New series of high resolution and efficiency VPH gratings

MSE High Resolution Survey

Maunakea Spectroscopic Explorer

- MSE will include a High Resolution mode for Galactic Archaeology.
- 11m telescope, >1000 simultaneous HR spectra, R=40,000, 3 bands.

$\Rightarrow$ the HR spectrograph costs form a very large fraction of the total.

- Would like to use VPHs for MSE, as for HERMES and 4MOST (efficient, tuneable, cheap, robust, Littrow).
- But as telescope sizes and resolution requirements increase, are they viable design solutions?

Beam Size

Spectrograph cost/difficulty/risk strongly driven by the collimated beam size:

$$B = R\, D_T\, \phi_F / (2 n_1 \tan\alpha_0)$$

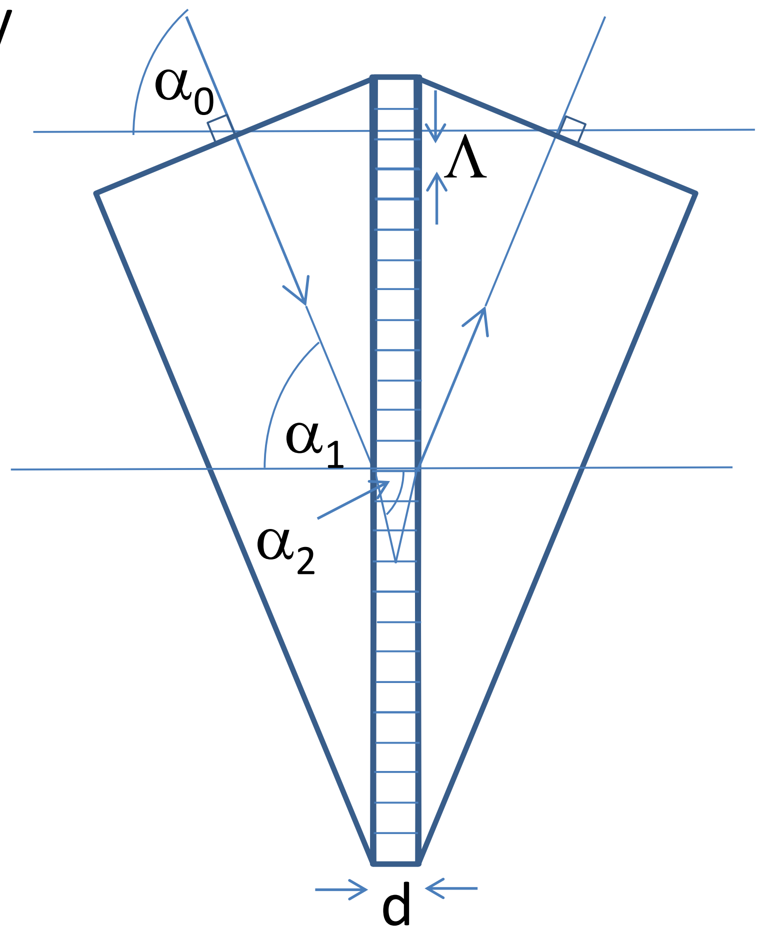
(***R*** is the resolution, D_T is the telescope diameter, ϕ_F is the angular slit width, n_1 is the index of the immersion medium, and α_0 is the overall grating angle)

B scales directly as ***R***, D_T, ϕ_F

All fixed (unless image-slicing used)

$\Rightarrow$ Larger grating angle is very desirable.

But efficiency also paramount!



Diffraction efficiency

Peak efficiency of VPH gratings was approximated by Kolgenik (1969):

$$\eta \approx \tfrac{1}{2}\sin^2\left(\frac{\pi \Delta n_2 d}{\lambda \cos\alpha_2}\right) + \tfrac{1}{2}\sin^2\left(\frac{\pi \Delta n_2 d}{\lambda \cos\alpha_2}\cos 2\alpha_2\right) \qquad (1)$$

(λ is the wavelength, Δn_2 is the index modulation, d the DCG thickness, α_2 is the grating angle *within the DCG*, and the two terms are for ***s*** and ***p*** polarizations respectively).

