PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

VPHGs for WEAVE: design, manufacturing and characterization

Andrea Bianco, Giorgio Pariani, Matteo Aliverti, Alessio Zanutta, James Arns, et al.

Andrea Bianco, Giorgio Pariani, Matteo Aliverti, Alessio Zanutta, James Arns, Johan Pragt, Remko Stuik, Kevin Middleton, Ian Tosh, Gavin Dalton, Scott Trager, Don Carlos Abrams, Jose Alfonso Lopez Aguerri, Piercarlo Bonifacio, Antonella Vallenari, Esperanza Carrasco, "VPHGs for WEAVE: design, manufacturing and characterization," Proc. SPIE 10706, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, 107064X (10 July 2018); doi: 10.1117/12.2311693

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

VPHGs for WEAVE: design, manufacturing and characterization

Andrea Bianco*[1], Giorgio Pariani[1], Matteo Aliverti[1], Alessio Zanutta[1], James Arns[2], Johan Pragt[3], Remko Stuik[3,4], Kevin Middleton[5], Ian Tosh[5], Gavin Dalton[5,6], Scott Trager[7], Don Carlos Abrams[8], Jose Alfonso Lopez Aguerri[9], Piercarlo Bonifacio[10], Antonella Vallenari[11], Esperanza Carrasco[12]

[1]Osservatorio Astronomico di Brera, INAF, via E. Bianchi 46, 23807 Merate (LC), Italy;
[2]Kaiser Optical Systems, Inc., 371 Parkland Plaza, Ann Arbor, MI 48103, USA
[3]NOVA Optical- Infrared Instrumentation Group at ASTRON, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
[4]Leiden University, Leiden Observatory, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[5]RALSpace, STFC Rutherford Appleton Laboratory, Harwell Oxford, OX11 0QX, UK
[6]Dept. of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK
[7]Kapteyn Institut, Rijksuniversiteit Groningen, Postbus 800, NL-9700 AV Groningen, Netherlands
[8]Isaac Newton Group, 38700 Santa Cruz de La Palma, Spain
[9]Instituto de Astrofisica de Canarias, 38200 La Laguna, Tenerife, Spain
[10]GEPI, Observatoire de Paris, Place Jules Janssen, 92195 Meudon, France
[11]Osservatorio Astronomico di Padova, INAF, Vicolo Osservatorio 5, 35122, Padova, Italy
[12]INAOE, Luis Enrique Erro 1, Tonantzintla, Puebla, Mexico

ABSTRACT

WEAVE is the next-generation optical spectroscopy facility for the William Herschel Telescope (WHT). It shows two channels (blue and red) and two working modes, a low-resolution (R=3,000-7,500) and a high-resolution (R=13,000-25,000). The dispersing elements of the spectrograph are Volume Phase Holographic Gratings (VPHGs), two for the lower resolution mode and three for the higher resolution mode. Such gratings have a large size (clear aperture > 190 mm) and they are characterized by some key features, i.e. diffraction efficiency, wavefront error and dispersion that affect the final performances of the spectrograph. The VPHGs have been produced by KOSI based on the WEAVE design. After that, the VPHGs have been characterized, showing interesting results in terms of diffraction efficiency that reached peak values of 90%. As for the wavefront distortion, which is one of the critical aspect in VPHG technology, a different behavior between medium and high resolution elements was found. A larger wavefront distortion have been measured in the high resolution elements, because of the higher aspect ratio. A polishing process on the assembled VPHGs has been performed in order to reduce the wavefront distortion. Here, the results are presented and the specific issues discussed.

Keywords: astronomical spectrographs, dispersing element, volume phase holographic grating, resolution.

1. INTRODUCTION

Multi-object survey spectrographs are becoming key facilities in modern astronomy and astrophysics, since they allow for the collection of many (hundreds) of spectra of objects simultaneously. Such large multiplexing capability is crucial, especially if the spectrograph fits a 3-4 m class telescope covering wide fields of view. They will address topics like the redshifts of thousands of galaxies; they will be complementary to mission like GAIA in providing chemical element abundances. In this framework, different facilities are under design or construction, such as 4MOST[1], DESI[2] and of course WEAVE[3]. All of them are fiber-fed and provide not only spectral capabilities, but also spatial resolution by means of IFUs, making the observation of extended objects possible. The spectral range of these facilities is about 350 – 1000 nm.

*andrea.bianco@brera.inaf.it; tel +390272320460

Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, edited by
Ramón Navarro, Roland Geyl, Proc. of SPIE Vol. 10706, 107064X · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2311693

WEAVE is designed for the 4.2-m William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos (La Palma, Canary Islands). It will allow astronomers to take optical spectra of up to ~1000 targets over a two-degree field of view in a single exposure (MOS), or to carry out integral-field spectroscopy using 20 deployable mini integral-field units (mIFUs) or one large fixed integral-field unit (LIFU)[4].

In such complex instruments, there are some critical elements, surely the fiber system, but also the dispersing element for the spectrograph. Indeed, it is known that the dispersing element is one of the less efficient optical elements of the system. This feature has an important impact on the total throughput of the instrumentation. Therefore, it is crucial to find a suitable technology for the dispersing element that maximizes the efficiency providing the required dispersion and resolution. In the last 20 years, Volume Phase Holographic Gratings (VPHGs) have been the technology of choice, especially for optical spectrographs. The main reasons are: i) the large diffraction efficiency at very high angular dispersions; ii) the easy customization (each grating is a master grating); iii) the robustness[5–7].

It was natural that such technology was chosen for the dispersing elements of WEAVE. Kaiser Optical Systems, Inc. (USA) manufactured all the VPHGs and they have been fully characterized at the INAF – Osservatorio Astronomico di Brera (Italy).

In this paper, we present the work done on the five VPHGs for the WEAVE spectrograph, starting from the design phase, moving to the procurement and characterization steps. After an overview of the spectrograph and of the VPHG technology, the specifications of the WEAVE's gratings will be discussed and finally their performances reported.

2. VOLUME PHASE HOLOGRAPHIC GRATING TECHNOLOGY

VPHGs are diffraction gratings that work thanks to a periodic modulation of the refractive index (Δn) stored in a holographic material with a defined thickness (d)[8]. The periodic modulation of the refractive index is induced by means of a two-laser beams interference pattern that promotes a sinusoidal modulation. Usually the VPHGs work in transmission; however, it is possible to design reflection VPHGs. For standard ruled gratings, the diffraction occurs thanks to a periodic modulation of the thickness and they can work both in reflection and in transmission.

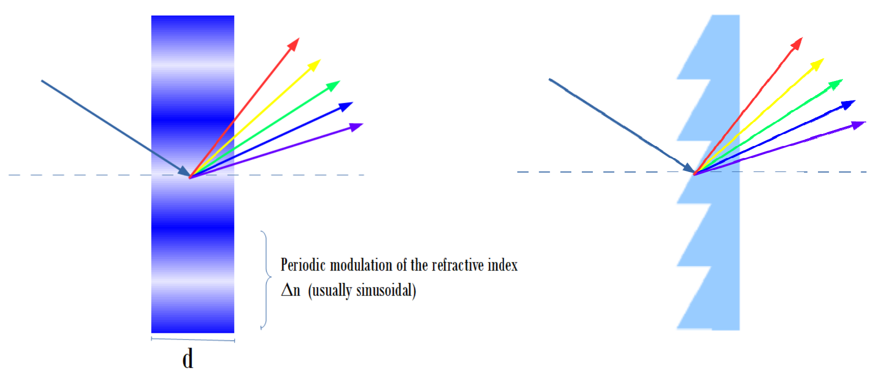


Figure 1. Scheme of a Volume Phase Holographic Grating (VPHG) and of a ruled grating both working in transmission.

