DISPERSING ELEMENTS:

an overview

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Dispersing elements for astronomy

Prisms can be used as dispersing elements for astronomy especially in the IR, but:

- just for low resolution (big size and weight for increasing R);
- dispersion strongly varies with the wavelength;
- used as cross disperser in echelle spectrographs.

Diffraction gratings are the best candidates for both low and high resolution spectrographs.

- the dispersion is often constant (almost);
- flexibility in the instrument design;
- it is the optical element with the lowest efficiency of the spectrograph!

Prism + Grating can be used for:

- Increasing the resolution by a refractive index factor (immersed gratings);
- Developing instruments for both imaging and spectroscopy (GRISM).

Dispersing elements for astronomy: prism

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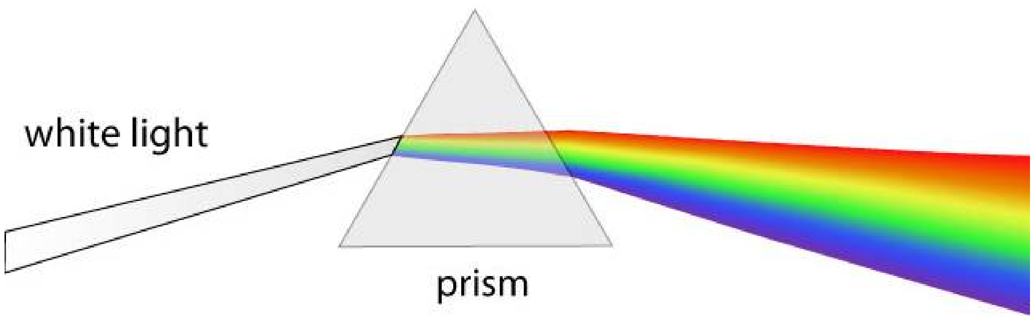

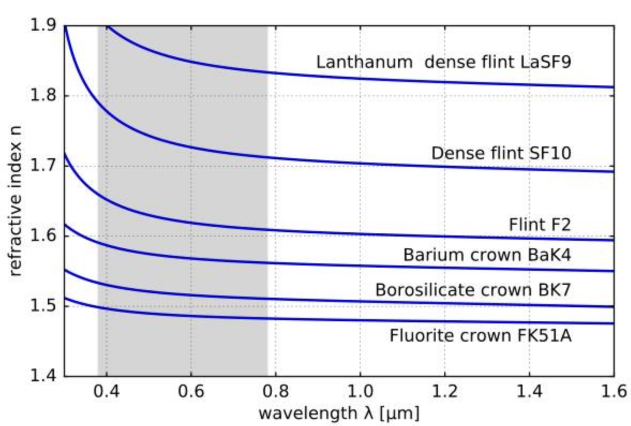

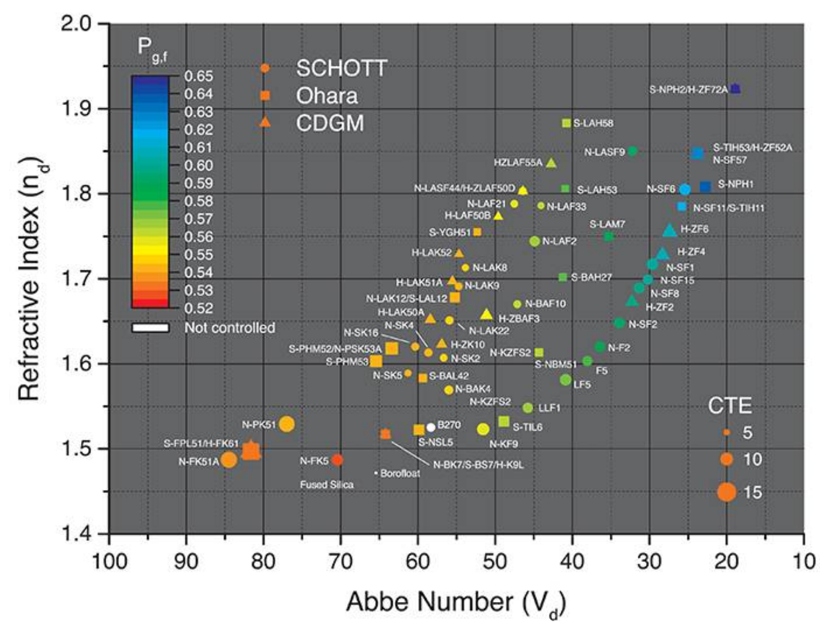

Dispersing elements for astronomy: grating

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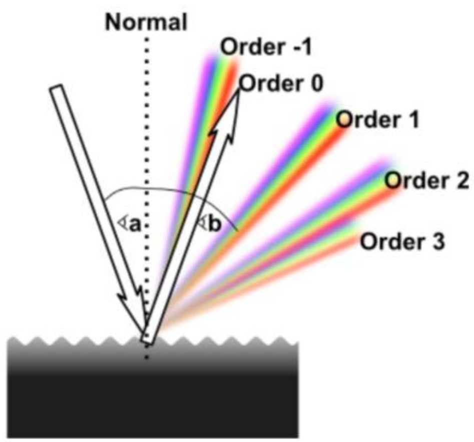

Grating equation

$$\frac{mG\lambda}{n} = \sin\alpha + \sin\beta$$

Dispersion

$$D = \frac{d\beta}{d\lambda} = \frac{mG}{\cos\beta}$$

Resolution

$$R = \frac{mG\,\lambda\,W}{\chi\,D}$$

G = line density l/mm

m = diffraction order

n = refractive index

χ = Slit width (arcsec)

W = grating size, D = telescope diameter

Dispersing elements for astronomy: grating

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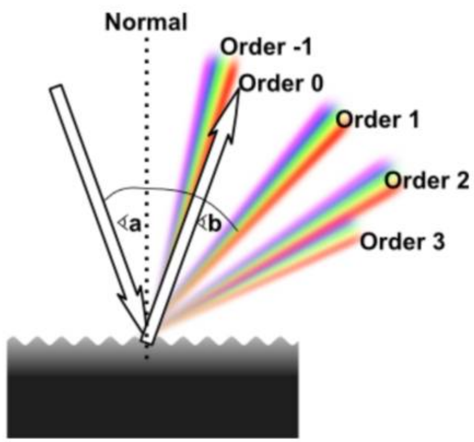

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Dispersion

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Resolution

$$R = \frac{mG\lambda W}{\chi D}$$

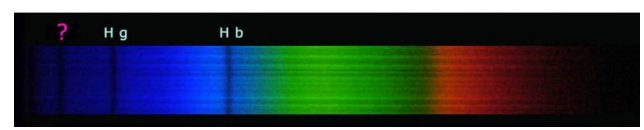
<u>Large dispersion for large resolution:</u>

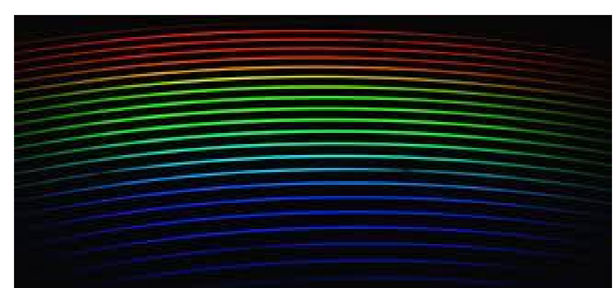
mG ↑↑

→ m=1 G ↑ "Normal" gratings

→ m ↑ G ↓ Echelle gratings

CCD spectrum

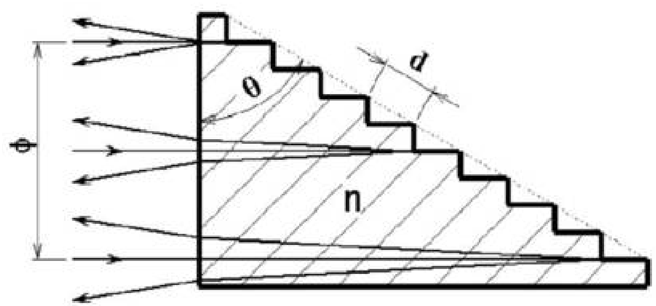




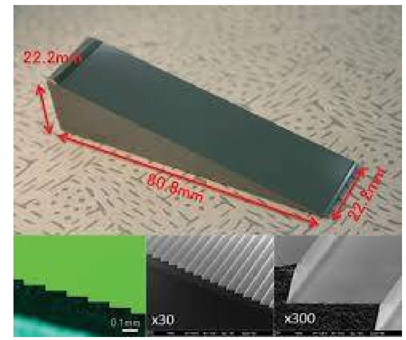
Dispersing elements for astronomy: P+G

Prism + Grating can be used for:

- Increasing the resolution by a refractive index factor (immersed gratings);



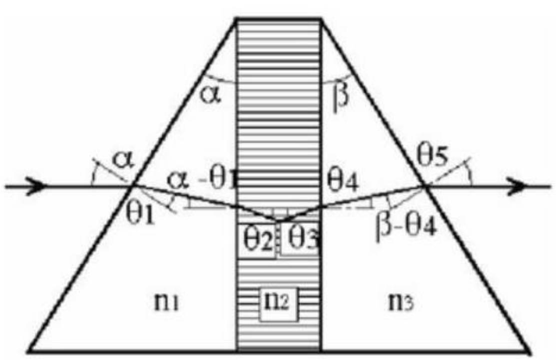
immersion grating

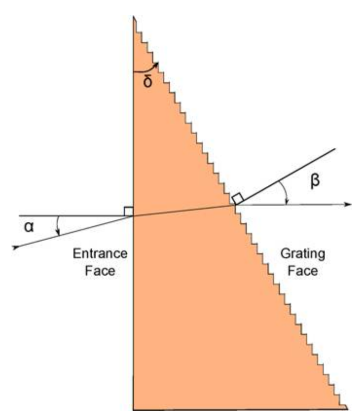


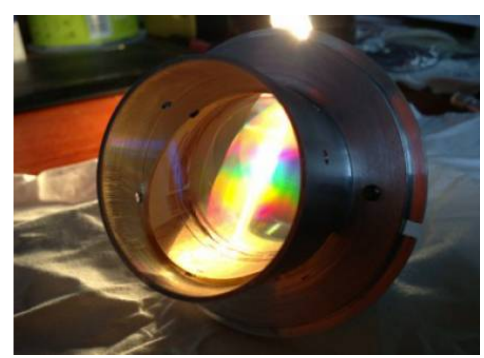
Proc. SPIE 9906, 990637 (2016)

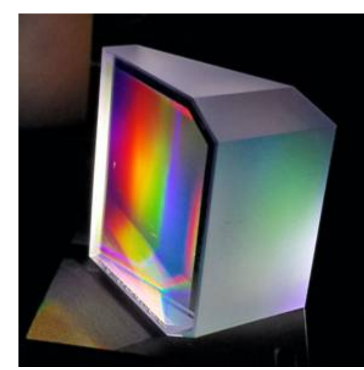
The gain in resolution is the refractive index **n** of the prism (in reflection)

- Developing instruments for both imaging and spectroscopy (GRISM);
- Can help in reducing the incidence angle in HR gratings.









VPHG in astronomy

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GRATINGS - New holographic gratings look at the cosmos

09/01/1999

Samuel Barden, Willis Colburn, and James Arns

FIGURE 1. Multiplex volume-phase holographic grating is illuminated by candlelight. Two spectra are visible, one formed by each of the two gratings contained within the element. The shorter spectrum arises from the 1200-l/mm grating component and the longer from the 1620-l/mm component.

Back to 1998 – 1999...

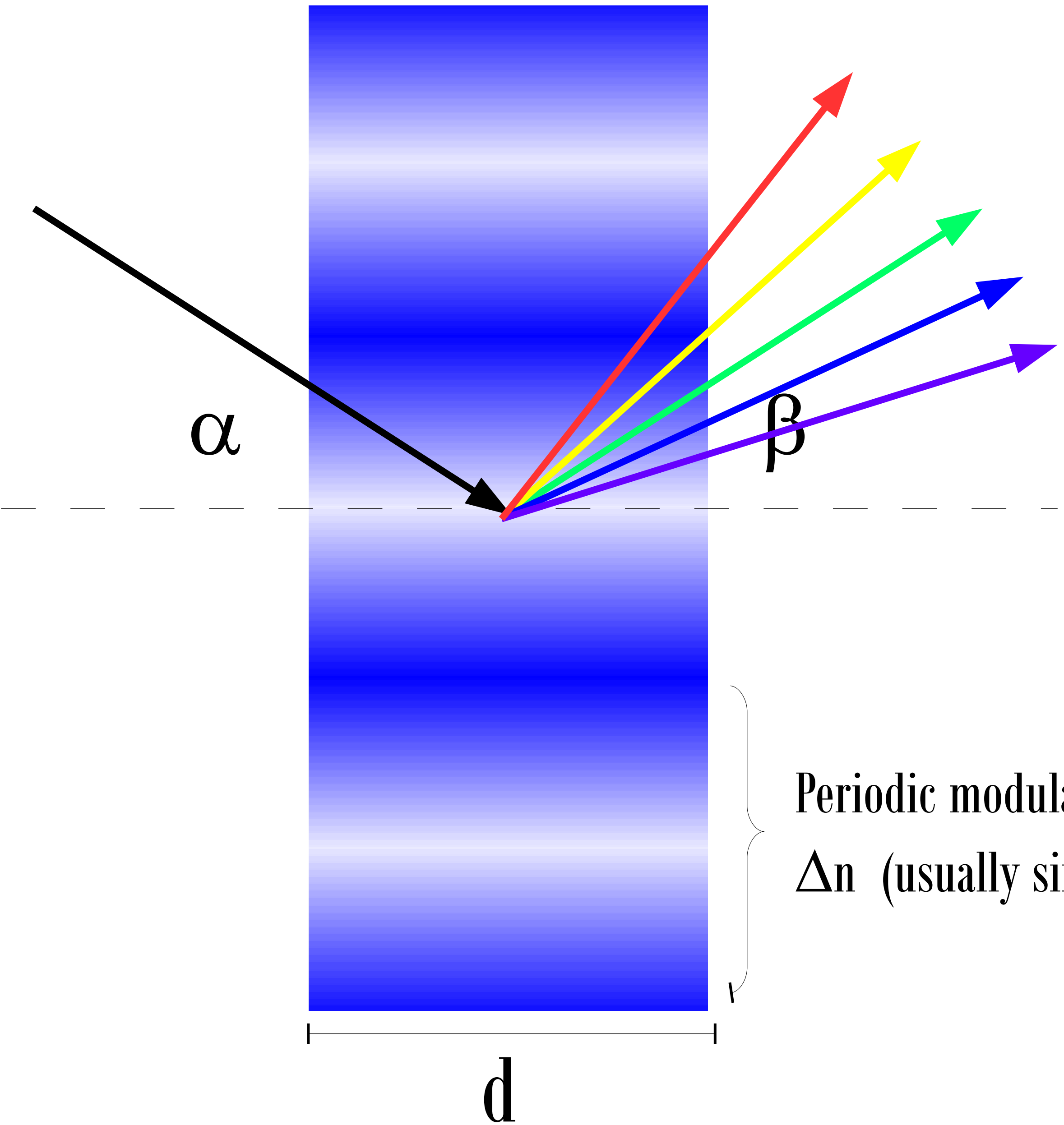
Proc. SPIE, vol. 3749, pp 52-53
Presented at the 18th Congress of the International Commission for Optics–Optics for the Next Millennium
August 2, 1999