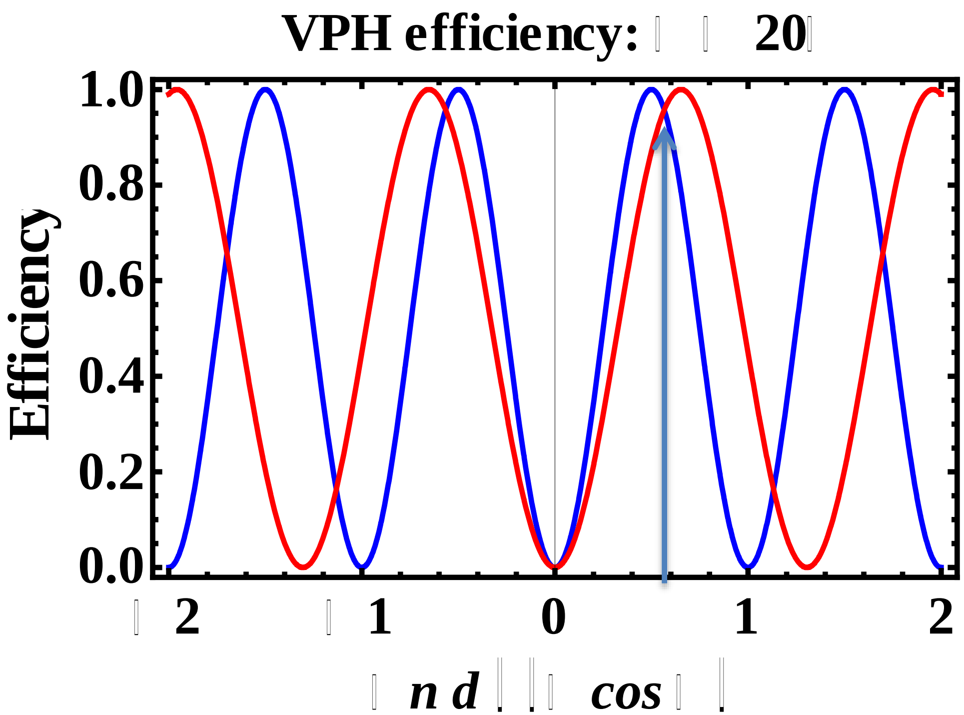
For each polarization, can get ~100% efficiency by choice of d and Δn_2, to get $\pi/2$ within the brackets*

For highest bandwidth, normally want **small *d*** and **large Δn_2**

*(or **3π/2** or **5π/2** etc).

Diffraction efficiency

- For small angles, $\mathbf{cos\ 2\alpha_2 \sim 1}$, and hence excellent peak efficiency is possible in both polarizations simultaneously.
- But as α_2 increases, the $\mathbf{cos\ (2\alpha_2)}$ term introduces a mismatch between the desired DCG properties for each polarization.