Considering the diffraction efficiency of the VPHGs (in the case of pure phase gratings), it depends mainly on:

- Film thickness (d);
- Refractive index modulation (Δn);

If we consider a sinusoidal refractive index modulation stored in the holographic material and the possibility to have light diffracted just in one order, we can apply the Kogelnik model[9] for the diffraction efficiency calculation. In this framework, a large peak diffraction efficiency is possible if the Bragg condition is met, meaning the incidence angle (α) and the diffraction angle (β) on the grating are equal. Moreover, a large peak efficiency is achieved when the product of the film thickness (d) and the refractive index modulation (Δn) is equal to half of the target wavelength. For astronomical applications, a high peak efficiency is not enough, indeed, it is important to have large efficiency across the target bandwidth. According to the same model, the bandwidths (angular and spectral) of the diffraction efficiency curve are inversely proportional to the line density (G) and to the film thickness[10].

Therefore, a large peak efficiency can be obtained playing with the two film parameters d and Δn, but in order to obtain a wide efficiency band, it is necessary to decrease the film thickness, d, especially for small pitch grating (large G values). If d decreases, of course the Δn must increase to maintain a high peak efficiency. This makes the VPHG manufacturing more difficult and risky. The large G condition occurs for the VPHGs used in the high-resolution modes of the spectrographs.

Moreover, for large G values, the incidence angle increases and in VPHGs, there is a polarization effect, i.e. the diffraction efficiency in the two polarizations becomes more and more different, making it difficult to achieve a large efficiency for unpolarized light[7].

3. WEAVE SPECTROGRAH OVERVIEW AND GRATING SPECIFICATIONS

The WEAVE spectrograph is a fiber-fed instrument. The fibers form a long slit, the light is collimated and sent to two arms by means of a dichroic mirror. The two arms, namely blue and red can work in a low resolution (R=3,000-7,500) and high resolution (R=13,000-25,000) modes. The optical scheme from the fiber exit is reported in figure 2.

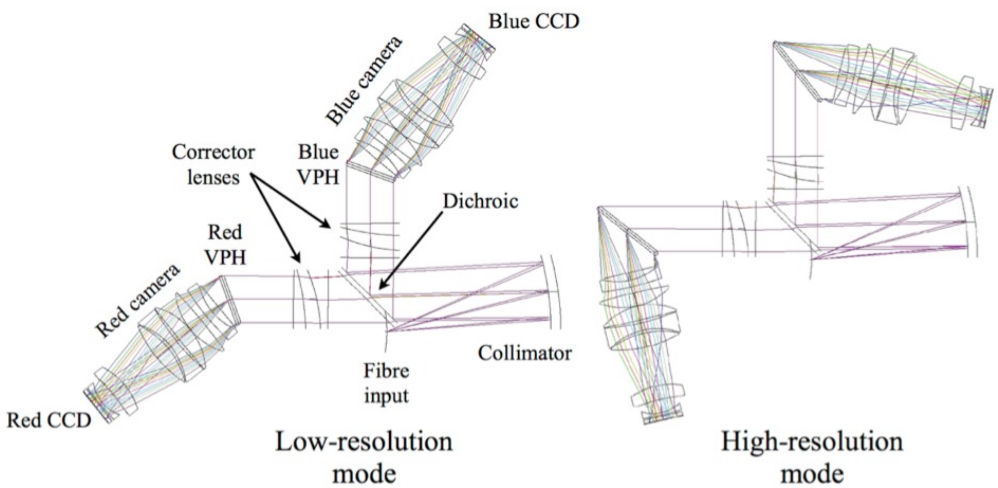


Figure 2. Optical scheme of the WEAVE spectrograph showing the two channels in the low-resolution and high-resolution modes.

The switching between the low and high resolution modes occurs thanks to the rotation of the camera arm together with the switch of the VPHG. Indeed, the incidence angle on the VPHG increases, when higher dispersion and resolution are required.

There will be a total of five VPHGs installed in WEAVE, two at low resolution (LR, one blue and one red) and three at high resolution (HR, one red and two blues). The specifications of the VPHGs are reported in table 1.

Table 1. Main specifications of the five VPHGs to be installed in the WEAVE spectrograph as dispersing elements.

Property	**Value**		
Operating temperature	Room temperature		
Operating pressure	$0.8x10^5$ Pascal		
Outer shape	Rectangular, grating grooves aligned along shorter side		
Clear aperture	See Figure 3 and Figure 9		
De-centering of the footprint in respect to the substrate	Yes	Yes	Yes
Total substrate thickness (without considering gelatine and cement thickness)	38 mm	50 mm	50 mm
Substrate material	Fused Silica		
Optical quality of transmitted beam over the clear aperture	≤ 4λ		
A/R coating on external substrate surface	Yes		
Fringe angular orientation (in respect to the reference glass substrate)	+/- 15 arcmin		
Grating name	Blue LR Red LR	Blue HR1 Red HR	Blue HR2
Centre (Littrow) wavelengths	490 nm (blue) 775 nm (red)	438 nm (blue) 645 nm (red)	513 nm (blue)
Blue wavelength coverage	366 nm – 606 nm	404 nm – 465 nm	473 nm – 545 nm
Red wavelength coverage	579 nm – 959 nm	595 nm – 685 nm	
Blue VPH ruling density	1385.2 lines / mm	3579.6 lines / mm	3056.9 lines / mm
Red VPH ruling density	875.9 lines / mm	2430.7 lines / mm	
Ruling density accuracy	+/- 1 line/mm		
VPH incidence angle (in air) blue	22.72°	54.43°	54.46°
VPH output angle (in air) blue	17.01°	48.98°	48.98°
VPH incidence angle (in air) red	19.82°	51.59°	
VPH output angle (in air) red	19.86°	51.65°	

We notice some important differences between the LR and HR gratings that play an important role in determining the final behavior of the dispersing element.

First of all, the aspect ratio of the LRs shows an almost squared aspect ratio, whereas the HRs are rectangular (about 3:2). The total thickness of the HR gratings is bigger than that of the LR gratings in order to maintain a good stiffness of the optical element. The size of the substrate has also to be large enough to allow for the writing of the grating without the laser illuminating the edges of the substrate at the defined angle (which is set according to the line density). As for the footprints, they are not centered in the substrate, but an offset that varies from grating to grating is present to fit the opto-mechanical constraints of the spectrograph.

The other large differences are in the line density and working angles. Indeed, the LR gratings work around 20° with line density near 1000 l/mm; the HR VPHGs work at about 50° of incidence angle with line densities of 2500 – 3500 l/mm. Clearly, the red gratings working at longer wavelengths require lower line density value to achieve the same dispersion according to the grating equation[11]. The accuracy in the line density (+/- 1 l/mm) is not a tight requirement in spite of the fact that common accuracies are of the order of a few l/mm. The fringe angular orientation represents the maximum rotation of the VPHG "grooves" in respect to the reference substrate. The requirement of +/- 15 arcmin is not an issue for the manufacturing process of VPHG developed at KOSI.

Regarding the working angle, we notice that the Bragg condition is not matched; this is due to the fact that the grating fringes are slanted in order to minimize the presence of Littrow ghosts on the detector overlapped to the spectra[12].

