Diffracted wavefront measurement of a volume phase holographic grating at cryogenic temperature

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Flatness of the wavefront diffracted by grating can be mandatory for some applications. At ambient temperature, the wavefront diffracted by a volume phase holographic grating (VPHG) is well mastered by the manufacturing process and can be corrected or shaped by postpolishing. However, to be used in cooled infrared spectrometers, VPHGs have to stand and work properly at low temperatures. We present the measurement of the wavefront diffracted by a typical VPHG at various temperatures down to 150 K and at several thermal inhomogeneity amplitudes. The particular grating observed was produced using a dichromated gelatine technique and encapsulated between two glass blanks. Diffracted wavefront measurements show that the wavefront is extremely stable according to the temperature as long as the latter is homogeneous over the grating stack volume. Increasing the thermal inhomogeneity increases the wavefront error that pinpoints the importance of the final instrument thermal design. This concludes the dichromated gelatine VPHG technology, used more and more in visible spectrometers, can be applied as it is to cooled IR spectrometers. © 2006 Optical Society of America

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1. Introduction

Modern spectrometers are designed more and more often with a volume phase holographic grating (VPHG) as a dispersive element.[1–3] This is due to the intrinsic advantages of this technology over classical grooved gratings. Actually, VPHGs are extremely sturdy: they can be cleaned in the same way conventional optics are, they have demonstrated efficiency capabilities very close to 100%, and the superblaze property allows us to access a large domain of the spectrum.[4,5] In spite of their effectiveness even in the far infrared, their actual use is restricted to spectrometers running at ambient temperature. This is because of the lack of knowledge of their behavior in cooled instruments as in IR spectrometers.

In a general way, producing a VPHG involves a sensitive layer (dichromated gelatine, photosensitive polymer, or resin) coated on a substrate.[6] Recording is made by the holographic method where two light beams coming from a single laser cross each other inside the media (volume), interfering and producing dark and bright fringes. Chemical reactions, depending on the nature of the sensitive layer, occur and convert the intensity pattern into refractive index modulation (phase). Some media require a chemical development process to enhance the modulation.

Light going through a VPHG experiences diffraction due to the bulk refractive index modulation pattern, which modifies the optical path. No absorption (amplitude) modulation is required. This gives rise to their original and useful properties cited above.

To protect the optical layer from further environmental aggressions, the active layer is often encapsulated with optical glue and a hard transparent cover. So, the final element is a stack of several materials enclosing the thin grating. This could suggest a concern that in a VPHG, differential thermal contraction might bend the whole system and induce large wavefront error.

New applications and instruments are always more demanding in terms of efficiency, size, bandwidth, wavefront, thermal behavior. In previous papers, we have presented our facility, which allows for the manufacturing of monolithic VPHGs with diameters up to 35 cm.[7] We have introduced the mosaic technique, which consists of assembling various elements recorded and processed independently to make larger gratings.[8] We, as other authors, have investigated the diffraction efficiency and wavelength according to temperature down to cryogenic liquid nitrogen.[9–13] Recently, we have analyzed the wave-

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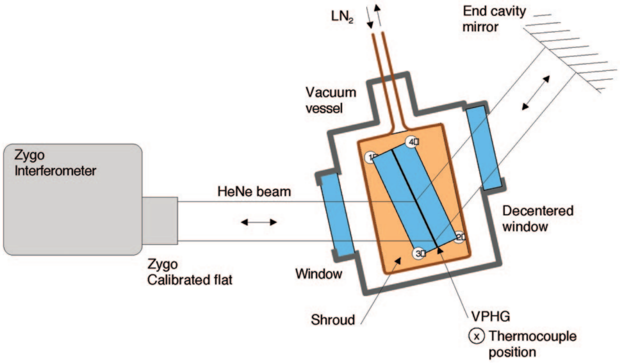


Fig. 1. (Color online) Low temperature wavefront measurement setup.

front diffracted by VPHGs and used a postpolishing technique to correct and shape its form as wished.[14] Now, to qualify VPHGs for cooled infrared spectrometers requiring diffracted limited optics, this paper will focus on the diffracted wavefront measured at low temperatures.

