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Abstract: **The ESA Euclid mission is intended to explore the dark side of the Universe, particularly to understand the nature of the dark energy responsible of the accelerating expansion of the Universe. One of the two probes carried by this mission is the Baryonic Acoustic Oscillation (BAO) that requires the redshift measurements of millions of galaxies. In the Euclid design, these massive NIR spectroscopic measurements are based on slitless low resolution grisms. These grisms with low groove density and small blaze angle are difficult to manufacture by conventional replica process. Two years ago we started a CNES R&D program to develop grism manufacturing by the photolithographic process which is well adapted to coarse gratings. In addition, this original method allows introducing optical aberration correction by ruling curved and non-parallel grooves in order to simplify the instrument optical design. During the Euclid Phase A, we developed several prototypes of gratings made by photolithography. In this paper, we present the optical performance test results, including tests in the specific environment of the Euclid mission.**

Keywords: grism; grating; photolithography; efficiency; wavefront correction.

I. INTRODUCTION

To understand the nature of the dark energy and dark matter, ESA selected in the fall 2011 the Euclid mission in the context of the Cosmic Vision program. Designed to tackle one of the most challenging questions of modern cosmology, the Euclid design is based on two primary probes: weak lensing (WL) and Baryonic Acoustic Oscillations (BAO). The BAO probe requires the redshift measurements of millions of galaxies to analyze their spatial distribution in the Universe. In the Near Infrared Spectroscopic Photometer (NISP) channel of Euclid, low resolution grism used in slitless mode have been selected to perform this massive redshift measurement. A grism wheel allows to remove the grism and thus to simply perform photometric imagery of the same field.

A grism [1-4] is a combination of a grating and a prism to make the light undeviated at a chosen wavelength. Usually, the sawtooth profile of a ruled master is replicated on the hypotenuse of a prism [5]. In the NISP design, the combination of low groove density (19.29 g/mm) and small blaze angle

(2.88°) makes the manufacturing of the master itself extremely difficult.

In January 2010, we started a R&D program funded by the Centre National d'Etudes Spatiales (CNES) to develop grism manufacturing by the photolithographic process [6,7] which is well adapted to coarse gratings. In addition, another advantage of this method with respect to conventional ones is its ability to write curved and non-equidistant grooves. Indeed, this allows to correct optical aberrations and thus to simplify of the NISP optical design.

First, we had to demonstrate the feasibility of making large diffractive elements like the 140mm diameter Euclid grism by photolithographic process. Second, we had to check that the optical performances of the grism, mainly efficiency and wavefront correction, remain unchanged in the NISP operational environment (T=100K). This paper describes the photolithographic process and the optical tests done on samples and on the full size prototype to demonstrate that we reached the Technical Readiness Level (TRL) 5 as required at the end of Euclid Phase B.

II. PHOTOLITHOGRAPIC FULL SIZE GRISM DEVELOPMENT

A. *The choice of the photolithographic process*

A grism is usually made by replication of a ruled master on a layer of resin deposited on the hypotenuse of a prism. The ruling technique works well for straight grooves and down to a groove density of 30 g/mm. Euclid grisms combine curved lines, low groove density (19 g/mm) and small facet angle (2°) which make it impossible to manufacture by usual methods whereas photolithographic process appears promising to overcome these Euclid grism manufacturing issues.

In the context of Euclid, the need of large pieces of optics (140mm diameter) led us to investigate the direct laser writing in photosensitive resin with the French company Kloé. Their custom-made photolithographic system is a mask less process based on a fixed laser source and two high precision (100nm) stages. It can write complex patterns on up to 305mm diameter substrates. In addition, Kloé masters all the process since they have also developed their machines and their own organic-inorganic hybrid materials synthetized by the Sol-Gel process.

B. Full Size prototype development phase

Before manufacturing the Euclid full size grating prototype on a fused silica substrate (Figure 1), Kloé produced small (20*20 mm) samples on thin (0.5 mm) glass substrates. The goal of these samples was to determine the required number of laser paths and exposure time per groove to produce sufficiently straight and low roughness facets.

In the Euclid optical design we took advantage of the interesting capability of photolithography to write curved and non-equidistant grooves. Indeed, this makes the grism able to introduce wavefront correction in the optical path, thus to simplify the optical design.

