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OVERVIEW OF DIFFRACTION GRATINGS TECHNOLOGIES FOR SPACE-FLIGHT SATELLITES AND GROUND-BASED TELESCOPES

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I. INTRODUCTION

The diffraction gratings are widely used in Space-flight satellites for spectrograph instruments or in ground-based telescopes in astronomy. The diffraction gratings are one of the key optical components of such systems and have to exhibit very high optical performances.

HORIBA Jobin Yvon S.A.S. (part of HORIBA Group) is in the forefront of such gratings development for more than 40 years. During the past decades, HORIBA Jobin Yvon (HJY) has developed a unique expertise in diffraction grating design and manufacturing processes for holographic, ruled or etched gratings.

We will present in this paper an overview of diffraction grating technologies especially designed for space and astronomy applications. We will firstly review the heritage of the company in this field with the space qualification of different grating types. Then, we will describe several key grating technologies developed for specific space or astronomy projects: ruled blazed low groove density plane reflection grating, high-groove density holographic toroidal and spherical grating, and finally transmission Fused Silica Etched (FSE) grism-assembled grating. We will not present the Volume Phase Holographic (VPHG) grating type which is used in Astronomy.

II. HJY GRATINGS HERITAGE FOR SPACE FLIGHT SATELLITES AND IN ASTRONOMY

HORIBA Jobin Yvon produced a wide range of diffraction gratings for many prestigious space-flight experiments since 1968 [1]. Among these missions, we can mention the famous Lyman-Far Ultraviolet Spectroscopic Explorer (FUSE) (NASA/JHU) where we manufactured high-resolution 5800gr/mm, aberration-corrected, holographic gratings on 300x300mm light-weight substrates. Then, for the Hubble Space Telescope, we produced the full set of the 7 gratings embedded in the Cosmic Origin Spectrograph (COS) or in the Space Telescope Imaging Spectrograph (STIS).

The space qualification of the whole range of HJY diffraction gratings was performed previously during the Long Duration Exposure Facility (LDEF) mission. LDEF was deployed in orbit in 1984 and carried on-board a full set of diffraction gratings from HORIBA Jobin Yvon listed below:

- Replica ruled 1200gr/mm grating blazed at 250nm, in dimensions 40x40mm, Aluminium coated ;
- Master holographic 3600gr/mm grating optimized for 50-150nm, in dimensions 40x40mm, Platinium coated ;
- Master holographic ion-etched 1200gr/mm grating blazed at 250nm, in dimensions 40x40mm, Aluminium coated.

The optical performances of these three grating types, representative of HJY capabilities, were tested in space vacuum and environment exposure. Correlation with identical components, stored on ground under Air-Nitrogen pressure during all the experiment duration was made. Integrity, wavefront quality, diffraction efficiency and stray light were the four main parameters checked and compared in this mission.

The tested gratings were in space vacuum during a long exposure (69 months, about 34000 orbits) with thermal cycle/orbit from -30°C to +70°C and in space environment with cosmic dust and sun irradiation during ten months.

The LDEF mission results proved the space qualification with a Test Readiness Level (TRL) 9 of the different grating types manufactured by HJY [2].

The different grating technologies (ruled, holographic, ion-etched) space-qualified above allow to address a large numbers of projects and missions with grating design optimized from Soft-X rays to Mid-Infrared, groove density from ~30gr/mm to ~5800gr/mm, different substrate shape (plane, spherical or toroidal), dimensions up to 500mm, master or replica gratings, reflection or transmission gratings.

III. KEY DIFFRACTION GRATING TECHNOLOGIES DEVELOPPED FOR SPACE FLIGHT AND ASTRONOMY APPLICATIONS

A. Ruled blazed low groove density plane reflection grating

Three years ago today, the Juno spacecraft (NASA/JPL) launched from earth and set off on its journey to Jupiter. For the Jovian Infrared Auroral Mapper (JIRAM) instrument which is an image spectrometer that will explore Jupiter, carried by the Juno spacecraft, we have manufactured very low groove density ruled plane reflection gratings (Figure 1). These ruled gratings, ~30gr/mm groove density, were optimized for a large spectral range in the mid-IR from 2µm to 5µm, in order to probe the upper layers of Jupiter's atmosphere.

