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INTEGRATED PHOTONICS FOR FIBER OPTIC BASED TEMPERATURE SENSING

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Abstract - One of the promising space applications areas for fibre sensing is high reliable thermal mapping of metrology structures for effects as thermal deformation, focal plane distortion, etc. Subsequently, multi-point temperature sensing capability for payload panels and instrumentation instead of, or in addition to conventional thermo-couple technology will drastically reduce electrical wiring and sensor materials to minimize weight and costs.
Current fiber sensing technologies based on solid state ASPIC (Application Specific Photonic Integrated Circuits) technology, allow significant miniaturization of instrumentation and improved reliability. These imperative aspects make the technology candidate for applications in harsh environments such as space. One of the major aspects in order to mature ASPIC technology for space is assessment on radiation hardness. This paper describes the results of radiation hardness experiments on ASPIC including typical multipoint temperature sensing and thermal mapping capabilities.

I. INTRODUCTION

Fibre optic sensing, and in particular Fibre Bragg Grating sensing, is receiving an increasing amount of interest and momentum in a wide variety of applications and markets, including that of space where the advantage of a small footprint multi-sensing platform is evident.
One of the promising space applications areas for fibre sensing is high reliable thermal mapping of metrology structures such as lens and mirror systems (or even CCDs) for effects as thermal deformation, focal plane distortion, etc. Thermal mapping can help detect weak spots, providing feedback information for optimized control of systems and structures.
In order to transcend this novel interrogation technology to the specific needs and reliability levels required for the space environment, work is being performed in several development projects. Under the ESA program of AO7765 'Photonically wired spacecraft panels', Technobis has investigated the state of technology regarding the FBG sensing with a focus on ASPIC interrogators. Based on the findings in literature and the requirements from sensing, it was established that knowledge on fundamental aspects on the radiation hardness of PICs is currently limited [3]-[8]. This is especially in regard to the specific sensing requirements on for instance the change in refractive index ($\mathrm{Re}(\varepsilon)$) on the chip waveguide medium (InP platform), apart from the attenuation ($\mathrm{Im}(\varepsilon)$).

II. RELIABILITY FOR SPACE APPLICATIONS

A. Reliability Assessment Framework

For effective assessment of applicability, prospects and approach of unknowns in relation to roadmaps it is essential to have a clear description of the application context, in which considering:

- Environmental conditions during a mission lifetime, i.e. design aspects in relation to radiation, temperature, pressure and launch conditions.
- Application requirements, how and why the sensing system is implemented and what the functional requirements and limitations are.
- Qualification and acceptance towards mission specific requirements as thermal and vacuum cycles, and radiation hardness.

These considerations eventually will determine the reliability of the system and differ from case-to case. For a typical sensing application, the external environmental conditions are mostly clear, as well as the system configuration possibilities in an industrial (ground base) setting. The combination requires testing on component and system level for qualification or to establish the limitations / necessary mitigation points.
One case of particular interest is that of thermal mapping and multi-point temperature sensing in photonically wired panels in small geostationary satellites. The desire to measure temperature in a stable and accurate fashion on multiple locations is in favour of the FBG sensing approach, as many sensors can be incorporated in a single fibre strand. As a function of temperature the central wavelength of the FBG shifts (length and index of the fibre changes), by an amount that is dependent on the fibre embedment.

B. Radiation Hardness Assessment of ASPICs for FBG sensing

The ESA project Photonically Wired Spacecraft Panels includes the assessment of PIC technology for fibre sensing systems and in particular the performance of specific radiation experiments towards the usability of PIC functionality in SGEO and LEO applications. Both Active and Passive integrated photonics functionality is evaluated under radiation both in a biased and non-biased configuration. Two radiation facilities have been selected for these experiments, the Co-60 gamma radiation facility at ESTEC in Noordwijk, and the AGORFIRM facility at KVI for proton exposures in Groningen, the Netherlands. For the experiments multiple AWGs (Arrayed Waveguide Gratings) and SOAs (Semiconductor Optical Amplifiers) were subjected to γ-radiation doses up to100Gy, and proton doses up to 10^{12}/cm^2.

