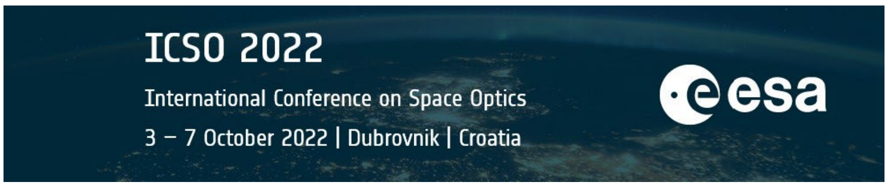
International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,



Black aperture coating with an anti-reflective clear aperture – developed and qualified for space-based applications

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127775I · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691027

Black aperture coating with an anti-reflective clear aperture – developed and qualified for space-based applications

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ABSTRACT

The monitoring of anthropogenic CO_2 by satellites (part of Copernicus, the European Union's Earth Observation and Monitoring program) requires a special dispersive spectrometer. As a highly efficient light dispersing element, a Prism-Grating Prism (PG-P) optical element will operate in the program, mentioned above.

Anti-reflection (AR) coatings and light blocking apertures are requested to suppress optical losses, to reduce stray light and to shape the beam. Beside the AR-coatings, deposition of "black" aperture as a coating directly on the PG-P element, allows to abstain a mechanical aperture. Thereby, reduced number of elements in the optical setup and therefore reduced payload of the satellite can be achieved. For this purpose, an antireflective coating inside a clear aperture combined with a light blocking and absorbing aperture-coating outside the clear aperture was realized. The developments shown in this contribution were performed for the application wavelength of 1590 - 1675 nm.

Keywords: Coating, aperture, clear aperture, black, anti-reflection, prism.

1. INTRODUCTION

Enabling the monitoring of anthropogenic CO_2 by satellites is part of Copernicus, the European Union's Earth Observation and Monitoring program. As part of this mission, the CO_2 monitoring shall be realized by means of a dispersive spectrometer with three channels. The NIR-channel is around the wavelength of ~ 760 nm, the SWIR1-channel is around the wavelength of ~ 1630 nm and the SWIR2-channel is around the wavelength of ~ 2040 nm. The spectral bandwidth of all channels is < 110 nm.

As a highly efficient light dispersing element, a Prism-Grating Prism (PG-P) configuration was developed at Fraunhofer-IOF [1] and is applied for the mission, mentioned above. Different fused silica types were chosen as prism materials, depending on their suitability for the particular channel. In addition, separate optical coatings have been done for all three channels. In this contribution, the PG-P for the SWIR1-channel is considered.

The Prism-Grating Prism (PG-P) assembly, as shown in Figure 1, consists of the disperser prism that is bonded to a grating and a counter prism, which is used for aberration correction and aperture definition [2].

Anti-reflection coatings are necessary on all entrance and exit surfaces [3]. Otherwise, considerable Fresnel losses would appear due to high angles of incidence (AOI) [4]. As shown in figure 1, different AOIs exist for the three different entrance and exit facets. However, a single anti-reflection (AR) coating was developed, which covers the three different AOI ranges. Thus, the same AR-coating could be applied for all three sides.

For the entrance surface of the counter prism, a light blocking aperture is requested to suppress stray light and shaping the beam [5]. To minimize stray light inside the disperser setup, black apertures, which absorb light outside the clear aperture (CA), are an effective tool. By depositing a black aperture as a coating directly on the surface of an optical element, a mechanical aperture can be replaced, and a precise beam guidance can be realized [6]. This substitution is of great interest in space-based applications, due to the possibility of reducing the number of elements in the optical setup and payload of satellites [7].

This contribution is focusing on the entrance surface, because both - the AR-coating and the aperture - have to be implemented at this surface. At Fraunhofer IOF, the development and fabrication of a black aperture with an antireflection coating inside the CA, directly deposited on the optical surface of a prism has been realized. Figure 2 shows a picture of the manufactured entrance surface of the counter prism.

