

International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny



Advances in IBS Coatings for space applications on the topics of curved surfaces and laser damage

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ABSTRACT

IBS Coatings are a good candidate for high performance applications. They are hard, dense, exhibit a small thermal shift, and have the best scattering and surface roughness performance of the various coating technologies. In addition, they feature a highly stable refractive index for the coated materials allowing the production of complex coatings. Because of their high density and resistance towards high energy radiation IBS coatings are also well suited for space applications. For high power laser applications, the vacuum stable damage threshold and low defect concentration qualify especially reactive ion beam sputtering as a suitable deposition method for space applications.

In the paper, results on coating activities using the IBS process are discussed in respect to two aspects. One is the adaption of the IBS to strongly curved surfaces like lenses exemplified by the FM lenses for the Copernicus Sentinel-4 mission. The other is a study to increase the laser-induced damage threshold for future LIDAR systems. This is accomplished by eliminating nano-scaled particles that act as damage precursors during laser radiation.

Keywords: curved surfaces, ion beam sputtering, LIDT

1. APPLICATION OF IBS COATINGS ON CURVED SURFACES

1.1 Introduction

The fabrication of demanding coatings with high accuracies is fundamental for many optical instruments. The coating of lenses and other curved substrates presents an additional challenge. Due to the curvature a coating applied without additional means will be inhomogeneous. This will in turn lead to a varying optical performance over the lens surface. To overcome this two things need to be added. First an additional rotation of the lens on the (rotating) calotte is necessary. This will ensure a rotational symmetry of the coating and eliminate any shadowing effects that the lenses might cause. The second is a shadow mask that is specifically tailored to the lens surface that is coated. Production and verification of the mask can be time consuming and difficult. We will show that a system of specialized jigs can be used to overcome these difficulties and allow an easy verification of the mask and process. Moreover this can be done using simple witness samples without the need for an actual lens to test the process. The jig also allows having several witness samples in a coating run that unravel the optical performance of the coating at different positions of the lens. The ease of analysis of these witness samples adds control and reliability to the process.

This process has been applied to the flight hardware coating in the Sentinel-4 mission. The lenses that were coated are part of a high resolution Ultraviolet/Visible/Near-IR (UVN) sounder instrument that aims to monitor the Earth atmospheric composition and air pollution. This instrument is part of the Sentinel-4 mission within the COPERNICUS program, coordinated by the European Commission and financed and implemented by the ESA member states. Airbus Defence and Space GmbH is the prime contractor for this instrument which is to be deployed on the geostationary MTG-S satellites. In this program LZH acts as supplier to Jena-Optronik GmbH (a subcontractor to Airbus Defence and Space GmbH) to provide the dielectric coatings to most optical components of the Telescope Assembly, the UV-VIS Spectrograph Assembly and the NIR Spectrograph Assembly. The spectral bands used in the instrument are 305nm-500nm for the UV-VIS Spectrograph and 750nm-775nm for the NIR spectrometer.

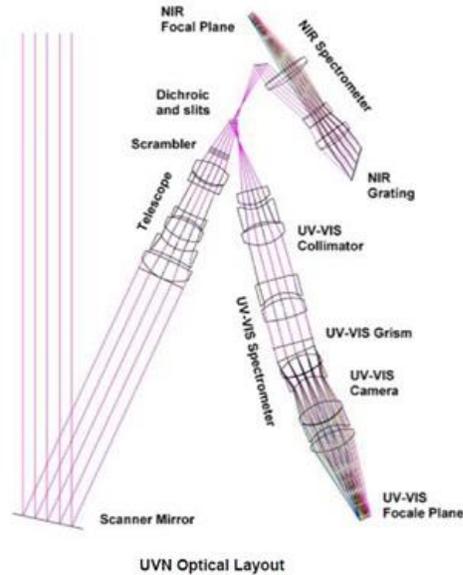


Figure 1. Setup of the UVN Instrument. All components of the instrument except the dichroic, scrambler and NIR Grating are coated by LZH.

