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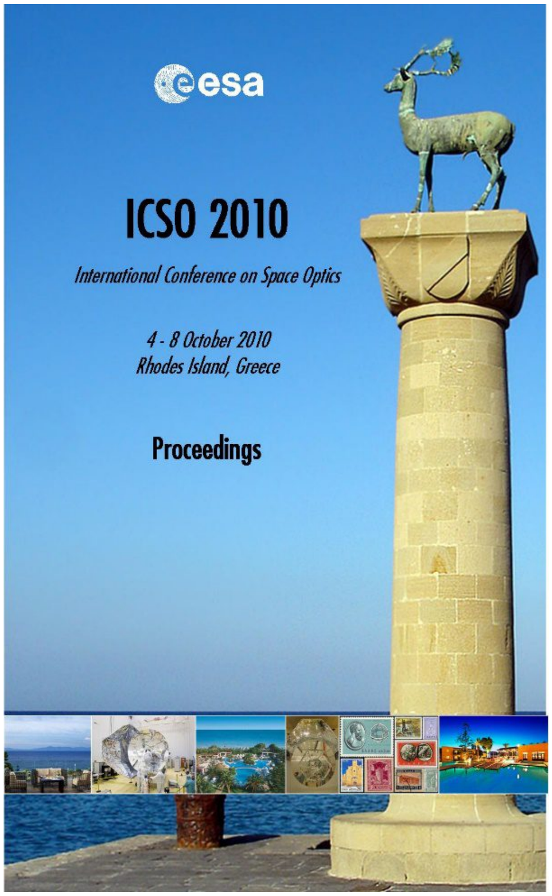

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DEVELOPMENT OF A LARGE BLAZED TRANSMISSION GRATING BY EFFECTIVE BINARY INDEX MODULATION FOR THE GAIA RADIAL VELOCITY SPECTROMETER

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INTRODUCTION

Gaia is an ambitious ESA mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and cinematic census of about one billion stars in our Galaxy. The payload consists of 2 Three Mirror Anastigmat (TMA) telescopes (aperture size ~1.5 m x 0.5 m), 3 instruments (astrometer, photometer and spectrometer) and 106 butted CCDs assembled to a 0.9 Giga-Pixel focal plane.

The Radial Velocity Spectrometer (RVS) of Gaia measures the red shift of the stars in the spectral band between 847 nm and 874 nm. The spectrometer is a fully refractive optics consisting of 2 Fery prisms, 2 prisms, a pass band filter and a blazed transmission grating (instrument mass about 30 kg). It is located in the vicinity of the focal plane and illuminates 12 of the 106 Charge Coupled Devices (CCDs).

Gaia is in the implementation phase, the launch of the 2120 kg mass satellite is planned in Dec. 2012.

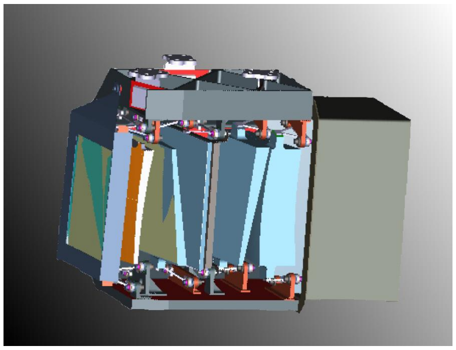

Figure 1: The Gaia RVS Spectrometer (courtesy Astrium SAS)

KEY REQUIREMENTS FOR THE RVS GRATING

The blazed transmission grating is working in the +1 diffraction order. Star spectra observed by the RVS travel due to the constant satellite rotation speed across the RVS CCD detectors. All CCDs are operated in TDI mode (Time Delay Integration) which means that the charges in the CCD are transferred at the same speed as the spectra. For that reason the RVS instrument is relatively large compared to the aperture size. The optical footprint for one field point on the RVS is only about 55x45 mm in size, but because of the TDI scan of the spectra the required grating size is 155 x 205 mm.

