Large-scale DCG transmission holographic gratings for astronomy

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ABSTRACT

The recent interest of the astronomer community for volume phase holographic gratings is directly related to the enhancement of spectrograph throughput since this kind of grating can rise higher diffraction efficiency. Indeed, dichromated gelatine technology has demonstrated capability for 70–90 % efficiency. From the heritage of several diffractive and holographic projects and applications, the Centre Spatial de Liege has recently decided to invest in the large-scale DCG grating technology. This paper will present the new facility which is now fully operational, its capability and first results obtained.

Keywords: dichromated gelatine, spectrograph, grating, holography.

1. INTRODUCTION

1.1. CSL background

The Centre Spatial de Liege (CSL) and the University of Liege have been involved in holographic R&D program since more than 20 years. Interferometry, recording materials, and optical elements have been extensively studied. Dichromated Gelatine (DCG) is worldwide recognized as the holographic material with the uppermost diffraction efficiency thanks to its capability to record the highest refractive index modulation. The authors started to investigate that material in 1990[1] in the field of holographic optical elements. Very efficient reflection and transmission holographic gratings were recorded.[2] Works are also conducted in the field of surface-relief gratings by recording on a photoresist material.[3] Polarizer gratings[2–4] and master gratings for embossed holography have also be made in small size.

CSL theoretical background in the field of diffraction gratings was related to polarization analysis in diffraction gratings. The theory from R. Petit and al.[5] is the most powerful base for computation of surface-relief gratings. In the field of volume gratings, the Kogelnik[6] theory of coupled-waves is still the most popular one. However, since the eighties, new grating properties were highlighted and required the use of vectorial theory instead of scalar theory. M.G. Moharam and T.K. Gaylord[7] were very successful in defining a rigorous vectorial extension of the well-known Kogelnik coupled-wave theory.

Nowadays, commercial softwares are available for analyzing volume gratings (i.e. G-Solver™). However, several labs preferred to write their own code based on the Rigorous Coupled-Wave Theory (RCWT) including recent numerical improvements[8] and the extension to surface-relief gratings.[9] This is the case of CSL and the University of Liege which are using the RCWT code since 1994. This powerful tool is very flexible to study specific gratings.

This CSL know-how in holography and DCG was estimated as a realistic starting point for a commercial activity in diffraction gratings. Our major threshold toward the market of Volume Phase Holographic Gratings (VPHG) was certainly the size and the quality criterion that is required.

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1.2. VPHG in astronomy

Since a few years, astronomers found several interests using VPHG's instead of ruled (surface-relief) gratings.[10] Their major advantage is the capability to reach higher diffraction efficiency with very low noise. The relative easiness of manufacturing (compare to ruling), and the flexibility for changing the line frequency are very attractive. Of course, recording several 100,000 lines on a substrate by a quick laser shoot seems much easier and faster than diamond-ruling each lines one by one !

The main drawback of VPHG is certainly related to its angular and spectral selectivities (Blaze), compared to ruled metallized gratings. The useful wavelength range for a fixed incidence angle is relatively shorter when the grating is depicting low index modulation. For that reason, the present technology requires the highest index modulation to be recorded on a DCG layer with optimized thickness to verify the maximum efficiency at the central wavelength of operation. Based on those considerations, KOSI[11] and RALCON[12] were the first companies to manufacture VPHG for astronomers. Some of those gratings are now successfully operating. However, their production size is limited to around 10 cm with further size extent to be expected.

It has to be noted that this selectivity consideration is due to the present spectrometer geometry. Indeed, by using a variable incidence geometry, diffraction can be tune along the superblaze curve which is broader and flatter than for ruled gratings.

Currently, the holographic recording of plane gratings requires a set-up with two interfering collimated laser beams. The realization of large collimated beams with high optical quality is challenging due to the optical elements size and weigh that must stabilized during the holographic recording. The required laser power is also demanding since spatial filtering must withstand a huge amount of energy. In order to reply to the astronomers request, CSL has investigated ways to find funding for large-scale VPHG facility.

