Publication Year	2022
Acceptance in OA	2025-03-12T10:15:39Z
Title	VPHGs for astronomy: What we learnt in OPTICON EU and manufacturing perspectives
Authors	BIANCO, Andrea, FRANGIAMORE, Michele, ZANUTTA, Alessio, GALLI, Paola, Garzon, Francisco, Insausti, Maider
Publisher's version (DOI)	10.1117/12.2629361
Handle	http://hdl.handle.net/20.500.12386/36697
Serie	PROCEEDINGS OF SPIE
Volume	12188

VPHGs for astronomy: what we learnt in OPTICON EU and manufacturing perspectives

Andrea Bianco*[a], Michele Frangiamore[a], Alessio Zanutta[a], Paola Galli[a], Francisco Garzon[b], Maider Insausti[b]
[a]INAF – Osservatorio Astronomico di Brera, via Bianchi 46, 23807, Merate, Italy; [b] Instituto de Astrofísica de Canarias, C/ Vía Láctea, s/n E-38205 La Laguna – Tenerife, Spain

ABSTRACT

Volume Phase Holographic Gratings (VPHGs) are optical element widely used in astronomical spectrographs as main disperser or cross-disperser in high resolution echelle instruments. In spite of the fact that other technologies are available on the market, the VPH technology remain a key one. In the EU funded OPTICON project, different activities were carried out in order to consolidate the design and production of VPHGs for astronomy. In particular: i) a production process based on innovative high performance holographic materials (by COVESTRO AG) has been defined; ii) high quality VPHGs > 170 mm in diameter were manufactured; iii) innovative configurations, such as multiorder and multiplexed gratings were proposed and the devices realized. Now, more than 10 devices based on this technology are mounted on observing facilities and several more are in development or planned. Here, we retrace the achievement of the VPH activities in the last years and we propose our roadmap for future improvements in the VPHG design and production for supporting the requests of the astronomical community starting from the ORP EU project.

Keywords: diffraction gratings, VPHG, holography, photopolymer, spectroscopy.

1. INTRODUCTION

Spectrographs are key elements in astronomical observatories. A large and increasingly important fraction of the information gathered by astronomers come in the form of spectral energy distributions of the target objects. Being astrophysics mostly an observational science, its progress cannot be pushed without the constant development of new telescopes and associated instrumentation that enable the detection and observation of ever more distant and fainter sources. In this regard, increasing the sensitivity of astronomical instruments is an important factor that drives the selection of the instrument to be developed in the coming years. The Dispersing Element (DE) has been and it is still a crucial element in modern optical spectrographs for astronomy. Moreover, it is one of the less efficient optical elements in the system. Looking at the spectroscopic instruments under design, both small/medium dedicated facilities and large/very large facilities, we notice there is and will be an important request of tailored DEs with different requirements. Their design and the choice of the best technology is therefore crucial.

Volume Phase Holographic Gratings (VPHGs) were introduced in the astronomical world in 1998[1,2]. Since then, they provided a significant improvement in low and medium resolution spectrographs with an apparent throughput step up and allowing for an optimization of each single element[3–10]. Indeed, they are still considered the baseline for the DE in low and medium resolution spectrographs. Indeed, they are relatively cheaper than the other technologies on the market. In spite of this interest, some weaknesses exist concerning the VPHGs: i) the lack of European companies that designs and produces such elements; ii) the reference American company, KOSI, discontinued the production of VPHGs for astronomy with the end of 2021 and a few of them exists in the world (such as Wasatch Photonics); iii) the common manufacturing process is based on Dichromated Gelatin (DCG), which is a dated holographic material containing chromium and that requires a complex wet chemical developing process. Moreover, it is sensitive to humidity.

Notably, other technologies are fortunately entering the field, in particular binary lithographic gratings that provide a valuable contribution especially for high dispersion DEs. Such gratings can be produced by using lithographic[11–13] or holographic[14,15] approach, they show an apparent versatility and large gratings can be produced. Notwithstanding these possibilities, they cannot be considered the final solution.

*andrea.bianco@inaf.it; phone +390272320460

Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V,
edited by Ramón Navarro, Roland Geyl, Proc. of SPIE Vol. 12188, 1218823
· 0277-786X · doi: 10.1117/12.2629361

Consequently, this situation can be risky for the future, because a void in the production could occur turning into delays in the astronomical spectrograph realization and/or the increase in costs.

In this context, an important activity for developing VPHGs at the European level has been carried out in the framework of Optical Infrared Coordination Network for Astronomy (OPTICON) funded in the FP6, FP7 and H2020 EU programs.

In this paper, we review the features of the VPHGs; then, we describe the path followed in the OPTICON EU project for the development of the gratings and we show the perspectives.

2. VPHG THEORY AND KEY PROPERTIES

VPHGs work thanks to a periodic modulation of the refractive index (Δn) stored in a holographic material with a defined thickness (d) as shown in figure 1[16,17]. The periodic modulation is commonly induced by means of a two-laser beams interference pattern that promotes a localized photoreaction. The result of this photoreaction is a change in the material density and/or molecular polarizability, sometimes after a chemical development process.

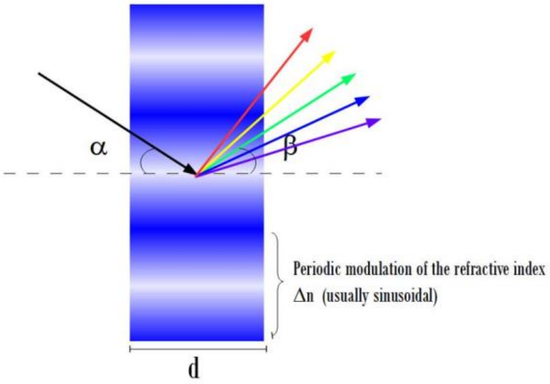


Figure 1. Scheme of the functioning of a VPHG.

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

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

When a sinusoidal refractive index modulation is stored in the holographic material and the light diffracted is just in one order, the Kogelnik model[8] is valid and describes very well the efficiency behavior: a large peak diffraction efficiency is obtained if the Bragg condition is met, i.e. the incidence angle (α) and the diffraction angle (β) are identical. An approach to move out of the Bragg condition is the slanting of the fringes (they are not perpendicular to the grating surface)[18,19]. This approach has been also exploited to avoid ghosts in VPH based spectrographs[20].

As a rule of thumb, a high efficiency is achieved when the product of Δn and d is close to half of the target wavelength[21]:

$$d \times \Delta n \approx \frac{\lambda}{2} \qquad (1)$$

it follows that increasing the working wavelength, moving from visible to the NIR, the holographic material has to provide higher Δn or to be thicker. For astronomical applications, it is very often important to have high efficiency across the working spectral range. According to the same model, the bandwidths (angular and spectral) of the diffraction efficiency curve show the following dependence:

$$\Delta\alpha \propto \frac{1}{Gd} \qquad \frac{\Delta\lambda}{\lambda} \propto \frac{\cot(\alpha)}{Gd} \qquad (2)$$

Where G is the line density of the grating. A high 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 according to eq. 1. We have to consider that the increase of number of pixels in the detectors pushes to have wider spectral ranges also at high dispersion, making challenging to preserve a high efficiency.

For low dispersion gratings, the light can be diffracted with a certain efficiency in more than one order; the Kogelnik model cannot be applied and the RCWA (rigorous coupled wave analysis) method must be applied to compute the diffraction efficiency[22]. Since the grating usually works in a single specific order (usually the first), it is important to quantify such amount of light diffracted in orders different from the first. A rough approximated of this amount (LP) is the following[4]:

$$LP = \frac{1}{\rho^2} \qquad \rho = \frac{\cot(\rho G)^2}{n\Delta n} \tag{3}$$

Where n is the average refractive index of the holographic material. For low dispersion gratings (low values of G), if we increase the refractive index modulation, the diffracted light is spread in more and more orders, reducing the efficiency of the target order. Hence, the optimization of the efficiency by choosing d and Δn follows different paths depending on the features of the grating and the required spectral response. In general, the trend for the optimization is reported in figure 2:

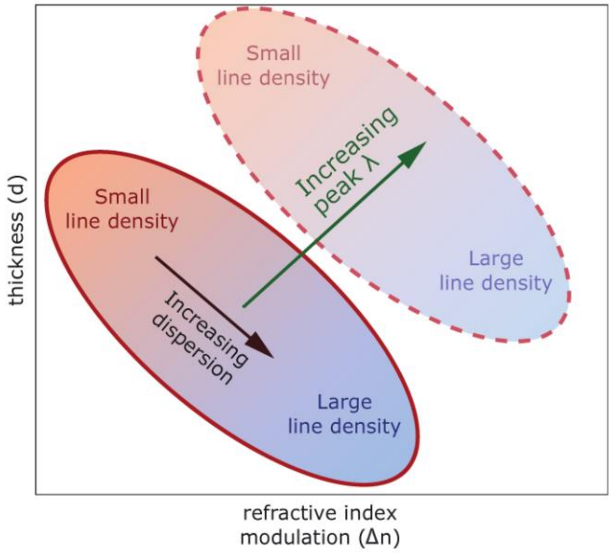
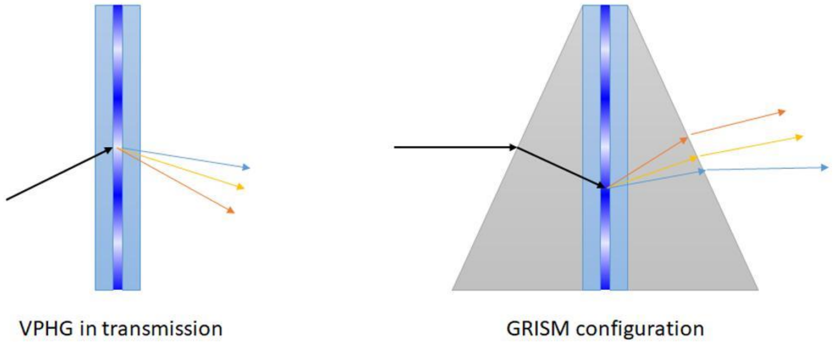


Figure 2. Diagram showing the range of optimization parameters d and Δn for gratings with different line density (G)[23].

Low dispersion gratings require a low Δn and a large thickness d in order to avoid the loss of efficiency in orders higher than the first and the bandwidth is not an issue. High dispersion gratings require, on the opposite, the largest possible Δn to obtain a large peak efficiency and a wide bandwidth at the same time. In general, VPHGs are not suitable for working at high diffraction orders; therefore, they cannot be used in echelle spectrographs[24]. For high dispersion VPHGs, increasing the working angle, the diffraction efficiency in the two polarizations can be also very different and the design becomes more challenging[17].

The VPHGs are commonly used in transmission and two main configurations: i) the VPHG tilted of the incidence angle in respect to the chief ray; ii) the VPHG coupled with prisms to have a GRISM configuration (figure 3).


VPHG in transmission

GRISM configuration

Figure 3. Schemes of the use of VPHGs in transmission: simple grating on the left and in (symmetric) GRISM configuration on the right.

The GRISM configuration has been implemented in spectroimagers such as the FOSC instruments[25], where you can switch easily from imaging to spectroscopy and you can have different dispersing elements without changing the camera position. The main drawback is a limited resolution and the need of heavy and expensive prisms for large size spectrographs.

3. WHAT HAS BEEN DONE

In OPTICON EU projects (funded in both FP7 and H2020 programs), one the Joint Research Activity (JRA) focused on the development of new materials and processes for the realization of VPHGs. Such activity was carried out at INAF-Osservatorio Astronomico di Brera in collaboration with other European institutions and in particular with IAC (Instituto de Astrofísica de Canarias). Innovative materials were developed together with Covestro AG that has become the leader in the production of photopolymers (Bayfol®HX) for holography[26]. The main advantage of these materials is the fact that they are self-developing (no chemical process is required). Moreover, they are panchromatic and with a high sensitivity, that turns into short holographic exposure times. Using such innovative materials, the VPHG manufacturing is much easier and the design and assembly of the devices are more flexible. Photopolymers do not contain heavy metals (such as Chromium); therefore they are environmental friendly.

Notably, in the last ten years, there have been an improvement of the holographic materials and the manufacturing capabilities at INAF-Osservatorio Astronomico di Brera. With respect to the improvement of the material, the main point was the increase of maximum Δn. Indeed, looking at figure 2, this directly translates in the possibility to produce VPHGs with wider bandwidth at higher dispersion. Moreover, a better sensitivity and lower scattering were achieved. From the grating production side, the holographic setup increased its size moving from 50 mm to 200 mm in collimated laser beam. In addition, the initial green laser setup was improved to an RGB system. A manufacturing procedure suitable for industrial production was also defined in order to minimize the requested time for the grating production and to optimize the use of holographic film.

The results were extremely positive and encouraging. The production of VPHGs with a size > 170 mm of clear aperture was demonstrated; moreover, unconventional architectures based on VPHGs (multiplexed and multiorder gratings) were implemented. The most solid proof is that 10 VPHGs (from 40mm to 100mm in diameter) based on this technology are mounted nowadays on astronomical spectrographs. Such important and positive feedback supports the thought that we are on the right path.

3.1 Bayfol®HX holographic material

The key aspect of the process developed in the framework of OPTICON is the use of innovative photosensitive holographic materials. Dichromated Gelatin (DCG) is the commonly used material for making VPHGs and it has been extensively employed[27–29]. The process is established and the raw material available on the market. Moreover, the performances in terms of Δn are impressive. Indeed, it is possible to reach values well above 0.1 and this allowed for the realization of high dispersion VPHGs with good efficiency across the bandwidth. Such performances are obtained upon a chemical developing process that follows the holographic exposure. The need of a chemical process, together with the presence of Chromium and low light sensitivity stimulated us to look for different materials that were “self-developing”, i.e. no need of chemical development. We addressed our attention to photopolymers that found a large interest at the end of the ’90 especially for the memory market[30–32]. After 2010, the interest increased again and some companies developed some commercial materials. COVESTRO AG was one of the company that started the production of Bayfol®HX family of photopolymers[26]. Their key features are the following:

- Panchromatic system with high light sensitivity (exposure time of the order of tens of seconds with low irradiances);
- Produced in protected foils with a constant thickness in large sizes (meter long rolls, tens of cm wide);

They can be easily used by laminating the film on the glass substrate and then performing the holographic exposure (see figure 4). After that, a bleaching with incoherent visible and UV light fixes the final hologram. The foil can be then removed, cut, deposited on a different substrate or on top another photosensitive layer.

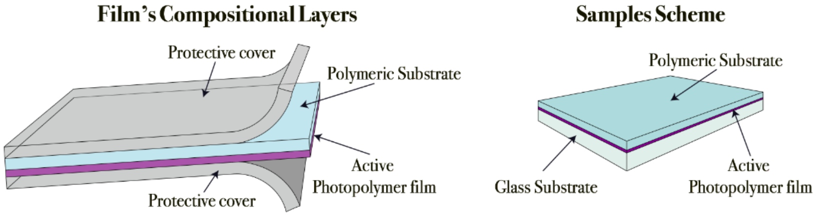


Figure 4. On the left: structure of a Bayfol®HX film with the different layers. On the right: the film laminated on the glass substrate.

Different aspects of the material have to be carefully considered when used in the production of VPHGS: i) the range of d and Δn; ii) the transparency range; iii) the light scattering. Concerning the film thickness, d, the range is very broad, from 3 μm to about 70 μm. This is an important feature considering that the value is constant over wide areas and allows for the realization of efficient gratings with a very low dispersion. Moreover, there is not the risk of development of thick films that occurs in the case of DCG. The Δn is the other parameter to consider. Because of the mechanism behind the phase hologram formation (a mass transfer during the photopolymerization and change in density[33,34]), we cannot expect values comparable with those of DCG. Fortunately, important improvements have been done in the last years and the values from 0.02 have reached 0.07 in reflection and 0.05 in transmission[35]. With these values, it is possible to develop efficient VPHGs in wide bands with a medium dispersion. High dispersion gratings are possible only in narrow bands. The control of the Δn at specific value, which is extremely important for low dispersion gratings, can be obtained both changing the irradiance of the writing laser or by performing a pre-exposure with incoherent white light[36,37]. The light scattering is important in astronomical spectrographs and can be an issue when photopolymers are used, especially at short wavelengths, because the final hologram is readily obtained; whereas in DCG, only the latent holograms is stored upon holographic exposure[38]. A strategy to reduce the light scattering in photopolymers is the use of longer wavelength of the lasers and reduce as much as possible the exposure time[37]. Regarding the spectral range, we have to consider two aspects: the absorption of the writing chemistry that introduces a cutoff in the UV and the polymer substrate that has some residual absorption at long wavelengths. In the latter case, the absorption depends on the kind of polymer used and its thickness. In figure 5, the absorption spectrum of a panchromatic 17 μm thick Bayfol®HX film on TAC (Cellulose triacetate) substrate is reported before and after the optical bleaching.

