Design and development of the high-resolution spectrograph HERMES and the unique volume phase holographic gratings

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ABSTRACT

We report on the grating development for the High Efficiency and Resolution Multi Element Spectrograph (HERMES). This paper discusses the challenges of designing, optimizing, and tolerancing large aperture volume phase holographic (VPH) gratings for HERMES. The high spectral resolution requirements require steep angles of incidence, of 67.2 degrees, and high line densities, ranging between 2400 and 3800 lines per mm, resulting in VPH gratings that are highly s-polarized that push the fabrication process to its limits.

Keywords: Large aperture, VPH, grating, high spectral resolution, polarization

INTRODUCTION

In May 2009 the Australian astronomical community decided that a dedicated survey instrument should be built for the Anglo-Australian Telescope (AAT) that enable chemical tagging of stars in our Milky way. This science is known as galactic archeology. Four wavelength bands have been identified that should be covered by the spectrograph, see table 1. To support the efforts of the Australian astronomical community the Australian Astronomical Observatory (AAO) is building a 4-channel VPH-grating High Efficiency and Resolution Multi Element Spectrograph (HERMES) [1] for the 3.9 meter AAT. HERMES will provide a nominal spectral resolving power of 28,000 for Galactic Archaeology with an optional high-resolution mode of 45,000 by narrowing down the slit with a slit mask.

HERMES Galactic Archeology science channels	
BLUE	470.8 – 489.3 nm
GREEN	564.9 – 587.3 nm
RED	648.1 - 673.9 nm
IR	759.0 - 789.0 nm

Table 1: HERMES Galactic archeology science channels

HERMES is fed by a fibers positioned by a robot called 2dF at the AAT telescope prime focus. There are a total of 784 science fibers, which interface with the spectrograph via two separate slits located at the entrance of the spectrograph, each comprising of 392 science fibers. The opto-mechanical design of HERMES allows for reconfiguration of the bands to enable astronomers to pursue other spectral bands of interest between 370 - 1000 nm. The spectrograph will use four large 500 x 200mm VPH gratings.

VPHG DESIGN AND CONSIDERATIONS

The HERMES science specification requires a nominal spectral resolution of about 30,000 and signal to noise ratio (SNR) of about 100 for 14th magnitude (V) stars in approximately one hour of integration. These two requirements set the design for the gratings in the spectrograph. Previous work done in a feasibility study[2] showed that the use of an Echelle grating was too impractical. An incidence angle of at least 75 degrees would be required resulting in a grating length of over 700 mm. The alternative, a VPH grating, allows higher line densities resulting in a reduced angle of incidence to 67.2 degrees with corresponding effective length of 500 mm.

The starting point for the design, is the accepted rule that a VPH grating is most efficient in a Littrow configuration where the incidence and diffracted angles α and β are equal for the central wavelength, λ_c. The grating equation is shown below in which the diffraction order 'm' is one for HERMES.

$$m\lambda_c \upsilon = \sin(\alpha) + \sin(\beta)$$

The resolution is described with:

$$R = \frac{\lambda_c}{\partial\lambda} = \frac{\sin(\alpha) + \sin(\beta)}{\cos(\beta)\cdot\partial\beta}$$

The angular extend is ∂β, that corresponds to the spectral extent, ∂λ and the size of the smallest resolving element for a resolution of R=30,000. The ratio of the two, or the dispersion of the grating, depends as follows on the angle of diffraction and the line density:

$$\frac{\partial\lambda}{\partial\beta} = \frac{\cos(\beta)}{m\nu}$$

The minimum sampling is 2 pixels across a resolving element at high resolution mode, R = 45,000. The multiplying factor of 1.33 is found by dividing 45,000 by 30,000. Thus the resolving element for R= 30,000 should be minimum of 3 pixels across the point spread function (PSF) at full width half maximum (FWHM). Using fibers with 140 µm cores and 392 slit objects, HERMES became a spectrograph with 4k by 4k detectors (15 µm pixels) with 320 mm cameras (F/1.68) and an average spectral resolution of 28,000.