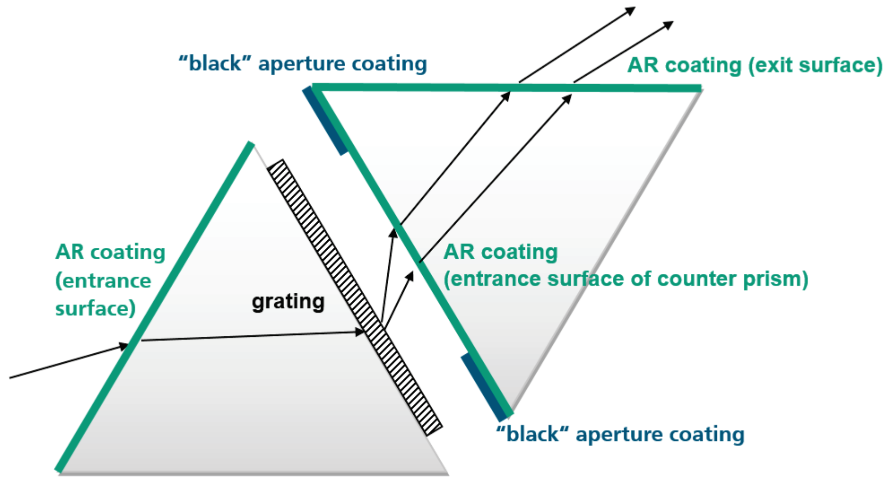

Figure 1: Scheme of the Prism-Grating Prism assembly for the CO2M SWIR1 channel.

The blue area in figure 2 shows the "black" aperture. The blue color results from the interference effect of the multilayer, which is optimized for the SWIR1 wavelength range between 1590nm and 1675nm and an angle of incidence (AOI) of 50.6°- 60.1°. For these conditions, the aperture has a "blackening" effect, which means that the reflections and transmission is minimized. The green area in figure 2 shows the CA with the AR-coating. In analogy to the "black" aperture, the coating is tailored for an optimal AR effect in case of the SWIR1 channel (wavelength and AOI of SWIR1 channel).

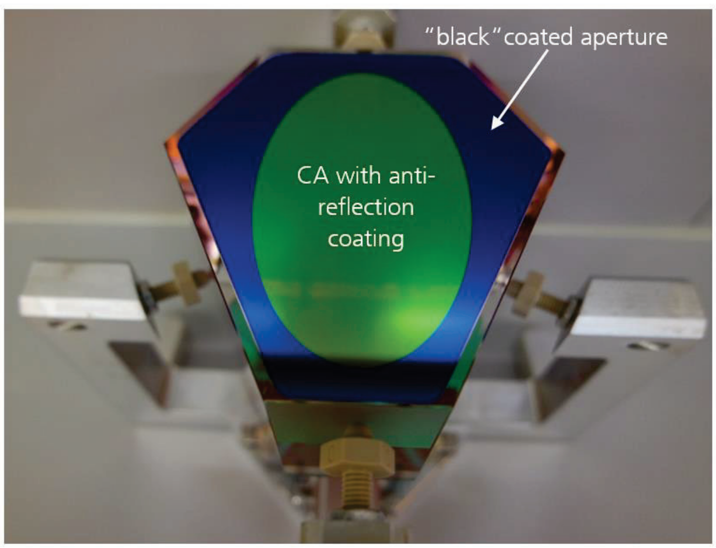

Figure 2: Prism with anti-reflection (AR) coating inside the CA and a coated "black" aperture.

2. MANUFACTURING OF THE COATED BLACK APERTURE WITH AN ANTI-REFLECTIVE CLEAR APERTURE

The main manufacturing steps of the coated black aperture with an anti-reflective clear aperture are shown in figure 3. The detailed description is part of the sections of this chapter.