In March 2012, Kloé manufactured a full size grating prototype corresponding to the 1100-1400 nm NISP bandpass with the aberration correction specific to this channel. The term « grating » instead of grism is used since the groove pattern has been written on a plane-parallel plate and not a prism. This choice avoided the fabrication of a specific tilted mount for the pattern writing machine, thus shortening the manufacturing process. Using a prismatic substrate is included as the next step in the Euclid grism development plan. Figure 1 shows the 140 mm diameter grating prototype, with a 132mm clear aperture, average groove density of 15 g/mm (which was the specification at the moment of this R&D) and curved grooves.
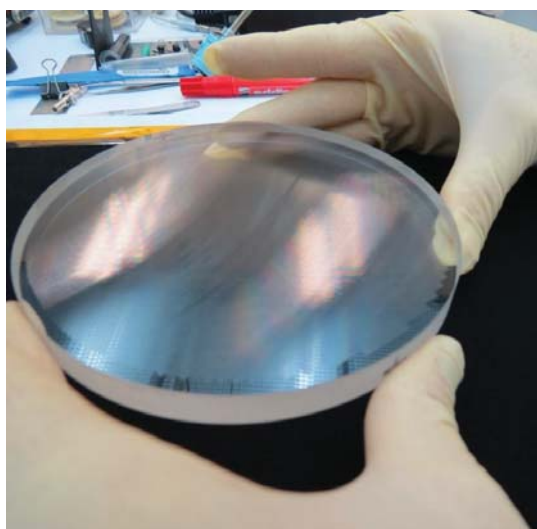

Figure 1.   140mm diameter full size grating (K-LAM-120307-GE).

C. Performances validation methodology

To validate optical performances of the grism, we focus on three main parameters: groove profile, diffraction efficiency, and transmitted wavefront quality, including aberration correction characteristics introduced by the curved lines. In addition, we verified the stability of these optical performance criteria in thermal and radiation environments relevant for the Euclid mission.

The transmission efficiency curve is measured in the first order of the grating with a Perkin Elmer spectrometer associated with a customized fiber fed optical bench. This measurement is compared to the theoretical efficiency curve calculated by the software PCGrate derived from the average groove profile measured with our interferential microscope Wyko NT9100. The efficiency curve of the full size grating was measured before and after 8 thermal cycles from 300K to 100K. In addition, the efficiency was measured for a small sample at 140K which is the operating temperature of Euclid grisms.

The transmitted wavefront is measured with a Fizeau interferometer with a 100mm diameter parallel beam. The measured Zernike coefficients are compared to those obtained by the Zemax model of our measurement setup. The wavefront measurement of the full size grating was performed before and after 8 thermal cycles from 300K to 100K.

III.   EFFICIENCY AND SPECTRAL BANDPASS VERIFICATION

A. Efficiency measurement

Figure shows the setup used to measure the efficiency of the full size gratings at room temperature (left) or at cryogenic temperature (only for small samples) with the cryostat (right).
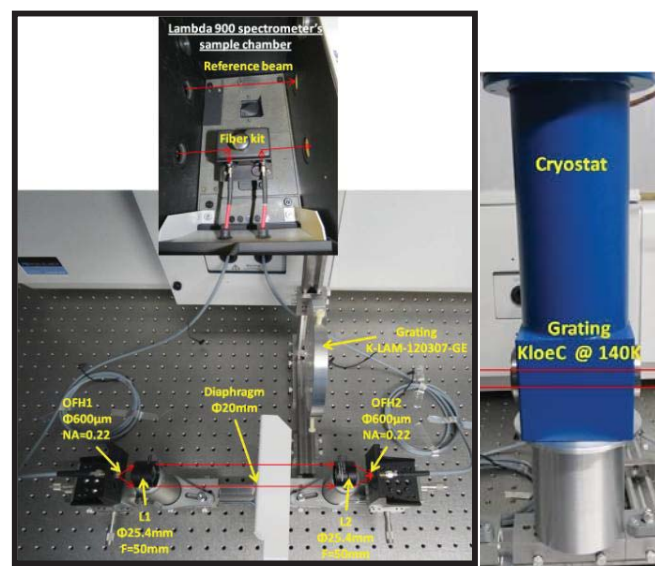

Figure 2.   Setup for efficiency measurement of the grating at room temperature (300K).

We use a Perkin Elmer spectrometer 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 to reinject it into the spectrometer associated with a custom optical bench between the two optical fiber heads (OFH) which allows measuring transmitted efficiency in orders 0 and 1 at several wavelengths.

Fiber diameter (600µm) and lens focal length (50mm) are determined so as to isolate a single diffraction order. Beam diameter (20mm) ensures optimal use of fiber numerical aperture (0.22).

B. Groove profile and theoretical efficiency curve calculation

We use an interferential microscope Wyko NT9100 to measure the groove profile of the grating. This groove profile

measurement is used as an input for the PCGrate software to calculate the theoretical transmission efficiency curve of the grating.

