

Technological development of an interferometer for Multi Spectral Partial Interferograms (MSPI)

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ABSTRACT

This paper deals with the technological development of an **interferometer** dedicated to the observation of the atmosphere in the **SWIR** band. As part of an optical instrument in fused silica, the interferometer is a static system composed of a beamsplitter and the two interferometric arms (Reflected – transmitted (RT) and transmitted – reflected (TR)) without motion of them. The beamsplitter is an assembly made of two semi-hexagons put together by a specific method of **direct bonding**. A **semi-reflective coating** is deposited between the two bonded surfaces to separate the beam. The interferometric arms are made with air gaps and glass plates integrated to the hexagonal **beamsplitter** by surface bonding as well. To create the optical path difference (OPD), the distance in air, the shapes and the slopes of the glass plates are optimized by design and during the integration to reduce the as built uncertainties. The two beams which are recombined at the output port of the interferometer go through a back telescope before focusing on a detector.

Thales Alenia Space Cannes leads the space development of this technology from the heritage of **Compact Gas Imager** (CGI) breadboard developed by IRT. The optics are manufactured and integrated with the surface bonding process by OTéO while the different coatings (semi-reflective, anti-reflective and mirror) are designed and applied by Institut Fresnel. The design is secured with prequalification of processes like part and coating manufacturing and bonding of parts stressed by **multilayers coating**.

Keywords: Interferometer, SWIR, Direct bonding, Semi-reflective coating, Beamsplitter, Compact gas imager, Multilayers coating.

1 INTRODUCTION

The static interferometer integrates a hexagonal beamsplitter (HBS) and the two interferometric arms in one piece made of glass plates in fused silica and air gaps. The beamsplitter is an assembly of two semi-hexagons integrated together with a semi-reflective coating in between to split the input beam. As the concept is a static interferometer, the optical path difference is performed by the arms definition without motion of the arms. The optical beam goes through the two channels where the glass plates and mirrors of each channel are optimized in terms of thicknesses, slopes and distances (air gaps) to create the OPD. The optical components are manufactured and integrated by OTéO Optics using the direct bonding process (molecular bonding). The same process is also applied between the two semi-hexagons where a 7 μm thick semi-reflective coating is deposited before bonding. The induced stress due to the coating deposition has an impact on the surface of the substrate which needs to be controlled and compensated to perform the direct bonding with a flatness better than 80 nm (objective < 70 nm) Peak-to-Valley.

To secure the concept of the interferometer and increase its technology readiness level, the validation of the coatings as well as the qualification of the direct bonding with a surface coated with a multilayers coating of few μm thick is necessary. Dedicated samples, models and simulations are part of a development plan to reduce the final cost and derisk the flight model.

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2 METHODOLOGY

The direct bonding on fused silica is the expertise of OTéO and has been demonstrated on the CGI-VA mock-up with a cubic interferometer. The CGI breadboard and the flight model consider a hexagonal interferometer with the same components than the mock-up (glass plates, mirrors and the beamsplitter). To achieve a qualitative direct bonding the success criterion on the bonded surfaces remains the same: < 80 nm (objective < 70 nm) Peak-to-Valley.

The flatness criterion has also to be respected with the hexagonal beamsplitter where the semi-reflective coating is applied. The requirements which drive the SR coating design in terms of thickness, layers and materials are expressed in the Table 1:

Table 1. Main requirements of a semi-reflective coating in the SWIR.

Requirements	Value
Spectral bands	1.27 μm 1.6 μm
Glass substrate	HPFS
Angle Of Incidence (AOI) for a telecentric beam	30° in glass
$P = \left \frac{R_s T_s - R_p T_p}{R_s T_s + R_p T_p} \right \times 100 \%$ must be lower than	0.1 %
The global efficiency given by the reflectance-transmission (RT) product shall be higher than	24 %

To be less sensitive to the polarization, an AOI of 30° in glass is needed but even with this angle it is difficult to fulfill the requirements as shown in the Figure 1. The design ends with more than 30 layers of SiO₂ and Nb₂O₅ for an overall thickness of 7 μm .