In earlier radiation hardness investigations on III-V platform devices, displacement damage precedes ionization effects with regard to degradation of functionality, e.g. photodiode responsivity reduction and increased laser threshold currents. Damage levels appear not only material and device type dependent, but also geometric and operational conditions, like active annealing, mode of operation, voltage biases, etc.

With the radiation experiments the first steps regarding the assessment of FBG sensing ASPIC interrogators and custom light sources on radiation hardness are presented. Two test chip designs have been selected on the commonly used PIC platform of InP, one which is characteristic for the light source, a Semiconductor Optical Amplifier (SOA) which can be used as a broadband light source, and an interrogator chip which has spectrometry functionality based on an Arrayed Waveguide Grating (AWG).

The radiation conditions, in proximity of the conditions faced during a ~10yr mission at GEO are simulated by exposing the samples to gamma and proton radiation, at respectively the Co-60 facility of ESTEC, Noordwijk [9] and AGORFIRM of KVI-CART, Groningen [10]. Two identical sets of chips of Technobis, produced by Smart Photonics, were selected for passive exposure and pre/post characterization. For both facilities, a single SOA and an AWG chip were packaged for live monitoring during exposure under biased conditions. The bare SOA dies were die-bonded to a metal submount to allow for better heatsink in the characterization and easier handling. An overview of the test samples and the exposure levels is presented in Table 1. The SOA chips are tested on photodiode response (Voltage, Current and Optical output power) and spectral response using an optical spectrum analyser (ANRITSU MS9710C). The AWG chips are tested on the spectral binning characteristics, attenuation and overall photodiode responsivity.

The conditions at the Co-60 facility were as follows. The source activity at the start was 46.1 TBq, Temperature 20.5 ± 0.1 °C during exposure time (3 days), field non-uniformity was < 5%, The uncertainty budgets (according to TEC-QEC/PR001 section 12) are: 4.2 % (k=2) for absorbed dose to water and 4.4% (k=2) for absorbed dose rate to water. The proton irradiation field was produced by scattering the primary proton beam using a 0.6 mm lead foil, 3m up stream of the irradiation position. The scattered beam is collimated using a number of collimators; the last collimator (30cm upstream of the device) defines the size of the field. A 100 mm diameter field collimator was used to define the field on target. The primary beam energy was 66.5 MeV: After energy loss in the scatter foil, air and beam intensity monitor the energy is 58.3 MeV. Beam non-uniformity across the chip surface is < 2%. Temperature in the facility was 20.3 ± 0.1 °C.

Table 1: Overview of SOA and AWG test samples and radiation exposure levels.

Sample IDs SOA/AWG	Dose rate (water) / flux	TID (water) / fluence
SOA 9-17, AWG 314-2-4326	23.37 Gy/hr	110.7 Gy
9-18, 314-2-4346	23.37 Gy/hr	110.7 Gy
9-16, 314-2-436	~23.3 Gy/hr	1134 Gy
9-22, 314-2-4370	~23.3 Gy/hr	1134 Gy
9-26, 314-1-4343	10^8 p/cm^2 /s	10^{11} p/cm^2
9-28, 314-1-4346	10^8 p/cm^2 /s	10^{11} p/cm^2
9-30, 314-1-436	10^9 p/cm^2 /s	10^{12} p/cm^2
9-15, 314-1-4370	10^9 p/cm^2 /s	10^{12} p/cm^2
PCK 9-40 and 314-1-4326	~23.3Gy/hr	1134 Gy
PCK 10-16, 314-1-4356	10^6 p/cm^2/s (60s), 10^7 (60s), 10^8 (60s) 10^9 (17 min)	10^{12} p/cm^2

The SOA package is monitored for optical output under a bias of 200 mA (1.567V for 9-40 and 1.74V for 10-16) and a TEC control temperature of 25 °C. The AWG package is monitored for its photodiode response, i.e. the spectral binning for a fibre coupled laser input signal at 1513 nm wavelength for 314-1-4326 and 1516 nm for 314-1-4356 (Yenista TUNICS-T100S HP, P_{out}=0.3mW). The current from 8 photodiode signals on the output of the AWG are monitored continuously during radiation exposure. A laser is used in order to guarantee wavelength stability which would be difficult to establish with a FBG sensor on a picometer level.