Astronomical Applications of Volume-Phase Holographic Gratings

Samuel C. Barden
National Optical Astronomy Observatories
950 N. Cherry Ave.
Tucson, AZ 85719

James A. Arns and Willis S. Colburn
Kaiser Optical Systems, Inc.
371 Parkland Plaza
Ann Arbor, MI 48103

VPHG: Principle of work

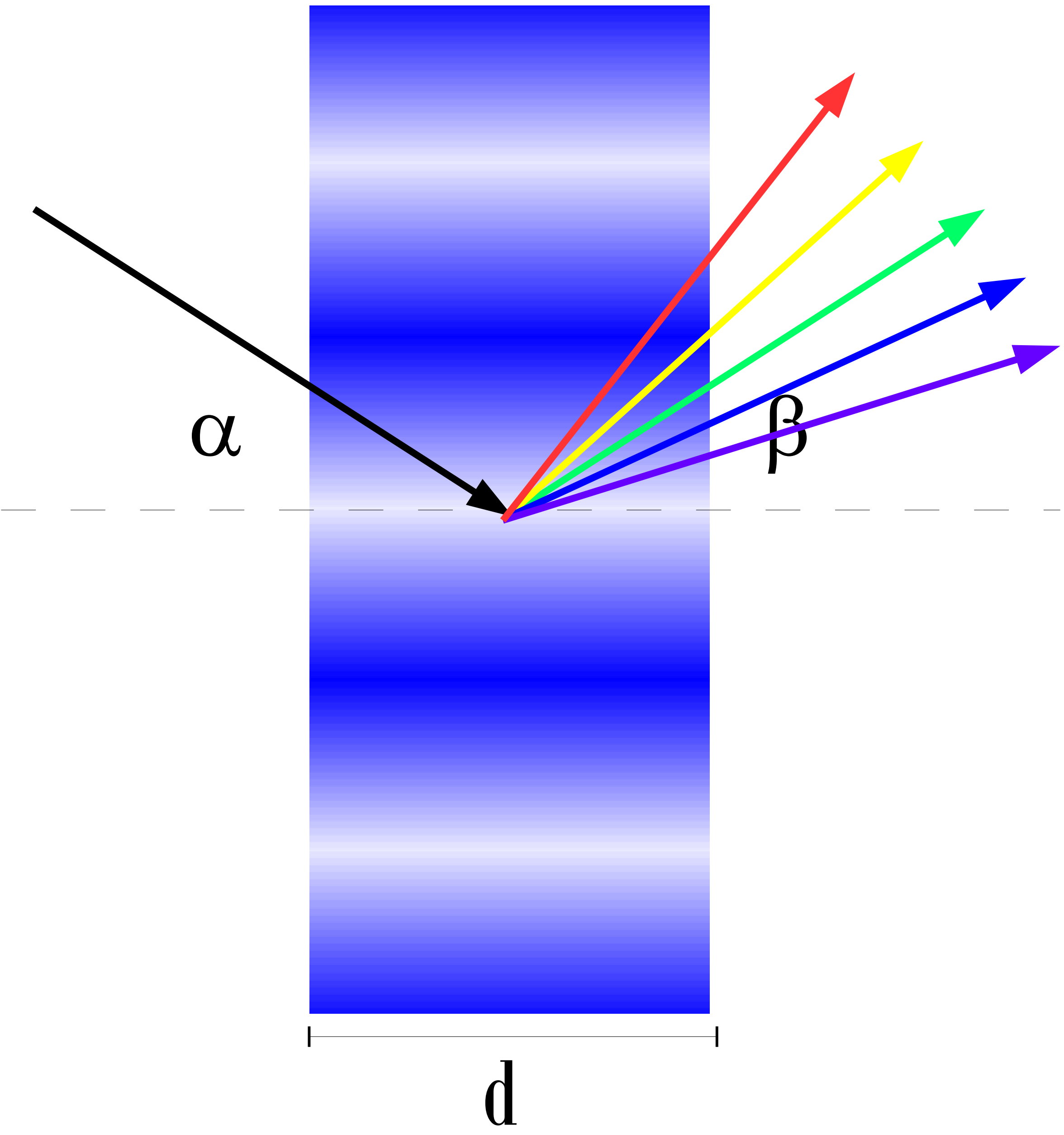


The diffraction occurs thanks to a periodic modulation of the refractive index in the volume of the material.

Periodic modulation of the refractive index

Δn (usually sinusoidal)

VPHG: Principle of work



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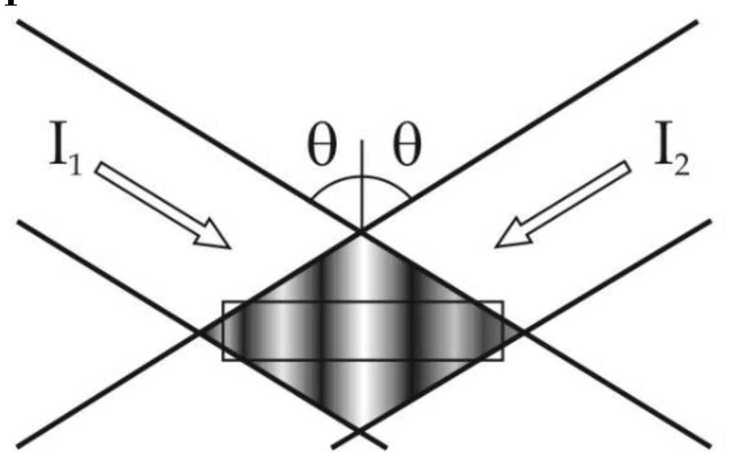
The writing step consists in the two laser beams interference applied to a photosensitive material:



VPHG in astronomy

VPHGs produced by KOSI (leader in the manufacturing of VPHGs for astronomy)

Year	Instrument	Telescope/Organization
1999	FORS2	VLT/European Southern Observatory (ESO)
2000	Subaru	National Astronomical Observatory of Japan (NAOJ)
2001	FTSP	U.S. Naval Observatory
2003	FORS2	VLT/European Southern Observatory (ESO)
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2005	FORS2	VLT/European Southern Observatory (ESO)
2006	FRODOSPEC	Liverpool Johns Moores University Telescope
2007	SWIFT	Hale Telescope/University of Oxford
2007	EFOSC2	U of Sheffield
2009	ACAM	William Hershel Telescope/Isaac Newton Group of Telescopes (ING)
2009	BOSS	SDSS Telescope/Astrophysical Research Consortium (ARC)
2009	OSMOS	Hiltner Telescope/The Ohio State University
2009	VIRUS-P	H.J. Smith Telescope/McDonald Observatory
2010	KOSMOS	Mayall Telescope/National Optical Astronomical Observatory (NOAO)
2010	VIRUS-W	H.J. Smith Telescope/Max Planck Institute for Extraterrestrial Physics
2010	APOGEE	SDSS Telescope/Astrophysical Research Consortium (ARC)
2011	PEPSI	Large Binocular Telescope/Astrophysics Institute Potsdam
2011	VIMOS	VLT/European Southern Observatory (ESO)
2011	MUSE	VLT/European Southern Observatory (ESO)
2013	HERMES	AAT/Australian Astronomical Observatory (AAO)
2014	IGRINS	H.J. Smith Telescope/McDonald Observatory
2015	APOGEE-S	Irénée du Pont Telescope/ Las Campanas Observatory
2015	ESPRESSO	VLT/European Southern Observatory (ESO)
2015	MAROON-X	Magellan Telescope/ Magellan Project, Gemini North / Gemini Observatory
2016	PFS	Subaru Telescope/National Astronomical Observatory of Japan
2017	DESI	Mayall Telescope/National Optical Astronomical Observatory (NOAO)

Credit: KOSI

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2006	FRODOSPEC	Liverpool Johns Moores University Telescope
2007	SWIFT	Hale Telescope/University of Oxford
2007	EFOSC2	U of Sheffield

- Mainly as main disperser for spectrographs;
- Sometimes as cross-disperser in echelle spectrographs (ESPRESSO);
- VPHG is (has been) considered the baseline as main disperser for next generation optical spectrographs up to medium/high resolutions: (MOONS@VLT, 4MOST@VISTA, HARMONI@ELT, MOSAIC@ELT)

Credit: KOSI

VPHG: Main features

- The peak efficiency can be theoretically 100%. Easily, values of 90% are obtained;
- The efficiency curve (blaze curve) can be tune in wavelength by changing the incident angle, allowing to cover a wide range of wavelengths with very high efficiencies;
- The devices are robust since the active material is usually embedded in between two glass windows and multilayer coatings can be applied;
- Large VPHGs can be produced if a big holograph is available meeting the requests of big spectrographs;
- Large dispersion. High efficient gratings with line density up to 6000 l/mm can be obtained;
- The device is easily customizable and complex structures (multiplexing) can be obtained.

VPHG: Limitations

- Not suitable for making echelle gratings (working at high diffraction orders);
- Spectral range: 0.3(5) – 2.5 μm => not suitable for MIR (OK up to K band);
- Difficult to have a very low dispersion (better to use ruled gratings),
- WFE control in large and high dispersion elements;
- Few manufacturers.

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- Large dispersion. High efficient gratings with line density up to 6000 l/mm can be obtained;
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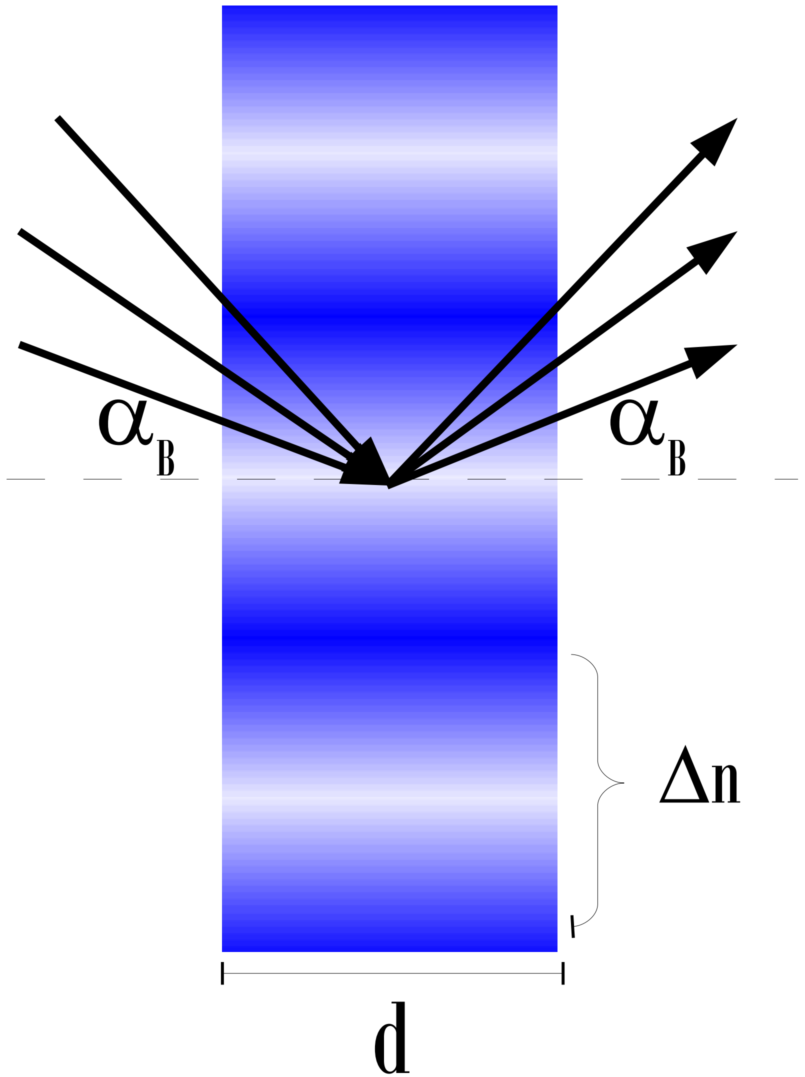
- Possibility to slant the fringes for a tuning of the blaze curve.

VPHG: Efficiency

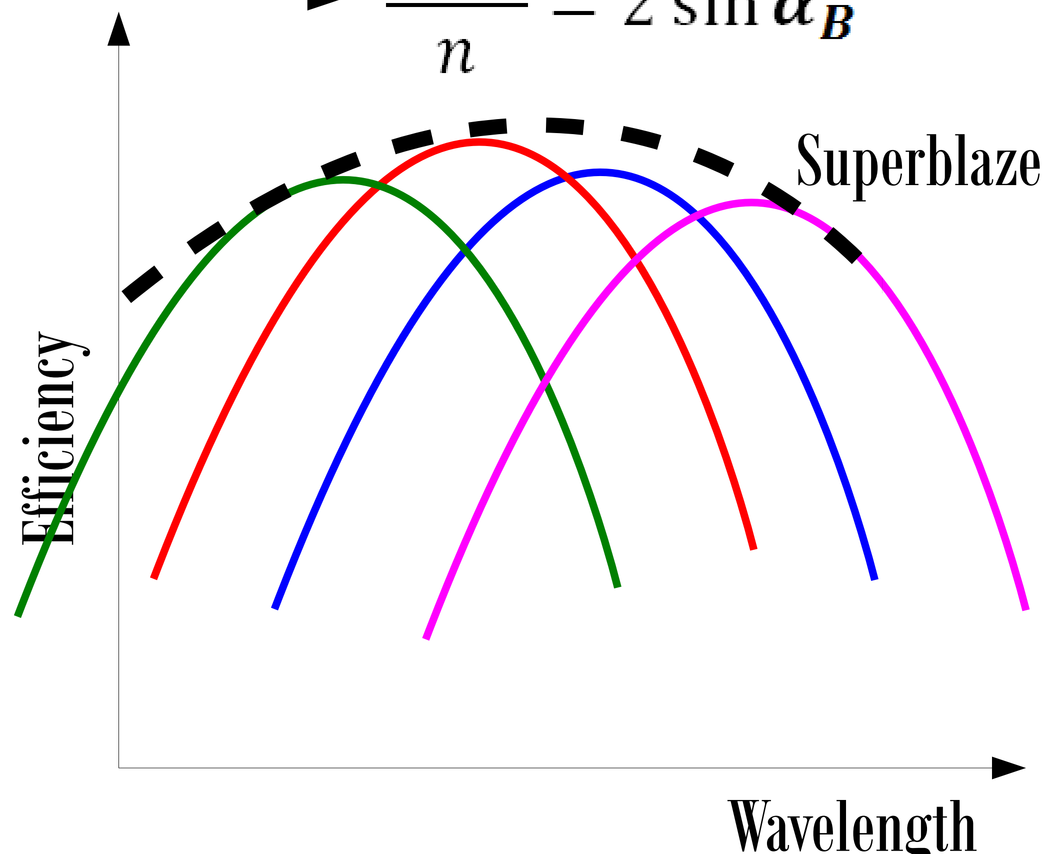


High peak efficiency is achieved when...