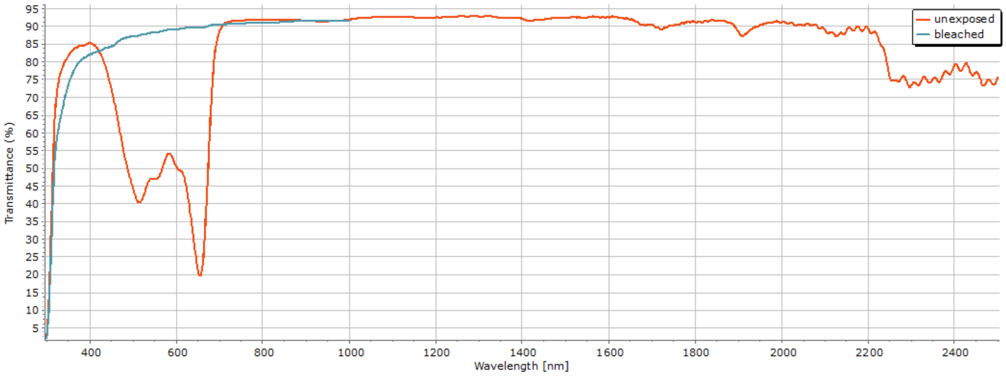


Figure 5. Transmission spectrum (no correction of the reflection losses) for a panchromatic Bayfol®HX film (17 um thick) on TAC substrate before and after bleaching.

The UV cut-off is about 0.31 μm, but some residual absorption is present starting at 0.35 μm; in the NIR, we notice significant absorption only above 2.2 μm (the absorption is of the order of 20%), which reduce the final throughput of the VPHGs. The 0.6 – 1.6 μm is surely the best spectral range of work and this is independent from the polymeric substrate and the photopolymer thickness.

3.2 Production process and standard VPHGs

The manufacturing of a VPHG using the photopolymers requires a set of activities and a precise sequence. This is necessary to obtain the expected performances keeping the time and costs under control. The procedures were defined and developed a few years ago during the OPTICON H2020 and they are summarized in figure 6[39].

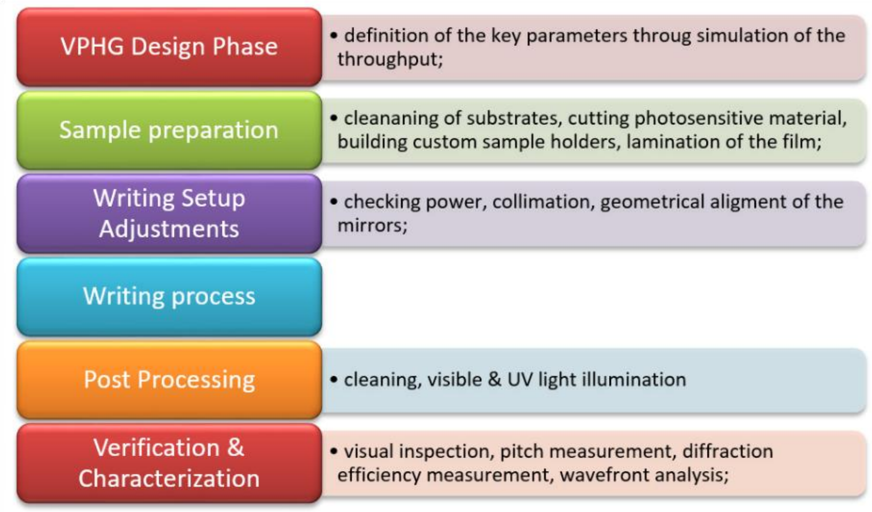


Figure 6. Scheme of the production steps developed for the production of Bayfol®HX based VPHGs.

The procedure was developed having in mind an industrial context and not a research context. This was necessary to prove that the technology was ready for the production of VPHGs for spectrographs matching the time requirements. The design phase is performed using both optical CAD (mainly Zemax®) and custom procedures developed in Matlab® for the diffraction efficiency calculation using the rigorous coupled wave analysis (RCWA) approach. In the efficiency evaluation, we consider the measured properties of the holographic materials, such as the transmission spectrum, thickness, maximum Δn.

After that, the sample is prepared paying attention to the substrate cleaning and film deposition. Sometimes, it could be necessary the manufacturing of a custom mechanical holder for the substrate and a filter applied on the back surface in order to avoid the laser back reflection that writes secondary holograms. In parallel, the writing setup is checked and set to write the defined line density with, if necessary, the slanting angle. Some writing tests on small samples are performed to find the optimal writing conditions. Finally, the holographic exposure is performed; then, the optical element is bleached and characterized. These last steps can be performed different times to reach the target performances. Usually, the most challenging step is the slanting angle setting.

Different VPHGs were produced in the last 10 years using this innovative technology responding to the requests of the astronomers. Most of them are related to FOSC instrument with a (circular) size of 40 mm. The main features of these gratings are reported in table 1. The plot in figure 7 summarizes the spectral range and resolution of the produced VPHGs.

Table 1. Main properties of the GRISMs mounted on FOSC instruments and based on Bayfol®HX VPHGs.

Device	Instrument	Central λ (um)	Spectral range (um)	R	Line density (l/mm)	Notes
VPHG4	AFOSC	0.66	0.62 – 0.70	3600	1720	---
VPHG6		0.80	0.62 – 0.98	720	285	---
VPHG7		0.53	0.35 – 0.80	458	280	Single prism GRISM with slanted fringes
VPHG8		0.70	0.55 – 0.80	1380	600	
GRISM #18	ALFOSC	0.43	0.34 – 0.52	1130	1086	---
GRISM #19		0.56	0.44 – 0.69	1110	823	---
GRISM #20		0.79	0.58 – 1.00	896	484	VPHG deposited onto the order sorting filter
GRISM#6	BFOSC	0.44	0.33 – 0.55	1200	640	Single prism GRISM with slanted fringes
GRISM#8		0.69	0.60 – 0.75	2400	910	Asymmetric prisms with VPHG deposited onto the order sorting filter

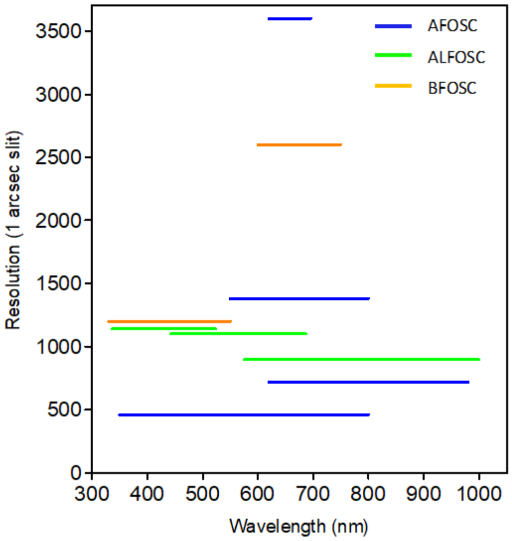


Figure 7. Plot of the installed GRISMs, which are based on Photopolymer VPHGs as function of the wavelength range and resolution.

It is worth noting that the VPHGs we developed are stable; indeed, they have been working for almost 10 years without significant performance degradation. Moreover, we tested the stability in laboratory both at relatively high temperature (40°C) and in cryogenic environment (85 K), which is important for the development of infrared spectrographs. The results confirmed the system stability as evident from the plots in figure 8[40].

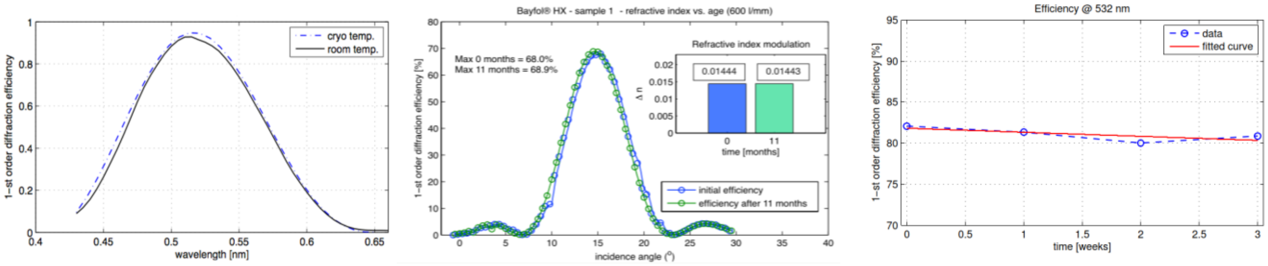


Figure 8. On the left: the diffraction efficiency curve of a VPHG at room temperature and in a cryogenic environment (85 K). Center: the diffraction efficiency curves as function of the AOI for a VPHG in one year time. On the right: Peak diffraction efficiency as function of time for a VPHG kept at 40°C.