Figure shows an example of groove profile measurement on the sample Kloé C. The triangular shape and the facet quality are good with a roughness of 50±15nm.
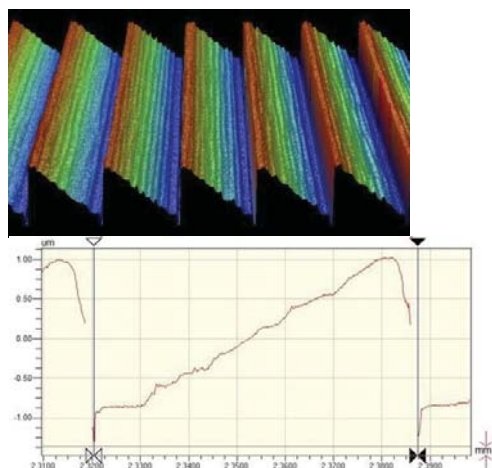

Figure 3. Groove profile measurement of the small thin sample Kloé C.

The groove profile of the full size grating is a little worse than Kloé C's: there is a double bump at the summit of each groove and the mean roughness of a facet is about 100±25nm. However, this defect is uniform over the entire surface of the grating and is due to less laser paths per groove than Kloé C in order to reduce the laser writing duration. However, as Kloé increased their laser writing speed since the full size grating manufacturing, they will be able to get back to the same number of laser paths as Kloé C for future prototypes.

C. Results

Figure 4 shows the transmission efficiency curve of the full size Kloé's grating measured at room temperature in orders 0 and 1 before and after thermal cycling compared with the theoretical one calculated by PCGrate from the groove profile measured.

We can point out that this full size grating presents a good agreement with required optical performances: a spectral bandpass of about 300nm width (357nm required) where efficiency is superior to 65% (in band transmission requirement including filter) in the nominal working order 1. Regarding the Kloé C measurement, we can anticipate a gain of 5 percent with a better groove facets quality. 72% maximum transmission efficiency is yet an excellent result.

However, we can point out that the blaze wavelength is shifted toward the visible by an amount of about 250nm due to a groove height less than the specified one which involves a smaller facet angle.

The facet quality and angle will be easily corrected for the future demonstration model foreseen by the end of 2013.

Otherwise, we can see that the efficiency is not affected by the thermal cycling and that theoretical efficiency curves calculated from the measured groove profile are fully consistent with our measurements in the two orders.
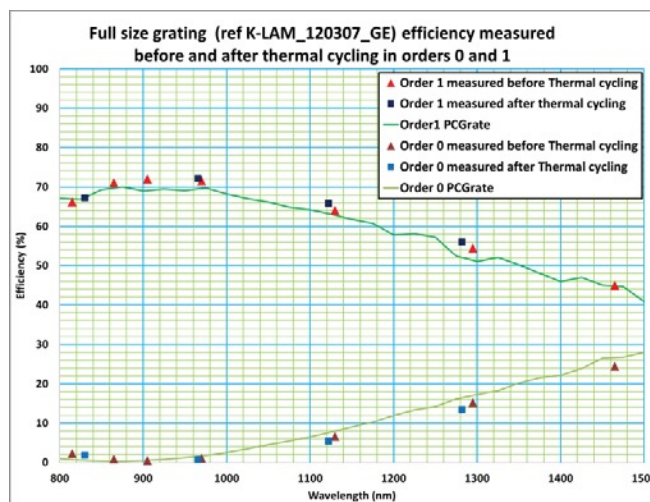

Figure 4. Comparison between efficiency measurements done before and after thermal cycling of the full size grating K-LAM_120307_GE and theoretical validation of resulting curves.

To completely establish that the Sol-Gel layer behaves well at the grism working temperature of 140 K, we decided to measure in a small cryostat the sample Kloé C made with the same Sol-Gel. We placed our cryostat in the parallel beam of the setup described in Figure 2. The efficiency results are identical at 300K and at 140K within a few percent which is the measurement precision. Therefore, we can conclude that the transmission efficiency of the grism is not affected by the operating temperature.

In addition, during the R&D phase, we measured the efficiency of another small grating before and after exposing it to electron radiation (50krad) typical of Euclid space environment. Measured efficiency was not affected by this radiation test.

IV.   TRANSMISSION WAVEFRONT VERIFICATION

A. Wavefront measurement

The goal of this measurement is first to check that the amount of wavefront correction introduced by the curved grooves is the specified one and second that it is not affected by the thermal cycling (300-100 K). Using a 100 mm diameter Fizeau interferometer and a high precision flat reference mirror (flat to $\lambda/10$ @632.8nm), we measured the central part of the full size grating in double pass in order 1.