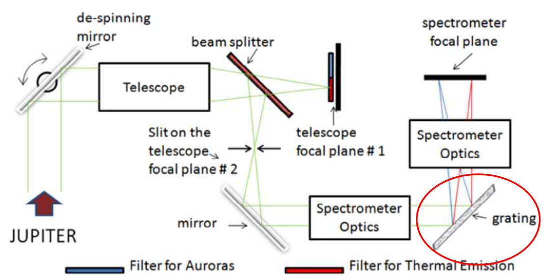

Fig. 1. Optical Layout of the JIRAM spectrometer with the diffraction grating [3]

Thanks to a precisely optimized low blazed angle allowed by the ruling machine, a peak absolute efficiency of about 91% at ~2.75µm was obtained and an over whole efficiency from 2µm to 5µm higher than 50% given in the Figure 2 below:

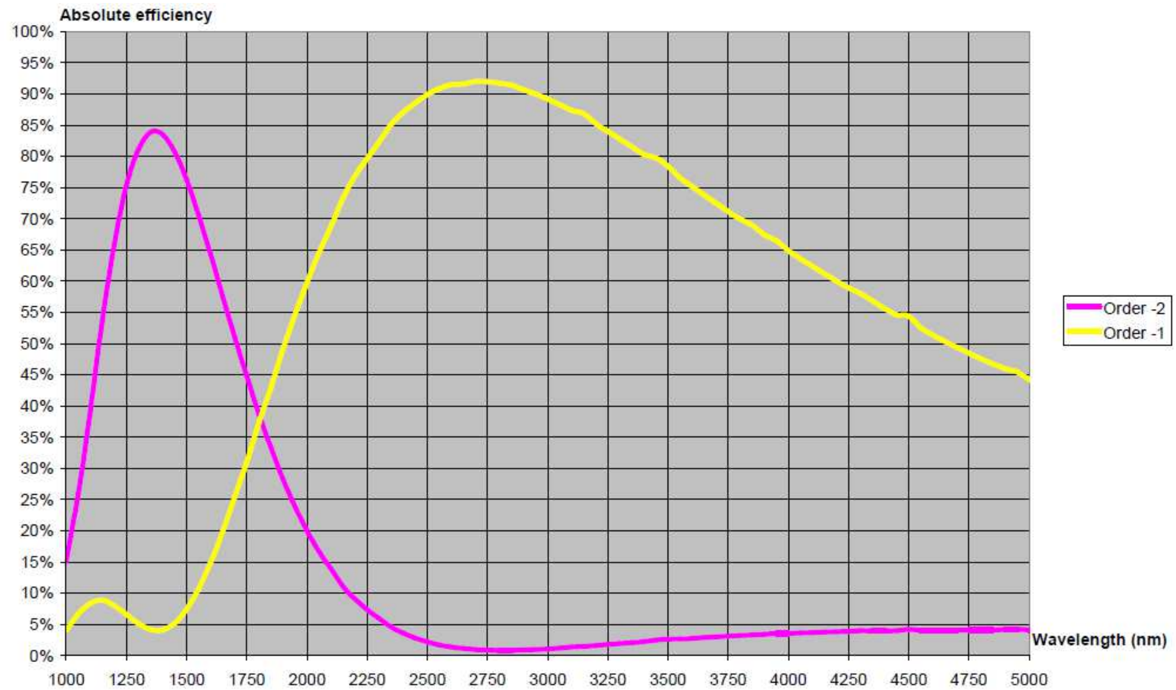

Fig. 2. Computed absolute diffraction efficiency with the experimental groove profile of the low groove density 30gr/mm ruled plane grating, for unpolarized light, 1st order (pink curve) and 2d order (yellow curve), from 1µm to 5µm.

