

Multi-zone holographic aberration-corrected concave blazed EUV gratings for the MUSE mission

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ABSTRACT

The NASA MIDEX mission MUSE (Multi-Slit Solar Explorer) will investigate the dynamics and heating of the solar corona. Its spectrograph is optimized for a small set of narrow extreme ultraviolet passbands. A key element of the spectrograph is a concave blazed diffraction grating that must simultaneously disperse three EUV wavelengths, each incident on different regions of the grating due to a segmented optical filter geometry. Here, we report on the fabrication of multi-zone holographic aberration-corrected EUV gratings manufactured on concave fused silica substrates at ZEISS. The grating lines and blaze profile are generated in a single holographic exposure using an interference lithography setup with aberration correction. A subsequent three-step reactive ion beam etching process, combined with zone-selective metallic masks, transfers the resist profile into the substrate with tailored blaze angles in three areas. Atomic force microscopy demonstrates highly uniform groove width and blaze/anti-blaze ratios, with blaze angles matching design values. Rigorous coupled-wave analysis based on the measured profiles predicts excellent peak grating efficiencies for all wavelengths. Ray-tracing spot diagram analysis confirms that the aberration-corrected gratings meet the spectrograph requirements enabling high-cadence, high-resolution coronal spectroscopy for MUSE.

Keywords: holography, interference lithography, blazed grating, EUV optics, MUSE, space mission

1. INTRODUCTION

The NASA MIDEX mission MUSE (= Multi-Slit Solar Explorer) currently scheduled for launch in mid-2027 [1] aims at making a significant step in understanding the dynamics within the sun's corona. It focusses on investigating physical processes in the solar outer atmosphere leading to the heating of coronal plasma, the dynamics of solar wind and events such as flares as well as coronal mass ejections. For the first time, it will be possible to perform spectroscopic measurements with unprecedented spatial and temporal resolution as well as spatial coverage by using a multi-slit technology and a rigorous focus on a few pre-selected and narrow extreme ultraviolet (EUV) spectral passbands.

The mission satellite carries two main instruments operating in the EUV regime: a 25 cm EUV multi-slit spectrograph (SG) and a 20 cm EUV context imager (CI), please see Figure 1 for illustration.

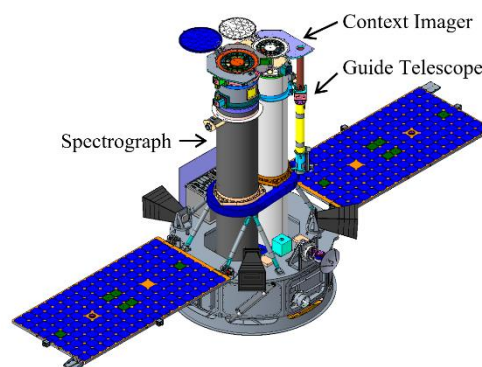


Figure 1. Illustration of MUSE satellite carrying Spectrograph (SG), Context Imager (CI) and Guide Telescope. Courtesy of the MUSE project [2].

While the CI module is intended to take images of the solar corona at spectral bands 19.5 nm and 30.4 nm, the SG unit will perform spectral imaging at three different wavelengths chosen for optimum count rates with respect to the expected solar emission spectrum: 10.8 nm, 17.1 nm, 28.4 nm, respectively [3],[4]. The anticipated higher photon budget allows for shorter illumination times enabling temporally resolved spectra with a cadence of 12 s [5].

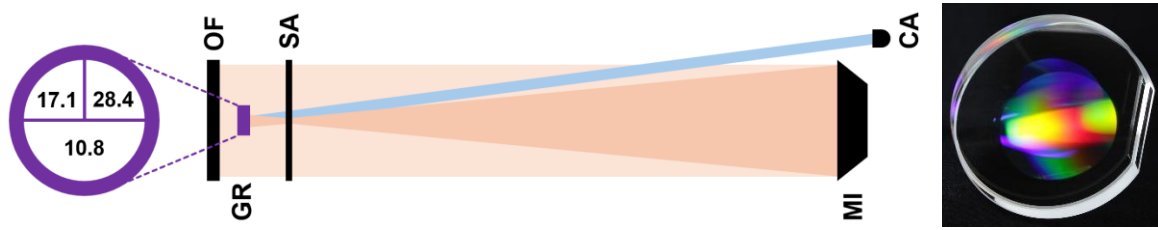


Figure 2. Left: Schematic of the MUSE spectrograph (SG) in the satellite (side view). Solar light travels through optical filters (OF), is reflected by a mirror (MI) and propagates further through the slit array (SA) onto the grating (GR). The diffracted light journeys towards a back-illuminated CCD (CA) where it is detected. Right: Picture of the holographically exposed resist grating sample.