The present minimum size needed by astronomers is around 20 cm of diameter. It is foreseen that, if this technology emerges, there will be a demand for larger scale gratings. For that reason, CSL has decided to consider the production of, at least, 30 cm diameter VPHG. Thanks to the Walloon Government and to the EGUNA Consortium,[13] the activity started on November 2000. The EGUNA Consortium is directed by the European Southern Observatory (ESO) and it is composed of several world leading astronomic Institutes. Now, this feasibility project is reaching its end. Encouraged by the first results, we are going into production.

2. CSL FACILITIES AND SET-UP

Facilities have been scaled to accommodate blanks up to 40 cm × 40 cm. The DCG coating machine can hold 50 cm × 70 cm flat glass. Optical quality is obtained on 40 cm × 60 cm. Gelatine layers from 5 μm up to 25 μm when dried can be coated with 2 μm peak to valley deviation over the full surface.

Recording is performed on a 1.5 m × 5 m optical bench. The laser source is an argon laser Innova Sabre$^{\text{TM}}$ TSM 25 from Coherent, which can deliver 4.8 watts at 488 nm. The set-up geometry is shown in figures 1 and 2. The argon laser beam comes up from a hole drilled into the table center. It is splitted in two beams having the same intensity and polarization (not mandatory). They are then filtered with pinholes holding out high energy. To ensure homogeneous illumination in the sample area, beams are broadened nearly twice the useful diameter. Two off-axis parabolic mirrors collimate the useful beams. Their clear aperture diameter is 41 cm with a focal length of 200 cm. To adjust illumination angle, two flat mirrors with 38 cm clear aperture diameter fold the beams. Thus, the fringe frequency can be changed continuously from 315 lp/mm (figure 2(a)) up to 3300 lp/mm (1500 lp/mm shown in figure 2(b)). Higher frequency could, of course, be recorded in DCG layer. For this latter case, the recording set-up should include large-scale prisms for increasing the beam angle inside optical media.

Due to edges diffraction, the requested optical quality for recording beams is achieve on a diameter up to 35 cm.

The development laboratory is set up with thermostated baths. Inner baths are 53 cm × 65 cm. Forced convection oven with interior dimensions 80 cm × 60 cm × 50 cm dries the developed holograms.

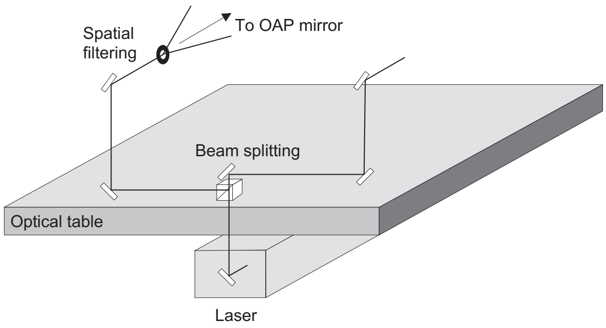
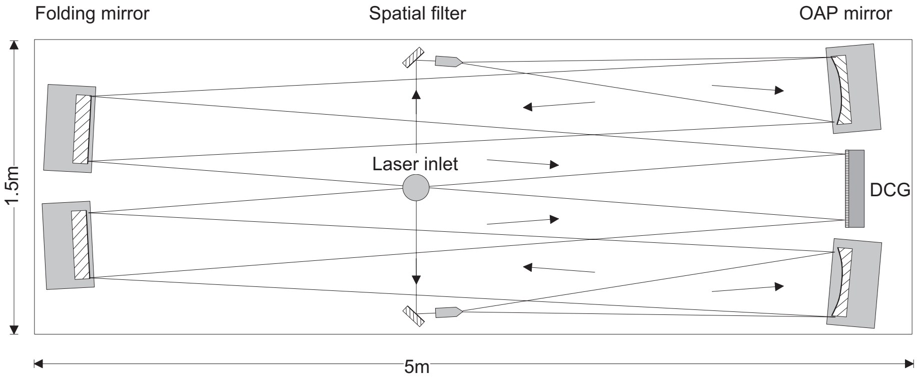
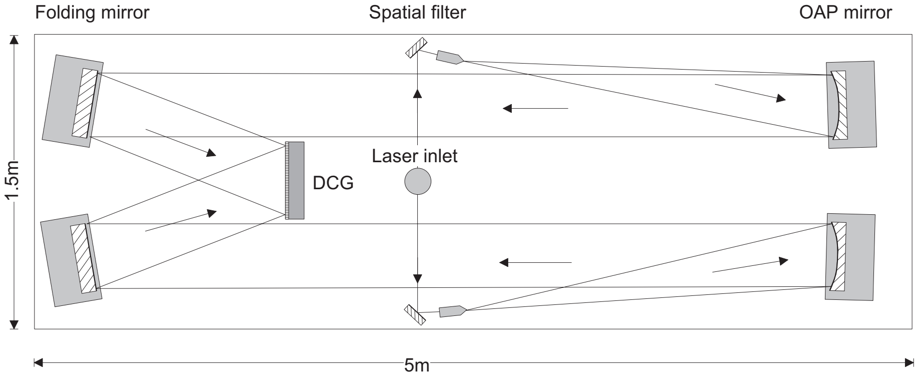


