Feature Article

High Performances Diffraction Gratings for Scientific Applications

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High performances diffraction gratings are usually key components for many scientific applications. Diffraction gratings are used in scientific studies to analyze, measure, propagate or tailor the light sources issued from nature, laser radiation or synchrotron radiation. The three main scientific applications we present are based on three different grating types: *Laser Pulse Compression Gratings, Space Flight Gratings* and *XUV Synchrotron Gratings*. These high performances diffraction gratings for scientific applications are designed and manufactured by HORIBA Jobin Yvon SAS (HJY part of HORIBA Scientific) at Longjumeau (France) in the Optical Components Division.

Introduction

The history of HJY can be traced back to 1819, and began with the collaboration of famous physicists such as Augustin FRESNEL and François ARAGO. Committed to excellence and high performances in optics from its very beginning, it has consistently been one of the leading innovators of state-of-the-art diffraction gratings. In 1968, HJY introduced the first commercially available holographic diffraction grating opening the door to new scientific experiments and applications. Projects are typically identified well in advance since gratings represent a key component for these major facilities and/or projects and such programs may last for 3 or 4 years before the final gratings are needed.

In the laser field, HJY provided the first large gold-coated gratings for the demonstration of the Chirped Pulse Amplification[1] (CPA) technique in 1983. Since this date, HJY pulse compression gratings are widely used by scientists in laser facilities worldwide to produce ultra-short pulses in the femtosecond regime (1 femtosecond = 10^{-15} second) and ultra-high peak power (Petawatt regime = 10^{15} Watt) and intensity up to 10^{20} W/cm^2. Such ultrahigh-peak-power laser systems are used in fundamental research areas, such as high-field physics and the generation of ultra-short energetic electrons and ions. One of the main applications of ultra-intense lasers using HJY pulse compression gratings is the particle acceleration. Scientists develop very compact particles accelerators by laser-plasma interaction. The goal of these compact particles accelerators is to accelerate electrons to very high energies (1 GeV, or a billion electron volts) in a distance of centimeters rather than hundreds of meters with classical accelerator.

Synchrotron facilities and XUV beamlines require for radiation instrumentation very high performances diffraction gratings. HORIBA Jobin Yvon's holographic ion-etched lamellar gratings exhibit ultra-low stray light levels, making them ideal for synchrotron and VUV to soft X-ray applications. These gratings are fully compatible with the latest synchrotron systems, as they are fully engraved in the substrate material and can therefore withstand high thermal loads. A recent innovation developed by HJY in collaboration with SOLEIL Synchrotron is the Variable Groove Depth (VGD) grating we present here.

For space flight missions, HJY is often selected by NASA or ESA agencies for their most demanding experiments. For example, HJY supplied the first 400×400 mm 6000 gr/mm aberration-corrected grating for the Lyman Fuse mission. Similarly, the Hubble Telescope is equipped with an imaging spectrograph, STIS whose gratings are from HJY. In 2000, the company received a rare NASA award in recognition of the holographic gratings for the Cosmic Origin Spectrograph (COS) instrument that will enable a new generation of scientific exploration for the Hubble Space Telescope. More recently, in 2006, NASA Jet Propulsion Laboratory, Organized an award ceremony to acknowledge the on-time delivery of 3 «remarkable» gratings from the HJY production team for the Orbiting Carbon Observatory (OCO) satellite. The OCO satellite's mission consists in accurately measuring the CO_2 content in the atmosphere, in order to evaluate the effect of human activity on our climate and global warming. In 2009-2011, both projects Jovian InfraRed Auroral Mapper (JIRAM) conducted by NASA and Visible Infrared Hyperspectral Imager (VIHI) conducted by ESA, we present here were a great challenge for HORIBA Jobin Yvon grating team. The very high performances gratings produced for these projects were among the most difficult and challenging we have ever produced.

Laser Pulse Compression Gratings Application

Particles Acceleration by Laser-Plasma Interaction

One of the main applications of ultra-intense lasers using HJY Pulse Compression Gratings (PCG) is the particle acceleration. Scientists develop very compact particles accelerators by laser-plasma interaction. The goal of these compact particles accelerators is to accelerate electrons to very high energies (1 GeV, or a billion electron volts) in a distance of centimeters rather than hundreds of meters with classical accelerator. Such ultra-intense lasers are developed worldwide, as for example the BELLA Petawatt laser developed by THALES company for Lawrence Berkeley National Laboratory (LBNL) or the PULSER Petawatt laser developed by Gwangju Institute of Science & Technology - Advanced Photonics Research Institute (GIST-APRI, South Korea).

