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BULK SILICA NIR BLAZED TRANSMISSION GRATINGS MADE BY SILIOS TECHNOLOGIES

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ABSTRACT

In order to study the dark universe (energy and matter), EUCLID space mission will collect near infrared spectra and images of millions of galaxies. This massive measurement survey requires a slitless spectroscopic channel including GRISMs (for "Grating pRISMs") in NISP (Near Infrared SpectroPhotometer). Very special technical specifications are required for the grating manufacturing: large aperture, low groove frequency and blaze angle, line curvature. In addition, it has to withstand space environment. Therefore, in the frame of a R&D project funded by the CNES, we developed bulk silica gratings in close collaboration with the French company SILIOS Technologies. SILIOS delivered two resin-free blazed gratings with curved lines engraved directly into the fused silica substrate of 80mm and 108mm useful aperture. At LAM, we measured very high optical performances of these prototypes: >80% transmitted efficiency, <30nm RMS wavefront error, groove shape and roughness very close to theory and uniform over the useful aperture. In this paper, we give specifications of these gratings, we describe the manufacturing process developed by SILIOS Technologies, we present briefly optical setups and models allowing optical performances verifications at LAM and we show very encouraging results obtained on the two gratings.

Keywords: Grating, Resin-free, Ion etching, Masking photolithography, Wavefront correction, High Efficiency

I. INTRODUCTION

A. Brief scientific context

The dark universe is one of the hot topics of astrophysics. To unravel mysteries of dark matter and dark energy, astrophysicists need millions of galaxies infrared spectra and images. These massive measurement surveys require new space instrument concepts including slitless spectroscopic channel with GRISMs (for "Grating pRISMs", see section B).

For instance, four GRISMs mounted on a motorized rotated wheel are designed for the NISP (Near Infrared SpectroPhotometer) instrument of the Euclid space mission selected by ESA in 2011 and foreseen to be launched in 2020.

B. What is a GRISM?

A GRISM[1] is a combination of a blazed transmission grating and a prism. It allows combining image and spectroscopy of the same field of view with the same optical system and detector, thus simplifying the instrument optical concept. Indeed, the prism angle and the height of the grating grooves (or "blaze angle") are defined such that at a selected wavelength we obtain the maximum transmitted efficiency in the not deviated beam direction.

The layout presented in **Fig. 1** describes roughly the optical function of a GRISM.

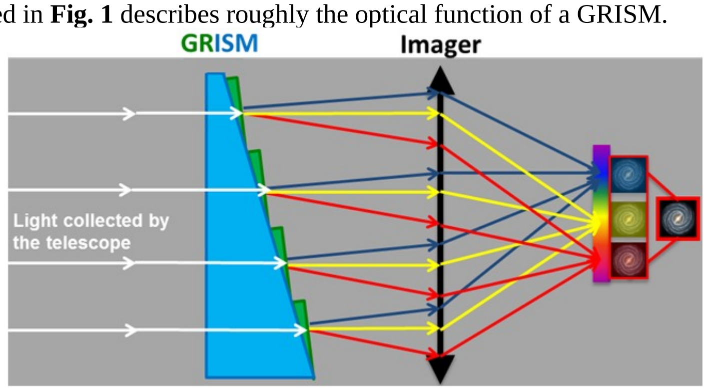

Fig. 1. Layout of GRISM optical function.

When the GRISM is not in the collimated beam coming from the telescope, high resolved images of all observed objects in the field of view are obtained on the detector. Introducing the GRISM on the beam disperses the light of each object and spectra are imaged on the same detector and at the same position for one chosen wavelength (represented by the yellow beam on this layout).

C. *Technical context and objectives of our project*

Since 2010, in the frame of an R&D project funded by the CNES, several grating manufacturing processes have been studied at LAM (see [2], [3], [4] and [5]). Now LAM is responsible for NISP GRISMs opto-mechanical development.

For these GRISMs, very special specifications are required for the grating manufacturing: large useful aperture (>100mm), low groove frequency (<30g/mm), small blaze angle (<3°) and, last but not least, line curvature allowing wavefront correction.

Laser writing photolithography can reach these requirements as demonstrated in the frame of the Euclid project [5]. This method consists in writing the grating line by line into a photosensitive resin.