Figure 1. Holographic recording set-up geometry. Perspective view.



(a) Fringe frequency 315 lp/mm



(b) Fringe frequency 1500 lp/mm

Figure 2. Holographic recording set-up geometry. Top view.

These three laboratories, i.e. coating, exposure and development, are air conditioned in both temperature and hygrometry. Following the technical heritage of CSL in space optical payload qualification, laminar fluxes maintain laboratories as clean rooms of class 100.

3. METROLOGY AND CERTIFICATION

Our goal is to control each process steps to produce very high quality holograms. Therefore, metrology and certification take an important part of our effort.

Dry gelatine thickness is measured with a fiber spectrometer according to parallel and perpendicular coating axis. This technic allows a 1 mm spatial resolution and 0.1 μm in thickness. Thus, we make sure there is no unwanted waves nor tilt in the gelatin layer and we certify specifications before recording the hologram.

Recording setup geometry is tuned by theodolite measurement and autocollimation. OAP's position is checked by large (85 mm apperture) shear plate and interferometry. During recording, phase compensation is activated by a piezoelectric transducer, locking fringe position at the recording location.

Diffraction efficiency and diffracted phase are monitored over the full hologram surface by the use of an interferometer. The later is installed directly after one of the spatial filter as shown in figure 3. The diffracted beam is retro-reflected by a flat mirror placed behind the hologram. Thus, we are exactly in the same conditions as during the recording. To correct the phase from distortion introduced by the whole system, we subtract the phase recorded without any sample.

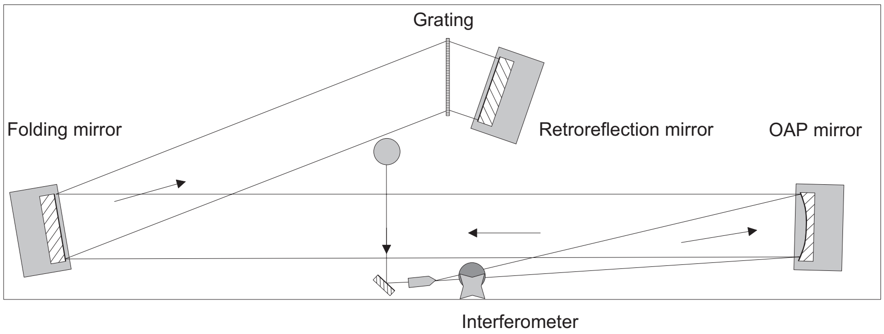


Figure 3. Diffraction efficiency and phase measurement setup.

The diffraction efficiency map is measured by blocking the reference beam of the interferometer. Thus, we record an image diffracted back and forth by the hologram.

Diffraction efficiency according to the incidence angle can be measured at several wavelengths: 488, 514, 546, 633 and 780 nm.

We use an optical fiber spectrometer to measure Blaze and superblaze curves into the wavelength ranges of 350–800 nm and 380–1050 nm. Hologram most representative positions could be chosen thanks to the information coming from the diffraction efficiency map.

With the use of our own RCWT code, experimental data permit to interpolate blaze as well as superblaze grating characteristics. The hologram index modulation and mean refractive index are accessible by that way. As we will see in the next section, this software allows us to extrapolate spectral behavior such as the blaze and superblaze profile at wavelengths out of the spectrometer range.

