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Convex blazed gratings for high throughput spectrographs in space missions

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ABSTRACT

In next generation space instrumentation for Earth and Universe Observation, new instrument concepts include often non planar gratings. Their realization is complex and costly. We propose a new technology for designing and realizing convex blazed gratings for high throughput spectrographs.
For this purpose, our requirements are driven by a Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the Telescopio Nazionale Galileo (TNG) and called BATMAN. The two-arm instrument is providing in parallel imaging and spectroscopic capabilities. The objects/field selector is a 2048 x 1080 micromirrors DMD, placed at the focal plane of the telescope; it is used as a programmable multi-slit mask at the entrance of the spectrograph. The compact Offner-type spectrograph design contains a low density convex grating to disperse light. For optimization of the spectrograph efficiency, this convex grating must be blazed.
A blazed reflective grating has been designed with a period of 3300 nm and a blaze angle of 5.04°, and fabricated into convex substrates with 225 mm radius of curvature and a footprint diameter of 63.5 mm. The blaze is optimized for the center wavelength of 580 nm within the spectral range of 400 – 800 nm. Convex blazed gratings have been fabricated and coated with protected silver, with a final 5.7° blaze angle over the whole surface. Efficiency close to 90% on the 1st diffraction order at 700nm has been obtained.
This new type of non-planar reflective gratings will be the key component for future high throughput spectrographs in space missions.

Key words: non-planar grating, convex blazed grating, spectro-imager, multi-object spectrograph, astronomical instrumentation, MOEMS.

1. INTRODUCTION

In next generation space instrumentation for Earth Observation, new instrument concepts (hyper-spectral imaging and spectroscopy) must be compact, highly efficient and versatile. MOEMS devices may provide new observational modes as generating *a smart-slit* at the entrance of the spectrograph for removing clouds and bright objects (and then decrease greatly the straylight in the instrument), or be the key component of *wide field programmable spectrographs*. [1] These new instrument concepts include often non planar gratings.

Next-generation infrared astronomical instrumentation for ground-based and space telescopes could be based on MOEMS programmable slit masks for *multi-object spectroscopy* (MOS). MOS is used extensively to investigate astronomical objects optimizing the Signal-to-Noise Ratio (SNR): high precision spectra are obtained and the problem of spectral confusion and background level occurring in slitless spectroscopy is cancelled. Fainter limiting fluxes are reached and the scientific return is maximized both in cosmology, in galaxies formation and evolution, in stellar physics and in solar system small bodies characterization.

Major telescopes around the world are equipped with MOS in order to simultaneously record several hundred spectra in a single observation run. Next generation MOS for space like the Near Infrared Multi-Object Spectrograph (NIRSpec) for the James Webb Space Telescope (JWST) will use a programmable multi-slit mask. MOEMS programmable slit masks would be next-generation devices for selecting objects. The programmable multi-slit mask requires remote control of the multi-slit configuration in real time. During the early-phase studies of the European Space Agency (ESA) EUCLID mission, a MOS instrument based on a MOEMS device has been assessed. Due to complexity and cost reasons, slitless spectroscopy was chosen for EUCLID, despite a much higher efficiency with slit spectroscopy.

MOEMS devices such as micromirror arrays (MMA) [2, 3, 4] or micro-shutter arrays (MSA) [5] are promising solutions. MMAs are designed for generating reflective slits, while MSAs generate transmissive slits. In Europe an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy (collaboration LAM / EPFL-CSEM). [6, 7] By placing the programmable slit mask in the focal plane of the telescope, the light from selected objects is directed toward the spectrograph, while the light from other objects and from the sky background is blocked. To get more than 2 millions independent micromirrors, the only available component is a Digital Micromirror Device (DMD) chip from Texas Instruments (TI) that features 2048 x 1080 mirrors and a 13.68µm pixel pitch. DMDs have been tested in space environment (-40°C, vacuum, radiations) by LAM and no showstopper has been revealed. [8]