The efficiency measurements at available wavelengths have shown a good agreement with the computed values. These gratings have been space qualified with extensive environmental tests (thermal cycling from -173°C to +70°C) and characterized to be installed in a spectrograph.

Based on this expertise, in the frame of BepiColombo/Mercury Planetary Orbiter mission (ESA/JAXA), we have developed at HJY with our ruling machine another customized blazed ruled grating. With a low groove density of 62gr/mm, this plane reflection grating exhibited a broadband absolute efficiency and low polarization dependence over the whole considered spectral range (VIS-NIR) (Figure 3).

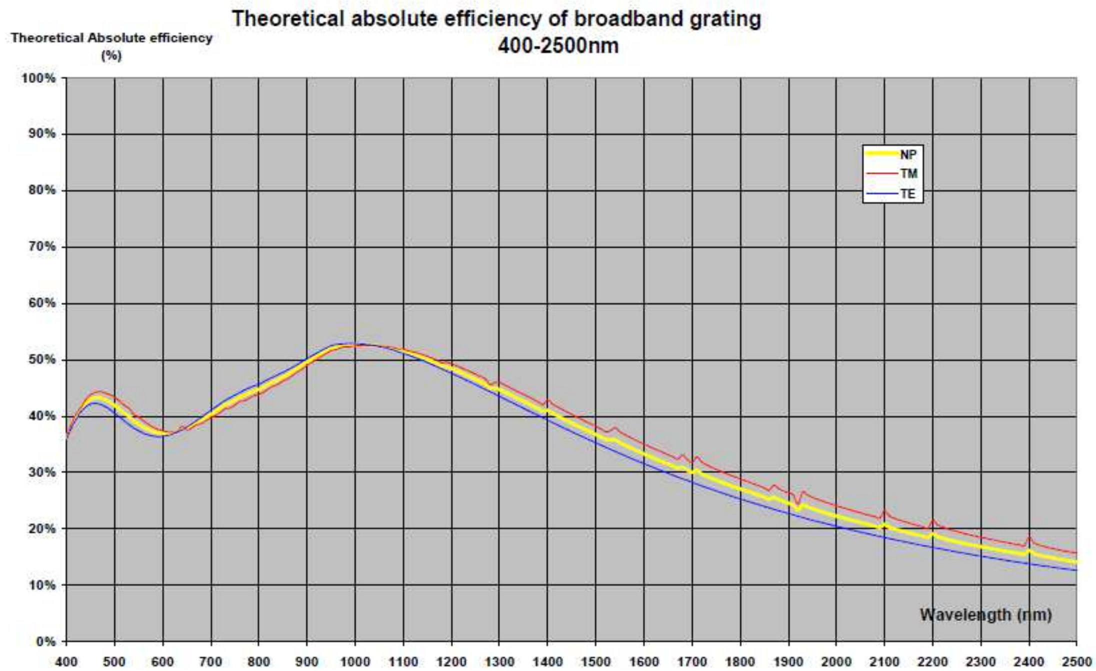

Fig. 3. Theoretical absolute diffraction efficiency of the low groove density 62gr/mm ruled plane grating, for TE, TM polarization and unpolarized light, from 400nm to 2,5µm.

The absolute efficiency was also measured from 400nm to 1100nm, before and after environmental tests. These measurement results were in good agreement with the theoretical efficiency.

As the result, in the frame of these two projects, we have developed at HORIBA Jobin Yvon a precise design method and accurate manufacturing techniques to address space-flight or ground-based instruments which need ruled blazed plane reflection gratings.

B. High groove density holographic toroidal and spherical grating type

For very high resolution purpose, high groove density (>2400gr/mm) holographic and free form or spherical shape gratings can be used for space-flight instrument. This type of complex grating design is presented below.