4. PRODUCED GRATINGS

Our first produced VPHG's were ordered by ESO. They consist of four 140 mm × 150 mm gratings with 850 lp/mm (blaze angle = 18.4° in air), 740 nm central wavelength, and range of use from 620 nm to 860 nm define as the FWHM of blaze profile excluding surface losses. Simulations done with our RCWT program indicate that these properties could be achieved with a gelatine thickness around 12 μm for 0.03 index modulation.

Making these gratings starts with the coating of the right gelatine thickness. Example of thickness measurements done on a produced gratings is presented in figure 4. Means are 12.1 μm for each directions, with 0.4 μm standard deviation over 200 data points.

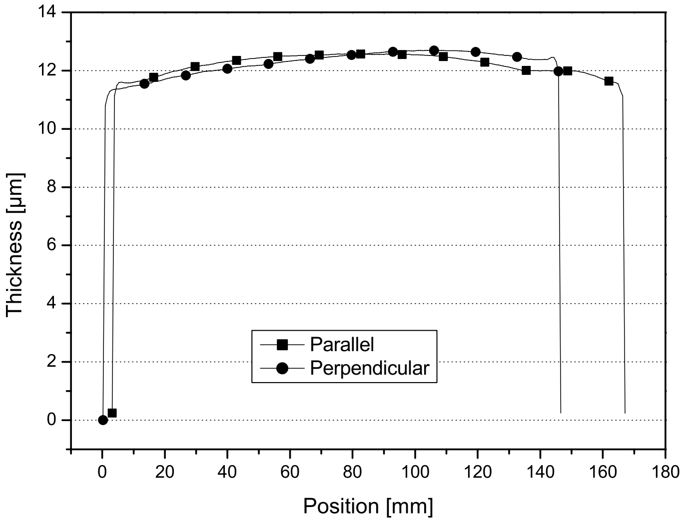


Figure 4. ESO VPHG thickness measurement.

Diffraction efficiency measured according to incidence angle at 633 nm is shown in figure 5. The laser beam is polarized along TE and is 1 cm diameter. The mean loss over all angles is 14 % and is mainely due to air–glass interface back reflection. This loss have been added to data in order to compare them with RCWT simulation. Bragg angle is measured to be 15.75°. Transpose to 740 nm, the Bragg angle is 18,5°. The diffraction only reaches 54 % at 633 nm but, measured at 780 nm and along TE, this grating has 98 % diffraction efficiency (7.4 % reflection loss) and only 1 % remaining in the Bragg zero order.

Theoretical curve is drawn over experimental data in figure 5. Best fit parameters are: thickness $= 12,5$ μm, index modulation $= 0.035$, fringe frequency $= 850$ lp/mm. Using the same parameters, we can extrapolate the angular selectivity of this grating for other wavelengths (figures 6) or calculate blaze and superblaze (figures 7). This latter extrapolation shows we are slightly overmodulated since superblaze curves for TE and TM polarizations cross at 850 nm. Nevertheless, we still into specifications for 740 nm.

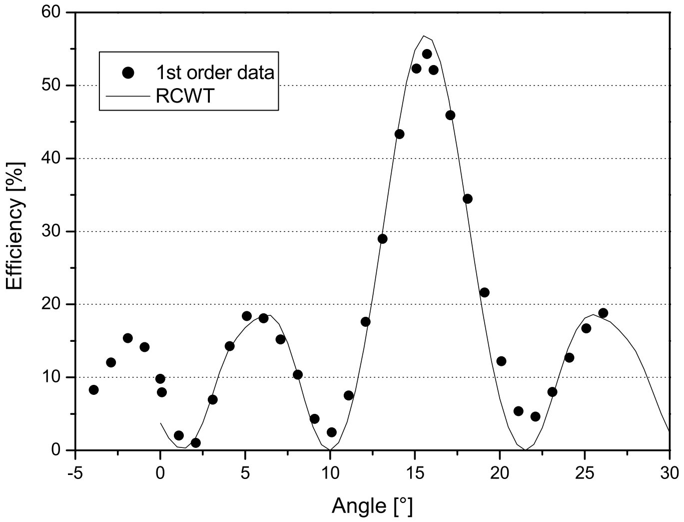


Figure 5. ESO VPHG diffraction efficiency according to incidence angle at 633nm (TE polarization). Comparison between experimental and theoretical data.$d = 12.5\mu\text{m}$, $\Delta n = 0.035$

