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THE POLARIZATION MODULATORS BASED ON LIQUID CRYSTAL VARIABLE RETARDERS FOR THE PHI AND METIS INSTRUMENTS FOR THE SOLAR ORBITER MISSION

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ABSTRACT

A technical development activity was carried out from 2009 to 2011 under ESA supervision to validate the Liquid Crystal Variable Retarders (LCVRs) as polarization modulators for the Solar Orbiter mission. After this, the technology achieved the Technology Readiness Level 5 (TRL5) corresponding to ñComponent Validation in Relevant Environmentò. Afterwards, additional tests and characterizations were performed in order to select the final specifications of the LCVRs cells to optimize their performances under the mission environmental conditions.

The LCVRs will be used to measure the complete Stokes vector of the incoming light in PHI (The Polarimetric and Helioseismic Imager for Solar Orbiter) and the linear polarization in the case of METIS (Multi Element Telescope for Imaging and Spectroscopy). PHI is an imaging spectro-polarimeter that will acquire high resolution solar magnetograms. On the other hand, METIS is a solar coronagraph that will analyze the linear polarization for observations of the visible-light K-corona.

The polarization modulators are described in this work including the optical, mechanical, thermal and electrical aspects. Both modulators will consist of two identical LCVRs with a relative azimuth orientation of 45º for PHI and parallel for the METIS modulator. In the first case, the configuration allows the analysis of the full Stockes vector with maximum polarimetric efficiencies. In the second setup, wide acceptance angles (Ò±4º) are obtained.

The polarization modulators will be thermal controlled to reach a stability better than ±0.5ºC during the measurement acquisition time (Ò60s) under all the operational thermal conditions. This is required to fulfill the required polarimetric accuracy (Ò10^{-3}), because the LCVRs behavior has a dependence on temperature. The mechanical design has been conceived to minimize mass, volume and the thermal conductivity as well as the mechanical stress produced by the mounts to the cells, but taking into account the vibration environment due to the launch loads that the device shall withstand. Additionally, the optical clear aperture has been maximized and the design avoids breaks due to thermo-elastic deformations produced during the thermal cycling.

Finally, the electrical cables and connections have been designed to obtain a very compact, modular and robust device.

I. INTRODUCTION

Solar Orbiter is a M-class mission of the Cosmic Vision program of the European Space Agency (ESA), being developed in collaboration with NASA. The objective of this space mission is to observe the Sun, using a suite of advanced scientific instruments and at an approach point to the Sun as close as 0.28 AU during part of its orbit. The scientific goals are the exploration of the uncharted innermost regions of the solar system, the observation of the Sun from close-up allowing extended observations in a quasi synchronous orbit with the rotation rate of the Sun and imaging the Sunôs polar regions from latitudes out of the ecliptic higher than 25º. It will allow scientists to better understand the dynamic of our star and answer questions as the origin of the high temperature in the solar corona (around 2.106K against 5600K in the inner photosphere) and its influence on the space weather, which has a fundamental importance for our daily lives on Earth. The mission baseline foresees that Solar Orbiter will be launched by NASA on an Atlas V launch vehicle (with Delta IV as a possible back-up) in July 2017.

The Solar Orbiter payload consists of 10 instruments: 6 remote-sensing instruments and 4 in-situ instruments. The remote sensing instruments SO/PHI (The Polarimetric and Helioseismic Imager for Solar Orbiter) and the METIS (Multi Element Telescope for Imaging and Spectroscopy) will carry out polarization measurements and their design includes Liquid Crystal Variable Retarders (LCVRs) as polarization modulators and, to our knowledge, for the first time in a space mission .