2. Setup and Measurements

The VPHG we produced for this specific experiment was made using dichromated gelatine technology.[15] It is a 15 cm × 16 cm grating diffracting 95% at 633 nm with a Bragg angle of 25°. Blank and cover are both 15 mm thick BK7 glass, polished at better than $\lambda/4$. Manufacturing details can be found elsewhere.[8]

The Zygo interferometer with a 10 cm of diameter HeNe beam that is presented in Fig. 1 constitutes the measurement setup. The grating is enclosed in a vacuum vessel closed by two polished BK7 windows. The cooling is ensured by a copper shroud outside which a copper coil is brazed. Liquid nitrogen flows inside the copper coil to cool the VPHG. No contact is made between the shroud and the grating so the latter is cooled by radiation only. This ensures no strain is applied to the grating due to thermal contraction of the shroud. A multilayer insulating mattress surrounds the shroud to avoid thermal transfer to the vessel.

The Zygo 633 nm beam enters the vacuum vessel and is diffracted by the grating at 50°, twice the Bragg angle. Leaving the vessel, the beam is retroreflected by a $\lambda/20$ polished mirror. Thus before reentering the interferometer, the beam is diffracted a second time by the grating. In our previous paper, we have demonstrated that this geometry does not compensate for the grating wavefront error but doubles its value as for classical optics.[14]

The temperature is recorded by four thermocouples. They are positioned at each corner of the grating and alternately on both sides to check the thermal homogeneity. Thermal stabilization is achieved by regulating the liquid nitrogen flow.

Wavefront of the beam going through the whole system without any grating (i.e., two vessel windows plus the end of cavity mirror) has been measured at a working internal vessel pressure lower than 1 mb. A wavefront error of 0.26λ p.v. and 0.046λ rms mostly due to astigmatism is to be reported.

The diffracted beam wavefront was recorded at various temperatures and temperature homogeneities. In Fig. 2, four Zygo interferometer measurements are reproduced. The beam shape is not perfectly round due to baffling by the shroud and vessel windows. At higher temperature inhomogeneities [Fig. 2(d): $\Delta = 20$ K], a dark parasite interference fringe furthermore reduces the observable region. Hopefully, this does not prevent the drawing of conclusions.

3. Discussion and Conclusions

First, it has to be noted that the grating has to perfectly withstand various thermal cycling down to the temperature of 133 K. Neither glass breaking, glue delamination, nor shift of the blaze curve is to be reported. The initial cooling speed was about 10 K/min. The maximal thermal difference we have induced between the blank sides was 30 K. These values are several times what is commonly met in IR spectrometer instruments. So VPHGs comply with their working strains.

