Key Optical Components for Spaceborne Lasers

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ABSTRACT

Spaceborne lidar (light detection and ranging) systems have a large potential to become powerful instruments in the field of atmospheric research. Obviously, they have to be in operation for about three years without any maintenance like readjusting. Furthermore, they have to withstand strong temperature cycles typically in the range of -30 to +50 °C as well as mechanical shocks and vibrations, especially during launch. Additionally, the avoidance of any organic material inside the laser box is required, particularly in UV lasers. For atmospheric research pulses of about several 10 mJ at repetition rates of several 10 Hz are required in many cases. Those parameters are typically addressed by DPSSL that comprise components like: laser crystals, nonlinear crystals in pockels cells, faraday isolators and frequency converters, passive fibers, diode lasers and of course a lot of mirrors and lenses. In particular, some components have strong requirements regarding their tilt stability that is often in the 10 µrad range. In most of the cases components and packages that are used for industrial lasers do not fulfil all those requirements. Thus, the packaging of all these key components has been developed to meet those specifications only making use of metal and ceramics beside the optical component itself. All joints between the optical component and the laser baseplate are soldered or screwed. No clamps or adhesives are used. Most of the critical properties like tilting after temperature cycling have been proven in several tests. Currently, these components are used to build up first prototypes for spaceborne systems.

Keywords: Solid state lasers, spaceborne lasers, optomechanics, laser crystal, pockels cell, faraday isolator

1. INTRODUCTION

Especially in the field of atmospheric research there is a strong demand on high resolution data of different atmospheric parameters with global coverage. Active optical systems on board of satellites have a great potential to generate this kind of data. One of the key elements of such a system is a laser source with in most of the cases very special and defined properties like single frequency operation. Due to reliability and lifetime issues it seems advantageous to use full solid state lasers as baseline concept.

Based on the InnoSlab concept different laser sources for lidar systems have been developed until now. The development of these lasers started with a laboratory model of the ATLID laser source for the spaceborne atmosphere backscatter lidar instrument named ATLAS [1]. Based on this setup, three tailored pump-laser sources were developed for the airborne LIDAR lidar system A2D2G and CHARM-F [2]. A2D2G is designed to measure wind profiles based on the Doppler shift. CHARM-F is being used to analyze column-averaged volume mixing ratios of CH_4 and CO_2 measured by integrated path differential absorption (IPDA) [4]. Currently, the laser source for the franco-allemande climate mission MERLIN [5] is being developed at ILT. Within this mission it is planned to launch a CH_4 IPDA (Integrated Path Differential Absorption Lidar) system onboard a satellite in 2020. Based on the previous laboratory breadboards and on the airborne system CHARM-F the optical design was developed for MERLIN. The optical performance is being validated with an appropriate MERLIN laboratory breadboard. An overview of the above mentioned lidar lasers and further laser sources for industrial and scientific application based on the InnoSlab concept are given in [6].

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Typically, the development of a spaceborne laser system is a multi-step procedure comprising different models for risk reduction. Firstly, the optical parameters have to be demonstrated in simple low cost laboratory models, which can be adjusted very easily and which allow for simple and fast adaptions. The main drawback of those setups is the low thermomechanical stability which might make occasional readjusting necessary. In airborne systems the lidar instrument can be investigated and validated in the field. Here, more realistic measurement data including atmospheric scattering and ground reflections can be obtained. As the appropriate laser system has to withstand mechanical vibrations and shocks during integration, start and landing as well as temperature and pressure changes more stable optomechanics should be used. But in airborne system occasional readjusting is still possible. Therefore, a rugged single piece aluminum baseplate together with commercially available single piece flexure mounts were used for the above mentioned airborne systems (see [2]). Before integration, the tilt behavior of some mounts had been tested in a climate chamber.