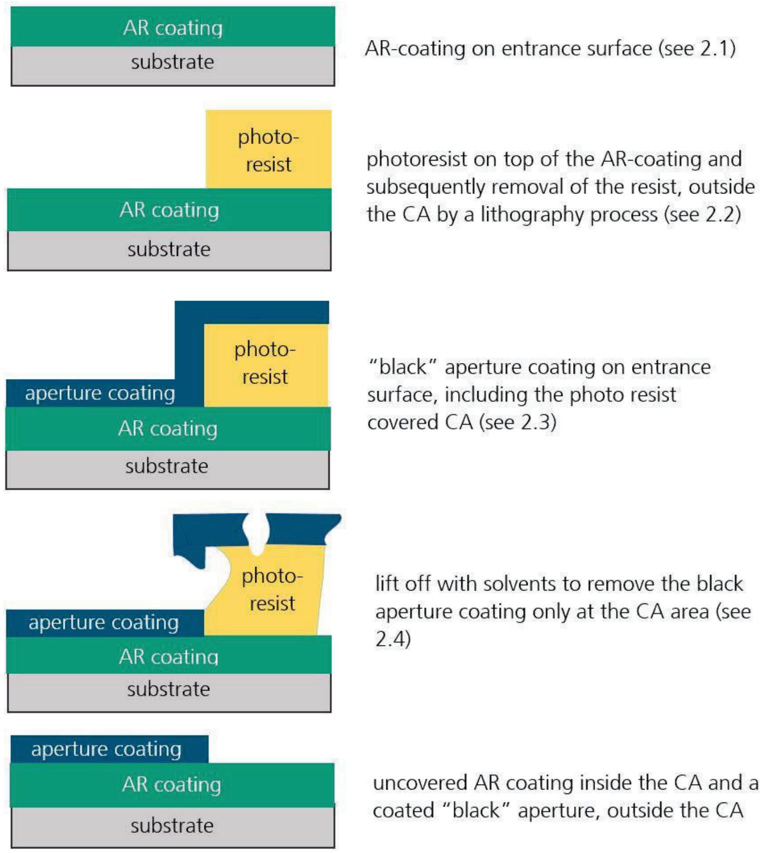

Figure 3: Flowchart for the manufacturing of the coated black aperture with an anti-reflective clear aperture. The sketch is not to scale.

2.1 AR-Coating for CA-area

As coating technology, plasma-ion-assisted vacuum evaporation (Bühler Syrus Pro 1100) at elevated temperature was used. All materials were evaporated by electron beam gun. Silica and tantala were deposited as low- and high-index materials using optimal assistance parameters with the APS plasma source to produce high dense and shift-free coatings. For the silicon evaporation, an intensively cooled crucible was used. High pure silicon (99.999 % from Umicore) granules were first pre-melted to an ingot, and electron beam gun parameters for the ingot were adapted to be suitable for a splash-free evaporation at 0.4 nm/s. Thickness control for all layers was performed by quartz crystal monitoring. All transmittance measurements were performed with an Agilent Cary 7000 UMS dual beam spectrophotometer, which is suitable for measuring polarization resolved spectral transmittance and reflectance from 200 nm to 2500 nm at AOIs between 5° and 75°. Coatings were deposited on one side of fused silica (OHARA SK1300) test samples with a diameter of 1'' and a thickness of 1 mm. The reflectance of the samples uncoated rear side was mathematically subtracted.