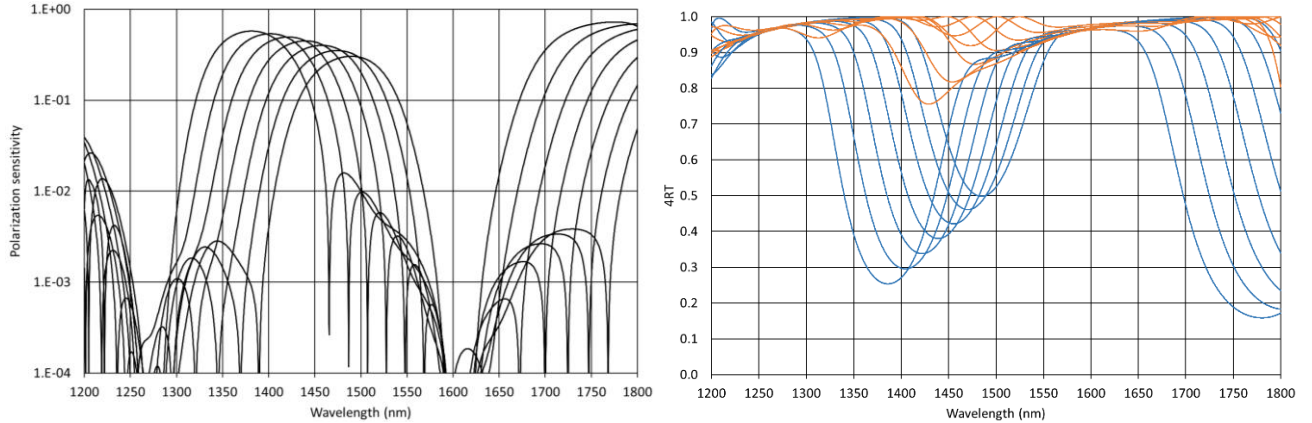


Figure 1.: Simulations of the results (left: polarization sensitivity, right: RT product) for several angles of incidence around 30° considering a 7 μm coating design.

In addition to the spectral performances of the coatings design, the deformation can be derived from the theoretical stress^[2] σ induced by the multilayer stack considering the properties of the substrate and the materials used for the deposition. To calculate the radius of curvature, the Stoney equation is implemented:

$$\sigma = \frac{E_s t_s^2}{6 t_f (1 - \nu_s) R} \quad (1)$$

and

$$R_{s+f} = \frac{E_s t_s^2}{6(1 - \nu_s)(\sigma_H \Sigma t_H + \sigma_L \Sigma t_L)} \quad (2)$$

Where E_s and ν_s are the Young modulus and the Poisson coefficient of the substrate with t_s , t_f the respective thickness of the substrate and the film deposited.

From the equation (2), R_{s+f} is the radius of curvature after deposition with Nb_2O_5 as high-index material (H) and SiO_2 as low-index material (L). The stress coefficient for each material is:

- $\text{Nb}_2\text{O}_5 = 85 \text{ MPa}$
- $\text{SiO}_2 = 470 \text{ MPa}$

To be compliant with the direct bonding, a compensation process on the opposite face is established and will be validated by experiments.

A set of glass plates with parallel faces is manufactured with a flatness of $\lambda/10$ at 632.8 nm to be compliant with the molecular bonding and quantify the effects of the coating.

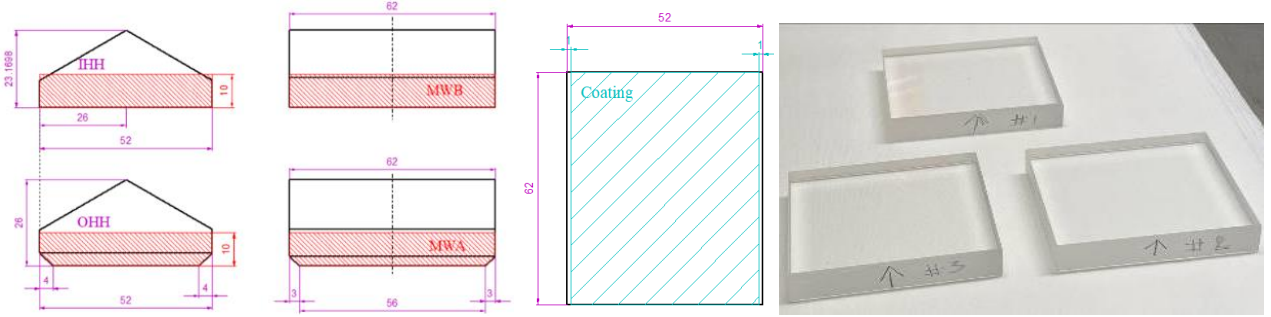


Figure 2. Shape and dimensions of the samples: 52 mm x 62 mm with a thickness of 10 mm.

The measurements plan is to consolidate the process with the associated equipment, to qualify the direct bonding with intermediate steps. In parallel the measured SFE of the different samples will be implemented in a finite element model (FEM) developed by Thales Alenia Space. This model is a starting point to establish a simulation and apply the case to the hexagon of the interferometer for the breadboard model and anticipate the deformations on a specific shape like the semi-hexagon where it is non usual to calculate the deformations linked to a complex form.

3 EXPERIMENTS AND RESULTS

3.1 Experiments on measurement & reference samples

A first batch of six samples in HPFS has been manufactured and the surface form error (SFE) was measured at the end of the manufacturing and after the experiments. The coatings were performed with a Bühler Leybold Optics HELIOS 800 using the Plasma Assisted Reactive Magnetron Sputtering (PARMS).