SO/PHI is an imaging spectro-polarimeter that will acquire high resolution solar magnetograms. In order to do this, it shall be able to measure the polarimetric state of the incoming light. For this purpose, the polarimetric signals have to be transformed into intensity levels that will, therefore, be modulated. Different polarimetric modulation principles are possible: spatial or temporal [1]. SO/PHI uses temporal modulation as provided by a Polarization Modulation Package (PMP) that allows measuring the complete polarization state (PMP is also called Polarization State Analyzer). On the other hand, METIS is a solar coronagraph that will analyze the linear polarization for observations of the visible-light K-corona. SO/PHI consists of two telescopes: the High Resolution Telescope (HRT), and the Full Disk Telescope (FDT). The HRT and FDT PMPs will be identical and the METIS PMP will use the same components, but in a slightly different configuration as explained in Sections II and III. It will allow reducing costs during the qualification campaigns of these subsystems

The polarization modulation shall be carried out by two Liquid Crystal Variable Retarders (LCVRs). This technology will be used for first time in a space instrument. Nevertheless, the polarization modulators based on Liquid Crystal Variable Retarders is a well-know technology for ground applications and currently in use by many instruments [IR01]. For space applications, LCVRs become a powerful alternative to the traditional rotating polarizing optics since they require less mass, volume and do not need to use any form of mechanisms. These are significant advantages for an instrument onboard a spacecraft, where the resources are very limited and the risk of a mechanical failure should be minimized.

Our team has the heritage of the development of the IMaX instrument [2][3] for the SUNRISE mission [4] where a PMP based on LCVRs was used as well. Even though, the SUNRISE mission was a solar telescope in a stratospheric balloon, not a space mission, many of the lessons learnt are applicable for Solar Orbiter. Besides, we carried out a validation of the LCVRs technology for the Solar Orbiter mission within a ESA Technical Development Activity from 2009 to 2011. The result was the achievement of the Technology Readiness Level 5 (TRL5) for the PMPs based on LCVRs [5].

In the following Sections the PMPs for both instruments, SO/PHI and METIS, will be described as the current status of the development and the foreseen activities.

II. PMPs BASED ON LCVRS

A. General description

The SO/PHI polarization modulator package (PMP) consists of two Anti-Parallel Nematic (APAN) LCVRs oriented with their fast axes at 45° with respect to each other followed by a linear polarizer (the polarizing beam-splitter, the polarization analyzer) aligned with the fast axis of the first LCVR. The PMP generates four modulations of the polarization state in order to extract the Stokes parameters of the solar incoming light.

For METIS, only one LCVRs is necessary in the PMP with a quarter-waveplate (not included in the PMP, but placed previously) in order to analyse the linear polarization. Nevertheless, an additional LCVR has been included with its fast axis parallel to the first cell, but with the pretilt angles of the liquid crystal molecules in opposite direction to obtain an extended and wider acceptance angle [6].

Obviously, in both instruments, a linear polarizer is included before the detector to be able to analyse the signal as change in the detected intensity.

As mentioned previously, LCVRs provide electro-optical modulation of the polarization, avoiding the use of any mechanism (like a continuously rotating crystal retarder). Polarization modulation with APAN LCVRs is obtained thanks to the anisotropy (uniaxial) of the liquid crystal molecules inside each LCVR cell. They have an ordered orientation and this orientation of the optical axis can be changed applying an electric field due to their polar properties. Then, the effective birefringence of the cell can be changed by application of a voltage, introducing optical retardances (phases) in the orthogonal polarization components of the light and, therefore, introducing a change (modulation) of the polarization state. The optical retardance introduced by each LCVRs can be selected from the full 360º range for voltages with amplitudes lower than 15V.

LCVRs shall include a thermal control system in order to obtain a suitable repeatability of the optical retardance induced, since the thermal agitation reduces the molecules order. The thermal stability required is typically around ±0.5ºC during the adquisition time. The response times of APAN LCVRs are in the range of tens of milliseconds or better, adequate for a space magnetograph. LCVRs are easy to synchronize with the detector readout due to their electro-optical nature, simplifying instrument control. Their power consumption is negligible and only the driving electronics, which can be efficiently designed for low consumption, need to be considered.