Diffraction efficiency

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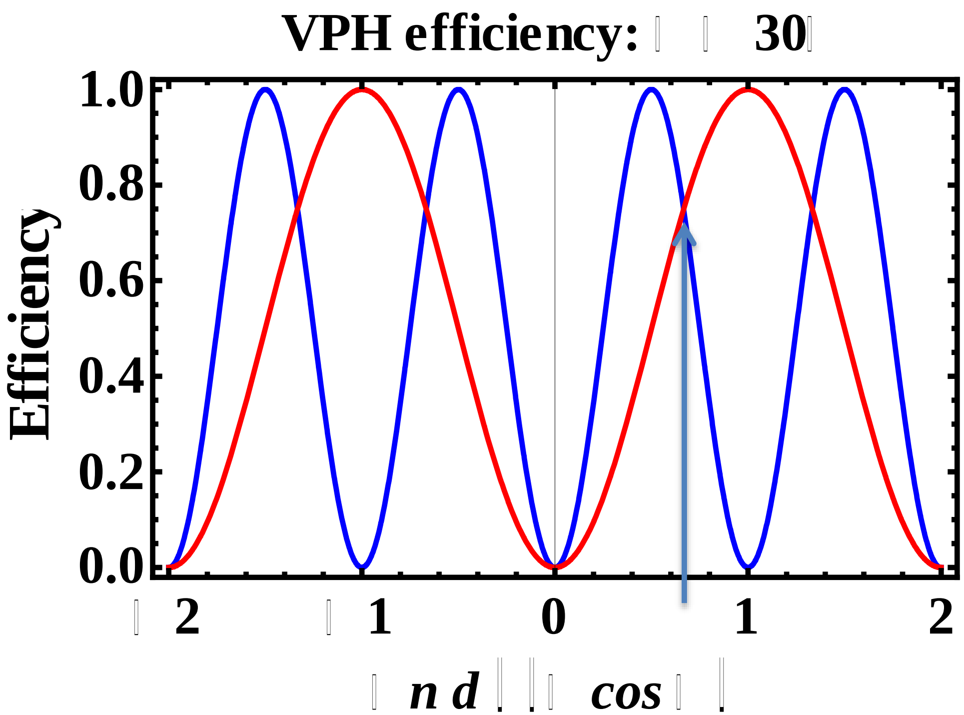
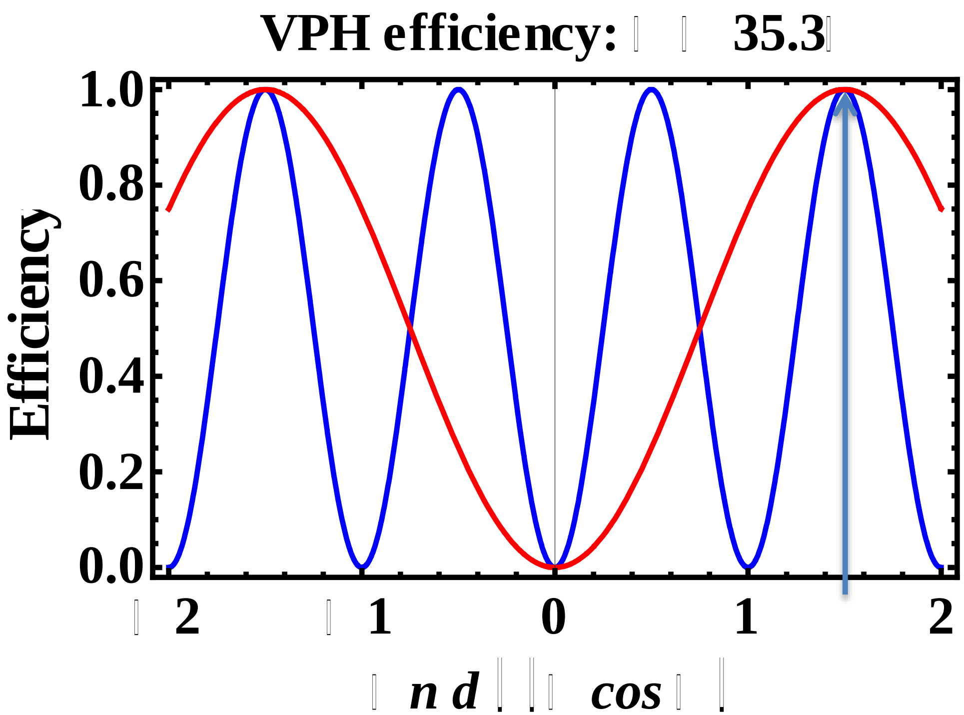
- For small angles, **cos 2**α_2 **~1**, and hence excellent peak efficiency is possible in both polarizations simultaneously.
- But as α_2 increases, the **cos (2**α_2**)** term introduces a mismatch between the desired DCG properties for each polarization.



Diffraction efficiency

- Simultaneous high efficiency for both polarizations is still possible for special values of α_2, by matching an efficiency peak in the ***s*** polarization with a *different* peak in the ***p*** polarization. 'Dickson gratings'