In addition of the rectangular samples, for each test, a circular sample with a diameter of 1 inch and a thickness of 1mm is placed beside the measurement sample to have a reference each time.

The first sample is used for a thermal test to ensure that the behavior of the sample is not affected by the environment of the chamber. The substrate is integrated on a mechanical support and positioned in the chamber to perform a secondary vacuum (10^{-6} mbar) and apply a temperature of the chamber of 150 °C. There is no deposition on this sample, the test is only to demonstrate that the environment including temperature has a no impact on the substrate.

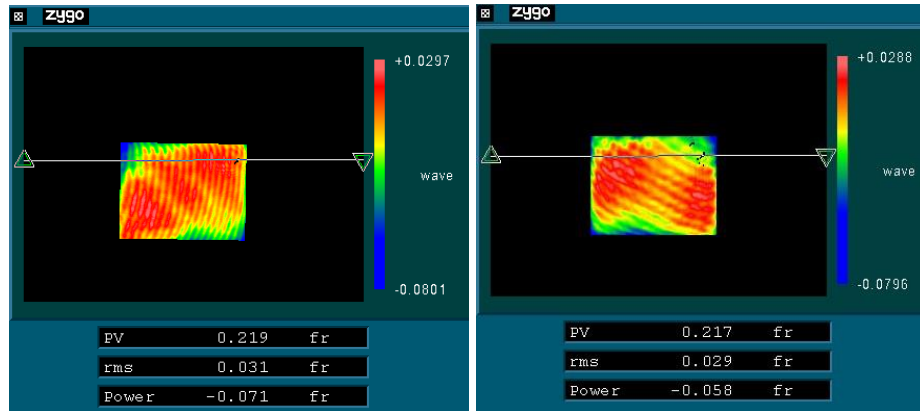


Figure 3. SFE before (left) and after (right) with no deviation due to the environment.

The sample #2 is coated with a single layer of 400 nm of SiO_2 and the sample #3 is coated with a single layer of 500 nm of Nb_2O_5 . They are used for unitary test to determine the stress parameters with a single layer of hundreds nm of deposition on each sample with the same approach than the one described in [1].

Flatness is measured before and after coating using a Zygo GPI. From this flatness value (or its associated radius of curvature), and knowing the substrate and layer thicknesses, it is possible to calculate the associated stress value using the Stoney Equation.

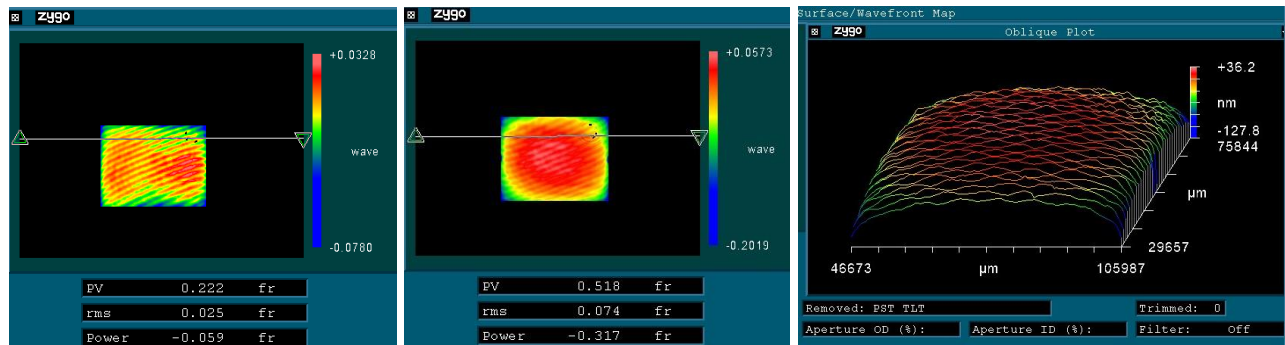


Figure 4. SFE of the sample #2 before (left) and after (middle) with an increase of the SFE of 0.3 fringes.

On the right side of the Figure 4 the concave shape indicates a compressive stress with a deformation of 164 nm PV on the SFE while the Figure 5 shows a lower deformation measured after the test almost not visible on the 10 mm thick sample.

