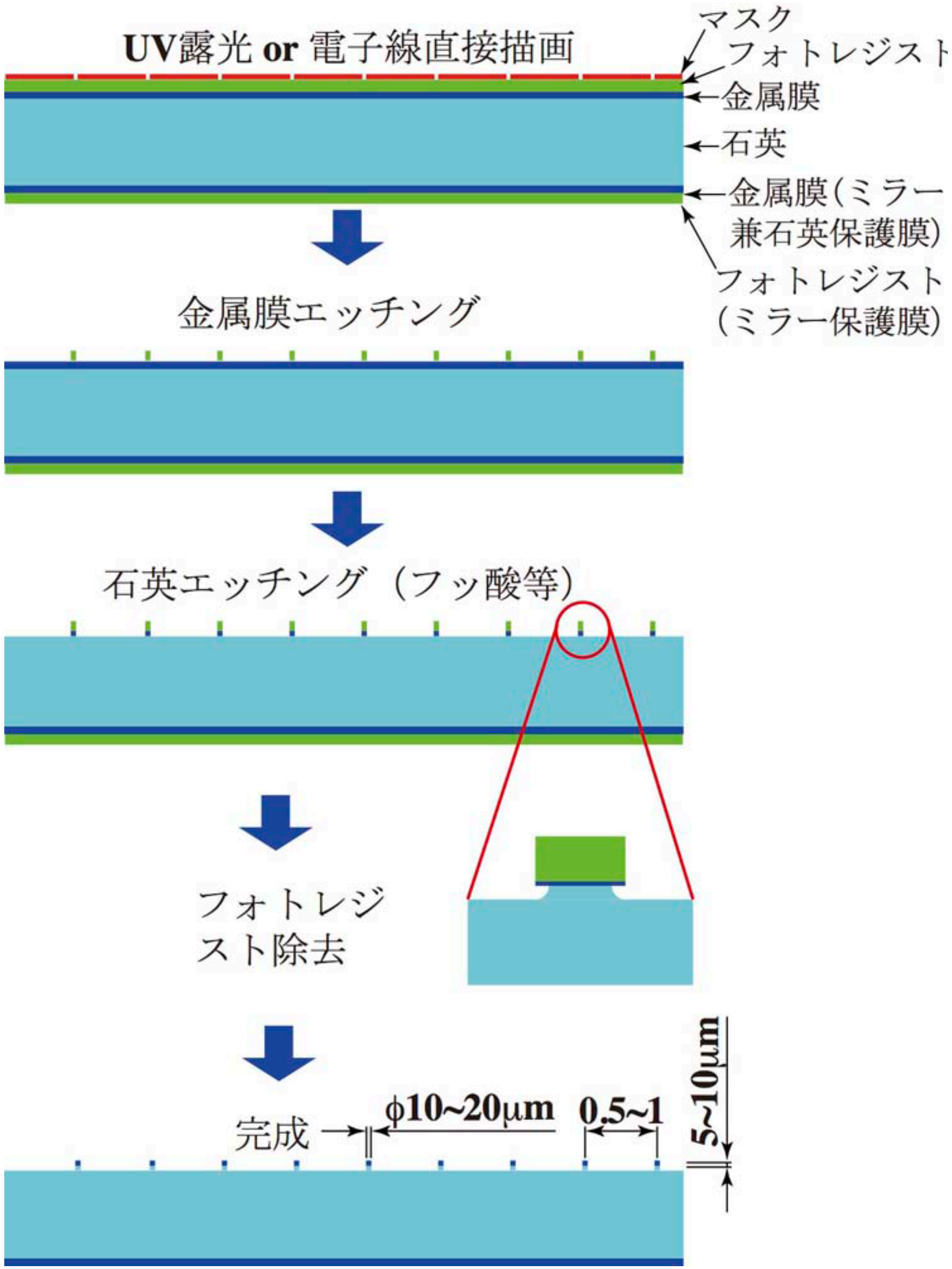
Laminated by gold fusion
in room temperature