However, in space instruments, GRISMs are subject to environmental stresses and the use of resins may not be suitable. Indeed, observation in the near infrared requires a nominal operating temperature of the optical system less than 150K. Differential thermal expansion coefficient between glass prism and resin grating at cryogenic temperatures could cause some issues. The worst case is a delamination of the resin layer, particularly in case of such large optics (140mm diameter). In any case, the substrate deforms and generates hardly predictable and measurable optical aberrations. Moreover, the properties of this resin in terms of outgassing caused by space vacuum, resistance to cosmic rays and high-energy electromagnetic radiations and ageing are largely unknown and difficult to characterize.

Therefore, still in the frame of this R&D project, the objective is to develop and validate a method for producing bulk silica GRISMs which consequently will withstand extreme conditions of space environment without problem but also satisfy our technical specifications. Another advantage of resin-free gratings is the potential extension of the operating spectral range where resins transmission is low.

For this purpose, the experience on grating optical characterizations acquired by LAM is well combined with advanced manufacturing techniques controlled by SILIOS Technologies; a French company specialized in micro structured optics. Two resin-free blazed gratings with curved lines engraved directly into the fused silica substrate with respectively 80mm and 108mm useful diameter were delivered by SILIOS.

The grating specifications, the SILIOS manufacturing process and the LAM optical verifications tests are summarized in this paper since it is detailed in [6] about the first 80mm grating. Here, we focus on comparing manufacturing precisions and optical performances measured on both gratings to define the effects of increasing the grating dimensions.

II. RESIN-FREE GRATINGS DESCRIPTION

The specifications for both gratings are based on EUCLID NISP GRISMs requirements. High efficiency in the first diffraction order (>72%) on a large spectral bandpass (1100 to 1457nm), medium spectral dispersion coefficient (500) and wavefront correction (<30nm RMS WFE) required lead to very special technical specifications for the grating manufacturing: large useful aperture (136mm), low groove frequency (19.3g/mm or 51.84µm period), small blaze angle (3.1°) and line curvature (the grating is defined as a “binary 1” optical surface in the NISP Zemax model with 20 coefficients for the phase map equation).

Fig. 2 shows side and face layouts of both gratings with dimensions required and a picture of the real 80mm diameter grating manufactured by SILIOS.

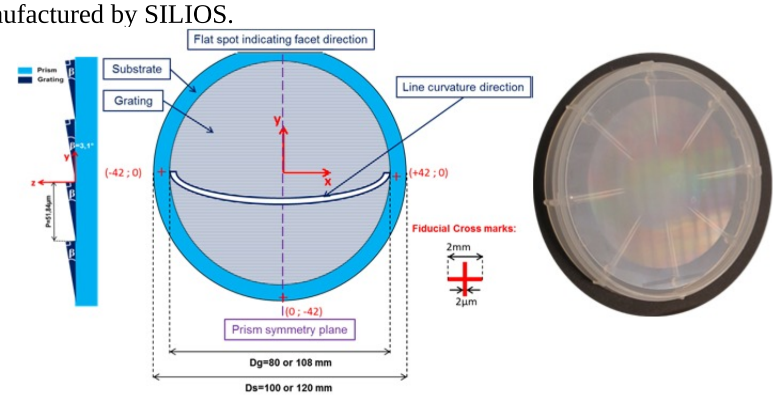

Fig. 2. Gratings side and face layouts with dimensions required (left) and photo of the real 80mm diameter grating manufactured by SILIOS.

Only the clear aperture diameter of 136mm required for NISP GRISMs is not applied for these gratings. We developed two prototypes with respectively 80mm (standard size) and 108mm diameter (thanks to mechanical adaptions on SILIOS facilities).

Other mechanical and optical modifications of SILIOS setups will allow the manufacturing of a full size GRISM for EUCLID/NISP, that is a 136mm diameter grating engraved on a 140mm diameter prism.

III. SILIOS GRATING MANUFACTURING PROCESS

SILIOS Technologies SA ([7]) is a French company expert in passive micro-structured optics. SILIOS takes benefit from the semiconductor manufacturing facilities, processes and methods to produce its optical components in clean room (ISO 5 to 3). The main part of its products is diffractive optics like our gratings manufactured using a cumulative etching technology.

The cumulative etching technology allows reaching multilevel stair-like topologies. The technology is based on successive masking photolithography and reactive ion etching (RIE) steps (i.e. successive etching steps through resin masks). The cumulative etching of N mask levels allows reaching depth profile discretized over 2^N steps. The whole grating is engraved at the same time resulting in a very high uniformity of the groove profile over the useful aperture.