B. Polarization modulation scheme

Firstly, SO/PHI polarization modulation scheme will be considered because the METIS one is a particular case of it, as it will be shown. SO/PHI is a Stokes polarimeter and therefore is a system that determines the four Stokes parameters of incoming light: I, Q, U and V. Detectors are only sensitive to the intensity of light (I), but insensitive to the particular values of the rest of the Stokes parameters. Therefore, it is necessary to transform Q, U and V into I changes, to be able to measure them. For this purpose, some kind of polarization optics is required (in general, wave plates and polarizers) that can affect the polarization state of light (perform polarization modulation), described by Mueller matrices. The set of polarization optics used in a polarimeter to perform this task is known as PMP. In the SO/PHI case, it will consist in two LCVRs oriented with their fast axes at 45° with respect to each other followed by a linear polarizer aligned with the fast axis of the first LCVR as explained previously.

Also, because we need to measure four quantities (*I*, *Q*, *U* and *V*), at least four intensity measurements should be carried out. This is the selected measurement number for SO/PHI. In the case of a partial Stokes polarimeter, fewer intensity measurements will be needed depending on the number of Stokes parameters of interest. This is the case of METIS: the linear polarization . Therefore, for METIS, the parameters of interest are *I*, *Q* and *U* and the minimum intensity measurements required are three. It can be done with a quarter-waveplate with its fast axis at 0º and one LCVRs with it fast axis at 45º followed by a linear polarizer at 0º.

The basic polarization detection is as follows [1][6]. Incoming light Stokes vector $S = \begin{pmatrix} I & Q & U & V \end{pmatrix}^t$ is transformed by a polarization modulation *M* (Mueller matrix of PMP) into $S_0 = \begin{pmatrix} I_0 & Q_0 & U_0 & V_0 \end{pmatrix}^t$. However, because only the intensity of I_0 of S_0 is measured, we are sensitive to only the first row of M. Now, an intensity measurement at the detector is

$$I_0 = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \tag{1}$$

with M_{ij} being the elements of the Mueller matrix *M*. The Mueller matrix of the polarization modulator changes after a different value of the voltage has been applied to the LCVRs. These voltage changes are carried out 4 times in total so that 4 intensity measurements are produced. Then, we will have the system of equations

$$\begin{pmatrix} I_0^{(1)} \\ I_0^{(2)} \\ I_0^{(3)} \\ I_0^{(4)} \end{pmatrix} = \begin{pmatrix} M_{11}^{(1)} & M_{12}^{(1)} & M_{13}^{(1)} & M_{14}^{(1)} \\ M_{11}^{(2)} & M_{12}^{(2)} & M_{13}^{(2)} & M_{14}^{(2)} \\ M_{11}^{(3)} & M_{12}^{(3)} & M_{13}^{(3)} & M_{14}^{(3)} \\ M_{11}^{(4)} & M_{12}^{(4)} & M_{13}^{(4)} & M_{14}^{(4)} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = OS \tag{2}$$

where *O* is the so-called modulation matrix. Inverting Equation (4), the incoming light Stokes parameters are obtained by

$$S = O^{-1} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = DI \tag{3}$$

Where *D* is the demodulation matrix and it governs the polarization demodulation process (obtaining the Stokes parameters from the measured intensities). Because the result is a linear system of equations, a minimum of four modulations are necessary. A larger number of modulations can be performed to minimize the error in the measurements by performing a least squares inversion of the resulting over-determined system of equations.

It is clear that for any polarimeter *O* must be measured, and the accuracy to which it is known will determine the accuracy of the measure Stokes parameters. The measurement of *O* is part of the calibration of the system, and the procedure is out of the scope of this work. Nevertheless, it is clear that the key component of a polarimeter is that one that modifies the value of *M* for each measurement. It should be taken into account that sufficiently different configurations must be attainable to be able to have an invertible *O* matrix. This is quantified through the condition number of the demodulation matrix [8], or through the efficiency vector [9]. The efficiency vector gives a measure of the level of error propagation for each one of the components of the Stokes vector. It is known [9] that the maximum efficiency vector for a complete Stokes polarimeter is

$$\xi_i = \left(n \sum_{j=1}^{n} D_{ij}^2 \right)^{-1/2} \tag{4}$$

Where *n* is the measurement number and *i* goes from 1 to 4 (corresponding to the four Stokes parameters).