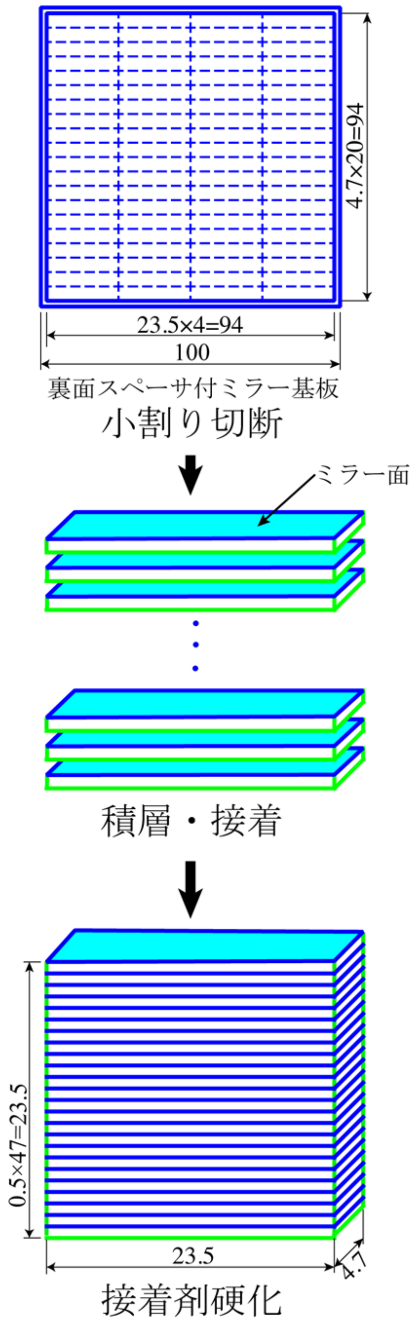


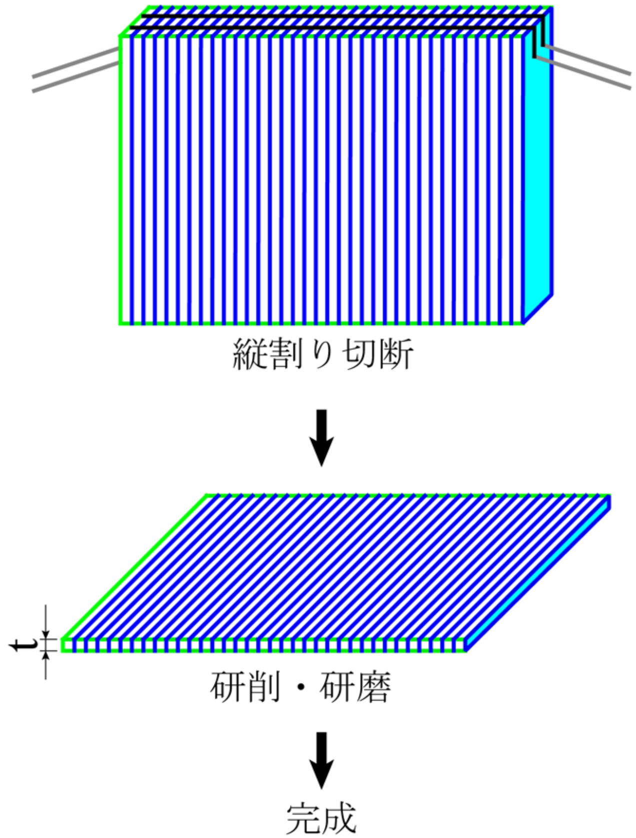
Wire saw cutting.

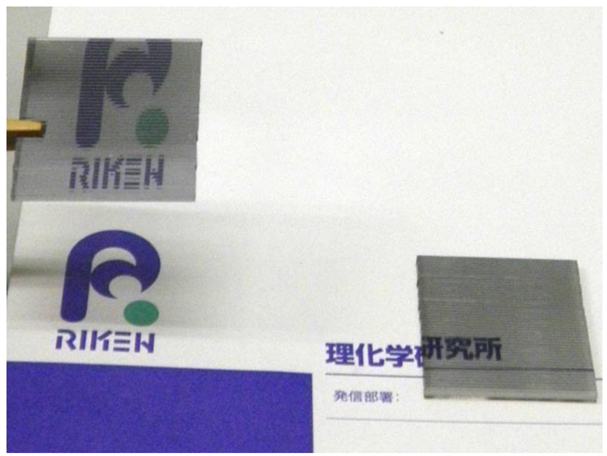
- 20 sheets of quartz glass substrates of $\phi 25 \times {}^{t}0.5$, that the gold deposited by sputtering on both sides, are stacked by a room-temperature bonding (Tohoku University Shimadzu laboratory).
- Thickness to ${}^{t}1.1$ by wire saw cutting.
- Thickness to ${}^{t}0.9$ by polishing.