Looking at the other parameters, we can notice that the wavefront error of the diffracted beam must be smaller than 4λ, which is a large value. Clearly, if the WFE is focus, it can be easily compensated by the focusing system in the camera, but if the WFE is due to other terms, the compensation will be less effective. In principle, 4λ is acceptable only if it consists roughly in half focus and half astigmatism. We have to stress that the control of WFE in VPHGs is an open issue and there are not established rules. Indeed, the WFE could come from the optical aberrations of the holographic writing set-up that are transferred in the grating pattern and/or come from the deformation of the whole grating system after the gluing of the substrates. In the past, the WFE issue has been highlighted in the case of HERMES[13] and SUBARU PFS[14]. Since the total wavefront error budget in modern spectrograph is tight, the grating should have a WFE under control. An interesting option is the post polishing of the VPHG, as already performed in the case of dispersing elements of HERMES. Such approach is risky, since the polishing occurs on the fully assembled VPHG and not on the substrate before the grating is recorded. In addition, it is necessary to apply a cold AR coating to avoid any damage of the holographic pattern and it is known that cold AR coating are typically less performing, especially at high incidence angle (the case of high resolution VPHGs) and with a wide angle range. Another consideration related to this approach regards the recording of secondary holograms in the VPHG during the writing step because of the reflection losses on the uncoated substrate that become important especially when increasing the incidence angle. Such secondary holograms reduce the diffraction efficiency in the first order. In the case of WEAVE's VPHGs, two different strategies have been followed: for the LR VPHGs, the substrates were provided to the manufacturer with the AR coating already deposited on one surface; for the HR VPHGs, the substrates were provided uncoated.

It is worth noting that the spectral ranges of both the LR and HR VPHGs are wide if we consider the degree of dispersion. The result is of course a long spectrum on the CCD, but also strong requirements in the holographic properties (d, Δn) in order to provide acceptable diffraction efficiency at the edges of the spectral bands.

4. LOW RESOLUTION VPHGS

The LR VPHGs are, in principle, quite simple to manufacture from both an efficiency point of view and the overall optical quality. Indeed, it is not required a too large modulation of the refractive index for achieving the target efficiency and the aspect ratio is square. In figure 3, the technical drawings of the two VPHGs are reported showing the footprint and the holographic aperture.

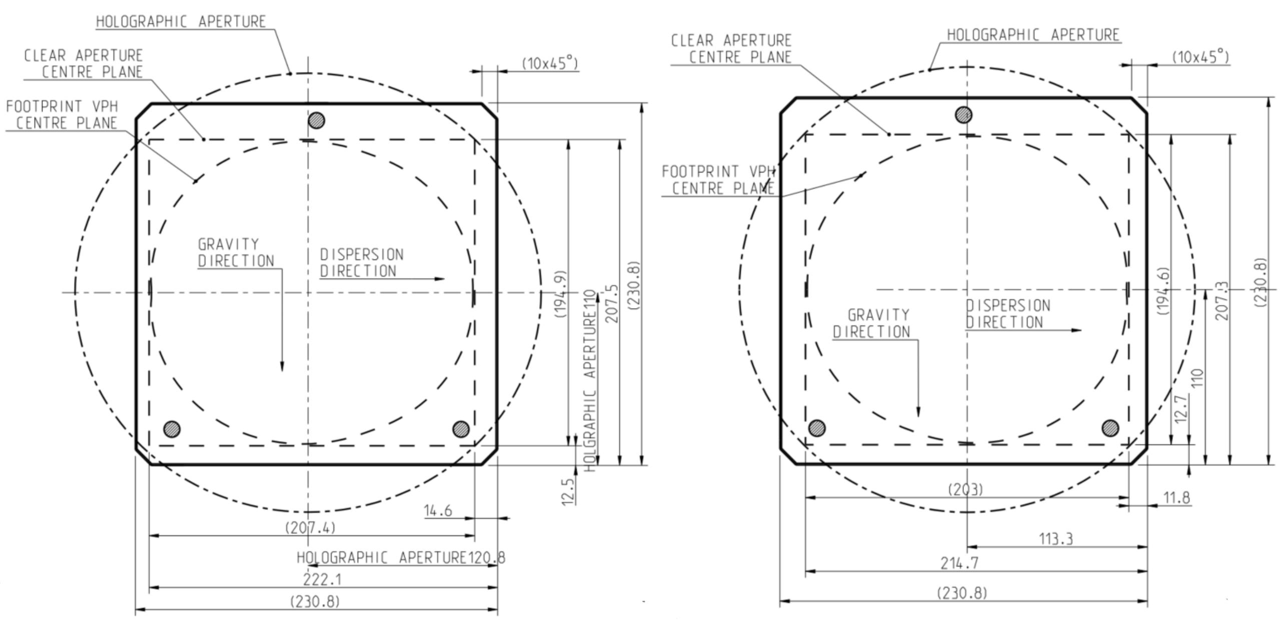


Figure 3. Technical drawings of the footprints for the Blue and Red LR VPHGs (left and right respectively).

We notice how the footprint is not oval as expected considering that fields coming from the fibers forming the long slit and considering the different wavelengths in the spectral range. We clearly see that the writing area, defined by the holographic set-up, is much wider than the footprint of the VPHGs.

The predicted diffraction efficiency by KOSI for the two VPHGs are reported in figure 4 considering unpolarized light, a perfect AR coating and the nominal incidence angle (see table 1).

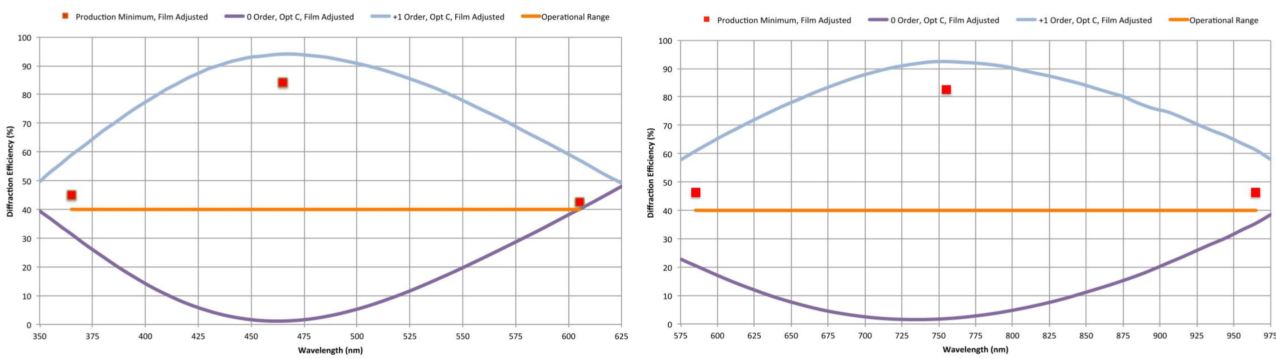


Figure 4. Plots of the diffraction efficiency (order +1 and order 0) for the two LR VPHGs (blue on the left and red on the right) at nominal incidence angle considering unpolarized light. The red squares represent the production minimum guaranteed by the manufacturer at the central and edges wavelengths.