The use of the Chirped Pulse Amplification (CPA) is widely employed to produce high-energy laser pulses in the femtosecond and picosecond regimes. The basic scheme of a high-intense femtosecond laser is presented on Figure 1. A femtosecond oscillator generates an ultra-short laser light in the near-IR, nanojoule energy, MHz repetition rate. By using only the femtosecond oscillator, the scientific applications are really limited, so an increase of the laser energy and intensity is needed. To increase the laser intensity, the laser pulses need to be stretched from femtosecond to nanosecond duration to avoid damages in optical components. Then, several stages of optical amplifiers allow achieving the Joule energy level. The final stage and the most critical part of the laser is the gratings pulse compressor. The compressor stage is based on a pair or a quadruplet of reflection diffraction gratings; associated with the need to have large gratings with high efficiency, laser-induced damage threshold remains the main limiting factor towards generating higher-energy

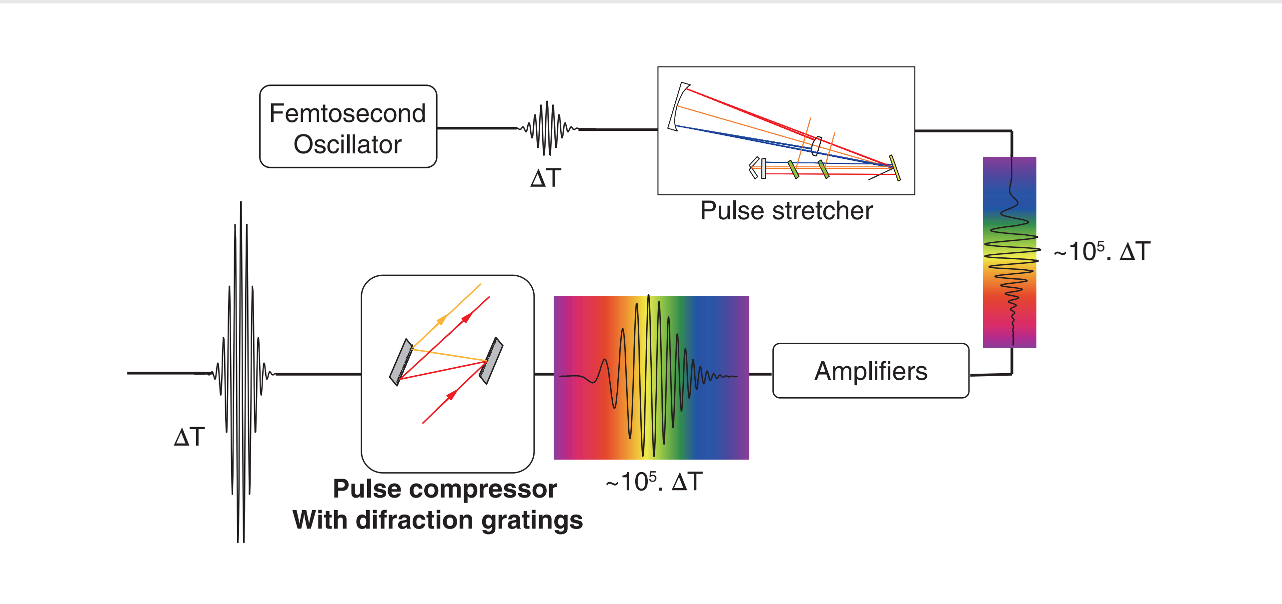
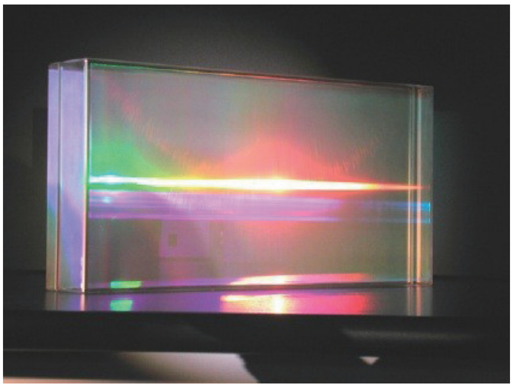


Figure 1 Chirped Pulse Amplification (CPA) technique using high performances diffraction gratings for pulse compression



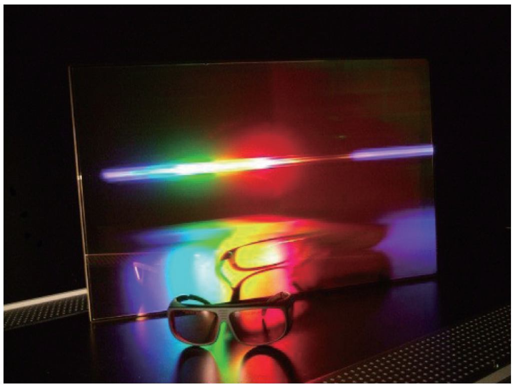


Figure 2 Picture of Multi-Layer Dielectric (MLD) grating (left) and Gold-coated grating (right)

compressed pulses.

