LASER MODULATOR FOR LISA PATHFINDER

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ABSTRACT

LISA Pathfinder is an ESA experiment to demonstrate the key technologies needed for the LISA mission to detect gravitational waves in space. The LISA Pathfinder spacecraft represents one arm of the LISA interferometer, containing an optical metrology system and two proof masses as inertial references for the drag-free control system.

The LISA Pathfinder payload consists of two drag-free floating test masses located in the inertial sensors with their control electronics and an optical metrology subsystem. The optical metrology subsystem monitors the movement of both test masses relative to each other and to the spacecraft with very high sensitivity and resolution. This is achieved with a heterodyne Mach-Zehnder interferometer. This interferometer requires as input two coherent laser beams with a heterodyne frequency difference of a few kHz.

To generate the two laser beams with a heterodyne frequency difference a Nd:YAG laser is used together with the Laser Modulator. The Nd:YAG laser generates a single coherent laser signal at a wavelength of 1064nm which is fibre coupled to the Laser Modulator. The Laser Modulator then generates the two optical beams with the required heterodyne frequency offset. In addition, the Laser Modulator is required to perform laser amplitude stabilization and optical path difference control for the two optical signals.

The Laser Modulator consists of an optical unit – the LMU – and RF synthesiser, power amplification and control electronics. These electronics are all housed in the Laser Modulator Electronics (LME).

The LMU has four primary functions:

- Splitting of the input laser beam into two paths for later superposition in the interferometer.
- Applying different frequency shifts to each of the beams.
- Providing amplitude modulation control to each of the beams.
- Providing active control of the optical path length difference between the two optical paths.

The present paper describes the design and performance of the LMU together with a summary of the results of the Laser Modulator engineering model test campaign.

1. INTRODUCTION

LISA (Laser Interferometer Space Antenna) is a joint ESA-NASA mission that shall detect gravitational waves in space [1]. LISA comprises three spacecraft placed in a triangular configuration in space, each carrying test masses and a high resolution interferometer to detect the possible movements of the test masses by excitation from the gravitational waves. A schematic diagram of the LISA spacecraft in formation as they orbit around the Sun is shown in Fig. 1. The spacecraft are separated from each other by 5 million kilometres and trail behind the Earth at a distance of 50 million kilometres (equivalent to 20 degrees).

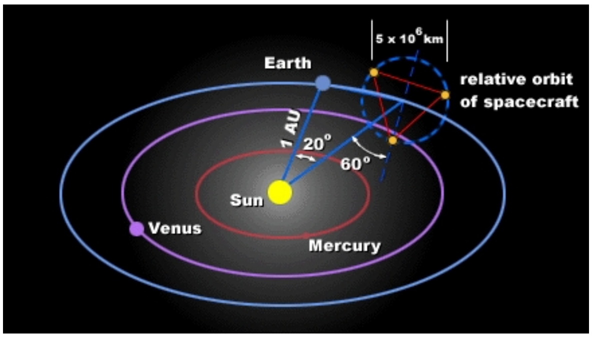

Fig. 1. Schematic of the LISA Orbit

As a precursor to the LISA mission, ESA is currently developing the LISA Pathfinder experiment to demonstrate the key technologies needed [2]. These are:

- Demonstrating that a test mass can be put in pure gravitational free-fall.
- Demonstrating laser interferometry with a free-falling mirror.
- Assessing the reliability of micro-Newton thrusters, lasers and optics in a space environment.

The LISA Pathfinder spacecraft represents one arm of the LISA interferometer. One payload element is the LISA Technology Package (LTP) that consists of two proof masses, a drag-free control system and an optical metrology system [3]. The optical metrology system monitors the movement of both test masses relative to each other and to the spacecraft with a distance measurement precision of 10^{-12} m in the frequency band 10^{-3} - 10^{-1} Hz. This is achieved with a heterodyne Mach-Zehnder interferometer. This interferometer requires as input two coherent laser beams with a heterodyne frequency difference of a few kHz.

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The two laser beams with a heterodyne frequency difference are generated within the Laser Assembly (LA). The LA comprises a Nd:YAG laser and a Laser Modulator that are connected using optical fibre.

Within this paper we present the flight design of the Laser Modulator in section 2. In section 3 the performance of the Laser Modulator engineering model is summarised.

