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CRYOGENIC OPTICS FOR SPACE APPLICATION

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ABSTRACT

For space born Astronomy as well as Earth Observation from space, more and more focal plane instruments are operating in the near or mid infrared and require therefore optics operating at cryogenic temperature (down to liquid nitrogen temperature or less).
Through several examples of typical past or on-going realizations for different projects requiring such cryogenics optics (e.g. MTG=Meteosat Third Generation program for ESA), the presentation will point out the main technical issues and corresponding solutions for design, manufacturing and testing of necessary lens assemblies, mirrors and relevant optical coatings.
A brief review of the corresponding existing "state of the art" for these technologies in Thales Seso will conclude the presentation.

Keywords: cryogenic optics, cryogenic coatings, WFCAM, EMIR, MIRI, MTG

I. INTRODCUTION – GENERAL CONCERNS ABOUT CRYOGENIC OPTICS

When comparing an optomechanical system operating around ambient temperature/pressure with another similar one operating at cold temperature, and possibly also in vacuum, we are facing different additional issues as follows:

a) The good acknowledge of the optical and mechanical material properties at cold temperature. This is valid for mechanical properties such as CTE/thermal conductivity as well as for optical properties such as refractive index change.

b) A compliant mounting solution for the optics inside their supports meeting simultaneously positioning stability requirements (wrt. 6 degrees of freedom) and allowable max thermal stresses (worst is to avoid risk of breakage). So, the baseline for the design here is always to have "sufficiently smooth" system, in order to allow relative thermal dilatation, but also a "sufficiently stiff one", in order to withstand mechanical loads and keep good alignments.

c) The necessity of having compliant and qualified optical coatings keeping good spectrophotometric performances for wide range of temperature while offering perfect adhesion, cleanability and durability properties on large range of optical substrates with significantly different relative CTE.

d) The demonstration of the final optical performances at operating conditions requiring complex test set-ups in simulated environment, i.e. cryogenic test chamber with optical window and different on-board instrumentation with its own qualification in terms of optical performances.

Such brief presentation cannot give of course an exhaustive analysis of all kinds of technical difficulties met in all kinds of situations (with mirror systems or with lens objectives) and cannot therefore propose all related solutions, but thanks to several typical examples given hereafter, we will provide here the demonstration of the ability of Thales Seso to manage such problems.

We will in particular point out and comment the following different heritages or on-going projects, mainly linked to the items b) and c) so "mounts for cryogenic optics" and "solutions for cryogenic coatings". Provided examples will come for either ground based Astronomy (for which since long time many experiment are operating in cryogenic conditions in the near infrared spectral band 1µm-2.5µm) or from Space born experiments

II. HERITAGE IN CRYOGENIC OPTICS (few examples)

II.1 example of cryogenic mount for mirrors:

This sub-assembly was developed in the early 2000's for the UK Astronomy Technology Center (ATC) in Edinburgh-Scotland. It is the tertiary mirror unit of the Wide Field Camera (WFCAM) of the UK Infrared Telescope located in Hawaii. So, basically it a for a ground-based use but it should have been developed as well for a space born use, of course may-be with some additional efforts regarding the minimization of the mass. The mirror unit is represented on the following figure 1.

Fig. 1: view of WFCAM tertiary mirror unit

The key features of this sub-assembly are:

- Low expansion glass mirror (such as Zerodur) in order to meet tight optical specification (WFE < 80nm RMS all inclusive) that were not possible to reach using alternative diamond turned aluminium mirror technology.
- Mirror diameter: Φ820mm
- Mirror shape: on-axis aspherical (elliptical) CV
- Mirror geometry: "double-arch" lightening concept. This was sufficient in this case but it could have been designed with an improved fully lightened concept with open back cells ort under-cut cells.
- Gravity in use: Optical axis vertical (+/-30° around zenith and with mirror facing up)
- Operational temperature: 150°K (so -123°C)

For this mirror, the mounting concept was designed as follows:

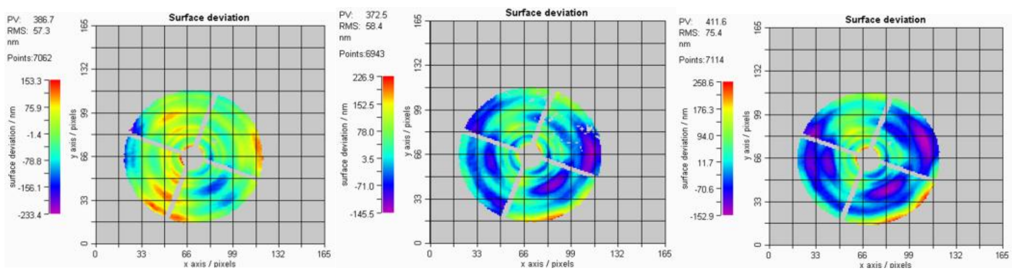
- Attachment of the mirror to the cryostat housing with 3 flexures located at 3*120° at 2/3 of the diameter (i.e. around Φ550mm)
- Material of the Cryostat housing = aluminium (high CTE)
- Material of the (3) flexures: INVAR (very low CTE)
- Attachment of Flexures onto cryostat housing => with screws
- Attachment of flexures onto mirror => with structural glue compatible with cryogenic use

In this example, we had to manage quite 2mm (!!) relative thermal dilatation between diameter of the interface ring onto the mirror (this does not change very much from ambient down to 150°K) , where the 3 flexures are glued, and the same diameter onto the cryostat baseplate.

For this purpose, the DFMs were designed sufficiently smooth in order not to distort the front active optical surface but sufficiently stiff in order to maintain the mirror alignment (mainly in X and Y centering and Θx and ΘY tilts) within specified limits vs. gravity orientation changes. After AIT activities in Thales Seso premises based on measurements at room temperature only, the system was delivered to customer for further operational test in full real conditions, so cold temperature in vacuum.

Interferometric tests were done at conjugates using interferometer (located in air, passing through a window) and a (small) concave retro-reflecting mirror (located inside the test cryostat). Recording of the double path WFE vs. temperature was done from 289°K (+16°C, so close to the temperature of manufacturing/mounting) down to a temperature close (188°K= -85°C) to the operating temperature (148°K = -125°C) (limitation due to chamber)

Records of equivalent single pass Mirror wavefront were as follows:



289°K (+16°C)
WFE=57nm RMS

215°K (-58°C)
WFE=58nm RMS

188°K (-85°C)
WFE=75nm RMS

Fig. 2: interferograms of WFCAM tertiary mirror vs.; temperature

Conclusions were:

- In all cases, WFE is within specification (i.e. < 80nm RMS)
- There are relatively poor changes from -50°C to -100°C (less than 20nm RMS)
- From ambient to -50°C, we noted quite same RMS value but with some inverted colours concerning trefoil errors, meaning that the major relative deformation is there (i.e. from +57nm RMS down to -58nm RMS with a symmetric trefoil effect).
- Actually, this was clearly predicted by our FEM design and we were counter-balancing some polishing effects (measured at ambient) with the expected thermal deformations so that final measurements were fully in line with our expectations.
- Good cryogenic behaviour of selected glue (was tested in a second step when in operation in real cryostat)

II.2 example of cryogenic lens holders

Thales SESO was manufacturing in-between 2006-2010, the optics for the EMIR spectrograph of the Instituto de Astrofisica de Canarias-IAC (camera assembly+collimator assembly+large diameter filed lens Φ500mm). EMIR is an infrared spectrograph (0,95µm-2,5µm) for the GRANTECAN telescope, operating at 77°K (= -196°C). The sub-assemblies “Collimator” and “Camera” we are speaking about are represented on the following drawings of figure 3

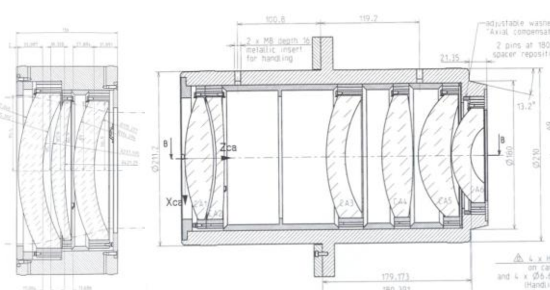


Fig. 3: EMIR collimator (on left) and camera (on right)

⇨ For Collimator, lens diameters are in the range of 160-180mm and glasses are Silica, BaF2 and IRG2

⇨ For Camera, lens diameter 100-140mm and glasses are BaF2, IRG2, Silica and ZnSe