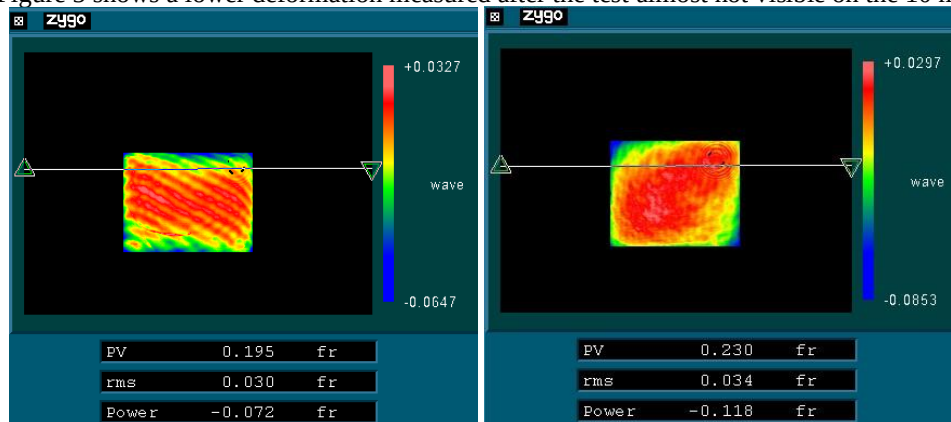


Figure 5. SFE of the sample #3 before (left) and after (middle) with an increase of the SFE of 0.03 fringes.

As the deformation is function of the substrate thickness, with the reference sample thinner than the measurement sample (1 mm instead of 10 mm), the delta SFE before and after is more pronounced which gives a better accuracy for the stress determination. The measurement of the coated and the opposite face is performed with a ZYGO NewVIEW.

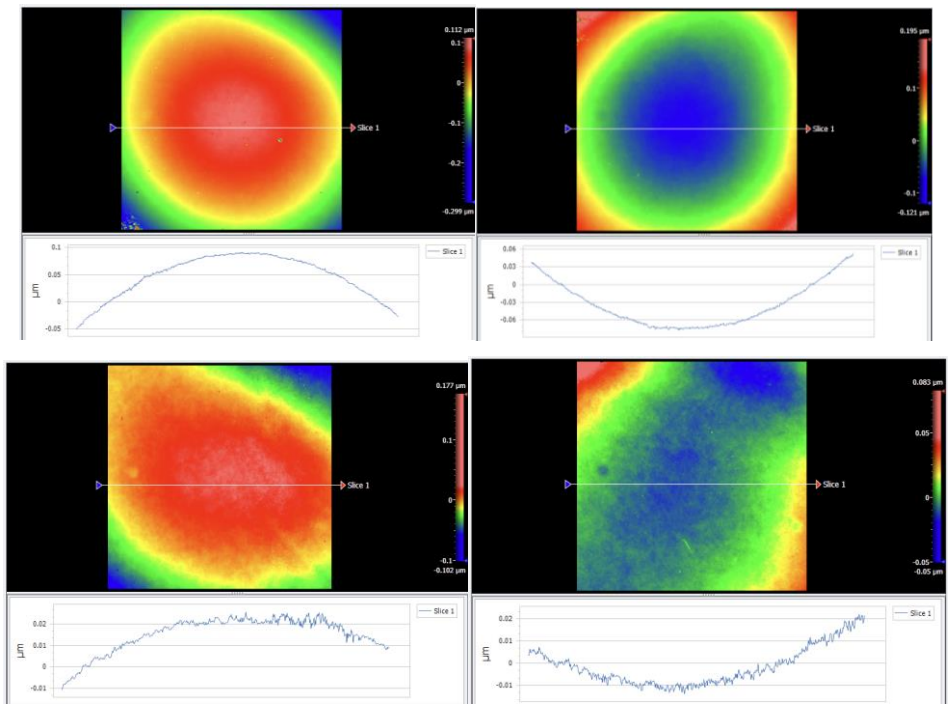


Figure 6. Measured SFE on both faces on the reference samples #2 (top left and top right) and #3 (bottom left and bottom right)

Table 2. SFE and deformation associated to unitary tests samples

Reference samples (1mm thick)	Mean SFE Measured	Measured stress
Reference sample #2 analyzed over 8.66mm diameter	122 nm	470 MPa
Reference sample #3 analyzed over 8.66mm diameter	27 nm	85MPa

A multilayer coating is applied on the measurement and reference samples #4 with a total thickness of 1.14 μm representative of the 50 % mirror coating design made of SiO₂ and Nb₂O₅. The goal of this test is the validation of the stress determined previously and is also an intermediate step between the unitary tests and the final semi-reflective coating deposition.