Other key requirements for the grating are: Grating efficiency as high as possible (>70% required, >74% as a goal), Wave Front Error (WFE) of the diffracted beam as small as possible (<8 nm RMS), Low polarization sensitivity (<7%), operation in cryogenic and vacuum environment, low stray light generation.

EFFECTIVE MEDIUM BINARY INDEX MODULATION PRINCIPLE

The fabrication of the grating has been done at the Center for Advanced Micro- and Nano-Optics (CMN-Optics) at IOF in Jena by electron beam lithography and reactive ion etching in fused silica. For the high precision lithographic exposure a SB350 OS e-beam writer (Vistec Electron Beam GmbH) has been used. Due to its shaped beam writing principle it is achieving a very high throughput while its placement accuracy is considerably better than 15nm. The exposure of substrates with lateral dimensions of up to 300mm is possible.

The typical structuring process for the realization of photonic sub-micrometer structures consists of the following four steps:

1. The fused silica blank is coated with a chromium layer and a resist. The resist is exposed by the electron beam.

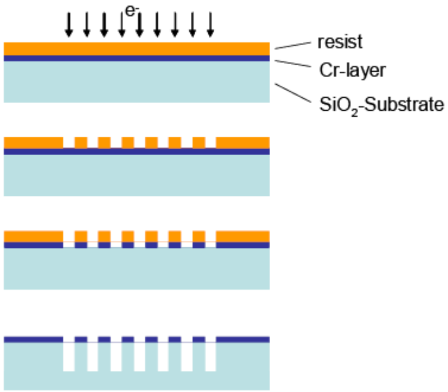

Figure 2: Photonic Sub-Micrometer Structuring Process

2. After development of the resist the chromium in areas that later will be deep etched are exposed. In the other areas the chromium is protected by the resist.
3. In the next step the chromium mask on the substrate is developed by RIE (Reactive Ion Etching).
4. Deep etching of the substrate is then performed by ICP etching (Inductively Coupled Plasma). After stripping of the unnecessary chromium layer the part is finished.

To utilize this process for a blazed transmission grating limitations of the process and machinery had to be respected. Therefore it was agreed to expose the demonstrator gratings on standard 6-inch and 9-inch blanks for which chucks existed at the SB350 OS facility.

Because of the grating size it was decided to utilize a single layer binary process. Different layers would have caused alignment problems of the layers over the entire grating surface as the allowed budget for misalignment was too small to be technically mastered.

For the representation of the blazed line profile with a binary structure each line of the grating ("unit cell") is divided into "patches" to locally modulate the effective index of refraction. As the texture features in each patch are smaller than the shortest wavelength (847 nm) they are not spatially resolved. The local effective index of refraction can therefore be considered as mean value of the patches of refractive material. Considering a simple 5-patch-per unit cell binary design as shown in Figure 3 it can easily be seen that the floating average of the local index over the average wave length forms indeed a blazing profile.

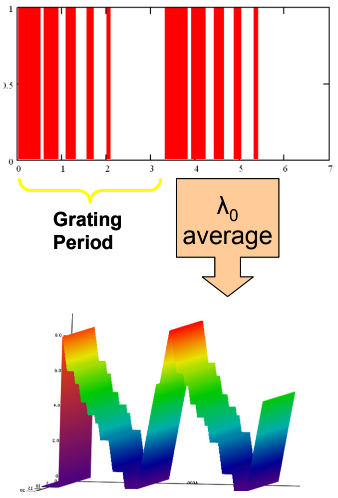

Figure 3: Effective Medium Binary Index Modulation

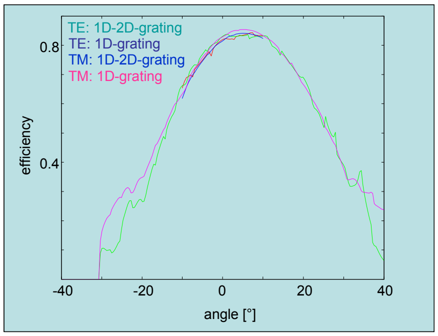

Figure 4: Diffraction Efficiency 1D Grating vs. 2D

For the optimum blaze the grooves depth generate a phase difference of 2π along the unit cell. For a fused silica grating (n=1.4525) working in the RVS spectral band this means that the groove depth needs to be 1.9 µm. This is in line with the IOF standard process.