The major problem to solve with this EMIR spectrograph was to allow possibility of diametric dilation of the lenses from Room temperature (= mounting/adjustment temperature) down to 77°K (= operating temperature):

- without risk of thermal breakage, because barrel is made out of aluminium, so with a CTE different than the ones of the glasses.
  - ⇨ Silica INFRASIL (for lenses CO2+CA3) = 0,5 e-7
  - ⇨ BaF2 (for lenses CO3+CA1+CA4) = 14,7 e-6
  - ⇨ IRG2 (for lenses CO4+CA2+CA5) = 8,8 e-6
  - ⇨ ZnSe (for lenses CA6) = 5,5 e-6
  - ⇨ While Aluminium CTE of barrel is 21 e-6
  - ⇨ All CTEs are averaged ones (RT=>77°K)
- All this keeping correct centering of the lenses (i.e. within specifications so in this case within less than 20-25µm) in order to get a good image quality and good stability of image plane at RT and also simultaneously at cryogenic temperature.). This solution made also easier the alignment and factory test of the complete integrated objective because it can be performed at RT (cheaper test that performing it at cold temperature). The testing sequence in this case was only:
  - ⇨ Measurement at ambient
  - ⇨ Cryogenic cycling (but not optical tests during cycling or at low temperature)
  - ⇨ New measurement at ambient (+ visual check) to verify recovering of initial image quality

To solve that double requirement, Thales SESO solution was to install lens inside intermediate cells which are flexible annular rings manufactured with appropriate CTEs (i.e. something in-between CTE of the glass and CTE of aluminium).

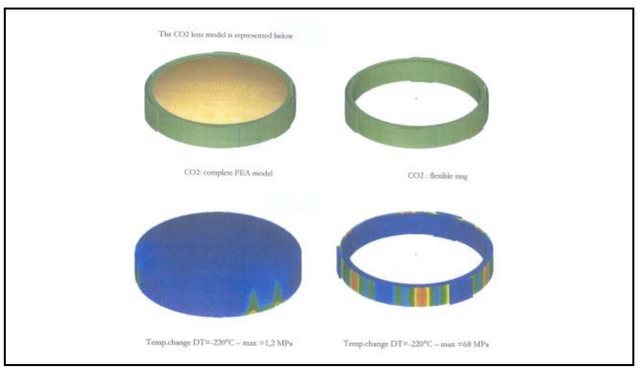


Fig. 4: FEM analysis of worst case # 1 = CO2, because lens made out Silica which is a « strong » material with a CTE very far from the one of aluminium)

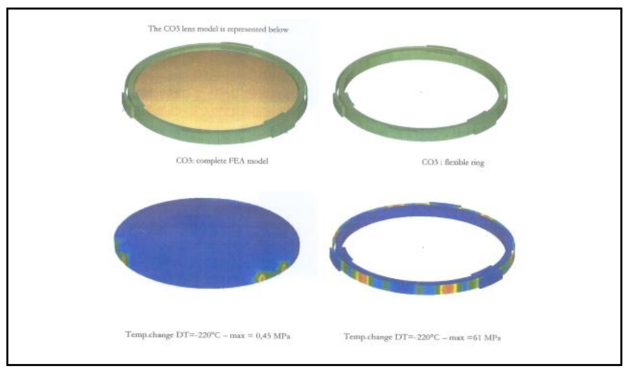


Fig. 5: FEM analysis of worst case #2 = CO3, because lens made out BaF2 with CTE close to but but it is a very fragile material

- ⇨ FEM analysis gave a Max tensile strength in the lens of 1,2MPa in the case of the fig. 4
- ⇨ FEM analysis gives a Max tensile strength in the lens of 0,45 MPa in the case of the fig. 5

We got a sufficient margin in all cases with regard to max acceptable tensile strength. However, we were installing some indium shims in-between glasses and metallic parts .