In the pulse compressor, two or four large pulse compression holographic gratings (gold-coated or ion-etched on multi-layer dielectric coating represented on Figure 2) are installed in a vacuum chamber to generate a peak power in the range of the Petawatt (10^{15} W) and an achievable intensity up to 10^{20} - 10^{22} W/cm^2.

To achieve these performances, HJY has continuously improved the process and capabilities to be able to propose now to the laser community very large gratings (up to H360×W565×T40 mm). Manufacturing processes and characterization of such pulse compression gratings (PCG) are extremely long and complex.

By installing HJY large pulse compression gratings in the laser system, GIST-APRI team in Korea has succeeded to compress femtosecond pulses up to 1 Petawatt at 0.1 Hz repetition rate[2] which is the world record of peak power at this repetition rate. In parallel, the objective of the BELLA laser, developed by THALES company for LBNL, is to generate 1.3 PW at 1 Hz repetition rate.[3] The large pulse compression gratings manufactured by HJY have been installed in 2011 in a large vacuum chamber to allow the generation of high peak power (Figure 3).

Figure 3 Pulse Compressor vacuum chamber with four HJY gold-coated diffraction gratings

Pulse Compression Gratings manufactured by HJY achieve very high-performances:

- High diffraction efficiency better than 90% to transmit the precious amplified energy,
- Broadband efficiency over 150-200 nm to preserve the amplified spectrum and recompress to the Fourier transform-limit pulse duration,
- High wavefront quality to be able to focus in a diffraction-limited spot,
- High laser damage threshold (LDT) to resist to the highest energy and intensity in the laser system,
- Compatible with air and vacuum,
- Long life time in a pulse compressor.

These gratings can be customized to be adapted to various laser configurations.

XUV Gratings for Synchrotron Application

Synchrotron facilities and XUV beamlines requires for radiation instrumentation very high performances diffraction gratings. HORIBA Jobin Yvon's holographic ion-etched lamellar gratings exhibit very high performances in terms of stray light, diffraction efficiency and by reducing the harmonics contamination. Depending on the application, different types of VUV gratings can be manufactured with various shape (plane, spherical, cylindrical, toroidal), groove density (constant, aberration corrected or Variable Line Spacing (VLS) type)

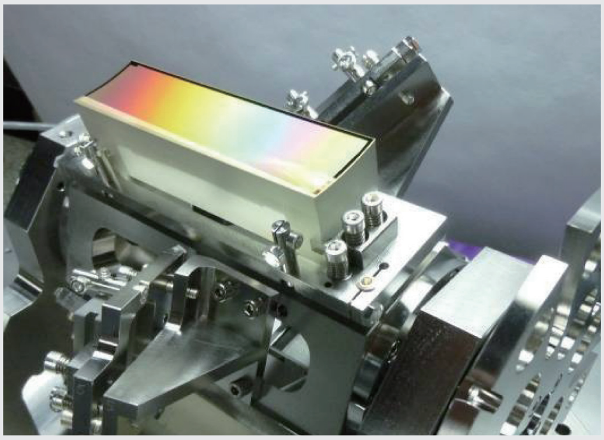


Figure 4 VUV Synchrotron Grating

(Figure 4). The Variable Line Spacing grating displays a groove density variation that is defined by a polynomial law. This type of grating is commonly used in synchrotron beamline designs to correct for the defocusing of a grating monochromator. HORIBA Jobin Yvon and the synchrotron community together have developed software tools to define holographic recording geometries for VLS gratings, which allow us to produce gratings according to an arbitrary polynomial VLS law.

In the VUV gratings field, HJY took part of a major innovation: the Variable Groove Depth (VGD) grating type. The VGD grating type, developed in collaboration with SOLEIL Synchrotron (France), consists in tuning the groove depth of the VUV grating (Figure 5).

By tuning the groove depth from h_{min} to h_{max} (~ 3 or 4 h_{min}), VGD gratings allow a continuous blaze wavelength adjustment and harmonic contamination adjustment, with the same dispersion (same groove density). So, the groove depth is continuously varying from one edge of the ruled area to the other edge. As a result, the grating energy range is enlarged only by translating the VGD grating and all the other high performances of classical HJY ion-etched holographic VUV gratings are conserved. As it is shown on the Figure 5, for different value of groove depth (*h*), the maximum efficiency can be shifted in the energy range.