The diffraction efficiency prediction for the gratings is less straight forward. Theoretically, rigorous coupled wave analysis (RCWA) will yield a grating design that will efficiently diffract s and p-polarization 100%, as can be seen in figure 1. Figure 1 was generated in the conceptual design study of HERMES[1]. In the figure, diffraction efficiency varies as a function of grating depth. Four efficiency peaks can be clearly seen for Ts. Tp has a slower modulation that can be co-aligned with the Ts peaks. It was the goal of the project to at least obtain the 2nd diffraction efficiency peak where Tp finally begins to rise. Discussions with fabricators had hinted that the second peak would be difficult to achieve because the designs were pushing the gelatin material to the extremes. The first peak was achievable without rigorous research and development costs. Prototype VPH gratings were made with the intention of hitting the 2nd diffraction efficiency peak. Sadly, the effort resulted in a less efficient grating due to the complexities of controlling the gelatin to co-align the Ts and Tp modes, see the measured efficiencies in the next paragraph. As a result the grating design for HERMES has settled on the first Ts peak.

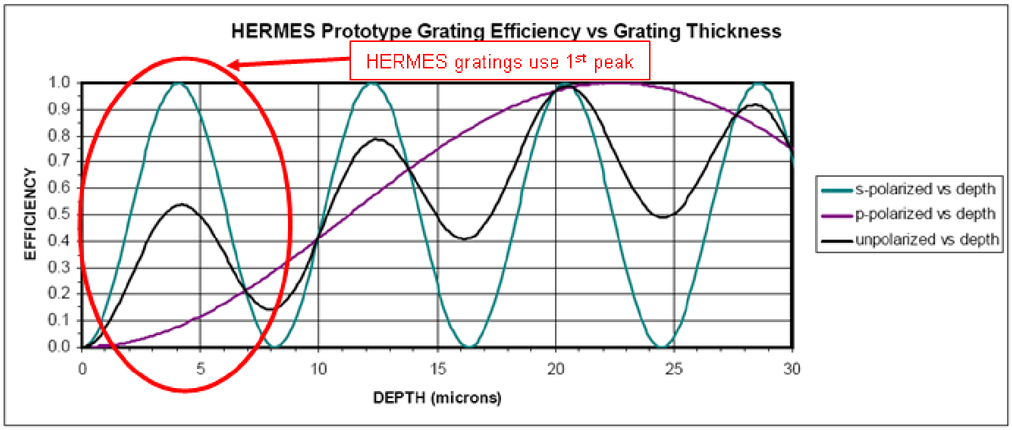

Figure 1: RCWA results for modulation depth versus efficiency of the proposed design

GRATING APERTURE AND MOSAIC

The pupil of HERMES is 200mm in size and is placed at the VPH grating. With a grating angle of 67.2 degrees the pupil stretches to a highly elliptical shape of 500mm in length. This is very large and for the most part will exceed the size of vendor's construction beam. Some time and effort needs to be placed into investigating whether a mosaic, a multiple exposure grating, is required to fill the pupil. For this the fabricators largest available collimated beam size, taking into account the reduced aperture needed to maintain superior wavefront quality, and the exposing laser's wavelength, λ_l, is needed to recreate the extent of the elliptical interference pattern on the gelatin. The line density, ν, is created by the interference pattern given by

$$\upsilon = \frac{2\sin(\alpha')}{\lambda_l}$$

As it turned out, not all the HERMES gratings require a mosaic. Only the red and IR gratings will be manufactured with a mosaic of two exposures as the vignetting losses of the non matching ellipses, pupil versus exposure extent, would become unacceptable.