For spaceborne systems strong requirements with respect to thermal and mechanical stability have to be fulfilled over the whole mission lifetime of typically several years. Here, certainly any maintenance is no option. Therefore, the key optomechanical components have been developed for the requirements given in Table 1. The laser system has to withstand an operation mode where the active temperature control is switched of. This might happen during on ground and in flight transport. During this time the laser is not in operation. During operation the temperature range is reduced due to active temperature control. Furthermore, especially during launch strong vibrations occur.

Table 1: Basic requirements for optomechanical components

Requirement	Value
Lifetime	> 3 years
Non-operational temperature range	-30 °C .. +50 °C
Operational temperature range	+10 °C .. +30 °C
Non-operational random vibration spectra	~ 14 g_{rms} Freq (Hz): ASD (g^2/Hz) 20: 0,026 50: 0,16 800: 0,16 2000: 0,026 Duration: 2 minutes
Material selection	No additional organic material for minimum outgassing

2. KEY COMPONENT SELECTION & REQUIREMENTS

For the development of the spaceborne lasers the optical setup has been subdivided into several key components. Within this publication the focus will be given to an extract given in Table 2. Soldered laser crystals which are commonly soldered to heat sinks are state of the art and do not have strong tilt stability requirements. Therefore, mirror and lens mounts, pockels cells and faraday isolators will be described within this section in detail.

Table 2: Key optomechanical components

Component	Tilt requirement	Optical requirements
Adjustable and non-adjustable mirrors and lenses	< 10 up to multi 100 µrad	Optical requirements have to be fulfilled by optical substrates

Pockels cells	< 100 µrad	Losses: < 30 dB (transmission > 99.9 %) Contrast ratio: > 30 dB
Faraday isolators	>> 100 µrad	Isolation: > 30 dB

2.1 Adjustable and non-adjustable mirrors and lenses

The component type that is most frequently used is typically an adjustable mirror mount. Experimental and numerical tilt analysis of some of the above mentioned laser systems show that long term stabilities of less than 10 µrad have to be fulfilled. This requirement certainly depends strongly on the laser design and the requirements of the laser with respect to its energy stability, pointing etc. These lasers were designed to have a comfortable working point in the stability diagram without any single mirrors having very high tilt stability requirements. Furthermore, the bending of the laser plate has to be taken into account which gives an additional contribution to the tilt error. But the latter issue is not covered by this publication.

Typically, the whole adjustment of a laser system is done with some mirrors. For a linear laser resonator normally 8 degrees of freedom are required in order to match both position and angle of the laser mode in both axes to the pumped volume. This can be adjusted with two independent mirrors (for example the end mirror and the outcoupler of a laser cavity). The remaining mirrors can be named as folding mirrors as they are not required for adjustment tasks. As the main function of folding mirrors is the redirection of the laser light from one mirror to the next the requirements for adjustment precision are typically >100 µrad. But certainly, at least the two adjustment mirrors need an adjustment precision of less than 10 µrad. Especially, in case of the small optical components with a footprint of less than 10 mm in both directions it becomes clear that the direct mechanical machining of surfaces with the required tilt precision is a hard task. The flatness of the surface must be better than 100 nm. Furthermore, the angle of all surfaces have to be references to each other. That is the reason why usually somehow tiltable mounts are used for adjustment. A further approach is to clamp all mirrors to fixed surfaces and to adjust the whole setup with optical wedge pairs which have very low tilt stability requirements.

In contrast to the above mentioned adjustable mirrors a laser typically comprises some non-adjustable mirrors or lenses. Non-adjustable means in this case that their fixation can be done with machined parts. This is for example true for all lenses within the pump optics of the InnoSlab amplifier. But on the other hand these components might have lager dimensions and masses.

2.2 Pockels cells

For Q-switching BBO-pockels cells are used. In these crystals the difference retardation of two perpendicular polarization axes is controlled with high voltages in the kV-regime which is applied to two opposite sides of the BBO-crystal. As the retardation effect depends on the crystal axes the crystal has to be adjusted with respect to the laser beam in order to have the mentioned effect.