Bragg Condition:

$$\alpha = \beta$$

$$\frac{mG\lambda}{n} = 2\sin\alpha_B$$



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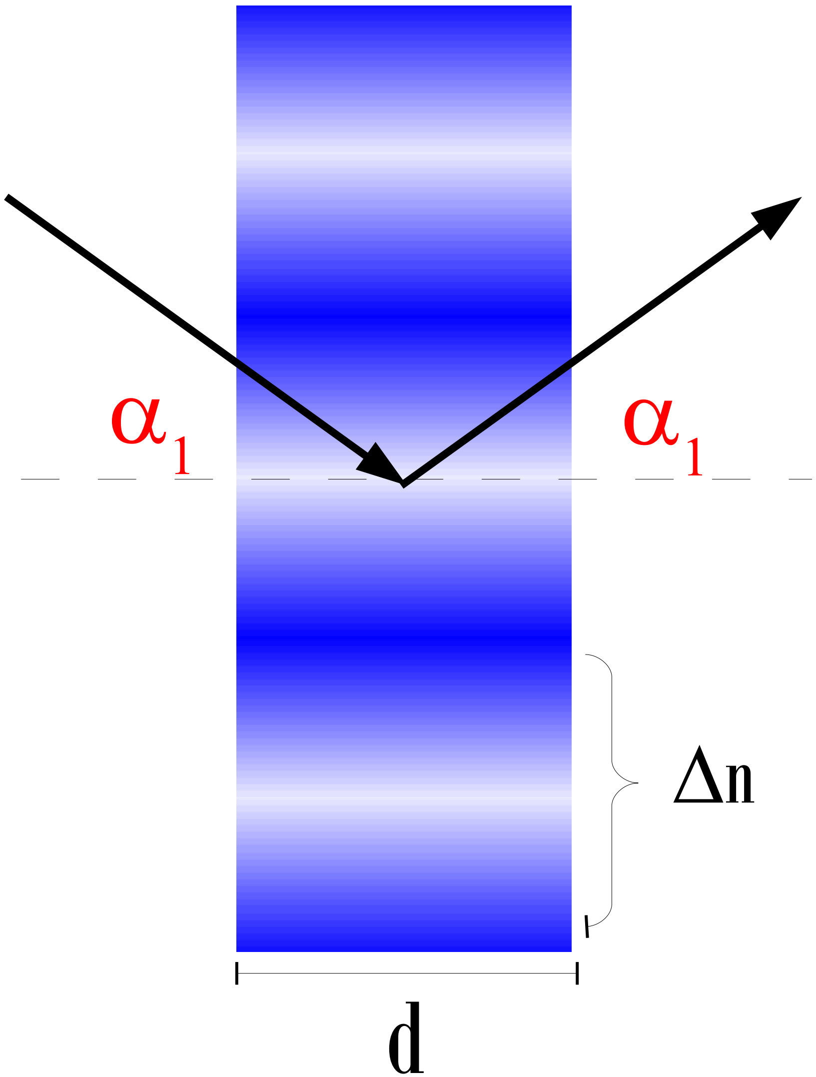

High peak efficiency is achieved when…

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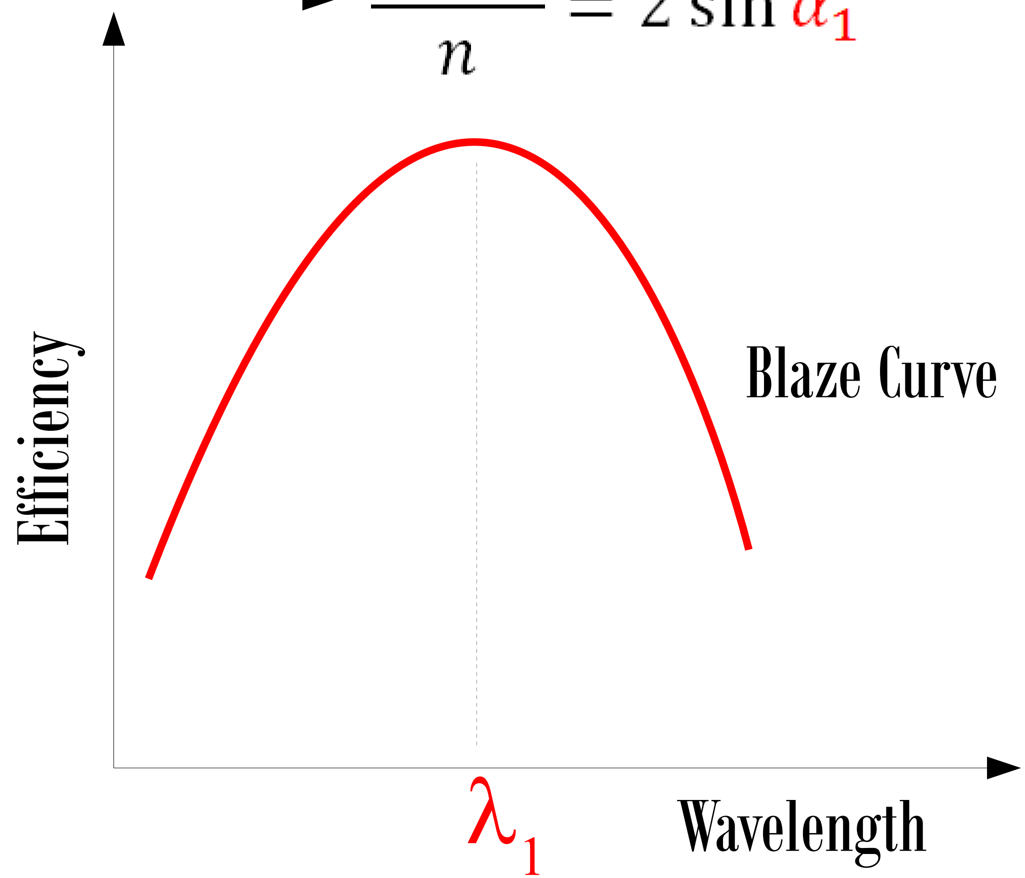
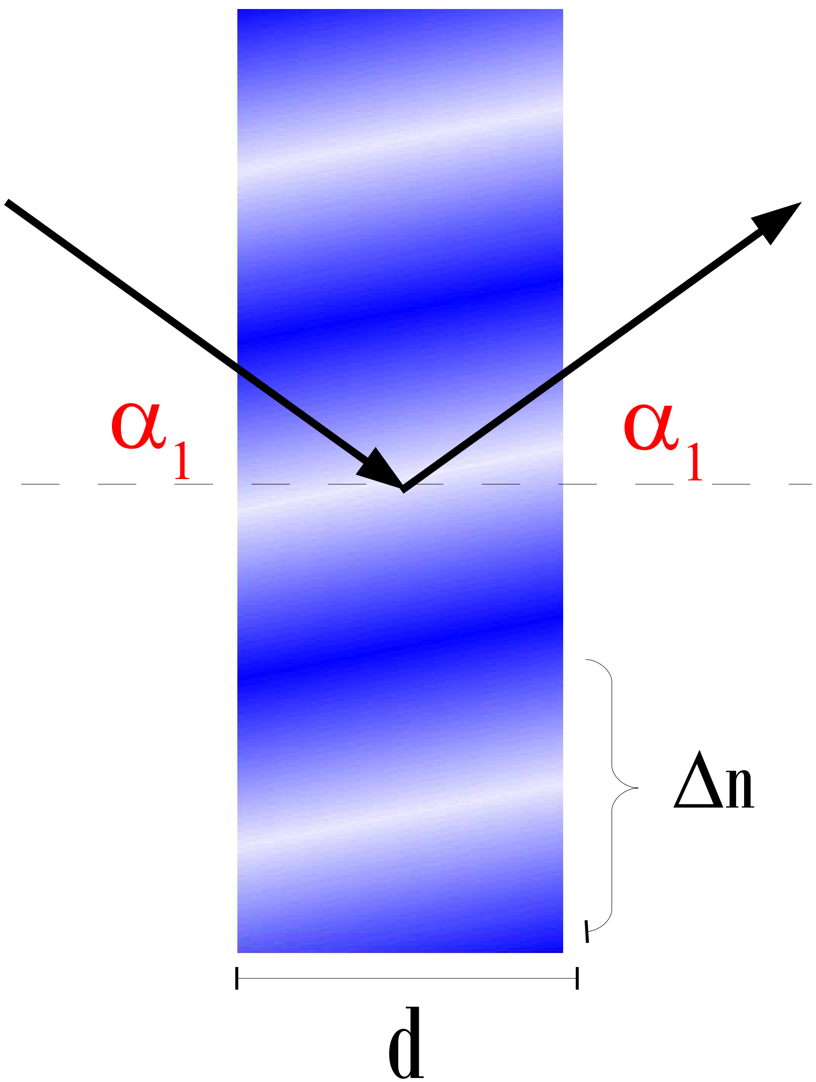


VPHG: Efficiency – slanting



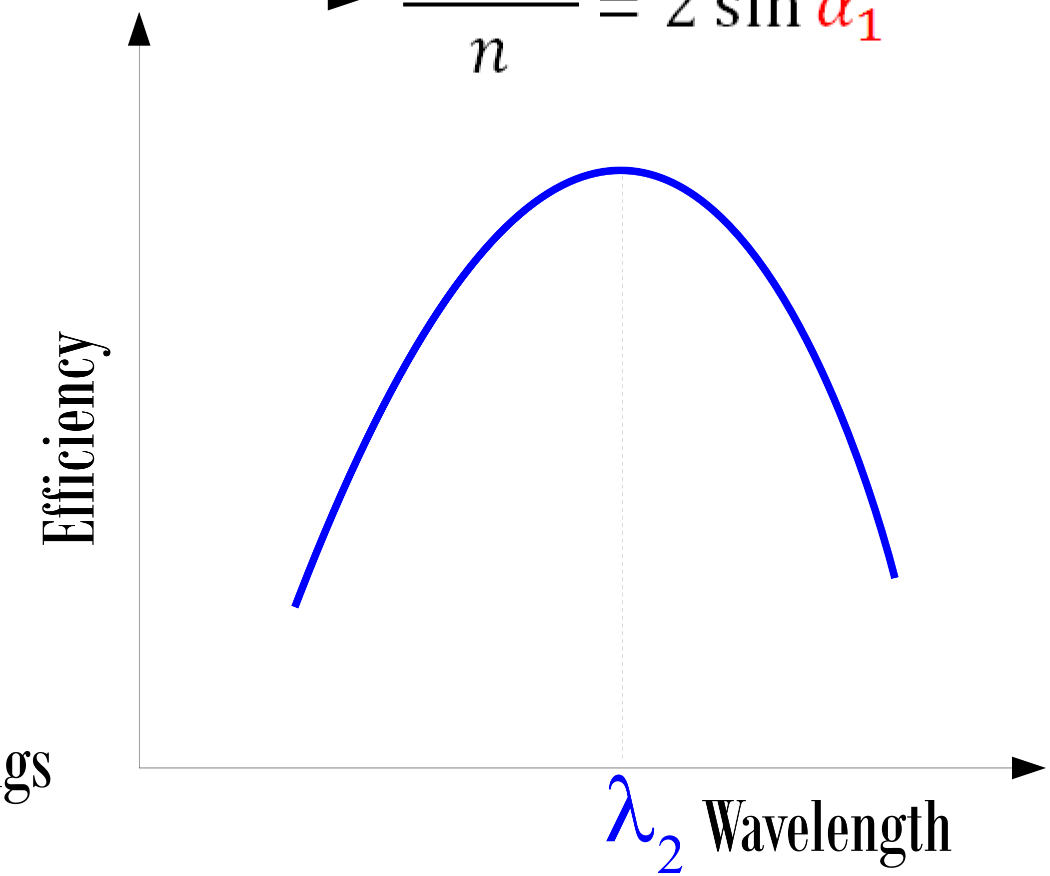
Similar to the blaze angle in ruled gratings

High peak efficiency is achieved when…

Bragg Condition:

$$\alpha = \beta$$

$$\frac{mG\lambda_2}{n} = 2 \sin \alpha_1$$



VPHG: Diffraction Efficiency

The diffraction efficiency of a VPHG depends on:

- Film thickness (d);
- Refractive index modulation (Δn);
- Profile of Δn;
- Average refractive index;
- Line density (G).

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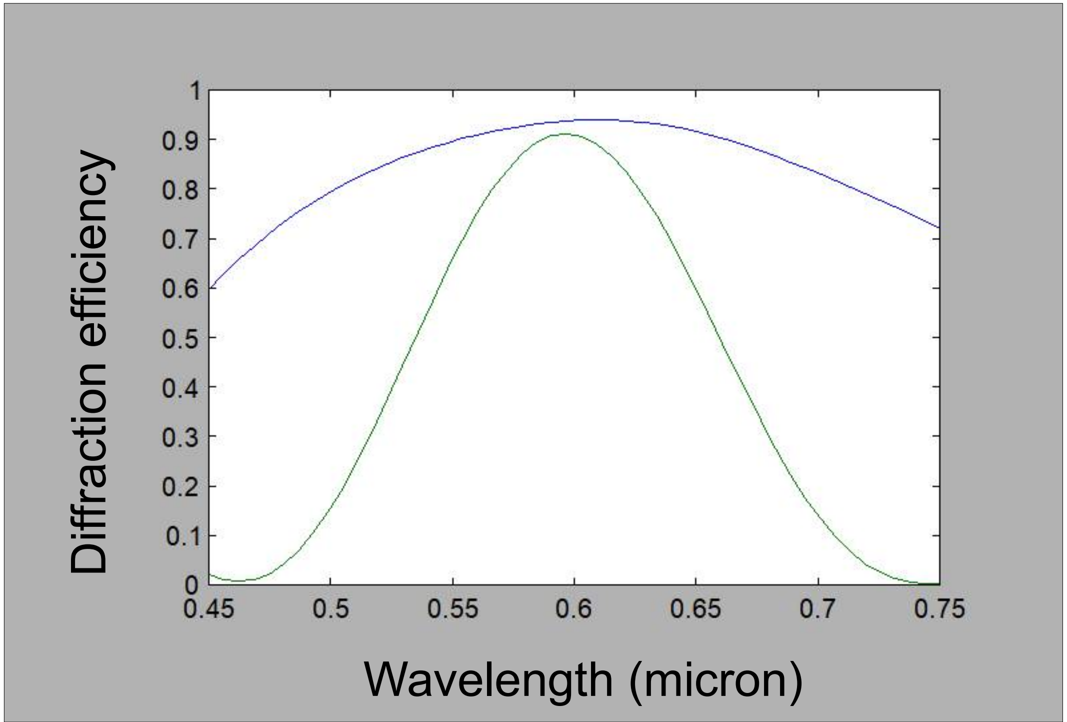
Not only the peak efficiency is important, but also the bandwidth



VPHG: Diffraction Efficiency

From Kogelnik model...

