International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

Long-term vacuum tests of single-mode vertical cavity surface emitting laser diodes used for a scalar magnetometer

C. Hagen

M. Ellmeier

J. Piris

R. Lammegger

et al.

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105634Y · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304073

LONG-TERM VACUUM TESTS OF SINGLE-MODE VERTICAL CAVITY SURFACE EMITTING LASER DIODES USED FOR A SCALAR MAGNETOMETER

C. Hagen[1], M. Ellmeier[2], J. Piris[3], R. Lammegger[2], I. Jernej[1], W. Magnes[1], E. Murphy[3], A. Pollinger[1], C. Erd[3], W. Baumjohann[1].
[1]*Space Research Institute, Austrian Academy of Sciences, Austria,*
[2] *Institute of Experimental Physics, Graz University of Technology, Austria,*
[3] *European Space Research and Technology Centre, The Netherlands.*

I. INTRODUCTION

Scalar magnetometers measure the magnitude of the magnetic field, while vector magnetometers (mostly fluxgate magnetometers) produce three-component outputs proportional to the magnitude and the direction of the magnetic field. While scalar magnetometers have a high accuracy, vector magnetometers suffer from parameter drifts and need to be calibrated during flight. In some cases, full science return can only be achieved by a combination of vector and scalar magnetometers.

A new type of scalar magnetometer, called Coupled Dark State Magnetometer (CDSM), is currently under development in a close cooperation between the Space Research Institute (IWF) of the Austrian Academy of Sciences and the Institute of Experimental Physics of the Graz University of Technology (TUG). The first Flight Model will be launched into a low Earth orbit aboard the Chinese Seismo-Electromagnetic Satellite (CSES) mission by the end of 2016. It will be the first demonstration of this new measurement principle in space. Furthermore, the CDSM was selected for the JUpiter ICy Moon Explorer (JUICE) mission of the European Space Agency (ESA) to visit the Jovian system. With a currently scheduled launch in 2022, the JUICE mission will focus on the study of Jupiter's Galilean moons Ganymede, Callisto, and Europa.

The CDSM is an optically pumped magnetometer, which uses the energy from a specifically modulated laser diode for exciting the electrons of Rubidium atoms in order to measure the magnitude of the magnetic field. For this excitation process the Rubidium atoms require light with a wavelength of 794.978nm which is additionally modulated at 3.4GHz. Vertical Cavity Surface Emitting Laser (VCSEL) diodes in general supply all features which are required for the application in the CDSM.

In order to prove the lifetime of the VCSEL diode of up to 17 years as required for the above mentioned JUICE mission, an endurance test of diodes from three different manufactures has been started at the Optics- and Opto-Electronics Laboratory (OOEL) [1] of the European Science and Technology Center (ESTEC) beginning of March 2014. Since this test is ongoing the names of the manufacturers are kept anonymous.

The paper includes the measurement principle of the CDSM, the technical realization of the laser long-term test setup and a detailed discussion of the test results from the first 5 months.

II. MEASUREMENT PRINCIPLE OF COUPLED DARK STATE MAGNETOMETER

The Coupled Dark State Magnetometer (CDSM) is a laser-pumped absolute scalar magnetometer, which is based on two-photon spectroscopy of Rubidium atoms in a glass cell. The measurement is based on the Coherent Population Trapping (CPT) and Zeeman effects. The magnetic field dependent energy shift of the Rubidium electrons is described by the so-called Breit-Rabi formula [2] where only fundamental natural constants are contained.

In a special laser based excitation mode, three different magnetic field dependent coupled CPT resonances arise in the presence of an external magnetic field. They reach their maximum strengths at different angles between magnetic field direction and the optical path of the laser excitation field through the sensor glass cell [3].

