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Boosting the performance of the ASTRI SST-2M prototype: reflective and anti-reflective coatings.

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Abstract: ASTRI is a Flagship Project of the Italian Ministry of Education, University and Research, led by the Italian National Institute of Astrophysics, INAF. One of the main aims of the ASTRI Project is the design, construction and verification on-field of a dual mirror (2M) end-to-end prototype for the Small Size Telescope (SST) envisaged to become part of the Cherenkov Telescope Array. The ASTRI SST-2M prototype adopts the Schwarzschild-Couder design, and a camera based on SiPM (Silicon Photo Multiplier); it will be assembled at the INAF astronomical site of Serra La Nave on mount Etna (Catania, Italy) within mid 2014, and will start scientific validation phase soon after. The peculiarities of the optical design and of the SiPM bandpass pushed towards specifically optimized choices in terms of reflective coatings for both the primary and the secondary mirror. In particular, multi-layer dielectric coatings, capable of filtering out the large Night Sky Background contamination at wavelengths $\lambda \gtrsim 700$ nm have been developed and tested, as a solution for the primary mirrors. Due to the conformation of the ASTRI SST-2M camera, a reimaging system based on thin pyramidal light guides could be optionally integrated aiming to increase the fill factor. An anti-reflective coating optimized for a wide range of incident angles faraway from normality was specifically developed to enhance the UV-optical transparency of these elements. The issues, strategy, simulations and experimental results are thoroughly presented.

Keywords: mirrors, interferential coatings, ASTRI, CTA, TeV astronomy, IACT.

1 Introduction

ASTRI (”Astrofisica con Specchi a Tecnologia Replicante Italiana”, [1]) is a flagship project of the Italian Ministry of Education, University and Research (MIUR) strictly linked to the development of the ambitious Cherenkov Telescope Array (CTA) [2, 3]. CTA plans the construction of many tens of telescopes divided in three kinds of configurations, in order to cover the energy range from tens of GeV (Large Size Telescope), to tens of TeV (Medium Size Telescope), and up to 100 TeV (Small Size Telescope, SST). Within this framework INAF, the Italian National Institute of Astrophysics, is currently developing an end-to-end prototype of the CTA SST in a dual-mirror configuration (SST-2M) to be tested under field conditions [4]. For the first time, a wide (semiaperture 4.8°) field of view dual-mirror Schwarzschild-Couder (SC) optical design (proposed already in 1905 but never applied in astronomy yet, see e.g. [5]) will be adopted on a Cherenkov telescope, in order to obtain a compact (f-number f/0.5) optical configuration and small aberrations across the whole field of view[6]. Moreover the prototype will be equipped with a light and compact camera [7] based on Silicon Photo Multipliers (SiPM) instead of the photomultiplier tubes (PMT) that have been extensively adopted so far; this is a viable (as shown by FACT [8]) and promising solution, because SiPM avoid some of the disadvantages of PMT: namely the large dimensions, weight and power consumption. The ASTRI SST-2M prototype will be placed at Serra La Nave, 1735 m a.s.l. on the Etna Mountain near Catania (Italy) at the INAF ”M.G. Fracastoro” observing station[9]; the data acquisition is scheduled to start in 2014. Detailed information on all the aspects of the prototype can be found in these proceedings. In this paper we will discuss the development of thin-film coatings for the mirrors and the reimaging system of the ASTRI SST-2M prototype. The peculiarities of the ASTRI SST-2M prototype in terms of optical design and sensors led to original issues regarding the reflective coatings to be adopted for the elements of the optical chain, that will be addressed in the following sections. More specifically the design requires three different coatings: two high reflectance coatings for the primary and secondary mirrors: the planned solution for these are presented in section 2. Moreover the design of the ASTRI SST-2M prototype comprises one anti-reflective coating, to be deposed on the front surface of the light guides that could be adopted to enhance the fill factor of the SiPM array covering the focal surface. This development will be addressed in section 3. A fourth element involved in the optical path is the water-tight curved plexiglass cover protecting the focal surface. This element also will need a trasmission-enhancing coating but this development will be treated elsewhere.