Trial Fabrication of Quasi-Bragg Grating 3





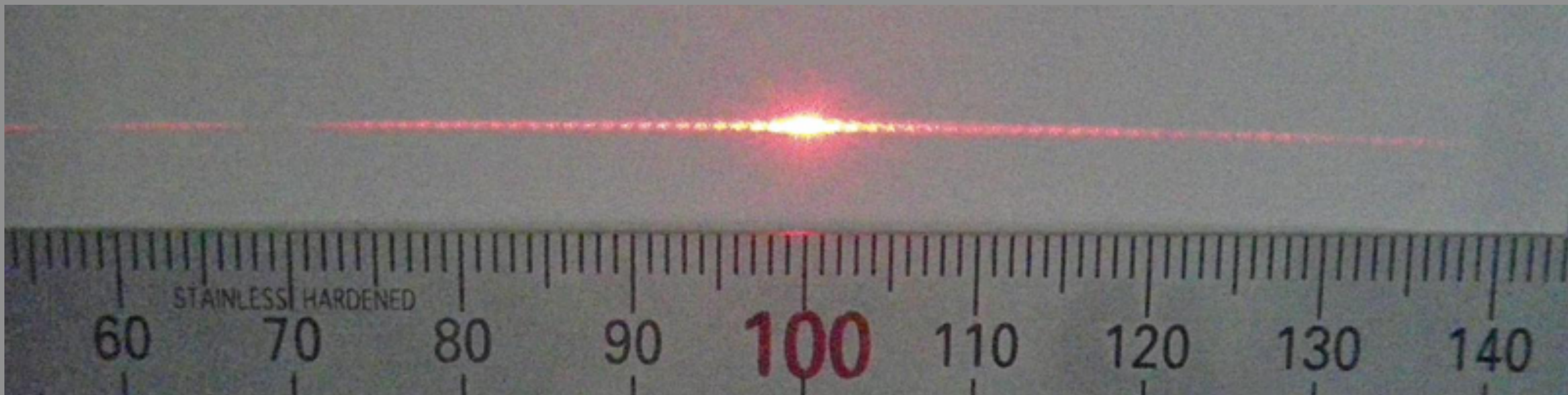




Diffraction Images of Quasi-Bragg Gratings

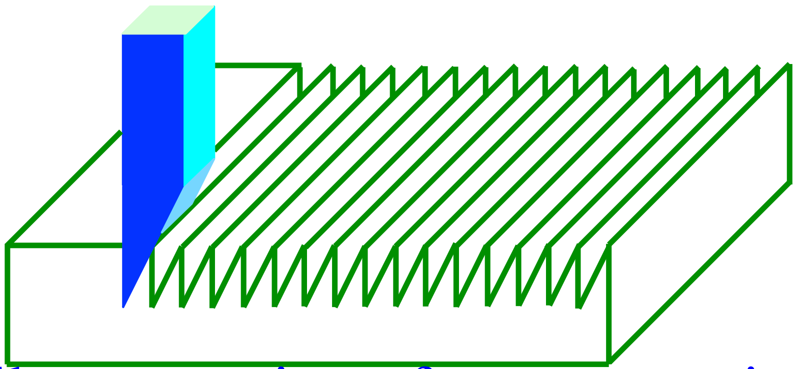
Laminated by adhesive with glass beads (Trial fabrication 1)

Laminated by gold fusion in room temperature (Trial fabrication 2)

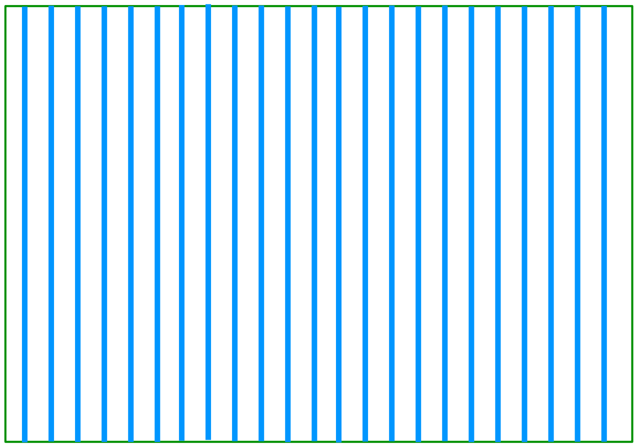


Embossed mirror substrates laminated by adhesive (Trial fabrication 3)