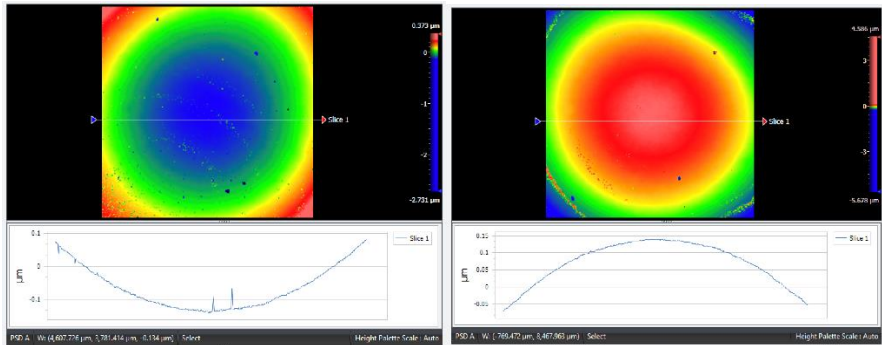


Figure 7. SFE of the reference sample #4: coated face (left) and rear face (right).

The 1.14 μm coating shows a non-compliance to the direct bonding with a SFE of 206 nm PV on the reference sample (190 nm PV on the measurement sample).

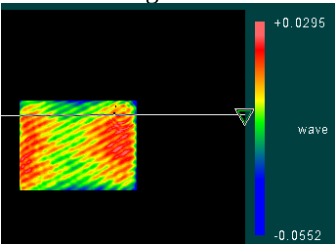
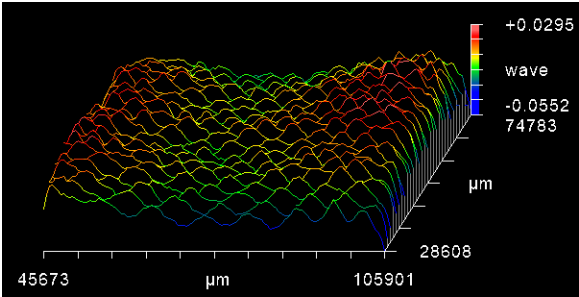
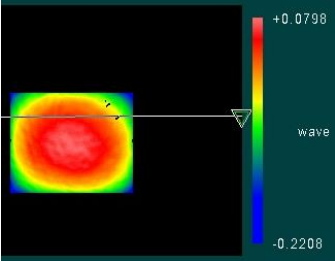
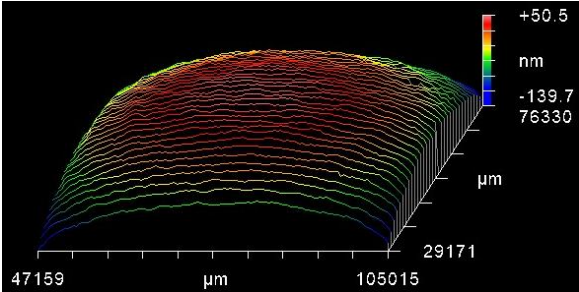
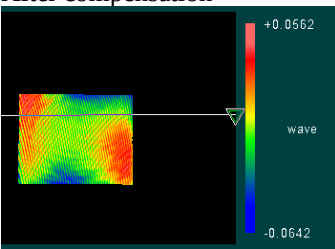
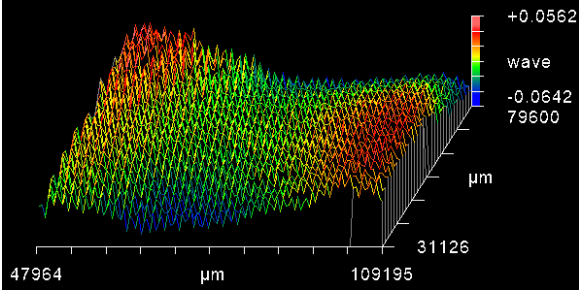
Table 3. SFE measured on the reference sample #4 and the calculated deformation associated to the 1.14 μm coating.

Reference sample (1mm thick)	Mean SFE Measured Face A and B	Calculated deformation
Reference sample #4 analyzed over 8.66mm diameter	206 nm	183 nm

A single layer of SiO_2 will be deposited on the opposite face of the sample #4. Its refractive index is close to the one from the substrate meaning that there is no influence on the optical performances but the stress is compensated. To calculate the thickness, the following equation is used considering the stress measured on the previous samples.

$$R_{s+f}[FACE1] = -R_{s+f}[FACE2] \Rightarrow [\sum_{i=1}^{N_H} \sigma_H(t_{Hi})t_{Hi} + \sum_{j=1}^{N_L} \sigma_L(t_{Lj})t_{Lj}][FACE1] = \sigma_L(t_L)t_L[FACE2] \quad (3)$$

Table 4. SFE measured before and after coating and after compensation on the measurement sample #4

Measurement sample #4	Surface shape	Measured SFE
Before coating 		0.169fr 54 nm PV
After coating 		0.601fr 190 nm PV
After compensation 		0.241fr 77 nm PV

The SFE after compensation is above the objective criterion (> 70 nm PV) but better than the target (< 80 nm PV). With this result, it is decided to rework the measurement sample #1 to proceed to the direct bonding with the sample #4.