Theoretical considerations [9] show that the maximum obtainable polarimetric efficiency of a modulation scheme is given by

$$\begin{gathered}\xi_{\max,1} = 1 \\ \sum_{i=2}^{4} \xi_{\max,i} = 1\end{gathered} \tag{5}$$

If ones want to obtain, e.g., uniform efficiencies in Stokes Q, U and V, the maximum achievable polarimetric efficiency of the modulation scheme is:

$$\xi_{\max} = \left(1 \quad 1/\sqrt{3} \quad 1/\sqrt{3} \quad 1/\sqrt{3}\right) \approx \left(1 \quad 0.577 \quad 0.577 \quad 0.577\right) \tag{6}$$

The required modulation efficiencies for SO/PHI (HRT and FDT) is

$$\xi_{\max} \geq \left(1 \quad 0.45 \quad 0.45 \quad 0.45\right) \tag{7}$$

Note that the real parameter of interest are *Q/I*, *U/I* and *V/I* and, therefore, all the vector and matrixes are normalized. The allowed transmission losses of the PMP usually are specific requirements.

Considering the SO/PHI PMPs, the LCVRs optical retardances of the four polarization modulation states which optimizes the polarimetric efficiencies are [7]:

[deg]	PM_1	PM_2	PM_3	PM_4
$LCVR_1$	225.00	225.00	315.00	315.00
$LCVR_2$	234.74	125.26	54.74	305.26

Table 1. Optical retardance of the during the SO/PHI four polarization modulations (PM). The modulation cycle has been preliminary selected to minimize the response time of the devices

METIS is a particular case where the goal is to obtain maximum polarimetric efficiencies for linear polarization (Q and U) and the modulation efficiency of the circular polarization is not relevant. Therefore, it can be selected a modulation scheme with the following maximum achievable polarimetric efficiencies:

$$\xi_{\max} = \left(1 \quad 1/\sqrt{2} \quad 1/\sqrt{2} \quad 0\right) \approx \left(1 \quad 0.707 \quad 0.707 \quad 0\right) \tag{8}$$

The required polarimetric efficiencies are not defined yet. The scheme utilized, as explained presviously, is a LCVR, a quarter-waveplate and a linear polarizer. The LCVR optimum retardances are those that differ by 120 deg. Nevertheless, the number of modulations and the optical retardances for METIS are under discussion currently.

[deg]	PM_1	PM_2	PM_3
$LCVR_1$	δ_0+0	δ_0+120	δ_0+240

Table 2. Optimal optical retardance for the METIS three polarization modulations (PM). δ_0 is a retardance offset.

III. PMP DESIGN

A. Design parameters

LCVRs have some critical points that must be taken into account when used for imaging polarimetry with high SNR. All of them are addressable, and therefore should be important points that must be kept in mind in the design stage of an instrument. As a summary, the critical points of LCVRs that can affect the polarization modulation are:

1. Angle of incidence dependence of retardance
2. Temperature dependence of retardance
3. Homogeneity of retardance across clear aperture
4. Response times
5. Chromatism