The peak efficiency is larger than 90% and the overall efficiency in the entire range is larger than 50%. The zero order is almost symmetric in respect to the first order at least at longer wavelengths, meaning that no other orders are propagating. At shorter wavelengths, a small contribution (about 10%) from the second order is possible. Since the second order is diffracted at double angles, such component is screened out by the VPHG holder. Of course, there could be blue light diffracted in the second order by the red VPHG, but there should not be blue light in the red arm thanks to the dichroic mirror.

The LR VPHGs were produced and characterized by KOSI and at INAF – Osservatorio Astronomico di Brera. In figure 5, photographs of the two VPHGs are reported.

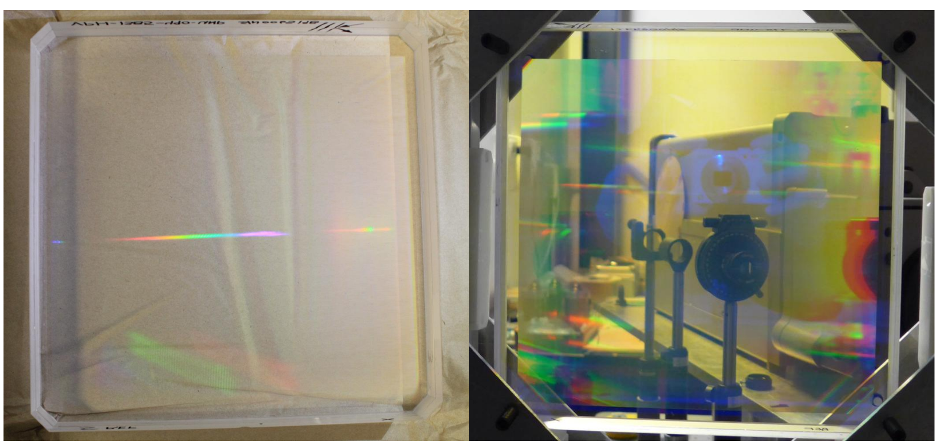


Figure 5. Photographs of the blue (left) and red (right) LR VPHGs for WEAVE.

The values of line density, groove orientation and clear aperture are reported in the next table.

Table 2. Values of the line density, fringe orientation and clear aperture for the LR VPHGs.

Grating	Line density (l/mm) specification/measured	Orientation (arcmin) specification/measured	Clear Aperture (mm)
LR BLUE	1385.2 / 1385.3	+/- 15 / 2.464	212.0 x 205.0
LR RED	875.9 / 875.5	+/- 15 / 3.573	208.6 x 202.0

All the quantities are in specification. The clear aperture, which is slightly rectangular, is larger than the minimum required to avoid a partial loss of diffracted light.
Regarding the diffraction efficiency, it has been measured by KOSI (averaged over 13 areas in the clear aperture) and at INAF – Osservatorio Astronomico di Brera at different laser wavelengths on the completely clear aperture. Figure 6 reports the results for the two VPHGs.

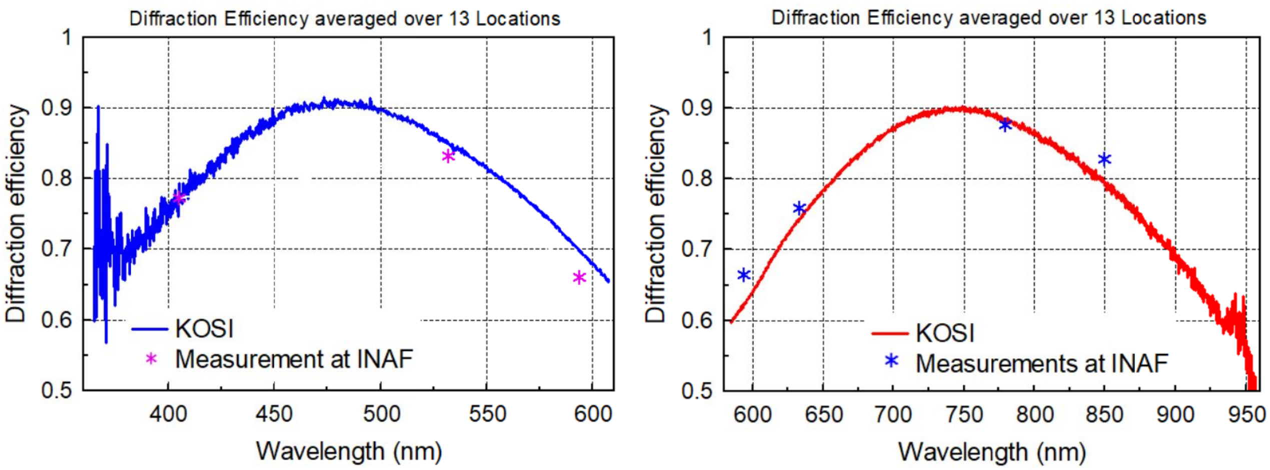
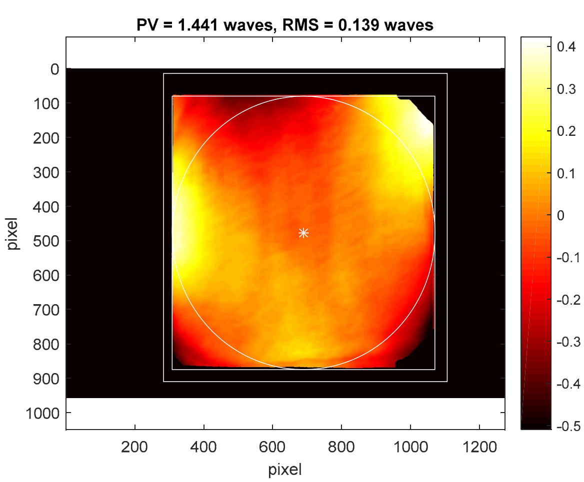


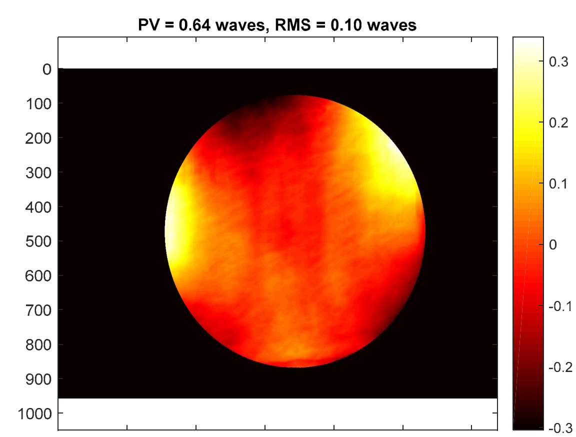
Figure 6. Plots of the measured diffraction efficiency of the 1st order for the blue (left) and red (right) LR VPHGs at nominal incidence angle using unpolarized light.

At short wavelengths for the blue VPHG and at long wavelengths for the red one, the measurements are noisy, due to the low sensitivity of the instrumentation.

For the blue VPHG (left panel in figure 6) it seems that the peak efficiency is smaller, but the bandwidth wider in comparison to the predicted curves (see figure 4). This can be an effect of a thinner gelatin film with a slightly larger refractive index modulation. For the red VPHG, the predicted and measured curves are more similar. We have to consider also the presence of a real AR coating on the two VPHG sides that reduces the efficiency. In any case, the results are really good, much better than the minimum quoted. We also notice how the two sets of measurements are consistent.

The most critical issue was the WFE introduced by the VPHG. WFE (tip/tilt removed) of the first order of diffraction has been measured with a 100 mm collimated beam at 632.8 nm and stitched to obtain the entire clear aperture. The incidence angle was set at a value similar to the working angle. Figure 7 and 8 report the WFE maps for the two VPHGs.