2 High reflectivity coatings for the mirrors

The mirrors for the ASTRI SST-2M prototype will be produced with adaptations of the cold shaping method developed by the Brera Astronomical Observatory [10, 11]. Details on the optical design and on the structure and production of the mirrors can be found in [6]. The baseline for the mirror coatings of the prototype is represented by the well proven Al+SiO_2 design that is already in operation, for instance, on 100 m^2 of panels built with the same technology adopted here[12] and installed on the MAGIC-II reflector since 2009 [13]. This coating design grants all the needed characteristics both in terms of performance and durability, and has been robustly proven along years of scientific operation in an hazardous mountain environment. Given the novelty of the design of the ASTRI SST-2M prototype, we accordingly studied new solutions for the coatings. The main specificity of the ASTRI SST-2M design, driving this work, is the choice of SiPM as sensors instead of the long-standing standard constituted by PMT. The photon detection efficiency (PDE) of the SiPM adopted for the prototype has a non negligible tail above 700 nm and up to 900 nm. This implies a strong contamination by intense molecular bands of the Night Sky Background light (NSB) in a region where the Cherenkov signal is relatively dim. This pushes towards the introduction of a low-pass filter in the optical chain, achievable by means of interferential coatings deposed onto glass substrates, for instance, by means of physical vapour deposition (PVD, see e.g. [14]) of dielectric materials such as SiO_2, TiO_2, Ta_20_5, MgF_2 and many others. This approach is widely investigated within the CTA Collaboration [15, 16] also because many of the eligible materials are expected to adhere to glass better than aluminium, thus improving durability and resistance to environmental hazards. In this technique multiple layers of materials characterized by different refractive indexes, are deposed onto the glass substrate with uniform thicknesses ranging from tens to hundreds of nanometers. A proper tuning of the materials and of the layer thicknesses can approach closely an ideal bandpass filter, with transmittance (or reflectivity) approaching 100% in the band of interest and very small values elsewhere. These optical properties arise from the interference of incident and reflected rays at each layer interface, therefore the optical behaviour is severely dependent from the angle of incidence (AoI). From the technical point of view, the preferential site for installing this filter would be the focal surface, because it would allow to coat substrates of very small dimensions (see figure 3); but in the SC design the focal surface is interested by rays spanning a huge ($20^\circ - 70^\circ$) interval of AoI, spoiling the uniformity of the filter transmittance. As a consequence in the case of the ASTRI SST-2M prototype an effective cut can be obtained only by tuning the reflectivity curve of the primary dish, where AoI span the range 0-15°, while already the secondary mirror works under incidences in the wide $20^\circ - 60^\circ$ interval.

2.1 Optimization of the bandpass

On the pathway to design properly an interferential coating for the ASTRI SST-2M primary mirror, we tried to assess the optimal position of the red cut of the passband, in order to tune the desired performance of the coating (assumed as a good approximation of an ideal step function) and hence its design. We evaluated under very simple assumptions the impact of a low-pass wavelength cut onto the signal-to-noise ratio (SNR) obtained in a pixel interested by NSB and a Cherenkov signal. In the background limited case, and assuming that NSB is Poisson distributed around its average rate B, the excess S due to Cherenkov has:

$$SNR(\lambda) = \frac{S(\lambda)}{\sqrt{B(\lambda)}} \tag{1}$$

where λ is the long wavelength cut that is meant to be optimized, and $S(\lambda)$ and $B(\lambda)$ are the integrated counts up to the wavelength λ. The maximum condition is therefore