1.2 Experimental

All coatings were fabricated using ion beam sputtering (IBS). A dedicated AR coating was developed for the telescope and the UV-VIS subassembly. The AR coating for the telescope components covers both spectral bands (305nm-500nm and 750nm-775nm) while the AR coating for the UV-VIS subassembly only covers the first band from 305nm-500nm. In both subassemblies lenses made of SiO₂ and CaF₂ are used. The telescope has a total of 6 lenses and the UV-VIS spectrograph has 10 lenses. For each lens surface a jig was manufactured that can fit several witness samples. The samples are placed in the jig such that each represents a defined spot on the surface of the lens. This is true for position and inclination angle of the surface.

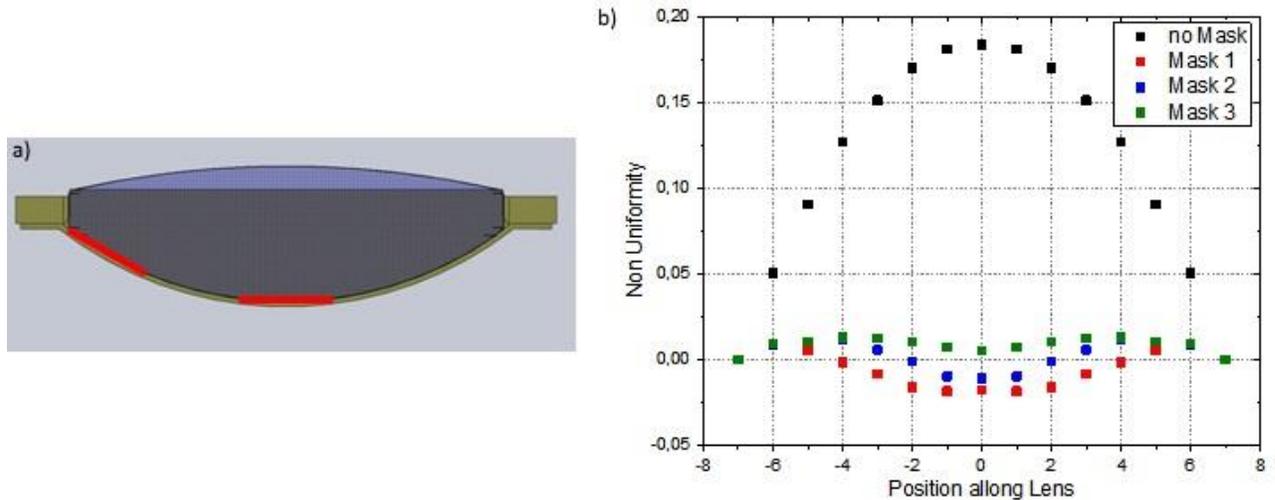


Figure 2. a) Schematic view of witness sample positions. A cut of the lens is depicted in blue and two possible positions for witness samples in red. Any position along the lens surface can be chosen. b) Uniformity profile of a lens created from measurements of witness samples. In black the uniformity without a mask is shown (~18%). Red, Blue and Green show the uniformity for different masks.

The spacing of the samples is ~5mm. Measuring these samples a map of the uniformity of a coating on the surface of the lens can be created. The data collected from these measurements is used to create a shadow mask that ensures uniformity

for the specific surface. Using the uniformity of a surface with no mask as input an initial mask is calculated. In an iterative process this mask is then optimized to fulfill performance needs. For all lens coatings in the Telescope and UV-VIS subassemblies a uniformity of 1% had to be achieved. The jigs are also used to verify the performance of the mask over its lifetime. During flight hardware coating the jigs are used to create witness samples that can be measured to validate the coating performance over the whole lens. These samples are exposed to the same process steps than the flight hardware. The NIS Spectrograph consists of three lenses. Two of these lenses are also coated with an AR coating. In this case the coating is limited to the NIR band 750nm – 775nm. The first lens in the NIS Spectrometer is however coated with a bandpass. In combination with the dielectric folding mirror it block all radiation outside of the desired NIR band. For a bandpass filter uniformity is more critical than for an AR coating. This is due to the sharp rise of the transmission/reflection at the filters spectral edges. A non uniformity will introduce a shift in the spectral position of the band. In order to ensure sufficient transmission the passband needs to be widened. This will in turn reduce the blocking and allow more parasitic radiation to pass through the filter. Thus the uniformity needs to be as good as possible. In sample measurements a uniformity of 0.5% was achieved. The bandpass was designed as a combination of a low and a high pass filter. Each is applied to one face of the lens.