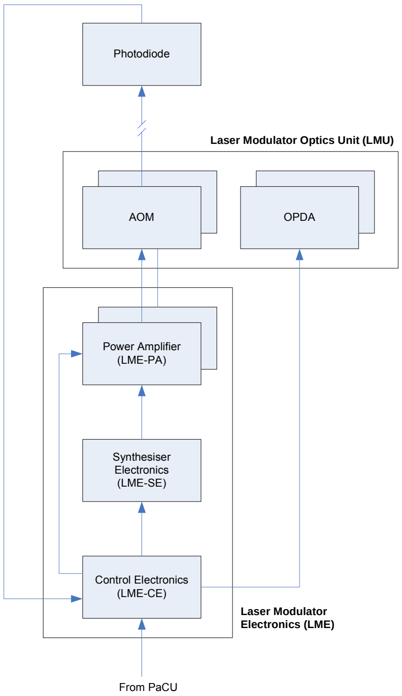

Fig. 2. Block Diagram of the Laser Modulator

2. LASER MODULATOR FLIGHT DESIGN

To achieve the required functionality of the Laser Modulator the following elements have been incorporated in the design:

- Splitting the incoming laser beam into two separate optical paths (Beam Splitter).
- Controlling the amplitude and introducing the heterodyne frequency to each optical signal using two acousto-optical modulators (AOM).
- Introduction of the optical path length control for each optical path by means of two optical path length difference actuators (OPDA).

A block diagram for the Laser Modulator is provided in Fig. 2. The Laser Modulator (LM) consists of two main units – the LM Optical Unit (LMU) and the LM Electronics (LME). An electrical harness connects the the LMU to the LME. The LMU is located with the laser at a thermally controlled interface within the LISA Pathfinder spacecraft. The LME is to be integrated with the Power and Control Unit (PaCU) to form the Laser Control Unit (LCU).

2.1 LME Design Overview

The Laser Modulator Electronics (LME) interfaces to the spacecraft for receiving control commands, providing status information and being supplied with electrical power. The LME provides the LMU with electronic control of its active components.

The Laser Modulator Electronics (LME) comprises the following:

- Control Electronics (LME-CE) which provides the low-frequency control and digital interface functions. To achieve the laser signal amplitude stabilization and close the loop between the LM and the optical interferometer the photocurrent from the monitor photodiodes are fed in as a control signal to the LME-CE.
- Synthesizer Electronics (LME-SE) which provides the synthesis of two spectrally pure RF frequencies using two phase-locked loops.
- Power Amplifier (two pieces, LME-PA1 and LME-PA2) are complete modules (including their own housings), providing the required RF power levels to the acousto-optic modulators (AOM) in the LMU.
- Electrical Harness (LME EH) which comprises the internal harness consisting of two coax cables connecting the LME-SE with each of the LME-PAs and two multi-core cables connecting the LME-CE with each of the LME-PAs. Connection between the PCBs is by flexprint as is the connection between the LME-CE board and several external LME connectors.

A photograph of the LME engineering model is shown in Fig. 3. This shows the LME-CE board above the two LME-PAs located in the base of the LME housing. Located on the other side of the LME is the LME-SE electronics board. The mass of the LME is 2.6 kg and maximum power consumption is 12.4 W.

Fig. 3. Photograph of the LME EM

2.2 LMU Design Overview

The Laser Modulator Optical Unit (LMU) is the optical sub-system of LM. The main functional blocks of the LMU can be directly associated to the components used to implement the previously mentioned functions of LM, namely:

- Splitting of the input laser beam into two paths for later superposition in the interferometer.
- Applying different frequency shifts to each of the beams. This has been implemented using two acousto-optic modulators – one for each optical path through the LM.
- Providing amplitude modulation control to each of the laser beams. Again this is achieved with the acousto-optic modulators.
- Providing active control of the optical path length difference between the two optical paths. This has been implemented in the LM by using two optical path difference actuators (OPDA) developed for the LM by Cedrat Technologies.

The possible technical realisations of the these building blocks may vary between two extremes which are summarised as:

- The "all fibre" solution consisting of a fibre-optical beam splitter (Y-coupler), pigtailed AOM and a fibre-optical OPDA ("fibre stretcher").
- The "all free beam" solution which is built from optical components comprising fibre collimator, beam splitter prism, AOM, an actuated reflector as OPDA and a fibre coupler.