We are developing a 2048 x 1080 Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the 3.6m Telescopio Nazionale Galileo (TNG) and called BATMAN. [9] A two-arm instrument has been designed for providing in parallel imaging and spectroscopic capabilities. BATMAN will be mounted on the folded Nasmyth platform of TNG. Thanks to its compact design, high throughput is expected. The two arms with F/4 on the DMD are mounted on a common bench, and an upper bench supports the detectors thanks to two independent hexapods. The stiffness of the instrument is guaranteed thanks to a box architecture linking both benches. [10] The volume of BATMAN is 1.4x1.2x0.75 m^3, with a total mass of 400kg. Mounting of all sub-systems has been done and integration of the individual arms is under way. BATMAN on the sky is of prime importance for characterizing the actual performance of this new family of MOS instruments, as well as investigating the new operational procedures on astronomical objects (combining MOS and IFU modes, different spatial and spectral resolutions in the same FOV, absolute (spectro-) photometry by combining imaging and spectroscopy in the same instrument, automatic detection of transients …).
This instrument will be placed at TNG by 2019. [11]

BATMAN concept has also been proposed for a space mission as *BATMAN flies*. [12]

The BATMAN compact Offner-type spectrograph design contains a low density convex grating to disperse light. In order to optimize the spectrograph efficiency, this convex grating must be blazed at the right angle for maximizing the light in the first order of diffraction.

This paper describes the design, the realization and the characterization of a new type of non planar reflective gratings, key components for future high throughput spectrographs in space missions.

2. CONVEX BLAZED GRATING PARAMETERS

BATMAN is a compact spectro-imager with two arms in parallel: a spectroscopic channel and an imaging channel. Both arms are fed by using the two DMD mirrors stable positions (Fig. 1). [9]

The compact Offner-type spectrograph design contains a low density convex grating (SGR in Fig. 1) to disperse light. In order to optimize the spectrograph efficiency, this convex grating must be blazed at the right angle for maximizing the light in the first order of diffraction.

The grating requirements are:

- Convex substrate
- Radius of curvature 225 mm
- Diameter 63 mm
- Number of lines: 300 l / mm

- Wavelength range 400-800 nm
- Center wavelength 580 nm
- Blaze angle 5.04°
- Incidence angle (in-plane) 24°