The photolithography tool is a contact photo-masker with an UV400 source. The reachable critical dimension (smallest lateral feature size) is about 2 µm. The groove period required for our grating is 51.84µm so it can be divided into 25 steps maximum measuring 2.07µm width. Therefore, five masks are needed for our gratings and 25 levels are used over the 32 discretization levels available. The groove angle required is 3.21° corresponding to 2.79µm groove height so each individual step of the groove slope is 112nm high.

Two main manufacturing inaccuracies can lead to distortion of the groove profile, thus to the reduction of the grating efficiency: inaccuracy on the etched depths and inaccuracy on the alignment of each mask pattern with the others.

The etching accuracy on each depth level has to be much lower than the smallest step (112nm in our case) to avoid strong distortion of the profile. To control the depths, several test patterns are positioned all around the grating useful aperture on each mask (see Fig. **3** left). These patterns are measured using a contact mechanical profilometer and the depth for one mask is updated from the previous mask measurement. Specific fused silica processes have been developed by SILIOS during the past 10 years to obtain an etching accuracy in the range of +/- 5 to 10nm insuring a very small groove profile deviation from specification.

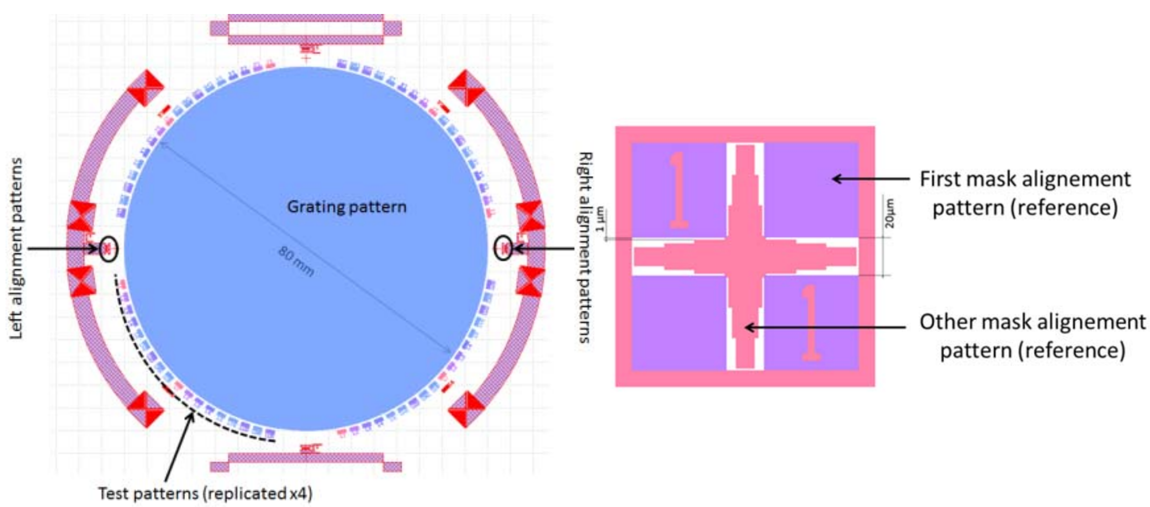

Fig. 3. General masks design (left) and zoom on one alignment pattern (right).

The inaccuracy on the alignment of each mask pattern with the others is potentially a much bigger source of grating transmitted efficiency decay. Misalignment in between masks levels produces unwanted hollows or bumps located on the edges of the steps. During the photolithography process, each mask is aligned relatively to the first mask used thanks to specific patterns (see Fig. **3**, right) engraved on the left side and on the right side of the grating. Relative position from mask to mask is measured with an optical microscope. Precision on our grating is within ±0.5µm required except for one level of the 108mm diameter grating (0.8µm) but the impact on optical performance is acceptable.

IV. GROOVE PROFILE VERIFICATION

The interferential microscope Wyko NT9100 is used to measure the groove profile and the facet roughness on several locations of the two gratings clear aperture. Certified standards are used to verify measurements accuracy in the three directions. The grating tip/tilt is precisely adjusted so as to measure groove dimensions directly on original data without post processing.

Fig. **4** shows the groove profile measured on each grating (right: 80mm, left: 108mm) on several locations indicated by the coloured diamonds on grating layouts.