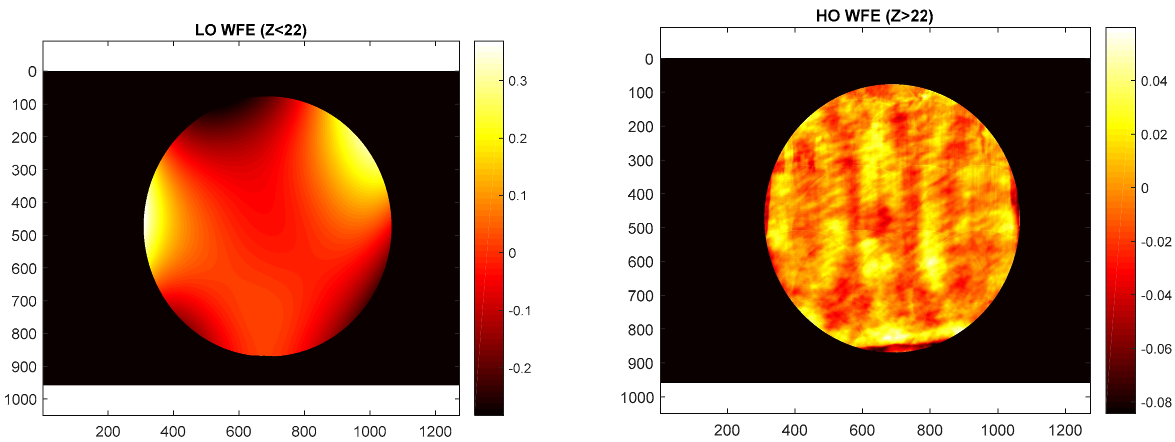


Figure 7. Top: Stitched WFE of the whole blue LR VPHG (on the left) and of the clear aperture (on the right). Bottom: Decomposition of the WFE in the low orders (on the left) and high orders (on the right).

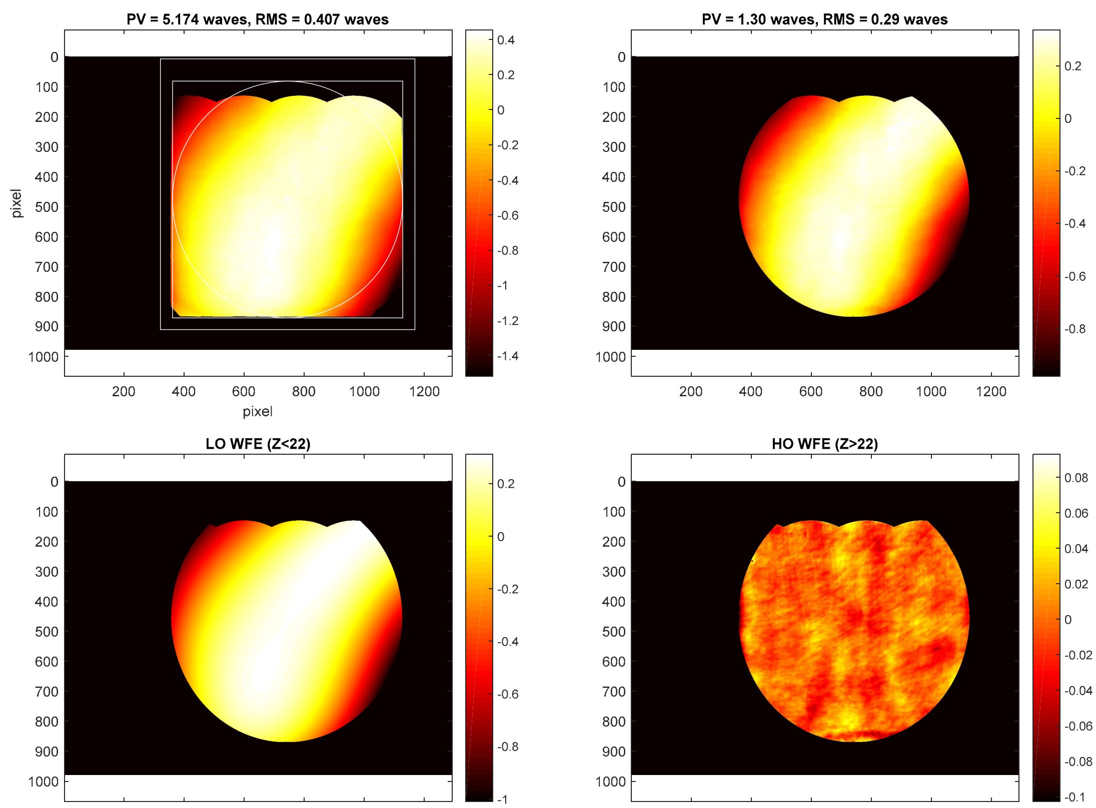


Figure 8. Top: Stitched WFE of the whole Red LR VPHG (on the left) and of the clear aperture (on the right). Bottom: Decomposition of the WFE in the low orders (on the left) and high orders (on the right).

The blue LR VPHG shows a smaller WFE than the red VPHG. In both cases, the WFE (PtV) is well below the 4λ, which was reported in the specifications table. This is a good result since it means that both the writing procedure and the assembling process (gluing of the second substrate to cover and to protect the gelatin layer) are under control.

5. HIGH RESOLUTION VPHGs

The HR VPHGs are much more difficult to manufacture from both an efficiency point of view and the overall optical quality. Indeed, they work at high incidence angle and it is known that high diffraction efficiencies for unpolarized light are difficult to achieve. The technical drawings for the three HR VPHGs are reported in figure 9.

