Development of a large blazed transmission grating by binary index modulation for the GAIA Radial Velocity Spectrometer

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A blazed transmission grating with a spacing of about 300 lines per mm is the dispersive element of the GAIA RVS spectrometer. The required dimensions of the grating, imaging performance, efficiency (>70%) and the qualification for space applications are the main requirement for this component. IOF successfully built and tested a full size grating demonstrator for ESA.

1. 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 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 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 CCDs.

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

2. 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: efficiency as high as possible (>70% required, >85% goal), Wave front error of the diffracted beam <8 nm RMS, Low polarization sensitivity (<7%), cryogenic and vacuum environment, stray light.

3. Effective Medium Binary Index Modulation Principle

Each line of the grating ("unit cell") is divided into "patches" to locally modulate the index of refraction. As the patches 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.

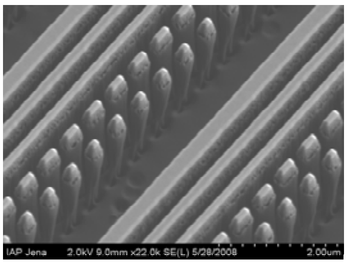

Figure 1: Small Size Grating

For the optimum blaze the grooves depth generate a phase difference of π 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 in size. This is too small to be technically mastered and the risk of such small features to collapse is too high. For the small features of the potential to use the 2nd dimensions 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.

4. 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 to continue with the next phase.

- *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 month after the study kick-off in March 2008 the small demonstrator sample was finished and the performance was characterized. The small size demonstrator consisted of six different grating designs; each 3x3 cm in size on a 6-inch fused silica blank (see Figure 1). Five of the six gratings fully complied with the specification; the best grating 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 because the so called RIE-lag (etching depth is a function of the groove width) improved the physical diffraction properties of the pattern. The feasibility of the concept was therefore concluded to be demonstrated and the second phase of the study to build a full size model was started.

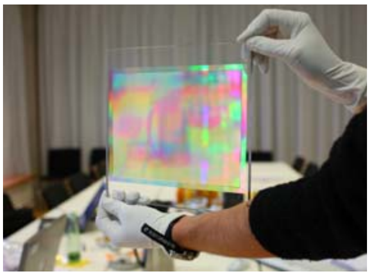

Figure 2: Full Size Grating

In November 2008, 8 month 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. 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.

5. Qualification Testing Campaign

In parallel with the 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 intact

→The grating performance was found to be unchanged

6. Conclusion

Effective medium binary index modulation is a novel 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.

ESA would like to thank IOF for their excellent work and results achieved during the study.

In January 2009 IOF was selected as a supplier for Gaia RVS flight gratings

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