The composition of the SG unit can schematically be seen in Figure 2. The EUV light enters the module through the optical filter module, is reflected by the primary mirror, then travels through the multi-slit array to the central dispersive element, the EUV grating. The diffracted part of the incident light is finally collected by a CCD camera. The optical filters (based on carbon nanotube pellicles [6]) are arranged in three sectors in a way that only light with a wavelength of around 28.4 nm passes through the upper right part of the filter, only light with around 17.1 nm through the upper left part and only light with around 10.8 nm through the bottom half of the filter – effectively trisecting the incident beam cross section and likewise mapping the different wavelengths in their respective sectors onto the multi-slit arrays as well as the grating (see sketch in Figure 2). Consequently, the required grating needs to disperse three different wavelengths in three different areas, thus making it inevitable to establish a multi-zone manufacturing strategy to selectively adjust grating parameters. The optical design of the spectrograph further requires the grating to have a concave surface, a grating efficiency of $> 60\%$, a spectral resolution of > 8000 and an aberration-correction to ensure detector images as small as $23\ \mu\text{m}$ (geometrical radius) and $10\ \mu\text{m}$ (RMS radius), respectively.

2. DETERMINISTIC CHANGE OF LOCAL GRATING PARAMETERS

Over the past decades, several techniques were developed that achieve local variations within a blazed grating by either altering the groove height, the groove period or the groove shape. One of the main driving forces behind all these efforts is a longing for maximum diffraction efficiency, i.e. for the compensation and enhancement of locally varying grating efficiency for specific diffraction orders. Special care was given to avoid or suppress wavefront discontinuities at the boundary of neighboring segments. For the MUSE mission, incident light is already divided into separate segments by optical filters at the SG entrance, thus making it less important to optimize the overall wavefront. However, since EUV optics always suffer from limited photon budgets due to e.g. low mirror reflectivity, every individual segment needs to be fine-tuned for maximum diffraction efficiency to achieve a sufficient signal-to-noise ratio.

Most famously, mechanical ruling machines can divide a grating into several sections with different groove characteristics by adjusting the tilt of the diamond tip in use and thereby approximating the locally blazed angle in a stepwise manner. While on the one hand mechanically ruled gratings are easy to fabricate, they are on the other hand known for the formation of uncorrelated line patterns with inferior imaging performance and suffer from stray light (e.g. Rowland ghosts). A more mature choice for the manufacturing of high-quality blazed gratings for space applications is a combination of advanced lithography techniques (such as grey-scale lithography, e-beam lithography or interference lithography) and reactive ion-beam etching. Grey-scale lithography and e-beam lithography offer flexible, arbitrary topographies on a single substrate but suffer from limited resolution and long exposure / processing times. Therefore, the natural choice among the litho-family would be interference lithography (or holography) that provides highly uniform periodic patterns over large areas.

Holography can be viewed as the formation of Bragg grating-like regions with spatially varying development rates (i.e., solubility in alkaline developers) within a photoresist layer by generating a standing wave pattern from at least two interfering waves at the surface of a photoresist-coated substrate. Since this exposure occurs simultaneously over the entire grating area within a defined time window, the standing wave pattern must remain as stable as possible during recording

to achieve high solubility contrast and thereby obtain an optimal resist profile after development. The spacing of the Bragg planes depends on the local refractive index and is therefore, for example, smaller in the substrate than in air. In the photoresist, the standing Bragg-like intensity modulation is “imprinted” into the material by inducing chemical changes in its properties. Consequently, the local solubility of the resist in alkaline developers increases with increasing exposure dose. By choosing suitable development conditions, a “developing sweet spot” can be achieved in which the development front advances predominantly parallel to the former Bragg planes, resulting in a blazed surface-relief photoresist grating [7],[8].