$$\frac{dS(\lambda)}{S(\lambda)} = \frac{dB(\lambda)}{2B(\lambda)} \tag{2}$$

and is independent by the intensity of the signal relative to background under these assumptions, but depends only on the spectral shape of the Cherenkov signal and of the NSB, and on the PDE curve. Adopting NSB and Cherenkov spectra taken from literature, and a PDE interpolated from measurements performed within the activities described in [7] we computed that the maximum SNR is reached integrating signal up to $\sim$ 500 nm. Extending the band redwards reduces progressively the SNR but the drop is less than 10% up to 700 nm, allowing a tolerance useful to match the constraints cast onto the development of the real coating by the limited choice of suitable materials and other technical and industrial issues. Another constraint to keep into account is that given the small ($\sim$ 7 m^2) effective area of the pupil, the design must at the same time tend to preserve a large fraction (e.g. 80%) of the signal photons detectable by SiPM. Moreover, especially for the large signals preferentially associated to multi-TeV showers that are the core target of SST, the width of the passband increases the signal photon statistics and hence the precision in the measurement of the integrated light of the shower and eventually of the energy of the primary. Eventually, the performance is meant to meet the CTA requirement for mirror reflectivity, implying average reflectivity in the $300 - 550$ nm passband $R_{300}^{550} \geq 83\%$.

2.2 Coating for the primary dish

The primary dish of ASTRI SST-2M is composed of 18 hexagonal panels, each 85 cm wide (face to face; radius of the circumscribed circle $\sim$ 98 cm), arranged in three concentric rings [6]. The radii of curvature (RoC) are different for each ring, ranging from $\sim$ 8 m for the inner ones up to $\sim$ 10 m for the outer ring, with a sagitta $S \simeq 11 - 13$ mm. The relative flatness of the surface and moderate dimensions of each panel make the primary dish the preferential locus for application of an interferential filter made of a multi-layer (ML) coating, from an applicative point of view. This converges with the more fundamental constraint that in the adopted design the primary dish is the only optical element interested by rays incoming with AoI within a narrow range around normality (up to 15°). A first test was performed in the ZAOT S.r.l. laboratories[1] with a ML adopting SiO_2 as low index material and TiO_2 as high index material. Sample glass windows where coated along the diagonal of the hexagon in order to check uniformity across the width of the coating chamber. The reflectivity curve was then averaged weighting for the surface area at each distance from the center, in order to obtain the average response of the panel at each wavelength under the assumption of azimuthal simmetry. The sharpness of the cut was conserved in the averaged reflectance, proving that a good spatial homogeneity of the deposition process was achieved, with the exception of small central

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[1] `http://www.zaot.com`

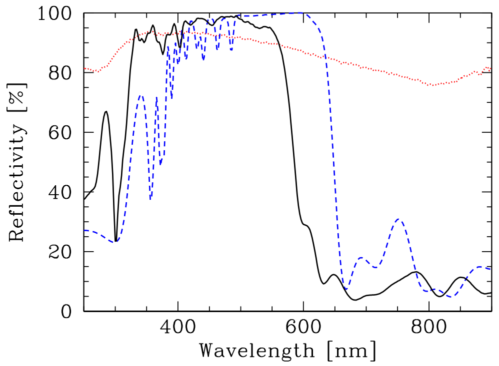

Fig. 1: Measured reflectivities for the considered coating designs: *Al*+SiO_2 (dotted red) SiO_2+TiO_2 ML (dashed blue) and SiO_2+mixture ML (solid black).

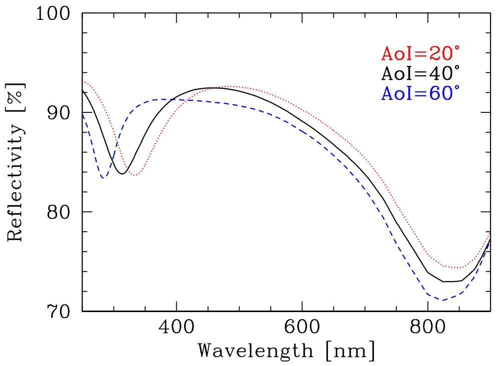

Fig. 2: Simulated reflectivity for the simple *Al*+SiO_2 design optimized for the ASTRI SST-2M secondary mirror. Curves for incidence angles of 20° (dotted red), 40° (solid black), and 60° (dashed blue) are plotted.