2.3 Faraday-Isolators

Furthermore, Faraday-isolators are typically used in order to avoid feedback effects which for example might cause spectrally unstable operation of sensitive seed laser sources. A Faraday isolator consists typically of a Faraday rotator placed between two linear polarization filters that are tilted at an angle of 45° to each other. For the rotator typically TGG-crystals are placed in a strong magnetic field. The tilt requirements of the crystal and the polarization filters are very low (>> 100 µrad class).

3. DESIGN & PERFORMANCE

In order to fulfill the material selection requirements for low outgassing values only screw and solder joints are used for all different components. The soldering technique was inherited from the development of soldered diode bars and soldered laser crystals.

3.1 Adjustable and non-adjustable mirrors and lenses

A mirror mount was designed in order to fulfill the above mentioned requirements. The mount has the following general structure. The mechanical interface to the laser baseplate is given by a submount made of metal, typically aluminum. This submount is connected with a screw interface to the baseplate. This interface is only used for fixation but not for alignment tasks. An electrically isolating ceramic plate is soldered on the top-side of the submount (see Figure 1).

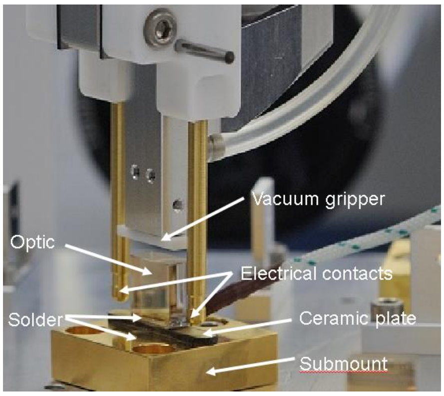

Figure 1: Adjustable Pick&Align mirror on a submount & details of the mounting tool

This ceramic plate has on its upper side a metal coating which allows for electrical heating. The optic is then soldered to the ceramic plate. The latter solder interface is used for all adjustment tasks. The adjustment procedure works as follows. The metal coated ceramic plate is contacted with two electrodes. The metal coating and also the solder are heated up until the solder is in the liquid phase. During that process the optic is griped with a vacuum gripper which is connected to micromanipulator. The manipulator allows for very precise adjustments with steps in the sub µrad range. For a more comfortable adjustment a mounting stage with two independent grippers is used (see Figure 2).

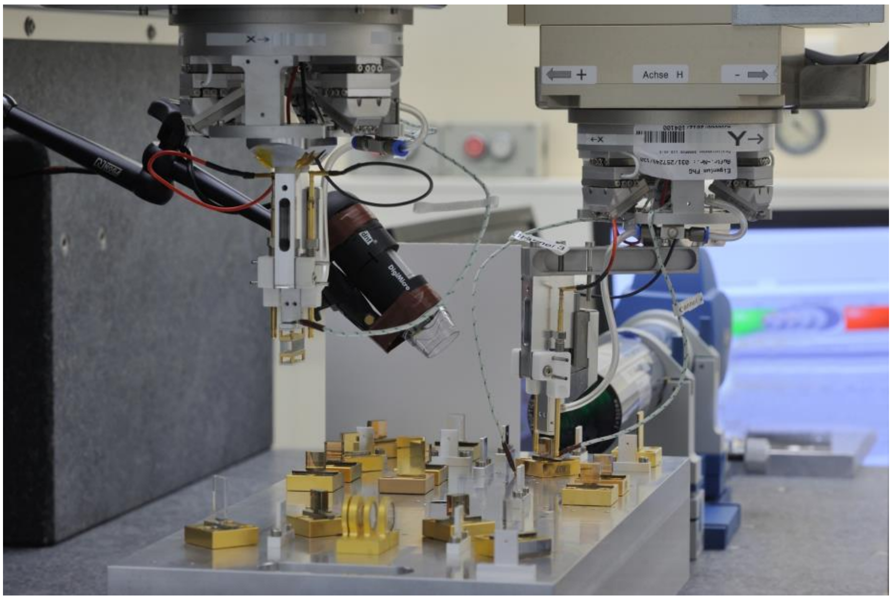

Figure 2: Mounting portal that is used for the adjustment of mirror mounts with two independent grippers and mircomanipulators