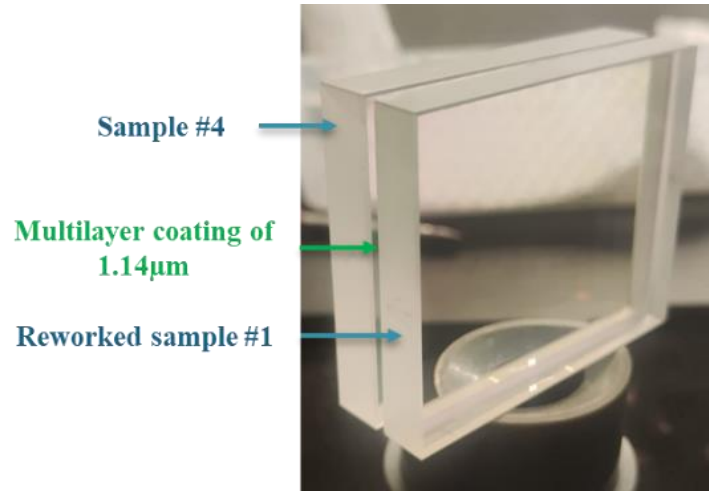


Figure 8. Molecular bonding between the two measurement samples separated by a multilayer coating of $1.14\mu\text{m}$.

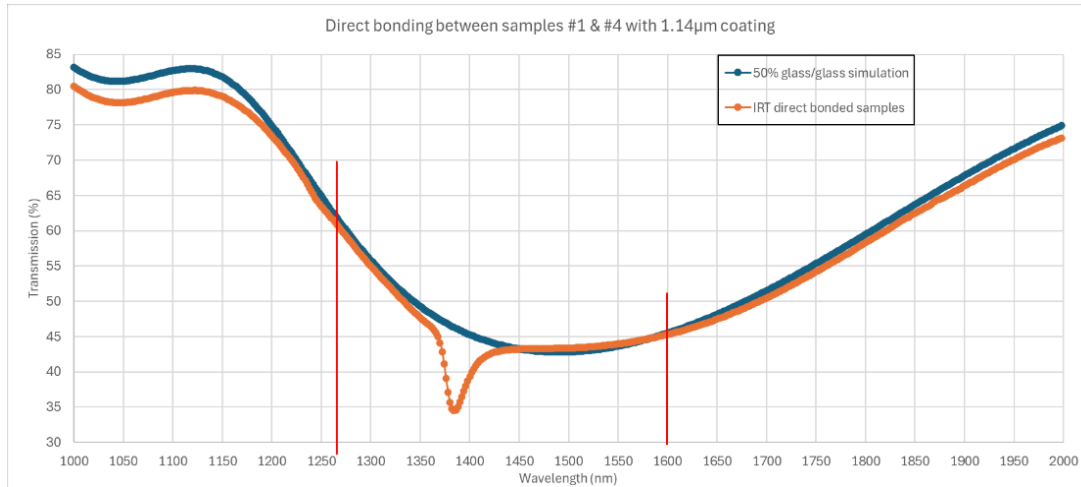


Figure 9. Simulated spectral response (blue) vs measurement spectral response after direct bonding (orange).

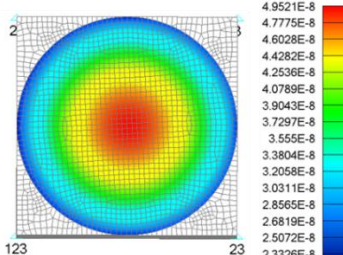
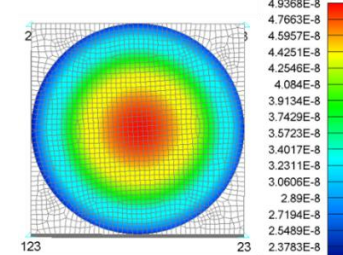
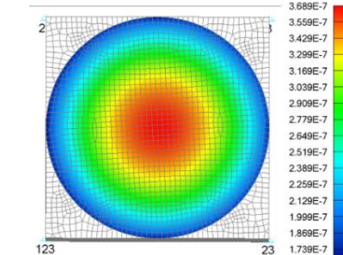
By using a spectrophotometer (Photon RT from Essent Optics) the spectral response is measured between 1000 nm and 2000 nm. In the optimized bands, the response between the simulated SR and the measurement are close to each other with a deviation of 1.4 % at $1.27\mu\text{m}$ and 0.6 % at $1.6\mu\text{m}$. The H₂O absorption line is measured around 1370 nm but has no impact on the optical performances.

3.2 Finite elements model from measurements results

The stoney formula doesn't work with for the final geometry of the semi-hexagon. The FEM model has been implemented and to reproduce the measurements performed with the samples. It has been validated then adapted to the final shape of the interferometer to anticipate the deformation on the different faces.