Space Flight Gratings

HORIBA Jobin Yvon manufactures since a long time space flight gratings either holographic or ruled, in reflection and in transmission. In the past two years, two main projects drove us beyond what we thought being our limits for the manufacture of ruled gratings.

A Grating for JIRAM – Jovian InfraRed Auroral Mapper

The goal of the first one, the NASA JUNO mission, was to obtain a high resolution image of the Jupiter atmosphere and to retrieve its spectral properties in the 2-5 µm spectral range. The JIRAM instrument, for which a low density and low blaze angle grating had to be made, was one of the instruments of this mission. Such a ruled grating is difficult to obtain because of the heavy load on the diamond, which corresponds to tons per cm^2. This makes all the characteristics inherent to ruled gratings more difficult to obtain than for more conventional ones (medium density – few hundreds gr/mm and medium blaze angle). Groove profile (giving the efficiency) and

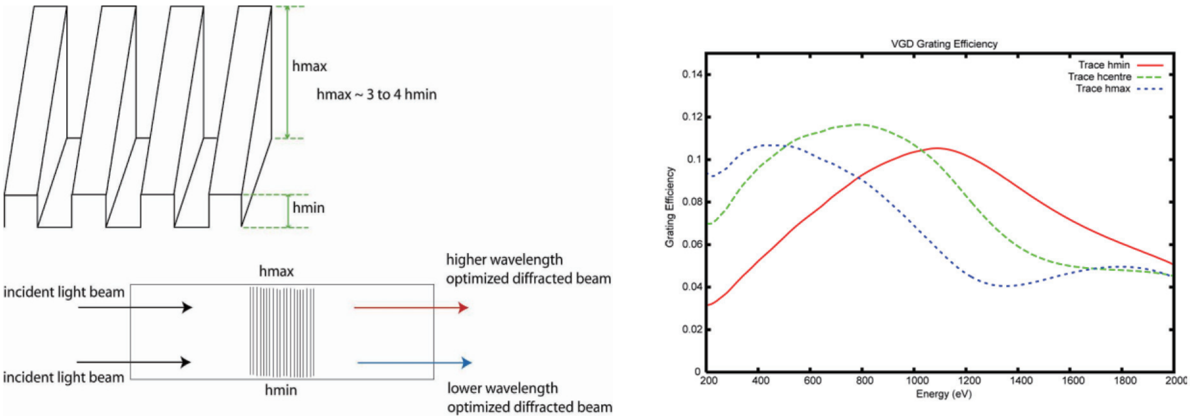


Figure 5 Variable Groove Depth (VGD) grating

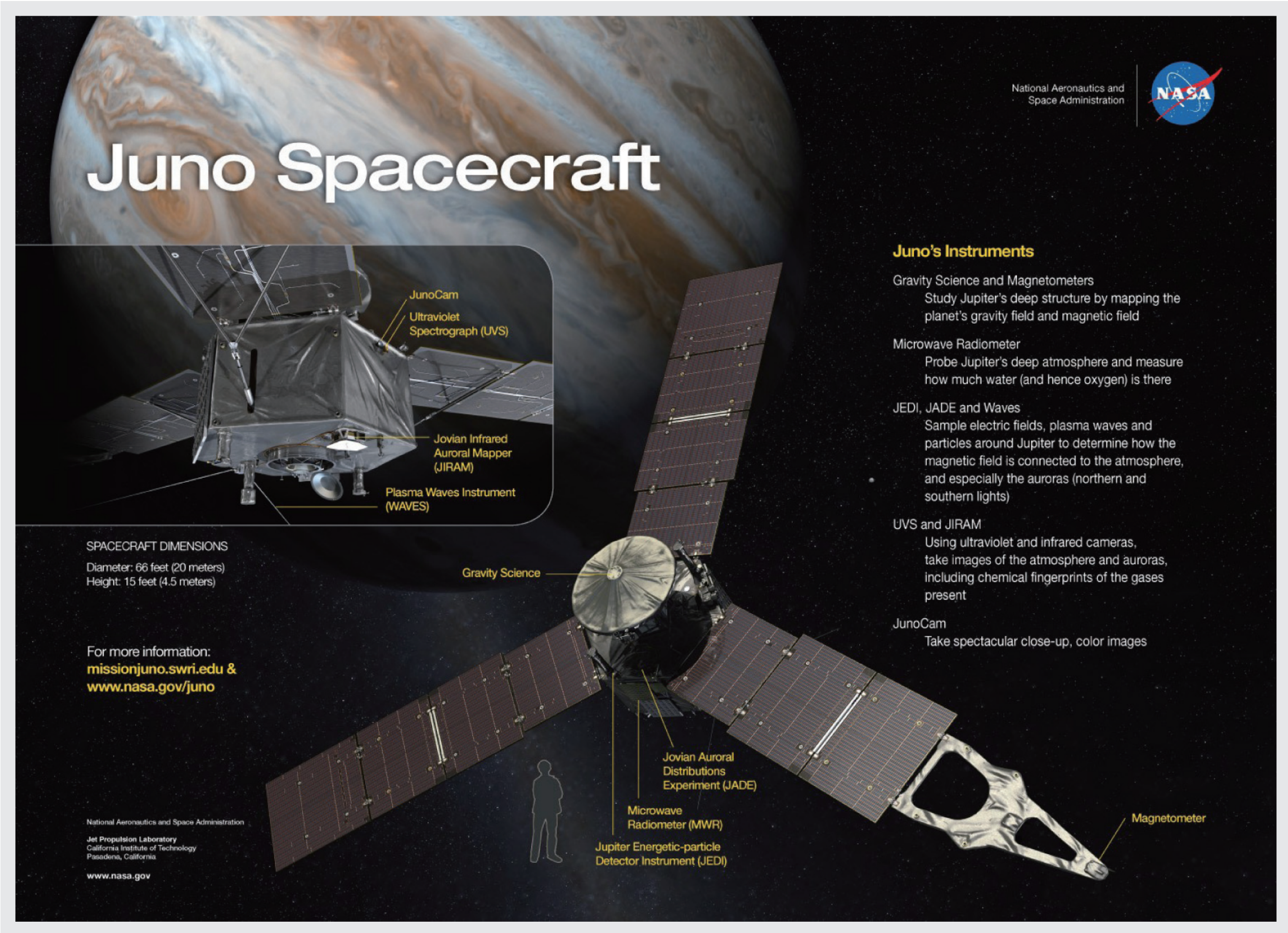


Figure 6 Picture of the JUNO Spacecraft including the HJY grating in the JIRAM instrument

straightness of the grooves (giving the wavefront deviation) are the most critical. The grating, 60×32 mm in dimensions, has 30.3 gr/mm and a very small blaze angle. A relative efficiency of 50% at the peak expected by our customer was raised to more than 90% absolute for the flight model and 85% absolute for the qualification model. The total amount of stray light, mainly due to random groove position errors as low as 18 nm RMS, was also a good surprise for the customer who expected much more from a ruled grating. The permitted wavefront deviation of λ was crushed to λ/8.