First, these measurements show the high uniformity of the groove profile over the full aperture of both gratings. Second, the comparison between profiles dimensions of both gratings demonstrates the high level of repeatability of the cumulative ion etching process controlled by SILIOS.

In addition, groove dimensions lie very well within the specifications. Groove period is 51.75±0.15µm on the 80mm grating and 51.9±0.15µm for the 108mm grating to be compared to 51.84µm (19.29l/mm) specified. Groove depth is 2.85±0.15µm on the 80mm grating and 2.9±0.15µm on the 108mm grating.

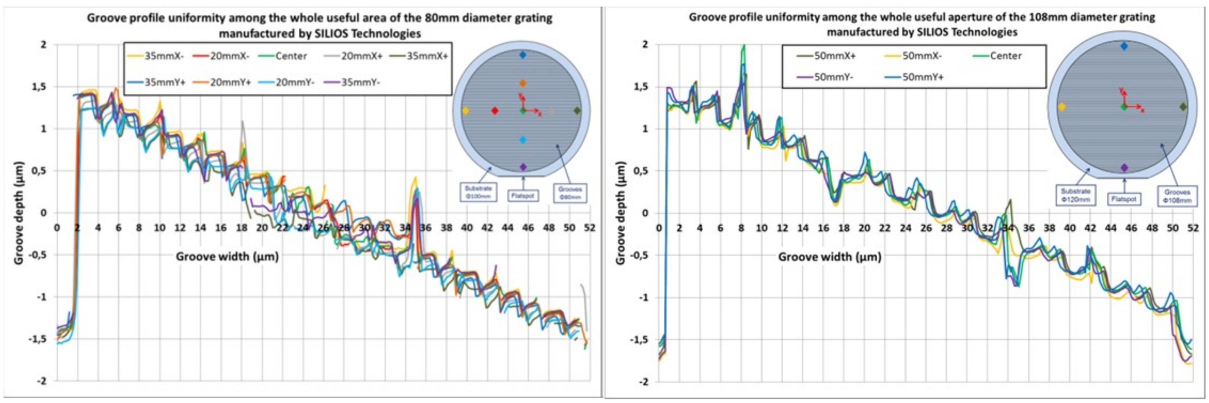

Fig. 4. Groove profile measured on several locations (indicated by coloured diamonds on the grating layout top right) on the 80mm and 108mm diameter gratings useful area.

The groove angle is 3.3±0.15° for both gratings, to be compared to 3.21° required. The effect on optical performances should be a spectral bandpass slightly shifted towards higher wavelength in the first order. This is confirmed by efficiency measurements presented on Fig. **7** in section V.

Fig. **5** shows one groove facet measured on a 94x51µm² area on both gratings. We are interested in the RMS roughness of the facet inducing efficiency decrease and straylight into the optical system. The groove facet is more irregular on the 108mm grating than on the 80mm inducing probably slightly more straylight. This optical characterization will be done later since we foresee to update our visible goniophotometer for near infrared measurements.