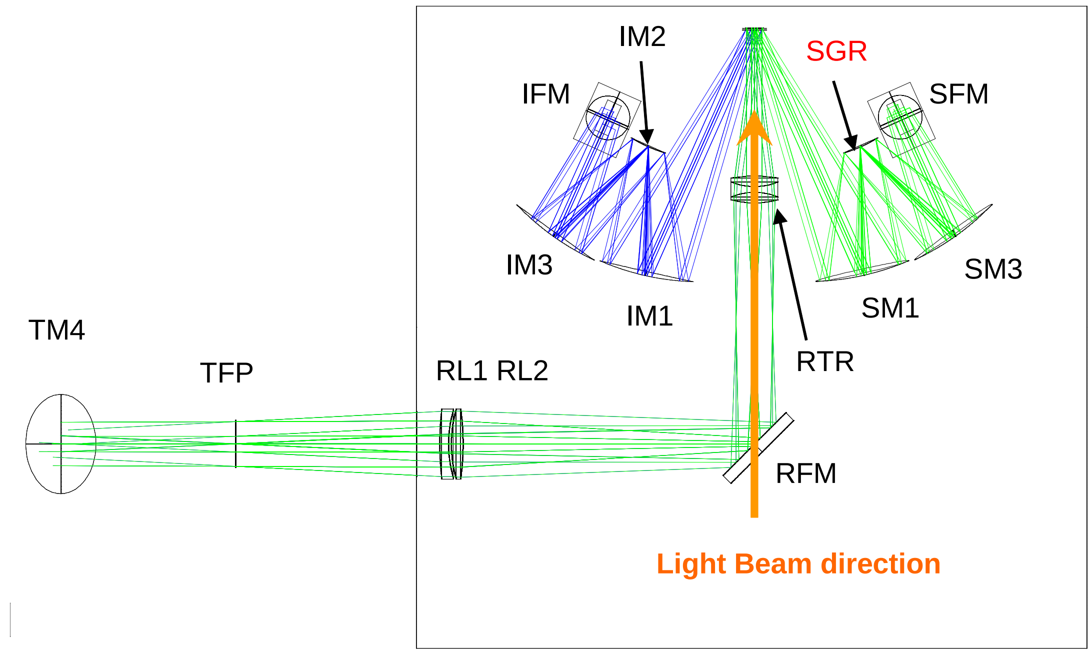

Fig. 1: Principle of BATMAN spectro-imager

The substrate requirements are:

- Quartz / Silicon Oxyde
- λ / 4 surface quality
- Grating pattern etched in substrate

The coating requirements are:

- Protected silver
- Conformal deposition on grating surface

3. CONVEX BLAZED GRATING REALIZATION

The description of the process to realize the master plane blazed grating is shown in Fig. 2.

The master of the blazed grating structure has been originated on a flat substrate starting from a rectangular grating with a period of 3300 nm. The rectangular grating was UV replicated twice using Sol-Gel material and subsequently converted into a blazed shape by angular Ar ion etching. The desired blazed grating parameters like depth and blaze angle have been reached by adjusting the initial grating depth in Sol-Gel as well as the Ar etching angle and duration.

The transfer of the blazed grating from a flat surface onto a convex substrate needs a flexible support. A flexible stamp was generated by UV replication of the blazed grating, utilizing a flexible nanoimprint material (Fig. 3).

- Step 1: 1st Replication.

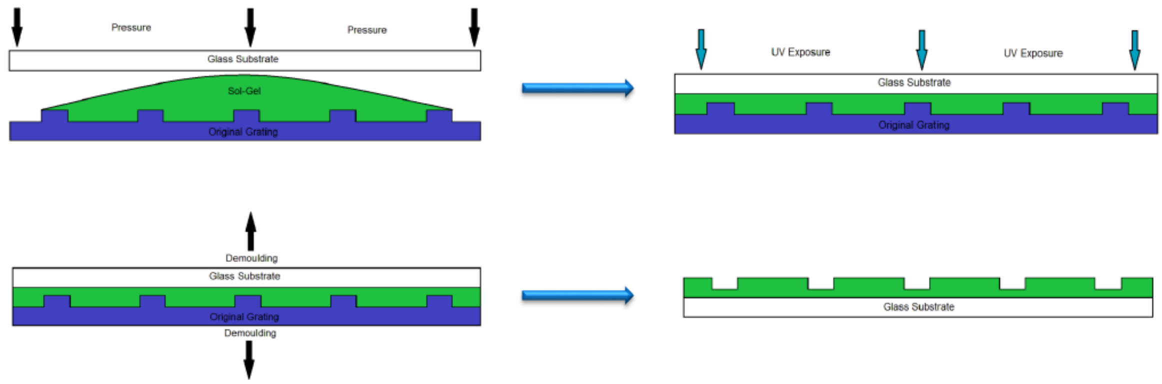

Fig. 2: Convex blazed grating realization (step 1)