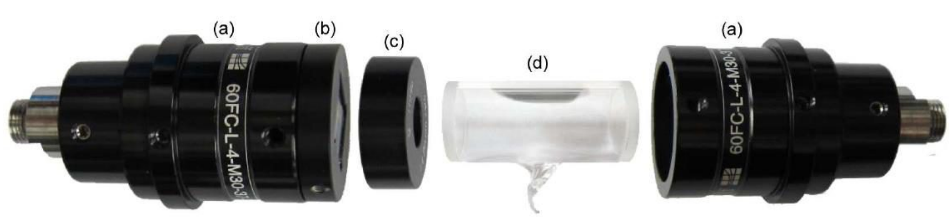

Fig. 1. Main elements of the CDSM sensor with two fibre couplers (a), a polarizer (b), a quarter-wave plate (c) and a 25mm long Rb-filled glass cell (d)

Dependent on this angle the strongest resonance is selected for the actual measurement [4] which allows an omni-directional scalar magnetometer with a moderately complex sensor design that does not include moving parts, feedback coils, or active electronics at the sensor (see Fig. 1).

III. VCSEL DIODE AND ACCELERATION FACTOR

A. Vertical Cavity Surface Emitting Laser (VCSEL) diode

The CDSM uses a Vertical Cavity Surface Emitting Laser (VCSEL) diode in single-mode operation for the excitation of the coupled CPT resonances. The VCSEL is a semiconductor laser diode whose structure consists of a small active region containing several quantum wells enclosed by high-reflective distributed Bragg reflectors. The name of this laser type results from the fact that its structure is grown in such a way that it allows the laser light to be vertically emitted from the surface of the wafer, which allows simple fabrication and integration [5], [6].

The VCSEL diode was selected for the CDSM prototype because it combines the requirements for the excitation of the coupled CPT resonances with the standard requirements for a space missions like small size, low mass and low power consumption.

The requirements for the excitation of the coupled CPT resonances include a sufficient high laser power (>200µW) as well as transversal and longitudinal single-mode operation. Since the VCSEL is a semiconductor laser diode, the laser wavelength can be adjusted by tuning the laser current or its temperature. Thus, the laser frequency can be easily locked to the ^{87}Rb D_1 transition frequency. Due to the small size of the laser diode chip the laser has a good high-frequency response which allows for a proper modulation of the laser output in the GHz-range via the supply current.

The line width of the laser is a critical parameter for the performance of the CDSM. With a smaller line width a more efficient excitation of the dark state resonances is in principle possible. During the characterization of the laser diodes selected for this endurance test also the laser line width was determined. It was measured with an accuracy of 10MHz. For these measurements a scanning Fabry-Pérot interferometer with a free spectral range of δ_{FSR}=1980MHz, finesse of F≈300 and a resolution of δν=7MHz was used. The VCSELs of manufacturer A and B showed line widths in the range of 100-150MHz. However, the VCSELs of manufacturer C revealed smaller line widths in the range of 40-100MHz (see Fig. 2).

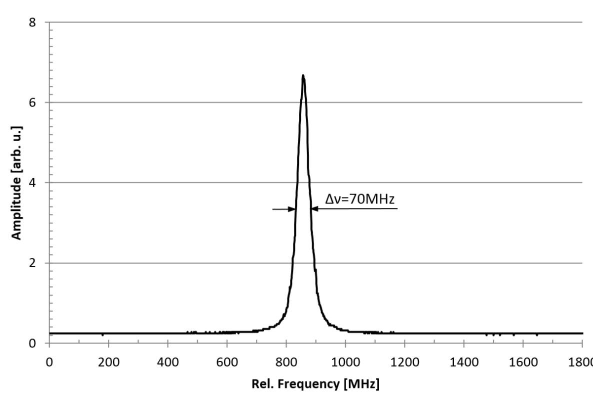

Fig. 2. Measurement showing a typical line width of the VCSEL diodes of manufacturer C

B. Acceleration factor

The duration of the endurance test of one year, the test temperature of approx. 70°C, and the supply currents are selected such that the aging corresponds to up to 17 years lifetime as required for the JUICE mission. The acceleration factor A.F. can, in general, be calculated as shown in (1) [7]:

$$A.F. = \frac{TTF_{op}}{TTF_{test}} = \left(\frac{I_{test}}{I_{op}}\right)^{n} \exp\left(\frac{E_A}{k_B}\left(\frac{1}{Tj_{op}} - \frac{1}{Tj_{test}}\right)\right) \quad (1)$$