Of the above list, the effect of items 1 and 3 can be minimized by a proper optical design of the polarimeter. The pros and cons of the different locations of the LCVRs in the optical train should be assessed considering a trade off between using them in a telecentric image plane or in a collimated beam. A telecentric configuration was chosen for the PMP of the SO/PHI FDT, the PMP for the SO/PHI HRT is in a convergent beam and the collimated beam option was selected for placing METIS PMPs. The selection depends on many factors. As example, for the FDT case, the LCVRs will be placed close to an intermediate image plane. The advantage compared to a collimated option is that the required LCVRs optical quality (i.e. Transmitted wavefront error) is relaxed and only cosmetic issues can be a concern (i.e.: dust on the LCVRs, scratches) because will have a direct impact on the scientific image. For this reason a purge system to be used during the ground operations has been included in the FDT optomechanical design. On the other hand, a cone of light beams will impact for every area corresponding to a particular Field-of-View (FoV) in the image. Due to the retardance dependence of the LCVRs on the angle of incidence (AOI), the resulting polarization modulation will imply an undesirable amount of light depolarization and, therefore, a decrease of the modulation efficiency. To minimize this effect, it has been required that the FDT optical design F# of this cone will be higher than 19, corresponding to AOI lower than ±1.5º. Additionally, it has been considered that the axis of the cones (chief rays) of the telecentric beam could be slightly different for every point of FoV. It can be solved by a FoV dependent polarimetric calibration. Nevertheless, the optimal retardances for maximizing the modulation efficiencies will not be introduced for all the FoVs. To avoid this effect the FDT optical design has been developed with a telecentric image in the FDT PMP location (<0.23º). It also allows to have a mean polarimetric calibration for all the pixels for fast processing purposes.

The LCVRs has a well-known AOI dependence since they are anisotropic materials that can be considered as a first approximation as uniaxial material whose optical axis changes with the application of voltage. The optical axis is parallel to molecules mean tilt. Additionally, it can be shown that LCVRs composed by double cells of the same LC mixture and opposite tilt direction have a significantly lower dependency with the AOI. These double cells are necessary for METIS due to the wide FoV required to measure the visible-light K-corona.

Point 2 requires the implementation of a thermal control in the instrument, which is a must for any kind of high-SNR polarimeter based on LCVRs (Section III.D). The temperature dependence of retardance has been studied for the LCVRs candidates [4]. Additional tests have been performed showing that the LCVRs works properly up to 90ºC (Fig.1). In our tests, we even subjected them to 115ºC (the so-called clearing point, or the transition to the isotropic phase), and their functionality was recovered and the optical response showed a good repeatability at 30ºC. From these studies, it has been concluded that the PMP operative range could be [-20ºC, +80ºC]. Due to the response time requirement, it should be reduced to [+40ºC, +80ºC]. The non-operative range has been established in [-40ºC,+90 ºC]. Although, the +90ºC upper limit has been demonstrated operative, this limit was defined in order to prevent any premature degradation with the time. To achieve the required modulation efficiencies, the optical retardances should be stable with time during the acquisition. Considering these data, the necessity of a thermal stabilization control of ±0.5ºC has been identified [4].

Item 4 is related to the time varying nature of the measurements: the measurement cadence is determined, apart from the efficiencies of the polarimeter as a whole (polarimetric efficiencies, transmittance, CCD sensitivities, etc.), by the scientific requirements (measurements should take less than a specified amount of time in which the solar target evolves). It can be managed by a proper selection of the liquid crystal mixture of the device, in accordance to the working temperature. For SO/PHI the selected LC mixtures, the temperature set point of the thermal control (Ó40ºC) and the pre-selected polarization modulation cycle guarantees that the required response times (<100ms) will be achieved. For METIS, the response time is not critical (<750ms) and it will be fulfilled as well.

Finally, point 5 is not an issue for SO/PHI, since it is quasi-monochromatic for the LCVRs. For METIS, the signal will be integrated in the spectral range from 580nm to 640nm. The LCVRs wavelength dependence has been studied and the resulting contrast of the corona measurements fulfils the scientific requirements. Hence, it was not necessary to implement other more complex solutions as achromatic LCVRs [4].