- Step 2: 2nd replication
- Step 3: Ar angle etching
- Step 4: Flexible stamp

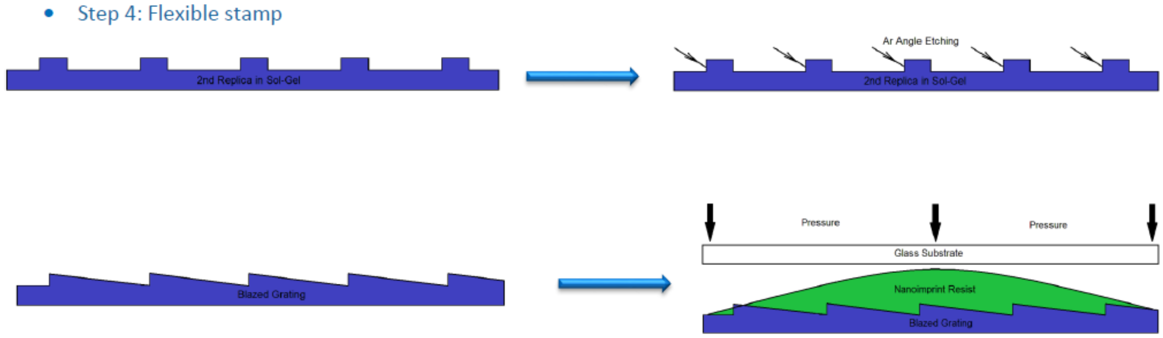

Fig. 3: Convex blazed grating realization (steps 2, 3, 4)

Two approaches have been studied to transfer the blazed grating from a flat surface towards a convex substrate:

- **Blazed Grating Transfer onto a Convex Substrate**
- **Blazed Grating Transfer into a Convex Substrate**

In the first approach, the flexible stamp was used to emboss Sol-Gel spin-coated on the convex substrate. In this approach, the final component is a convex substrate with a Sol-Gel layer carrying the grating structure (Fig. 4)

In the second approach, nanoimprint material is used as a masking layer for Reactive Ion Etching of the convex substrate. Again, the flexible stamp was used to emboss a thin layer of nanoimprint material spin-coated on the convex surface. After curing, the structure was transferred into the quartz substrate by etching. With this approach, the final component is a convex quartz substrate with the grating structure etched into the volume. The monolithic approach is considered more preferable due to the absence of a quartz to Sol-Gel interface prone to fatigue, perfectly suited for space environment. (Fig. 5)

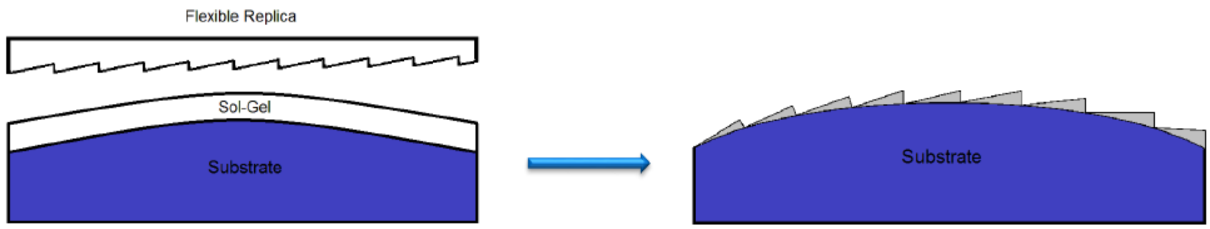

Fig. 4: Blazed Grating Transfer onto a Convex Substrate

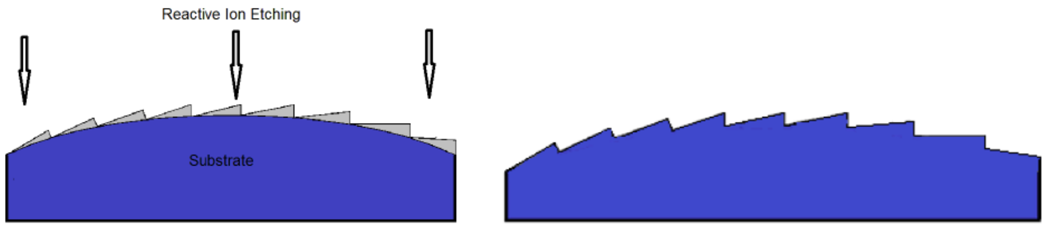

Fig. 5: Blazed Grating Transfer into a Convex Substrate

The two approaches are successful and two gratings have been fabricated. Their surfaces are characterized by Scanning Electron Beam Microscope. The blazed grating transferred onto the convex substrate exhibits very smooth lines and a grating profile with 7° blaze angle (with respect to the expected 5.04°).