Recently, we've developed large size VPHGs with a clear aperture larger than 170 mm in diameter. Two samples were produced one optimized for the blue and the other for the red. The main features are reported in table 2.

Table 2. Main parameters of the large size VPHGs produced at the end of the OPTICON H2020 project.

Parameter	**Value**	
	Red	**Blue**
Spectral range (nm)	624 – 696	400 – 500
Central wavelength (nm)	660	450
Line density (l/mm)	1720	1720
Incidence angle in air (°)	34.35	22.8
Clear Aperture VPHG	>170 mm in diameter	
Peak efficiency	>80%	
Minimum efficiency at the edges	>50%	
Substrate material	BK7	
Substrate size (L x H x T mm)	250 x 200 x 20	
Clear aperture (substrate)	>90%	
Surface quality	40/20	
WFE transmitted (PtV)	< 1λ	
AR coating	R<1% 400 – 700 nm	

The red one is a copy of the VPHG4 for AFOSC and it provides a medium dispersion; the blue one shows a lower dispersion working at smaller angles. The Blue grating was written on 6 μm thick Bayfol® HX film and the Red one on a 8 μm thick film. The target Δn was 0.04. The photo of the two samples and the corresponding diffraction efficiency is reported in figure 9.

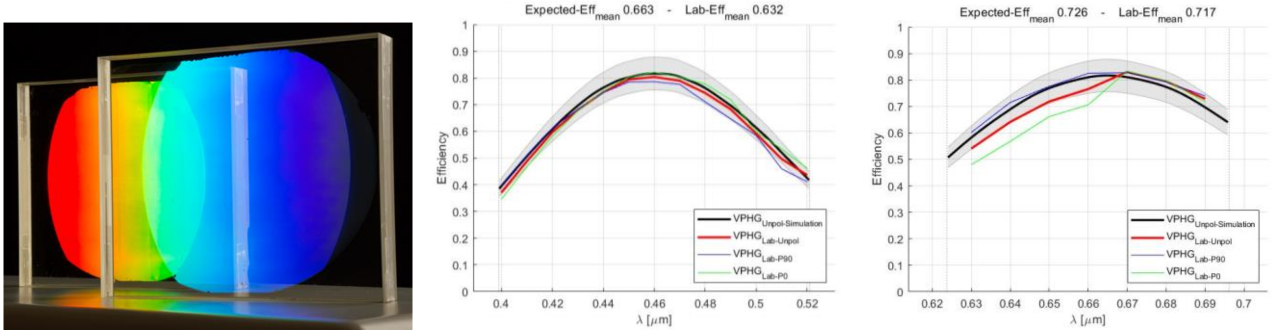


Figure 9. On the left: Photo of the two large size VPHGs. Center: diffraction efficiency curves in the two polarization and for unpolarized light for the Blue VPHG. Center: diffraction efficiency curves in the two polarization and for unpolarized light for the Blue VPHG.

The Blue VPHG has a symmetric diffraction efficiency curve and the Red one shows an asymmetric curve due to the presence of a small slanting of the fringes. The peak efficiency is slightly above 80% at the peak for both VPHGs and the bandwidth is larger for the Red element.

We measured the transmitted Wavefront Error (WFE) of the first diffraction order, using a Fizeau interferometer in double pass. The resulting WFEs are reported in figure 10 including or not the focus term.

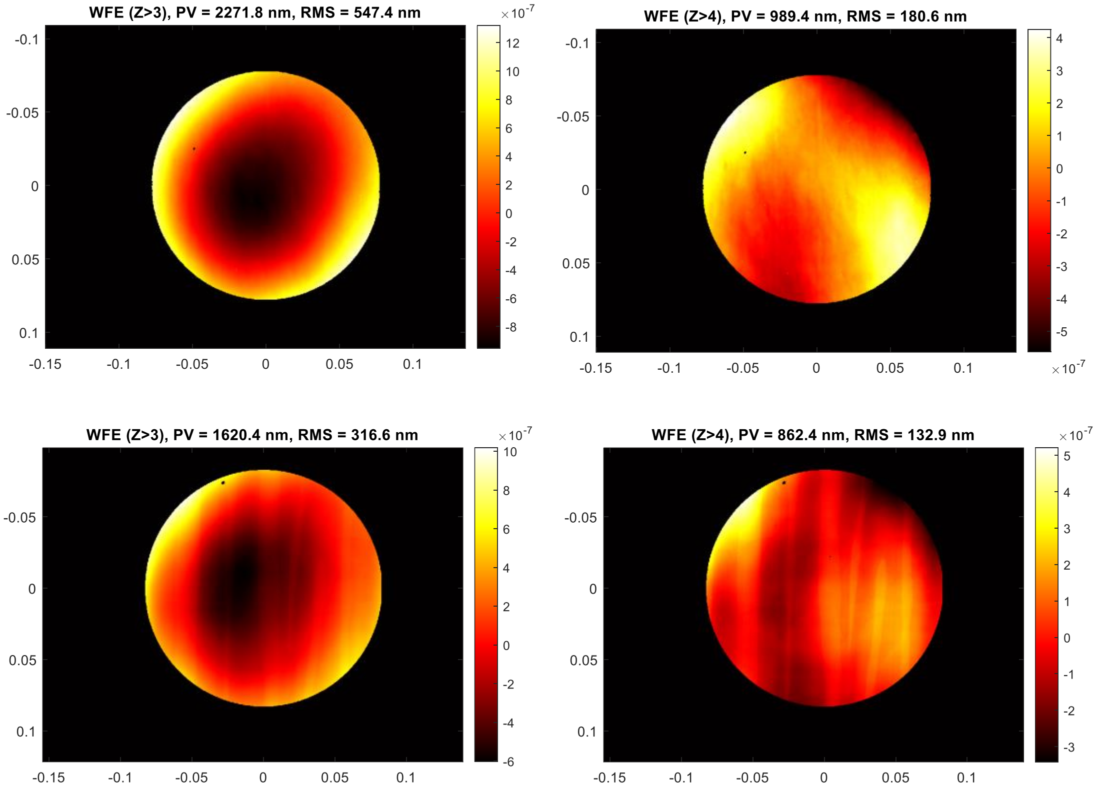


Figure 10. On top: Phase maps for the Red (top) and Blue (bottom) VPHGs. On the left the Zernike terms > 3 are considered; on the right the terms >4 (the focus term is removed).

The PtV value for the Red VPHG is about 2.2 μm, with 1.3 μm of focus. This aberration can be easily compensated in the spectrograph by changing the camera focus, but it can be removed by a better collimation of the beams in the holographic setup. The Blue VPHG shows a better WFE with a 1.6 μm PtV that becomes 0.86 μm after removing the focus. Considering the high orders, the PtV is 240 nm for the Red and 334 nm for the Blue. These values are reasonably small and can be ascribed to the photopolymer layer imperfections and laser beam quality. Recent tests based on VPHGs written with the optimized holographic setup showed a PtV of about 0.5 μm considering the focus with an RMS < 100 nm.

3.3 Non-conventional configurations

The features of the holographic materials employed made possible the development of non-conventional structures of the VPH based dispersing elements with the aim of increasing the combination of resolution – spectral range. Indeed, the size of the detector, determines the maximum spectral range once the dispersion is set. In order to obtain very high dispersion (resolution) and a wide spectral range, the echelle spectrograph is used, which exploits the high orders diffraction followed by a cross-dispersion of the orders to fill the detector. Without reaching very high resolutions (above 20000), some approaches can be developed. We proposed two configurations: i) a dual order VPHG to cover a very wide spectral range at low dispersion in a single exposure; ii) a multiplexed VPHG to mimic an echellete grating. The scheme of the two configurations are reported in figure 11.