C. Radiation Experiment Results

First and foremost, all live-monitoring experiments (SOA/AWG, gamma/proton radiation) showed functionality up to the end of the test. Also, no abrupt effects were observed during initiation of the irradiation.
More specifically the following observations were made. The SOA package under gamma irradiation, showed a linear decrease of output power from 850 μW to 746 μW, a percentage of 12% over a period of 3 days. During the first 3 hours the signal was still increasing (settling) to 857 μW, so the net radiation-induced attenuation is more likely in the 13-14% range. The degradation was linear over time (and thus with exposure level). Simultaneously the AWG package was monitored. Overall an attenuation of 7% was observed on the photodiode current and a wavelength shift in the order of 10-20 pm (laser accuracy 40 pm). To evaluate the extent to which this is due to the AWG itself needs further investigation (*e.g.* effect of TEC thermistor drift, input drift).
For the SOA package during proton irradiation the following was observed. The optical power output was still settling (increasing output), but in view of the schedule, irradiation was started. At the start the output was 232 μW, which still increased towards 250 μW during the exposure, the output decreased to 240 μW. An attenuation of 4 %, taking into account the increasing trend beforehand, the attenuation would be ~ 10%. This is line with the (V-I-P) measurement afterwards, shown in Figure 1, where it should be noted that the output fibre of package 10-16 broke during demounting and needed repair for the measurement.
The AWG package was exposed to the same sequence of radiation levels. Overall attenuation was on the order of 3%. The wavelength shift could not accurately be determined on the package, as contact with the thermistor was lost during damage in mounting. Although temperature was constant in the room, heat might have been produced during irradiation. The spectral response on the bare die AWGs shows little change, spectrally the response on average seems to blueshift an order of 50 pm for 314-1-436 and 314-1-4370 (proton radiation), which is close to the overall accuracy of the laser (40 pm). The bare die AWGs show on average no significant shift for the gamma-radiated bare dies 314-2-436 and 314-2-4370. An example of a spectrum is shown in Figure 2. As the TEC for the bare die setup has not been irradiated, the temperature conditions can be trusted to be identical (T=25°C), unlike the packaged devices.

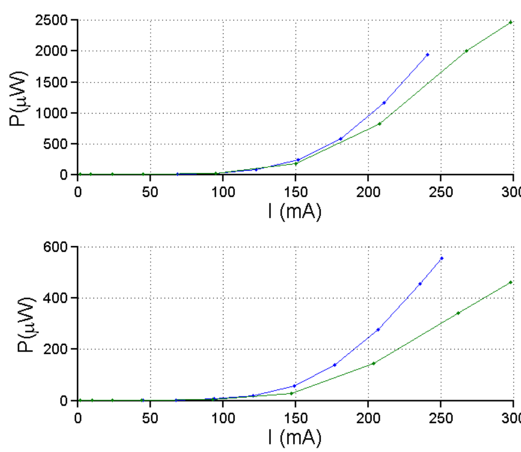

Figure 1: Current vs output power for the two packages pre and post irradiation (blue and green resp.) Top: ESTEC sample 9-40, Bottom: KVI sample 10-16.

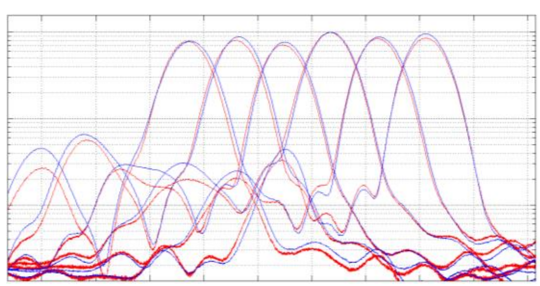

Figure 2: Indicative spectral response of 6 AWG output channels on chip 314-1-436 pre- and post-exposure (X-axis: wavelength, Y-axis: transmission (log-scale). Red and Blue resp., normalized).

Regarding the attenuation on the AWGs, it appears that the degradation is less than 10%. A more detailed analysis will be carried out in the near future, to determine the change in waveguide loss (dB/ cm) pre and post exposure based on relative waveguide length differences in order to correct for in-coupling efficiency variations. Overall, the results show that the ASPIC devices are very tolerant to demanding radiation environments and encourage the development towards dedicated ASPIC-based sensing systems in space applications.