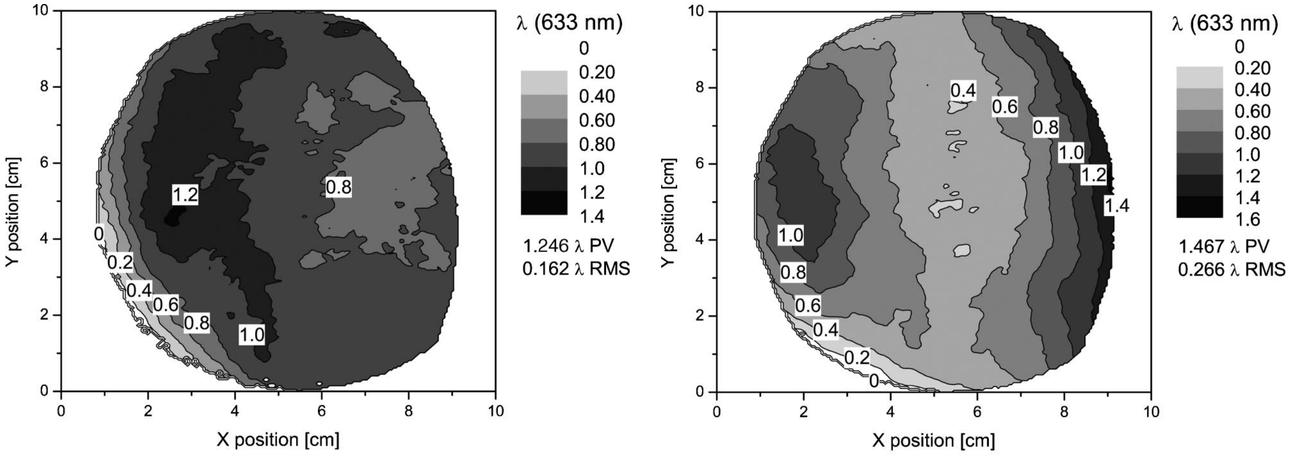
About the wavefront, whatever the temperature, the error induced by the VPHG is several times what is measured without it. So, the system error will be ignored. Comparing Figs. 2(a) and 2(b) show that, as soon as the cooling starts, a distortion is induced. However, the error increases only in a very moderated proportion since the peak to valley starts from 1.24λ to reach 1.46λ, less than 20% higher.

After this initial deformation, the wavefront error remains stable as long as the temperature inhomogeneity does not increase. This is pinpointed by Figs. 2(b) and 2(c), where the temperature decreases from 264 to 150 K with a thermal inhomogeneity nearly identical. The wavefront error remains constant, and its shape is comparable. Plotting the peak-to-valley wavefront error of our various measurements according to the temperature but at constant temperature inhomogeneity gives a nearly horizontal straight line as shown by Fig. 3.

On the other hand, when the thermal inhomogeneity increases, the wavefront error increases dramatically. This is shown in Fig. 4 where a difference of 20 K between the sides of the grating has increased the peak-to-valley wavefront error to higher than 3λ, even though the analyzed area is reduced [see Fig. 2(d)].

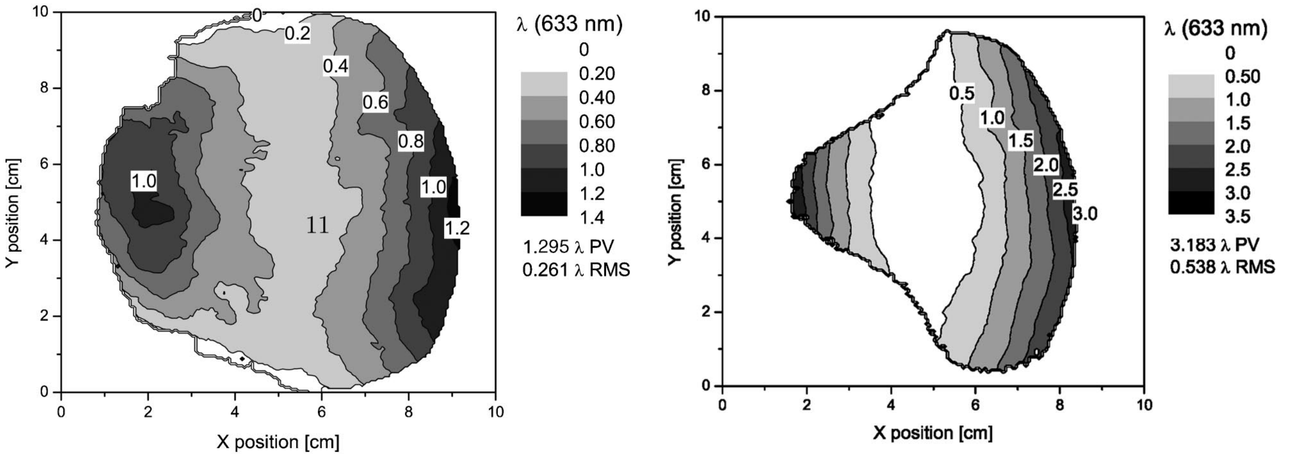
All these measurements allow for the conclusion that the bending of the wavefront during the cooling is mainly due to the thermal inhomogeneity over the VPHG volume. Compared to that effect, the differential contraction of the various layers is negligible on the wavefront error. This is a very important observation, since the thermal homogeneity of a grating can be mastered by a good instrument design. Typical values seen in cooled spectrometers are of 5 K per 100 mm; this is about what our grating has experienced in Figs. 2(b) and 2(c).