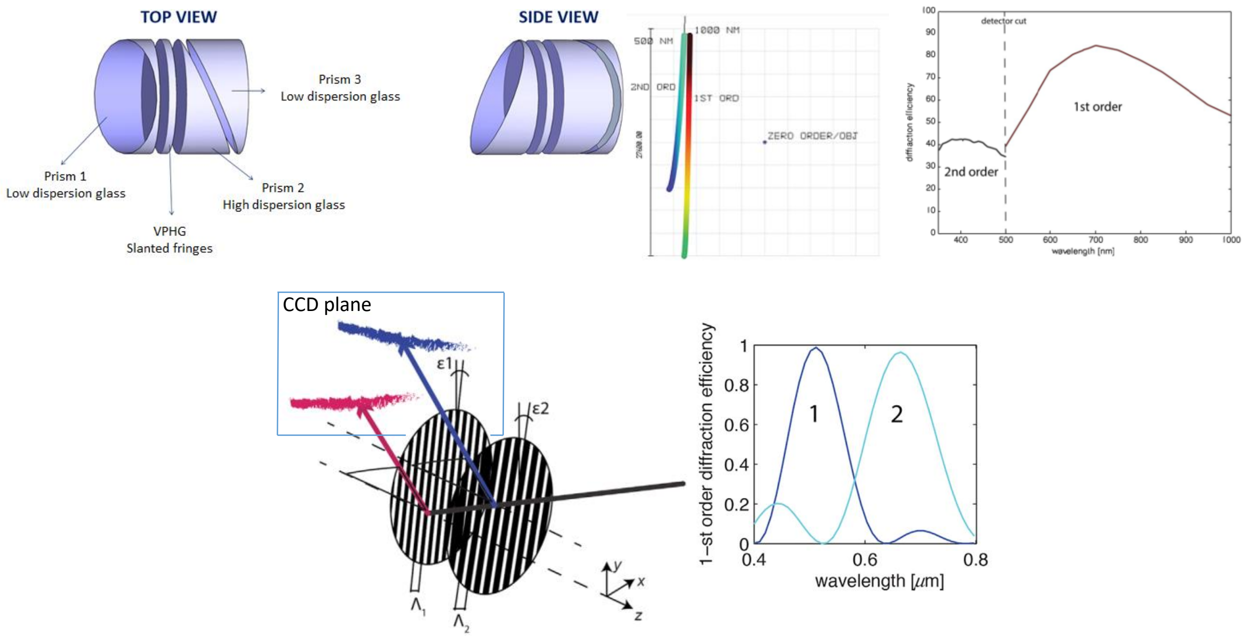


Figure 11. Schemes of the non-conventional configurations. On top: dual order GRISM with the combination of the three prisms and a slanted VPHG; the expected spectrum on the detector plane[41]. On the bottom: stacked VPHGs, one for the blue and one for the red with different line density (Λ) and rotating angle ε; on the right the expected diffraction efficiency of the stack[42].

The dual order VPHG has been used in a GRISM configuration and it employs three prisms (figure 11 top). The first one defines the incidence angle, which is set to have a zero diffraction angle for the central wavelength ($\beta = 0$). This is necessary because the exit couple of prisms (a sort of Amici prism) does not bend the beam in the dispersion direction as occurs in a standard GRISM, but the prisms are 90° rotated and act as a cross disperser for the two orders. One issue here is to have a separation of the two orders large enough to accommodate a slit catching the target object and the sky and this is mainly achieved with the high dispersion glass (its choice is critical if the device has to work down to UV because of the low transparency). Regarding the diffraction efficiency, the goal is to obtain a balance between the first and second diffraction orders with a decent efficiency in the crossing region (see the efficiency curves in figure 12).

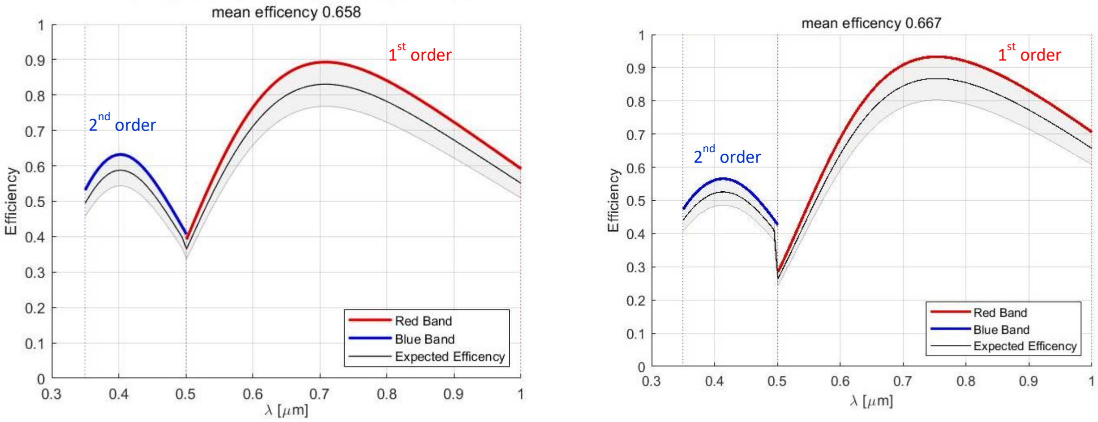


Figure 12. Calculated diffraction efficiency curves for a 341 l/mm VPHG (RCWA approach). On the left: 20 um thick film, $\Delta n = 0.0159$; on the right: 20 um thick film, $\Delta n = 0.0185$.

The first optimization in figure 12 (on the left) is more balanced with an efficiency at 0.5 μm of 40%. The second optimization (figure 12 on the right) favors the 1st order in the red part, but there is a mismatch at 0.5 μm and a less efficient 2nd order. Surely, the first design is a better choice.

A dual order GRISM (GRIS-U)[43] with a size of 100 mm in diameter is mounted in the Dolores spectrograph at the Telescopio Nazionale Galileo (La Palma, Spain) and it provide a resolving power of ≈ 400. It has been used for the classification of supernovae[44]. A new dual order device is under construction for the AFOSC instrument at Copernico telescope in Asiago (Italy) and it will work in the 0.35 – 1.00 μm range with a resolving power of about 900.

Concerning the multiplexed VPHG, we have a large flexibility in the optimization of the device and we do not need complex prisms to separate the orders, but it is the clock angle between the layers that separates the spectra on the detector. We can have two situations: i) split a large spectral range in shorter consecutive ranges; ii) collect small spectral ranges (usually around lines of interest) with a certain (high) dispersion. In the former case, the situation is similar to an echellette grating, with an overlap of the diffraction efficiency curves (see figure 13) that limits the overall efficiency at the spectral edges. In the latter, if the narrow target ranges are not consecutive a very high diffraction efficiency can be achieved for all of them in the whole ranges. The number of layers that can be stacked is in principle free, but it is better to have two or three layers maximum. This is due to the fact that the rotating angle between the different layers cannot be too large in order to have a feasible incidence angle without a too large conical diffraction. Moreover, each layer introduces a residual absorption that sums up through the element and reduce the overall throughput. This is especially true if the dispersing elements works in the optical range and it is less important in the NIR range up to the J band.

The diffraction efficiency optimization is tricky since, the different combination of orders have to be considered. In this regard, a custom Matlab® code has been implemented[45]. The device can work in both GRISM configuration and standard configuration. We developed a GRISM based system for the visible (0.4 – 0.7 μm) that consisted in three layers and provided a resolving power of about 5000[46]. More recently, a three layer device was designed and produced for the MCIFU spectrograph fully developed in the OPTICON H2020 project[42]. The instrument worked in the 1.0 – 1.6 μm spectral range and it was mounted at the focus of the AO CANARY at the WHT providing interesting results and paving the way to a new class of compact medium resolution IFSs for the infrared.

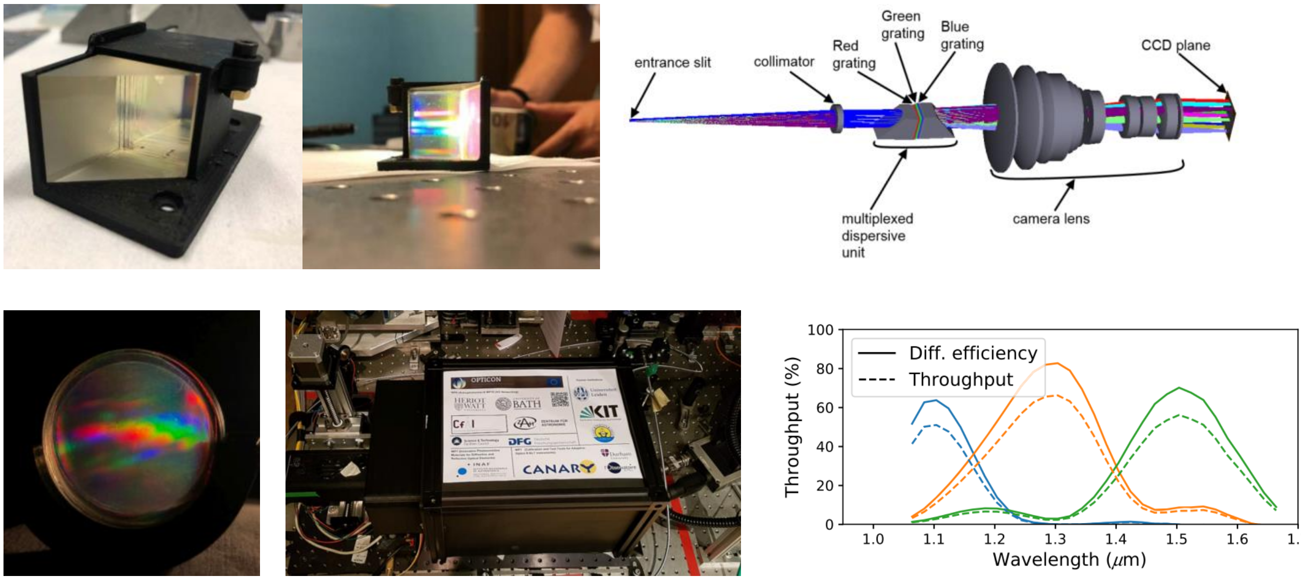


Figure 13. On top: photos of the three layers visible GRISM and the optical scheme. On the bottom: the three layers VPHG for MCIFU, the instrument on the optical bench of CANARY and the diffraction efficiencies of the three layers.