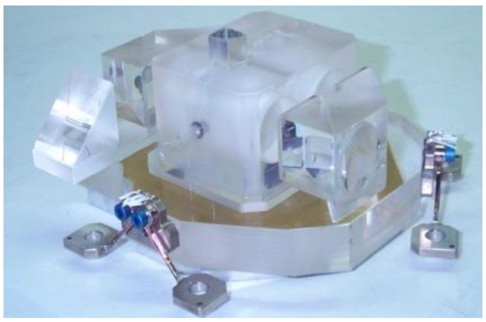
Then, the lens assemblies were:

- fully integrated, aligned and tested at room temperature in Thales SESO premises (optical quality + back focal distance) with our IR MTF test bench
- sent to Canarias for cryogenic cycling (carried out by customer)
- sent back to Thales Seso for comparative MTF test and we were not noticing any significant variation.

II.3 Molecular adhesion used at cold temperature

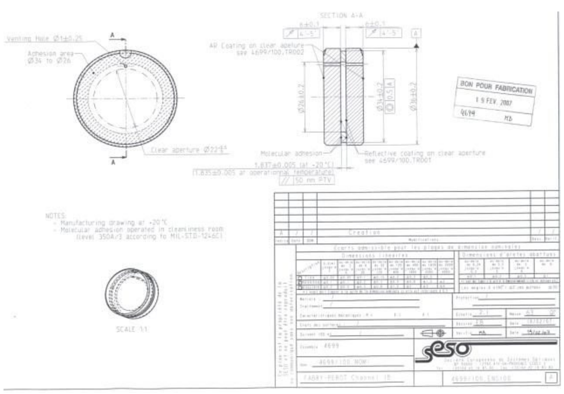
Molecular adherence is a solution to attach 2 pieces of glass without any glue (so without any constraints induced by glue). This is interesting for very accurate optical assemblies such as Fabry-Perot and particularly in case they are used for wide range of temperature.

We can highlight here the following 2 significant realizations in this field:



SESO has produced in 2003 a Silica “Double Channel” Fabry-Perot assembly qualified for Space Application.
Operating temperature is +20°C stabilised but qualification has been achieved from +60°C down to -40°C.
Attachment of the 3 accurate FP plates and spacer (accuracy in the range of λ/100PTV) was using optical contacting process (or molecular adherence)

Fig.6: first model of ALADIN Fabry-Perot assemby



Thales SESO has produced a ZnSe Fabry-Perot unit with specific Rmax and AR Coatings to filter the infrared band 5µ-7,7µ (= Channel 1A of MIRI, an experiment for the James Web Space Telescope). Mounting by molecular adherence (= optical Contacting) as well as optical coatings, have been tested successfully down to 20°K (= -250°C)

3 other units have also been made after for the 3 others MIRI channels: channel 1B (7.71µ-11.89µ, made out of ZnSe), channel 2A (11.89µ-18.35µ, made out of ZnSe) and channel 2B (18.39µ-28.3µ, made out of CdTe)

Fig. 7.: first unit of JWST-MIRI Fabry-Perot etalon for channel 1A

III. On-going project with cryogenic optics

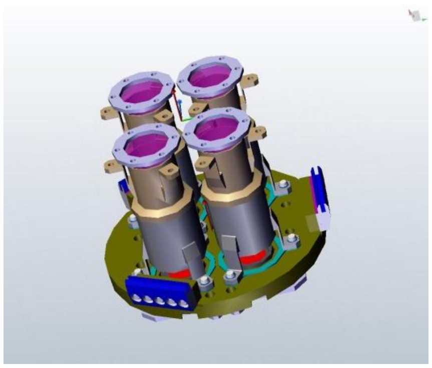
Thales SESO is presently under development of different optomechanical sub-assemblies for the master key project MTG (Meteosat Third Generation). Thales SESO works include the design, procurement and test of various optical assemblies (lens assemblies and dichroïcs) that are used in cryogenic conditions (down to 80°K)

III.1 Brief overview

The MTG program will provide the international community with meteorological and weather forecast data. It consists of two types of satellites. The imager mission named MTG-I, and the sounding mission named MTG-S. An instrument named FCI is currently under development by Thales Alenia Space and will be mounted on the MTG-I satellites (4 of them being ordered by ESA), to perform the continuation of service of the MSG mission. The satellites will be operating from a geostationary orbit above Europe and Africa, using a 3 axes stabilized platform.