D. Preliminary Radiation Hardness conclusion

The experiment analysis is still ongoing, but some key findings can be already presented. The results so far show that both the SOA light source and AWG-based on InP interrogator are suitable for application in a radiation hard environment.
Already at this stage of the analysis, it can be concluded that both active (SOA) and passive (AWG) chip functionality remain functional with the boundaries of these radiation tests, making this a viable case to promote the use of ASPIC-based sensor systems in satellites applications. A major next step in improving technology readiness is the developing of dedicate packages for testing mission specific and critical radiation requirements posed by ESA, as well as testing other demanding environmental conditions such as thermal cycling, and shock/vibration resistance.

III. TEMPERATURE SENSING

A. Multi-point Temperature sensing

Today revolutionary fibre-optic sensing systems, such as FBG interrogators, are being developed, which are based on integrated photonics [1]. By integration of optical functionalities on chip level in a small photonic package, an imperative step forward is made with regard to the system footprint (size, mass, power consumption, price) as well as performance. For the Space environment the advantages are apparent in for instance small satellite sensing applications, where fibre sensing is increasingly considered.

In the interest of multi-point temperature sensing, different types of sensors and fibre optic sensing techniques based on spectrometry and interferometry have been utilized successfully for sub-mK resolutions with noise densities of 0.6 am/√Hz. Efficient mechanical and thermal management of ASPIC functionality allow detection capability of extreme low thermal variations and mechanical vibrations.
Improvement of ASPIC buildings blocks with regard to for instance reduced waveguide losses, improved fibre coupling efficiency through spot size converters, modified ASPIC functionality like the AWG (Arrayed Waveguide Grating) for high performance sensing purposes, improved SOA (Semiconductor Optical Amplifier) for fast optical switching, etc., allows the development and manufacturing of versatile and complex optical systems feasible.

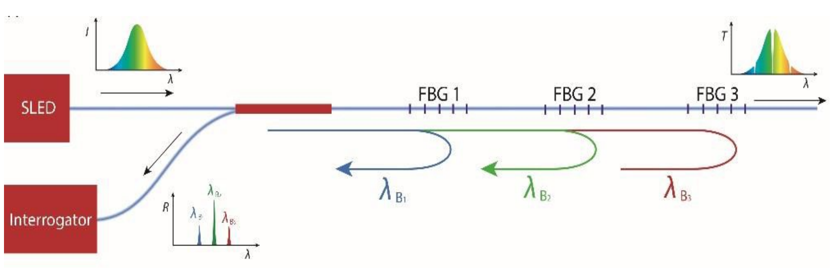

Figure 3: Basic scheme for FBG interrogation of an array of FBG sensors. Each FBG reflects only a specific wavelength.

Packaging of optical chips plays a significant role in the success of ASPIC technology. Connecting the ASPIC to the outside world with sufficient signal-to-noise ratios requires extremely low noise electro-optics. Stability is achieved through the implementation of thermal management capability down to mK resolution, using TECs based on FEM models and extensive analysis over local heat sourcing caused by active ASPIC functionality and electro-optic connectivity. These qualities and ASPIC behaviour control allows applications where temperature variations and mechanical vibrations of extreme low order can be detected.
ASPIC technology has proven extremely high Δλ resolutions, where conventional technology for fibre optic sensing ends at resolution of a factor 1000 lower. Controlled experiments have demonstrated detection of

wavelength shifts less than 100 attometer (10^{-16} m). Active fibre laser sensors where applied and demonstrated an accuracy of 5 micro-Kelvin at a sampling frequency of 3Khz. The measured dark noise floor resulted in 1 micro-kelvin noise contribution to the system. The fibre laser noise subsequently resulted in 5 micro-Kelvin contribution. These results proved that ASPIC technology itself – when designed properly - is not limiting the measurement capability given the current achievable quality of light sources and electronics.
The image below depicts the PSD of the noise level of the fibre laser sensor. The PSD of the strain signal is acquired using a fibre laser pump current of 440 mA, without any strain applied. The signal was measured in a time frame of 0.1s.