We think that these new approaches can be useful to improve the performances of spectrographs and should be considered in the design phase of low-medium resolution spectrographs. Clearly in the case of IFS, a tradeoff in the spatial and spectral resolution must be performed because the size of the detector is limited.

After the OPTICON experience, the development of VPHGs to improve the observing capabilities of small and medium facilities in Europe continued with the ORP (Opticon Radionet Pilot, EU H2020) project in a dedicated activity. Indeed, we have to consider that the change of the dispersing element is one of the most effective way to increase/change the spectroscopic capabilities. In this project, and based on scientific proposals, a set of dispersing element is selected, manufactured and commissioned. This approach is a very useful training in the development of dispersing elements.

4. ACTUAL AND FUTURE MANUFACTURING CAPABILITES

We know that the features of the VPHGs change dramatically from instrument to instrument; indeed, the size and architecture change together with the spectral range (in the infrared the instrument could be at cold), the dispersion (there is often a low resolution and high resolution modes). Consequently, it is important to have a flexible writing facility. Moreover, it is crucial to characterize the dispersing element not only in terms of diffraction efficiency, but also in the diffracted wavefront, fringe orientation. Hence, a suite of facilities are necessary.

4.1 Writing facility

The holographic setup (figure 14) is based on two collimated beams as commonly used for the grating holographic exposures. Three polarized DPSS Cobolt lasers are available with wavelengths of 457 nm (200 mW), 532 nm (1.5 W) and 660 nm (500 mW). The laser beam is split in two and each beam passes through a spatial filter to have a diverging and clean Gaussian profile. The intensity if the two beams can be tuned by using rotating polarizers. The collimation of the beams is guaranteed by a couple of 8 inches f/6 doublets. The beams are then reflected by two 10 inches flat mirrors that are mounted on rotating stages to set the incidence angle and so the line density at the sample position. The setup is mounted on a 2400mm x 1500 mm TCM optical bench and it is placed in a clean environment for reducing the dust contamination. With this set-up it is possible to write VPHG with a clear aperture of 180mm x 230mm. The range of line density is wide, from 200 l/mm to 3000 l/mm.

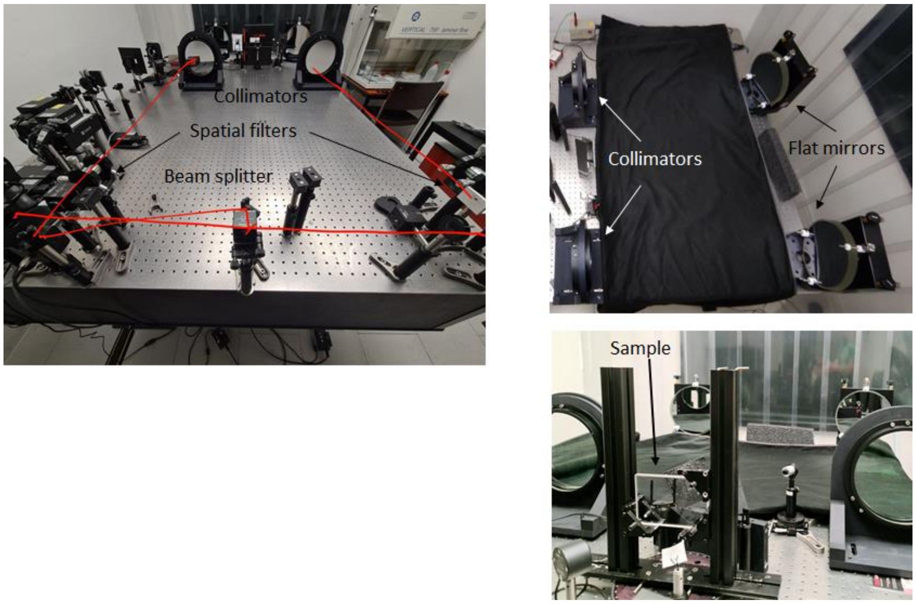


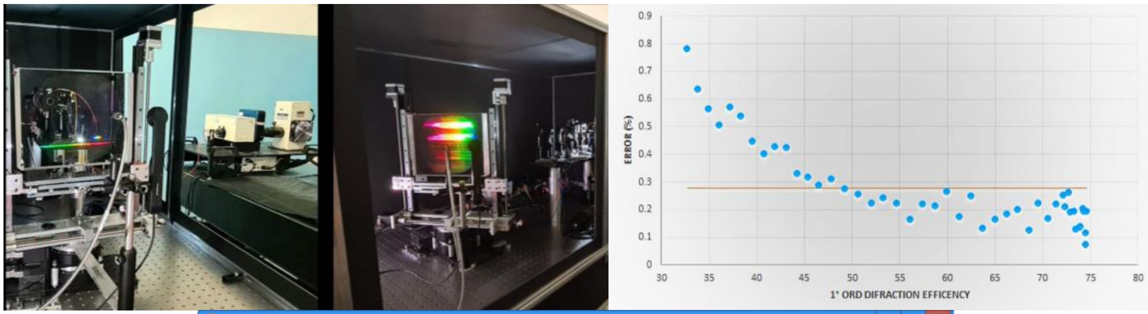
Figure 14. Photos of the holographic setup with the main components.

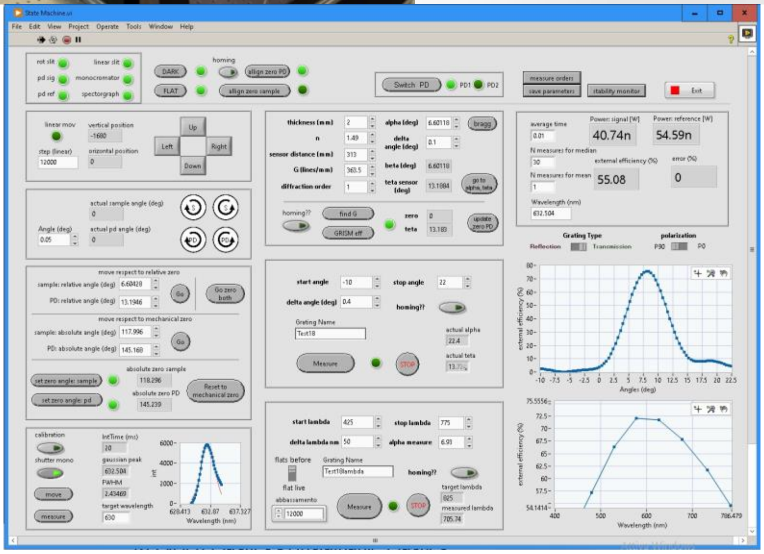
4.2 Diffraction efficiency measurement

A dedicated setup has been developed for the measurement of the diffraction efficiency of VPHGs. The system can provide the diffraction efficiency as function of:

- the wavelength from 0.3 μm to 2.0 μm;
- the light polarization;
- the Angle of Incidence (AOI);
- the position on the clear aperture (efficiency map).