One of the most famous was the ~2440gr/mm Toroidal Variable Line Spacing (TVLS) gratings HORIBA Jobin Yvon developed for the Solar Ultraviolet Magnetograph Investigation (SUMI) mission [4]. Six large (~150mm dimensions) TVLS gratings coated with Al+MgF2 coating were produced to be used simultaneously at 280nm and 155nm (the ultraviolet (UV) light emission from two types of atoms on the sun, Magnesium 2 and Carbon 4). These very complicated gratings took several years to be designed and produced accordingly; it was a real technical challenge.

The sounding rocket carrying the SUMI experiment was successfully launched on 2012. Preliminary results showed that good data was received.

More recently, spherical holographic 3000gr/mm gratings were manufactured for another Solar project. Based on the heritage of SUMI gratings, we have produced these customized high groove density gratings on spherical substrate of diameter 115mm.

Designed to work in normal incidence configuration and optimized at 121nm, these gratings with an Al+MgF2 coating can theoretically achieve an efficiency from 20 to 30% over the considered spectral range (110-160nm), as it is shown below on the Figure 4:

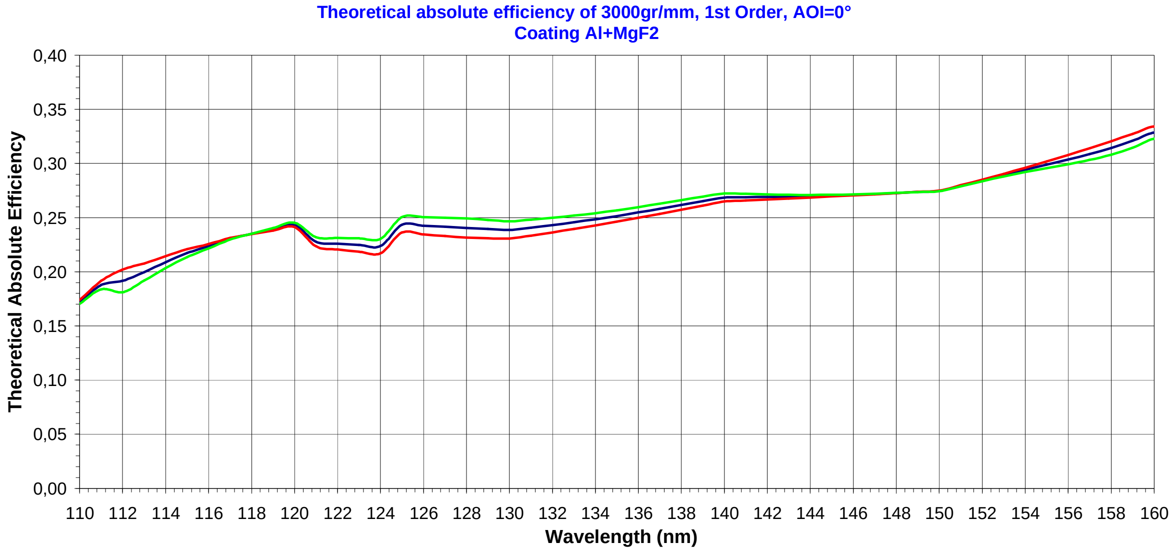

Fig. 4. Theoretical absolute efficiency calculation of the 3000gr/mm holographic spherical grating from 110nm to 160nm, for TE (red curve), TM polarization (green curve) and unpolarized light (blue curve).

An efficiency measurement under vacuum at 121nm to compare with the optimized grating profile theoretical model has been done. An absolute efficiency of ~25% ± 3% was measured and gave a good comparison with expected theoretical efficiency value.

C. Transmission Fused Silica Etched (FSE) grism assembled grating

New manufacturing techniques (diamond ruling or holography associated with patented fused silica etching) have led to efficient transmission grating, immersed grating or grisms designed to work in vacuum, from UV to NIR wavelengths, and withstand severe space and/or cryogenic environments.