A trade-off performed at the beginning of the project selected the free-beam solution since it best met the following key design drivers for the LMU:

- High optical transmittance.
- High (thermal) stability of the functional properties in the space environment.
- High spectral purity of the optical output beams.

A block diagram for the LMU based on the "all free beam" solution is shown in Fig. 4 together with a photograph of the LMU engineering model in Fig. 5. The mass of the LMU is 1.1kg. The input laser beam is collimated by a fibre collimator with a short focal length lens (approx. 3.1 mm) which generates a collimated beam. This beam is then equally split and then folded to propagate parallel to the optical bench using a beam splitter assembly. The optical bench is double sided in construction with one AOM, half-wave plate, OPDA and fibre coupler mounted to each side.

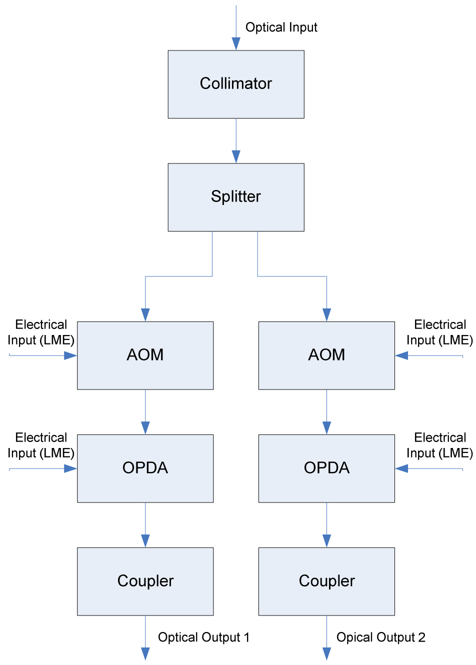

Fig. 4. Block Diagram for the LMU

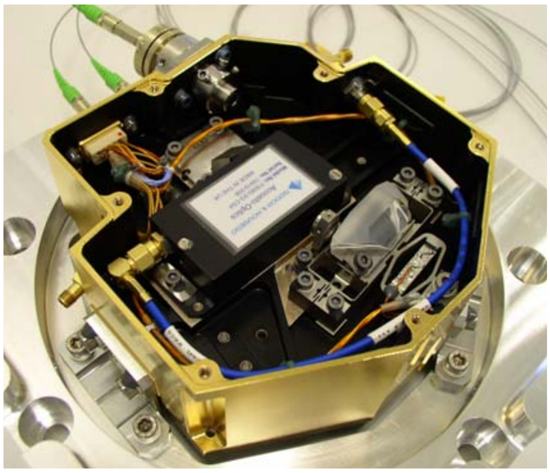

Fig. 5. Photograph of the LMU EM

The LMU interfaces mechanically (and thermally) using a quasi-isostatic interface to the spacecraft. Conductive heat dissipation and mechanical stability for the LMU is achieved through proper dimensioning of the wall thicknesses and ribs.

Acousto-Optic Modulator

A schematic illustration of the acousto-optic modulator (AOM) used in the LMU is shown in Fig. 6. The AOM comprises a birefringent TeO_2 crystal that is acoustically excited by a piezo-electric transducer (PZT) cemented to one of its surfaces. The RF signal used to drive the PZT is provided by the LME-PA housed in the LME. The acoustic signal from the PZT transducer sets up a periodic phase grating (resulting from variations of refractive index induced by a high-frequency acoustic wave) inside the TeO_2 crystal. The incident laser the beam is diffracted in the direction of the 1st order of the virtual grating. The transmitted beam is also affected by a small shift in frequency, which is the principle desired function of the AOM.