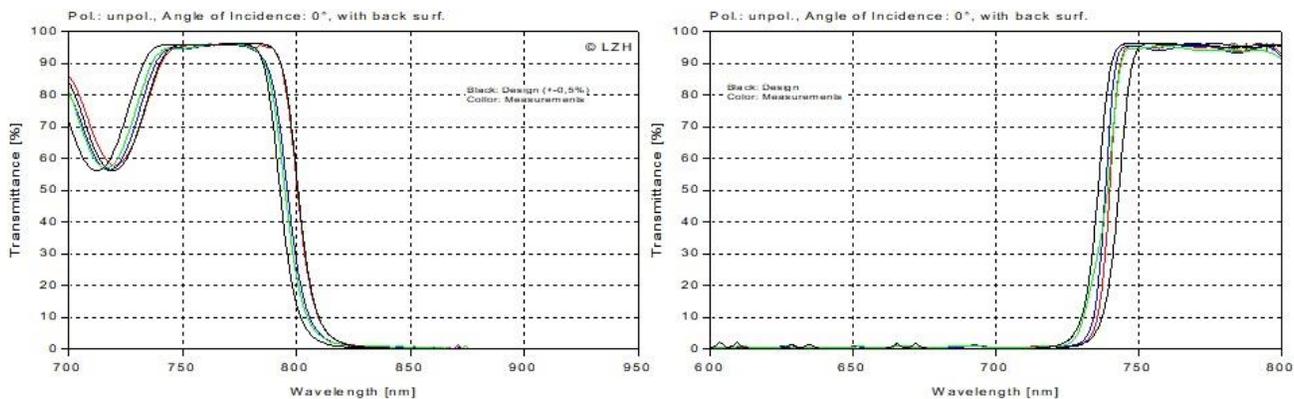


Figure 3. Depicted are the two filter designs. The black curves are the nominal design showing the minimum and maximum of a 0.5% uniformity. The colored curves are measurements of witness samples placed at several positions along the lens nominal surface.

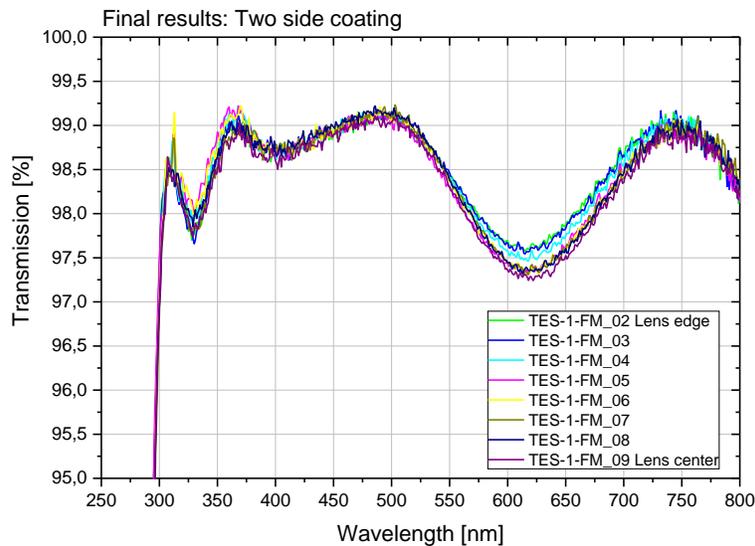


Figure 4. Transmission measurements of witness samples from a flight hardware coating. The samples are fully processed. The uniformity deduced from the measurements is far better than the desired 1%

1.3 Results and Outlook

Using the above process all telescope and UVVIS lenses were coated. The coated lenses have diameters from Ø50mm to Ø80mm and feature radii of curvature from 45mm to 3300mm. The lenses were either biconcave or biconvex. For all 32 different surfaces (16 lenses) the desired uniformity of 1% was achieved. The vast number of surfaces demonstrates the versatility of our approach. For many of the surfaces the uniformity was well below the desired value. Aside from the Sentinel-4 lens coating the process was evolved to yield even better uniformity. Ultimately on an area of Ø80mm a uniformity of 0,1% was achieved. To demonstrate the performance a narrow band filter at 990nm was produced. With this step forward in uniformity control in the future the deposition of more demanding filters will be possible.