The blazed grating transferred into the convex substrate with an additional dry etching step exhibits a final figure even closer to the requirement with a 5.7° blaze angle over the whole surface. All grooves are perfectly defined with a smooth surface (minimizing the straylight of the component). In Fig. 6 are shown a general view and the profile of the realized grating.

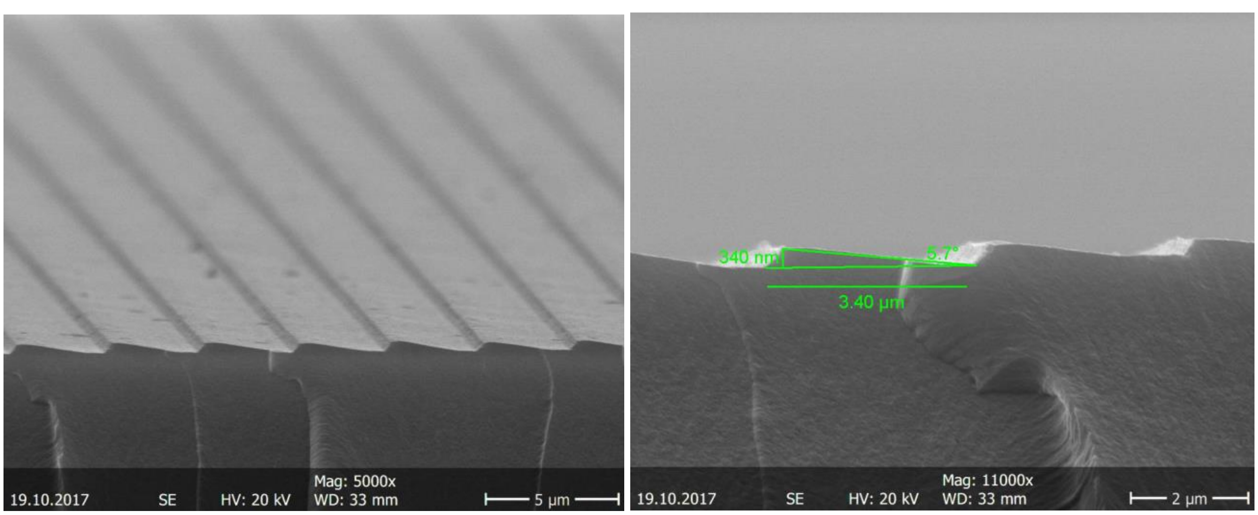

Fig. 6: Blazed Grating Transfer into a Convex Substrate: a final figure of 5.7° blaze angle has been obtained on the whole surface, very close to the required value; general view and profile

The grating coating is protected silver from Optics BALZERS, identical to other BATMAN mirrors coating. The spectral response of the realized coating has been measured by the manufacturer and is shown in Fig. 7. The reflectivity is over 98% over the whole wavelength range (400-800nm).

