Mosaiced and high line frequency VPH gratings for astronomy

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ABSTRACT

To increase the size of the volume phase holographic gratings the Centre Spatial de Liège can produce, mosaic technic has been tested and characterized. This method consists of assembling VPH gratings recorded and processed independently into one larger grating. By this way, the final grating size becomes virtually unlimited and dispersive elements can accommodate the largest telescope beams.

The second research line about VPH gratings was the high line frequency domain: $\nu > 3000\,\mathrm{lp/mm}$. Actually, for these frequencies, diffraction according to TE and TM modes is maximum for different wavelengths. However, it is possible to tune the index modulation to three times what is usually required to use the first diffraction TE peak. In this case, the second TE maximum matches the first TM maximum and unpolarized light is so entirely diffracted.

This article also summarizes our prospects in the field of very high index modulation gratings where Δn as high as 0.14 has been reached; cryogenic temperature operation for which we have demonstrated our VPH gratings stand -180°C without any Blaze modification; and wavefront correction by post-polishing to minimize diffracted beam aberrations. With this latter technique, $\lambda/6$ wavefront over 10 cm diameter has been obtained in the first trial.

Keywords: dichromated gelatine, spectrograph, grating, holography.

1. INTRODUCTION

Volume phase holographic gratings are now well known by the astronomer community. Their many advantages over classical surface relief gratings make them the best choice for VIS-NIR spectrometer dispersor.[1,2] The new instrument generation fully uses all the possibilities of VPH gratings as superblaze, Littrow configuration or grism.[3,4] But, designers would like to increase both size and dispersion of their very next spectrometers, pushing always further the limits of what manufacturers can do. So, even our large-scale VPH facility,[5] where 380 mm of diameter gratings can be produced, begins to be too small to accommodate the demand and we were looking for new technical solutions.

Within this situation, the NOAO has funded CSL through a technological project to demonstrate the very large size VPH grating feasibility as well as the benefit of high line frequency gratings ($\nu > 3000$ lp/mm). Aims of this running contract are:

- The fabrication of either monolithic and/or mosaiced large format, dichromated gelatine, VPH grating having dimensions of up to 500 by 1000 mm.
- The fabrication of dichromated gelatine, VPH grating with line frequencies of 3000 to 3500 lp/mm and first order peak diffraction efficiency in both polarization states of grater than 60% in the 400 to 600 nm wavelength regime for a 200 by 400 mm elliptical aperture on the grating.

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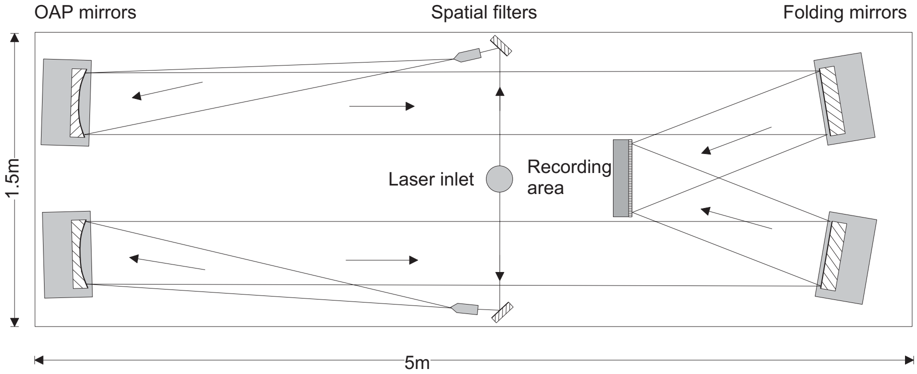
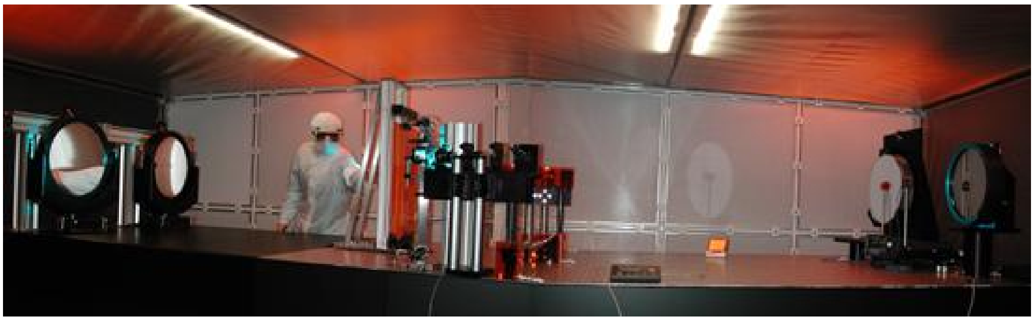
2. MOSAICED GRATING