TTF_{op} and TTF_{test} stand for time to failure under normal operation and endurance test conditions, respectively. The current acceleration constant n is provided by the laser manufacturers and derived from their reliability testing. For the lasers used in this test, n is 2 and 2.6 respectively (see Table 1). I_{op} and I_{test} represent the laser currents in normal operation (as used in the CDSM application) and in the test condition at OOEL, respectively. E_A represents the activation energy necessary for failure and is also provided by the laser manufacturers. For the lasers used in this test, E_A ranges from 0.4eV to 0.8eV (see Table 1). The Boltzmann constant k_B is 8.6173 x 10^{-5}eV/K. Since the junction temperatures in normal operating and accelerated test conditions (Tj_{op} and $Tj_{test)}$ cannot be measured at the lasers directly, they have to be calculated as shown in (2):

$$Tj_x = Tambient_x + R_{th} \cdot \left(I_x \cdot V_x - P_x \right) \tag{2}$$

During endurance testing, the ambient temperature $Tambient_{test}$ is set to approx. 70°C, which is the interface temperature of the VCSEL mounting block. The term inside the brackets represents the power turned into heat inside the VCSEL diode and is the difference between dissipated electrical power (current I_x times voltage V_x) and emitted optical power P_x. In combination with the thermal resistance R_{th} between laser junction and package outside, which is also provided by the manufacturer, the difference in temperature between case ambient and junction can be calculated. The nominal operating temperatures are individual for each VCSEL manufacturer and dependent on the required temperature and current pair, which enables a wave length of 794.978nm.

With the parameters of Table 1 and the actual test conditions of the laser diodes during the endurance test (supply current and junction temperature), it is possible to calculate the acceleration factor for each diode. It ranges between 7 and 17 for the selected diodes of the three manufactures.

Table 1. Parameters required for the calculation of the acceleration factor

VCSEL Type	E_A [eV]	R_{th} [°K/mW]	n	P @ T_{op} [mW]	P @ 70°C [mW]	I_{op} [mA]	V_{op} [V]	T_{op} [°C]
A	0.7	2.7	2	0.15	0.101	1.90	2.26	26.5
B	0.4	3.5	2	0.24	0.218	2.9	2.35	19.2
C	0.8	3	2.6	0.23	0.182	3.50	2.04	32.2

IV. TEST SETUP AND PROCEDURE

The endurance test under vacuum conditions was started at the OOEL of ESTEC beginning of March 2014. It focuses on the long-term stability of output power, wavelength and line width. It shall last for at least one year.

A. Test Setup

The basics of the optical and electrical setup are shown in Fig. 3. The VCSELs are mounted by pairs into mounting blocks, which again are mounted on temperature stabilized carriers, which also provide the mechanical support and the electrical interfaces. Each carrier is inserted in a vacuum chamber equipped with several optical windows that allow the laser beams to exit and impinge an external optical detector for on-line optical power monitoring. Each carrier also has got its own Pt1000 sensor for temperature surveillance. The optical detectors are Hamamatsu S8746-01 Si photodiodes with a photoactive area of 5.8 x 5.8mm^2 and a built-in operational amplifier that is operating as transimpedance amplifier. By selecting the transimpedance resistor, the optical power to output voltage ratio is set. To get a focused laser beam on the detector's surface when positioned directly opposite to the laser, a lens is mounted in front of each laser diode. For the test of all 12 VCSEL diodes, two separate chambers on top of each other are used, each one containing two VCSELs of each manufacturer.

The VCSELs are biased by custom current sources. Each current source drives 6 VCSELs in total (2 of each manufacturer A, B and C) with their individually defined current. Each VCSEL gets its own separate bias and ground connection. All current sources contain shunt resistors with buffer amplifiers to get a current proportional voltage output as well as voltage followers to get a decoupled laser diode voltage output for data logging. The VCSEL voltages, currents and temperatures are logged by a Data AcQuisition (DAQ) system.