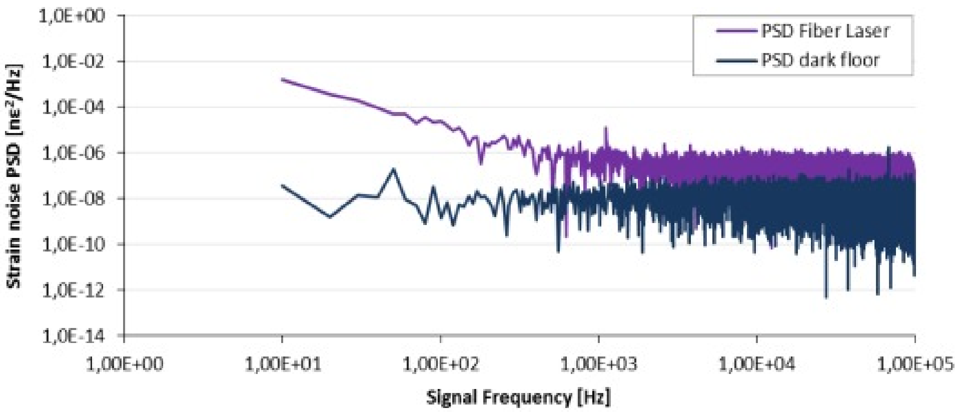

Figure 4: Power spectral density of the dark noise floor and fiber laser noise.

B. Thermal Mapping

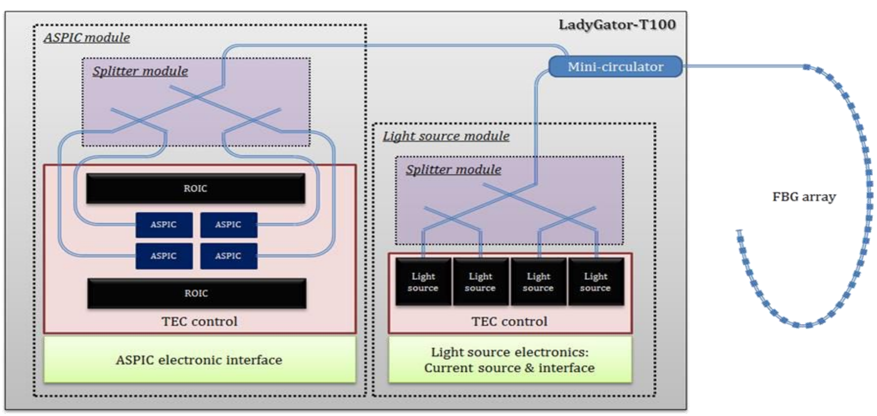

Figure 5: T100 Gator system architecture concept for high performance Thermal Mapping purposes.

Following up on the capabilities of extreme fibre sensing capabilities with ASPIC technology numerous fibre sensing architectures can be designed to perform temperature measurements, based on spectrometry, interferometry or a combination of these. In terms of a specific system design the T100 Gator is being developed as a succession on a free space optics polarized maintaining FBG interrogator, incorporating state of the art ASPIC functionality on an applicable system level (see Figure 5). The system utilizes ASPIC technology for minimizing package size and optimized temperature stabilization. Its purpose is for Thermal Mapping applications in demanding environments for sub-milliKelvin resolution temperature measurements for up to 100 FBG sensors in a single fibre. Prior to this T100 development the T20 system is being developed based on the same measurement principle and is expected to be launched early 2017 as a miniature desktop model. This system complies to the current design standard of the basic Gator system and is designed to demonstrate the specific T20/100 chip architecture.
In this development different aspects are considered that contribute to the primary goal of minimizing footprint, increase of reliability and economically efficient producibility. One of the alternatives is using SOI instead of InP for optical chip manufacturing; producing SOI is a more mature process and allows larger chips, hence allowing a single chip instead of multiple chips. The thermal control in the package is an explicit item; The light sources and the overall electronics are significant heat production elements within the complete device housing