Peak efficiency: $d \times \Delta n \approx \frac{\lambda}{2}$

Spectral Bandwidth: $\frac{\Delta\lambda}{\lambda} \propto \frac{\cot\alpha}{Gd}$

Angular Bandwidth: $\Delta\alpha \propto \frac{1}{Gd}$

- The peak efficiency depends both on d and Δn, more difficult at longer wavelengths;
- Bandwidths depend on the line density G and thickness d (thin films => broader band and large G => narrower band)

Kogelnik, H., Bell System Technical Journal, 48, 2909-2947 (1969).
Baldry I.K., et al. PASP, 116:403–414 (2004)
Barden, S. C., et al. PASP, 112(772), 809-820 (2000).

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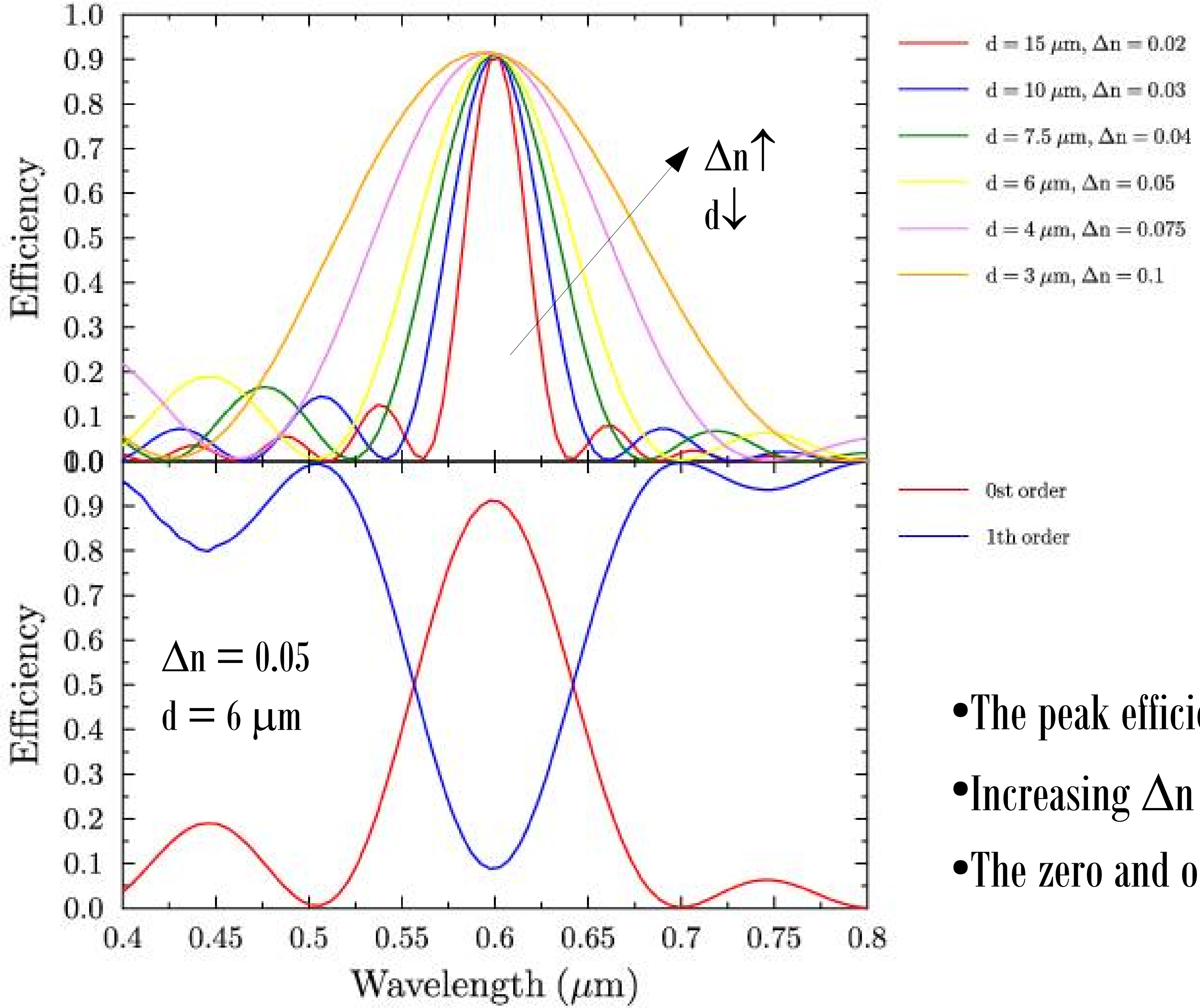
- Bandwidths depend on the line density G and thickness d (thin films => broader band and large G => narrower band)

For large dispersion (high resolution) the bandwidth is challenging:
- G is large;
- d must be small;
- Δn very large but there is a limit (max 0.12).

Kogelnik, H., Bell System Technical Journal, 48, 2909-2947 (1969).
Baldry I.K., et al. PASP, 116:403–414 (2004)
Barden, S. C., et al. PASP, 112(772), 809-820 (2000).

VPHG: Efficiency – G = 2000 l/mm



Bragg @ 600 nm

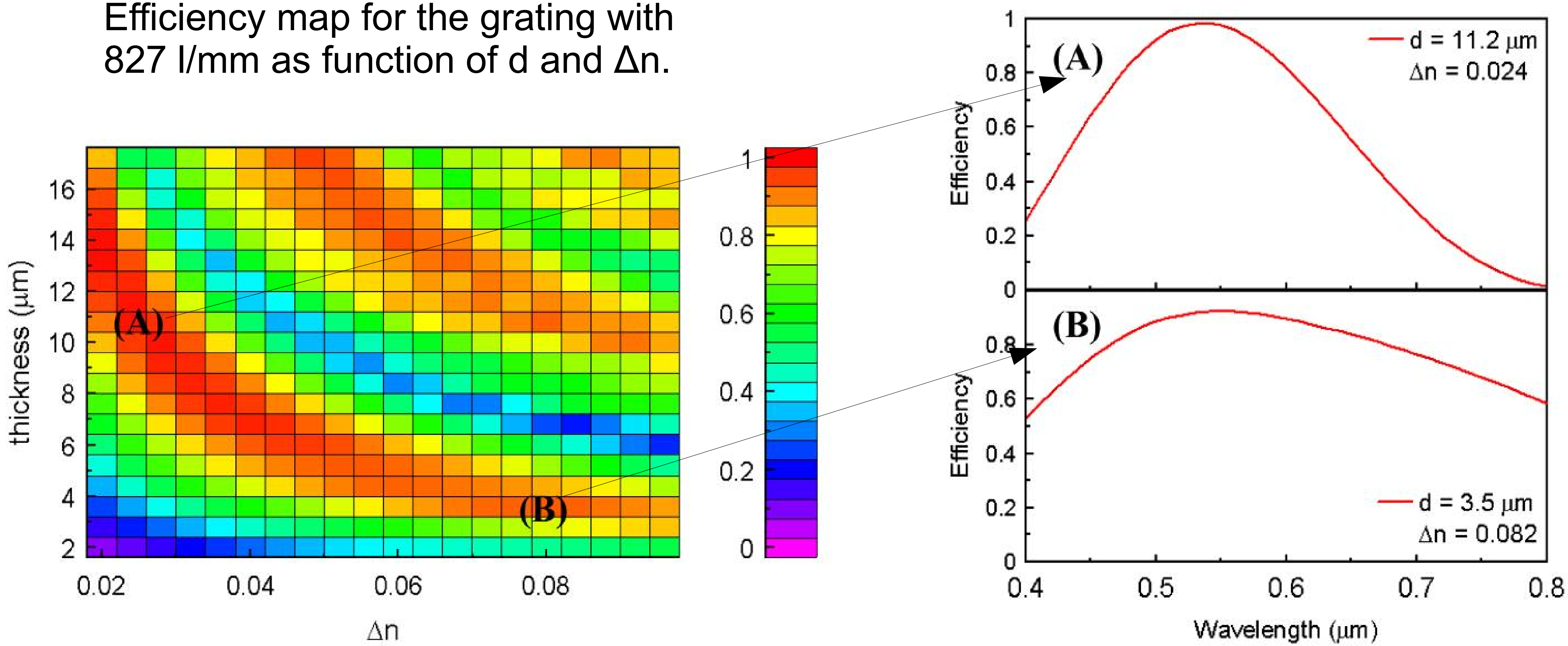
Unpolarized light

- The peak efficiency is almost constant,
- Increasing Δn the bandwidth increases;
- The zero and o first order are specular

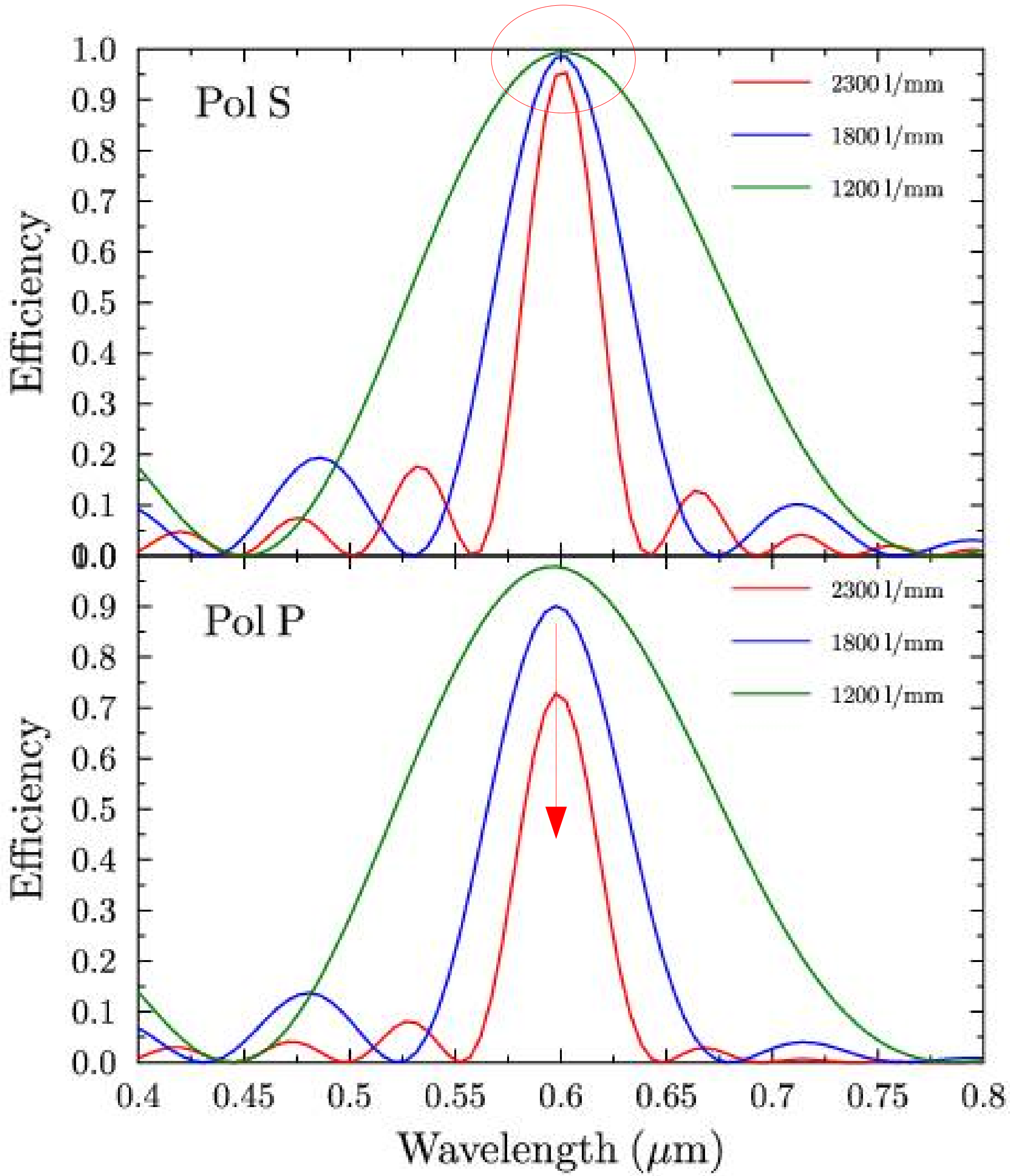
VPHG: Efficiency d - Δn

Efficiency map for the grating with 827 l/mm as function of d and Δn.

Efficiency curves for an incidence angle in Bragg at 600 nm.