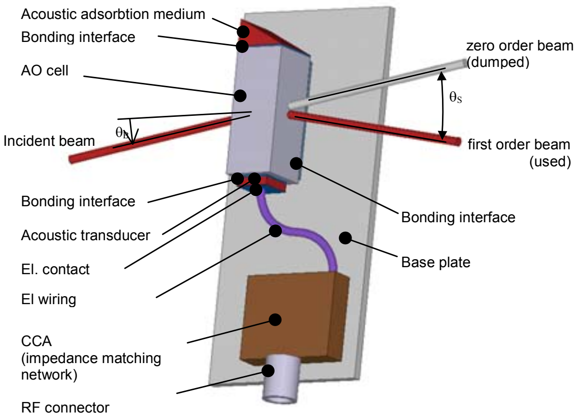

Fig. 6. Schematic Illustration of an AOM

By varying the RF power used to generate the acoustic waves, the 1st order diffracted beam can also be intensity modulated and this property is used by the LME to reduce amplitude noise and to control and match the nominal intensities of the transmitted optical beams. The optical transmission of the 1st order diffracted beam as a function of the RF power used to drive the AOMs is shown in Fig. 7 below.

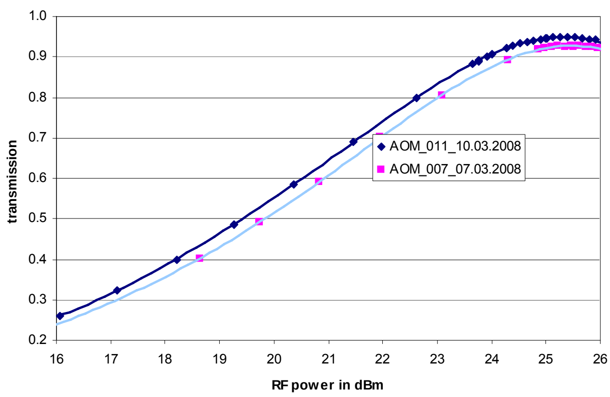

Fig. 7. Optical Transmission of the AOMs

After leaving the AOM each of the 1st order beams traverses a halfwave plate (HWP) before entering an optical path difference actuator (OPDA). The HWP is used to rotate (only performed during assembly and integration) the direction of linear polarisation of the beam in order to eliminate depolarisation effects in the triple prisms.

The AOMs used in the LMU are commercial devices available from Gooch & Housego that have been tailored and modified by Oerlikon Space for use and compatibility in a space environment. These modifications included changes to the housing of the AOM, space compatible materials and adhesives being selected and screening of a number of devices to select the flight models and flight spares to be used for the LISA Pathfinder mission. Verification of the design modifications made to the AOMs has been achieved through a qualification test campaign.

OPDA

The optical path difference actuator (OPDA) is required to provide active control of the optical path length for the two optical paths. This allows to correct for small variations in optical path length difference between the two arms of the LTP interferometer. Although in optical terms just one OPDA would be sufficient, both arms are equipped with an OPDA, for reasons of redundancy.

The constituent parts of the OPDA are shown in Fig. 8. This figure shows the triple prism retro-reflector mounted to a mechanical baseplate which itself is mounted to a piezo-actuator driven translation stage. Each of the Triple Prisms can thus be translated back and forth along the optical axis, thereby producing the required changes in optical pathlength of the interferometer. The triple prism functions as a tilt-insensitive retro-reflector, introducing a lateral offset to the beam in a plane parallel to the surface onto which all of the optical components are mounted.

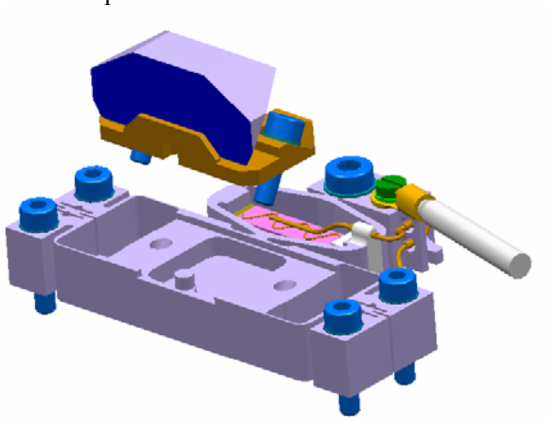

Fig. 8. Optical Path Difference Actuator

The OPDA has a travel range that exceeds 80 µm and can be moved with nanometer resolution over this full travel range. The electrical resolution of ± 1 bit is equivalent to ± 3.3 mV. The measured voltage stability of the OPDA is < 1µV rms. The electrical stability of the OPDA is therefore well within the bit resolution of the device.