Environmental tests have been performed with several mounts in order to verify their compliance of the tilt stability requirements. Especially, for space application each mount is tested before integration. The environmental tests comprise a thermal cycling test and a random vibration test. The thermal test is as follows. All components are mounted on testplates which give the reference for angular measurements. The mirrors on the testplates are placed in a climate chamber. The temperature test profile covers the non-operative and the operative load cases (see Figure 3). At first, two non-operative cycles with a maximum temperature grade of 0.5 K/min are run starting with the low temperature case. After the first full cycle the starting temperature (that is also the mean operation-temperature) is kept for four hours. Then a second full cycle is applied where the temperature is also kept constant for four hours after the first half cycle. After the non-operational test phase one full temperature cycle within the operational range from 10°C to 30°C is applied with a hold time of two hours at minimum, intermediate and maximum level. Finally, the temperature is set to the starting temperature of 20°C.

The tilt angle of the mirror with respect to the baseplate is measured online during the complete temperature test as given as an example in Figure 3. It can be seen that this mirror shows a tilt of about 15 µrad during the first cycle but which is vanishes completely after the first cycle. During the second cycle a residual deviation of about 7 µrad during plateau 2 is observed. But over the whole operational range the mirror has a tilt deviation of about 5 µrad which is well in specification.

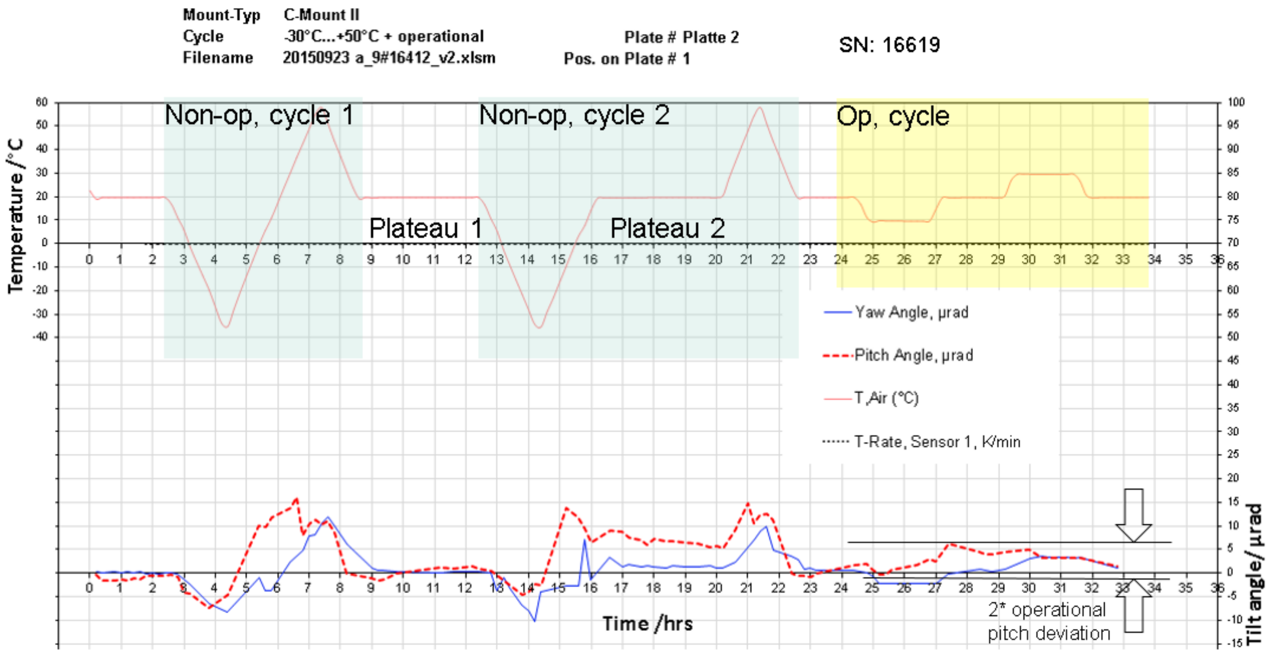

Figure 3: top: Temperature profile for environmental tests, bottom: Tilt angle of the mirror with respect to the baseplate.