The initial purpose of our facility was the production of large size monolithic VPH gratings for astronomy spectrometers. By year 2000, and according to astronomer's prospects, the gratings size has to be at least 300 mm of diameter. However, larger the optics of the recording setup, higher their price and harder it is to stabilize them at an acceptable level for interferometry. Moreover of the mirrors direct cost, larger optics require more laser power to illuminate the whole hologram surface. All weigh up, we bought two 395 mm clear aperture out of axis parabolic mirrors (OAPs) to collimate beams from a 25 watts Coherent Innova Sabre laser.

The recording setup geometry is shown in figure 1(a) and a picture is presented in figure 1(b). The folding mirrors are flat and slightly larger than the OAPs to compensate their tilt geometry. The argon laser is used as monomode and locked by its Fabry-Perot internal cavity. The 488 nm light goes through spatial filters and polarizers before being spread out twice the OAP surface to ensure uniform illumination over the recording area.



(a) Set-up geometry. Fringe frequency 1500 lp/mm.



(b) Set-up picture.

Figure 1. Holographic recording set-up.

Due to the optical table width (1.5 meter), blanks size that the recording setup can accommodate without encroaching on the collimated beams is 420 mm. Larger blanks can be used, but this will reduce the beam diameter. Nevertheless, this can be compensated by beams ovalization when casted to the recording holder for some line frequency.

It has to be noted that this setup is not proprietary to dichromated gelatine but can be used for holographic recording onto other medias as photopolymers, photoresine, silver halogenure emulsions, ... In a same way, the setup can be used for recording holographic mirrors or holographic optical elements (HOEs).

The largest monolithic VPH gratings we did by now were two 380 nm diameter gratings for gOlem, Osservatorio Astronomico di Brera (Italy). Their specifications were:

- 'Brera Blue' line density ≈ 1200 lp/mm, central wavelength = 475 nm;
- 'Brera Red' line density ≈ 500 lp/mm, central wavelength = 850 nm.

Blanks were float glass squares of 400 mm side. A picture of one of those gratings can be seen in figure 2 where the light from an halogen lamp is diffracted to a screen.

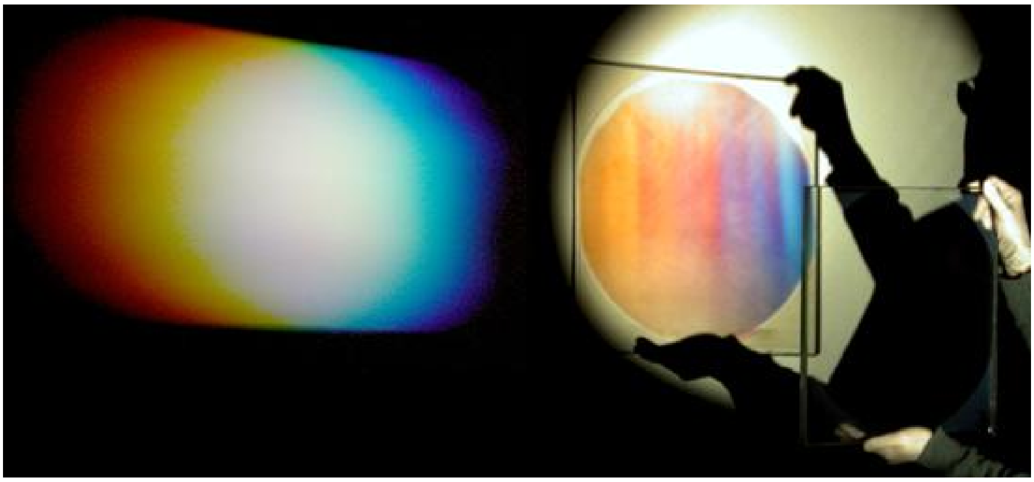


Figure 2. Picture of a 380 mm diameter grating produced by CSL.