Each OPDA sub-assembly is mounted onto (opposite sides of) the optical bench plate of the LMU housing.

3. LASER MODULATOR PERFORMANCE

3.1 Overview

A test program was devised to evaluate the ability of the laser modulator to fulfil its technical functions both at room temperature and with the optical unit (LMU) placed in thermal vacuum conditions. Additionally, as part of the test schedule, the LMU was subjected to environmental tests (random vibration testing and thermal vacuum cycling testing) to evaluate its ability to withstand the harsh conditions of space flight. The LMU vibration test was performed with the LMU switched-off. A vibration level of 16.3 g RMS was used. For the LMU thermal vacuum cycling test, functional performance tests were carried out at 21°C and at 31°C. These tests were followed by thermal vacuum cycling of the unit with it switched-off. Four thermal vacuum cycles were performed between -20°C and +60°C. A summary of the test schedule is shown in Fig. 9.

For the test program, LM functional performance tests were performed at the beginning and at the end of the test program. Since both sets of test results were similar (within the repeatability error of the test), only the final set of results is presented in this paper.

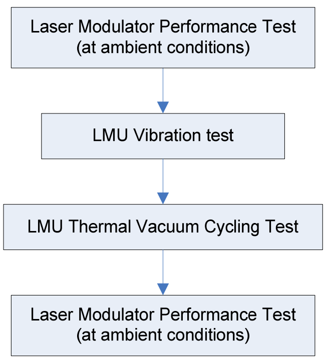

Fig. 9. Laser Modulator EM test program

3.2 Test setup

In the scope of the Laser Modulator Performance Test, four principle tests were used to evaluate the functional performance of the laser modulator:

- Optical Power and Polarisation Extinction Ratio (PER) Tests. These tests were performed using a Newport laboratory optical power meter and a Thorlabs PA410 Polarimeter respectively to measure the optical characteristics at the LMU output.

- Amplitude Modulation Control Tests, consisting of:
  - the Loop Gain Test, whereby a FFT analyzer (Stanford Research Systems SRS 785) was used to inject a swept sine wave (100 Hz to 100 kHz) into the sum-point of the LME loop error amplifier (S1 for Ch1) and the output of the error amplifier (EA1 for Ch1) was measured (see Fig. 10).
  - the Laser Relative Intensity Noise (RIN) Test, whereby the RIN at the optical output of the LMU was measured using a New Focus 2011 photoreceiver and a FFT Analyzer (for RIN measurements between 500-2000 Hz) or directly from the electrical output of the in-loop photodiodes at EA1 (or EA2) using an Agilent 3458A voltmeter for RIN measurements between 1-30 mHz.

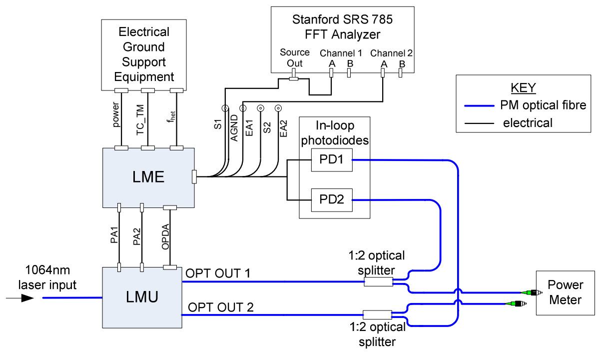

Fig. 10. LM Loop Gain test setup

- Spectral Purity tests, whereby the amplitude of sidebands in the optical outputs were evaluated at 500-2000 Hz offsets from the carrier frequency (~80 MHz) when the LMU input optical signal (f_0) was beat against the LMU output optical signal (f_0 - 80 MHz + f_{het}/2) or (f_0 - 80 MHz - f_{het}/2). This setup is shown in Fig. 11.

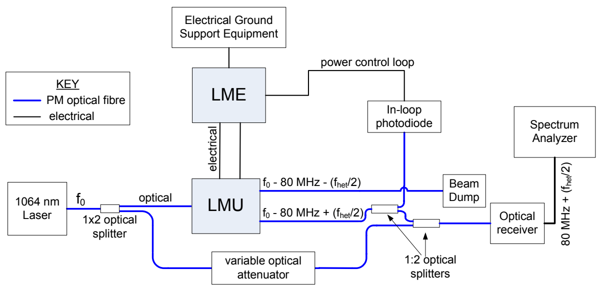

Fig. 11. Frequency stability test setup

- Optical Pathlength Delay Actuation (OPDA) Tests, whereby the OPDA travel range and the optical power stability (after a linear polarizer) were measured as a function of the OPDA movement.