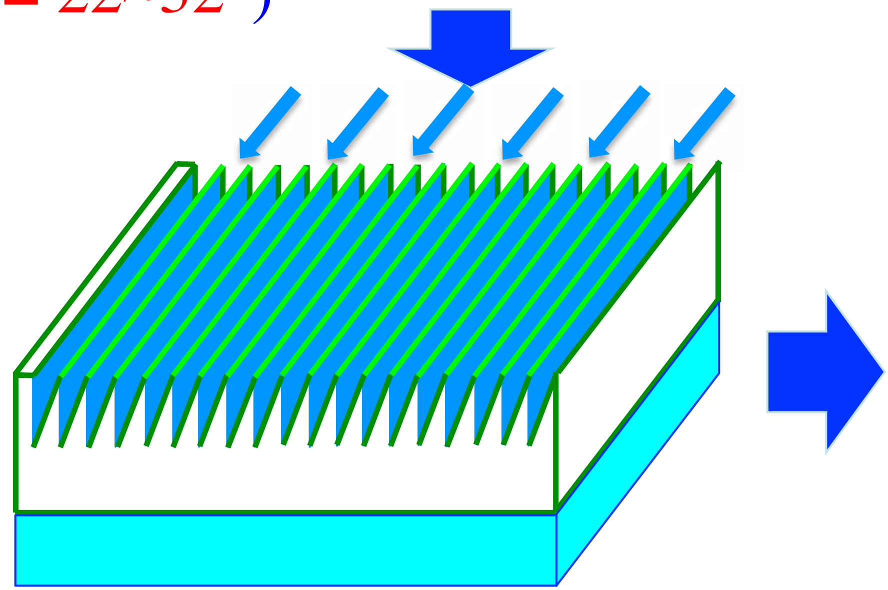
Fabrication Method of Quasi-Bragg Grating



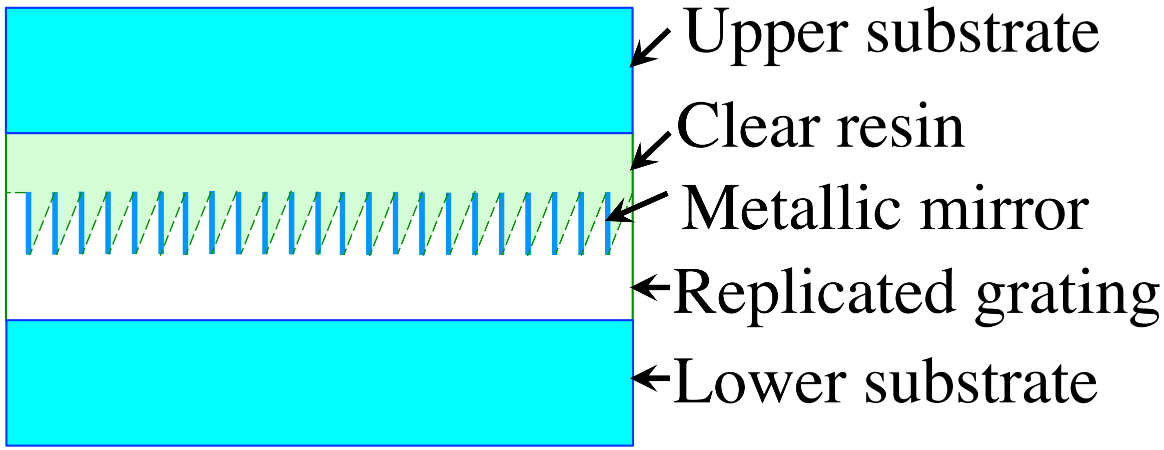
Shaper cutting of master grating (work：Ni-P alloy of non-electrolytic plating, Λ= 2~5μm, γ = 22~32°)



Top view



Oblique ion assisted spattering of metallic mirror (Al, t~100nm).