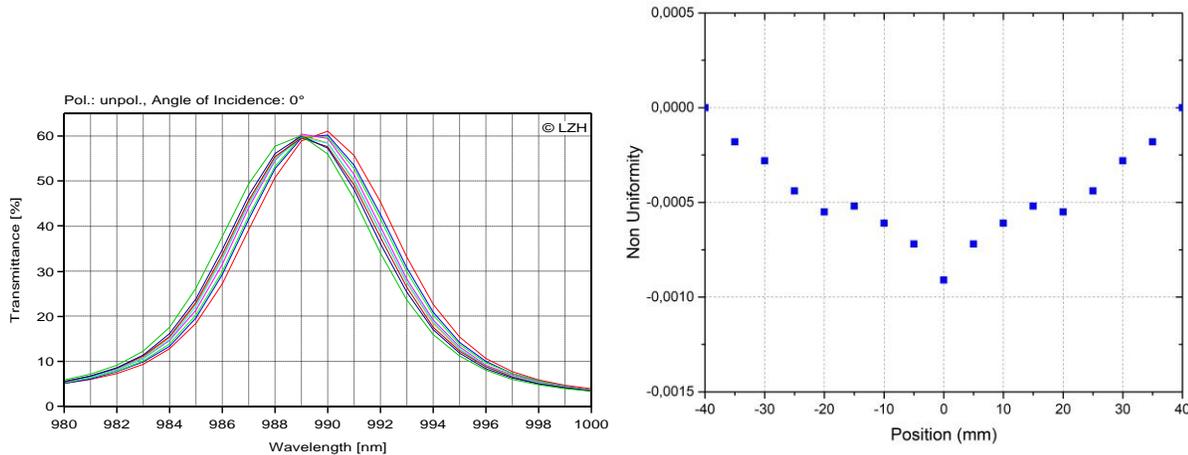


Figure 5. Left: Filter centered at 990nm. All curves are measurements taken on position from center to the edge offer a distance of 40mm. Right: Uniformity over Ø80mm area of the filter. The achieved value is 0.1%

2. DEFECT-LIMITED DURABILITY OF OPTICAL COATINGS

2.1 INTRODUCTION

The transmitter technology of current space-based LIDAR systems comprise of high power pulsed radiation sources in the nanosecond regime, with high pulse energies up to 100mJ at repetition frequencies in the range of a few Hz to kHz. Typical energy densities applied to the optical components for frequency conversion, beam shaping, and guiding are in the range of mJ/cm² to J/cm² at the fundamental, second and third harmonic wavelength of typical q-switched solid state laser systems. Aiming at high sensitivity and high accuracy, the increasing laser pulse energies open up a challenging demand on optical components with highest durability, especially under various environmental conditions. In contrast to the deterministic damage initiation in the ultra-short pulse regime, and the absorption limited durability for long pulses, laser-induced damage in the nanosecond time domain is closely related to localized defects, voids and other imperfections in interfaces and layers of coated optical components. The statistical nature of the defect distribution introduces challenges along the whole production chain of such laser optics – starting from mitigation strategies for cleaning and coating, the surface inspection, and the final quality assurance by both, laser-induced damage- and laser-induced contamination testing.

2.2 LASER-INDUCED CONTAMINATION

In the application the careful control of environmental conditions is critical. Especially under low pressure conditions, the optical components are exposed to contaminants because of outgassing of mechanical and electrical components in the vicinity. When applying laser radiation to the exposed surfaces, a contamination growth can be observed, mostly leading to a failure of the optical component after a characteristic number of laser pulses. The photo-physical and –

chemical mechanisms responsible for the build-up of LIC are complex and because of the broad variety of possible contaminant materials, coating materials, and deposition techniques with their very own abilities, it is still a very active field of fundamental research.