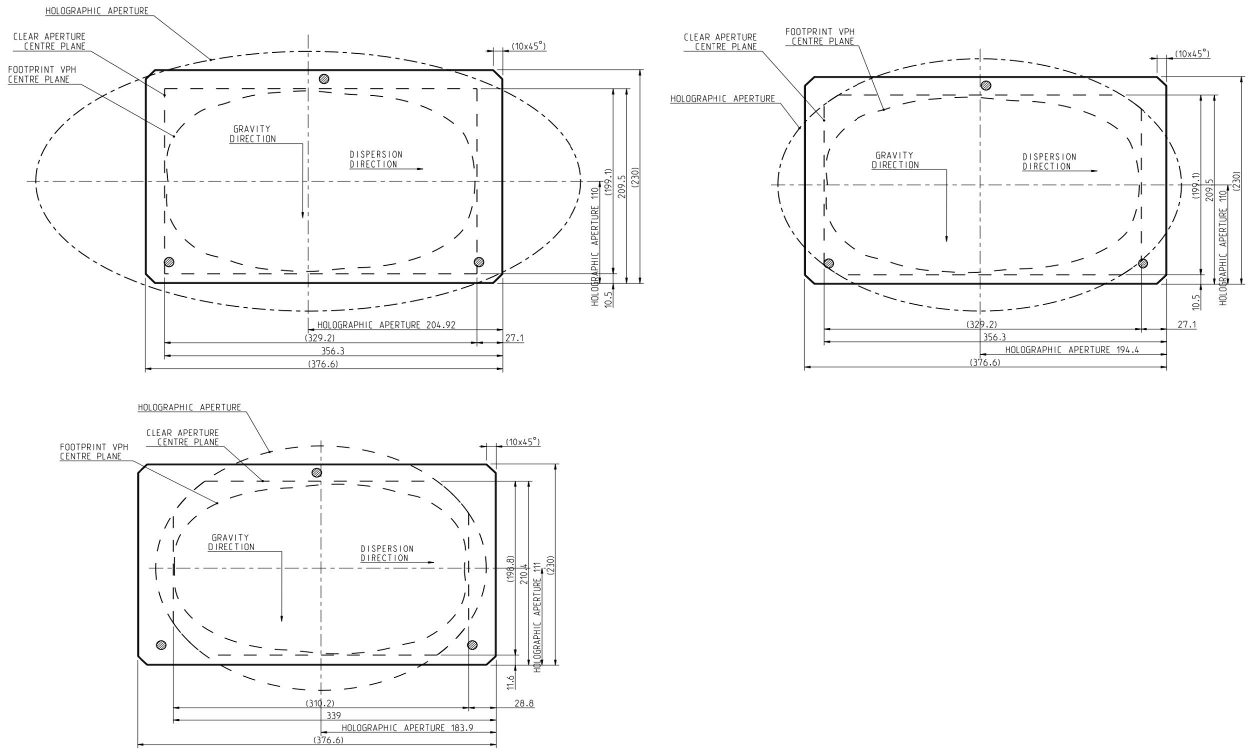


Figure 9. Technical drawings of the footprints for the Blue1, Blue2 (top left and top right respectively) and Red (bottom).

We notice that the substrate size is the same for the three gratings, but the size and shape of the footprint are different. For the three VPHGs, there is not a limit introduced by the size of the holographic set-up (see the holographic aperture in figure 9). KOSI designed the VPHGs in terms of diffraction efficiency and the curves are reported in figure 10.

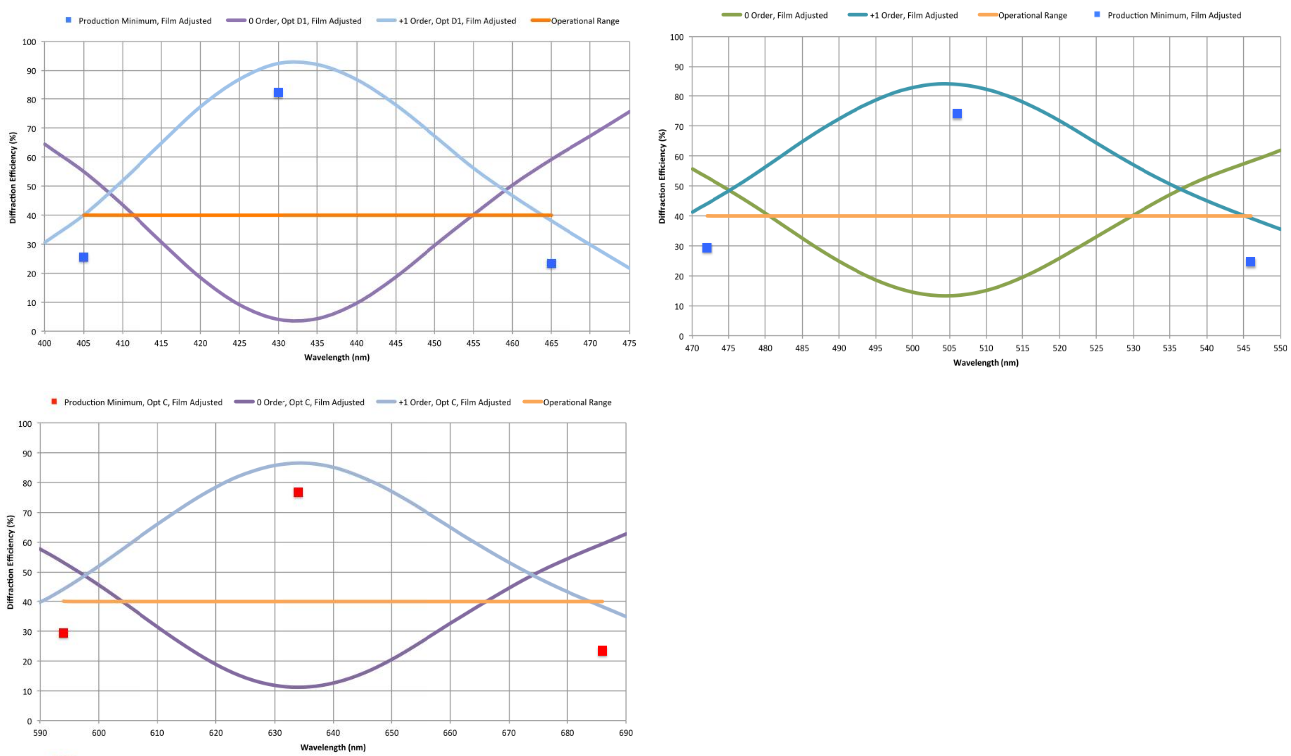


Figure 10. Plots of the diffraction efficiency (order +1 and order 0) for the three HR VPHGs at nominal incidence angle considering unpolarized light. Top left: Blue1, top right: Blue2, bottom: Red. The squares represent the production minimum guaranteed by the manufacturer at the central and edges wavelengths.

The peak efficiency is between 85% and 93% for the three HR VPHGs, but the efficiency at the edges of the spectral ranges is much smaller than in the case of LR VPHG. This is not surprising, since the bandwidth is inversely proportional to the line density. It can be compensated in some extent by increasing the refractive index modulation, but of course a limit due to the material exists.

The three HR VPHGs were produced by KOSI starting from uncoated fused silica substrates. The idea was to perform post-polishing and AR coating deposition on the assembled gratings.

Figure 11. Photographs of the Blue1, Blue2 and Red HR VPHGs (from left to right).

The values of line density, groove orientation and clear aperture are reported in table 3.

Table 3. Values of the line density, fringe orientation and clear aperture for the HR VPHGs.

Grating	Line density (l/mm) nominal/measured	Orientation (arcmin) nominal/measured	Clear Aperture (mm)
HR BLUE1	3579.6/3578.9	+/- 15/---	372.90 x 227.26
HR BLUE2	3056.9/3047.7	+/- 15/---	372.94x227.15
HR RED	2430.7/2430.5	+/- 15/---	372.65x227.07

The line density measured by INAF was in agreement with the nominal value for the HR Blue1 and Red; whereas a discrepancy has been found for the Blue2. Moreover, the KOSI measured value was in agreement with the nominal value. At the moment, there is not a clear understanding of the difference and further measurements will be carried out. As for the fringe orientation, at the moment the values are under measurement.

The diffraction efficiency has been measured by KOSI and averaged over 17 measurement locations. Since no coating was applied, two curves are reported: the measured efficiency with and without the correction for a perfect AR coating (see figure 12).