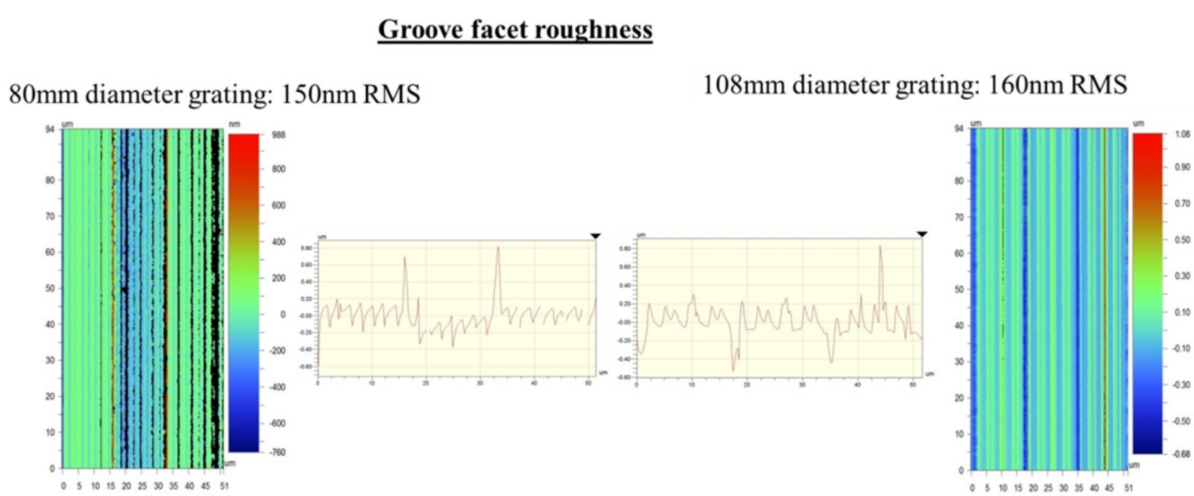

Fig. 5. Facet roughness measurement on one groove facet of both gratings.

V. SPECTRAL BANDPASS AND TRANSMITTED EFFICIENCY VERIFICATION

The measurement setup is shown on Fig. **6**. We use a spectrophotometer (Perkin Elmer Lambda 900) as source and detector devices. Due to the deviation of the beam, we need an optical fiber kit to extract the light and reinject it into the spectrophotometer. Grating absolute efficiency is measured on several locations with a 20mm diameter collimated beam in orders 0 and 1 between 1100 and 1600nm (see [6] for details on this setup and the measurement method).

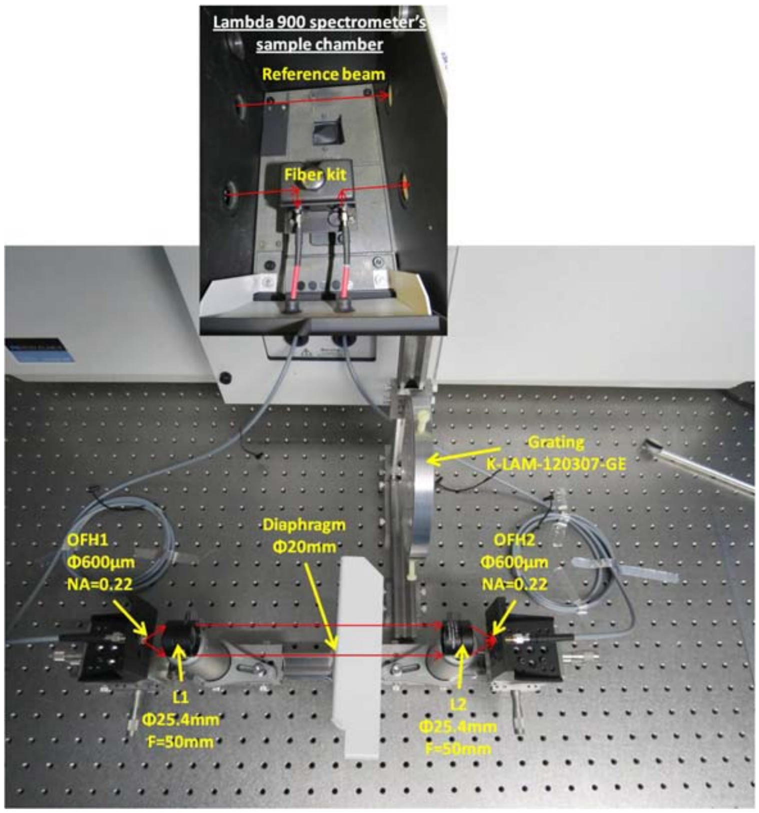

Fig. 6. Transmitted efficiency measurement setup.

We compare our transmitted efficiency measurement to theoretical calculations from the software PCGrate. PCGrate calculates efficiency performances for almost all types of gratings, solving equations of electromagnetic theory and taking into account all shapes of groove profiles, theoretical or measured.

We calculate the efficiency of our grating in all transmitted orders in the spectral band from 1000 nm to 1600 nm in the case of one particular groove measured and reproduced over all the clear aperture of the grating. This model gives relevant and precise results since the groove profile is very uniform (see Fig. **4**).

Fig. **7** shows transmitted efficiency measured in orders 0 and 1 (points) compared to PCGrate models (curves) for both gratings.

The grating is designed to have at least 72% efficiency in order 1 in the spectral bandpass from 1100nm to 1457nm, so blaze wavelength required is about 1250nm. Fig. **7** shows that these optical performances are completely fulfilled for both gratings even if the bandpass is 50nm shifted toward higher wavelength as predicted from the groove angle measured slightly higher than specified (see section IV).