There are other aspects of the instrument that can be affected by the properties of LCVRs (or any other polarization modulation device), but are not linking directly to the polarization performance of the polarimeter, but rather to its optical performance as an imager:

1. Wavefront error
2. Alignment quality (which can produce depolarization).

It has been found that the major wavefront error contribution is a negative lens-like behavior, which can easily be corrected by the compensators present in the assembly of the polarimeter. The alignment quality, however, is determined by the type of the LC material used (ferroelectric liquid crystals for example are known to exhibit difficulties in delivering devices of high alignment quality and stability) as well as the type of alignment layer. Nevertheless, the validation activity demonstrated the high optical quality of the LCVRs that will be used for the PHI PMPs, thanks to the excellence level achieved by the providers (Arcoptics, Switzerland) in the manufacturing process [4]. They obtain WFE lower than $\lambda/20$ and a high stability of the LC molecules alignment. Besides, the suppliers have provided during the validation activity LCVRs with retradance homogeneities around 4% rms over all the clear aperture. Considering our design it is enough to achieve the modulation efficiencies and take into account that a FoV dependent calibration could be used to minimize this effect.

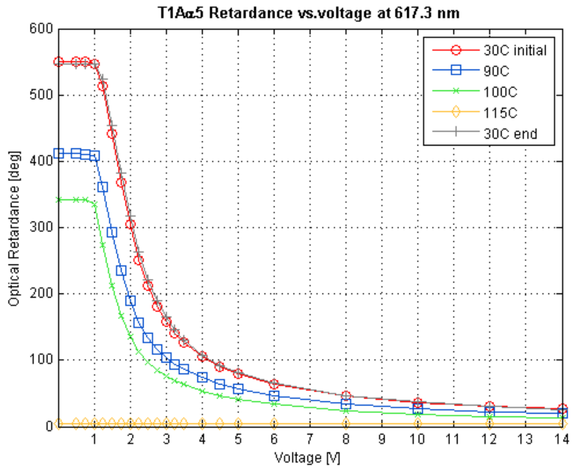

Fig. 1. Performance at high temperatures of T1Aα5 cell.

B. LCVRs cell design

As mentioned previously, an activity to validate the LCVR technology considering the harsh environment of the Solar Orbiter mission was undertaken under the supervision of the European Space Agency (contract Nº 22334-09-NL-SFe). The activity aimed at increasing the relevant Technology Readiness Level (TRL) from TRL4 ñ*Component Validation in Laboratory Environment*ò to TRL5 ñ*Component Validation in Relevant Environment*ò by providing a significant step towards full space qualification of high-performance LCVRs for the Solar Orbiter mission. The work finished on May 2011 successfully and the duration was above two years obtaining highly valuable information. Eight different types of liquid crystal cells were characterized and their performances were verified under ionizing, non-ionizing and ultraviolet radiation as well as after exposure to vibration and shock loads and thermal-vacuum cycles. Additionally, the features of the LCVRs were measured at the foreseen operational temperature range. A summary of the obtained results can be found in [4]

As result of the LCVRs validation activity, an optimized design or the cells was found. All the LCVRs cells used for the FDT and HRT PMPs will be identical in order to optimize the required resources during the manufacturing and the qualification of the cells. Also, it allows optimizing the procurement of spare devices. The LCVR cell design consists of two glass substrates of 5mm coated for one side with a transparent conducting material (indium tin oxide, ITO) and the other side with an antireflective coating at the working wavelength (580-640 nm, optimized at 617.3nm) of the LCVRs. The ITO sides are coated with an additional alignment layer (rubbed polyimide) which is the responsible for the orientation of the liquid crystal (LC) molecules inside the cells. The glass substrates are hold apart by a mixture of glass fibre spacers, whose diameter define the thickness of the LC layer, and a glue that will be provide the adhesion point between the two substrates (Gasket). The cell is assembled together and partially sealed to let an opening for LC filling. The LC is filled by vacuum filling and finally the cell is completely sealed with a glue or stopper. An external part of the ITO coating is electrically connected to the electrode. The final architecture, as described previously, for the LCVR cells will be APAN (Anti-parallel Aligned Nematic) using a positive nematic liquid crystal mixture.