The FCI will produce images of the Earth simultaneously in different spectral channels, ranging from the visible spectrum to thermal infra-red, in order to fulfil the scientific needs. At the main MTG telescope output, there is a spectral separation into 5 channels:

- VIS: without changing the focal length of the telescope (so, no relay optics needed here)
- NIR, IR1, IR2, and IR3: by collimating the 4 corresponding output beams, and adapting the magnification ratio in order to achieve the required instrument focal length for each channel. This is made thanks to 4 different Cold Optics lens assemblies (CO-I) that are developed by THALES-SESO.



After being spectrally separated and collimated, the NIR/IR optical beams reach the cold optics, which are located inside a common cryostat.
There are 4 cold optics housings, one for each spectral group, which are made out of Titanium alloy.
The lenses are in classical IR materials such as mono-crystalline Germanium, fused silica, ZnS and ZnSe. Diameters are in the range of a few centimeters.
The cold optics will be operating at a temperature about 80°K with their full performances.

Fig.8: view of the cryostat including the CO-I optics

III.2 Cryogenic coatings for MTG

General requirements and drivers for the coating design:

Infrared coatings for MTG use, so up to 15 µm wavelengths, generally present some absorption starting around wavelength 12-13 µm. This absorption is related to the selection of some materials in the coating design. A proper selection, linked to a good mastering of the deposition conditions, shows some optimization of the performances. In parallel the use of such coatings under vacuum and in cryogenic conditions induces further constraints in the design and optimization of the stacks. Also, one must take care of the possible deformation (degradation of WFE performances) that could be induced by thermal stress between the coating layers and the polished substrates.

To overcome these different difficulties we have developed a series of coatings for application on different substrates (Ge, Si, ZnSe and ZnS). These coatings have been tested in operating conditions using a liquid nitrogen based Dewar equipped with a pumping connection. The following sections will describe the deposition conditions and then the measurement methods and tools.

Coating tools for deposition and controls:

The deposition capabilities at Thales SESO include 4 different chambers, based on 2 different techniques (evaporation and magnetron sputtering) and allowing the coating of parts with size up to 1.7 m in diameter. However, because of the small size of the optics of the MTG program, qualification has been with our Leybold Q700 coating chamber. The layers are evaporated and we can combine quartz monitoring and optical monitoring to optimize the repeatability and the accuracy of the deposited layers. Substrates are heated to a temperature optimized regarding the selected materials for the corresponding design. The baseline pressure for starting the deposition is below 1 10^{-6} mbar.

The measurements are made using a FTIR spectrophotometer (SHIMADZU IR-Affinity). This spectrophotometer covers more than the requested spectral range by MTG (4µm-15 µm). The spectrophotometer can be used:

- At room temperature, either in transmission (without any further accessory) or in reflection using various accessories (fixed incidence 8°, 12° absolute reflectance, 30° to 80° variable incidence, combined with a polarizer to select the polarization orientation in any measurement).
- Or At cryogenic temperature (-196 °C) using a cryogenic Dewar which can be cooled thanks to a liquid nitrogen tank. This Dewar allows making measurements both in transmission and in reflection.

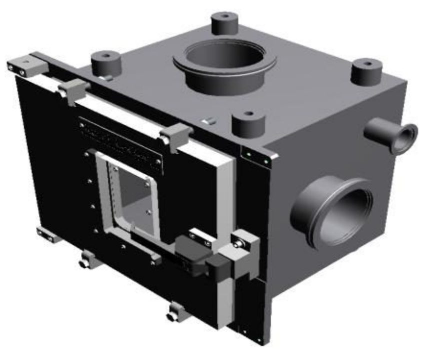
- The Dewar can be adapted onto our 12° absolute reflectance accessory.

The Dewar can be adapted onto our 12° absolute reflectance accessory. Connected to a controller, it can also allow heating the sample in high temperature conditions (up 350°C) to allow measurements in good conditions. The Dewar is equipped with ZnSe windows which are heated to avoid condensation. The cell can be brought to vacuum using a convenient connection to a pumping system. It can also be used under dry nitrogen for simpler configuration.

Fig. 9: Dewar on absolute reflectance accessory

From the different measurements, we can deduce the behaviour both for transmission and for reflection of the manufactured coatings at room temperature as well as in cryogenic conditions and under vacuum. The measurement accuracy is +/-0.5%.

For the measurements of the surface deformation (that could be induced by thermal stresses), we use a Zygo interferometer. The substrate is measured before coating and then after coating of the dedicated surface. The variation in curvature allows getting the stress induced in the coating, but is mainly used to anticipate this deformation during preliminary polishing phase.