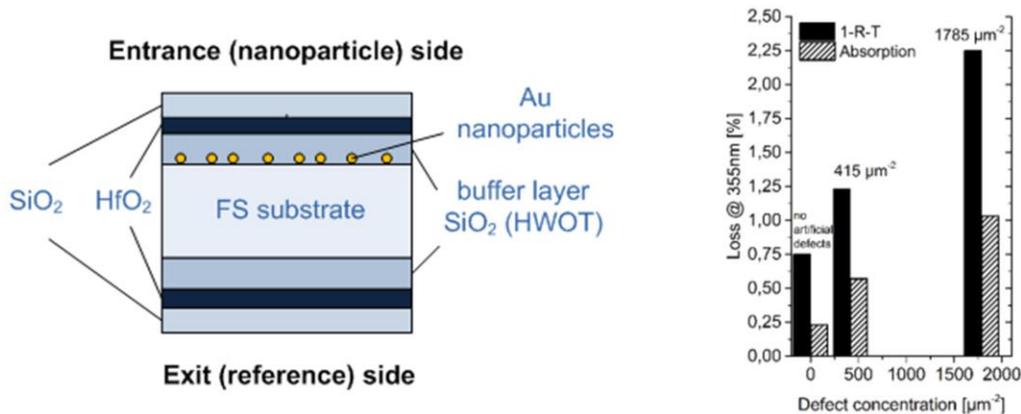


Figure 5. Schematic layout of the AR-coatings with artificial defects at the substrate surface [3] (left), and optical loss and absorption of the samples with different defect concentrations. (right).

It is mostly verified that in analogy to the laser durability, the susceptibility to LIC is higher for porous coatings. Adsorption of the contaminant into the layer favors the built-up of structures on top of the coating that resemble the intensity profile of the laser beam. Typically, after a certain time, a transition towards ablation of the deposited material occurs after further exposure to laser radiation. Utilizing a typical Gaussian-like distribution of the lateral laser beam intensity, the characteristic pancake- and doughnut-like structures are observed on the sample surfaces (compare Figure 5). Even though the susceptibility for laser-induced contamination is lower for dense coatings, the described mechanism can also be observed for dense IAD- and IBS coatings with a surfaces roughness suitable for high power laser applications. Going even further, it was demonstrated in [1] that localized defects embedded deeply in a dense layer system can affect the optical breakdown due to LIC dramatically, without being directly in physical contact to any contaminant material.

2.3 DEFECT MITIGATION IN OPTICAL COATINGS

Controlling the defect distribution of a substrate and its coatings is the key to controlling the durability of an optical coating, independently on the environmental conditions. A lot of effort was put into the pre-treatment of optical substrates before application of the coating to reduce surface near defects. One approach is to use ion etching for substrate conditioning to remove dust particles, polishing residues, and sub-surface damages. The annual SPIE laser damage competition regularly gives an overview on the current state-of-the-art in laser radiation resistivity of optical components. In a contribution of C.J. Stolz et al. [2] an exceptionally high LIDT was presented for an EB mirror for 1064nm that was ion etched before coating. Sun et al. [3] improved the LIDT of fused silica substrates at 355nm for 3ns of pulse duration, and verified for an optimized etching process very low atomic carbon concentration at the surface, as well as improved surface roughness. In current activities, this promising technology is validated for UV antireflective coatings within the ESA contract 4000119563/17/NL/BJ. The novelty concerning previous studies is the simultaneous etching during coating, to control not only substrate defects, but also defects embedded during the coating deposition in the coating plant. The principal setup of the IBS coating chamber with additional ion source is shown in Figure 6. A specialty of the setup is the additional degree of freedom of the additional ion source. The angle between the surface of extraction grid and substrate is tunable.