VPHG: Efficiency – Polarization



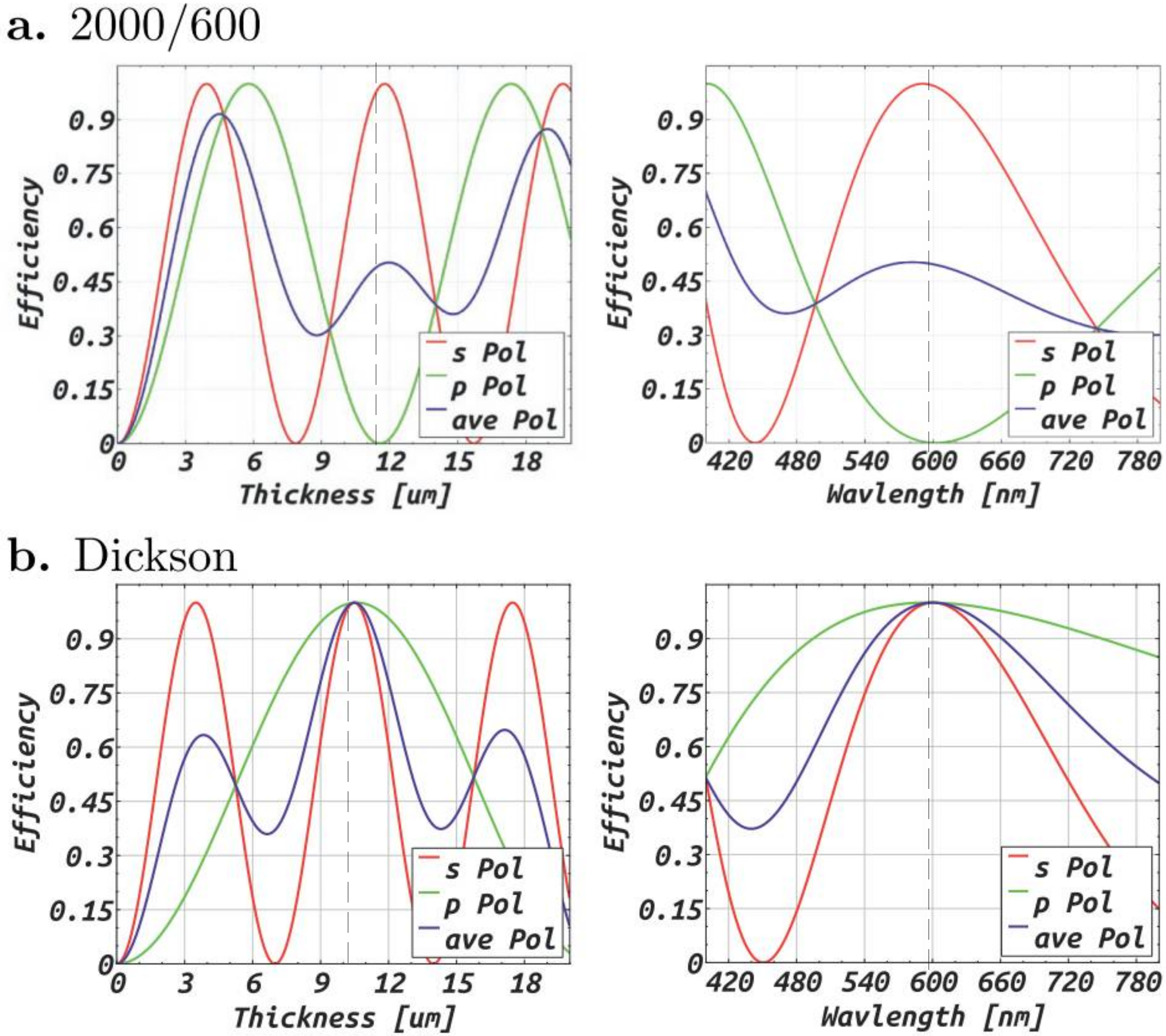
Dickson, LD et al. Applied Optics, 33(33), 5378-5385 (1994).

The diffraction efficiency depends on the polarization of the light.

Increasing the Bragg angle (α_B), so the line density G and/or λ, the efficiency difference between the two polarization increases.

For high dispersion VPHGs (high values of G), it will be difficult to achieve high diffraction efficiencies for unpolarized light.

VPHG: Efficiency – Polarization

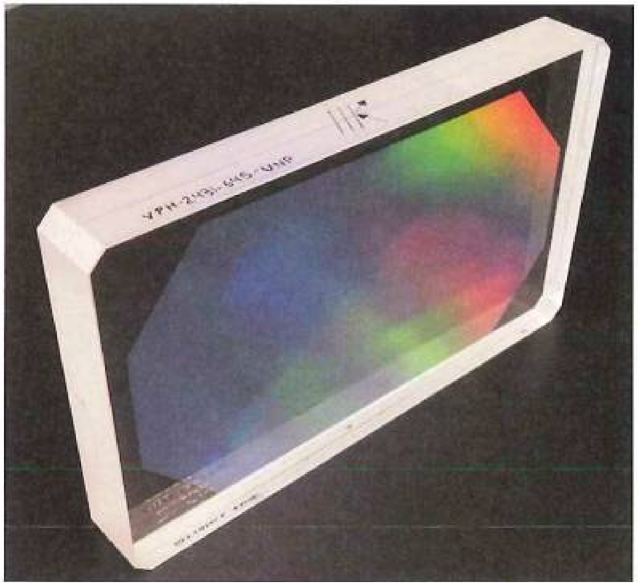


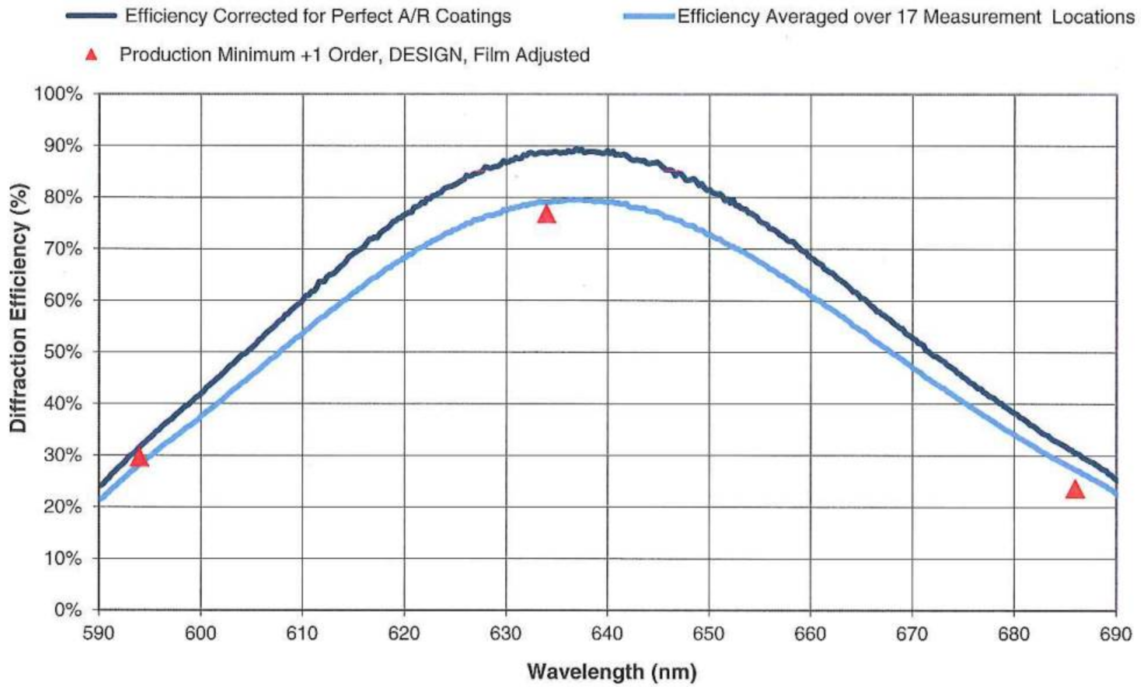
Polarizing selective VPHG

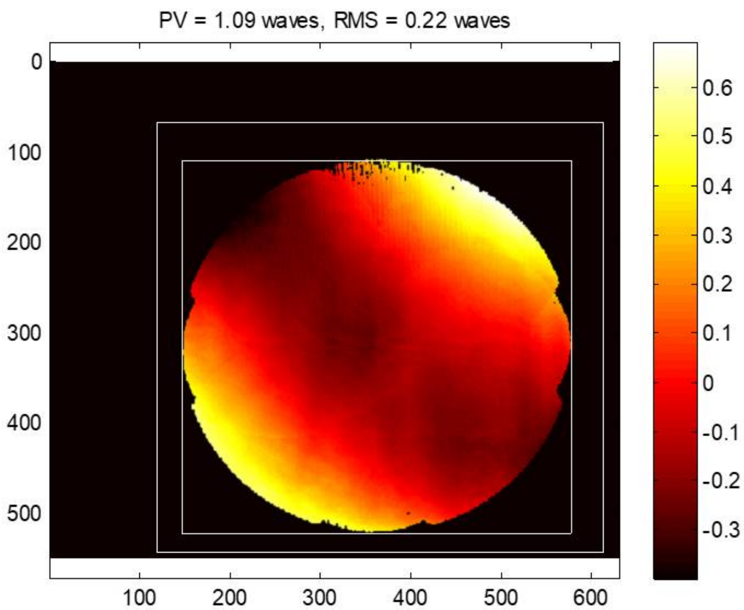
High efficiency VPHG

New Astronomy 75 (2020) 101303

WEAVE@WHT – VPHGs HR Red





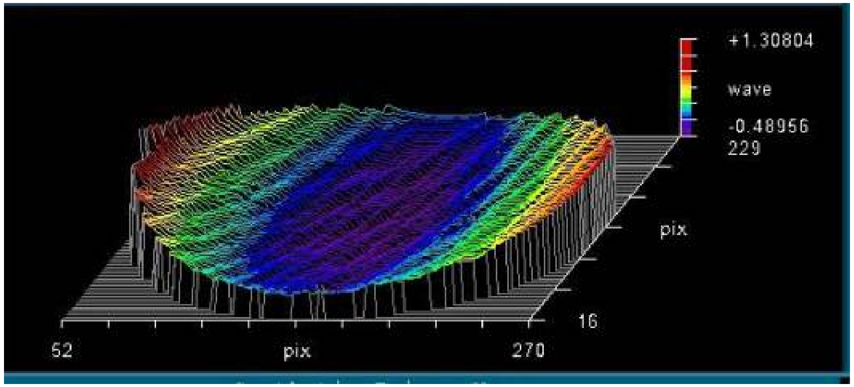


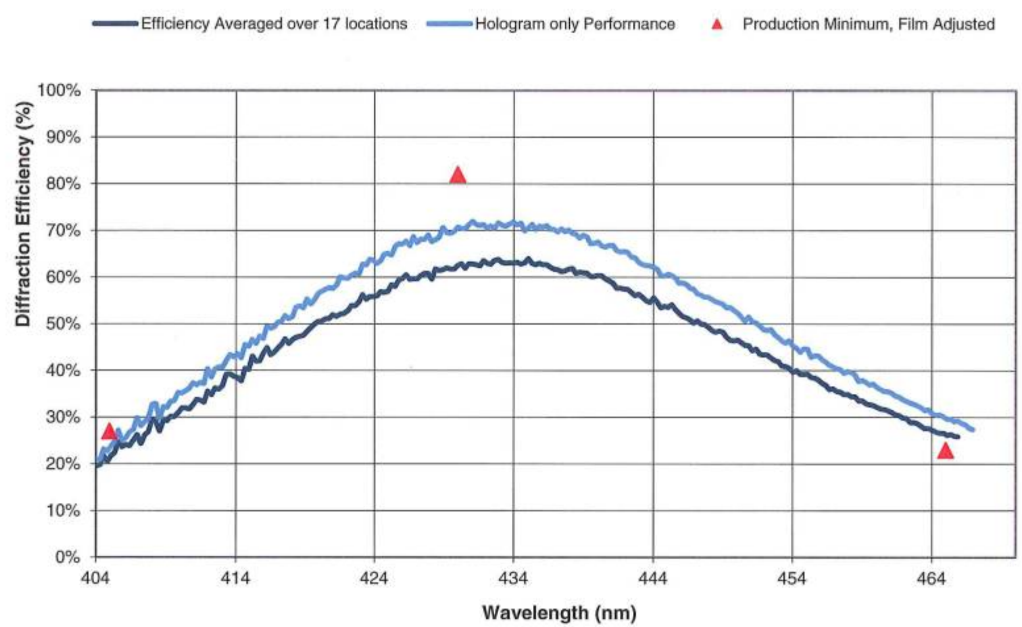
Credits: KOSI

- Peak efficiency = 80 – 90% @ 635 nm;
- Edge efficiency about 20-30%;
- Relative large spectral ranges.

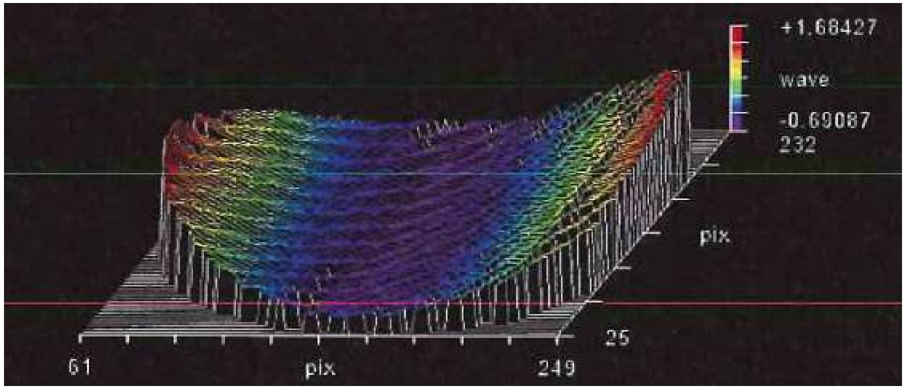
WEAVE@WHT – VPHGs HR Blues

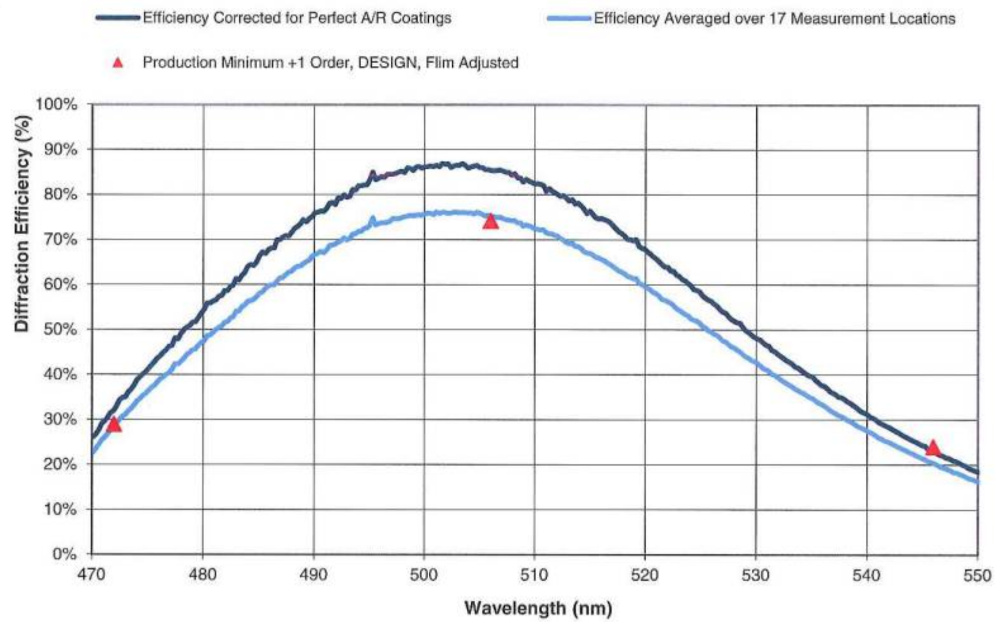
Blue 1 3500 l/mm @ 430 nm





Blue 2 3050 l/mm @ 505 nm





Credits: KOSI

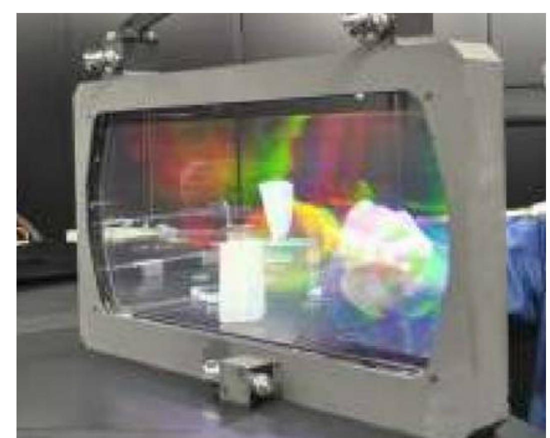
Other Requirements: Size

The astronomers require large gratings for increasing resolution in large spectrographs

- Big holographic set – up (actual limit < 30 cm "in height", 60 cm in length)
- Mosaic approach (for example VPHG for APOGEE, HERMES)

Issues:

- It is necessary to have films with uniform thickness over a wide area, uniform light exposure and high sensitive materials (no too thin layers);
- Mosaic: non negligible gap between the apertures (efficiency reduction);
- Limited substrate thickness (weight issue) and rectangular shape;
- Substrate oversize for writing step.