This setup makes also the measurement of the line density possible with an accuracy < 1 l/mm. The main light source is a tunable light source Newport TLS130B-300X, which is fiber fed. The quasi-monochromatic light (2 nm bandwidth) is then collimated, passes through a depolarizer and a rotating polarizer (to set the –s or –p polarization). Then, it is split with a small component that reaches a photodiode (to monitor the temporal stability). Most of the light hits eventually the sample. This element is mounted in a holder that can move in X-Y for the efficiency map measurement and on a rotating stage to set the AOI. A concentric rotating stage holds through an arm the measuring photodiode that rotates following the diffracted beam. A set of lasers is available for recording precise diffraction efficiency curves as function of the AOI and polarization to retrieve the d, Δn and slanting angle of the VPHG. A custom made LabView® software fully control the setup. Figure 15 reports photos of the setup, a screenshot of the GUI to control the measurements and the repeatability that is very good with an error < 1%.





linear mov
vertical position -1680
step (linear) 12000
orizontal position 0
actual sample angle (deg) 0
Angle (deg) 0.05
actual pd angle (deg) 0

move respect to relative zero
sample: relative angle (deg) 6.60428
PD: relative angle (deg) 13.1946

move respect to mechanical zero
sample: absolute angle (deg) 117.996
PD: absolute angle (deg) 145.168

absolute zero sample 118.296
absolute zero PD 145.239

IntTime (ms) 20
gaussian peak 632.504
FWHM 2.43469
target wavelength 630

thickness (mm) 2
n 1.49
sensor distance (mm) 313
G (lines/mm) 363.5
diffraction order 1
alpha (deg) 6.60118
delta angle (deg) 0.1
beta (deg) 6.60118
teta sensor (deg) 13.1884
homing??
zero 0
teta 13.183

start angle -10
stop angle 22
delta angle (deg) 0.4
homing??
Grating Name Test18
actual alpha 22.4
actual teta 13.72

start lambda 425
stop lambda 775
delta lambda nm 50
alpha measure 6.93
flats before
flat live
Grating Name Test18lambda
homing??
abbassamento 12000
target lambda 825
measured lambda 705.74

average time 0.01
Power: signal [W] 40.74n
Power: reference [W] 54.59n
N measures for median 30
external efficiency (%) 55.08
error (%) 0
N measures for mean 1
Wavelength (nm) 632.504

Figure 15. Top left: photos of the characterization setup with a mounted large size VPHG. Top right: the plot of the diffraction efficiency error for a set of measurements. Bottom: Screenshot of the GUI that controls the characterization setup.

As already reported, in the section 3.2, the WFE is measured by means of a Fizeau interferometer in a double pass collimated configuration using a reference flat mirror as retro-reflector. If the clear aperture is larger than the collimated beam (100 mm in diameter), a stitching procedure is employed[47]. Other dimensional measurements and fringe alignment in respect to the glass substrate can be measured using a combination of a portable CMM (Coordinate-measuring machine) and a laser based optical setup[47].

4. CONCLUSIONS

VPHGs are considered key dispersing elements for astronomical spectrographs. In the last years, the manufacturing capabilities at INAF-Osservatorio Astronomico di Brera have been improved thanks to the support of the OPTICON project. Some VPHGs are now mounted on observing facilities providing good performances; moreover, new architectures, such as multiorder and multiplexed VPHGs have been developed to improve the resolution/spectral range combination. In order to continue with the development and to promote the spread of these VPHG for small and medium observing facilities in Europe, a dedicated activity is funded in the ORP project. Such devices are based on new materials of the class of photopolymers. They have been chosen thanks to specific advantages in comparison to DCG (higher sensitivity and self-development). The performances of these materials are improving. The goal in the future would be a $\Delta n > 0.07$ and a transparency windows in between 0.33 um and 2.50 μm and this could be achieved through an R&D activity with the development of new tailored chemical compounds. In this way, it will be possible to cover most of the requests of the astronomical market at least for gratings without a very large dispersion; for which, it is better to look at other technologies (such as binary gratings). As for the size of the VPHGs, a clear aperture < 200 mm in diameter is the limit because of the size of the holographic setup, but it is working for the development of a much bigger facility with a target size of 400 mm. In this way, there will be the possibility, together with the other available manufactures, to satisfy the request of dispersing elements for very large facilities, i.e. ELT instruments.

ACKNOWLEDGEMENTS

This work was partially supported by ORP (Opticon Radionet Pilot, EU H2020, grant agreement 101004719) and OPTICON (Optical Infrared Coordination Network for Astronomy, EU H2020, grant agreement No 730890). The authors are grateful to Covestro AG for providing the Bayfol®HX materials and for the useful discussions on their use.

REFERENCES

[1] Barden, S. C., Arns, J. A., Colburn, W. S. and Williams, J. B., “Volume-phase holographic gratings and the efficiency of three simple volume-phase holographic gratings,” Publications of the Astronomical Society of the Pacific **112**(772), 809–820 (2000).

[2] Barden, S. C., Arns, J. A. and Colburn, W. S., “Volume-phase holographic gratings and their potential for astronomical applications,” Proc. SPIE, **3355**, 866–876 (1998).

[3] Wilson, J. C., Hearty, F., Skrutskie, M. F., Majewski, S. R., Schiavon, R., Eisenstein, D., Gunn, J., Holtzman, J., Nidever, D., Gillespie, B., Weinberg, D., Blank, B., Henderson, C., Smee, S., Barkhouser, R., Harding, A., Hope, S., Fitzgerald, G., Stolberg, T., et al., “Performance of the Apache Point Observatory Galactic Evolution Experiment (APOGEE) high-resolution near-infrared multi-object fiber spectrograph,” Proc. SPIE **8446**, 84460H (2012).

[4] Sheinis, A., Barden, S., Birchall, M., Carollo, D., Bland-Hawthorn, J., Brzeski, J., Case, S., Cannon, R., Churilov, V., Couch, W., Dean, R., De Silva, G., D’Orazi, V., Farrell, T., Fiegert, K., Freeman, K., Frost, G., Gers, L., Goodwin, M., et al., “First light results from the Hermes spectrograph at the AAT,” Proc. SPIE **9174**, 91470Y (2014).

[5] Bianco, A., Pariani, G., Aliverti, M., Zanutta, A., Arns, J., Pragt, J., Stuik, R., Middleton, K., Tosh, I., Dalton, G., Trager, S., Abrams, D. C., Aguerri, J. A. L., Bonifacio, P., Vallenari, A. and Carrasco, E., “VPHGs for WEAVE: design, manufacturing and characterization,” Proc. SPIE **10706**, 107064X (2018).

[6] Spanò, P., Zerbi, F. M., Norrie, C. J., Cunningham, C. R., Strassmeier, K. G., Bianco, a., Blanche, P. a., Bougoin, M., Ghigo, M., Hartmann, P., Zago, L., Atad-Ettedgui, E., Delabre, B., Dekker, H., Melozzi, M., Snÿders, B., Takke, R. and Walker, D. D., “Challenges in optics for Extremely Large Telescope instrumentation,” Astronomische Nachrichten **327**(7), 649–673 (2006).

[7] Kashiwagi, M., Oka, K., Irisawa, M., Ebizuka, N., Iye, M. and Kodate, K., “Optimal design and fabrication of high dispersion VPH grism for Subaru telescope,” Proc. SPIE **5494**, 217–227 (2004).

[8] Arns, J. A., “Performance characteristics of a suite of volume phase holographic gratings produced for the Subaru prime focus spectrograph,” Proc. SPIE **9908**, 99087O (2016).

[9] Arns, J., Wilson, J. C., Skrutskie, M., Smee, S., Barkhouser, R., Eisenstein, D., Gunn, J., Hearty, F., Harding, A., Maseman, P., Holtzman, J., Schiavon, R., Gillespie, B. and Majewski, S., "Development of a large mosaic volume phase holographic (VPH) grating for APOGEE," Proc. SPIE **7735**, 77351C (2010).

[10] Pepe, F., Cristiani, S., Rebolo, R., Santos, N. C., Dekker, H., Cabral, A., Di Marcantonio, P., Figueira, P., Lo Curto, G., Lovis, C., Mayor, M., Mégevand, D., Molaro, P., Riva, M., Zapatero Osorio, M. R., Amate, M., Manescau, A., Pasquini, L., Zerbi, F. M., et al., "ESPRESSO at VLT: On-sky performance and first results," Astronomy and Astrophysics **645**, A96–A96 (2021).

[11] Saunders, W., Zhang, K. and Flügel-Paul, T., "Higher dispersion and efficiency Bragg gratings for optical spectroscopy," Proc. SPIE **10706**, 107065C (2018).

[12] Zeitner, U. D., Dekker, H., Burmeister, F., Flügel-Paul, T., Bianco, A. and Zanutta, A., "High efficiency transmission grating for the ESO CUBES UV spectrograph," Experimental Astronomy, doi: 10.1007/s10686-022-09840-1 (2022).

[13] Harzendorf, T., Michaelis, D., Flügel-Paul, T., Bianco, A., Oliva, E. and Zeitner, U., "Surface relief gratings manufactured by lithographic means being a candidate for VLT MOONS instrument's main dispersers," Proc. SPIE **10706**, 1070621 (2018).