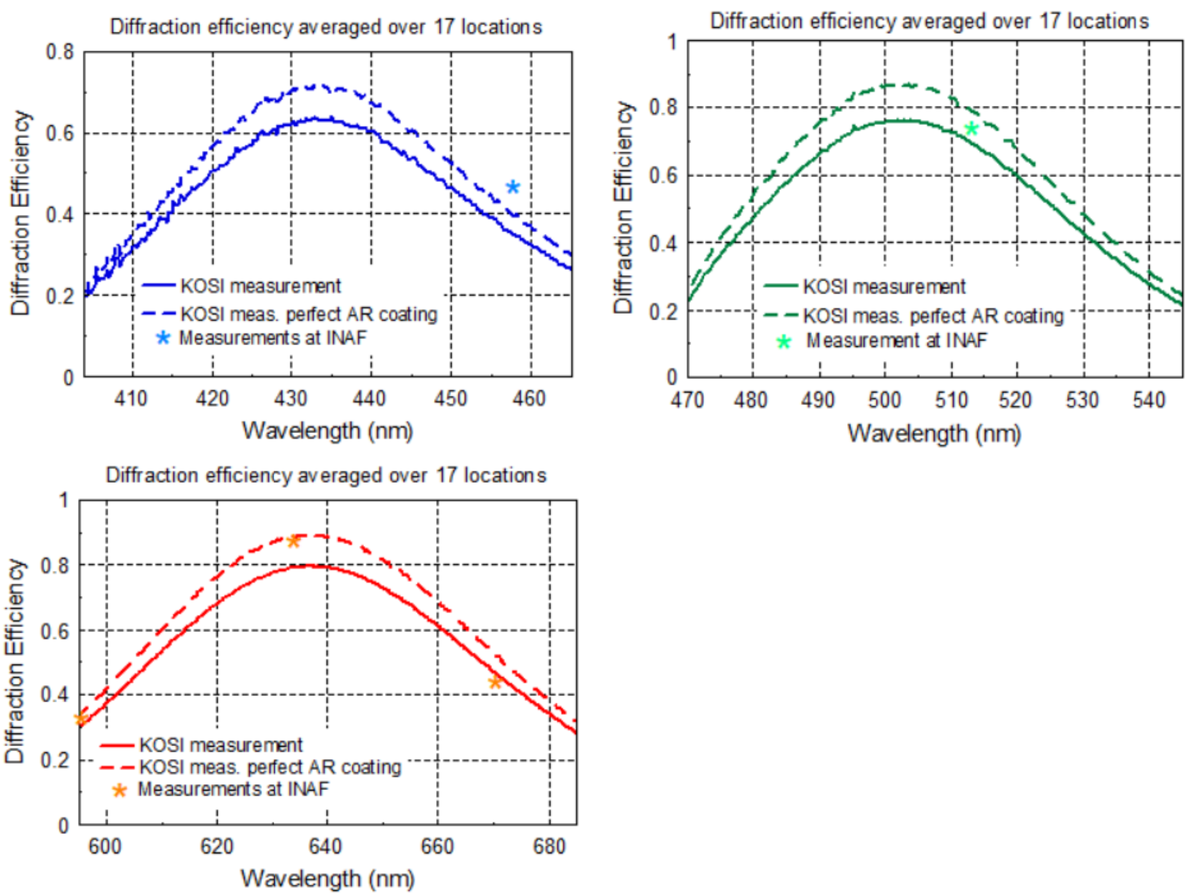


Figure 12. Plots of the measured diffraction efficiency for the first order for the three HR VPHGs at nominal incidence angle using unpolarized light. The two curves represent the raw measurement and the correction with a perfect AR coating. Top left: Blue1, top right: Blue2, bottom: Red. The * represents the measured efficiencies at laser lines performed at INAF.

The measurements by INAF – Osservatorio Astronomico di Brera were performed on the AR coated VPHGs (the cold coating has been applied by Cascade Optical Corporation – USA).

Both the Blue2 and Red HR VPHGs are in specifications also without taking into account the presence of the AR coating and this is an important result. As for the Blue1, unfortunately, it was not possible to reach the expected performances especially as peak efficiency. Indeed, the efficiency is sufficient at the edges. For sure, there is an effect by the lack of AR coating during the writing step, but probably the set of parameters d/Δn is different from the designed value. We have to consider the fact that the holographic material is reaching the performance limit in the case of HR VPHGs.

Another important effect that has to be considered is the polarization effect. Indeed, the diffraction efficiency of such HR VPHGs is completely different for the two polarizations, especially at the edges of the spectral band. This means that also a small degree of polarization of the light turns into large discrepancies in the values of the measured diffraction efficiency. In any case, the measurements at the laser wavelengths carried out at INAF are in a good agreement with the KOSI curves.

The WFE in the first order has been measured for the HR Red grating at the working angle. For the Blue2, the first order was measured at the interferometer laser wavelength (632.8 nm) but at very large angle (77°); whereas for the Blue1 only the measurement of the zero order was performed, at the working incidence angle (54°). Since the interferometer had a 100 mm diameter beam, a stitching approach has been applied.

It is worth to remember that the VPHG Blue1 and Blue2 were post-polished at Ariel Optics Inc. to improve the WFE after the measurements provided by KOSI. Such post-polishing consisted in the planarization of the two VPHG surfaces. In figure 13, the WFE for the three HR VPHGs is reported.