The optical requirements for the SWIR1 AR coating were specified with T > 97.5% for angles of incidence from 50.6° to 64.1°, and wavelengths between 1590 nm and 1675 nm. This wide angular range is defined by the light entrance and exit angles for the counter prism. Due to the light dispersion at the grating, the AOI range at the entrance surface of the counter prism is between 50.6° and 60.1°. At the exit surface, an AOI range of 54.1° to 64.1° needs to be covered by the coating, however, the lowest angle appears only at the highest wavelength and the highest angle only at the lowest wavelength. For all angles in between, a linear correlation was assumed. For this coating, an interference multilayer stack with 7 layers using a combination of two dielectric materials and silicon was developed. Due to the application wavelength in the infrared, silicon was chosen as a second high index material, which helps to achieve the 97.5% minimum transmittance and simultaneously reduces the number of layers considerably. A limited number of layers in such a stack design is important to keep manufacturing tolerances small. Additionally, to the T_{ave} > 97.5% requirement, the polarization sensitivity PS = $(T_{max}-T_{min}) / (T_{max}+T_{min})$ was specified with PS < 1%.

As shown in figure 4, the measured transmittance fulfills the required 97.5% for all angles between 50.6° and 60.1°. For the AOI 64.1°, only the shortest wavelength (1590 nm) has to be considered. The polarization sensitivity, which was calculated from measured T_p and T_s spectra, was with 0.65 as a maximum also within the specified PS < 1 %.

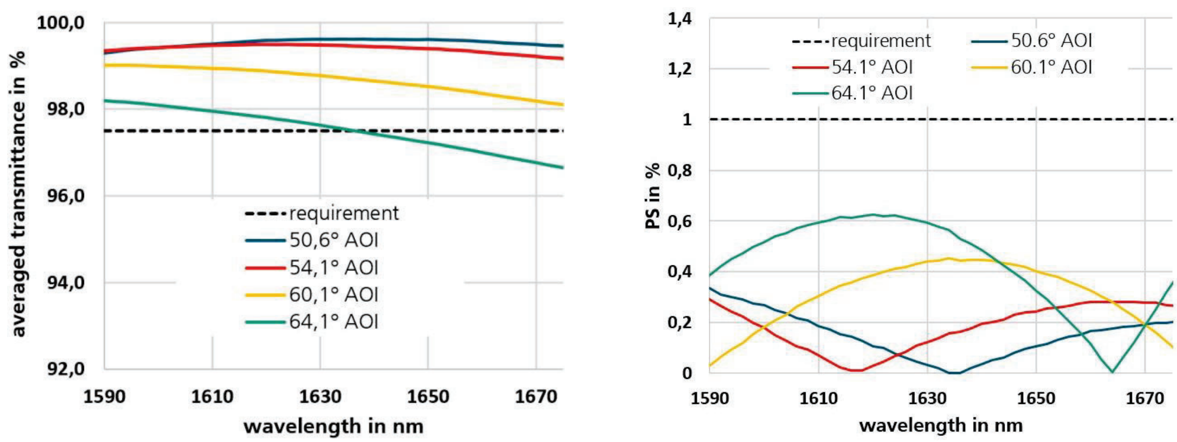

Figure 4: Transmittance (left) and polarization sensitivity (right) for the AR coating, measured under application AOIs on a coated fused silica witness sample. Coating on one side, rear side reflectance was mathematically subtracted.

2.2 Spray coating of resist and lithographic structuring of CA

A positive-tone DNQ based photoresist (AZ4562, Merck) has been applied by spray-coating on top of the AR-coated prism surface. It's softbake has been caried out in an oven at 100°C for 2h. This process has been chosen due to the bulk substrate and comparably large mass of ca. 1kg. The resist film thickness should exceed the one for the coating stack.

The lithographic patterning has been realized using a direct-writing projection stepper device using a LED-illuminated microdisplay, that is equipped with an alignment microscope and a high-precision air bearing stage [8]. Because the facet area is not allowed to carry alignment marks, the lithographic exposure has been adjusted with respect to the precision machined lateral faces of the prism. Their tolerances have an impact on the error budget of the CA placement, which has been set to ± 50 microns. By adjusting the resist film thickness, the thermal treatment, and the exposure dosage, the CA placement was confined to ± 15 microns and in addition, edge retraction could be prevented.

The development of the exposed resist has been done upside down in alkaline solution (AZ400K, Merck), to reduce risks in particle contamination.