But, whatever the size of the facility, it will always be limited and this will restrain the instrument designer creativity. To overcome this problem, we have tested the mosaic technic which consists to assemble several gratings recorded and processed independently.

Challenges are mosaic sub-elements have to diffract at exactly the same angle and efficiency, which means gelatine layer thickness and index modulation have to be perfectly tuned to produce the same Blaze and superblaze element to element. Assembly technic, for it, must minimize edge diffraction and shading as providing fine alignment of the gratings ensuring diffraction to the same direction.

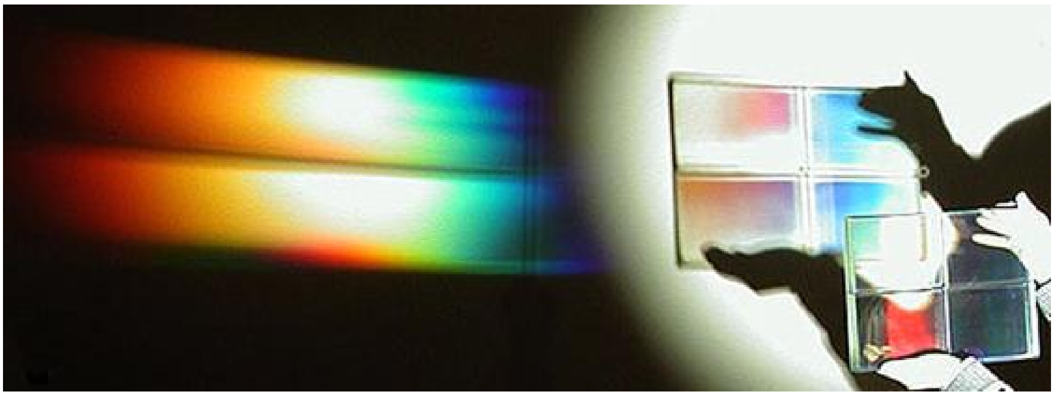


Figure 3. Picture of a 340 × 240 mm, 2 × 2 elements mosaic VPH grating produced by CSL.

Two mosaics have been produced for the NOAO, both constituted of four elements. Total size is 240×340 mm. Sub-element orientation have been ensured during the encapsulation process by monitoring the diffracted pattern of an extended HeNe beam. Diffraction picture of such a mosaic VPH grating is shown in figure 3.

3. HIGH LINE DENSITY VPH GRATING

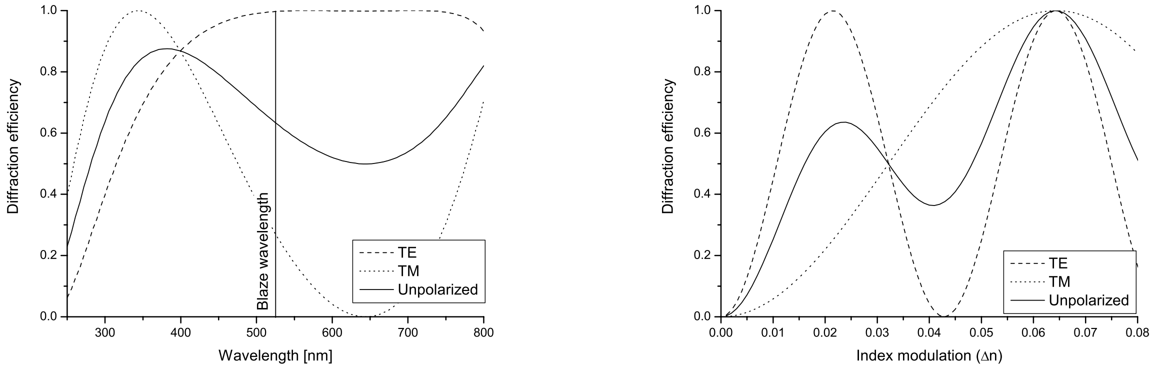
The second research line interesting astronomers was the domain of high line density VPH grating, that is to say, gratings with fringes frequency higher than 3000 lp/mm. Indeed, the light dispersion increases with the grating line frequency:

$$d\theta/d\lambda = m\nu/\cos\theta\ .$$

where θ is the angle of diffraction measured in the medium, λ is the light wavelength and ν the grating fringes frequency.