After development, the blazed resist profile must be proportionally transferred into the glass substrate. The peak efficiency of the blaze can be matched to the target wavelengths by tuning the etched profile depth in the substrate during the reactive ion beam etching (RIBE) step. The depth transfer ratio between resist and substrate can be adjusted depending on resist and substrate material. For fused silica, transfer ratios ranging from about 0.1 (profile shrinkage) up to 20 (profile amplification) can be achieved [9]. By splitting the transfer process into several steps, covering the sample with thin specially designed metal masks for every step and bringing these masks very close and accurately positioned above the resist pattern, pre-defined regions can be etched with different transfer ratios creating areas with different blaze profile characteristics [10].

3. GRATING FABRICATION

Suitable EUV substrates must combine extreme surface quality, dimensional stability, and vacuum compatibility. They require ultra-low surface roughness (sub-nm range) and form accuracy to minimize scatter and wavefront errors. The substrate material should exhibit low thermal expansion, high stiffness, and long-term mechanical stability, ensuring that temperature changes, self-weight, and mounting forces do not induce deformations. Chemical purity and compatibility with EUV multilayer coatings is also essential to guarantee high reflectivity and stable interfaces without diffusion or reaction under EUV exposure.

For this project, fused silica was chosen as base material. Although it does not possess ideal properties with respect to thermal expansion and mechanical stiffness, it offers compatibility to ultra-precision finishing processes such as deterministic polishing and ion beam figuring. Within this project, all grating substrates were fabricated in-house at ZEISS. By applying several steps of polishing (incl. pitch polish, ion beam figuring and AFM polish), surface microroughness as small as 0.2 nm and tangential slope errors of only 0.25 μ rad were achieved on concave fused silica substrates providing excellent surface quality for the targeted EUV applications.

Grating lines and blaze profile were exposed by using interference lithography in a standard holographic W-shaped optical setup [11] into a thin layer of spin-coated photoresist onto concave substrates. Herein, the whole grating aperture with a target line density of 2400 L/mm was exposed at once without separating individual grating segments. Additional auxiliary optics were used in the setup during exposure to compensate for aberration induced optical effects and minimize the final spot size on the spectrograph detector (please see next section for spot size calculations). The corresponding line density distribution was deduced from a Moiré pattern created by adding a reference field [12]. The aberration correction turns out to have terms up to 3rd order and shows that aberration effects are compensated best at the center of the substrate and deviate further towards the edges (not shown). The holographically exposed resist grating on its concave fused silica substrate can be seen in Figure 2, right.

area	λ (nm)	θ_B	h_B (nm)	m
A1	10.8	1.48	8.6	+2
A2	17.1	2.35	13.7	+2
A3	28.4	1.95	11.4	+1

Table 1. Target parameters for blaze angle θ_B and profile height h_B (assuming 80% effective blaze length) after etching for three different grating areas A1, A2 and A3, respectively. EUV passbands with wavelength λ and used diffraction orders m are given for sake of completeness.

The final step of grating fabrication for the MUSE mission is the most delicate. It consists of a subsequent three-fold transfer of the grating from the photoresist onto the substrate requiring reactive ion etching in three steps including the

usage of three different metallic masks. The predetermined target parameters for the individual etch steps can be found in Table 1.

4. GRATING CHARACTERIZATION

The final gratings were characterized by using atomic force microscopy (AFM). Respective exemplary measured height profiles are depicted in Figure 3 as blue curves. All different grating areas exhibit well-known asymmetric saw-tooth like profiles with distinct blaze (flat slope) and anti-blaze (steep slope) parts. Subsequently, both sloped regions were approximated linearly with least-square fits (shown as red lines). The derived fit parameters are given above each panel. Truly remarkable is the uniformity of groove width and blaze-to-anti-blaze ratio, a key feature of holographic gratings. In addition to that, achieved blaze angles after reactive ion beam etching match very well with target parameters (see Table 1) and show angular deviations $< 0.2^\circ$.