2.3 Deposition of "black" aperture coating

For the "black" absorber coating and the AR coating, the same coating technology was applied. Plasma-ion-assisted vacuum evaporation (Bühler Syrus Pro 1100). Temperature control during the deposition process was important, as the resist is sensitive to heat impact.

An absorbing (blackening) coating was deposited on the prism surface, which was covered completely by the AR coating and partly by a photo resist (the resisted covered the CA-area). This aperture coating shall be optically dense (> OD 4) and needs to work bi-directional as both, the light which comes from the air side and the light which comes back from the inside of the prism, shall be eliminated. Therefore, a coating design was compiled with dielectric and thin metal layers enclosing a thick Aluminium layer. The AOIs for the air side of the coating are 50.6° to 60.1° while for the glass side (looking to the inside of the prism) an AOI range from 6°- 45° was required. The reflection suppression in the absorber coating is based on an interaction of destructive interference and interference-enhanced absorption in thin metal layers. Due to the required bi-directionality of the absorber layer - reflection had to be suppressed both on the air side and against glass - it was necessary to take the underlying AR coating into account when calculating the layer sequence for the absorber. Taking these conditions and the application wavelength (1590 nm - 1675 nm) into account, the aperture coating was tailored. As shown in Figure 5, a reflectance < 1.5 % was measured for AOI 50.6° and < 3 % for AOI 60.1°, both is below the 4% reflectance, which is the specification for this application (SWIR1-channel).

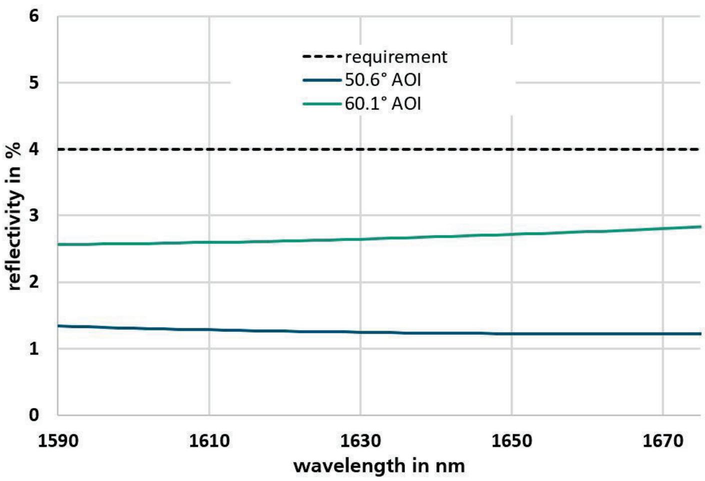

Figure 5: Measured reflectivity of the "black" aperture coating towards air.

2.4 Thermal treatment and lift off

The "black" aperture coating consists of materials, which cannot be treated by a single wet etching solution, within a lithographic pattering approach. Thus, a lift-off process has been chosen, dissolving the residual resist layer at the CA-position (see figure 3). The dissolving was carried out upside down in an acetone bath for 24 hours. By the upside down configuration, the risk of particles contamination is reduced. Subsequently, a rinsing with isopropyl alcohol from a spray gun has been applied, as an additional cleaning step before drying in a laminar airflow was done.

The transition zone between the CA with AR-coating and the "black" aperture has an impact of the optical performance of the coated prism. In this region, the coated aperture may not fulfill the complete specification of reflectance and optical density due to gradual thickness deviations in the coating stack. Thus, a uniform transition zone with a small width is required. From microscope analysis, see e.g. figure 6, the width of the transition zone between the CA with AR-coating and the "black" aperture can be determined. The zone width is ca. 6.5 microns and has been considered in the error budget of the CA size specification.