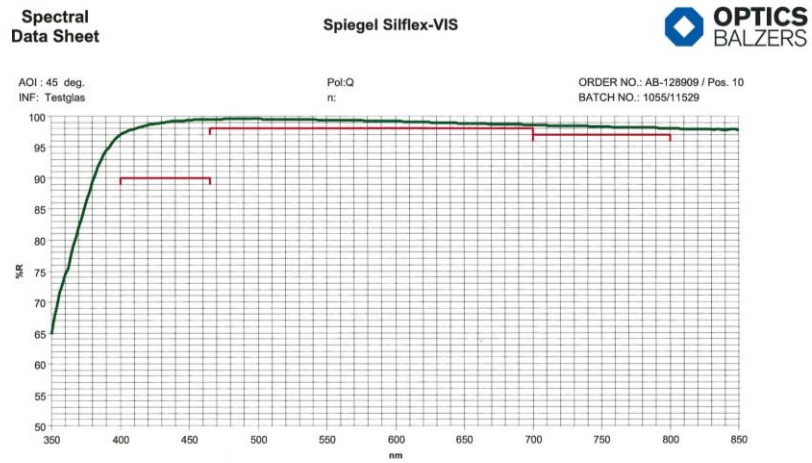

Fig. 7: Coating characteristics deposited on the blazed convex grating

4. CONVEX BLAZED GRATING CHARACTERIZATION

Characterizing a convex blazed grating requires an optical set-up able to collimate the optical beam on the convex surface and then to image the entrance slit on a detector. This complex system is actually equivalent to align one arm of BATMAN (see Fig. 1). Within this instrumental project, we have currently received all optics (mirrors and lenses) as well as all opto-mechanical mounts to hold the optical components. BATMAN integration has started by assembling all sub-systems on a Newport damped table in order to review both the integration procedure as well as a first performance evaluation (Fig. 8). The blazed grating efficiency measurement takes place in this process.

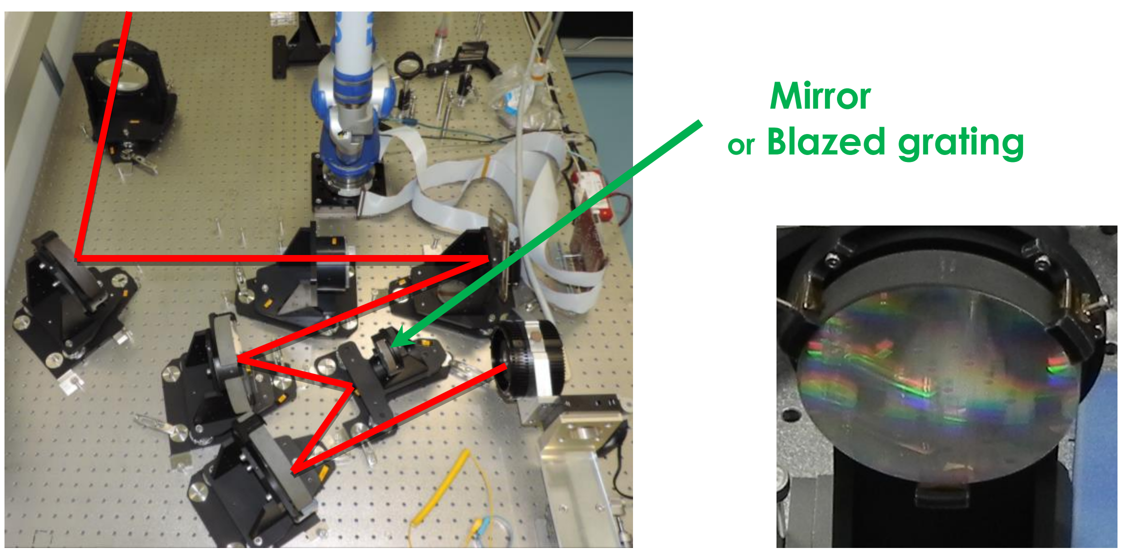

Fig. 8: Blazed convex grating characterization set-up, i.e. BATMAN spectro/imaging arm;
the light path is marked in red from top (instrument entrance) to bottom (detector)
close-view of the realized blazed grating

The input beam is issued from a fibered white light source with a nearly flat response in the visible range. A wavelength selection module is inserted at the output of the source in order to select any wavelength with 1nm wavelength bandwidth. The source is then tunable from 460nm up to 700nm; the output power could be also tuned. The fibre is then placed at the location of the entrance slit of the spectrograph, i.e. at the DMD centre location. The monomode fibre defines then a point source at the entrance of the spectrograph.