Dickson Gratings

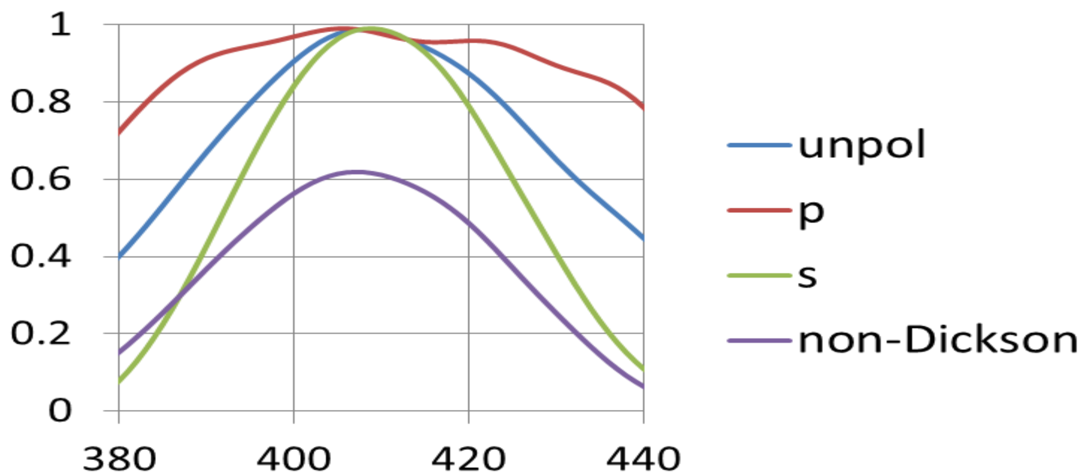
We need

$$\frac{2\pi\,\Delta n\, d}{\lambda \cos\alpha_2} = 2a+1 \quad (2) \quad \text{and} \quad \cos 2\alpha_2 = \frac{2b+1}{2a+1} \quad (3) \quad \text{for integral } a,\, b$$

Simplest Dickson grating has **(*a*,*b*) = (0,1)**, $\boldsymbol{\alpha_2 = 35.3°}$, $\boldsymbol{\cos 2\alpha_2 = 1/3}$.
Matches the 1st *p*-polarization peak with the 2nd *s*-polarization peak.

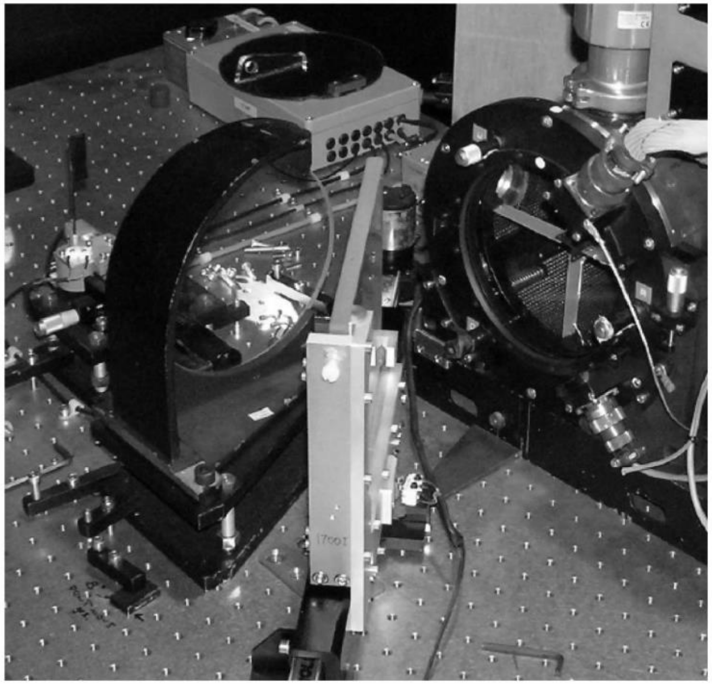
Leads to overall grating angle ~47° in air for unimmersed grating.

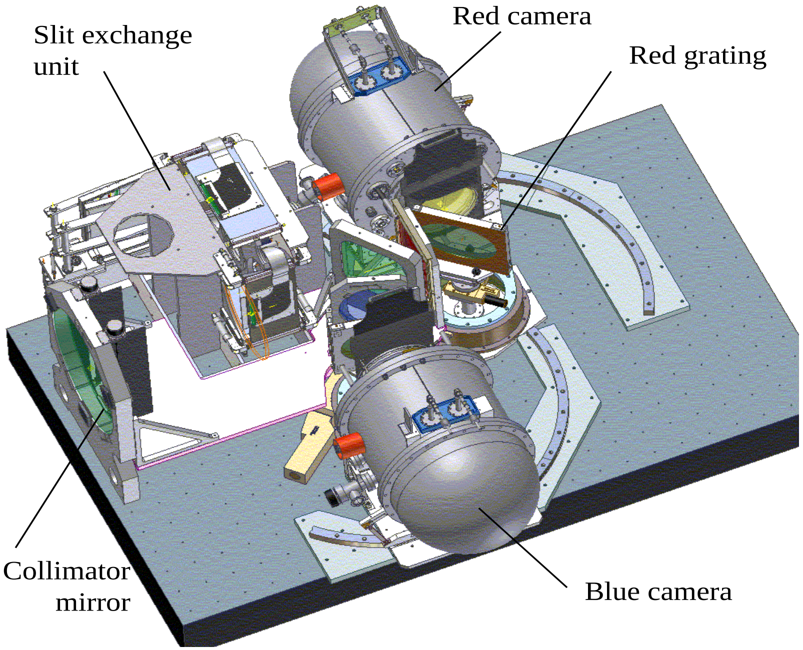
Large overall gain for plausible angular bandwidths.