The deformation is measured in ambient conditions, but a dedicated chamber is being prepared to allow a measurement under vacuum to assess the effect of environment.

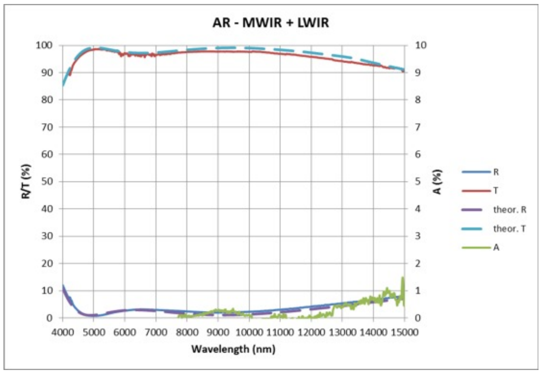
Fig. 10: view of Chamber used for vacuum test

Coating design and spectrophotometric measurements:

Actually, the process started with an iterative phase, between monolayers depositions (to characterize the exact optical indexes of the deposited materials over the complete range) and a real design phase to optimize the coating regarding the required performances
Notes:

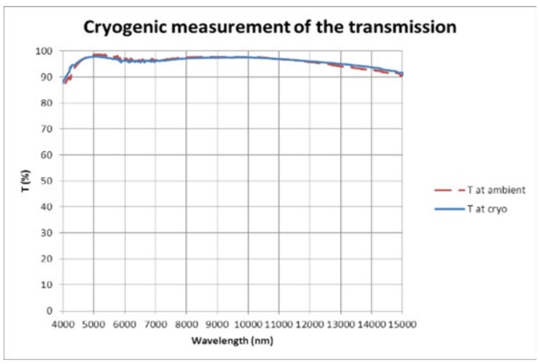
- Coating materials used are “confidential information” and cannot be disclosed).
- We focus here mainly onto the realization of the ZnSe polished/coated substrates, even though results also exist on the other infrared substrates needed for MTG. We just detail here after the process as run for the different materials.

Starting from above assumptions, we designed a complete antireflective coating for the range MWIR and LWIR (i.e. covering a need from 4.4 µm to 14.7 µm). The following curve shows the corresponding performances at ambient:



On this measured curve, we have superimposed the theoretical expected curves (dashed lines) and the measured one (solid lines, red for transmittance and blue for reflectance).
The absorption curve in green is calculated from
the relation R + T + A = 100%.
As mentionned above the residual internal transmission as evaluated in the curve above has previously been substracted. The residual absorption doesn't get higher than 1% at 15 µm wavelength, which is very atractive !

Fig. 11*: MWIR + LWIR AR coating at ambiant*

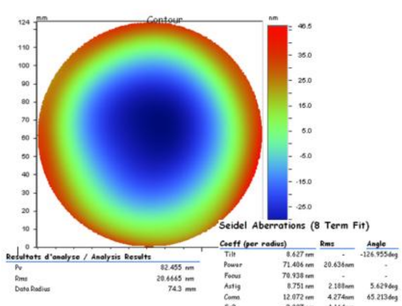


The same previous samples (figure 11) were measured also at liquid nitrogen temperature (inside Dewar at -196 °C).
The changes of performance that we have been able to measure were very low and presented in next figure 12.

Fig. 12: MWIR + LWIR AR coating in cold

Test of deformation:

An important concern with this kind of thick coating designs is the possible deformation induced onto the polished substrate due to stress in the coating layers. We therefore were developing some tests to specifically address this topic. The previous coating design was applied on a "larger scale" Φ127mm ZnSe window having 10 mm thickness. The measured deformation due to the AR coating applied on the first coated side is represented in figure 15.



The deformation induced by the coating is identified to be about 70 nm concave (on a clear aperture of 124 mm). The AR coating induces tensile stress in the layers. The plate was wedged to minimize the ghost images in the optical layout. The effect of the wedge on the measured deformation is limited, but not null: this is the reason why we observed a 9 nm astigmatism value oriented along the wedge direction

Fig. 13: Concave effect induced by the AR coating of 1 face of a Φ127 mm /10 mm thick ZnSe plate

V. REFERENCES

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