HERMES VPHG by KOSI

Rallison et al, Proc. SPIE, 4842, pp. 10-21 (2003)
Blanche, P. A.,et . al. Optical Engineering, 43(11), 2603-2612 (2004).
Arns J. et al., Proc. SPIE 7739, 773913 (2010)

Other Requirements: wavefront distortion

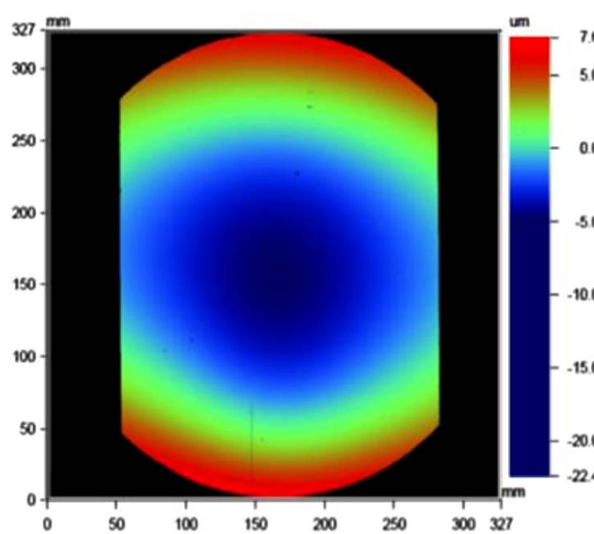
Wavefront distortion: it can be due to the aberrated fringe pattern (holographic set-up, post-processing) or due to assembling (gluing, material shrinkage,…).

•This is becoming important because of the tight error budget of the WFE.

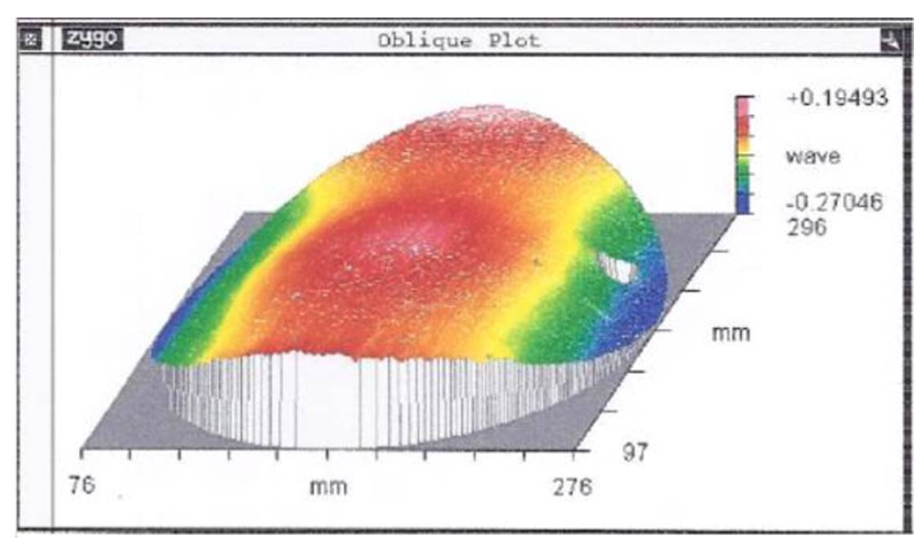
•No way to control it…still to learn.

•It can be critical for high dispersion large gratings (limited thickness and rectangular shape.

VPHGs for HERMES are an example: it was necessary a post polishing!

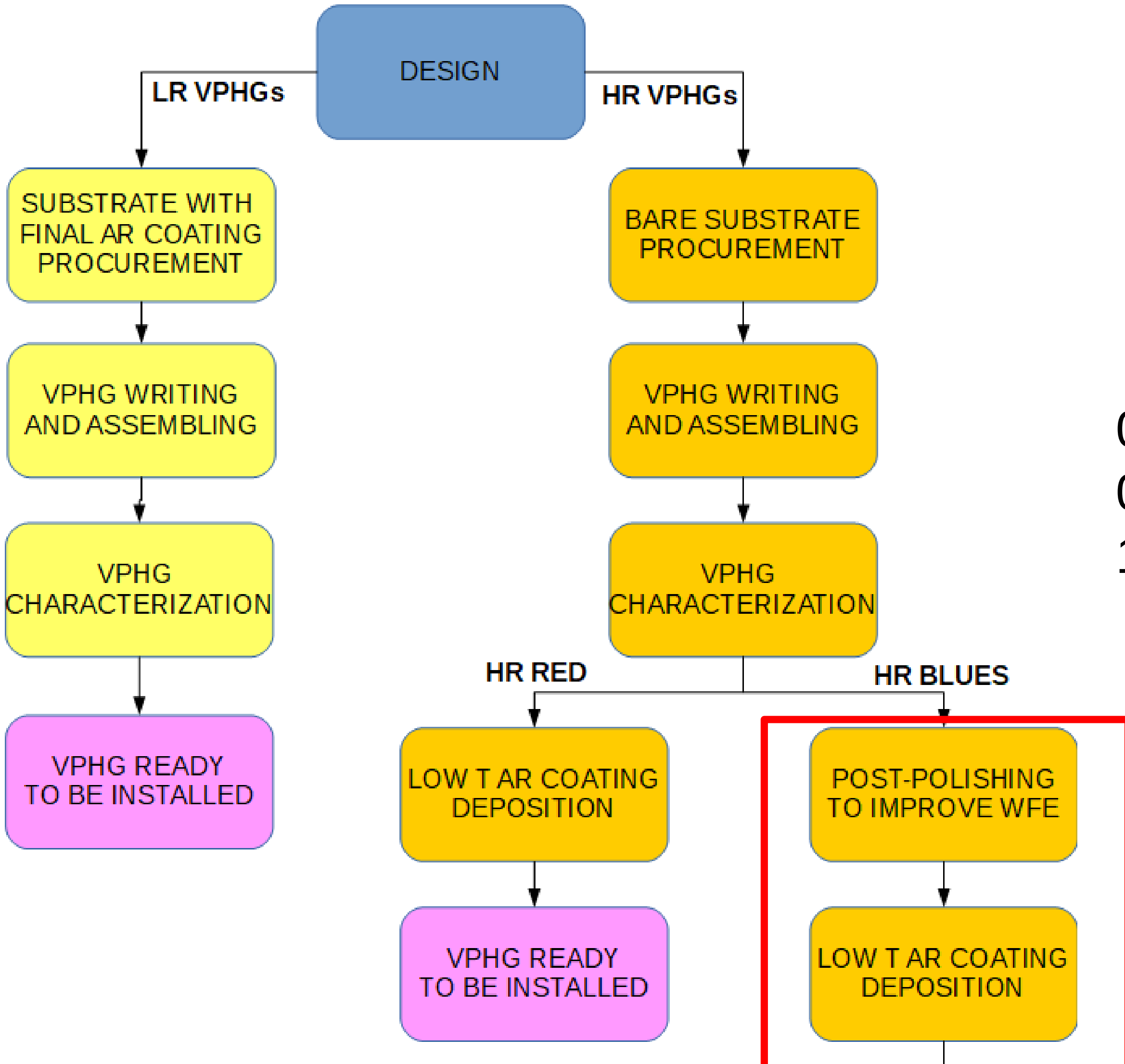
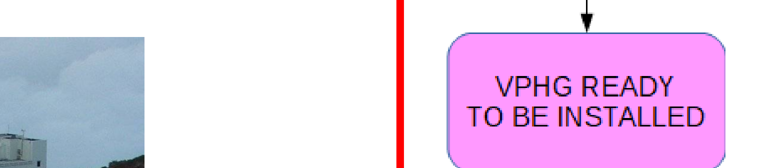


(a)



(b)

Other Requirements: wavefront distortion

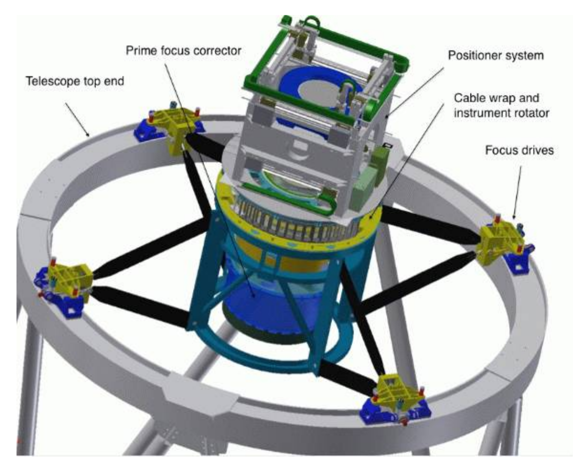
WEAVE High Res VPHGs:

Post-polishing +

Low T AR coating

0 order: before Post-P, PtV = 2.375 λ
0 order: after Post-P, PtV = 0.87 λ
1st order: after Post-P, PtV = 2.62 λ

Risky!

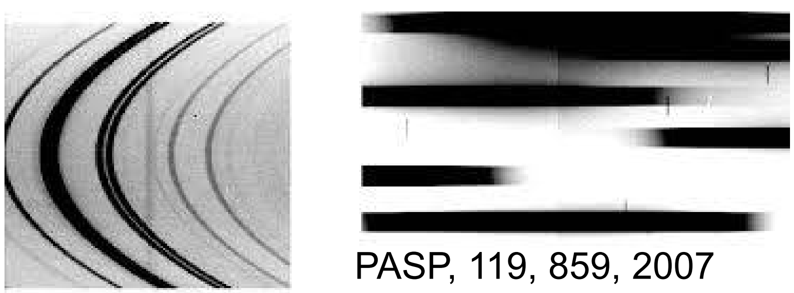


Other Requirements: S/N – scattering and ghosts

It is important to have low light scattering => homogeneous material before and after the exposure. **Still open issue! You cannot ask for a requirement on it.**

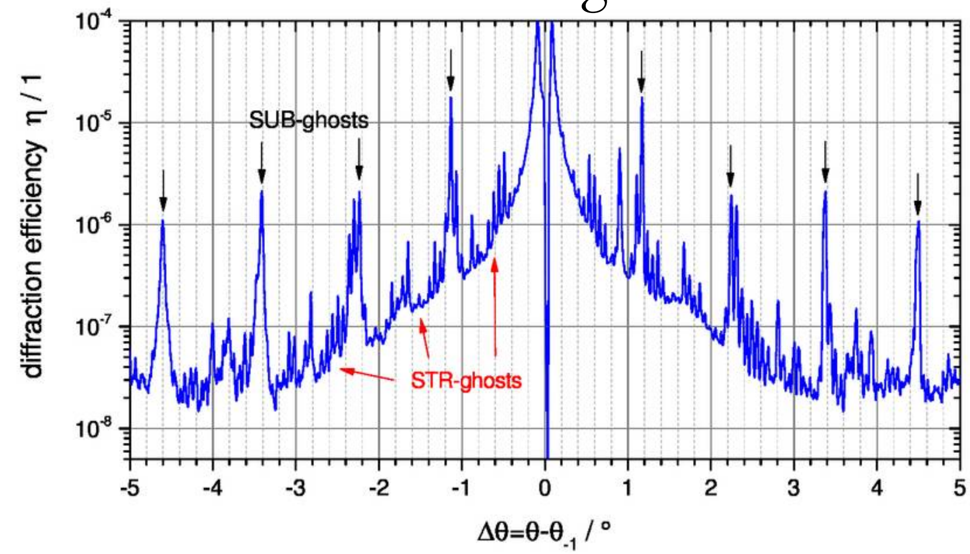
- No Rowland ghosts typical of ruled gratings;
- Littrow Ghosts have been detected in VPHG.