3.3 Test results

Optical transmission and polarization ER

Optical transmission test results for the laser modulator when operated at room temperature with the amplitude control loop open showed that the optical transmission was settable between 4.8% and 28.2% for Ch1 and 6.4% to 36.9% for Ch2. When operated with the amplitude control loop closed, optical amplitude stabilization was possible with control setpoint values corresponding to between 10%-26% transmission for Ch1 and between 10%-32% for Ch2.

Optical power results under the influence of temperature (21°C to 31°C) and vacuum (<1x10^{-5} mbar) during the thermal vacuum test showed optical transmission results (open loop) between 11.6% to 25.7% for Ch1 and between 12.7% to 30.1% for Ch2 over the whole temperature range.

The polarization extinction ratio for Ch1 and Ch2 measured at the optical fibre connector at the end of the output optical fibre harness were 24.3 dB and 25.7 dB at room temperature. Results measured under the influence of temperature (21°C to 31°C) and vacuum (<1x10^{-5} mbar) were always > 20 dB.

In summary, the optical performance (optical transmission and polarization extinction ratio) of the LMU measured before and after the environmental tests did not indicate that any degradation of the components or the alignment had occurred as a result of either the vibration or the thermal vacuum cycling tests. The variations of the results were within the range of the uncertainty for the particular measurements.

Amplitude Modulation Control Loop Tests

Laser Modulator loop gain test results at room temperature are shown in Table 1. The results show that the laser modulator control loop performs well above the 30 dB noise rejection specification for the frequency range from 500-2000 Hz.

Table 1. Summary of loop gain test results, LM EM

	Channel 1	Channel 2
Noise Rejection at DC	55 dB	55 dB
Noise Rejection at 500Hz	51 dB	52 dB
Noise Rejection at 2kHz	34 dB	34 dB
Phase margin	31°	31°

Heterodyne band (500-2000Hz) relative intensity noise (RIN) test results for the optical output of Ch1 at room temperature are shown in Fig. 11. The results show a maximum noise floor of 800 nV/√Hz from 500-2000 Hz, equivalent to a RIN of 1.87x10^{-7}/√Hz for a DC voltage of 4.28 V. The maximum amplitude of spurious (sideband) peaks in Fig. 11 was measured to be 14.83 μV_{RMS} at 1025 Hz. These results are well below the specifications of <10^{-6}/√Hz (noise floor) and <10^{-5} for spurious peaks (equivalent to < 42.8 μV_{RMS} for the measurement shown in Fig. 12).

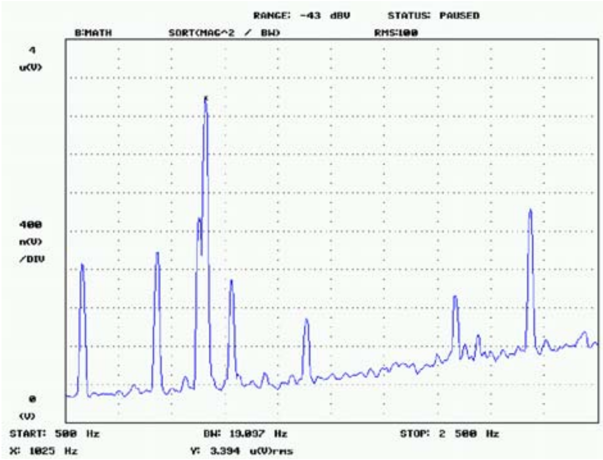

Fig. 12. Heterodyne Laser RIN of path 1 of LM EM (optical receiver DC voltage = 4.28 V)

RIN test results for the Laser Modulator in the milliHertz range (1-30 mHz) measured at room temperature are shown in Fig. 13. The results show that mHz RIN performance is well within the specification at frequencies >0.003 Hz. However, as expected, the RIN performance deteriorates at the lower frequencies but is still around 10^{-4}/√Hz at 1 mHz.

