Development and Application of Versatile, Highly UV Reflecting and Absorbing Coatings – UVcoat

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ABSTRACT

Sensitive optical instruments rely on mirrors with outstanding reflectivity and on efficient light absorbers. For this purpose, we are developing versatile, broad-band mirrors and light absorbers in the ultra violet (UV) region which meet engineering constraints such as excellent vacuum compatibility, high electrical conductivity, high voltage ratings, robustness to large temperature changes, attainable size, or formability. These requirements are typically encountered in laser applications, quantum computing, space science, etc. The developments in this work also pave the way for more efficient UV lamps, which is of interest due the increasing use of UV lights in modern society, e.g. in sterilisation of (medical) instruments or water purification.

Keywords: ultra violet light; UV mirror; UV light absorber; optical instruments

1. INTRODUCTION

Any sensitive detection instrument seeks to isolate a usually very rare signal out of an – often overwhelming amount of – undesired, disturbing background events. Hence, breakthroughs in an instruments' sensitivity are typically associated with more efficient detection of the former and/or more effective suppression of the latter. For sensitive optical devices this implies that the detection of the desired photons has to be optimised while sources of background or stray light into the photon-detection apparatus need to be minimised. Consequently, the right combination of highly reflective and highly absorbing surfaces is required to efficiently guide the photons of interest to the detection apparatus while maximally absorbing background light before it can enter the sensitive detection region. Identifying materials or coatings which exhibit high reflection or absorption characteristics over a wide spectral range in the ultraviolet (UV) region is still difficult. Moreover, optical instruments may impose strict requirements on these materials or coatings in addition to their UV reflection or absorption properties. These demands include minimal outgassing rates and excellent vacuum compatibility, firm structural stability under reoccurring thermal cycling to cryogenic or 'hot' temperatures, electrical properties such as high conductivity and high voltage rating, formability, or the attainable size of the highly UV-reflective or absorbing surfaces.

In a collaborative effort with industry partners, we have been developing and characterising novel materials and coatings with the highest reflection or absorption rates over the entire middle to near UV ranges (200 – 400 nm) which additionally also satisfy the requirements listed above. These materials and coatings are expected to become important for a wide range of optical and scientific instruments as well as, in the long run, for industrial applications of UV light in general.

Here, we report on the first results in the development of these versatile, highly UV reflecting and absorbing coatings. The concept of aluminium-based reflective coatings is introduced as well as a description of our bending station to obtain curved mirror surfaces. Dedicated test stations have been built in order to fully benchmark all developed coatings along the characteristics introduced above. First results on the remaining reflectivity of the UV light absorbing coatings as well as their vacuum compatibility are also presented.

2. STATE OF THE ART

UV reflective surfaces – In the UV range, dielectric or aluminium (Al) based mirrors are commonly employed. Dielectric mirrors excel in their high reflectivity (often > 99%) but are each limited to a narrow wavelength range. Moreover, their composition of multiple thin layers of dielectric material restricts their application to flat surfaces and are generally cost intensive, especially for larger surfaces and do often not withstand high temperatures.

Aluminium-based mirrors on the other hand exhibit a somewhat lower, but still high reflectance over the entire UV to infrared spectrum. Unfortunately, its excellent UV reflectance is easily compromised by oxidation of the Al surface. Thus, the reflective Al layer deposited onto a suitable substrate is typically coated with a thin protective layer, e.g. with MgF_2, to guard against oxidation. Due to this protection, however, the industrial available size of the mirror is limited, the coating of curved surfaces is not feasible, and the electrical conductivity is compromised. Moreover, the robustness of industry-standard MgF_2 coated mirrors against thermal stresses by repeated thermal cycles, e.g. to cryogenic temperatures is uncertain.