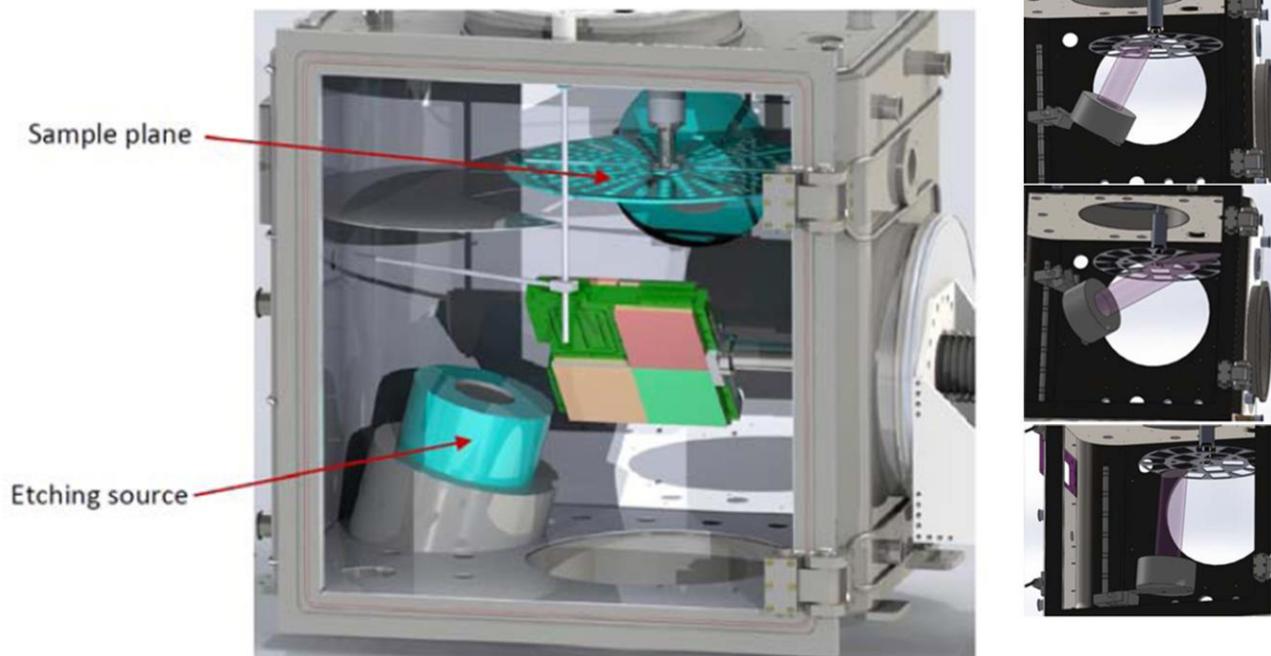


Figure 6. IBS coating machine for simultaneous coating and etching of UV coatings for high laser durability coatings (left) used for the ESA contract 4000119563/17/NL/BJ. The impact angle of the ions of the secondary ion source can be tuned to control the momentum transfer to the substrate surface (right).

2.4 SUMMARY

The defect driven nature of laser-induced breakdown of optical components in the nanosecond pulse duration regime is the critical aspect in the optical design of the transmitter technology for space-based LIDAR systems. It is well understood, that for reasons of environmental stability, dense coatings manufactured by high energy deposition techniques have to be utilized. However, in general, dense coatings exhibit significant coating stress, lowering the LIDT as was demonstrated in a model experiment in the literature. Nevertheless, the lowered susceptibility to LIC is the major advantage of dense coatings, since it determines the lifetime of an optical component. But since it was demonstrated in the literature, that absorptive defects embedded deep inside a dense IBS coating affect the LIC, it is obvious that not only the surface composition and structure influence the build-up of contamination under laser irradiation, but the amount of energy deposited in the optical component. This conclusion is supported by the dramatic increase of LIC at 266nm using toluene as contaminant material. The optical absorption of pure toluene exceeds the value at 355nm by several orders of magnitude. An increased absorption in the UV spectral range is also most likely the reason for a non-linear reduction of the LIDT in frequency conversion stages. The LIDT at simultaneous exposure to different wavelengths cannot be linearly scaled with the portions of the respective single wavelength LIDT. This manifold detrimental influence of defects on the performance of optical components in LIDAR systems necessitates the reduction of the defect density in optical coatings. We presented current research activities based on ion beam etching and laser conditioning during layer deposition to reduce defect concentrations not only near the substrate surface, but also coating defects.

3. REFERECES

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