A mosaic grating requires translation of the grating between exposures the required line homogeneity became of concern. This was therefore investigated and a prototype was made. The results of this are presented in the paragraph titled Efficiency Measurements of VPHG Prototypes. The stringent requirements also lead us to explore alternative VPH designs.

DOUBLE PASS GRATING DESIGN

An alternative VPH grating design was explored to increase the diffraction efficiency by placing two VPH gratings in series. This has the added benefit of minimizing the angle of incidence and the aperture of the grating. A useful relation can be used to find the average incident angle, α_{avg}, for each grating in series, $N_{gratings}$, by using the equation for spectral resolution in Littrow.

$$R \propto \tan(67.2) \approx N_{gratings} \times \tan(\alpha_{avg})$$

What one finds is that the resolution doesn't just simply add, but goes as a multiple of tangent. Therefore, to reach the equivalent resolution of a single HERMES grating the two gratings in series would still have had relatively steep angle of incidences, about 50 degrees, and large size, > 350 mm. This doesn't take into account that the second grating already see's diffracted light from the first grating making the second grating > 400 mm in size.

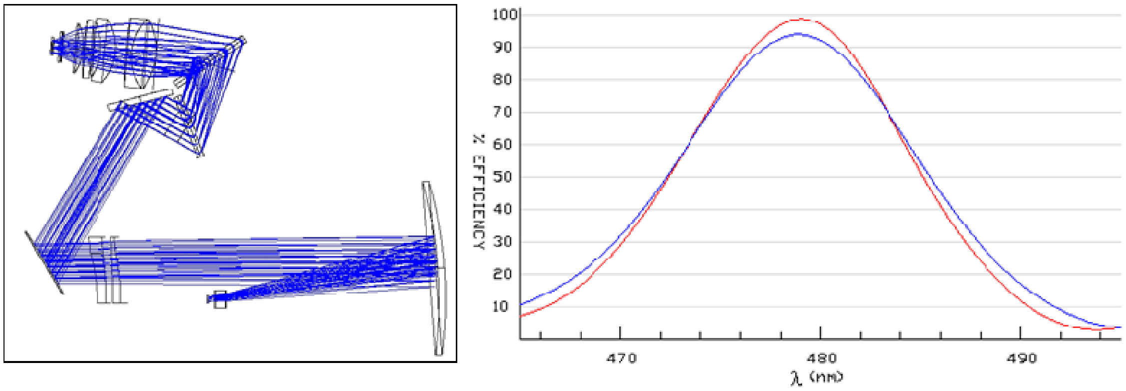

Figure 2: Double gratings in series for the Blue channel (left) and the theoretical diffraction efficiency (right)

This idea of using two gratings in series was proposed for the Keck Observatory[3]. The company SyZyGy was asked to explore the design and diffraction efficiencies of this concept using RCWA. In many fronts this was an attractive alternative if it would not have been that the diffraction efficiency sharply declined at the edges of the spectral band, < 30%. This was a result of the light incident onto the second grating was already dispersed and off the optimal operating (Bragg) angle.

VPHG LINE DENSITY TOLERANCING

The HERMES specification dictates a nominal spectral resolution of ~30,000. The resolution defines the fabrication tolerance of the VPH grating that controls the angle of diffraction. Using the resolving element size, the camera focal length, and the grating equation one can derive each of the tolerances listed in Table 2. The tolerances were then fed into the HERMES ZEMAX^{TM} model and verified empirically for various field positions. It should be noted that these tolerances are very similar to the VHP grating for the Apache Point Observatory Galactic Evolution Experiment[4]. This is not just a coincidence as optically these instruments are of a very similar form factor.