Laser current, voltage and temperature as well as the emitted laser light power are measured once an hour for each VCSEL individually. The emitted laser light power is measured twice per laser, firstly directly by one optical detector and secondly by another optical detector with a polarizer cube in front of the detector. This constellation was chosen to be able to detect jumps in the polarization plane of the tested VCSELs. The laser diodes are mounted into the mounting blocks so that polarization plane of polarizer and VCSEL light are identical. To move the detectors opposite to the lasers, a linear translator is used. Due to the need of using two vacuum tubes for this test and only one linear translator available, a mounting bracket was used to mount detectors in two different levels (see Fig. 4).

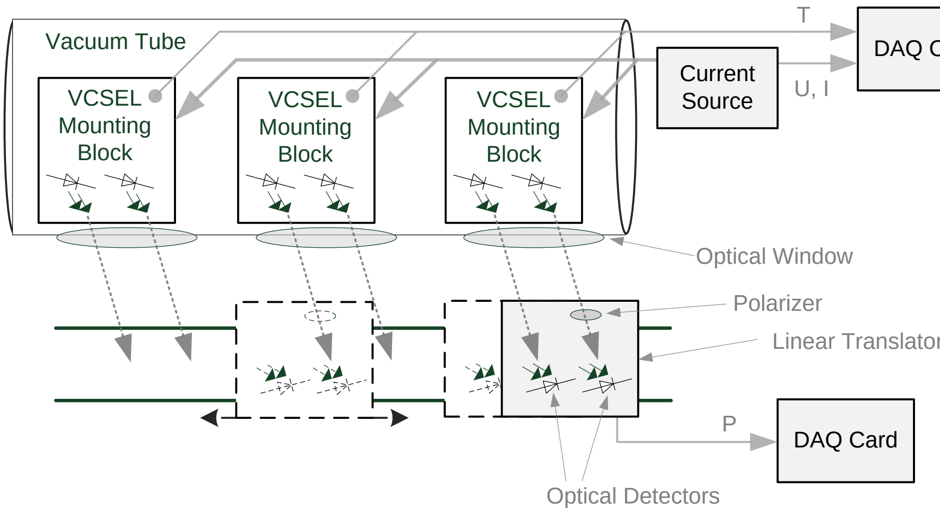

Fig. 3. Optical and electrical setup of the endurance test

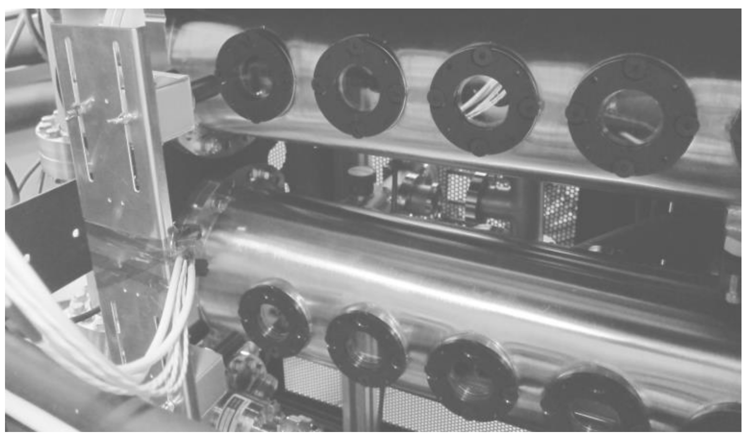

Fig. 4. Picture of the two vacuum tubes with its measurement windows and the mounting bracket with the two detector pairs on the left side