These tests have been performed with a number of about 200 mounts. Figure 4 shows the final pitch and yaw after testing as well as the operational pitch and yaw deviation for the last 28 mounts that have been tested. The latter value describes (max-min)/2-value within the operational test cycle. It can be seen that except for two mirror mounts the tilt values are within the 10 µrad requirement.

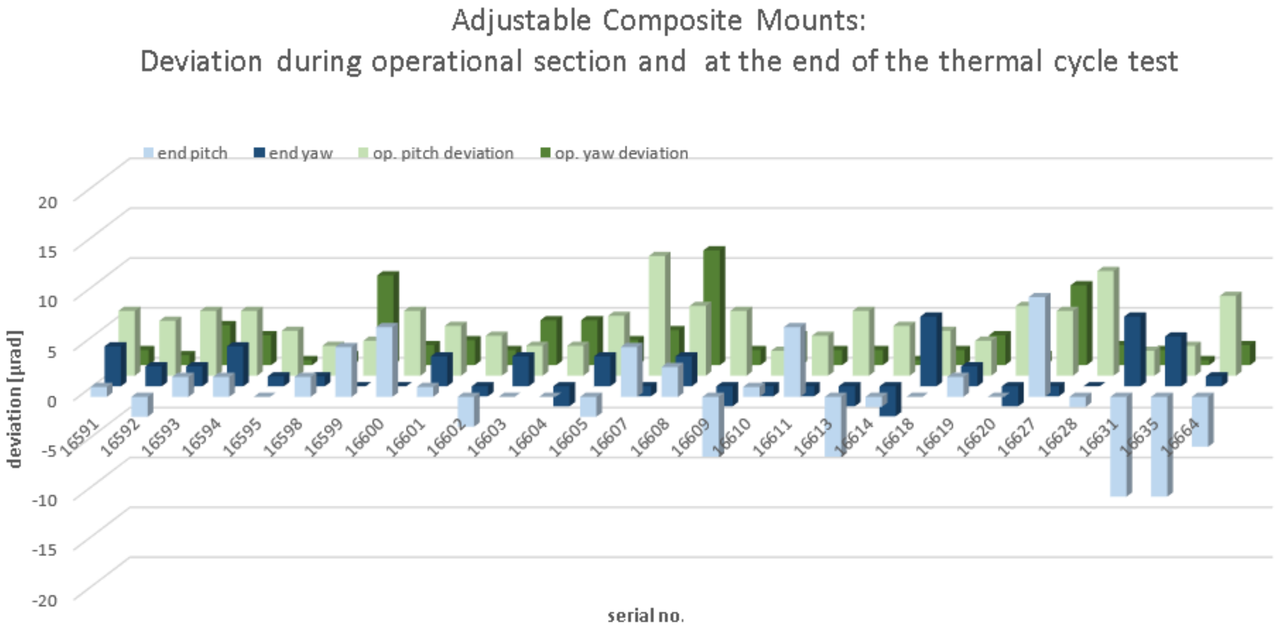

Figure 4: Test results of thermal cycling of 28 mounts. For all mirrors the tilt deviation after the complete test run (end pitch/ yaw) as well as the operational pitch/ yaw deviation were measured. The latter value describes half of the interval as described in Figure 3.

Table 3: Key optomechanical components

Parameter	**Mean Value ± Standard Deviation of Absolute Value**
End pitch	3.4 ± 3.1 µrad
End yaw	2.3 ± 1.8 µrad
Operational pitch deviation	5.4 ± 2.3 µrad
Operational yaw deviation	2.9 ± 2.6 µrad

Table 4: Mean value and standard deviation of the tilt deviation values given in Figure 4.