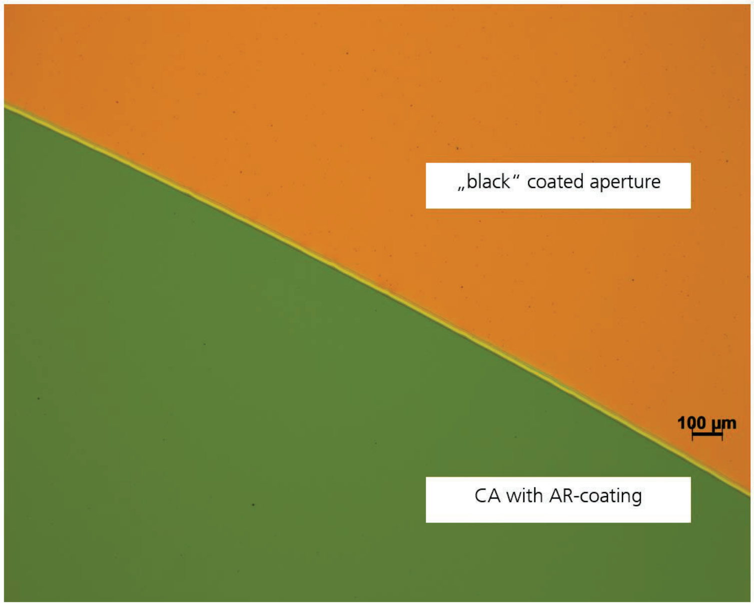

Figure 6: Microscopic images of the transition zone between the CA with AR-coating and the "black" aperture.

3. QUALIFICATION

The black aperture coating with an anti-reflective clear aperture was fully qualified on sample level. (Samples of 1-inch in size). To be representative, the type of substrate material is equal to the type of glass of the prism. In addition, the AR-coating was deposited directly on the substrate and the "black" aperture coating was deposited on the AR-coating (as applied for the prisms). The qualification program was developed according to ECSS-Q-ST-70-17C, a standard that specified requirements for durability testing of thin film coatings used in space. The following tests were performed according to the mission operating conditions based on ECSS-Q-ST-70-17C:

Optical performance

Both, reflectance and transmittance of the coating were measured in the wavelength range from 500 nm to 2000 nm in 2 nm steps before and after exposing to the environmental tests in each test flow. No change in optical performance greater than 1% was considered as a success criterion for passing a qualification.

Visual inspection

Visual inspection was performed by unaided eye. Qualification samples were inspected in a black box designed according to DINISO 9211-4:2014 attachment C. The black box is equipped with two 15-Watt fluorescent light tubes as the light source and has a matt black background. The success criteria for the visual examination were no evidence of:

- flaking
- peeling
- cracking
- blistering
- stains
- smears
- discoloration
- streaks
- cloudiness

Adhesion(Tape test)
With 3M 853 Tape (high tear-resistant, transparent Tape of polyester) according to DIN ISO 9211-4

Moderate abrasion test
With eraser abrader fully covered with cheesecloth pad 50 strokes with 5N bearing force were applied according to DIN ISO 9211-4

Humidity test
At the constant relative humidity of 95%±2.5% samples were exposed for a duration of 72h to the constant temperature of 49°C ±2°C

Thermal cycling test in atmosphere
50 cycles between -50°C and 50°C

Thermal cycling test in vacuum
10 cycles between -50°C and 60°C

Radiation test
An electron irradiation with a fluence of 2E11 electrons/cm2 and 0.1 MeV was performed on coated glass samples. This test was performed by DLR with the CIF-Irradiation Facility.

Wipe test
Wipe test was performed on the basis of last subsection “Cleanability and Solubility test” of the MIL-C-48497A, section 4.5.4.2. The soaked microfiber cloth was five times pulled over the coated sample

The described above tests were combined in test flows presented in the table 1.

Table 1. Test matrix applied for the coating qualification according to ECSS-Q-ST-70-17C.