The overall grating efficiency has been obtained for the grating inserted in its proper location within the instrument, by measuring the throughput of the set-up while the wavelength is tuned from 460 to 700 nm; these values are weighted by the throughput of the instrument with a convex mirror replacing the convex grating. The response is presented in Fig. 9: an efficiency close to 90% on the 1st diffraction order is obtained at 700nm.

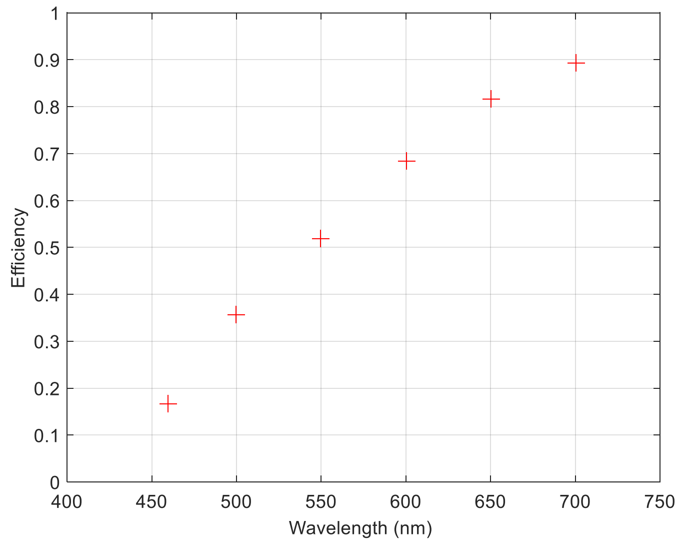

Fig. 9: Blazed convex grating efficiency from 460nm to 700nm

At short wavelength (450-500nm), the efficiency is rather low, leading to the fact that the central wavelength of the component has probably to be shifted to a shorter wavelength for a better balance of the efficiency within the entire wavelength range.

The next steps for the characterization of the blazed convex grating are the measurement of the efficiency for the complete wavelength range from 400 to 800 nm, and the evaluation of the dependence of the efficiency with respect to the polarization. Straylight measurement (BRDF response) is also scheduled.

This new technology is versatile for a wide parameters range, and, as the grating is etched into the substrate, this component is compatible for space applications. Space qualification campaign is then foreseen.

5. CONCLUSION

In next generation space instrumentation for Earth and Universe Observation, new instrument concepts will include non-planar gratings. We have proposed a new technology for designing and realizing convex blazed gratings for high throughput spectrographs.

The designed grating corresponds to the optical component needed for BATMAN spectro-imager instrument. This blazed reflective grating has a period of 3300 nm and a blaze angle of 5.04°. It has been successfully fabricated into convex substrates with 225 mm radius of curvature and a footprint diameter of 63.5 mm. The blaze is optimized for the center wavelength of 580 nm within the spectral range of 400 – 800 nm. Convex blazed gratings have been fabricated and coated with protected silver, with a final 5.7° blaze angle over the whole surface. Performance characterization shows an efficiency close to 90% on the 1st diffraction order at 700nm. This new technology is versatile for a wide parameters range, and, as the grating is etched into the substrate, this component is compatible for space applications

The first instrument demonstration on-sky of this new grating will be done on board BATMAN mounted on the Telescopio Nazionale Galileo by 2019.

This new type of non-planar reflective gratings will be the key component for next generation compact and highly efficient spectrographs.in space missions, for Universe Observation, Earth Observation and Planetology.