VPHG ghosts

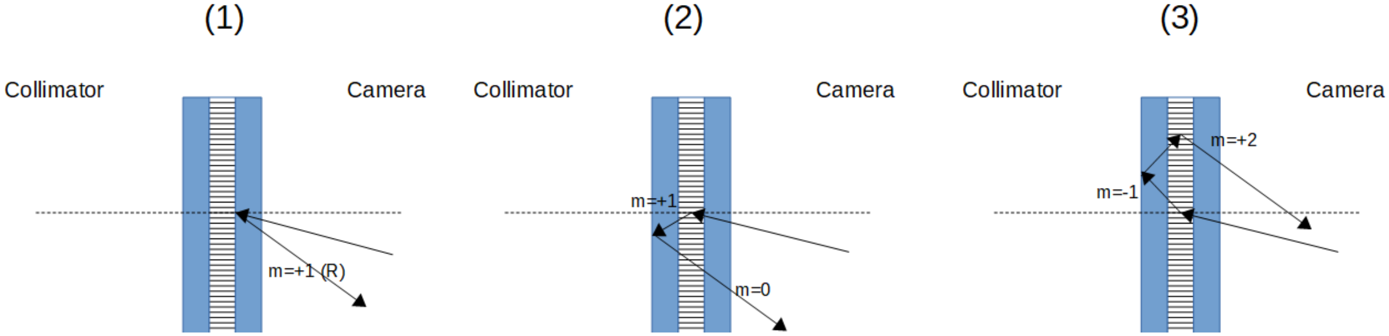


PASP, 119, 859, 2007

Rowland ghosts



Proc. SPIE 9759, 97590A, 2016



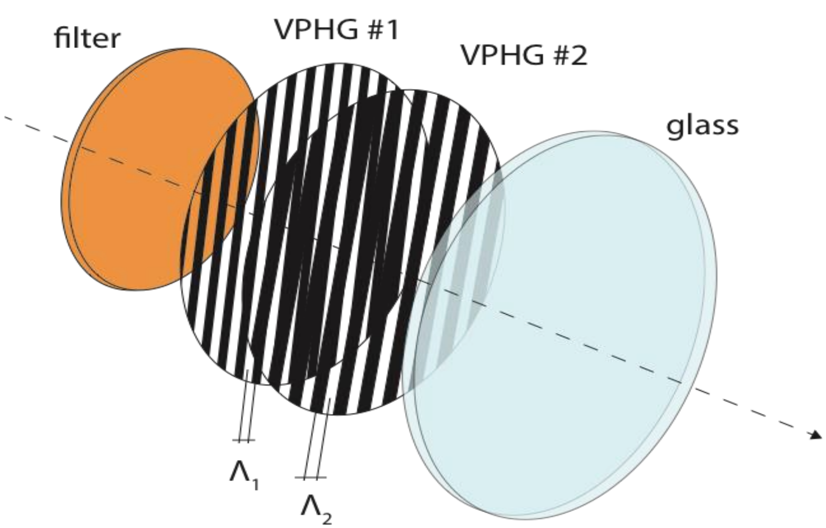
Different geometries of ghosts in VPHGs

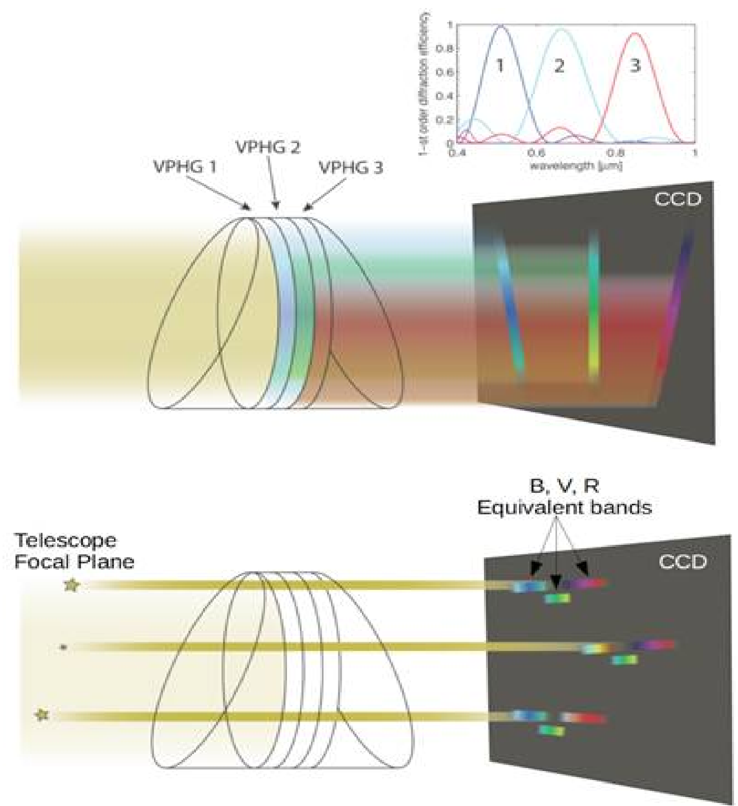
Multiplexed VPHG: extended range and resolution

ISSUE: increasing the resolution, the spectral range decreases due to the limited size of the detector. Multi exposures are necessary to cover a wide spectral range with the desired R.

IDEA: Combine more than one VPHGs with suitable clock angle in the same device to fill the detector in a similar fashion of an echelle. Target R = 3000 – 5000.

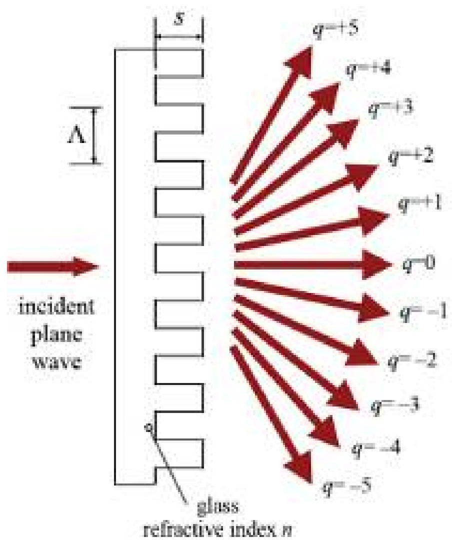
Provide "high" res spectra only of some target features.



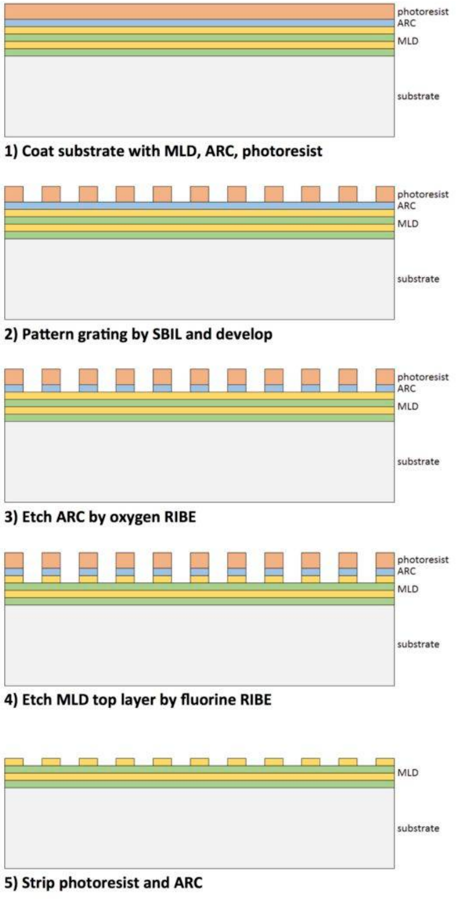


Other possibilities…binary (lithographic) gratings

- Lithographic gratings: the profile is binary or more complex and they are usually manufactured by means of optical or e-beam lithography;



http://www.holoor.co.il



https://www.plymouthgrating.com/

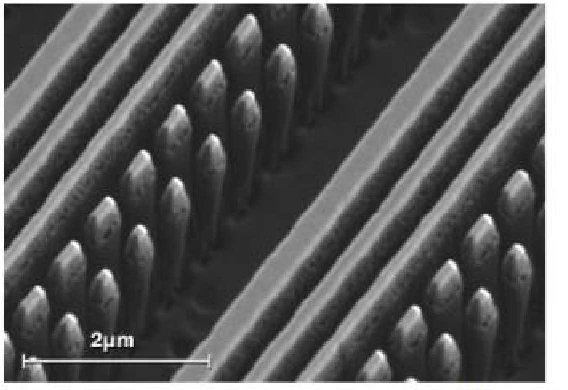
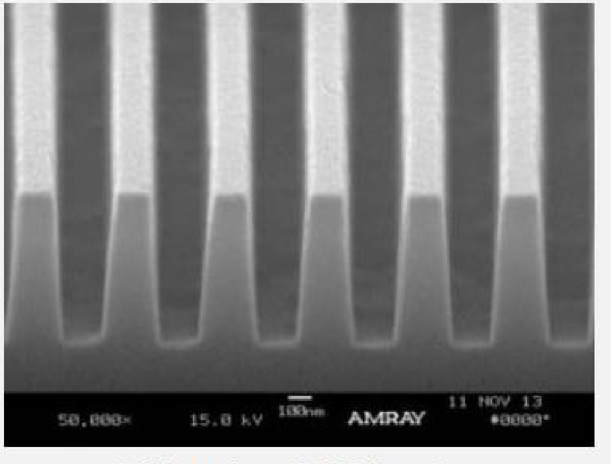


FIGURE 2: Spectrometer grating for the radial-velocity spectrometer of the GAIA

Fraunhofer IOF

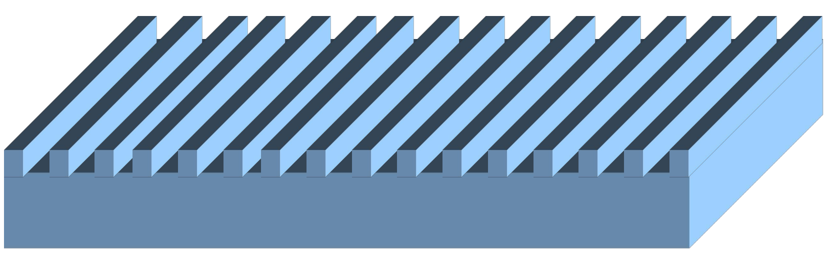


0.65 μm deep; 2,400 lines/mm

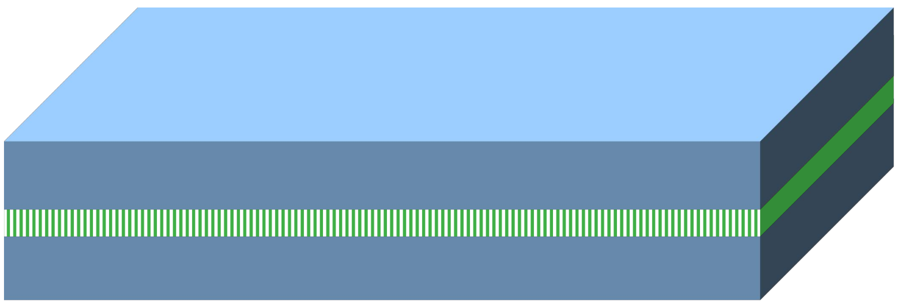
Binary gratings: features

- They are usually lighter, since they don't require two substrates.
  - Important for large gratings;
  - Small impact on the WFE (the single substrate could be thicker).
- Target WFE can be required;
- They required smaller substrate oversize during the production;
- Possibility to make mosaic with smaller gap;
- Monolithic grating or bonding of the thin layer with the pattern and the glass substrate.

Binary grating

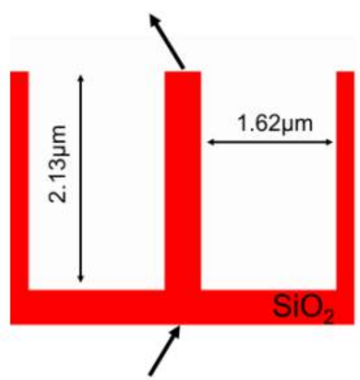


VPHG

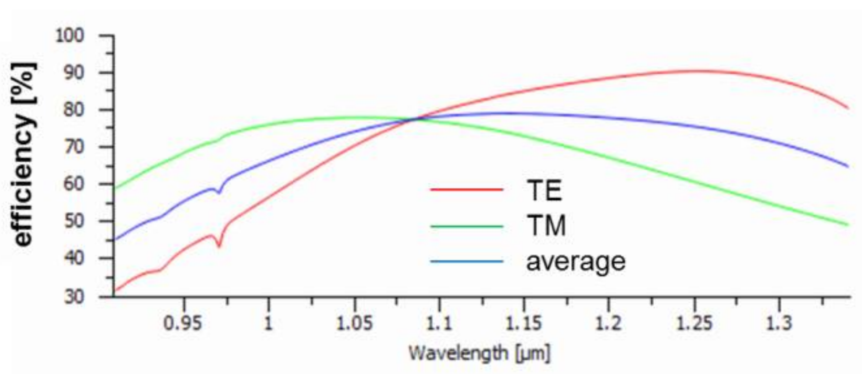


Binary gratings: efficiency

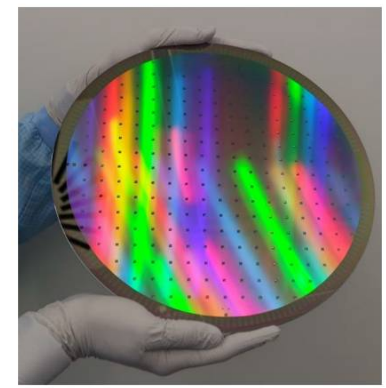
- Provide very good diffraction efficiency <u>especially at high dispersion;</u>
- Engineering of the profile to tune the efficiency, especially with ebeam lithography;
- With ebeam the size limit is about 300 mm.