C. Opto-mechanical design

Fig.2 and Fig. 3 show the opto-mechanical design of the FDT PMP including the LCVRs, the polarizer and the thermal control components.

The main structure will be manufactured of Vespel SP-1 in order to have enough mechanical stiffness and good thermal isolation. The voltage will be applied to the LCVRs through a kapton cable attached to the cells. This flexible cable also include the signal of temperature sensor (PT100) glued on it which will allow to know the temperature of the cell for the active thermal control. The cells will be mounted into two aluminium rings and a heater will be attached to them to provide the heating power. The opto-mechanical mount guarantee that no stressing loads are applied to the LCVRs in order to avoid the breaking of the LCVRs and increases of the wavefront error. A silicone material will be applied between the opto-mechanical mount and the LC cells that will serve as the elastic material to protect the cells from the vibration and shock loads.

The PMP total mass is around 200gr and the total mechanical envelop is approximately 74x60x32mm. These values slightly change from the SO/PHI PMP to the METIS one.

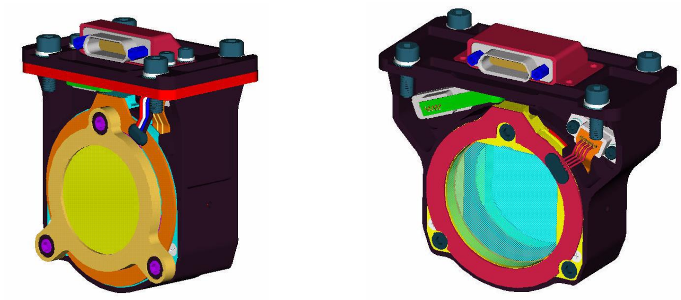

Fig. 2. FDT PMP optomechanical design. General view.