areas scarcely affecting the overall behaviour of the panel. The sample windows were then subject to tape tests, a thermal cycling between $-25°$C and $+60°$C and salt mist test, showing no degradation either in adhesion and appearance or in reflectivity. Two test panels produced with the composite technology described in [6] have already been coated, one with an *Al*+SiO_2 recipe and one with the SiO_2+TiO_2 ML coating. These panels have been exposed outdoors in the park of the Merate site of the Brera Observatory, as a comparative test for resistance to environmental hazards and mirror misting; the latter test is important as recent studies hint to dielectric coated mirrors being prone to condensation [17]. The ML performance in near UV is limited because TiO_2 causes significant absorption below 380 nm. A further improvement was then seeked substituting TiO_2 with a dioxide mixture with refractive index $n \simeq 2.1$. Again samples disposed along the diagonal of a panel were coated, the reflectivity measured and the spatial evolution of reflectance interpolated and area-averaged. This solution showed a better behaviour at wavelengths below 400 nm and is, together with the baseline coating represented by an *Al*+SiO_2 design, compliant with the current CTA requirement of an average reflectivity of at least 83% in the $300-550$ nm range. The measured reflectivities for the three designs are plotted in figure 1.

2.3 Coating for the secondary mirror

The secondary mirror of ASTRI SST-2M consists of a single panel, whether the full glass or composite (see [6]) solution will be preferred. The large (1.80 m) diameter, considerable weight ($\sim$ 120 kg) and pronounced curvature ($RoC = 2.2$ m, for a sagitta of $\approx$ 22 cm) discourage the deposition of complex coatings. Moreover, in the optical design the distribution of angles of incidence is wide and far from normality (20° to 60°, peaking at 40°). All these constraints together drove towards the simplest design, an *Al*-SiO_2 dual layer. This is a well known solution in the field, granting high reflectivity at all the wavelengths of interest and a well-established performance in terms of resistance and durability. This choice has the additional advantage that, if the composite mirror is the preferred solution for the secondary, the aluminium-quartz coating can be deposed onto the assembled panel, while other materials such as the dioxides (or fluorides) used in ML require high temperatures potentially harmful for the glues.

A dedicated simulation pinpointed a thickness of 150 nm for the SiO_2 layer as the optimal solution granting the required reflectivity in the blue part of the spectrum across the whole AoI range, as displayed in figure 2. Deposition tests and sample measurements will start in the second half of 2013 in a coating chamber that our industrial partner ZAOT S.r.l. is developing specifically for this task and is currently under commissioning.

3 Anti-reflective coating for the reimaging system

The Hamamatsu S11828-3344M SiPM units currently available for the ASTRI SST-2M focal surface are not designed for a tight array arrangement. Even if future sensors will overcome this problem, being based on a different configuration, however in the case of the ASTRI SST-2M prototype this introduces significant dead areas that could be recovered by a dedicated reimaging system. The system consists of 14 mm × 14 mm wide, 2.5 mm thick truncated pyramids made of LAK9, a high refractive index ($n = 1.69$) glass (see figure 3). Each light guide is meant to be glued onto a sensor unit and recover photons due to the total internal reflection onto its slanted faces (see figure 4).

Fig. 3: One of the light guides designed for the focal surface of the ASTRI SST-2M prototype.

An anti-reflective coating is then needed to reduce the light loss ($\sim$ 13%) due to the reflection on the bases of the light guides. This design is challenging as AoI on the focal surface range from 20° to 70°, and the bandpass of the coating must match the one of the filter implemented onto the primary across the whole range. This was obtained (see

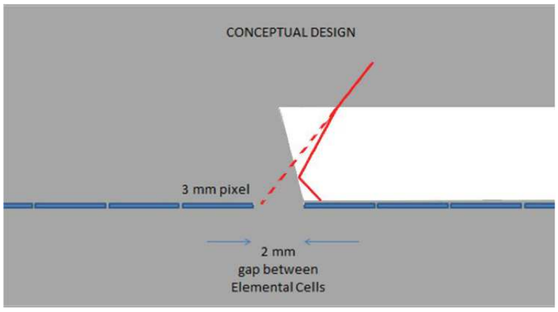

Fig. 4: Conceptual design for the reimaging system studied for the ASTRI SST-2M prototype. Photons directed onto the dead areas of the focal surface are recovered due to the inner total reflection onto the slanted faces of the light guides.