These developments of transmission gratings, used in the UV and NIR spectral range, are designed for high-efficiency purpose, low polarization dependence and compatible with severe environment (cryogenic for instance). Transmission grating design results in a very compact optical setup for instruments in Astronomy or Space projects. These gratings can be used as a single optical element, or assembled with one or two prisms to act as a Grism or used in an immersed grating configuration. The different described configurations were developed by HORIBA Jobin Yvon with different partnerships.

For the Galaxy Evolution Explorer (GALEX) mission, we developed, in collaboration with the Laboratoire d'Astrophysique de Marseille (LAM), a very special and complex type of low groove density transmission grating. Grating stayed in orbit during the 10 years GALEX life and provided in the instrument extensive results with remarkable accomplishment. This explorer mission has mapped and studied galaxies in the ultraviolet during a decade from 2003 to 2013, when NASA decommissioned the galaxy hunter spacecraft. GALEX met its prime objectives and the mission was extended three times before being decommissioned.

The 75gr/mm transmission grism developed for GALEX was initially ruled and then the blazed groove profile was transferred into the substrate. This grating operated in the first order of diffraction for the NUV channel (180–300 nm) and in the second order for the FUV channel (130–190 nm). Due to the NUV-FUV spectral range, calcium difluoride (CaF2) was preferred to fused silica.

Therefore, this grating exhibited very low absorption of UV radiation because the photosensitive material usually used to record the groove profile was removed by the transfer process. Despite very difficult manufacturing processes involved due to the blank material and the low groove density, the GALEX transmission grating was successfully produced (Figure 5). We measured an absolute diffraction efficiency of 80% (NUV) and 61% (FUV) in the first and second order, respectively [5-6].

At the Gran Telescopio Canarias (GTC), the EMIR instrument, which is a wide-field camera and a near-infrared multi-object medium-resolution spectrograph, high-quality FSE transmission gratings were designed and manufactured [7]. The extension of EMIR bandpass up to 2.5µm and the required spectral resolution (R = 3500) prevented the use of classical grisms. A custom design composed of a plane AR-coated transmission grating working in Littrow configuration and mounted with air gaps between two zinc selenide prisms.

To cover the whole spectral range (0.9µm – 2.5µm), three types of transmission grating, with groove density ranging from 486gr/mm to 1032gr/mm, were recorded by holography followed by an ion-etching process to imprint a deep and symmetric profile into the fused silica substrate. This FSE-type transmission grating has produced an absolute diffraction efficiency of ~75% at the blaze wavelength with low polarization dependence, and perfectly compatible with the EMIR cryogenic environment (77K).

The diffracted wavefront quality was measured by interferometry (at 632nm) and we achieved to be below lambda/4 peak to valley. A picture of an EMIR grating, in dimensions 135mm is shown in Figure 5.

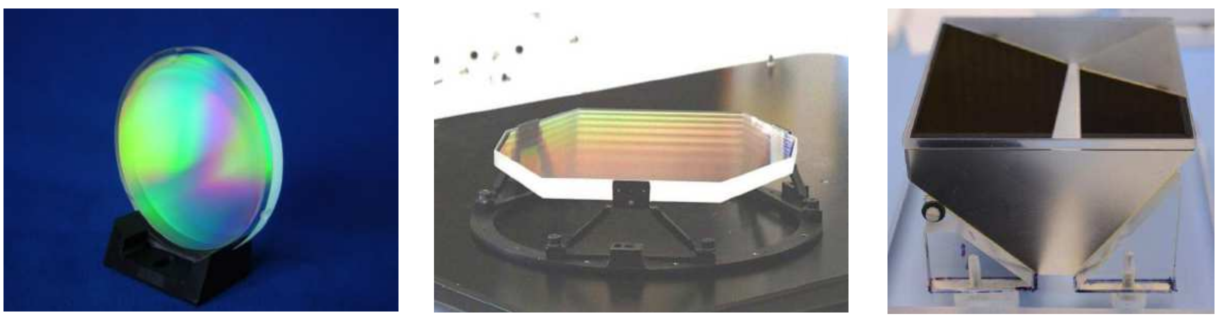

Fig. 5. Pictures of the 800gr/mm transmission NIR grating in size D135mm of EMIR instrument (GTC telescope), the 75gr/mm transmission FUV-NUV grism in size ~130mm of GALEX and the 3226gr/mm NIR immersed grating in size 120x120mm.

