FINAL REPORT OF THE PROJECT

Introduction:

The research done within the project 02 ELI / 18.10.2017 had as main objective the design and manufacture of laser mirrors with applications in the transport of femtosecond laser beams and high power densities. After completing the first stages of study and analysis, in order to graft the information obtained from the specialized literature on the knowledge already existing in the optical processing workshop and the optical coating laboratory, the researches were finalized with the elaboration of the substrate processing and coating performing technologies. These stages also included a wide range of tests, carried out during the technological development. After the completion of the prototypes, a final testing session was organized, in partnership with the CETAL laboratory in INFLPR, they having the only facility in Romania (TEWALAS), with which it is possible to evaluate the femtosecond laser induced damage threshold (LIDT) of the optical surfaces, by a method that was upgraded during this collaboration. Thus, while at the first testing session, done on a lot of test-plates, in 2018, in order to validate some optical coating design solutions and technological parameters, tests were performed by the "1 on 1" method, for the prototype testing session, the equipment was refined, becoming usable for "LIDT" tests by the "S on 1" method. All samples were tested for S = 1; 2; 5; 10; 20; 50; 100; 200 and 500 pulses. An extrapolation for $S = 10^8$ pulses was also calculated. The results obtained for the mirrors selected as "deliverables" are presented in table 3 of this report and the individual measurement sheets as well as the table with all the results obtained under the project, can be downloaded from the project website, at: www.prooptica.ro/remi

Description of the project stages:

The achievement of laser mirrors involved research activities in three main directions:

1. Substrate processing;
2. Optical coatings;
3. Tests and measurements.

An adjacent activity was the design and achievement of whide range of opto-mechanical assemblies, used as accessories both by the contractor (Pro Optica) and by the main partners (CETAL from INFLPR and IOEL).

1. Substrate processing

A suitable material to be used for the presented purpose had to have, firstly, a high value of hardness and fused silica glass, an amorphous formed silicon dioxide glass which is a synthetic material with a non-crystalline stateis was accepted as the most suitable. The substrate geometry was generated firstly by water jet, cutting a glass block with the desired thickness into a cylinder with a larger diameter than needed for the final piece. The final diameter was achieved using a rounding horizontal lathe.

Then, the rounde piece was mounted in a special designed „collet type" chuck (fig.1) that was meant to be used as a flexible tool system and therefor was adapted for use on multiple conventional type machines in the optical processing workshop.

Fig.1 – The collet type chuck

The flatness and surface roughness of the mirror were achieved using a top-level lapping machine („Lapmaster Wolters Model 48 Air Bearing Optical Polishing Machine") which combines a low speed lapping movement with the precision polishing properties of the pitch. This allows for very good control over the processing. During the entire process, flatness was tested as often as possible by a flat witness that is placed in the same carrier as the working piece.

Fig.2 – The Lapmaster machine working to super-polish the mirrors substrates

The surface flatness of the finalized substrates was tested using a phase interferometer. Fig.3 shows the image of an interferogramme.

Regarding the achievement of the optical substrates, a summary of the results is reported in the table below (Tab.1):

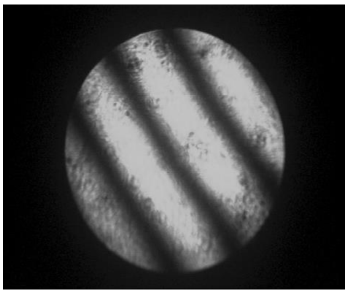

Fig.3 – Interferometric fringes of a measured optical surface

Table1

Diameter [mm]	**Number of parts**	**Overall characteristics**
Φ=25 / Φe=24	50+ (test-plates)	Flatness better than λ/4
Φ=63 / Φe=60	8	Flatness better than λ/4
Φ=80 / Φe=80	1	Flatness = λ/13
Φ=123 / Φe=120	2	Flatness = λ/12 and λ/14
Φ=156 / Φe=150	2	Flatness = λ/9; λ/13; λ/16

A more detailed immage of this research can be accessed from the published article at the next links: https://www.scientificbulletin.upb.ro/rev_docs_arhiva/rezec1_960352.pdf and http://www.club-discovery.ro/articol_substrat.pdf

2. Optical coatings, tests and measurements

Under the second and third work-packages (Optical coatings and Optical measurements and tests assurance) the activities were interconnected and mutually supportive. These were focussed on investigations on the fabrication flux in order to improve the quality of the final product, by tuning the technological parameters for mirror fabrication and finally, to achieve the deliverable. The researches performed in order to design and perform the optical coatings represented the main activity of the project. The theoretical study carried out in the first stage of the project, in conjunction with the professional experience of the responsible team, led, in a first phase, to the selection of the materials to be used to make the coatings. Firstly, in order to build the interferential package, the materials from the table 2 were selected:

Table 2

Indice de refractie mare	**Indice de refractie mediu**	**Indice de refractie mic**
TiO2	Al2O3 – used to test whether its excellent mechanical properties help to strengthen the optical coating.	MgF2 si **SiO2** Note: MgF2 was very quickly abandoned due to its fragility in multiple layers and thicknesess higher than 100nm.
TiO2+Al2O3 (mixtura)		
Ta2O5		
Ta2O5+ ZrO2 (mixtura)		
HfO2		

There followed a period in which doesens of batches were performed, in order to test the different combinations of materials and technological parameters.