UV absorbing surfaces – Several commercial manufacturers offer coatings with excellent absorption characteristics which result to a hemispherical reflectance of < 1% in the UV range. Although even higher absorption is always welcome, the main limitations for their wider applicability is typically found in a coating's mechanical stability, unclear or insufficient compatibility with ultrahigh vacuum, the uncertain performance at liquid helium temperatures, or its nonideal electric properties such as limited electrical conductivity and high-voltage (HV) ratings. Moreover, the attainable surface size may be small or even limited to planar surfaces.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In collaboration with industry partners, our present work is focused to resolve the aforementioned set of engineering challenges to obtain versatile, broad band, first-class mirrors and light absorbers in the UV region. Indeed, affordable, larger sized, broadband UV mirrors including wavelengths below 250 nm still remain a challenge today. In particular, the following engineering constraints are often faced which limit the application of state-of-the-art highly reflective and absorption materials, mirrors, and coatings for a wider range of optical devices.

- *electrical properties:* certain applications require excellent electrical conductivity and high voltage. For instance, the former is essential to avoid the undesired build-up of electric charge which could interfere with the operation or electronics of an (optical) instrument.
- *ultrahigh vacuum (UHV) compatibility*: minimal outgassing rates of all components including mirrors and light absorbers are essential to obtain excellent vacuum conditions. For instance, our own ion-trap and laser-spectroscopy based research requires optical applications to operate with pressures below 10^{-10} mbar. Furthermore, space applications impose strict limits on outgassing rates of all employed materials which otherwise influence measurements of the space medium (e.g. of mass spectrometry, degradation of optical devices) or could represent sources of voltage breakdowns or undesirable heat transfer.
- *firm structural stability,* especially during instrument assembly and operation such as under reoccurring thermal cycling to cryogenic or 'hot' temperatures: mirrors and light absorbers utilised in cryogenic environments must maintain their optical qualities at low temperatures. They must comply with the thermal stresses they are exposed to during frequent thermal cycling without losses of their mechanical integrity. Analogously, they must resist elevated temperatures when UHV demands require the baking of a vacuum chamber and its inner components to 200 – 250° C.
- *formability:* When other than planar shapes of the highly reflecting or absorbing surfaces are required, the respective machining or coating procedures need to be available for curved surfaces. Especially, elliptical shapes are of interest for collecting or focusing UV light.
- *attainable size*

Our present work addresses all of these requirements for highly UV reflecting and absorbing surfaces covering the middle to near UV range (200 – 400 nm). These advances open a unique path for next-generation applications in science, technology and industry (see Section 5).

4. PROJECT RESULTS

Highly UV reflecting coatings – The development of highly reflecting, flexible surfaces is approached by applying a plain aluminium coating on a thin (50 µm) glass substrate. This process is performed by the Fraunhofer Institut für Organische Elektronik, Elektronenstrahl- und Plasmatechnik. Aluminium is chosen since it offers the best reflectivity in the UV-range of interest and is a feasible choice for large-area coatings. No surface protection layer is applied to the coated substrate, which guarantees vacuum compatibility and electrical conductivity. To prevent oxidation, the coated substrates will be handled under an inert gas atmosphere which is evacuated before transport. Handling and packaging procedures were successfully tested.

A critical point is warping the thin substrates into an elliptical shape. The mirror is bent by approximately 270° within 25-cm edge length. To moderate the strain on the glass, an automated bending station was developed. The system, depicted in Fig. 1, warps the glass substrate (its edges are visible on the photo) into the desired oval shape which is used in collinear laser spectroscopy. The system is designed such that it can be modified to produce different concave forms of any size.