We can see a very good adequacy between measurements and theory within ±3% only mainly due to our measurement error.

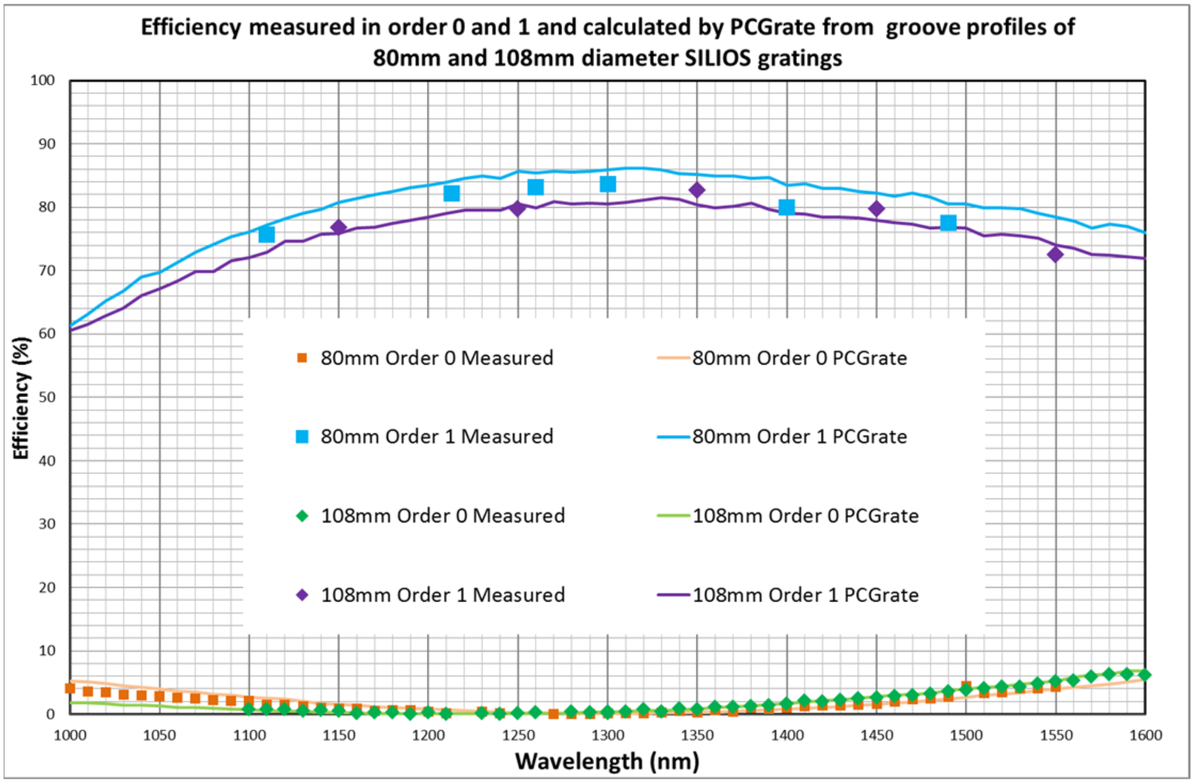

Fig. 7. Transmitted efficiency measurements compared with theory.

VI. TRANSMITTED WAVEFRONT CORRECTION

The grating line pattern is designed to correct some optical aberrations. We measure the transmitted wavefront in double pass with a collimated beam at 633nm in order 2 to have a maximum contrast. We compare our measurement to the theoretical transmitted wavefront of our grating calculated with the Zemax model of our setup. Measured and calculated wavefronts, represented by Zernike coefficients, are compared and RMS error is calculated.

The Fig. **8** shows the transmitted interferogram measured compared to the theoretical interferogram from the Zemax model for both gratings.