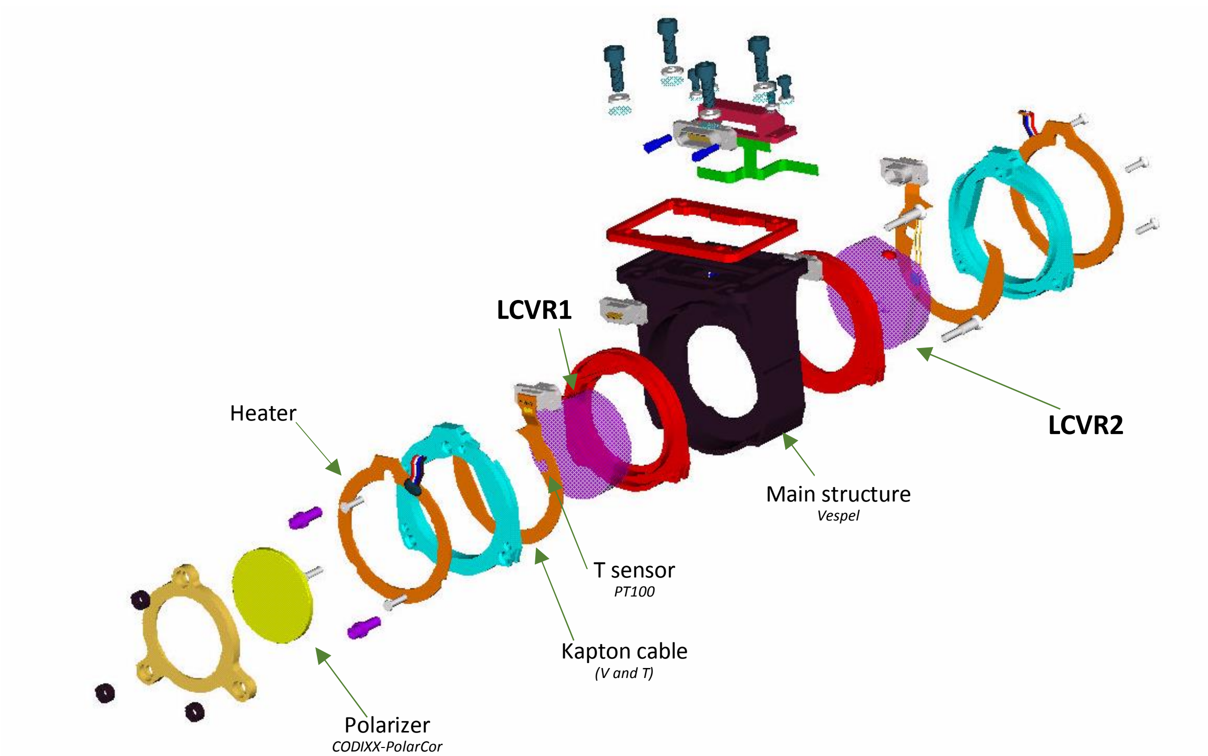

Fig. 3. FDT PMP optomechanical design. Exploited view.

D. Thermal design

An active thermal control has been design to have a PMPs thermal stability of ±0.5ºC during the acquisition. For that, a proportional-integral-derivative electronic driver has been design and included in the SO/PHI and METIS E-Units. As mentioned previously, a heater with a maximum power of 4W has been included in the PMP as shown in Fig.3 and a temperature sensor (PT100) has been included in the kapton cable located close to the clear aperture as used for the validation activity. On the other hand, the thermal analysis carried out for the instrument guarantee achieving the required temperature ranges (operative and non-operative) [IR19][IR20].

A complete description of the thermal models developed and the thermal analysis carried out for the PMPs is out of the scope of this work. Nevertheless, it can be seen in Table 3 the results of the transient cases studied. Table 3 presents the time necessary to reach +40ºC in the LCVR with respect to the power dedicated to PMP thermal control.

Power (W)	Time to reach 40ºC
1.8	Đ
1.85	10000 s = 2h 47min
1.9	6100 s = 1h 48min
2.1	3350 s = 56min
2.3	2650 s = 44min
2.5	2200 s = 37min

Table 3. Expected times to heat PMP LCVRs

IV. DEVELOPMENT STATUS

In September 2013 the Structural and Thermal Model of the SO/PHI PMPs were finished and delivered passing successfully the tests.

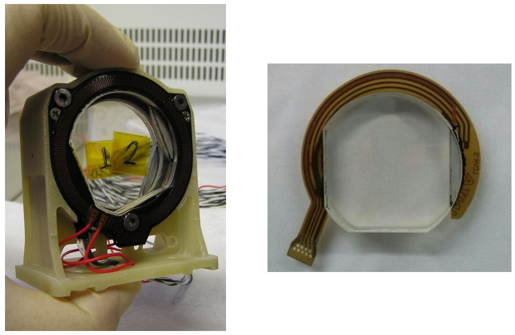

Fig. 4. Structural and Thermal Model (STM) of the SO/PHI PMPs. Left, the STM PMP integrated; right, cell with flexible cable including the temperature sentor.

During 2014 a detailed optical characterization of cells similar to the flight ones were done including thermal dependency of the optical performances, response time, birefringency dependence on the wavelength and trade-off between cells with medium and high birefringence. Currently, an elegant breadboard of the PMPs is under manufacturing. This model will be practically identical to the flight one except that the electrical components will have commercial quality.

Also a first batch (8 items) of LCVRs is being manufactured to check the final cell design as well as the manufacturing and integration processes. Finally, the Long Lead Items (LLI) as the cells substrates, are being provided. Two batches of 50 cells will be manufactured to be used during the qualification campaign of the LCVRs and the life test. The flight cells will be selected from these batches.

V. CONCLUSIONS

The SO/PHI and METIS PMPs for the Solar Orbiter mission have been described. They will be based on Liquid Crystal Variable Retarders (LCVRs). The general aspects of the polarimetric modulation have been presented as well as the optical, mechanical and thermal description of the devices.

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