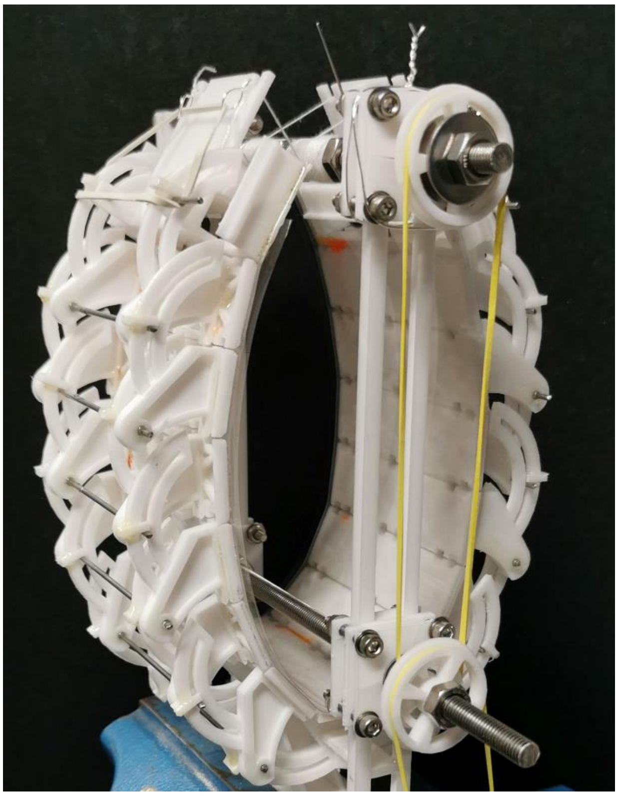

Fig. 1. The automated bending station warps the thin (50 µm) glass substrates into an oval shape. The modular design allows adaption to different concave shapes and substrate sizes.

The aluminium coating has to endure the warping process without spalling. With the use of the automated bending station, it is possible to detect defects in a batch of mirrors under a consistent warping procedure. By recording the maximum bending angle, the coating process parameters which are most critical for the durability can be precisely identified.

Finally, the coated, bent mirror will be used in a single-photon fluorescence detection region. To evaluate the performance of the mirrors off-line, we set up a test station that contains a dim light source with a variable wavelength and a single-photon counter. This virtual experiment allows comparing different sets of mirrors, detectors and shapes in a realistic environment, before using them in a concrete application such as in our case with an ion beam and lasers.

The test station allows evaluating the curved mirrors with respect to their optical quality, which is given by a convolution of their reflectivity and shape. It is also designed to accommodate a new generation of photon detectors which will be situated in vacuum and cooled to LN2 temperatures. Using those will test the robustness of the mirrors under extreme temperature gradients, yielding valuable information for further detector development.

UV absorbing coatings – The development of the UV absorbing coatings took place at Surrey NanoSystems Ltd, the creator of Vantablack, a 'ultra-black' coating based on carbon nanotubes. Building on Vantablack S-VIS, an existing coating with < 0.6% hemispherical reflectance in the UV range, the new coating Vantablack CX2 was formed. Compared to S-VIS, CX2 was designed for more robust mechanical strength as well as better electrical conductivity. Measurement results for the total hemispherical reflectance of S-VIS and CX2 are shown in Fig. 2. As a reference, they are compared to Graphite which has been used due to its suitable electric conductivity for stray-light suppression in our laser-spectroscopy work. Although CX2 exhibits a slightly worse reflectance compared to the S-VIS standard, it largely outperforms Graphite, especially in the UV range. For instance, at 280 nm CX2's reflectance is approximately an order of magnitude smaller than the one of Graphite. CX2 could hence represent an attractive combination of high UV absorption, mechanical stability, and good electrical conductivity.

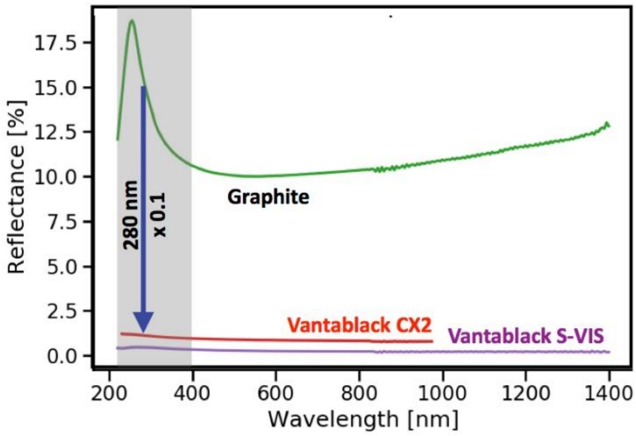

Fig. 2. Total hemispherical reflectance of Vantablack S-VIS and CX2 in comparison to Graphite.