Grating diffraction specifications	
Angle of incidence (degrees)	67.2
Angle of diffraction (degrees)	68.1
Line frequency variation across the clear aperture (Δν/ν)	< 2E-6
Mosaic tile to tile line frequency variance (Δν/ν)	< 2E-6
Mosaic tile co-alignment (arc-sec) (the grating line clocking alignment from one tile to the other)	≤ ± 3.0

Table 2: HERMES VPH grating global tolerance specifications

The concept of tiling a VPH grating on a monolithic glass encapsulate was investigated with the use of the prototypes. These prototypes confirmed that obtaining line frequency homogeneity maintained across the grating clear aperture as well as the rotational clocking of one tile with respect to the other in a multi-exposure is not a trivial matter, see figure 4. Current tests used an imaging camera with a focal length of 1700mm.

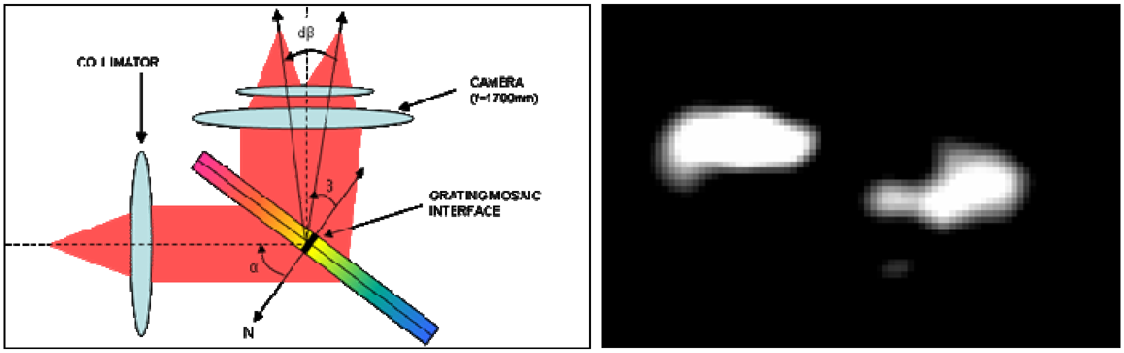

Figure 3: Initial test layout (left) and Image from a mosaic prototype VPH with a differential line frequency of one tile respect to the other, Δx = 12 arc-sec or Δν/ν = 1.82e-5, and a tile misalignment, Δy = 20 arc-sec (right).

This works for the relatively small sized gratings, 50 x 100 mm, but for the real HERMES gratings a different setup is needed that doesn't require a separate collimating optic and camera with a clear aperture of 200 mm. As result extensive work is being done to create a test that can accurately measure the line frequency variance (Δν/ν) and the mosaic tile co-alignment across the entire clear aperture. Tests on the final gratings will be done in double pass utilizing a laser source with a line width of 1.5MHz, a point source microscope (PSM)[5] used with 10x microscope objective, an off-axis Newtonian collimator with a 200 mm clear aperture, the grating in Littrow, and a 300 mm reference flat. The test does require high precision optics, much like an interferometer, to measure the angular tolerances dictated in table 2.

A physical separation of the grating tiles was investigated to reduce the tolerance on the homogeneity of the grating line frequency. The hope was that a large VPH grating could be made cheaper and easier by mechanically splitting the mosaic into two separate physical tiles. Using empirical results from simulations of the HERMES spectrograph in ZEMAX™ it was found that Δν/ν still had to be maintained to a level < 1.0e-5. This was an order of magnitude larger than our requirements, but based upon the cost and complexity of implementing a specialized mounting fixture a decision was made to solve this alignment during manufacturing of the grating.