This is so attractive to increase the number of lines per millimeter when using the grating as a dispersive element. But the grating efficiency should not be traded off.

Now, for frequencies ranging from 300 to 2000 lp/mm, TE and TM diffraction mode can be maximized for the same wavelength. Unfortunately, for higher line frequencies, diffraction according to TE and TM is maximum for different wavelengths and so, unpolarized light can not be fully diffracted. This phenomenon is simulated by rigorous coupled wave calculation at figure 4(a) where the index modulation has been chosen such as TE is at its first maximum (see figure 4(b)). For unpolarized light, the efficiency reaches only 63% for the 525 nm central wavelength.



(a) Superblaze. $\Delta n = 0.021$.

(b) Efficiency at 525 nm according to index modulation.

Figure 4. RCW diffraction efficiency calculation of a high line frequency VPHGs. Parameters are: $\nu = 3300$ lp/mm; $d = 10\mu\text{m}$; $\lambda_0 = 525$ nm.

Still, by tuning the index modulation to *three times* what is required to use the first diffraction TE peak, the second TE maximum matches the first TM maximum as it is shown in figure 4(b). For these parameters, it is possible to obtain a theoretical 100% diffraction efficiency for unpolarized light at the central wavelength.

Challenge for this kind of grating is to reach such a high index modulation without making the gelatine milky. CSL have successfully produced two 170 × 120 mm, 3300 lp/mm gratings without any visual scattering. An example of transmission spectrum is shown in figure 5 where RCW interpolation of both Blaze and superblaze is superimposed. Fitting parameters are: $\Delta n = 0.048$; $d = 12$ µm; $\nu = 3300$ lp/mm.

4. FURTHER PROSPECTS

In addition to the NOAO research project detailed in the previous sections, CSL has been active on various fields related to VPH grating for astronomy. Here is a summary of the subjects investigated.

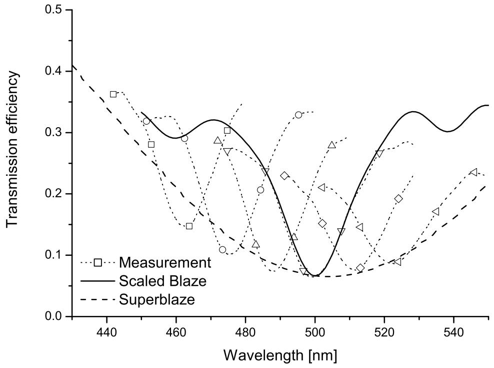


Figure 5. Transmission efficiency of a 3300 lp/mm VPH grating. Measurement at different incidence angles as well as Blaze and superblaze RCW interpolation.

4.1. High index modulation

For spectrometer applications, the most important parameter after diffraction efficiency and dispersion, is the wavelength bandwidth of the grating. For thick gratings,[6, 7] the coupled wave equations predicts this bandwidth is inversely proportional to the grating thickness. Since the efficiency is proportional to both thickness and index modulation ($\Delta n \times d$), one solution to have a broad bandwidth and a high diffraction efficiency is to induce a large index modulation in a thin gelatine layer.

The gelatine index modulation is linked to its processing, we have improved our method by a better thermal control of the development bathes and so reached the highest index ever. We have obtained a 80 × 80 mm VPH grating with 2.9 µm gelatine thickness and a *modulation of 0.14* as calculated by RCW. Scattering, often present into highly modulated gelatine, is not visible with naked eyes in our sample. Figure 6 shows the zero order transmission efficiency of this grating according to the wavelength. Measurements are interpolated by RCW calculation and scaled to take losses (mostly reflection) into account.