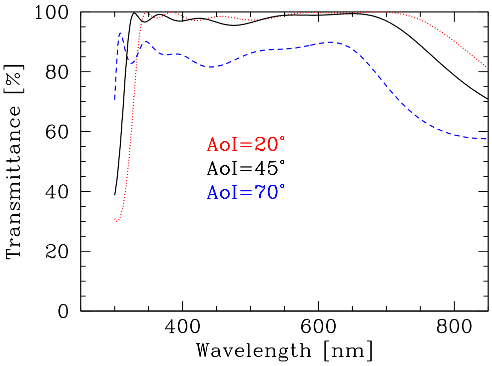

Fig. 5: Simulated transmission curves at the air-glass interface for LAK9 glass coated with the SiO_2+ZrO_2 multilayer designed for the ASTRI SST-2M reimaging system. Curves for AoI of 20° (dotted red), 45° (solid black) and 70° (dashed blue) are plotted.

figure 5) in the simulations with a design including SiO_2 and ZrO_2 alternate layers. A first set of ~ 80 light guides was coated by ZAOT S.r.l and the transmission measured at normal incidence (choice obliged by limitation of our measurement setup) is shown in figure 6, compared with the uncoated glass and with the simulation.

4 Conclusions

We conclude comparing (see table 1) the different designs produced so far for the coating of the primary dish, evaluating the effectiveness of the whole system (including the SiPM PDE) in terms of acceptance for the Cherenkov signal A and rejection power for NSB B. We also define a quality factor $Q \equiv A/(1-B)$. We use the measured reflectivity curves for the primary mirror, and the simulated curves for the reflectivity of the secondary and the transmittance of the reimaging system. The calculation is performed considering normal incidence on the primary and intermediate AoI on the secondary (40°) and on the focal surface (50°). The average reflectivity in the band $300-550$ R_{300}^{550} is also reported in the last column. The proposed dielectric solutions significantly contribute to optimize the performance of the ASTRI SST-2M prototype when compared to the baseline Al+SiO_2 design.

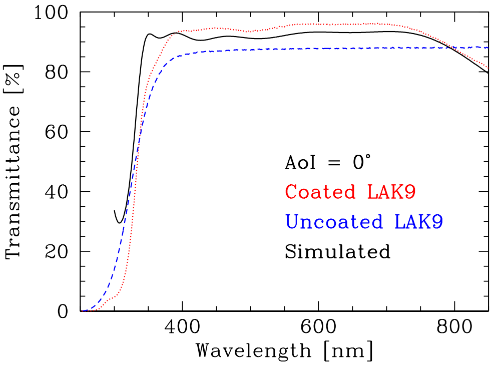

Fig. 6: Measured transmission curve for a coated sample of LAK9 glass under normal incidence (dotted red). The curve is compared with the uncoated glass sample (dashed blue) and the simulated behaviour of the adopted design (solid black). The careful reader will note that the simulated performance does not reach 100% transmission as in the curves of figure 5. This is partly due to the fact that the design is *not* optimized for normal incidences and partly because of the exit (glass to air) interface that is unavoidable in our measurement setup and was added specifically in the simulation reported here for a correct comparison.

Coating design	A [%]	B [%]	Q	R_{300}^{550} [%]
Al+SiO_2	24.0	94.1	4.1	91.9
SiO_2+TiO_2 ML	23.3	96.0	5.9	79.7
SiO_2+mixture ML	21.9	96.7	6.5	90.6

Table 1: Comparison of the different coating designs considered for the primary mirror (see text).

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