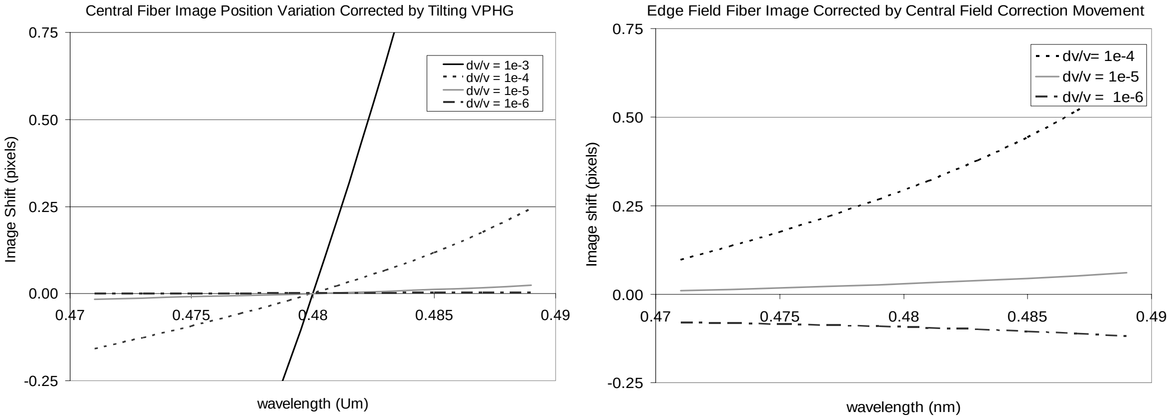

Figure 4: Image position correction for misaligned grating tiles. The central fiber image corrected for tile to tile line frequency shift by tilting one tile with respect to the other (left) and the edge field fiber image corrected using the same tilt correction for the central fiber image (right)

EFFICIENCY MEASUREMENTS OF VPHG PROTOTYPES

As discussed earlier, in the VPHG design, it was tried to achieve a VPH grating that efficiently diffracts Ts and Tp polarized light, see Figure 1. For this reason a prototype was made and evaluated. An image of the prototype under test is shown in figure 2 and the measured efficiencies for two grating designs are shown in figure 3. The grating that works according the “second peak design” shows it does not achieve the theoretical efficiency and turns out to be less efficient than the “first peak design”. This drove the decision to make the HERMES VPH gratings to be fully optimized for s-polarized light.

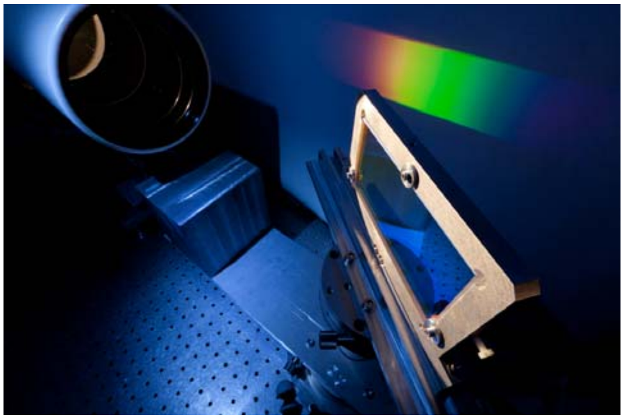

Figure 5: Prototype VPH under test

Measuring the grating efficiency is a fairly straight forward exercise and is well explained, for example see reference[6]. Not only is it essential to measure the true efficiency of the diffracted +1 order, but it is essential to also measure the zero’th order and the reflected light from glass encapsulate as stray light has the potential to worsen the SNR.

The size and quantity of the HERMES gratings has forced us to setup and purchase large test equipment to measure the fabrication tolerances over the entire grating clear aperture in one measurement to ensure there is no degradation in the SNR as it may be possible to miss a potential problem in discrete measurements. This is especially exacerbated by the 50% maximum theoretical efficiency of the gratings. Any reduction in the SNR has the potential to adversely affect the timescale and number of targets that can be acquired for the HERMES survey named GALAH.