Test	Flow I	Flow II	Flow III	Flow IV	Flow V	Flow VI	Flow VII
Optical performance and visual inspection	x	x	x	x	x	x	
Wipe test	x						
Moderate abrasion	x						
Humidity	x			x	x		Only storage
Thermal vacuum and cycling		x		x	x		Reference sample
Radiation			x	x	x		
Optical performance and visual inspection	x	x	x	x	x		
Adhesion	x	x	x	x	x		
Visual inspection	x	x	x	x	x		

Test flow I represents resistance to moisture effects. Test flow II represents resistance to thermal effect. Test flow III represents resistance to radiation loads. Test flow IV and test flow V are identical and represent cumulative effects on the coating. Test flow VI represents measured optical performance (no tests). Test flow VII represents storage, and no test are applied within it.

The black aperture coating with an anti-reflective clear aperture successfully passed the qualification completely fulfilling the above-described criteria for visual inspection and optical performance.

4. CONCLUSION

Thin film black aperture coating with an anti-reflective clear aperture was successfully realized for the application wavelength of 1590 - 1675 nm.

The AR-coating enables a transmittance of 97.5% for all angle of incidences between 50.6° and 60.1° and the polarization sensitivity of < 0,65 %. The "black" aperture is blocking the light (T = 0%) and the back-reflectance is < 3 % for angle of incidences between 50.6° and 60.1°.

By applying a lithographic process for the structuring of the CA, the CA placement was confined to ± 15 microns. In addition, the transition region between the CA with AR-coating and the "black" aperture is only about 6.5 microns.

This combination of black aperture coating with an anti-reflective clear aperture enables the suppression of optical losses, stray light and to beam shaping. By depositing the "black" aperture as a coating directly on the optical element (PG-P), replacing mechanical thus reducing payload of the satellite. As mentioned in the introduction, developed optical element will be applied for the monitoring of anthropogenic CO_2 by satellites (part of Copernicus, the European Union's Earth Observation and Monitoring program).

5. DISCLAIMER

Part of Copernicus, a program of the European Union, co-funded by ESA. Views and opinion expressed are however those of the authors only and the European Commission and ESA cannot be held responsible for any use which may be made of the information contained therein.

REFERENCES

[1] T. Flügel-Paul, C. Rothhardt, T. Benkenstein, K. Grabowski, S. Risse, R. Eberhardt, B. Guldimann, and U. D. Zeitner, "All-dielectric prism-grating-prism component realized by direct hydrophilic bonding technology for optical applications in space," Proc. SPIE 11180, 1118014 (2019).
[2] M. Heusinger, T. Flügel-Paul, K. Grabowski, D. Michaelis, S. Risse, and U. D. Zeitner, "High-dispersion TIR-GRISMs with flattened angular dispersion profile," Optica **9**, 412-418 (2022).
[3] C. Leverant, F. Gao, C. Nguyen, P. Jiang, Colloidal assembly to antireflection coatings, Reference Module in Materials Science and Materials Engineering, Elsevier, (2022).
[4] J. M. Bennett, "Polarization", in Handbook of Optics, M. Bass, ed., 2nd ed., Vol. 1., (1995).
[5] S. M. Pompea and R. P. Breault, "Black surfaces for optical systems," in Handbook of Optics, M. Bass, ed., 2nd ed., Vol. 2., (1995).
[6] V. Lagaki et al., "Stray-light suppression for the MIRACLS proof-of-principle experiment", Acta Physica Polonica B, Vol. 51, (2020).
[7] Pranav Mahamuni et al., "Finite element analysis of payload for space applications", IJREAT International Journal of Research in Engineering & Advanced Technology, Vol. 3, Issue 1, (2015).
[8] H.-C. Eckstein, U. D. Zeitner, R. Leitel, et al., "High dynamic grayscale lithography with an LED-based micro-image stepper," Proc. SPIE 9780, Optical Microlithography XXIX, 97800T (15 March 2016); https://doi.org/10.1117/12.2219099