[14] Cotel, A., Villier, B. and Gombaud, C., "Meter-size gratings for multi-petawatt lasers," CLEO 2016, SM2M.2 (2016).

[15] Cotel, A., Liard, A., Desserouer, F. and Pichon, P., "Overview of diffraction gratings technologies for spaceflight satellites and ground-based telescopes," Proc. SPIE **10563**, 105630P (2017).

[16] Kogelnik, H., "Coupled-wave theory for thick hologram gratings," Bell System Technical Journal **48**, 2909–2947 (1969).

[17] Baldry, I. K., Bland-Hawthorn, J. and Robertson, J. G., "Volume Phase Holographic Gratings: Polarization Properties and Diffraction Efficiency," Publications of the Astronomical Society of the Pacific **116**(819), 403–414 (2004).

[18] Arns, J. A. and Dekker, H., "Slanted fringe volume phase holographic gratings in astronomical instrumentation," Proc. SPIE **7014**, 70141R (2008).

[19] Bianco, A., Arns, J., Dekker, H., Spano, P., Zanutta, A. and Zerbi, F. M., "Slanted VPHGs in astronomical instrumentation: tests and perspectives," Proc. SPIE **8450**, 84503N (2012).

[20] Eric B. Burgh, M. A. B., Kyle B. Westfall, Kenneth H. Nordsieck., "Recombination Ghosts in Littrow Configuration: Implications for Spectrographs Using Volume Phase Holographic Gratings," Publications of the Astronomical Society of the Pacific **119**(859), 1069–1082 (2007).

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

[22] Moharam, M. G. and Gaylord, T. K., "Rigorous coupled-wave analysis of planar-grating diffraction," Journal of the Optical Society of America **71**, 811–811 (1981).

[23] Zanutta, A., Orselli, E., Fäcke, T. and Bianco, A., "Photopolymeric films with highly tunable refractive index modulation for high precision diffractive optics," Optical Materials Express **6**(1), 252–263 (2016).

[24] Bianco, A. and Pariani, G., "Volume phase holographic echelle grating: a theoretical study," Proc. SPIE **7739**, 77394O (2010).

[25] Wolfgang Mitsch, Gero Rupprecht, Walter Seifert, Harald E. Nicklas, and Swen Kiesewetter., "Versatile multi-object spectroscopy with FORS at the ESO Very Large Telescope," Proc. SPIE **2198**, 317-321 (1994).

[26] Bruder, F., Fäcke, T. and Rölle, T., "The Chemistry and Physics of Bayfol ® HX Film Holographic Photopolymer," Polymers **9**(472), 1–32 (2017).

[27] Rallison, R. D., "HOLOGRAPHIC OPTICAL-ELEMENTS (HOES) IN DICHROMATED GELATIN (DCG) - PROGRESS," Proc. SPIE **523**, 292–295 (1985).

[28] Chang, B. J. and Leonard, C. D., "Dichromated gelatin for the fabrication of holographic optical elements," Applied Optics **18**(14), 2407–2417 (1979).

[29] Phillips, N. J., Rallison, R. D., Barnett, C. A., Schicker, S. R. and Coleman, Z. A., "Dichromated Gelatin - Some Heretical Comments," Proc. SPIE **1914**, 101–114 (1993).

[30] Sheridan, J. T., Kostuk, R. K., Gil, A. F., Wang, Y., Lu, W., Zhong, H., Tomita, Y., Neipp, C., Francés, J., Gallego, S., Pascual, I., Marinova, V., Lin, S.-H., Hsu, K.-Y., Bruder, F., Hansen, S., Manecke, C., Meisenheimer, R., Rewitz, C., et al., "Roadmap on holography," Journal of Optics **22**(12), 123002 (2020).

[31] Lawrence, J. R., O'Neill, F. T. and Sheridan, J. T., "Photopolymer holographic recording material," Optik **112**(10), 449–463 (2001).

[32] Gambogi, W. J., Weber, A. M. and Trout, T. J., "ADVANCES AND APPLICATIONS OF DUPONT HOLOGRAPHIC PHOTOPOLYMERS," Proc. SPIE **2043**, 2–13 (1994).

[33] Bruder, F.-K., Deuber, F., Facke, T., Hagen, R., Hönel, D., Jurbergs, D., Rölle, T. and Weiser, M.-S., "Reaction-diffusion model applied to high resolution Bayfol HX photopolymer," Proc. SPIE **7619**, 76190I (2010).

[34] Liu, S., Gleeson, M. R., Sabol, D. and Sheridan, J. T., "Extended model of the photoinitiation mechanisms in photopolymer materials," Journal of Applied Physics **106**(10), 104911 (2009).

[35] Friedrich-Karl Bruder, Johannes Frank, Sven Hansen, Alexander Lorenz, Christel Manecke, Richard Meisenheimer, Jack Mills, Lena Pitzer, Igor Pochorovski, and Thomas Rölle., "Latest Bayfol HX® developments: ultrahigh index modulation and NIR recordable holographic films," Proc. SPIE **11788**,117880B (2021).

[36] Bruder, F.-K., Fäcke, T., Hansen, S., Manecke, C., Rewitz, C., Rölle, T., Orselli, E. and Wewer, B., "On the impact of incoherent pre-exposure on vHOE recording in Bayfol HX film for see-through applications," presented at Proc. SPIE, **10558**, 105580B (2018).

[37] Riva, G., Zanutta, A., Bruder, F.-K. and Bianco, A., "Tuning the Δn and scattering in Bayfol® HX based holograms," Optical Materials **109**, 110362 (2020).

[38] Xiong, L. W., Liu, S. H. and Peng, B. X., "Mechanism of hologram formation in dichromated gelatin with x-ray photoelectron spectroscopy," Applied Optics **37**(17), 3678–3684 (1998).

[39] Zanutta, A., Bianco, A., Landoni, M., Galli, P. and Muslimov, E., "Laboratory and on-sky evaluations of astronomical gratings with non-conventional designs," Proc. SPIE **11030**, 110300H (2019).

[40] Zanutta, A., Bianco, A., Insausti, M. and Garzón, F., "Volume phase holographic gratings for astronomy based on solid photopolymers," Proc. SPIE **9151**, 91515X (2014).

[41] Zanutta, A., Galli, P., Lorenzi, V., Molinari, E., Landoni, M., Righi, C. and Bianco, A., "New over-octave VPHG architecture for DOLORES spectrograph at TNG," Proc. SPIE **10706**, 107064W (2018).

[42] Haffert, S. Y., Harris, R. J., Zanutta, A., Pike, F. A., Bianco, A., Redaelli, E., Benoît, A., Maclachlan, D. G., Ross, C. A., Gris-Sánchez, I., Trappen, M. D., Xu, Y., Blaicher, M., Maier, P., Riva, G., Sinquin, B., Kulcsár, C., Bharmal, N. A., Gendron, E., et al., "Diffraction-limited integral-field spectroscopy for extreme adaptive optics systems with the multicore fiber-fed integral-field unit," Journal of Astronomical Telescopes, Instruments, and Systems **6**(4), 045007 (2020).

[43] https://www.tng.iac.es/instruments/lrs/grisu.html

[44] Benetti, S., Tomasella, L., Salmaso, I., Cappellaro, E., Turatto, M., Bianco, A., Zanutta, A., Landoni, M., Lorenzi, V., Fabrizio, L. D., Magazzu, A. and Poretti, E., "Classification of three type Ia SNe using the multispectral VPHG GRIS-U for DOLORES@TNG," Transient Name Server AstroNote **61**, 1 (2019).

[45] Zanutta, A., Landoni, M., Riva, M. and Bianco, A., "Spectral multiplexing using stacked volume-phase holographic gratings–I," Monthly Notices of the Royal Astronomical Society **469**(2), 2412–2422 (2017).

[46] Bianco, A., Zanutta, A., Landoni, M., Galli, P. and Righi, C., "Holographic diffraction gratings based on photopolymers: achieved results and new opportunities in astronomical spectroscopy," Proc. SPIE **10558**, 1055804 (2018).

[47] Bianco, A., Pariani, G., Aliverti, M., Zanutta, A., Arns, J., Pragt, J., Stuik, R., Middleton, K., Tosh, I., Dalton, G., Trager, S., Abrams, D. C., Aguerri, J. A. L., Bonifacio, P., Vallenari, A. and Carrasco, E., "VPHGs for WEAVE: design, manufacturing and characterization," Proc. SPIE **10706**, 107064X (2018).