An optimized 5-patch per unit cell design leads however to bars of about 80 nm lateral dimension in size. This is too small to be technically mastered and the risk of such small features to collapse during the grating handling and processing is very high. For the small features the potential to use the 2nd dimension were investigated. It was found by rigorous diffraction analysis that the grating performance of a 2D index modulation is well comparable to the 1D design approach. Efficiency curves of the two designs are shown in Figure 4 for comparison. Obviously the two different designs are identical with respect to efficiency and polarization behaviour. In the 2D design the smallest lateral dimension is increased to 200 nm which is technically manageable.

RVS GRATING DEMONSTRATOR DEVELOPMENT LOGIC AND RESULTS

The development of the RVS grating demonstrator was performed in three steps. After each step the development status was reviewed and it was decided whether to continue with the next phase or to stop the activities.

- First step: Development and testing of a small size sample grating → *verify the feasibility of the concept.*
- Second step: Development and testing of a full size sample → *verify that the concept can be scaled to the required grating size.*
- Third step: Qualification tests followed by grating inspections and performance measurements → *verify that the grating can be qualified for space applications.*

Only four months after the study kick-off in March 2008 the small demonstrator sample was finished and the performance fully characterized. The small size demonstrator consisted of six different grating designs, each 3x3 cm in size on a 6-

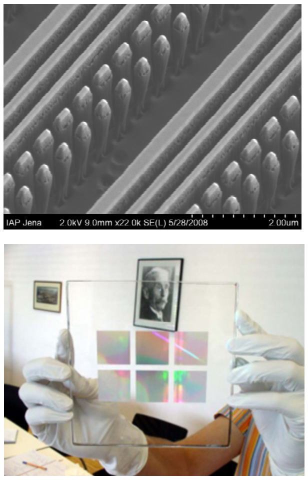

Figure 5: Small Size Grating

inch fused silica blank. Five of the six gratings fully complied with the specification, the best grating –grating nr. 6– had an efficiency of 74.4%. It is interesting to note that this grating is a 4-patch 1D grating.

The performance was better than theoretically predicted for the actual grating designs. The reason for this is a systematic effect, the so called RIE-lag (etching depth is a function of the local groove width) improved the physical diffraction properties of the pattern.
The feasibility of the concept was therefore clearly proven and demonstrated. The decision to continue with second phase of the study to build a full size model was taken.

In November 2008, 8 months after the study kick off, the full size demonstrator was ready and measured at different locations on the grating area. For the full size model demonstrator the RIE-lag, that was well characterized during the development of the small size grating, was utilized to simplify the binary pattern and enhancing the grating performance at the same time.

- All requirements were met even with a comfortable margin for efficiency and stray light.
- The grating efficiency was almost 85% and the variation of the grating efficiency was less than 2%.
- The stray light level that was generated by the diffractive surface was very low and comparable with a good polished optical surface.

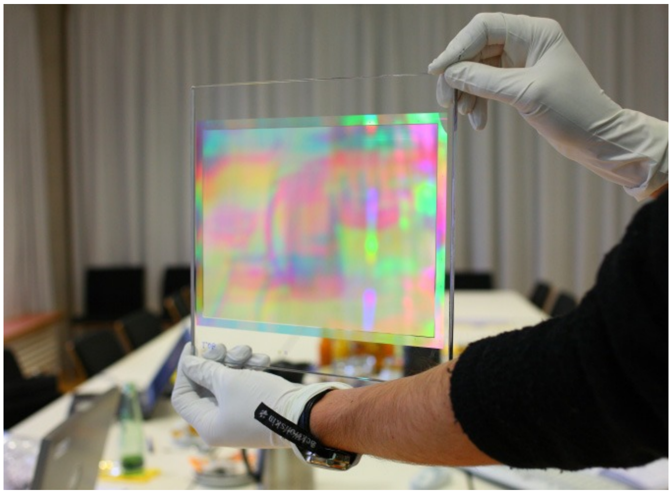

Figure 6: Full Size Grating Demonstrator

QUALIFICATION TESTING CAMPAIGN

After the decision to proceed in parallel with the design and fabrication of the full size grating the small size grating was subject to environmental qualification tests at ESTEC. The test plan consisted of thermal vacuum and humidity testing and consisted of two testing phases. After each phase the grating was measured and inspected.

