VPH gratings and low-dispersion spectrograph design

Will Saunders, AAO

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VPH gratings

• Thin layer of DCG (Dichromated gelatin) with sinusoidal refractive index modulation.

• Efficient, tuneable, cheap, multiple vendors, large beams ok, low scattered light.

• Now universal in low-dispersion spectrograph design.

• But three primary degrees of freedom (line spacing, thickness, index variation), all with strong effects on efficiency envelope.
Fixed-format spectrograph design

- Fiber diameter, fiber exit speed, detector spectral pixels are all fixed parameters.
- Hard requirements are wavelength coverage and resolution.
- Soft requirements are efficiency envelope and cost.
- Collimator speed defined by fiber exit speed.
- Camera speed then determined by required resolution.
- Beam-size is not fixed. Once beam-size is selected, grating angle and line density follow.
- DCG thickness and index modulation can then be tuned for best efficiency, then iterate and think again about 'fixed' and 'hard'.
- Smaller beam $\Rightarrow$ larger grating angles and grating line density.
- Need to explicitly include the grating to find optimal design.
- Up to 90% efficient at peak.
- Lower at higher dispersions because $s$ and $p$ polarisations cannot be simultaneously optimised.
- Narrower bandwidth than reflection gratings.
- Can shift efficiency peak to red or blue by tweaking input angle, but overall efficiency drops when used away from 'superblaze'.
- To zeroth order, angular bandwidth is fixed. Would favour larger beamwidths.
Gratings are defined by DCG thickness $d$, line spacing $\Lambda$, refractive index $n$, and index variation $\Delta n$.

Usage defined by input grating angle $\alpha$ and wavelength $\lambda$.

- $\lambda = 2\Lambda \sin \alpha$ (grating equation), $\Lambda \approx \lambda/2\alpha$
- $d \Delta n \sim \lambda/2$ for maximum peak efficiency
- Efficiency bandwidth maximised by large $\Delta n$ and small $d$.
- But losses to $0^\text{th}$ order when $\alpha d \leq \Lambda$ or $d \leq \lambda/2\alpha^2$

$\Rightarrow$ at low dispersion, need larger $d \Rightarrow$ lower $\Delta n$

$\Rightarrow$ Angular bandwidth is less at low dispersion
At higher dispersions, want highest possible $\Delta n$, and smallest $d$.

Angular bandwidth $\Delta \alpha \sim \lambda/2d$, $\sim$ constant with dispersion

But peak efficiency dropping ($s$ vs $p$ issues). Sweet spot at grating angles $\sim 20^\circ$.

Below this, spectral bandwidth is nearly constant.

So there is a minimum beam size, giving grating angle $\sim 20^\circ$. But above that, VPH efficiency is constant.
General considerations:

- Assume 550-950nm, 4000 spectral pixels, 100µm fibers, f/2.75 collimator, 2.5pix FWHM on detector (=0.25nm).
- Camera speed is then f/1.24! Very fast for transmissive.
- 20° grating angle corresponds to minimum beam-size ~125mm.
- Could shrink fiber size to 90µm and/or increase pixels/FWHM, to get ~f/1.5 camera (for transmissive design). Then minimum beam-size becomes even smaller, ~100mm.
Reflective vs transmissive

- **Reflective** (Schmidt-style) allows faster cameras, fewer optical components, superb imaging. Camera speeds up to ~f/1.2
- But detector is in beam $\Rightarrow$ obstruction losses
- Camera-as-dewar adds additional complexity
- Obstruction losses $\Rightarrow$ large beam (250mm+) preferred
- Schmidt correctors now cheaper and less risky with MRF technology

- **Transmissive** allows much smaller beam
- Difficult in blue but ok for 550nm-950nm
- Imaging not so good? Matters for PSF constancy.
- Max camera speed only ~f/1.5?
- Alignment difficulties at fast speeds?
Strawman transmissive design:

- JHU WFMOS design (SDSS pushed to 4K x 4K detectors) is lovely
- 159mm beam, 2 x f/1.5 cameras, $\lambda = 390$-1000 nm, R~ 3000
- Compact and affordable @ $1M each.
- Very efficient (70% peak)
- ~600 fibres/spectrograph for MOS

2230 mm x 1000 mm x 570 mm
318kg
$1M
Schmidt/Schmidt design, 250mm beam, F/1.3 camera.

Fixed format, so can put prisms between VPH and correctors, to reduce air-glass surfaces.

Lollipop dewar with field-flattener as dewar window

Optics are good (rms radius < 10μm).

Total hardware cost ~$300K (optics, dewar, detector, controller)

Two-armed version possible, twice the hardware costs.
Reflective design B

Maksutov design is much more compact. Double pass idea is new??? Detector is now outside camera.

All surfaces except field flattener are spherical.

Can go to F/1.2 camera (with <10\(\mu\)m rms spots)

Obstruction is at pupil, so very good shadowing between top-end obstruction on telescope and detector package \(\Rightarrow\) more efficient, >70% peak, competitive with transmissive designs