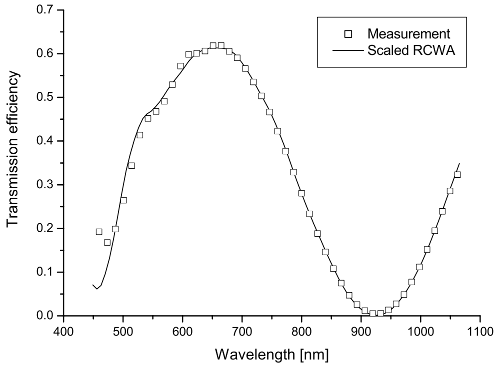


Figure 6. TE transmission efficiency measurement and RCW interpolation. Calculation parameters are: d = 2.9 µm; $\Delta n = 0.14$; $\nu = 1555$ lp/mm.

4.2. Cryogenic behavior

The astronomical infrared (IR) domain of observation is currently surfing on the top of the wave. Potential for organic molecules detection is one of the reasons why this wavelengths region is so attractive. Not to be blinded by instrument radiations, IR spectrometers have to operate at cryogenic temperature (around 100°K). In order to propose VPH gratings as IR dispersive element, CSL has developed and tested gratings that stand and perform at low temperatures.

'Low temp' samples were made by changing slightly the development process, raising the oven temperature to ensure a complete solvent evaporation. The gelatine layer was sandwiched between 3 mm thick and 8 × 8 cm glass plates. The stack is fitted together with optical glue standing up to cryogenic temperature. In order to fit into the measurement range of our spectrometer, the Bragg wavelength was not set in the IR but in the visible which do not influence the cryogenic certification at all.

The cryogenic measurement setup, showed in figure 7, is constituted of a vacuum vessel with two wide glass windows and a liquid nitrogen coil which cools down the sample mount. Sample is inserted between two coper plates that ensure thermal conductivity. Four thermocouples are fixed in different locations to measure the sample temperature. A fiber spectrometer records the sample zero order spectrum through the vessel windows. A rotating stage allows to change the incidence angle. Measurement spot size is around 1 cm in diameter.

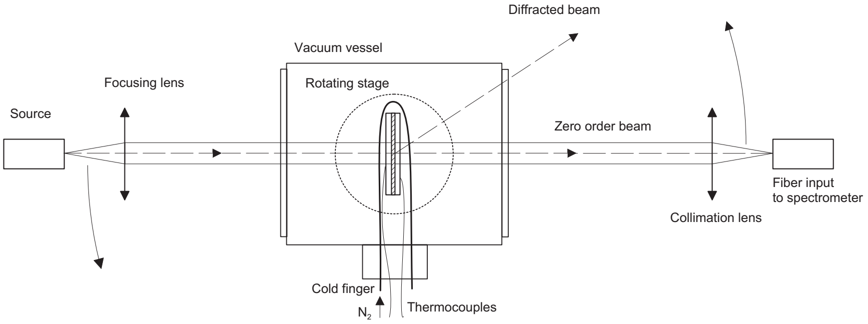


Figure 7. Cryogenic setup sketch.

To make sure the grating could physically stand cold temperatures, we have taken pictures of the grating before cooling it down. After 1 hour at -180°C (93°K), absolutely no visible defect was observed on the sample (i.e : no crack, scattering, spot, milkiness, . . .).

Afterward, we have measured the Blaze of a new sample at various temperatures: ambient (22°C), -50°C, -100°C, -150°C and -180°C. Then, we have let the sample 6 hours at -180°C and warmed it up before measuring the Blaze once again at ambient temperature.

Measurements displayed at figure 8 show Blaze curves recorded at various incidence angles before cooling and at -180°C. An undirectional deviation of less than 5% is to notice. It stands within the measurement uncertainty: rotating stage repositioning within 0.5°, thermal dilatation of the sample mount, source spectrum change, . . . So, the efficiency does not significantly decrease during nor after the grating cooling and, even more important, Blaze as superblaze curves remain the same.

It remains to conduct thermal cycling experiment to ensure there is no long term damage. Blank quality could also be an issue if their thermal dilatation coefficient is very different from the gelatin or the glue. Finally, we also have to test the wave front distortion when the grating is subjected to cryogenic temperature.

4.3. Post-polishing

Wavefront flatness can be mandatory for some applications, especially in new spectrographs which intend to be diffraction limited instruments, or in space based missions. These high stringent observatories need dispersive elements with distortion less than $\lambda/4$.