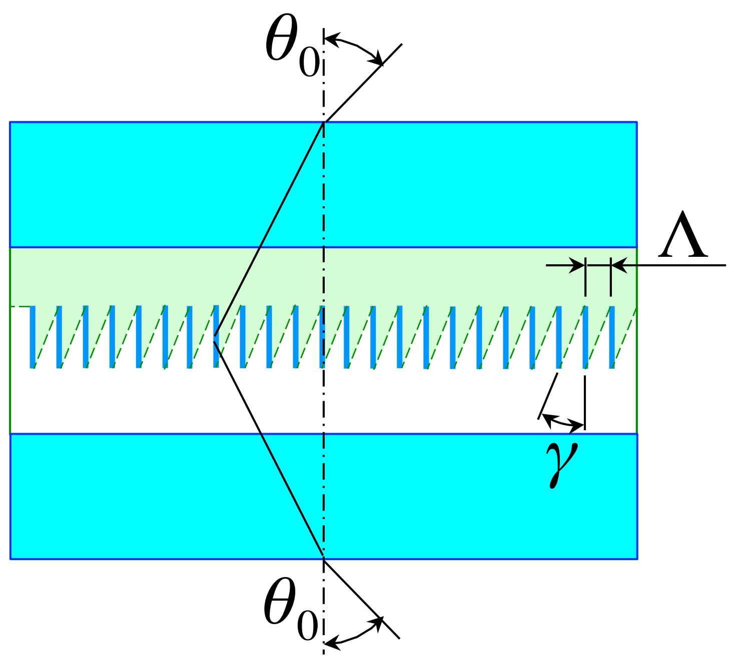


Front view

Filling of clear resin into grooves → Finish

Quasi-Bragg grating for TMT WFOS

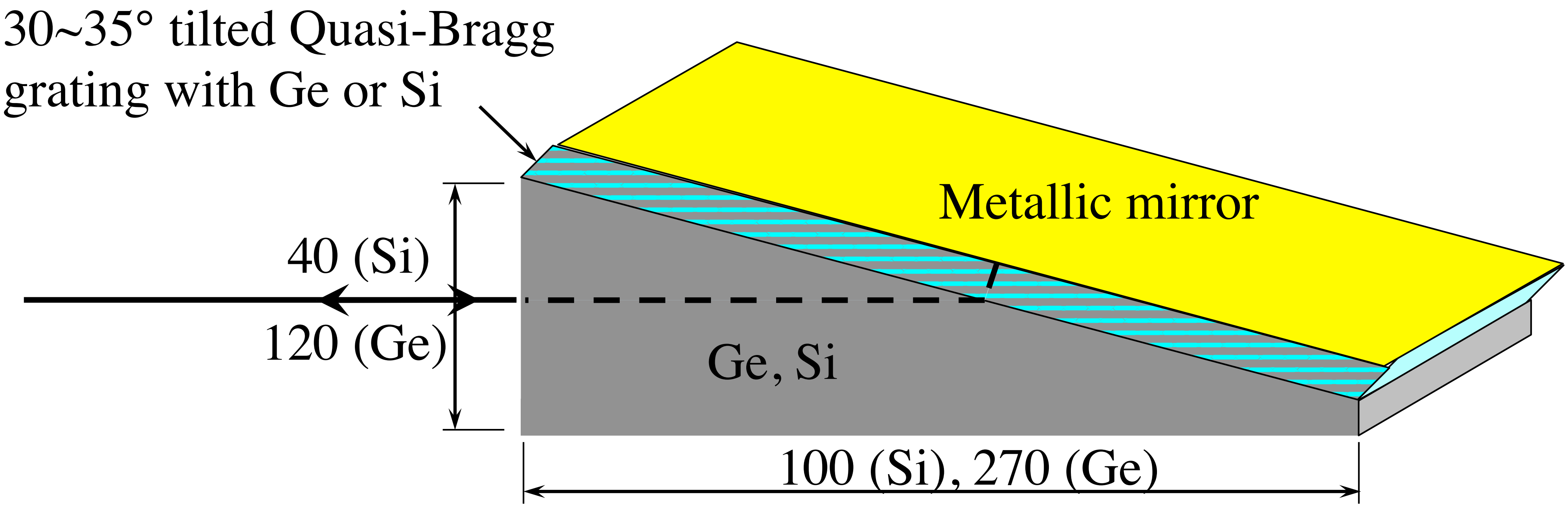
Item	Λ [μm] ([g/mm])	θ_0	γ	Order
Medium Res. Blue #1	2.17 (460)	36°	22.4°	5th~8th
Medium Res. Blue #2	2.70 (370)	38°	25.8°	7th~11th
Medium Res. Red	3.64 (275)	42°	23.6°	5th~9th
High Res. Blue	2.60 (385)	53°	31.2°	8th~13th
High Res. Red	4.65 (215)	53°	31.2°	8th~13th



Conclusions

- VPH grating achieves high diffraction efficiency and versatile for moderate angular dispersion for the 1st diffraction order.
- Test fabrication of VPH gratings with liquid crystal of UV curable is done by using a two beams interferometer of an UV laser.
- Surface relief grating with acute angle grooves for MOIRCS grisms are going to fabricate.
- Quasi-Bragg grating which mirror plates laminated by gold fusion in room temperature (Tohoku University) and embossed mirror substrates laminated by adhesive, are feasible even for echelle spectroscopy of visible wavelength.

Quasi-Bragg Immersion Grating



1. Near IR (1.0~2.5μm)
   - Material : ZnSe, Si etc.
   - Size × Layers: 40×0.5×t0.25×300psc.
   - Periodic error: 45nm (P-V), 9nm (rms)

2. Mid IR (5~30μm)
   - Material : Ge, CdTe etc.
   - Size × Layers: 120×2.0×t1.0×300psc.
   - Periodic error: 150nm (P-V), 30nm (rms)