The reference sample shape with the results from the Table 3 are used in a FEM study where the materials with their properties are implemented. An equivalent thermal load case is determined to fit the measured deformation with the simulated one.

Table 5. Thermal case determination by FEM from the reference samples and the measured SFE.

Sample #2	Sample #3	Sample #4
		
Tload 20°C → 1000°C PV = 122 nm	Tload 20°C → 200°C PV = 27.9 nm	Tload 20°C → 610°C PV = 208 nm

Once the thermal case is defined for the 50 % mirror coating, the same case can be applied taking into account the semi-hexagon defined in the design of the future interferometer as an intermediate step before applying the semi-reflective coating.

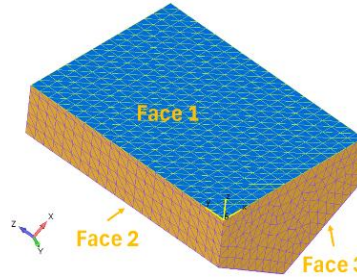


Figure 10. Semi-hexagon where the coating will be applied before direct bonding on the second semi-hexagon of the interferometer

The thermal case is applied on the face 1 and the deformations of all the surfaces are analyzed.

For a thickness of 1.14 μm applied on the face 1, the SFE of its surface is 55 nm PV and the two faces from the roof have a SFE of 29 nm PV.

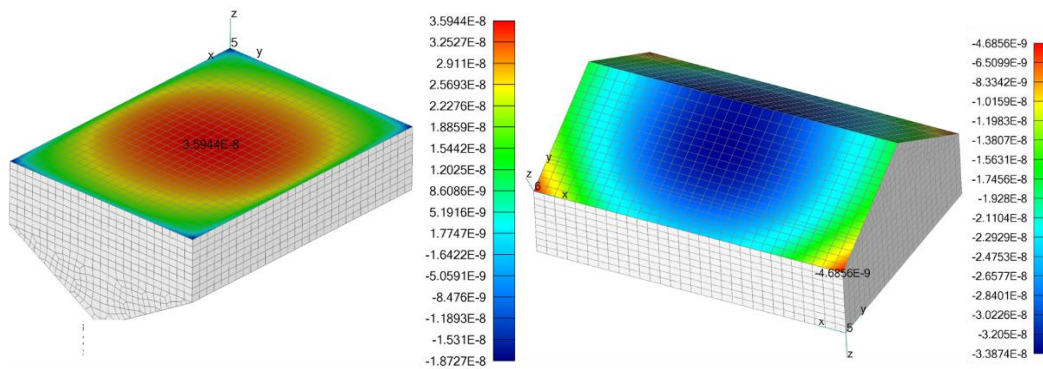


Figure 11. Deformations of the surfaces from the thermal case extrapolated from the sample #4.

The next part of the FEM is to apply the thermal case #2 on the faces 2 and 3 to compensate the face 1 and quantify the deformation which will be extrapolated later with the semi-reflective coating of 7 μm .

By addition of both thermal cases, the results give a SFE 48 nm PV for the face 1 and 23 nm PV for the faces 2 and 3 (roof faces).

The analysis is extrapolated at 7 μm for the SR coating with a compensation multiplied by the ratio of $\frac{7}{1.14} = 6.14$ to make a tolerancing. The results of the Table 6 show a high value of SFE which cannot be compensated by only 2.45 μm of SiO_2 . By increasing the thickness of the compensation layer, the face 1 would be compensated and the direct bonding would be feasible but the other faces would be deformed which is not compatible of the design of the interferometer as the glass and mirrors plate must be bonded on the face 2 of the same semi-hexagon receiving the SR coating.

Table 6. Results from an extrapolation of the coating and compensation thickness.

	Thermal case #4 extrapolated from 1.14 μm		Thermal case #2 extrapolated from 400 nm		Semi-reflective coating with compensation
Face	SFE at 7 μm	$\pm 10 \%$	SFE at 2.45 μm	$\pm 20 \%$	SFE
Face 1	335 nm	33.5 nm	40 nm	8 nm	295 nm
Face 2	179 nm	17.9 nm	38 nm	7.6 nm	171 nm
Face 3	179 nm	17.9 nm	38 nm	7.6 nm	171 nm

Due to the fact that the stiffness of the faces 2 and 3 of the semi-hexagon unbalance the SFE from the face 1, the compensation cannot be applied in the way that the flatness of the three surfaces is compatible of the bonding. According to the experiments and after a trade-off led between several solutions to improve the design of the interferometer, the decision is taken to split the semi-hexagon into a glass plate with parallel faces bonded to a smaller semi-hexagon.