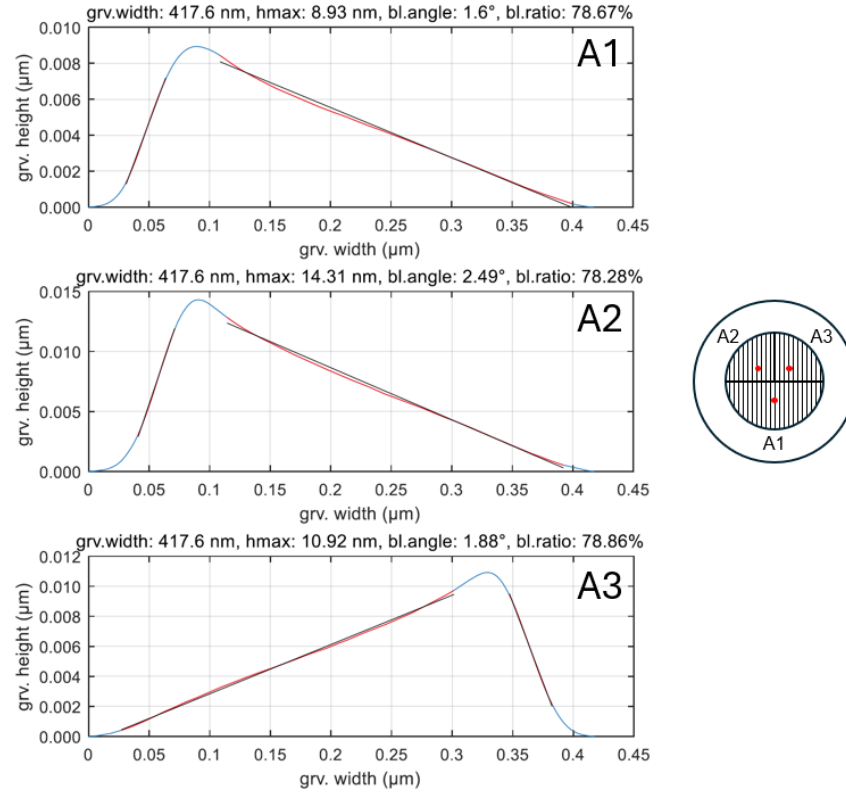


Figure 3. Height profiles (blue lines) for three different grooves from three different grating areas A1, A2 and A3, respectively, on a single concave fused silica substrate fabricated for the MUSE mission. The profiles were measured after final etching step by means of atomic force microscopy. The blaze and anti-blaze slopes were fitted (red lines) to derive crucial blaze properties. The profiles show excellent uniformity in terms of groove width and blaze/anti-blaze ratios as well as very good overall agreement with target blaze angle values. Right: Sketch of the grating substrate. Red dots indicate measurement positions.

To assess the diffraction efficiency of fabricated gratings, measured AFM profiles were used as input data for numerical calculations based on rigorous coupled-wave analysis (RCWA). Derived efficiency curves can be found in Figure 4 as function of wavelength for all three grating areas and for diffraction orders 0 to ± 4 . The top panel shows respective grating efficiencies for area A1 designed for an EUV wavelength of 10.8 nm (indicated by vertical black line). By using the corresponding blaze profile from Figure 3, the narrow +2nd diffraction order efficiency peak matches the target wavelength very well and simultaneously offers a grating efficiency of $> 60\%$. A very similar observation can be made for the A2 area and 17.1 nm target wavelength shown in the middle panel of Figure 4. A slightly different picture evolves for area A3 and EUV passband 28.4 nm (bottom panel). A broad efficiency peak from the +1st diffraction order can be observed around the target wavelength exceeding grating efficiencies of 70%.