All these performances were maintained after severe environmental tests: thermal cycling between 70 °C and -175 °C and 24 h at 50 °C and 95% relative humidity did affect neither optical properties nor aspect, proving that our masters can undergo space conditions. The 4 tons Juno spacecraft was launched August 5, 2011 on an Atlas V rocket from Cape Canaveral and its arrival above Jupiter is expected for July 2016.[4]

A Grating for VIHI – Visible Infrared Hyperspectral Imager

After the success of JIRAM, the customer came back to HJY, asking for a more challenging grating, with a low blaze angle, low groove density and very large spectral range.

The instrument called VIHI (Visible Infrared Hyperspectral Imager) was part of numerous instruments of an international mission Bepi Colombo for Mercury surface observation. Composed of a telescope and spectrometer, the optical configuration of VIHI permits to obtain hyperspectral imaging of the planetary surface in the spectral range 400 - 2000 nm (spectral sampling of 6.25 nm), with a spatial sampling down to 100 m at the periherm. The challenge was to make a single grating with the highest efficiency at the opposite sides of the spectrum were the wavelengths of interest were situated. Finally neglecting the middle of the spectrum, we designed and fabricated a grating with almost twice the efficiency expected by the customer at 400 nm and 50% above the one expected at 2000 nm. As for JIRAM, the gratings succeeded all the environmental tests without any degradation of the optical properties, proving once again the quality of our processes. The launch of the spacecraft is programmed for 2015 by an Ariane V launcher for an arrival in orbit in 2022.[5]

References

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[2] J. H. Sung, S. K. Lee, T. J. Yu, T. M. Jeong, and J. Lee, *Opt. Letters*, 3021-3023, vol.35, No.18 (2010).

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[4] http://www.nasa.gov/mission_pages/juno/main/index.html

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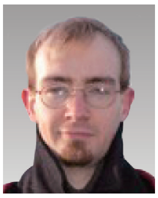

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