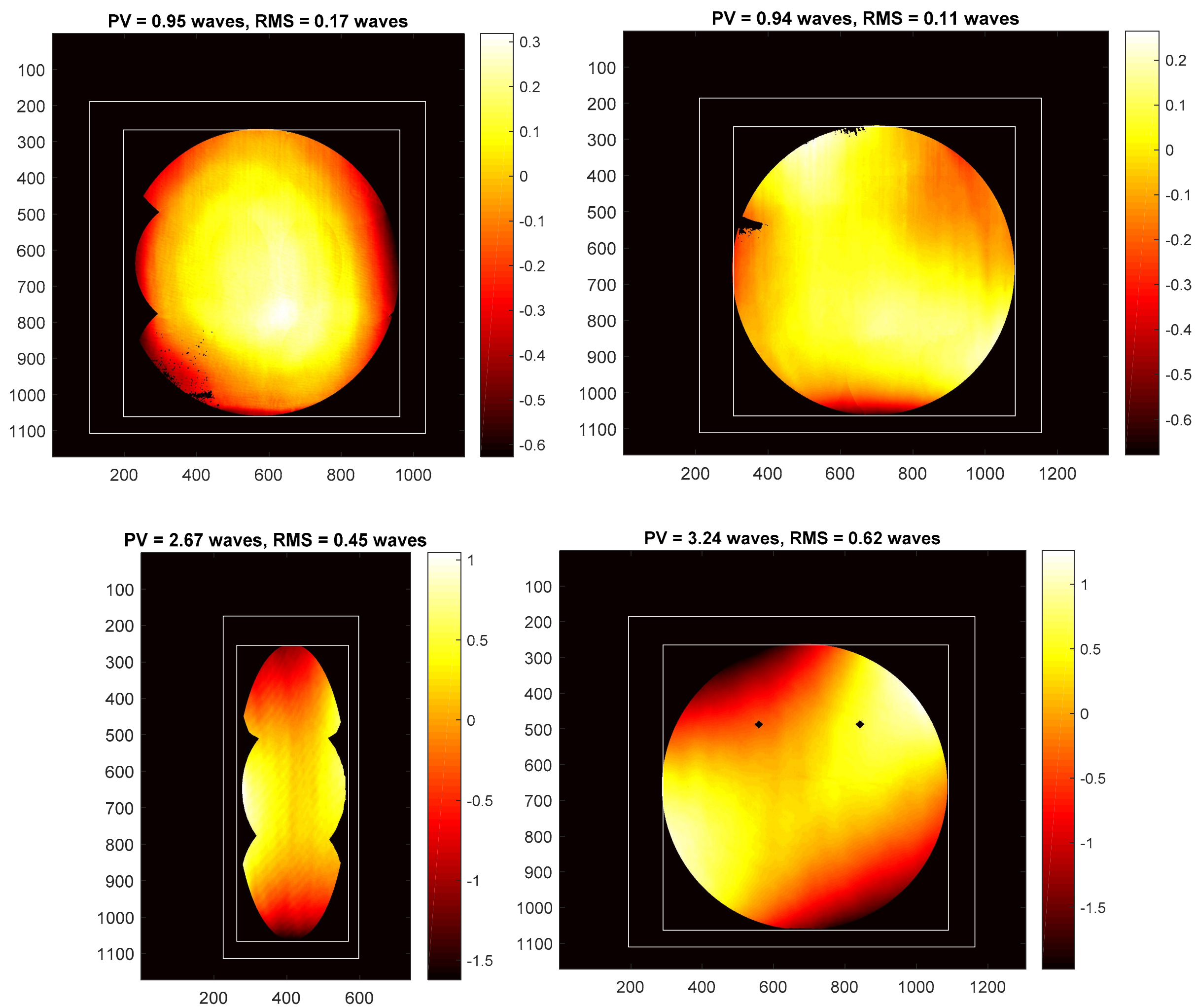


Figure 13. Top: Stitched WFE of the Blue1 HR VPHG for the zero order (on the left) and of the Blue2 HR VPHG for the zero order (on the right). Bottom: Stitched WFE of the Blue2 HR VPHG for the first order (on the right) and of the Red HR for the first order (on the right).

Concerning the Blue1 VPHG, before the polishing KOSI measured a value of 1.80 λ for a subaparture that covered about one third of the grating. We notice that the transmitted WFE after polishing reduced to 0.95 λ PtV, in agreement with the value provided by Ariel Optics (0.87 λ). This means that the post-polishing process was effective in reducing the aberrations of the transmitted wavefront that were due to the grating assembling deformation (probably during the cover substrate gluing). According to the WFE shape, astigmatism is the main source of error. Considering the Blue2 HR VPHG, we notice on the zero order WFE a very similar behavior to the zero order WFE of the Blue1. This is not surprising, since the two VPHGs followed the same production and polishing path. KOSI provided a value of 2.34 λ before post-polishing on a subaperture.

If we consider the WFE of the transmitted first order of diffraction of the Blue1 grating, a PtV of 2.67 λ has been measured, which is much larger than the zero order. Different factors may explain this evidence: i) aberration introduced in the holographic set-up during the writing step. Indeed, if the two laser beams are not perfectly collimated, the written pattern shows some astigmatism especially when the grating is used at a different angle than the writing angle (this is the usual condition). ii) The aberration could be due to the curved gelatin layer that is not compensated during the polishing, therefore the diffraction of the light occurs from a slightly curved grating. This second option seems to be negligible considering the possible grating radius of curvature. In any case, it is important to better understand this aspect from the production point of view. Focusing to the Red HR VPHG (figure 13 bottom right), we notice a PtV that is 3.24 λ, which is larger than the value for the Blue2. We have to consider that no post-polishing was applied to this grating, therefore aberrations due to the substrate and to the grating itself are present and sum up. In any case, in all the three HR VPHGs, the WFE is smaller than the 4 λ (best effort) which were required. Moreover, the impact on the spectrograph optical quality will be partially mitigated during alignment, since most of the WFE is due to focus and astigmatism that can be in part compensated.

6. CONCLUSIONS

The set of VPHGs, two LR and three HR, for the WEAVE spectrograph has been manufactured by KOSI and fully characterized. The LR VPHGs show very good performances in terms of diffraction efficiency and WFE. As for the HR VPHGs, the HR Blue1 VPHG does not reach the expected values of diffraction efficiency and the reasons, in terms of production parameters, will be studied in details. There is a discrepancy in terms of line density between the value measured by KOSI and by INAF for the HR Blue2. Also this aspect will be discussed. As for the WFE in the HR VPHGs, the post-polishing process was effective in reducing it especially at the zero order, whereas the impact on the first order is smaller. In general, the approach of post-polishing and AR coating deposition on the already assembled VPHGs can be effective.

REFERENCES

[1] de Jong, R. S., Barden, S., Bellido-Tirado, O., Brynnel, J., Chiappini, C., Depagne, É., Haynes, R., Johl, D., Phillips, D. P., et al., "4MOST: 4-metre Multi-Object Spectroscopic Telescope," Proc. SPIE, **9147**, 91470M (2014).

[2] Flaugher, B., Bebek, C., "The Dark Energy Spectroscopic Instrument (DESI)," Proc. SPIE, **9147**, 91470S (2014).

[3] Dalton, G., Trager, S., Abrams, D. C., Bonifacio, P., López Aguerri, J. A., Middleton, K., Benn, C., Dee, K., Sayède, F., et al., "Project overview and update on WEAVE: The next generation wide-field spectroscopy facility for the William Herschel Telescope," Proc. SPIE, **9147**, 91470L (2014).

[4] Dalton, G., Trager, S., Abrams, D. C., Bonifacio, P., Aguerri, J. A. L., Middleton, K., Benn, C., Dee, K., Sayède, F., et al., "Final design and progress of WEAVE: The next generation wide-field spectroscopy facility for the William Herschel Telescope," Proc. SPIE, **9908**, 99081G (2016).

[5] Barden, S. C., Arns, J. A.., Colburn, W. S., "Astronomical applications of volume-phase holographic gratings," Proc. SPIE, **3749**, 52–53 (1999).

[6] Spanò, P., Zerbi, F. M., Norrie, C. J., Cunningham, C. R., Strassmeier, K. G., Bianco, A., Blanche, P. A., Bougoin, M., Ghigo, M., et al., "Challenges in optics for Extremely Large Telescope instrumentation," Astron. Nachrichten **327**, 649–673 (2006).

[7] Baldry, I. K., Bland□Hawthorn, J.., Robertson, J. G., "Volume Phase Holographic Gratings: Polarization Properties and Diffraction Efficiency," Publ. Astron. Soc. Pacific **116**(819), 403–414 (2004).

[8] Arns, J. A., Colburn, W. S., Barden, S. C.., Williams, J. B., "Volume-Phase Holographic Gratings for Astronomical Spectrographs," Bull. Am. Astron. Soc. **194**, 839 (1999).

[9] Kogelnik, H., "Coupled-wave theory for thick hologram gratings," Bell Syst. Tech. J. **48**, 2909–2947 (1969).

[10] Bianco, A., Pariani, G., Zanutta, A., Bertarelli, C., "Materials for VPHGs: practical considerations in the case of astronomical instrumentation," Proc. SPIE, **8450**, 84502W (2012).

[11] Palmer, C., Handbook of Diffraction Gratings, 5th editio, Thermo RGL (2002).

[12] Eric B. Burgh, Matthew A. Bershady, Kyle B. Westfall, K. H. N., "Recombination Ghosts in Littrow Configuration: Implications for Spectrographs Using Volume Phase Holographic Gratings," Publ. Astron. Soc. Pacific **119**(859), 1069–1082 (2007).

[13] Sheinis, A., Barden, S., Birchall, M., Carollo, D., Bland-Hawthorn, J., Brzeski, J., Case, S., Cannon, R., Churilov, V., et al., "First light results from the Hermes spectrograph at the AAT," Proc. SPIE, **9147**, 91470Y (2014).

[14] Sugai, H., Tamura, N., Karoji, H.., Takato, N., "Progress with the Prime Focus Spectrograph for the Subaru Telescope : a massively multiplexed," Proc. SPIE, **9147** , 91470T (2014).