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REFERENCES

[1] Frederic Zamkotsian, Arnaud Liotard, Patrick Lanzoni, T. Viard, " Optical MEMS in space instruments for Earth Observation and Astronomy", *Proceedings of the SPIE conference on MOEMS 2013*, Proc. SPIE **8616**, San Francisco, USA, Février 2013

[2] R. Burg, P.Y. Bely, B. Woodruff, J. MacKenty, M. Stiavelli, S. Casertano, C. McCreight and A. Hoffman, "Yardstick integrated science instrument module concept for NGST", in *Proceedings of the SPIE conference on Space Telescope and Instruments V*, SPIE **3356**, 98-105, Kona, Hawaii, (1998)

[3] F. Zamkotsian, K. Dohlen, D. Burgarella, V. Buat, "Aspects of MMA for MOS: optical modeling and surface characterization, spectrograph optical design", in *Proceedings of the NASA conference on "NGST Science and Technology Exposition"*, ASP Conf. Ser. **207**, 218-224, Hyannis, USA, (1999)

[4] M. Robberto, A. Cimatti, A. Jacobsen, F. Zamkotsian, F. M. Zerbi, "Applications of DMDs for Astrophysical Research", in *Proceedings of the SPIE conference on MOEMS 2009*, Proc. SPIE **7210**, San Jose, USA, (2009)

[5] M. J. Li; A. D. Brown; A. S. Kutyrev; H. S. Moseley; V. Mikula, " JWST microshutter array system and beyond", Proc. SPIE **7594**, San Francisco, USA (2010)

[6] S. Waldis, F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij, "Micromirrors for multiobject spectroscopy: optical and cryogenic characterization", in *Proceedings of the SPIE conference on MOEMS 2008*, Proc. SPIE **6887**, San Jose, USA (2008)

[7] M. Canonica, F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij, "The two-dimensional array of 2048 tilting micromirrors for astronomical spectroscopy," Journal of Micromechanics and Microengineering, 23 055009, (2013)

[8] F. Zamkotsian, P. Lanzoni, E. Grassi, R. Barette, C. Fabron, K. Tangen, L. Valenziano, L. Marchand, L. Duvet "Successful evaluation for space applications of the 2048x1080 DMD," in *Proceedings of the SPIE conference on MOEMS 2011*, Proc. SPIE **7932**, San Francisco, USA (2011)

[9] F. Zamkotsian, P. Spano, L. Martin, M. Riva, P. Lanzoni, F. Zerbi, L. Valenziano, L. Nicastro, "DMD-based MOS demonstrator on Galileo telescope," in Proceedings of the SPIE conference on Astronomical Instrumentation 2010, Proc. SPIE **7735**, San Diego, USA, (2010)

[10] Frederic Zamkotsian, Harald Ramarijaona, Manuele Moschetti, Patrick Lanzoni, Marco Riva, Nicolas Tchoubaklian, Marc Jaquet, Paolo Spano, William Bon, Romain Alata, Luciano Nicastro, Emilio Molinari, Rosario Cosentino, Adriano Ghedina, Manuel Gonzalez, Walter Boschin, Paolo Di Marcantonio, Igor Coretti, Roberto Cirami, Filippo Zerbi, Luca Valenziano, "Building BATMAN: a new generation spectro-imager on TNG telescope ", in Proceedings of the SPIE conference on Astronomical Instrumentation 2016, Proc. SPIE **9908**, Edinburgh, United Kingdom, (2016)

[11] Frederic Zamkotsian, Patrick Lanzoni, Nicolas Tchoubaklian, Harald Ramarijaona, Manuele Moschetti, Marco Riva, Marc Jaquet, Paolo Spano, William Bon, Mathieu Vachey, Luciano Nicastro, Emilio Molinari, Rosario Cosentino, Adriano Ghedina, Manuel Gonzalez, Walter Boschin, Paolo Di Marcantonio, Igor Coretti, Roberto Cirami, Filippo Zerbi, Luca Valenziano, " BATMAN @ TNG: Instrument integration and performance", in Proceedings of the SPIE conference on Astronomical Instrumentation 2018, Proc. SPIE **10702**, Austin, USA, (2018)

[12] F. Zamkotsian, O. Ilbert, J. Zoubian, A. Delsanti, S. Boissier, A. Lancon, " BATMAN flies: a compact spectro-imager for space observation," in Proceedings of the SPIE conference on Astronomical Instrumentation 2014, Proc. SPIE **9143**, Montreal, Canada, (2014)