Spectral purity test results

Spectral purity test results for the Laser Modulator (Ch2) measured at room temperature are shown in Fig. 14. For this test, measurement difficulties occurred due to the acoustic sensitivity (microphonics) of the optical fibre measurement interferometer shown in the test setup in Fig. 10. Although acoustic problems with the test setup were observed, the spectral purity results shown in Fig. 14 show that sidebands at 500-2000 Hz from the carrier frequency are <-87 dBc. This measurement is slightly outside the requirement specification of <-100 dBc.

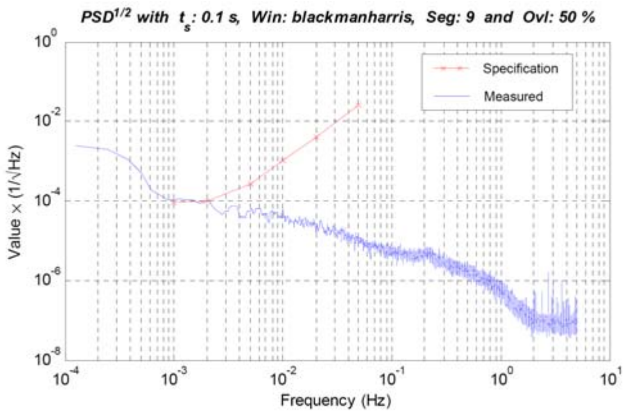

Fig. 13. MilliHertz Laser RIN of path 2.

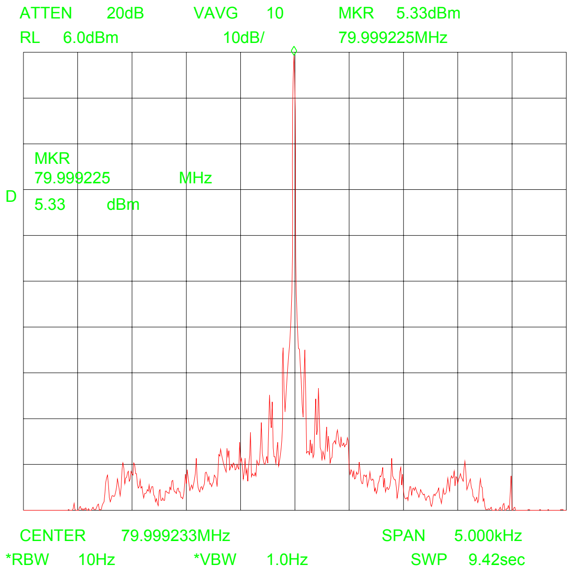

Fig. 14. Optical Spectral Purity Results with fhet = 1000 Hz for path 2 of LM EM

OPDA test results

Optical pathlength delay actuator (OPDA) results showed that each OPDA inside the LMU had a travel range of 82 µm and 83 µm for path 1 and path 2 respectively. These travel ranges were well within the design specification of >± 30 µm.

Test results for the optical power stability with a linear polarizer at the LMU output for path 1 and path 2 as the OPDAs were moved across their entire travel range showed a negligible effect on the measured optical power with the OPDA movement (<±0.3% and <±0.4% optical power fluctuation after a linear polarizer for path 1 and path 2 respectively).

4. CONCLUSIONS

The Laser Modulator optical unit (LMU) and laser modulator electronics (LME) engineering model were designed, built and tested to fulfil the requirements for the Optical Metrology Subsystem for the LISA Pathfinder Technology Package.

The engineering model laser modulator was subjected to functional tests to evaluate its performance. Key performance indicators were the laser RIN tests at 500-2000 Hz and 1-30 mHz, which were used to evaluate the ability of the amplitude control loop to remove optical noise present on the source laser.

As part of the engineering model test program, the LMU EM was subjected to mechanical random vibration tests (16.3 g_{RMS}) and thermal vacuum cycling tests (-20 to +60°C). Tests carried out before and after these environmental tests showed negligible performance changes, verifying the mechanical and thermal stability of the LMU design.

Based on the success of the engineering model program, Oerlikon Space has used the same design for the Laser Modulator Protoflight Model. This model shall be built and tested to a protoflight level standard. The protoflight model laser modulator is due to be delivered at the end of 2008.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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