In this sense, a testing session was organized in 2018, in partnership with the CETAL laboratory from INFLPR. The solutions selected following this session were improved during 2019, through a program of batches and rapid tests, presented in Figure 4, being used a laser equipment with a pulse duration of 7 ns made available by the partner IOEL. Even though the mechanism of interaction between the laser beam with ns pulse and the hard matter is different from the mechanism of interaction of the laser beam with fs pulses, the rapid test program was a real help in selecting some technological parameters for performing optical coatings. The witness plates of the prototypes were tested, again, at CETAL, using the upgraded femtosecond laser (TEWALAS) by the „S on 1" testing procedure and the final results, containing the main features of the laser mirrors selected as deliverables, are presented in the table 3.

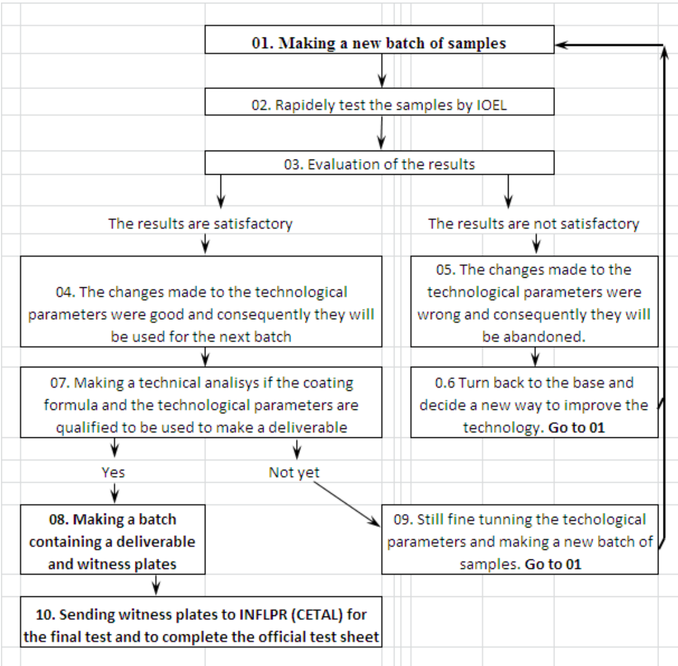

Fig.4 The scheme of the performed activity

3 Results and Conclusions

Following the procedure described in the figure 2 and after more than 20 batches, containing, many of them, samples for rapid evaluation and the others containing potential deliverables and witness plates, we decided to select for presentation, as prototypes for femtosecond laser mirrors, the assemblies from the table below (Tab. 3). Figure 3 shows a deliverable with 150mm as effective diameter.

Table 3 – Summary presentation of the deliverables:

Item code	**Effective diameter & thickness**	**Measured flatness**	**Coating**	**R[%] @ λ central**	**LIDT (**tests made on witness plates) [J/cm^2] where Hx = x% damage probability		
					H0 @ 500 pulses	H50 @ 500 pulses	H0 @ 10^8 pulses
Item 01	Φ_e150mm g = 45mm	λ/16	HfO2 – SiO2 26 layers	99% @ 862 nm	0.34	0.5	0.26
Item 02	Φ_e150mm g = 55mm	λ/12	Mix of TiO2/ Al2O3 - SiO2	99% @ 790 nm	0.30	0.44	0.30
REMI 1	Φ_e60mm g = 20mm	λ/7 (P-V)	HfO2 – SiO2 26 layers	99% @ 800 nm	0.34	0.5	0.26
REMI 2	Φ_e60mm g = 20mm	λ/8 (P-V)	HfO2 – SiO2 26 layers	99% @ 835 nm	0.34	0.5	0.26
REMI 3	Φ_e60mm g = 20mm	λ/5 (P-V)	HfO2 – SiO2 26 layers	99% @ 785 nm	0.34	0.5	0.26

As it can be observed in table 3, a very interesting situation appeared in the sense that, even if the coating based on HfO2 as high index and SiO2 as low index, seems to win the competition for a number of pulses from 1 to 500 that were physically shot on one site, if a mathematically extrapolation is made, for 10^8 pulses, the highest LIDT (0.3J/cm^2) is obtained by the version that contains a mixture of TiO2 and Al2O3 as big refractive index and SiO2 as low index. For comparison, we can refer to the official requirements for mirrors that can be used in the ELI infrastructure. These are conditioned by a LIDT value of 0.3J/cm^2 at 2000 pulses, under vacuum operating conditions. The values obtained, testing the mirrors achieved under this project, for 500 pulses, are all better than 0.3J/cm^2 (see Table 3), but obtained under normal atmospheric conditions. We admit that this could be a little different from the "vacuum LIDT" value, but nevertheless, we consider that values from Table 3 support the idea that the project objectives have been reached.

Fig. 5 A finalized deliverable

Besides the official deliverables presented in the Table 3, on the project's site (www.prooptica.ro/eli) can be seen "the big table containing all achievements of the project" which provides information about every achieved femtosecond laser mirror.

Another comment regarding the performing of coatings is that HfO2 is a quite tough material to be processed while the rest of the high index materials, such as Ta2O5, TiO2, ZrO2 or mixtures of them, including Al2O3 are easier to be melted and evaporated. The very high melting point of HfO2 (around of 3000°C) and its very poor melting bath increases the risk of splashing with material from the crucible. This phenomenon must be very carefully managed during the coating procedure because, if not, the entire batch can be lost. Another difficulty consists in the variation of the HfO2 refractive index from a batch to the next one. Because of this, sometimes, deviations up to 50 nm of the central wavelength can be met, compared to the calculated value. Finally, as a scientifiq impact, we believe that this project succedeed to achieve and share important knowledge in the field of glass processing and coating technologies and it succeded to create a solid bridge between Pro Optica, as coating performer and CETAL/INFLPR as testing supplier. Many discussion took place in this group regarding the test results and many ideas were risen, includding ideas for coating strengten after finishing the coating process.