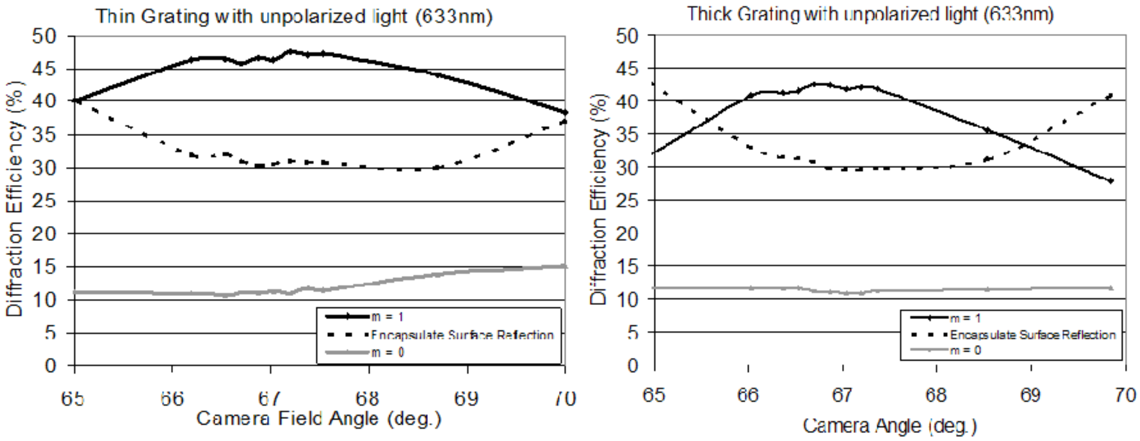

Figure 6: Measured prototype grating diffraction efficiencies for 1st peak optimized grating, thin grating (left) and 2nd peak optimized grating, thick grating (right)

SLIT CURVATURE

An F/6.3 off-axis Houghton derived collimator is used to relay light from the fiber slit to four separate channels in HERMES. The collimator requires the slit to lie on a spherical surface. In employing volume phase holographic (VPH) gratings in the spectrograph the full field experiences a non-linear diffraction. This results in a curved line of fiber images at the image plane, “a smile” shown in figure 1. To maximize the use of detector space the slit has been given an additional curvature to counter the spectral curve[7].

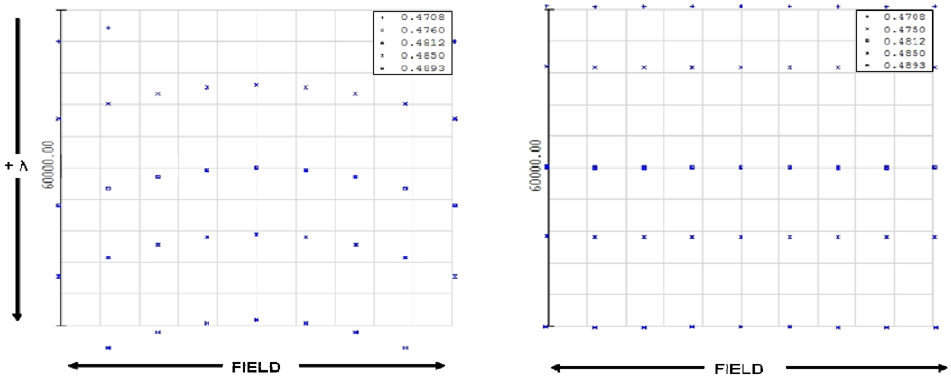

Figure 7: Image of fibres on detector with a linear slit (left) and the corrected image by shaping the slit along a spherical surface to compensate for the high angle of incidence non-linear diffraction grating (right).

The impact of working off the theoretical Bragg angle can be found by adding the offset angles to α and β in the equations above. The spectral resolution is for that reason somewhat lower in the shorter wavelength. A figure of the predicted resolution versus the wavelength for the blue channel is shown below. Also shown is the effect of the slit position on the resolution.