B. Test Flow

The whole test flow is visualized in Fig. 5. In the beginning of this test, VCSELs of all three manufacturers were named and characterized in terms of electrical and optical behavior. Their emitted wavelength, line width, polarization, and output power at nominal operation conditions were determined. Afterwards, they were assembled into mounting blocks by pairs, considering an identical polarization plane of all VCSELs. In February 2014, after transport from Graz to the ESTEC OOEL, a functional check was done. Then, the mounting blocks were installed onto the temperature-stabilized carriers, the carriers were put into the vacuum chambers and the optical detectors were mounted and adjusted onto the linear translator. All measurement outputs were connected to the OOEL data logging system, data logging was started, lasers were powered and evacuation process was initiated. After reaching a pressure of 3.6 e^{-7}Torr (4.8 e^{-5}Pa), the temperature of the carriers was increased to approx. 70°C. Since the vacuum pumps are operated continuously, a pressure of 5.2 e^{-8}Torr (6.9 e^{-6}Pa) was achieved by end of June 2014.

Twice during the whole test period, one carrier is removed from vacuum and its VCSELs are sent back to the TUG. It splits the entire test into three test phases. At the TUG, the lasers are subject to a more detailed inspection concerning their emitted wavelength, line width, polarization state and output power at nominal operating conditions. The second carrier is kept inside vacuum throughout the entire test.

The first phase was finished by end of June. During this phase in total three VCSELs (one laser per manufacturer) failed and all of them were surprisingly located in the same vacuum tube. This is why these parts were selected to be shipped back to TUG for electro-optical testing. During this process, the defective VCSELs were sent to their manufacturers for Destructive Physical Analysis (DPA) and replaced by new ones.

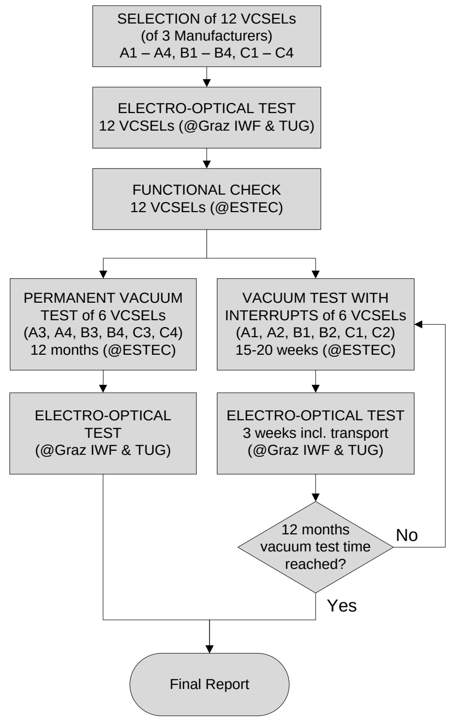

Fig. 5. Long-term vacuum test flow chart

After 12 months of operating time, all lasers will be shipped back to TUG and will be subject to the same electro-optical tests as in the beginning of this procedure. The test results including the outcome of the manufacturers DPA will be presented in a final report.

V. INTERMEDIATE TEST RESULTS AND DISCUSSION

After completion of the first phase, one laser of each manufacturer has failed. It is noticeable, that all of the failed devices were placed inside the same vacuum tube. Data of DPA performed by the laser manufacturers is not available so far. The constant current sources' setups as well as the wiring harnesses are identical for both vacuum tubes but these units have to be kept in mind as a possible sources for the parts' failures.

The VCSELs shipped back to TUG that had not failed were subject to a detailed inspection (A1, B1 and C2). Fig. 6 shows the comparison of the temperature and current pairs of these lasers at 794.978nm wavelength before the start and after the first 4 months of endurance testing. While VCSEL C2 does not show any changes in its temperature and current pair, the VCSEL A1 curve fell about 0.3K. The VCSEL B1 curve shows a minor change in its gradient. The temperature necessary for emitting light with 794.978nm wavelength at a current of 3mA declined by 1.0K.