1. Cryo-vacuum test, 8 cycles 100 K to 340 K
2. Humidity test, 90%RH, 60°C, 10 days and immediate 2nd cryo-vacuum test, 8 cycles 100 K to 340 K

After the first thermal vacuum test no differences of the grating –before/after– could be identified.
The grating was then put in the humidity chamber for 10 days and immediately after put back in the cryostat and the same temperature cycle as the first test run was performed again.
After this test a number of contaminants were found on the grating. However, contaminants were found to originate from the humidity chamber and not the product of a grating damage.

→Nano-structure of the gratings was unchanged and fully in tact
→The grating performance was unchanged

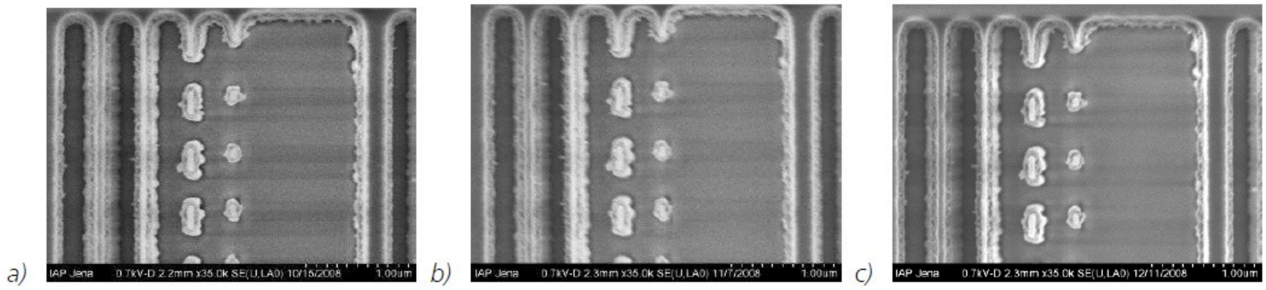

Figure 7: 35k Scanning Raster Microscope Picture a) Before Cryo Test b) After Cryo Test c) After Humidity and 2nd Cryo Test

FROM THE DEMONSTRATORS TO THE FLIGHT MODELS

Based on the excellent results that were reached on the grating demonstrator models in January 2009 IOF was selected as a supplier for Gaia RVS flight gratings. Astrium SAS in Toulouse placed a contract for the fabrication of 2 flight models at IOF. Additional processes and fabrication steps were necessary for the fabrication of the flight models:

- Polishing of the 9mm thin fused silica blanks to a very low WFE of 8 nm RMS
- Outer shape cutting from a 9-inch blank to the final required grating element shape ("dicing")
- Establishing and qualifying representative fused silica structural strength properties

For the demonstrator gratings standard fused silica blanks were used. Polishing of such thin plates to the low wave front error required for the flight model gratings is a difficult and lengthy operation. For the demonstrator a good WFE was not so important, only the impacts of the grating etching process on the wave front error was investigated and specified (differential measurement). For the flight models state of the art polishing processes like IBF (ion beam figuring) were used. Three blanks needed to be prepared (for 2 flight model gratings).

Cutting the grating to the required shape to be installed in the RVS was not a trivial task. It was studied and tested at what stage of the grating fabrication the cutting was best to be done. Cutting the blank before the exposure at the e-beam lithographic system SB350 OS was not an option. The machines exposure target interface is strictly limited to standard blank dimensions (chuck). Cutting the sample after the full development and etching of the grating was a high risk, as the grating surface is sensitive to mechanical impacts after etching. Mechanical works at the part at that stage should be done with extraordinary care and caution and generally kept to a minimum. However, the RIE- etching facility could be easily equipped with a modified target holder being able to support the RVS grating in the required shape. It was therefore concluded that the best moment to cut the grating is between chromium mask etching and the substrate Reactive Ion Etching process.