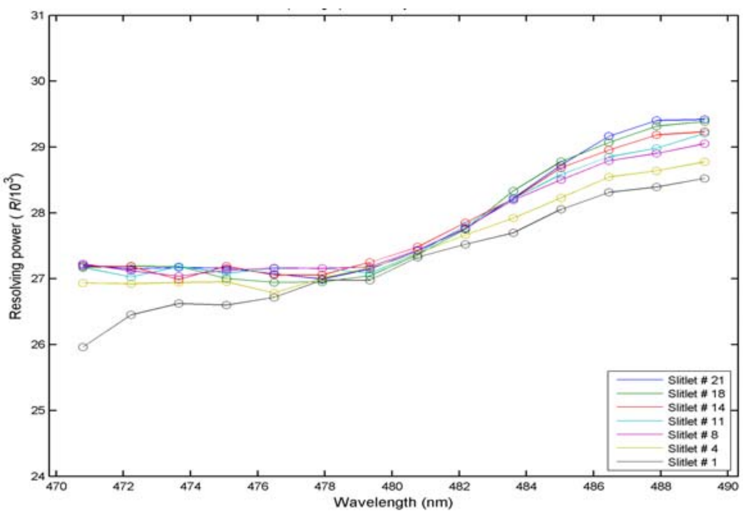

Figure 8: HERMES Blue channel spectral resolving resolution (center fiber is given by fiber #21)

ANTI-REFLECTIVE COATING

The anti-reflective (AR) coating for the VPH grating glass encapsulate has become a crucial part in obtaining the required performance of the spectrograph. Any loss of light above 1% per surface is unacceptable due to the complete loss of Tp in the diffracted beam. Many trade-offs can be introduced by optimizing the grating design to either offset or balance s and p-polarization states. However, a necessary extreme angle of incidence is required to achieve the idealized maximum resolution. The HERMES VPH grating utilizes an extreme angle of incidence of 67.9 degrees with an even greater maximum diffraction angle of 74.6 degrees. At these steep angles, we are theoretically seeing approximately 98% efficiency for Ts and less than 5% efficiency for Tp, yielding an immediate 50% degradation of light. As no surprise, at angle, the VPH gratings' glass encapsulate favors Tp over Ts, see figure 9. On the other hand, the VPH grating inherently favors Ts over Tp, see figure 1. At first glance, this may seem like a tragic misfortune for the Astronomer. As it turns out, this paradox can easily be resolved by the deposition of thin films.

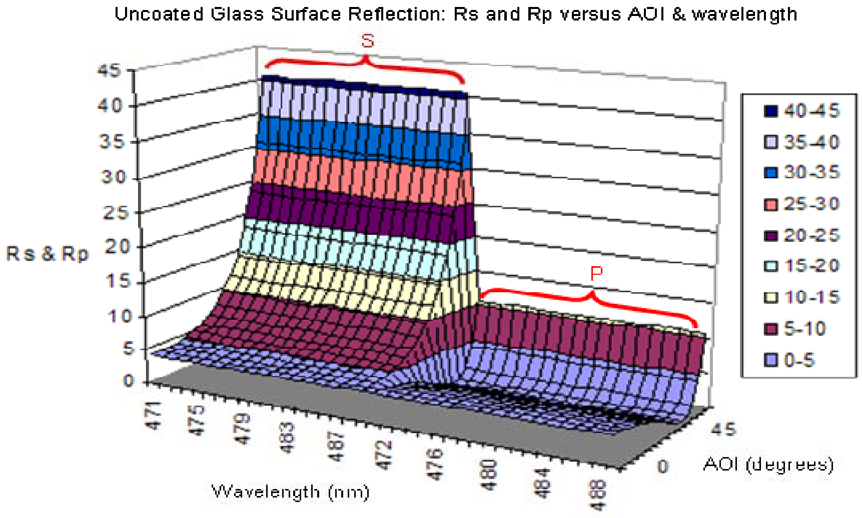

Figure 9: Uncoated Glass for Rs versus Angle versus Wavelength (left) and Rp versus Angle versus Wavelength (right). Notice the high reflectivity for Rs at steep angles of incidence.