Because of their unique properties, VPHGs prom-



(a) ambient temperature: 295 K, $\Delta = 0.1$ K.

(b) 265 K, $\Delta = 6$ K.



(c)

(d)

Fig. 2. Diffracted wavefront error recorded at various grating temperatures and temperature inhomogeneities.

ise to have a bright future in various applications requiring a dispersive element. Until recently, the wavefront error diffracted by those gratings could be a problem for diffraction-limited instruments. We have shown previously that a postpolishing technique can be applied to correct or shape the wavefront, sweeping up this restriction.[14] We have also shown that the blaze, the diffraction efficiency spec-

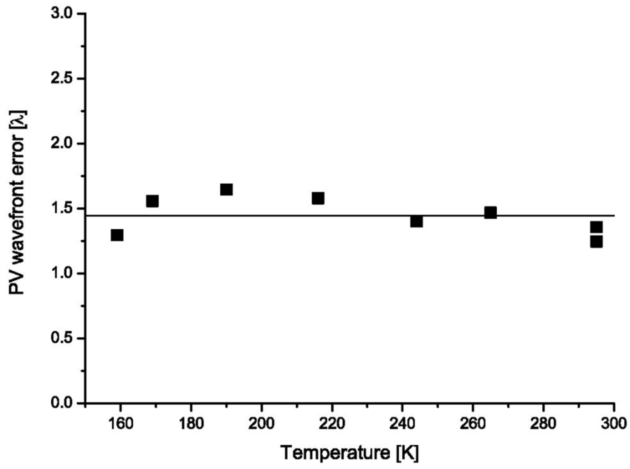


Fig. 3. Peak-to-valley wavefront error according to the temperature at constant temperature inhomogeneity.

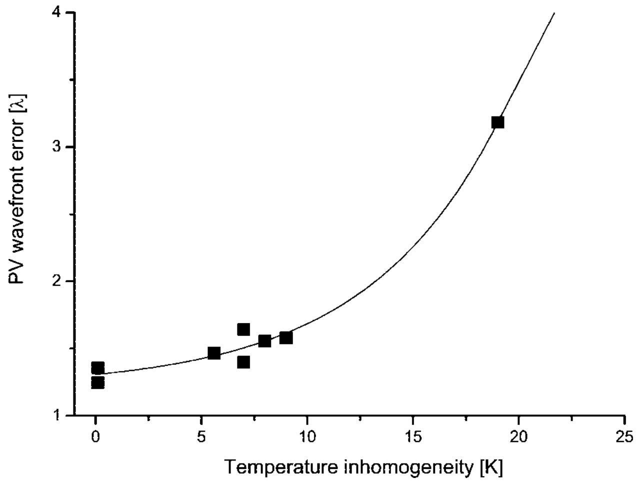


Fig. 4. Peak-to-valley wavefront error according to temperature inhomogeneity.

trum, is almost not modified between ambient and liquid nitrogen temperatures.[9]

In this paper, we demonstrated the wavefront error of a beam diffracted by a VPHG at the typical working temperatures of cooled spectrometers is about the same as at ambient temperature. The major factor influencing the wavefront error is the temperature inhomogeneity and not the temperature by itself. All the pieces are so gathered together to implement a gelatin VPHG into a cooled infrared spectrometer.

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