including the ASPIC package(s). The stability performance of the interrogator is dependent on the temperature stability of that housing. This requires dedicated control of the heat within the housing, the chip modules and the dissipation to the environment, using TEC-control loops and optimized housing design.
In the experiments with the free space optics interrogator - leading to this system design – two prototype fibres where used, each with an array of 50 FBG sensors on a 1 meter length segment of the optical fibre. Each FBG had a FWHM of 30pm and spectrally separated by 500pm. The FBGs where spatially separated by 20mm with a physical length of 15mm. The central wavelength of each FBG was tracked using a Dual Weighted Average (DWA) algorithm. The wavelength shift was equivalent to a degree of temperature shift in the FBG, which is in the order of 7 fm/mK. If no strain and temperature actuation is applied to the FBGs, the readout shows the resolution limit of the interrogator. The FBG noises are measured in a 50 Hz bandwidth. Due to the (undesired) envelope of the FBG gratings not all the FBGs conform the requirement of <1 mK. This can be solved by manufacturing a more homogeneous FBG array.

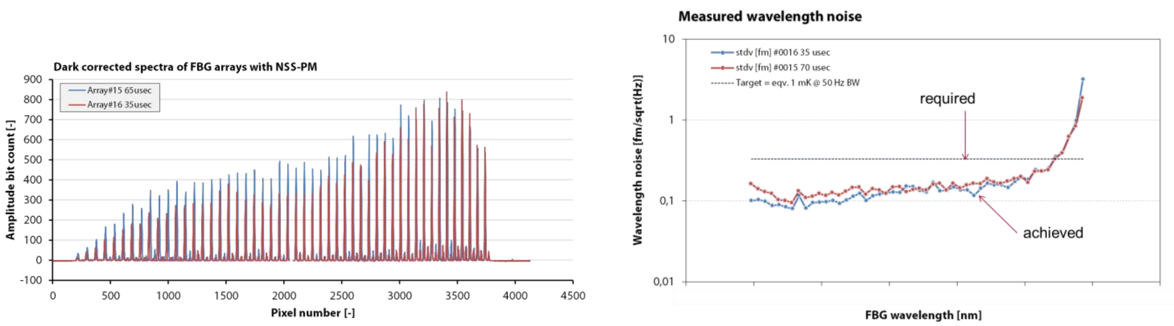

Figure 6: Readout spectrum of both FBG arrays (left). From the FBG peaks (Figure 1 2) measured temperature resolution in 50 Hz bandwidth, 7 fm is equivalent to 1 mK. The sampling frequency is determined by the maximum integration time (right).

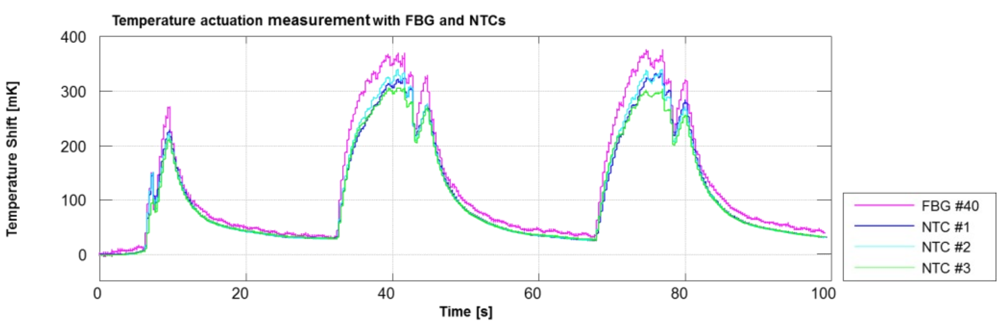

Figure 7: Results derived from results of temperature actuation of a classified application under contract research.

The feasibility of high resolution temperature measurements was assessed by comparison experiments with NTC temperature sensors (see Figure 7). In the experiment the sensors areas where locally heated using calibrated temperature actuators. The sensors where surface mounted on a metal surface using grooves and thermal paste for positioning and optimal heat transfer from the surface into the optical fibre. As demonstrated the response from FBG sensors and NTC is basically identical, in fact the FBG sensors demonstrated an even faster response.

Having the capabilities of reliable and stable, high resolution temperature measurement using miniaturized solid state equipment, combined with standard non-active, narrow-bandwidth, polyimide coated FBG sensors, proves a promising candidate for thermal mapping applications for demanding environments like space.
As an example the graphs below in Figure 8 demonstrate the use of an optical fibre with 100 FBG sensors thermally mapping a surface grid. In this example a temperature variation of 120 milliKelvin can easily be measured and reconstructed by means of 2-dimensional interpolation methods. The deviations visible can be improved by including boundary conditions in the interpolation scheme.