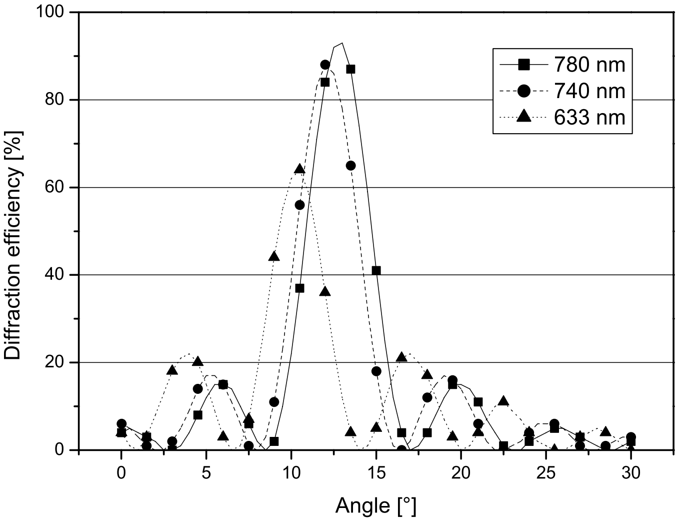


Figure 6. RCWT extrapolation of ESO VPHG angular selectivity for several wavelengths. $d = 12.5\mu\text{m}$, $\Delta n = 0.035$, TE polarization.

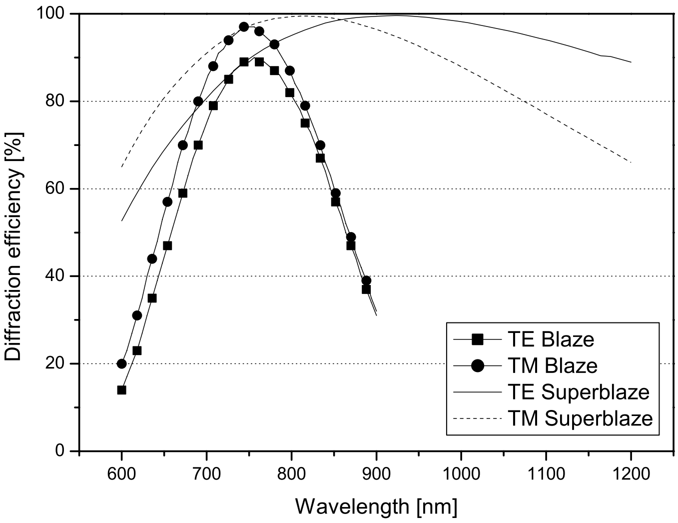


Figure 7. ESO VPHG blaze and superblaze simulation. $d = 12.5\mu\text{m}$, $\Delta n = 0.035$.

5. SCHEDULE AND COMMERCIAL START-UP

We are currently manufacturing the remaining VPHG's for the other members of the EGUNA Consortium. These grating specifications are:

- 140 mm × 150 mm, blazed at 510 nm with 1240 lp/mm.
- 200 mm × 211.5 mm, blazed at 880 nm with 740 lp/mm.
- 190 mm × 215 mm, blazed at 700 nm with 1000 lp/mm.
- 202 mm × 282 mm, blazed at 410 nm with 1200 lp/mm.
- 350 mm × 350 mm, blazed at 500 nm with 1000 lp/mm.

This project success and the astronomer further interest decide us to generate a spin-off company for end 2002. The main product of that spin-off will be large-scale VPHG's but further applications are expected (holographic optical elements, ion-etched holographic surface-relief gratings, ...).

Moreover, Walloon government has decided to renew their trust in our ability since a new grand has been allowed to pursue our researches and investigate the areas of mosaic gratings, echelle gratings, HOE's, ...

6. CONCLUSIONS

This paper summarized CSL activities in the field of Volume Phase Holographic Gratings for the Astronomer Community. Facilities are now fully operational and first VPHG's ordered by astronomers have been delivered. Production is mastered and we now focus on characterization setup to ensure a still better quality.

With the demonstration of grating size in the range of 30 cm diameter, CSL expects to quickly generate a commercial interest.

After the present R&D phase, the technological knowledge will be transferred to a new commercial company with core business in the field of holographic optical elements, including gratings.

7. ACKNOWLEDGEMENTS

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