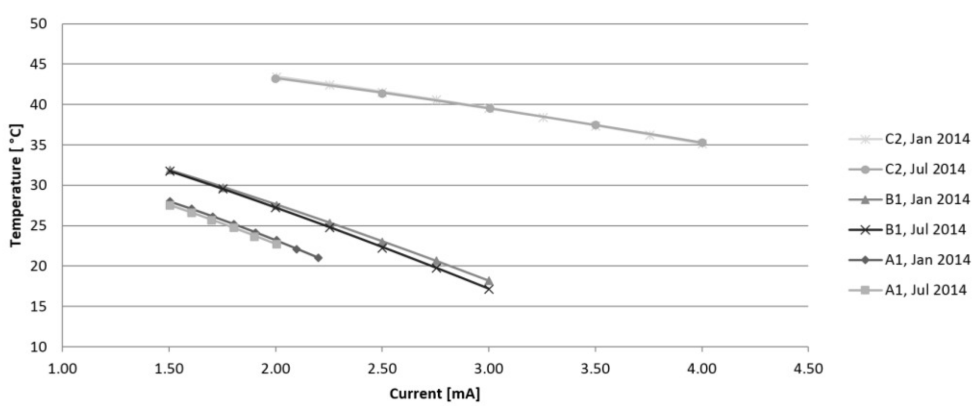

Fig. 6. Temperature and current pairs of VCSELs A1, B1 and C2 at 794.978nm laser wavelength before and after 4 months of endurance test

When considering the optical power output trend of VCSELs of manufacturer A (see Fig. 7 left), it can be seen that laser A2 started with less than 40µW output power at about 70°C and degraded to zero within one week. This behaviour was confirmed by the detector equipped with the polarizer.

The right part of Fig. 7 displays the optical power output trend of VCSELs of manufacturer B. Here also one VCSEL started degrading right after the start of the test. Both polarized and non-polarized readings again show the same trend. After 5 weeks B2 failed. In comparison with manufacturer A, all lasers of B show a steady decrease of output power over time.

The left part of Fig. 8 illustrates the power trend of VCSELs of manufacturer C. Also one laser of manufacturer C failed. In contrast to lasers A2 and B2, which degraded slowly, C1 degraded within 7 hours. Furthermore, in the first month of the test, the measured output power of lasers C increased, which is also contrary to lasers A and B. This is no measurement error because this trend cannot be found in the data of laser A and B (see Fig. 7) which are measured with the same detectors as the data of laser C. The ripple on the non-polarized data of laser C3 and C4 is not seen in the data of the lasers A3, A4, B3 or B4. Additionally it is also not seen on the polarized detector (left plot in Fig. 8). The explanation for this behaviour is that the laser beams of C3 and C4 do not hit the active region of the optical detectors perfectly and therefore small movements of bracket and detectors relative to the linear translator can be seen in the data.

The right part of Fig. 8 shows a jump in the polarization plane of laser A4 on 26th of July. The A4 polarized power dropped to approx. zero, while the polarized power reading of A3 and non-polarized power readings of A3 and A4 stayed constant. One can see that polarized and non-polarized detectors as well as both lasers are intact. Therefore, it is obvious that the polarization plane of A4 has changed.

To sum up, optical power data collected by detectors equipped with and without polarizers in this measurement setup match well and provide stable measurements. A polarization jump was clearly detectable by this measurement setup. The first 5 months deliver insight into the long-term behaviour in vacuum environment of different VCSELs. Causes for failures during this test will be further investigated by the manufacturers.