Since, the HERMES VPH gratings favor an Electromagnetic spectrum that is s-polarized. The VPHG designer is left with a very simple decision, to cover the encapsulate with an anti reflective coating that is exclusively optimized for s-polarized light, see Figure 10.

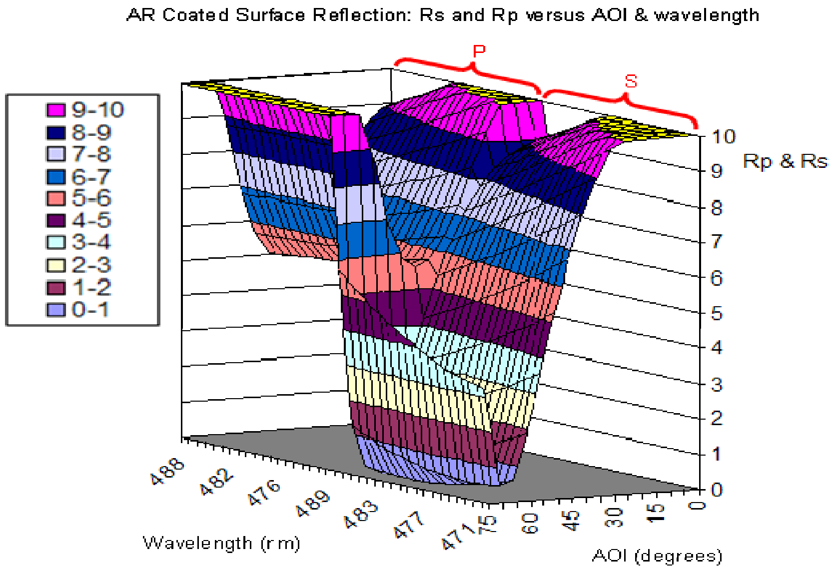

Figure 10: AR coating for Rp versus Angle versus Wavelength (left) and Rs versus Angle versus Wavelength (right). Notice Rs polarization is minimized at 67.2 degrees.

It was recommended by vendors that the encapsulate glass should be provided uncoated to the grating fabricator. From the point of view of using gratings 565 x 240 mm in size this very economical, but not lower risk. The grating fabricator requires a number of full sized glass blanks to maximize production efficiency and meet the tolerances for each grating. Pre-coating every glass blank before VPH fabrication for a specific band and hoping that the AR coating withstood the bath solutions used to fix the gelatin would surely increase the blank acquisition beyond a reasonable level and unrealistically drive coating costs through the roof. As it stands HERMES has purchased 14 high precision polished window glass blanks to minimize production time and cost for only four gratings.

Due to the large size of the HERMES grating, 565 x 240 mm, the choice of coaters became smaller. Of a number of vendors queried Cascade Optical has provided an excellent design, see figure 10, that is not only highly efficient, it is also a ‘simple’ two layer design that and can be applied cold, at temperature well below a 100º C, proving low risk for the VPH gelatin and the project as a whole.

In summary extensive work should be done with the VPH designer/fabricator using RCWA to find the polarization sensitivity of the VPH design. Next, an AR coater should be identified that can tune the AR coating design to the desired polarization output. The coating design should then be fed back to the VPH designer and iterated with the coater as needed until a balance is found. The final step is to incorporate the coating information into the stray light model of the system. The HERMES gratings will generate a significant amount of specular stray light from the zero’th order and the grating glass encapsulate for p-polarized light as the AR coating does minimize surface reflections.

CONCLUSION

From this overview on the VPHG development our main conclusion has to be that it is important to get the VPHG supplier involved as soon as possible to set the grating design parameters and to create an early prototype. Understanding the limitations of the grating suppliers such as collimated beam size, wavefront quality, laser wavelength and process material properties have clearly driven the HERMES gratings in different directions. Besides testing the efficiency it is equally important to test the image quality and PSF for a high resolution spectrograph. This can significantly reduce the development time and create realistic expectations if the science case is feasible

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