Several factors influence the diffracted wave front from a VPH grating element:

- the gelatine thickness homogeneity,
- the recording setup alignment,

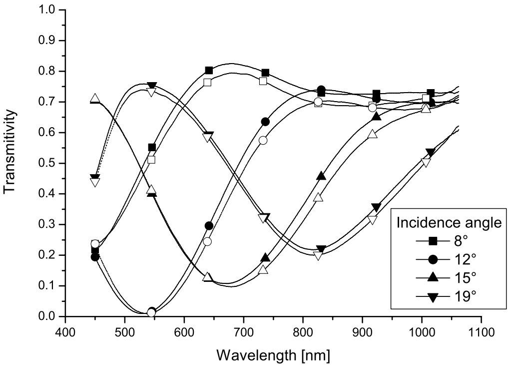


Figure 8. Comparison between zero order spectra recorded at 22°C (solid symbols) and -180°C (hollow symbols) for various incidence angles.

- the blank and cover homogeneity as their outer face flatness,
- the gelatine tension during processing,
- shrinkage of the optical cement used to glue the grating cover.

The three first parameters are very well mastered and are no more major sources of wavefront distortion. However, the gelatine and optical cement shrinkage during their process can not be avoided. Their combination can lead, on large VPH gratings, to wavefront error of several wavelengths. One solution is to post-polish the blanks after the VPH grating has been encapsulated.[8]

The VPH grating wavefront error can be a complex function without any symmetry. This is rather difficult to correct by conventional polishing. So, we have chosen to use ion beam figuring technique where an ion gun projects particles to the blank which etches the glass.[9] Time the ion beam stays on a blank location is calculated according to the measured wavefront and ablation profile. Thus, the right amount of material is removed.

It has to be noted that a VPH grating act as an hologram (diffractive element) and not like a conventional lens (refractive element). The diffracted beam has a reconstructed wavefront depending of the recording beams geometry. Changing the light entrance side or the Bragg angle sign, will determine which beam is reconstructed and thus, the amplitude and/or the sign of the diffracted wavefront error will change.

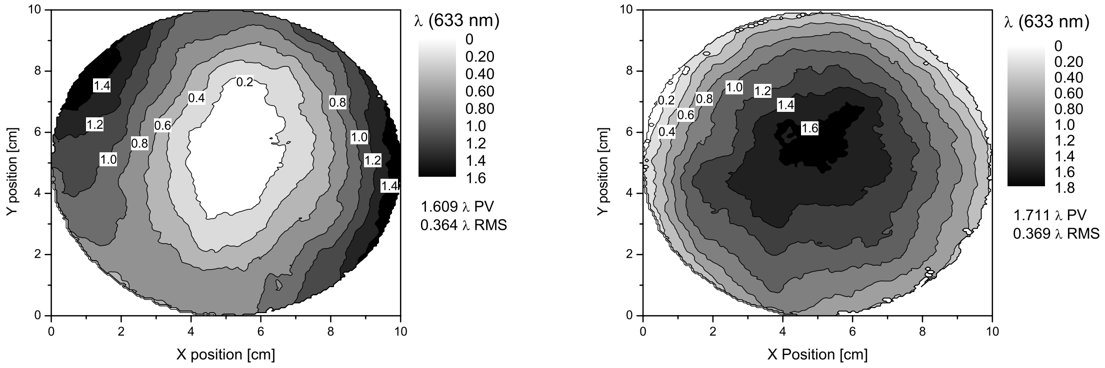
This characteristics is shown in figures 9, where are reproduced two Zygo interferometer measurements. For both figures, the laser beam coming from the Zygo is diffracted by the VPH grating, then is retro-reflected by a mirror ($\lambda/20$) to be one more time diffracted to the interferometer. From figure 9(a) to 9(b), the entrance side of the laser beam has changed and so the sign of the wavefront error.

This symmetry specificity must be taken into account for the wavefront correction but also when the VPH grating is used. To pinpoint this behavior, we post-polished one outer face of the grating introduced into figure 9. Figure 10 shows that the diffraction from one direction is now flattened to $\lambda/6$ (figure 10(a)). But, in the same time, the wavefront diffracted to the other direction is deteriorated to 0.7λ RMS (figure 10(b)).