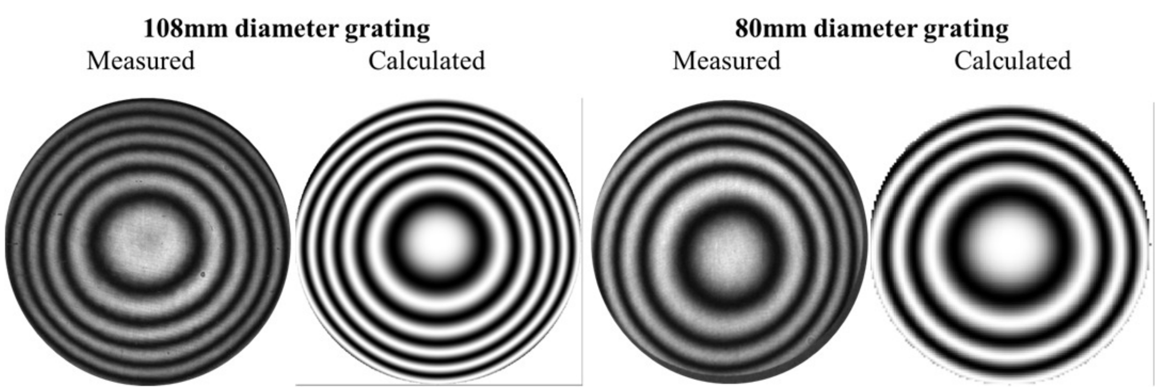

Fig. 8. Transmitted interferogram of both grating measured and calculated by the Zemax model.

Table 1 shows the comparison between our wavefront measurement and the one calculated with the Zemax model for both gratings. Delta is the difference between measurement and theory for each aberrations term. The residual total RMS error is only 8nm for the 80mm grating and 37nm for the 108mm which is slightly more than the 30nm RMS specified. The possible sources of error are cosmetics, line shape, deformation of the substrate during the manufacturing process and measurement errors.

Table 1. Comparison between wavefront measurement and theoretical one calculated with the Zemax model of the setup for both gratings.

	108mm Grating			80mm Grating		
	Order 2 Measured (nm)	Order 2 Zemax (nm)	Delta (nm)	Order 2 Measured (nm)	Order 2 Zemax (nm)	Delta (nm)
Total RMS	466.33	505.63		317.47	316.59	
Focus	-464.70	-499.86	35.16	-316.65	-313.7	3.0
X Astig 3	-33.42	-26.95	6.46	-18.60	-19.0	0.4
XY Astig 3	3.68	0.05	3.63	-1.46	0.0	1.5
X Coma 3	8.13	4.59	3.54	11.96	12.2	0.2
Y Coma 3	-0.16	-0.14	0.02	1.65	1.3	0.3
Spherical 3	-7.42	-1.32	6.09	-5.76	-1.3	4.4
X Trefoil 5	0.33	0.01	0.32	2.66	-1.6	4.3
Y Trefoil 5	-0.69	3.31	4.00	2.40	0.0	2.4
X Astig 5	1.99	2.16	0.18	-0.51	0.9	1.4
Y Astig 5	3.58	0.00	3.59	-0.89	0.0	0.9
X Coma 5	-10.80	-9.20	1.60	-3.42	-3.7	0.3
Y Coma 5	2.08	0.00	2.09	-0.38	0.0	0.4
Spherical 5	0.12	0.00	0.12	-0.89	0.0	0.9
X Tetrafoil 7	9.23	10.87	1.64	4.24	3.5	0.7
Y Tetrafoil 7	-1.92	0.11	2.03	0.89	0.0	0.9
Quadratic sum of all delta			**37**			**7.7**

VII. CONCLUSIONS AND PERPECTIVES

To conclude, SILIOS Technologies realized two high quality all-silica gratings thanks to an atypical manufacturing process combining masking photolithography and RIE. For the second prototype, SILIOS managed to increase the grating useful aperture up to 108mm diameter maintaining almost the same precision, uniformity and optical performances as the first standard size 80mm grating.

The high optical performances of both gratings were demonstrated by optical measurements and associated models done at LAM. Indeed, groove profile shape measured is well within the specified dimensions and very uniform over the clear aperture. This leads to high transmitted efficiency in the specified spectral bandpass. In addition, groove pattern has been successfully designed and engraved to obtain the required wavefront corrections within few tens of nm WFE.

In order to increase the grating size up to the 136mm diameter required for EUCLID/NISP, more important adaptations have been implemented by SILIOS, in particular the size of the insolation equipment of the photolithography setup and new substrate and mask holders. The final 136mm grating model will be delivered at the end of 2014 as a backup solution for EUCLID/NISP GRISMs.

At LAM, we are implementing new optical verification test setups aiming at measuring transmitted efficiency and wavefront on the full clear aperture of the grating as well as straylight in the NIR spectral bandpass.

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