To fully describe the performance of Vantablack CX2 in respect to our ambitious design goals, we have built multiple test stands. Among others, these include infrastructure for baking, outgassing, and vacuum testing, stray-light suppression, and an in-vacuum high-voltage test station operating with uncoated samples up to 75 kV. Vantablack coatings are guaranteed to suite vacuum chambers in pressure regimes down to 10^{-7} mbar, but little is known about its vacuum compatibilities in more demanding vacuum environments. For this reason, we have built a dedicated vacuum chamber which is capable to operate in the 10^{-11} mbar region and can host large coated aluminium plates (13 cm × 56 cm). It further hosts a residual gas analyser as well as equipment to bake the entire chamber to temperatures exceeding 200° C. Figure 3 shows the pressures readings during a baking cycle for a plate coated on both sides with S-VIS. A vacuum base pressure of $< 5\cdot10^{-11}$ mbar is achieved. This is identical to the pressure when a blank aluminium sample is used and establishes the compatibility of Vantablack S-VIS over the entire UHV range. Analogous measurements are currently performed with CX2 in parallel to the other previously mentioned characterisations.

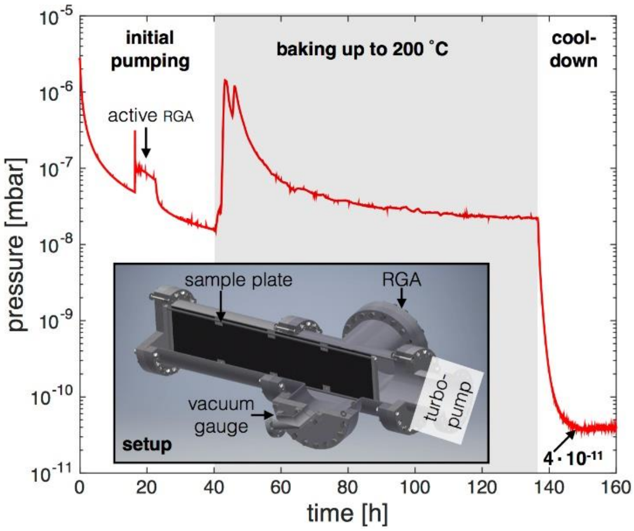

Fig. 3. Pressure readings during the baking cycle of a sample of Vantablack S-VIS. The setup, shown in the insert, hosts an aluminium plate (13 cm ×56 cm) which is coated on both sides. A residual gas analyser (RGA) and a vacuum gauge serve as diagnostics for the vacuum quality.

5. FUTURE PROJECT VISION

Highly UV reflecting or absorbing coatings and materials are important for many applications in optical imaging devices and sensors, space science and telescopes, fundamental science, laser optics, etc. Hence, we expect that the advances proposed here will be highly welcomed by a larger scientific and industrial community to boost the performance of the respective instruments. Moreover, UV light becomes increasingly important in drying and curing of inks, varnishes, or coatings, in UV lithography, but also for sterilisation and disinfection of (medical) instruments and surfaces. The use of UV light has also gained a boost in attention during the past months as an option to sterilize objects and surfaces from virus contamination.

While the generation and scope of UV light is not part of this project, curved mirrors allow UV light to be more effectively directed to a localised irradiation sample, e.g. when placing a typical cylindrically shaped UV lamp in the focal point/line of the curved and highly UV reflective mirror. This opens a noteworthy industrial potential of the proposed innovations, in particular as energy efficiency is becoming a major topic in all sectors of modern society. As a safety measure, more versatile and better UV absorbers will prevent UV photons to undesirably reach sensitive parts of a setup or even users of UV lamps or instruments.