B. Theoretical wavefront calculation

In order to compare transmitted wavefront measurements of the grating with the theoretical one, we implemented a simplified Zemax model of our setup. A parallel beam passes through the grating as defined by the "binary1" function extracted from the NISP Zemax model and interferes with a plane parallel wave.

Zernike coefficients are derived from the resulting simulated wavefront.

C. Results

Figure 5 shows transmission wavefront measurement of the full size grating before and after thermal cycling.

First, these results show that the grating is not microstructured which is prerequisite for efficiency and straylight performances. Second, the Zernike coefficients measured before and after thermal cycling are the same within 10 nm range which demonstrates that the transmission wavefront of our grating is not affected by thermal cycling.
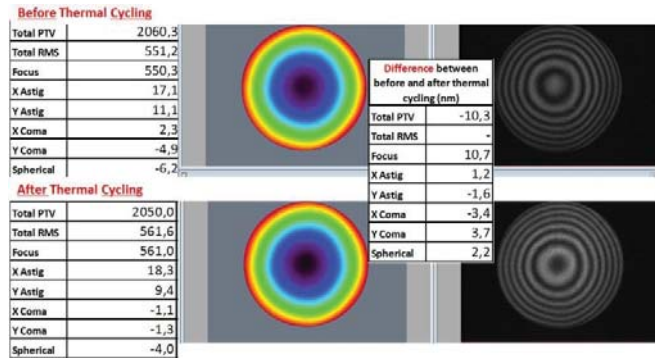

Figure 5. Transmission wavefront measurement of the full size Kloé's grating (K-LAM-120307-GE) in order 2 before and after thermal cycling (measured Zernike coefficients values are given in nm).

Figure shows the comparison between our measured wavefront Zernike coefficients and the theoretical ones calculated with the Zemax model in order 1. The most important value is the residual total RMS error of 16nm which reaches the 30nm RMS maximum wavefront error required by the project.

	Order 1- Order 0 measured (nm)	Order 1 Zemax (nm)	Delta Order 1 (nm)
Total RMS	249,264	261,426	15,988
Focus	248,817	260,123	11,306
X Astig 3	13,289	13,873	0,584
Y Astig 3	0,316	-0,033	-0,349
X Coma 3	-1,962	0,460	2,422
Y Coma 3	-1,076	-1,281	-0,205
Spherical 3	6,391	1,663	-4,728

Figure 6. Comparison between transmission wavefront measurement of the full size grating and theoretical one calculated with the Zemax model of the setup (only the six first Zernike coefficients are shown but RMS values take into account the full set).

V. CONCLUSION AND PERSPECIVES

First, we demonstrated that the photolithography is well adapted to manufacture gratings with curved grooves, low groove density, small facet angle, even for a large diameter as requested by the Euclid mission.

Second, our efficiency and wavefront measurements before and after thermal cycling show that the integrity and optical performances of the grating are not affected by the cryogenic temperature of the Euclid mission. Indeed, the remaining Sol-Gel layer could have been an issue in terms of adhesion to the substrate and/or change of optical properties in the cryogenic environment.

Last but not least, we demonstrated that the aberration correction introduced by writing curved grooves is a viable process since the discrepancy between the specified and the measured wavefront is within the 30nm RMS specified.

Nevertheless, full size grating efficiency measurement revealed two defects. The first is a shift of the specified blaze wavelength due to a facet angle of the grooves lower than the specification. Indeed, the thickness of the Sol-Gel layer deposited was not sufficiently controlled during the process. From now, an interferential microscope will allow to monitor the Sol-Gel deposition thickness.

The second defect is a maximum efficiency a bit lower (few percent) than the one measured on the small sample because groove facets quality of the full size grating is not as good as the small sample. This is due to less laser paths per groove in order to reduce the laser writing duration. In the future, Kloé will be able to get back to the same number of laser paths as for the small sample since they will increase the laser writing speed.

In addition to these improvements to correct the observed defects, further developments leading to a Demonstration Model (DM) will include the use of a prismatic substrate and the deposition of a multilayer filter on the opposite face of the grating substrate to isolate the grating spectral band pass.

In the DM development phase, we will improve our efficiency measurement setup in order to measure the transmitted efficiency on the 132mm useful diameter of the grism instead of a 20mm diameter in our present setup. We will also enlarge the test diameter for the wavefront measurement by using a 150mm beam expander of the Fizeau interferometer.

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