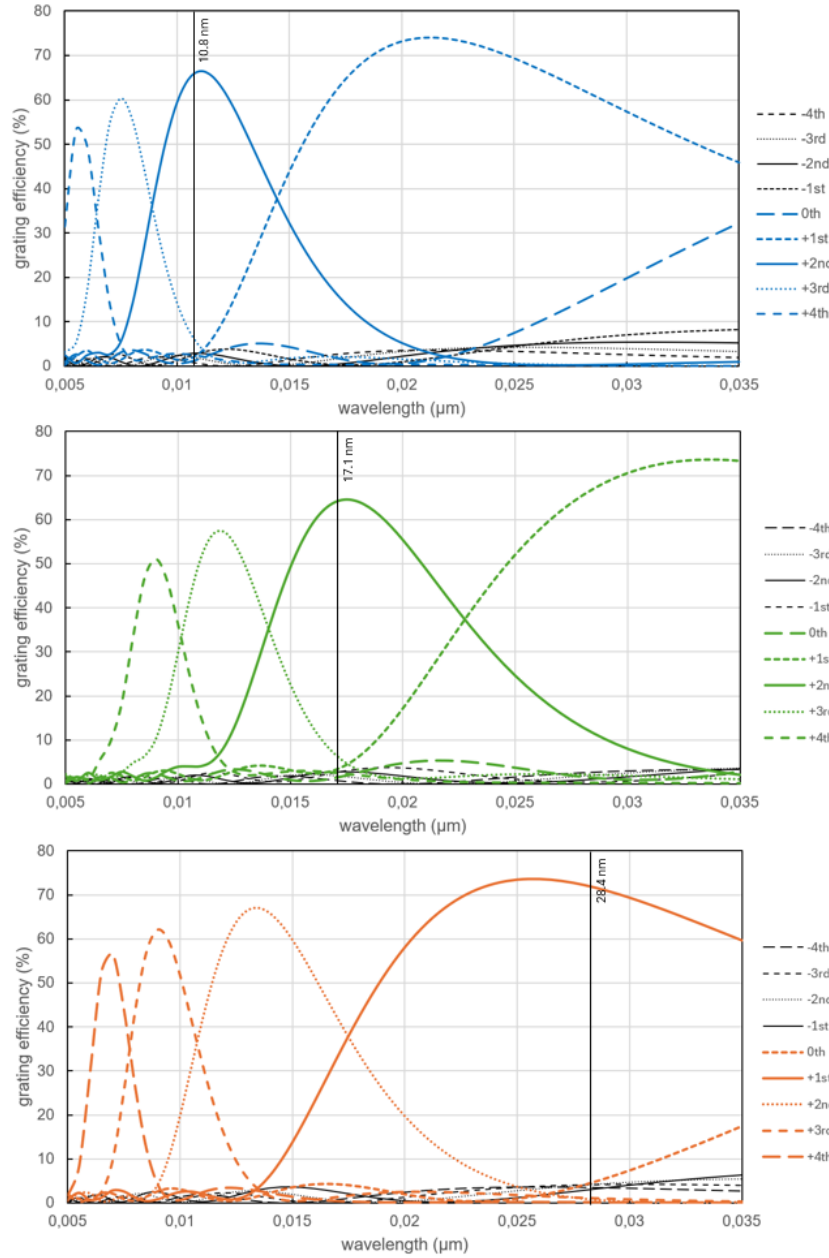


Figure 4. Calculated diffraction efficiency as a function of wavelength for three gratings areas of the MUSE grating optimized at different target wavelengths. Groove profiles from Figure 3 were used as input for the calculations, respectively. Each panel shows the efficiency of diffraction orders 0th to ± 4 th (line styles indicated in the legend). While grating areas optimized at 10.8 nm (blue) and 17.1 nm (green) show a pronounced efficiency peak in the +2nd order around the design wavelength, the grating area optimized at 28.4 nm exhibits a broad maximum in the +1st order around the target wavelength. Vertical lines mark the respective design wavelengths in each panel.

Besides individual grating parameters such as line density, groove profile and grating efficiency, also spectrograph properties such as spectral resolution and detector spot sizes are of major importance for assessing the SG performance. For this purpose, we have calculated spot diagrams for all three EUV passbands and for three different field angles that potentially form at the focal point in front of the SG detector. The corresponding images can be found in Figure 5. Their size and shape give insight into the quality of the focus as well as the applied aberration correction, respectively. Please

note that a fully focused and aberration-corrected spot would be circular and within the Airy disk (shown as black circle). Spot images show some off-axis contributions indicating remaining non-corrected aberrations but are in very well agreement with theoretical spot profiles (not shown). From the images we can easily deduce geometrical and RMS radii (values are given at the bottom of each panel). The extracted values match almost perfectly with grating specifications (see above).