Another interesting question is if the fused silica mechanical properties are influenced by the etching of the grating. It is well known that the mechanical strength of glass largely depend on the optical item surface properties. Generally the rougher the surface, the lower the maximum stress the item can withstand. It was not clear if the grating fabrication process result could be considered as a "rough surface" and consequently lowering the maximum allowable stress in the grating. Further to this the grating thickness is strictly limited to 9mm. For an optical part of 155 x 205 mm dimensions to be installed in a satellite this is unusually thin. High strains and stresses could be expected in this part during launch. To secure positive margins of safety and structural integrity of the grating, representative material properties and limits needed to be established by a sample testing campaign. More than a 100 samples with a representative grating texture in different orientations were prepared and destructively tested. The result shows that the grating etching process has no negative influence on the mechanical strength of fused silica. In fact the grating etching process can be considered as a classical etching process in terms of structural behavior of the part (higher critical Weibull stresses, lower Weibull modulus).

Two flight models of the grating were fabricated by IOF. Both gratings were compliant with the requirement and the better one was selected to be integrated in the RVS. The second grating will be the spare grating. Figure 9 shows the local grating diffraction efficiency at 850 nm wave length. The average efficiency is 80.7% with

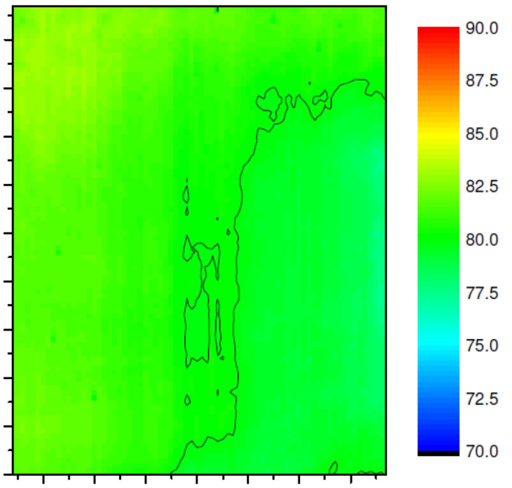

Figure 9: Flight Grating Diffraction Efficiency

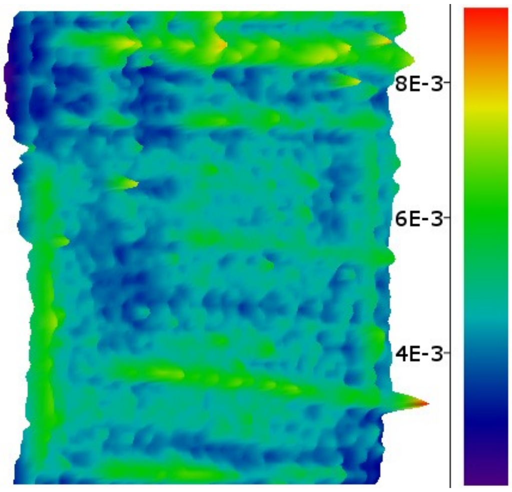

Figure 8: Spatially Resolved Scattering

6% variation over the grating surface.

Another interesting property of this sort of grating is the low scattering. Figure 8 shows the spatially resolved stray light measured in a cone in the vicinity of the 1st diffraction order. The stray light intensity ratio is shown as function of the grating position of the incidence beam in units of [1/SR] at 850 nm wave length. The average scattering over the entire grating area in Figure 8 is 4.8E-3 [1/SR]. With the assumption of a homogeneous scattering of that magnitude over 4πSR solid angle this would result in a Total Integrated Scattering (TIS) of 6E-2. This is a stray light level which would be comparable with an optical polished surface with a micro roughness of about 0.25 nm RMS!