Dickson Gratings

First astronomical uses of Dickson gratings were for 6dF/RAVE on the UK Schmidt (2003) and AAOmega on the AAT (2004), both for CaII triplet work (~850nm).





SuperDickson Gratings?

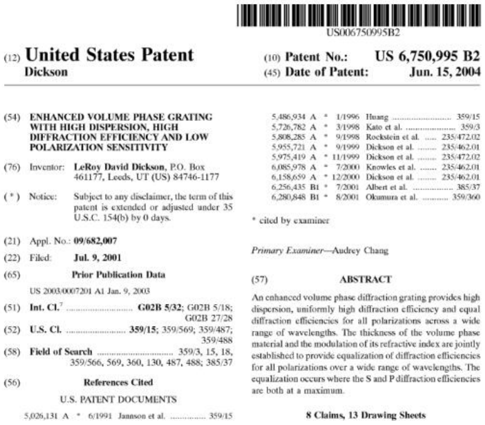
Wasatch took a patent on Dickson gratings in 2004, specifically covering ***a* = 0,1,2,3**… and ***b* = 0,1,2,3...**

Obvious that ***a*** must be +ve, from equation (2).

However, ***b*** is not so constrained, and **there are multiple families of further solutions with –ve *b*.**

All these new solutions have Bragg angles > 45°. This means they all need prisms to get the light into and out of the grating while avoiding TIR.

The two most interesting new classes of gratings are **(*a*,*b*) = (1,-1)** and **(*a*,*b*) = (0,-1)**.



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(12) **United States Patent**
Dickson

(10) **Patent No.: US 6,750,995 B2**
(45) **Date of Patent: Jun. 15, 2004**

(54) **ENHANCED VOLUME PHASE GRATING WITH HIGH DISPERSION, HIGH DIFFRACTION EFFICIENCY AND LOW POLARIZATION SENSITIVITY**

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(22) Filed: **Jul. 9, 2001**

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(52) **U.S. Cl.** **359/15**; 359/569; 359/487; 359/488

(58) **Field of Search** 359/3, 15, 18, 359/566, 569, 360, 130, 487, 488; 385/37

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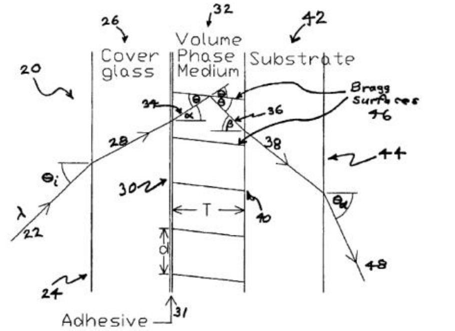
Primary Examiner—Audrey Chang

(57) **ABSTRACT**

An enhanced volume phase diffraction grating provides high dispersion, uniformly high diffraction efficiency and equal diffraction efficiencies for all polarizations across a wide range of wavelengths. The thickness of the volume phase material and the modulation of its refractive index are jointly established to provide equalization of diffraction efficiencies for all polarizations over a wide range of wavelengths. The equalization occurs where the S and P diffraction efficiencies are both at a maximum.