The latest design produced was a high dispersion NIR Immersed grating. Immersed grating technology offers to space-flight spectrometers a compact design, improved spectral resolution and high spectral quality. The immersed grating designed here was highly efficient in a small NIR bandwidth, from 750nm to 775nm (O_2A band). It was composed of an FSE transmission grating, with a groove density of 3226gr/mm, in a substrate size of 120x120mm (useful area of 110x110mm²), assembled with a prism of the same dimension and the same material (Figure 5).

The theoretical absolute efficiency of the optimized groove profile was calculated and gave a high efficiency, even close to 96% in one polarization, and a low polarization dependence over the 750-775nm (Figure 6). The other critical optical parameters such as wavefront quality and stray light were measured [8].

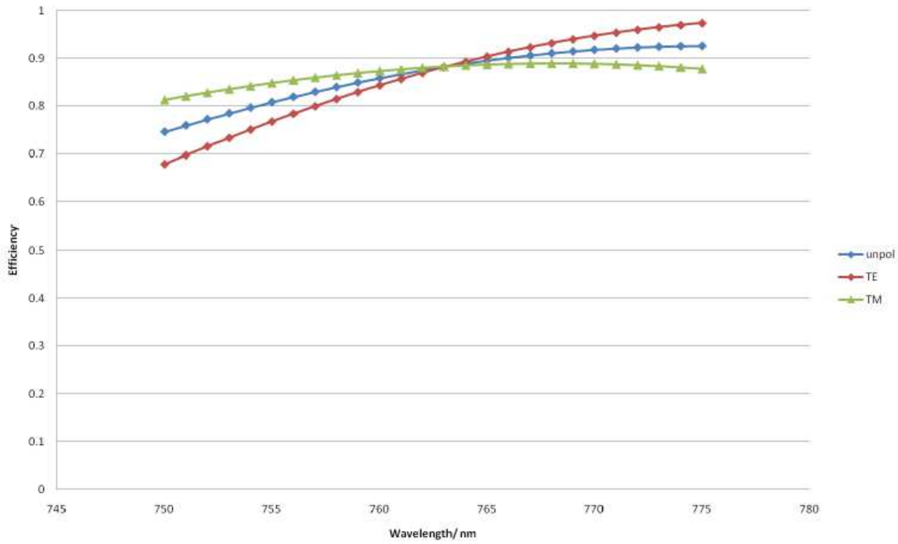

Fig. 6. Theoretical absolute efficiency of the 3226gr/mm transmission grating in TE polarization (red curve), TM polarization (green curve) and unpolarized light (blue curve).

The efficiency measurements ranging from ~75% to >90% for the 750-775nm spectral range, were in good agreement with the calculated efficiencies [8].

IV. CONCLUSION

We have in the paper an overview of diffraction gratings technologies for space-flight instruments or ground-based telescopes that HORIBA Jobin Yvon are able to design and produce. The four main state-of-the-art grating types (ruled blazed low groove density plane reflection grating, high-groove density holographic toroidal and spherical grating and transmission Fused Silica Etched (FSE) grism-assembled grating) were presented. The gratings key parameters such as diffraction efficiency, wavefront quality, compatibility with instrument environments needed for space or astronomy applications were reported theoretically and experimentally.

These achievements prove the high degree of flexibility of the diffraction gratings which can be designed to work in various spectral ranges (from soft-X rays to Mid-Infrared), with groove density from ~30gr/mm to ~5800gr/mm, with different substrate shape (plane, spherical or toroidal), in dimensions up to 500mm, master type or replicated, in reflection or transmission.

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