CONCLUSION

Effective medium binary index modulation is a new method to fabricate blazed transmission gratings of large size. The gratings have good diffraction efficiency up to 85% and excellent polarization, wave front error and stray light performance. As the gratings are fully monolithic, they are very well suited for space applications. Qualification tests consisting of thermo-cycling and humidity tests verified the grating robustness to the harsh space environment. The gratings even survived being dipped 6 times in liquid nitrogen without damage and performance degradation. The two flight gratings for the GAIA RVS have been fabricated and fully tested and qualified. Both gratings are compliant to the requirements. We think that this technology has a lot of potential and worth being exploited for other applications - not only for space.

ESA would like to thank IOF for their excellent work and results achieved during the study and the fabrication of the flight model gratings.

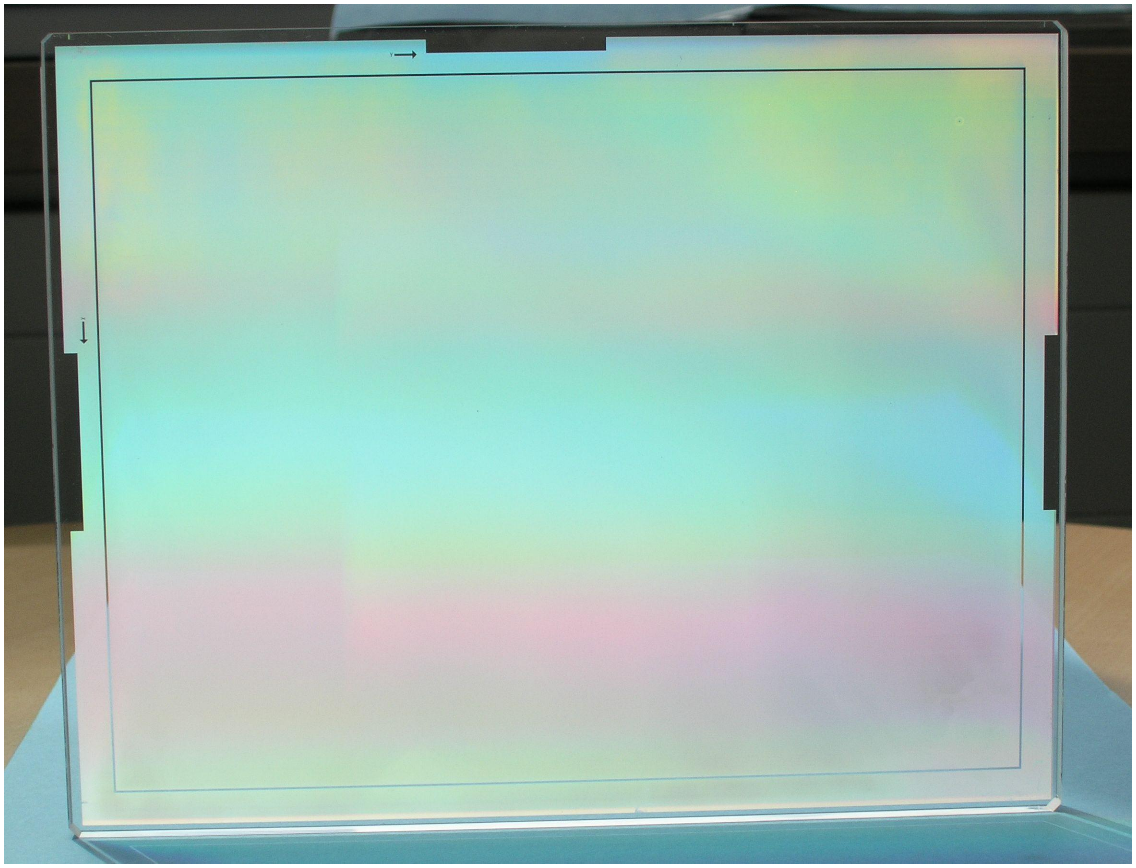

Figure 10: Picture of one of the RVS Flight Gratings

Acknowledgments: All gratings exposures for this study were done with an e-beam writer SB350 OS at the Fraunhofer IOF. The purchase of this facility has been supported by the European Union (FZK: B 408 – 04004)