The post-polishing technique is very effective to correct the VPH diffracted wavefront. However, care must be taken to use the VPH grating with the right orientation. Otherwise, rather than to benefit from a corrected wavefront, this latter is twice distorted.

5. CONCLUSIONS

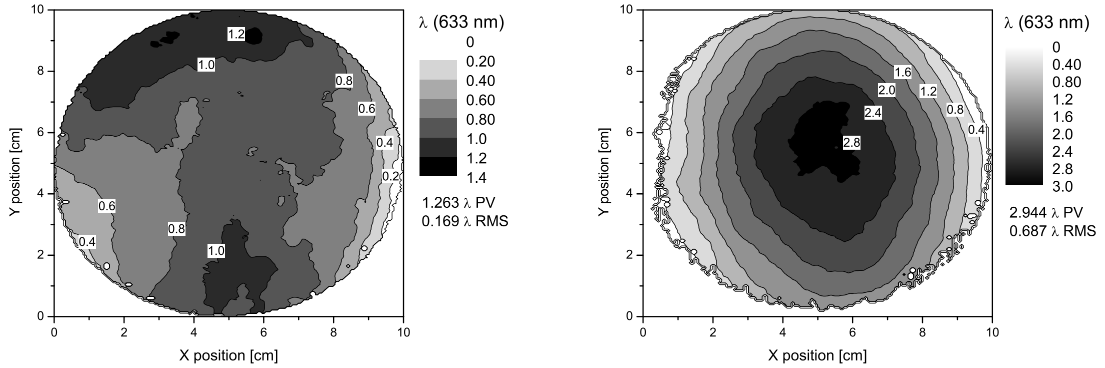
This paper summarized CSL activities in the field of Volume Phase Holographic Gratings for astronomers. We detail the research project funded by the NOAO for mosaiced gratings and high line density. In both cases, we succeed to make VPH gratings that fulfill the requirement.



(a) Laser beam entering face A to B.

(b) Laser beam entering face B to A.

Figure 9. Diffracted wavefront error according to the grating orientation.



(a) Laser beam entering face A to B.

(b) Laser beam entering face B to A.

Figure 10. Diffracted wavefront error according to the grating orientation after beam figuring.

Mosaic grating are made by assembling altogether several gratings recorded and processed independently. They have to match the same Blaze curve and be aligned strictly to diffract the same wavelength into the same direction. Using this technique, the setup size does no more matter and VPH gratings can be as large as wished. CSL has successfully made two 340 × 240 mm, 2 × 2 elements mosaics delivered to the NOAO.

High line density gratings ($\nu > 3000$ lp/mm) are attractive since higher line per millimeter means higher dispersion. Problem comes from the diffraction efficiency: for such a line density, diffraction maximum occurs at different wavelengths and angles for TE or TM polarizations. Solution lies in the index modulation: when this latter is three times what is normally requested to have a diffraction maximum into the TE mode, both polarizations have their diffraction maximum at the same wavelength and angle. Thus, theoretical efficiency for unpolarized light can be 100%. Two 3300 lp/mm VPH gratings, 170 × 120 mm with diffraction efficiency higher than 80% have been produced.

Other research fields tackled are the high index modulation, cryogenic behavior and post-polishing. The highest index modulation we did induce into the gelatine by now is 0.14. This is on a 2.9 µm thick gelatine layer since, thinner the DCG layer, higher can be the modulation.

About the cryogenic temperature, measurements done on our 'low temp' samples showed these VPH gratings stand easily -180°C and, moreover, there is no Blaze nor efficiency fluctuation during nor after the cooling.

To correct the diffracted beam wavefront error, VPH grating post-polishing by an ion beam figuring has been tested. Diffracted wavefront has been corrected from $\lambda/3$ to $\lambda/6$ over 10 cm diameter. For a first trial, it is a heartening success. We draw attention to the fact wavefront restoration applies only for one specified orientation. Used in the wrong orientation, the grating induces twice the error. This is due to the diffractive nature of the VPH gratings.

6. ACKNOWLEDGEMENTS

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