4 CONCLUSIONS

The first results have demonstrated the capacity to perform a direct bonding with a coating deposited on one surface. The finite elements models have been a major support to simulate phenomena with a complex design and improve the feasibility of manufacturing the future interferometer. The achieved work is in line with the development plan for the technology and the qualification of the semi-reflective coating of 7 μm with the compensation is the next step with the direct bonding achievement.

The sample #5 has been recently coated with the nominal semi-reflective design and compensated with few μm of SiO_2 .

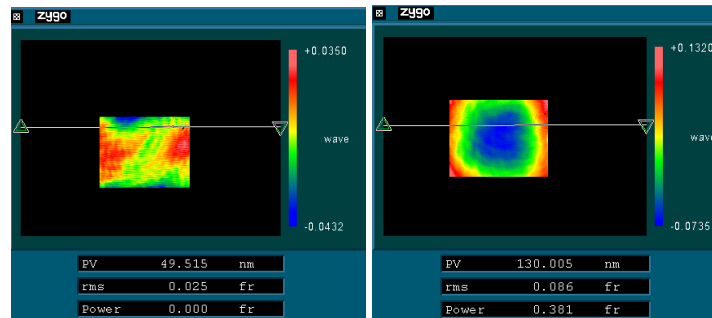


Figure 12. SFE measured on the sample #5 before coating (left) and after SR coating with compensation (right).

The SFE increased from 50 nm PV to 130 nm PV which leads to a no go to do the direct bonding. A second round of compensation is needed to reduce the deformation which is not an issue as the SiO_2 is optically transparent in our spectral bands.

The Figure 13 shows the spectral response of the reference samples placed next to the measurement sample at different steps. The theoretical curve coming from the design and simulation is in orange and is named "BS Qualif". The 260708-052-BS-IRT is the reference sample after coating and before compensation while 260708-052+053-BS-IRT is the reference sample measured with the coating and after the compensation.

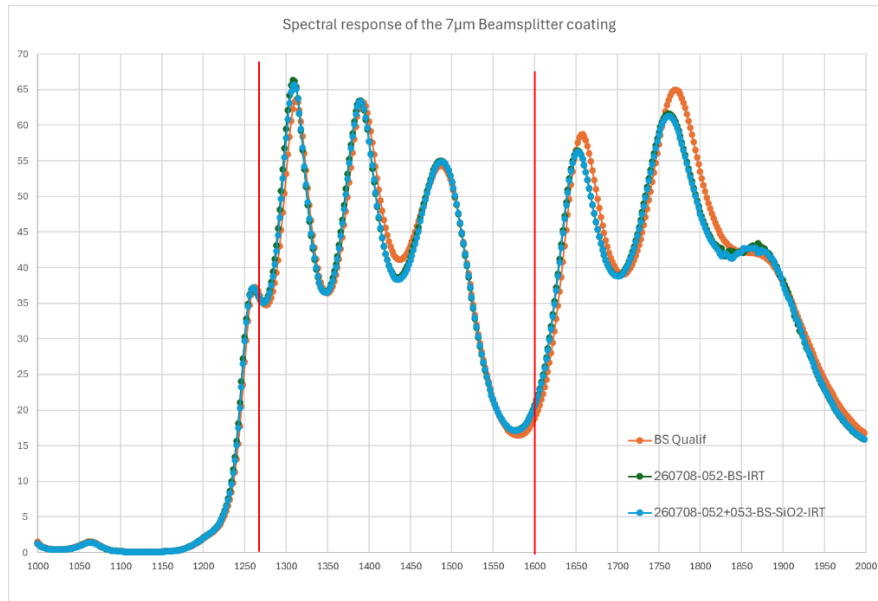


Figure 13. Theoretical spectral response (orange) of the reference sample coated with the semi-reflective coating of 7 μm (green) and compensated after (blue).

For measurement simplicity, the comparison is performed at normal incidence, for which the coating doesn't provide the optimized beamsplitter performances and where minor deviations can be observed.

The measured response before and after compensation are overlapped, showing that the SiO_2 compensation layer on the opposite face doesn't impact the spectral response.

The main objective of the samples #5 and #6 is to respect the thickness of the SR coating and be able to compensate the deformation and get the requested flatness to be able to do the direct bonding and confirm the feasibility of it.

The next steps of the technology development plan are:

- To build a full batch of samples dedicated to the mechanical stress qualification. For this purpose, the full process of coating with compensation is applied and the direct bonding is performed for several samples to quantify and qualify the mechanical stress constraint.
- To manufacture and test a Structural and Qualification Model (SQM) dedicated to environmental tests. This SQM is representative of the interferometer with the same components and processes but without optical performances requirements. Less coatings are requested, only the SR coating due to the direct bonding process on it.

Those qualifications take place in parallel of the interferometer breadboard dedicated to on ground characterization and performances to demonstrate the concept and derisk the proto flight model.

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