For vibrational tests a low force shaker (< 1 kN) is used. The non-operational random vibrations as specified in Table 1 have been applied to several mounts mounted on a reference plate for two minutes. The spectral density profile setpoint as well as the control signal of the shaker and an additional measurement of an accelerometer mounted on the testplate are given in Figure 5.

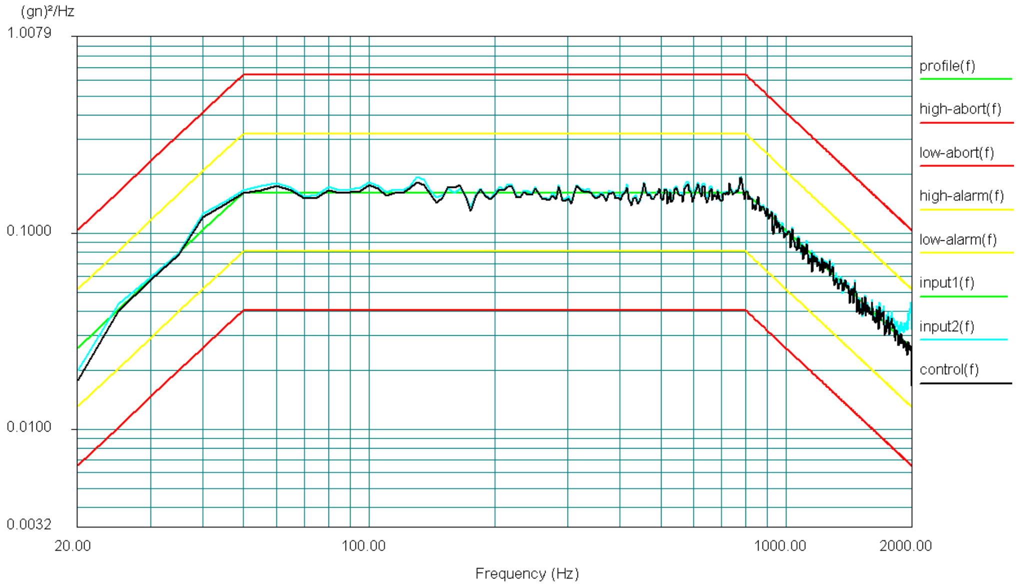

Figure 5: Spectral density of the vibration profile. Input 1: control signal of the shaker, Input 2: Measurement of an accelerometer mounted on the testplate. Measurement in x-direction (perpendicular to mirror surface)

The tilt of the mounts is measured before and after the vibration tests for all axes (x, y, z). The tilt deviation is for all cases for the mount 16643 lower than 3 µrad which is in the range of the measurement accuracy. Up to now only some single mounts have been measured. But they all show in case of proper mounting a tilt deviation of less than 10 µrad after vibration testing.

3.2 Pockels cells

The pockels cell package was tested with two different dimensions of the BBO-crystal (4*4*25 mm^3 and 5*5*25 mm^3). The crystals are connected with a solder joint to the electrodes. The complete package is free of organic substances like adhesives. The pockels cell has successfully been used as quality switch in laser resonators.

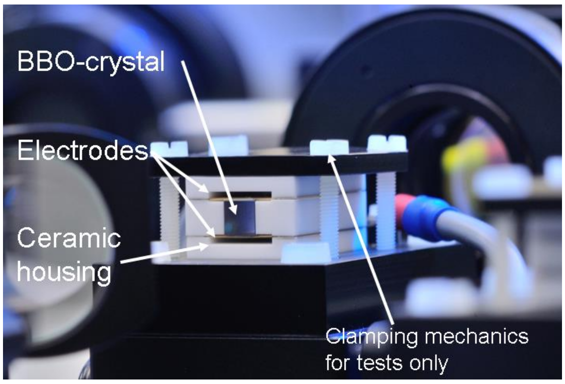

Figure 6: laboratory demonstrator of the soldered BBO-Pockkels cell package.