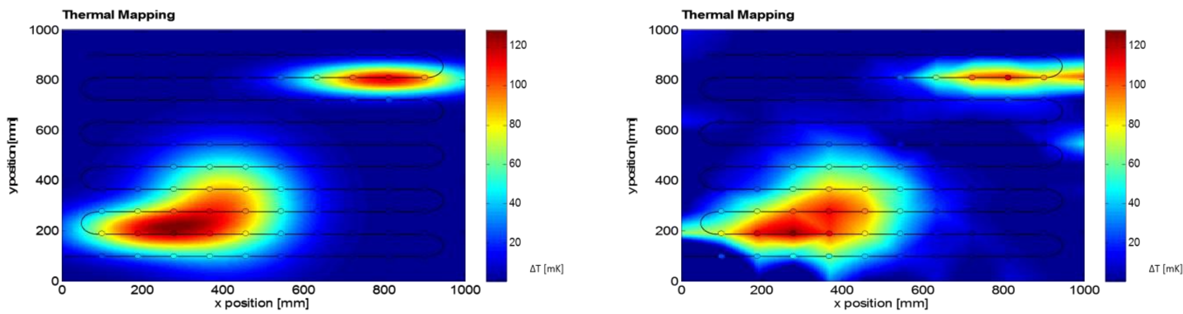

Figure 8: Example Thermal Mapping capability; On the left the original temperature map is displayed, on the right the reconstructed temperature map based on current measurement cabilities. The Temperature range is 120 milli-Kelvin

IV. OUTLOOK

The landscape for PIC-based fiber sensing systems for Space is expanding. The PIC-based development platform allows complex optical systems on just a few square millimeters. Dedicated packaging innovations make PICs work in stringent environments. For PIC technology in general, one of the tendencies in order to consolidate new technologies is standardization as a means to reduce costs and improve efficiency in the supply chain. Generic processing is one of the ambitions for integrated photonics in order to reach this state. The advantages are reduced costs and lead-time in the supply of PIC based components.

V. ACKNOWLEDEGMENTS

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The investigational prior to the radiation experiments and the execution of the radiation tests were performed by Thijs van Leest. Large part in achieving the extreme resolution levels and measurement validation leading to current system capabilities was due to by Michael Haverdings contribution. Both received high praise for the fantastic work.

VI. REFERENCES

[1] http://www.technobis.com/themes/integrated-photonics/
[2] T.v. Leest, R. Evenblij, P. Kat, "Photonic Integrated Circuits for FBG Sensing in Harsch Environments", *ISROS 2016, Otwock, Poland*, June 6-9, 2016
[3] M. Smit et al.,"An introduction to InP-based generic integration technology", Semicond. Sci. Technol. 29, 083001 (2014)
[4] A.H. Johnston "Basic Principles and Radiation Effects in Optical Emitters" Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
[5] M. Fukuda "Reliability Issues of Light Emitting, Amplifying, and Modulating Semiconductor Devices" Toyohashi University of Technology, Toyohashi, Japan
[6] C. Garden "Effects of Proton Radiation on InGaAs Photodiodes and Laserdiodes", *ESTEC Working Paper* EWP-2117, QCA ESTEC, May 2000
[7] R. Ratajczak, A. Turos, A. Stonert, L. Nowicki and W. Strupinski, "*Defect Transformations in Ion Bombarded InGaAsP*", Proceedings of the VIII International Conference ION 2010, Kazimierz Dolny, Poland, June 14–17 (2010)
[8] D. Gajanana, M. van Beuzekom, M. Smit and X. Leijtens " Irradiation tests on InP based Mach Zehnder modulator*"*, *Toptical Workshop on Electronics for Particle Physics* 2012, Oxford, U.K., September 17–21 (2012)
[9] ESA-ESTEC Co-60 facility. See https://escies.org/webdocument/showArticle?id=251 for more information
[10] KVI-CART AGORFIRM, University of Groningen, see http://www.agorfirm.nl/ for more information.