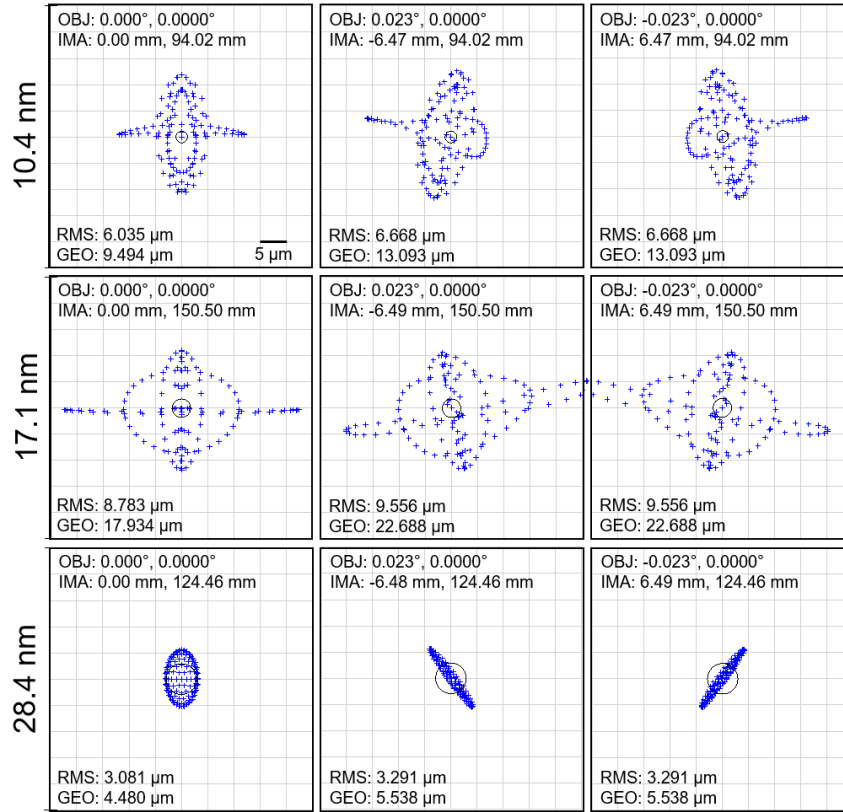


Figure 5. Spot diagrams of SG for different grating areas designed for wavelengths 10.4 nm (top), 17.1 nm (middle), and 28.4 nm (bottom). Different columns represent different field angles: on-axis field (left) and two symmetric off-axis field points (middle and right). Blue crosses represent ray intersections on the image plane; concentric circles indicate reference Airy disc. For 10.4 nm and 17.1 nm the spots are extended due to residual aberrations, whereas at 28.4 nm the spots are more compact.

5. SUMMARY

In conclusion, we have demonstrated a technology platform to successfully fabricate multi-zone holographic aberration-corrected concave blazed EUV gratings suitable for space applications such as the NASA MUSE multi-slit spectrograph. The spectrograph requires a single concave grating that efficiently disperses three EUV passbands at 10.8 nm, 17.1 nm, and 28.4 nm, with high diffraction efficiency, high spectral resolution, and small spot sizes ($< 23 \mu\text{m}$, geometrical radius, $< 10 \mu\text{m}$ RMS radius). To meet these requirements, ZEISS fabricated ultra-smooth concave fused silica substrates and used interference lithography in a W-shaped holographic setup, including auxiliary optics to implement aberration correction, to expose a blazed grating with a line density of roughly 2400 L/mm over the full aperture. A tailored three-step reactive ion beam etching process with zone-selective metallic masks then transferred the blazed resist profile into three distinct grating areas, each optimized for a specific wavelength and diffraction order. AFM measurements confirm highly uniform, asymmetric saw-tooth groove profiles and blaze angles matching the design angles within 0.2° , while rigorous coupled-wave analysis based on the measured profiles predicts peak efficiencies above 60% for the 10.8 nm and 17.1 nm bands in the +2nd order and above 70% for 28.4 nm in the +1st order. Spot calculations verify that residual aberrations are well controlled and that the grating meets the imaging and resolution goals of the MUSE spectrograph, enabling high-throughput, high-cadence EUV coronal spectroscopy during the span of the space mission.

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