Furthermore, the polarization losses were measured. Therefore, the pockels cell was placed between two crossed linear polarizers. The whole arrangement was illuminated with CW SM-fiberlaser at 1070 nm wavelength at about 100 W mean optical power. In case of parallel polarizers the setup transmits 103 W of optical power. This was measured with a Coherent LM 200 power meter. In case of crossed polarizers only optical powers in the 10 mW range are transmitted. This was detected with an Ophir 3A power meter. Without the pockels cell the arrangement transmits about 1.8 mW in case of crossed polarizers which means a depolarization loss of 48 dB. If the pockels cell without any voltage applied is inserted into the setup the transmitted power increased to 2.8 up to 4,9 mW depending on the cell. This corresponds to losses of 43 to 46 dB.

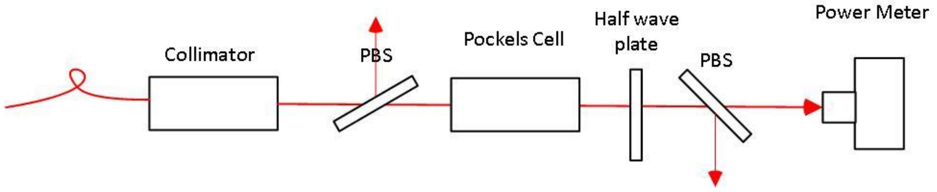

Figure 7: Setup for loss measurements

The contrast ratios of the Pockels cells were measured with the setup given in Figure 8. At first, the Pockels cell and the quarter wave plate are removed and the half wave plate #2 is adjusted to minimum transmitted power. Secondly, both quarter wave plate and the Pockels cell are inserted. Then, the rotation of the quarter wave plate is adjusted to minimum transmitted power. This is the case, when the crystal axes of the quarter wave plate and the have wave plate #1 coincide (0° position). The Pockels cells are operated without voltage. Depending on the Pockels cells the transmitted power is between 16 and 25 mW. Thirdly, the quarter wave plate is rotated by 45° (45° position) and the Pockels cell is operated at quarter wave voltage in order to compensate for the optical retardation given by the quarter wave plate. Here, 101 to 102 W were transmitted. This corresponds to a contrast ratio of 36 dB to 38 dB. This is exactly the measurement limit of this arrangement without Pockels cell. If the quarter wave plate is rotated to 0° position and the half wave plate #2 is adjusted to maximum and minimum power the above mentioned contrast ratios are obtained. Thus, the contrast ratio of the cell might be even higher. This would have to be measured with an optimized setup. But the requirements mentioned above have been fulfilled with margin. Different Pockels cells have been tested successfully in resonators in active high configuration.

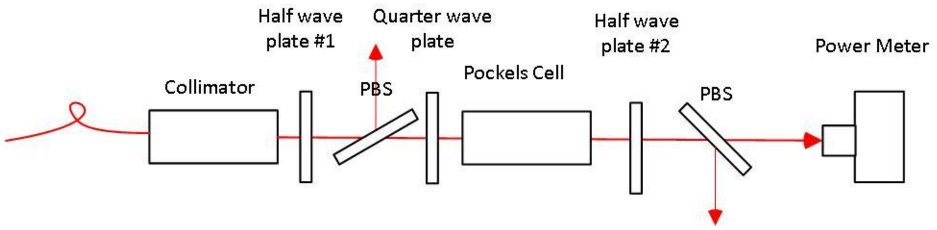

Figure 8: Setup for contrast ratio measurements

3.3 Faraday-Isolators

In order to fulfill the above mentioned requirements especially due to outgassing issues for both the arrangement of magnets as well as the TGG crystal and polarization mounting was adapted. On the one hand side the single magnets were mounted without any use of adhesives. On the other hand side the TGG crystal rod with a diameter of 4 mm and a length of 18.5 mm is soldered into an aluminum tube using soft solders. One thin film polarizer (TFP) is directly soldered onto this tube. A second TFP is soldered on a separate submount. Both elements are inserted into the magnet field arrangement and can then be adjusted to maximum isolation or maximum transmission if required. The complete isolator has a mass of 850 g with the dimensions 81x40x41.5 mm^3 including all optical and mechanical parts.