8 Claims, 13 Drawing Sheets



$(a, b) = (1,-1)$, $\alpha_2 = 54.7°$

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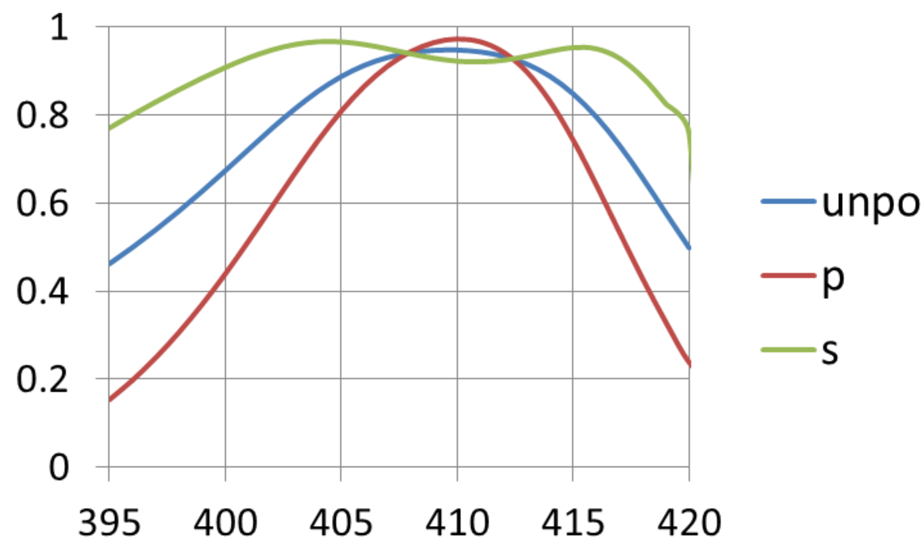
- Matches 1st p peak with -2nd s peak.
- $\alpha_0 \sim 48°$. Gives a dispersion ~50% larger than a classic unimmersed Dickson grating.
- DCG parameters look ok – e.g. **5378 lines/mm**, n_2**=1.35±0.15**, d **= 2.37μm**.



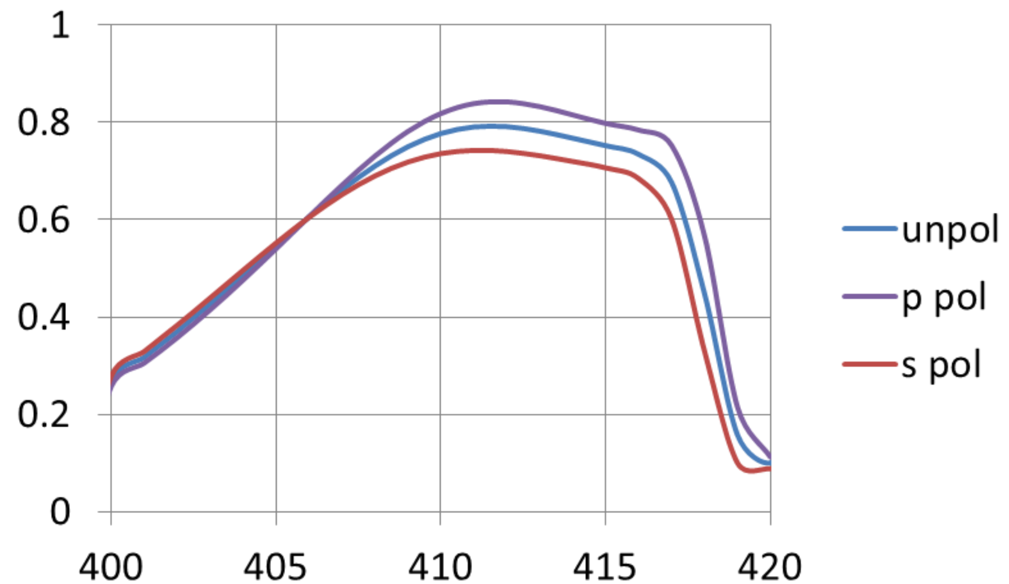
- The FWHM bandwidth is 6.4% in wavelength, or 0.16 rad (9°) in angle – useable but a bit narrower than we'd like.
- Referred to by Baldry *et al* (2004).

$(a, b) = (0,-1)$, α_2 <~90°

α_2 = 90° is unphysical, but as **$\alpha_2 \rightarrow$ 90°**, 1st *s* and -1st *p* peaks become phased.

Design shown has **$\alpha_0 \sim$ 65°**, **α_2 = 72°**, **6445** lines/mm, **d = 1μm**, **n=1.4±0.075**

FWHM bandwidth is 3.7%, 0.22rad, 12.5°, very nice!



The DCG is thinner than used in gratings to date, but the modulation is modest.

Larger angles possible but DCG thickness becomes even thinner.

2nd polarization comes 'for free' – almost no loss of bandwidth

Implications for Spectrograph design

MSE HR spectrographs require ***R*** ~ 40,000 in two arms (~409nm, ~481nm) each with $\Delta\lambda/\lambda$ ~ 1/30 . Telescope is 11m, fiber size 0.8″ or FWHM 0.69″.

If classic Dickson gratings used, beam size is 700mm!

New (1,-1) grating, still 450mm.

But with (0,-1) grating, ***B***=240mm.

240mm is feasible for KOSI

Camera optics sizes not too scary, largest lenses 300mm (vs 450mm in NIAOT CoDR design).