5.1. Technology Scaling

For the mirrors, extensive testing of different coating parameters is still in progress. The necessary testing station for experimental proof (TRL 3) and validation of the technology (TRL 4) are in place and ready to be used. With a successful mirror substrate, we can equip existing detection stations at experimental facilities to perform live experiments (TRL 5-7).

The performance of the black surfaces was validated in a laboratory environment (TRL 4) within ATTRACT phase 1. In the near future, experiments whose results are directly affected by the performance of the black coating will be performed and the results can be published. (TRL 5-7).

5.2. Project Synergies and Outreach

Light-absorbing coatings and high-reflective mirrors are used in several European and international scientific institutions. The light detection systems, which benefit from the novel technology, can improve their performance by employing these new mirrors and highly-absorbing coatings. Thus, we will present our results in expert conferences to a broader audience in the community, and we will specifically target collaborations which use similar setups. With these steps, we are determined to convince several research groups worldwide to employ the UV coatings that were developed and investigated in ATTRACT phase 1. We hope that in the near future, results of relevant experiments will be published in peer-reviewed journals which made use and mention the employment of the new UV mirrors and coatings.

Since every targeted project has specific demands and requirements, it will allow us to collect robust data especially concerning the versatility of the products. This information will be useful to advance the technology to different, more specific applications, and to promote it to users outside the field of science. Also, it is well possible that other projects that were funded in ATTRACT phase 1 could directly benefit from our findings, since the handling and application of UV light is an active field of industrial and scientific applications.

5.3. Technology application and demonstration cases

In laser spectroscopy, a laser beam with a specific, controlled frequency is overlapped with ions or atoms, which are then emitting photons when an atomic resonance condition is met. The observed transition "resonance" frequency is a fundamental property of the atom species and allows to infer properties of atomic nuclei. This is particularly interesting for rare and short-lived isotopes which can only be produced in small amounts at online facilities such as ISOLDE at the European Organization for Nuclear Research CERN. The experiments are typically limited by the achievable production rates for the particles of interest. Employing our novel highly-reflective mirror systems and black surface coatings can increase the efficiency and signal-to-noise ratio of the photon detection systems and thus lower the production demand for the respective particles. Representing our first demonstration cases, we expect that the new developments can, for example, bring experiments on ultra-rare and short-lived isotopes within reach.

Laser spectroscopy shares similarities with quantum computers with qubits realised in trapped ions. Here, laser-stray light needs to be minimised to increase the scope of such experiments. Black absorbing coatings that are compatible with ultra-high vacuum conditions could be especially beneficial for such experiments.

Outside science, the need for reliable surface sterilization methods is a currently a widely discussed topic. Viral contamination can be cleaned by irradiation with high-intensity UV light. Curved, high-reflectivity mirrors could help in making corresponding devices more efficient by guiding the light precisely to the areas of concern. Black surfaces can be used to shield the users from the damaging UV radiation.
Already today, UV light is applied in ~12% of the drinking water production in Europe [1]. Its importance is further illustrated by major European investments into new research and development in this sector, e.g. in the Eco-UV project. The novel highly UV-reflective surfaces as being developed here could make the use of existing UV lamps more (energy) efficient.

5.4. Technology commercialization

We have not initiated concrete steps to commercialize the products, or received interest from private investment stakeholders.

5.5. Envisioned risks

The reflectivity of the curved mirror systems still has to be tested. If it turns out that the warping introduces surface defects that reduces the reflectivity, the system might not be any longer superior to other systems.

5.6. Liaison with Student Teams and Socio-Economic Study

An exact characterization of the mirror sheets in different applications is a possible task for student teams. Especially the test stations that were developed at TU Darmstadt are attractive for versatile experiments that will lead to relevant scientific results. Thus, we can offer this opportunity to young scientists in our lab. Socio-economic studies are relevant only in the context of a commercialization of the coatings. We will be excited to provide any input and information to support such a venture.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] J.P. van der Hoek et al. ‚J. Water Supply: Research and Technology-Aqua 63 (2): 124 (2013)