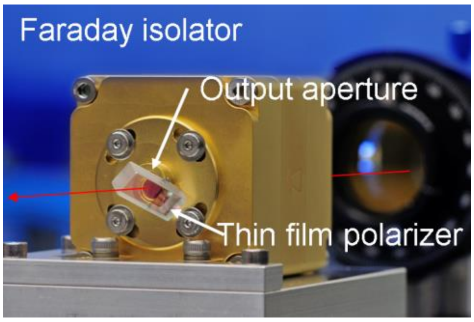

Figure 9: Faraday Isolator with soldered optics

The insertion loss as well as the isolation have been measured. The appropriate measurement setup is similar to the setup that was used for the Pockels cell characterization. Up to now a number of 3 isolators have been assembled and characterized. They show an isolation of better than 34 dB and an insertion loss of less than 0.2 dB. A single isolator has been assembled and environmentally tested as described above. No influence of these tests on the performance could be detected.

4. CONCLUSION & OUTLOOK

Especially spaceborne but also industrial laser systems require compact, robust and outgassing free key components in order to achieve maintenance free or low-maintenance operation over several years in rough environment. The soldering technique that has been developed for the mounting of diode laser bars as well as solid state laser crystals has been transferred to different laser optical key components. A selection of them is described here which are mirror and lens mounts as well as pockels cell packages and Faraday isolators. All of them are complete free from organic material and have been environmentally tested. All of these components were designed to meet the strong requirements for spaceborne laser systems. Currently, within the FULAS (Future Laser System) project (see [8]) a complete laser is being integrated based on these components. This laser comprises a single frequency oscillator one InnoSlab amplifier stage and second and third harmonic generation (SHG & THG).

Furthermore, a preliminary design was developed for the laser source of the MERLIN mission (see Figure 10). The concept was inherited from the FULAS laser. But in spite of SHG & THG converters the MERLIN laser comprises an OPO (optical parametric oscillator) which converts the pump light at 1064 nm wavelength into the measurement light at 1645 nm which is an absorption line of CH4. The OPO contains four adjustable mirror mounts and to special mounts for the KTP crystals that is not described here. Details about the optical design and performance are given in [7]. Two test modules of the OPO were assembled and climate tested with the test parameters described above. Both modules didn`t show any drop in efficiency due to this test.

The next step for space qualification of these components is an appropriate long term test with an adequate quantity of test samples. These tests are currently in process.

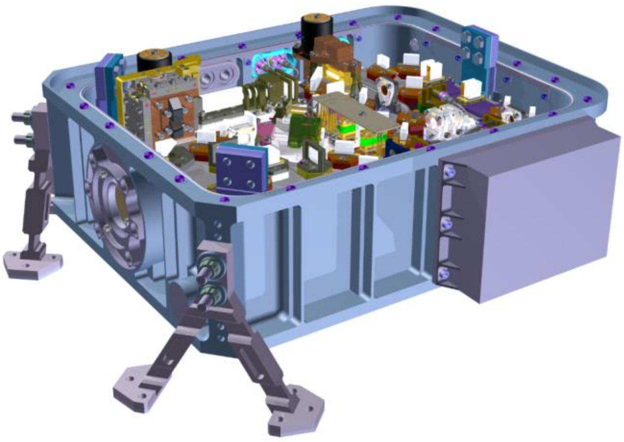

Figure 10: CAD model of the MERLIN laser

The mounting technology and the development of rugged key components is an important step for the development of resilient laser systems demanding very low maintenance effort for all kinds of applications. This is certainly true even for nonflying earthbound laser systems in industry and research.

5. ACKNOWLEDGMENT

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