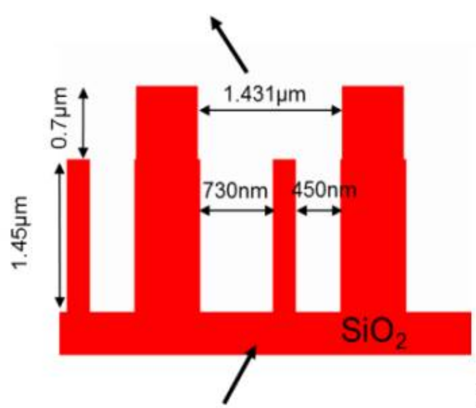


)

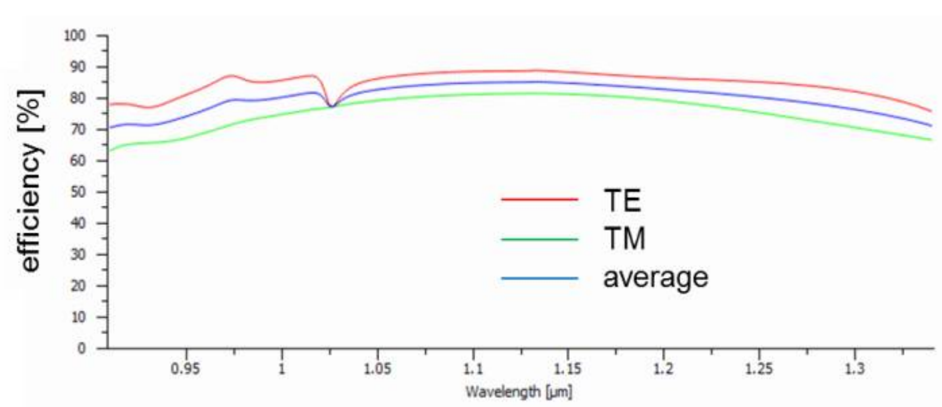


b)





b)



YJ MOONS

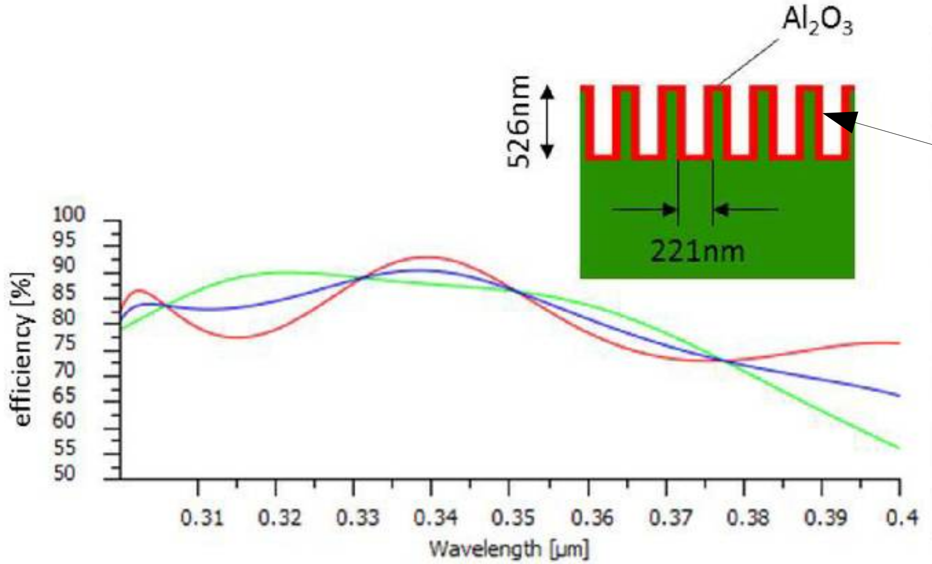
Grating type	Transmission
Period	2.045 µm
Polarization	TE and TM
Wavelength	910 – 1340 nm (channel YJ)
Angle of incidence	20 degrees (air)
Targeted diffraction efficiency in -1st order	> 70%
Target grating size	~ 300 mm in diameter

Table 1. Grating specification for the MOONS YJ channel

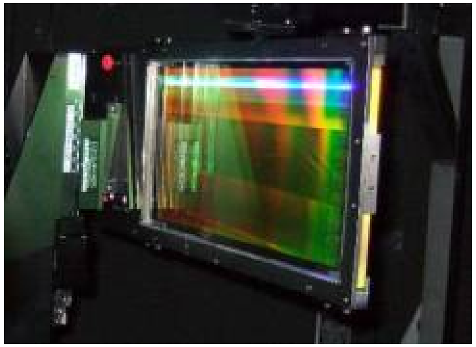
Proc. SPIE 10706, 1070621 (2018)

Binary gratings: efficiency (2)

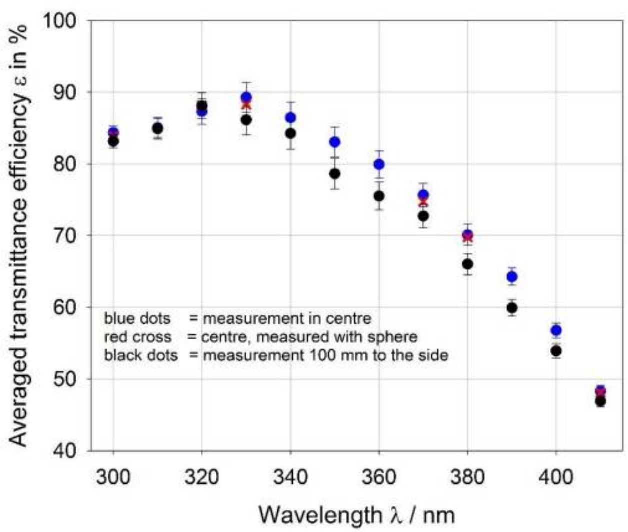
Another example comes from the grating for CUBES (UV spectrograph for VLT):



Two materials:
SiO_2 and Al_2O_3



U. Zeitner, Proc. SPIE, 8995, 899504 (2014)



PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin Nationales Metrologieinstitut

PTB-4.51-4093591

Ghosts due to the periodicity of the "ebeam writing tool"

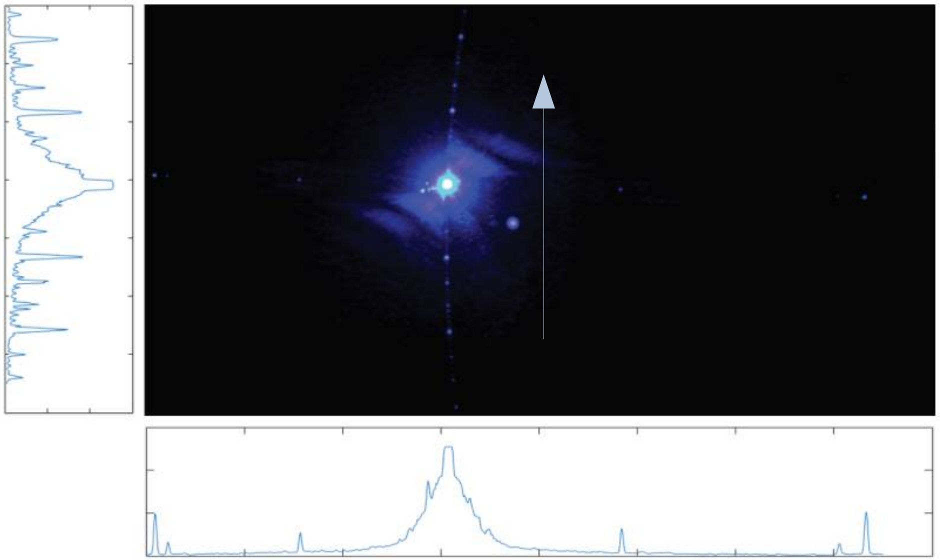
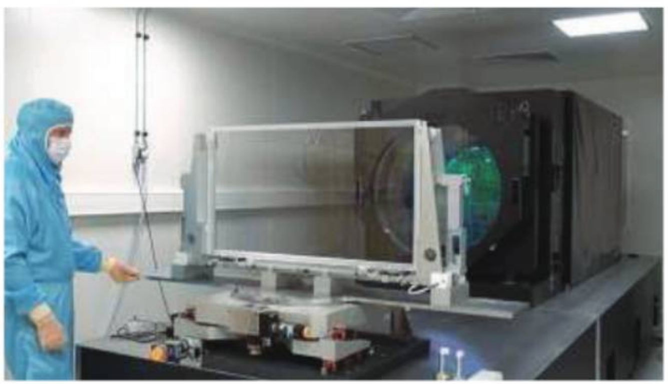


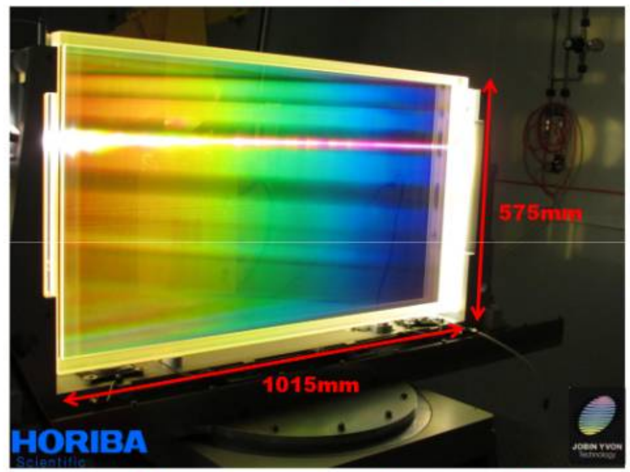
Figure 6: photo (closer distance) of the screen hit by the diffraction beam with the intensity profiles.

Other possibilities…square meter grating

- Gratings with binary profile up to one meter in size, developed for the high power lasers;
- Holography instead of lithography, but same flexibility;
- Monolithic silica gratings up to 70 cm;



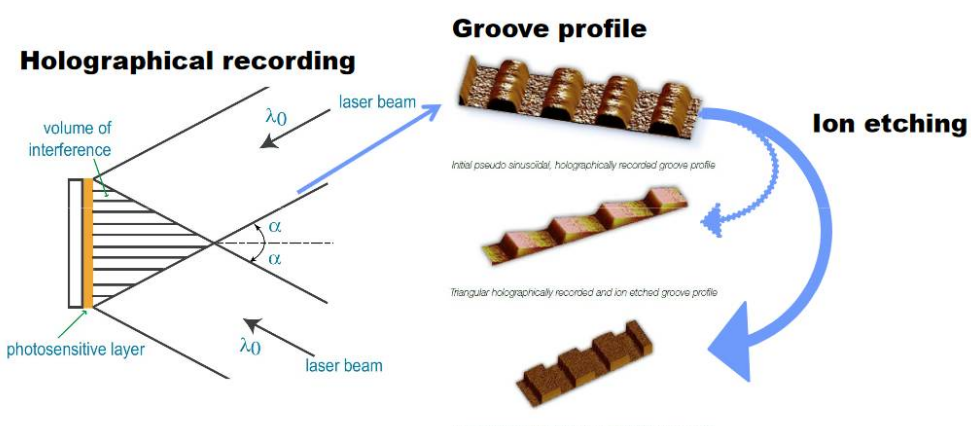
Holography*



World Largest Holographic Grating

KEY FEATURES :

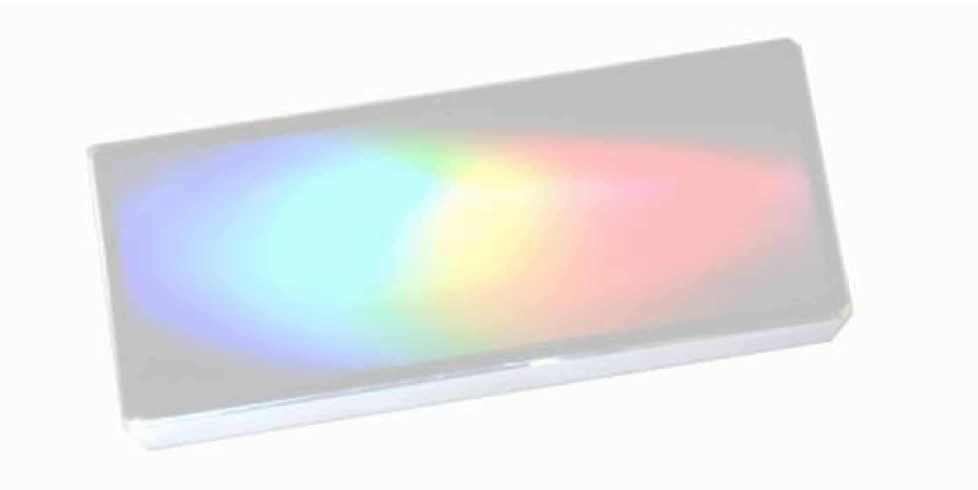
- Very high groove density up to **~6500gr/mm**
- Shape : plane, spherical, toroidal, free-form
- **Up to 1500mm** gratings capabilities
- Reflection or Transmission
- **High efficiency**
- **Low stray light**
- Replication possible (**TRL9**).



- The grating profile can be tuned during the development and with the ion etching.
- Less freedom than the ebeam approach.

Example: MOONS HR-I by Horiba

HORIBA
Explore the future



MOONS HR-I

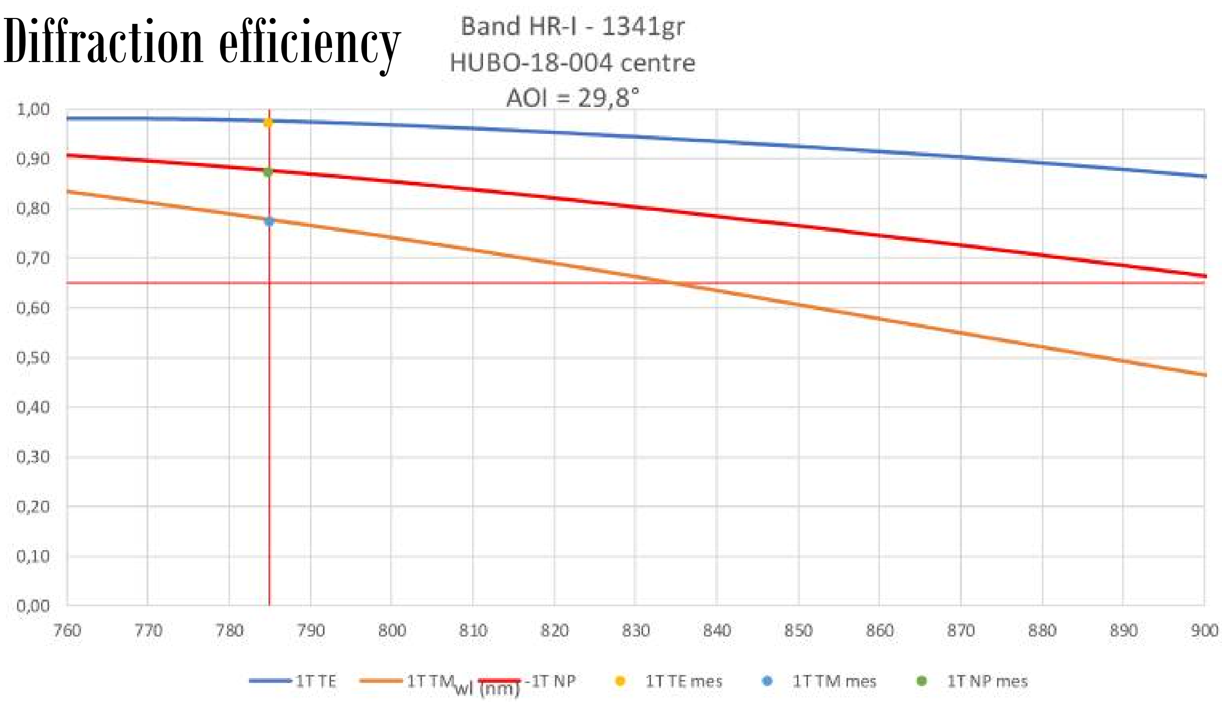
Size: 300 x 350 mm^2

Line density: 1341 l/mm

WFE: 125/209 nm (RMS, PV)

Spectral range: 0.76 – 0.90 micron

Diffraction efficiency



In conclusion...

- Dispersing element is a crucial element in astronomical spectrographs;
- It strongly affects the total throughput especially in HR spectrographs;
- The efficiency and dispersion are not the only properties to be considered;
- Fortunately, there are many possibilities!
- VPHG is probably the best compromise (efficiency, reliability, risk,...);
- Lithographic and binary gratings are interesting options;
- Design spectrographs with different kind of dispersing elements (MOONS in an example);
- Risks: reliability of the manufacturers. In any case, there are a few players, not always really interested in facing the astronomical issues;
- Costs and delivery time.

In conclusion...