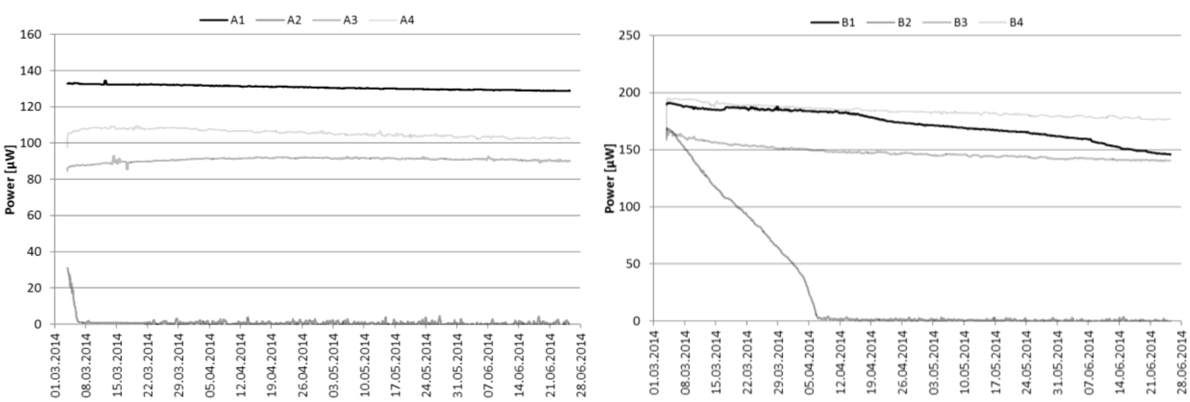

Fig. 7. Optical power of VCSELs A (left) and B (right) as measured by the detectors during the first four months of the test

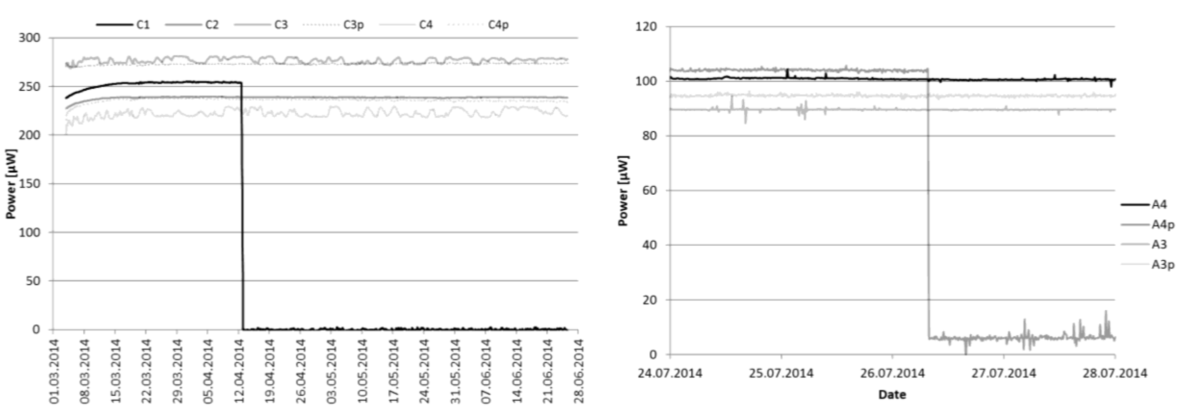

Fig. 8. Optical power output of VCSELs C (left) as measured by the detectors during the first four months of the test; polarization jump of VCSEL A4 on 26th of July (right)

REFERENCES

[1] J. Piris, L. Ferreira, B. Sarti, "Characterization and endurance testing of high power laser Diodes at ESTEC laser diode laboratory", *Proceedings of the 12th European Conference on Spacecraft Structures, Materials & Environmental Testing*, 2012.
[2] S. Knappe, W. Kemp, C. Affolderbach, A. Nagel, R. Wynands, "Splitting of coherent population-trapping resonances by the nuclear magnetic moment", *Physical Review A, Volume 61, 012508*, 1999.
[3] R. Lammegger, "Method and device for measuring magnetic fields", *Patent WO 2008/151344 A3*, 2008.
[4] A. Pollinger, "Development and evaluation of a control unit for the Coupled Dark State Magnetometer", *Dissertation, Graz University of Technology*, 2013.
[5] C. Affolderbach, A. Nagel, S. Knappe, C. Jung, D. Wiedenmann, R. Wynands. "Nonlinear spectroscopy with a vertical-cavity surface-emitting laser (VCSEL)", *Applied Physics B, Volume 70, Issue 3, pp 407-413*, 2000.
[6] R. Wynands, A. Nagel. Precision spectroscopy with coherent dark states, *Applied Physics B, Volume 68, Issue 1, pp 1-25*, 1999.
[7] C. Steidl, "VCSEL Reliability Methodology", Vixar Application Note, unpublished.