

Evaluation of TID Sensitivity of PICs: Ultra-narrow linewidth tuneable lasers and tuneable couplers.

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ABSTRACT

Photonic integrated circuits (PICs) are promising candidates for future space optical systems due to their compactness and high integration density. In this work, we evaluate the Total Ionising Dose (TID) sensitivity of commercial PICs provided by LioniX International: an ultra-narrow linewidth tuneable laser and a tuneable coupler. The two devices rely on different tuning mechanisms, based on thermal and piezoelectric (PZT) actuators, respectively. The devices were exposed to TID levels up to 100 krad(Si), with in-situ optical measurements performed during irradiation, followed by post-irradiation characterization and room-temperature annealing. For the tuneable laser, no significant radiation-induced degradation was identified within the measurement accuracy. For the tuneable couplers, changes in optical power and tuning contrast were observed during irradiation, suggesting sensitivity to TID. However, the low initial optical power of the tested devices limited the quantitative assessment of radiation-induced degradation. These results provide an initial assessment of the TID robustness of these PIC technologies and support further investigation of their suitability for space applications.

Keywords: Photonic Integrated Circuits (PICs), Total Ionising Dose (TID), ultra-narrow linewidth tuneable laser, tuneable coupler

1 INTRODUCTION

Photonic integrated circuits (PICs) are a promising technology that enables the integration of multiple photonic functions required in various equipment into a single chip. For spaceborne photonic systems, this can lead to a considerable reduction in size, weight, and power consumption (SWaP), as well as cost [1].

Our study aims to evaluate the radiation sensitivity of this technology, which needs to be advanced to expedite the adoption of PICs for space applications. In this study, radiation sensitivity refers to the sensitivity to Total Ionising Dose (TID). The approach taken is to irradiate a PIC-based commercial off-the-shelf (COTS) device composed of several building blocks, with the goal of determining the radiation sensitivity of each. For this study, two COTS devices were manufactured by LioniX International: a narrow linewidth tuneable laser source and a tuneable coupler.

This study will not be sufficient to generalize the behaviour to other circuit designs or to the platform as a whole. However, it will be extremely valuable in helping to assess the risks and suitability of this technology for the space environment.

2 DESCRIPTION OF THE COMPONENTS

The two components selected for the study are COTS manufactured by LioniX International. The two components are based on different technologies for the tuning effect: a laser with thermal effect actuators and tuneable couplers based on PZT actuators.

2.1 Ultra-narrow linewidth tuneable laser

The schematic overview of the photonic integrated circuit (PIC) of the laser module, and its specific Building Blocks, are described below:

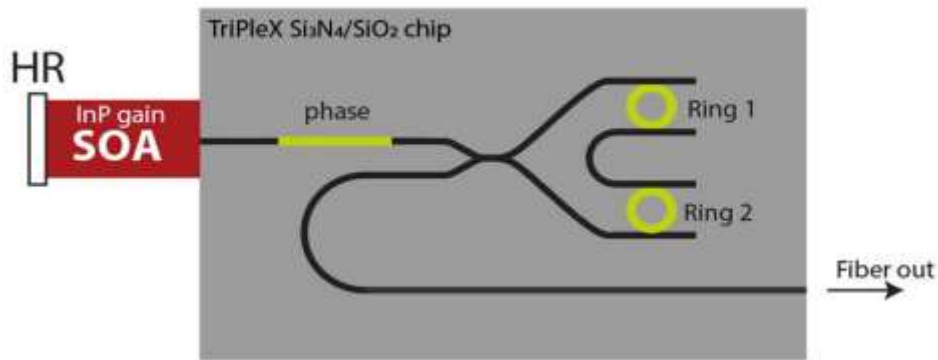


Figure 1 : Schematic overview of the laser integrated circuit, and its specific functional Building Blocks.

The component is composed of a Semiconductor Optical Amplifier (SOA) which is highly reflective on the left-hand side and anti-reflective on the right-hand side where it is connected to a TriPleX™ Silicon Nitride external cavity waveguide chip [2]. The waveguide chip contains two micro-ring resonators (MRRs), indicated as R1 and R2 with slightly different free-spectral ranges (FSRs) to ensure stable single frequency operation.

Three heaters are integrated:

- one phase actuator, that can be heated to adjust the length of the Fabry-Perot cavity.
- two actuators on the ring resonators R1 and R2. By heating the ring resonators, you change the refractive index of the rings which enable to change the wavelength of the laser.

By tuning the MRRs, the laser's frequency can be tuned over a large range[3].

General characteristics:

The optical performances of the laser shall be the following:

- Narrow linewidth <10 kHz
- Wavelength tuneable range over the C-band (1530-1565 nm)
- Output power > 0 dBm
- Low Relative Intensity Noise (RIN) < -160 dBm/Hz

2.2 Tuneable Coupler

The schematic overview of the photonic integrated circuit (PIC) of the coupler and its specific building blocks, are described below:

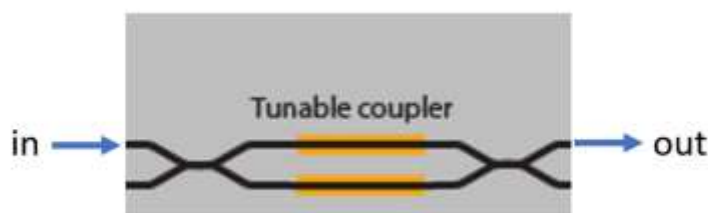


Figure 2 : Schematic overview of the coupler integrated circuit.

The coupler is a tuneable 2 x 2 (2 inputs and 2 outputs) optical coupler based on a Mach-Zehnder interferometric structure. The Mach-Zehnder is composed of piezoelectric actuators that control the relative optical phase between the two arms. By applying tension to the PZT actuators[4], the effective length of an arm and/or its refractive index can be modified. These variations can lead to a change in the wavelength transmitted by the coupler and/or the coupling ratios between the arms.

The variation in the coupling ratio enables several operational states:

- Bar/Bar or Cross/Cross: the light stays in the same arm, no crossing (coupling ratio 0%)
- Bar/Cross or Cross/Bar: the light is transferred to the other arm, crossing (coupling ratio 100%)

General characteristics:

- Wavelength tuneable range over the C-band (1530-1565 nm)
- Output power > 0 dBm

3 TID TESTING CONDITIONS

Based on internal know-how, ADS has established that a target level of 100krad(Si) will be well adapted to evaluate radiation behaviour for a device integrated in an internal equipment (not necessarily a payload, but located inside the satellite and including a frame/package). The test conditions are as follows:

- TID up to 100 krad(Si)
- Low dose rate (LDR) region, ie <360 rad(Si)/h
- In-situ measurement during irradiation
- 3 lasers and 3 couplers were irradiated. One laser and one coupler were monitored outside the chamber for reference
- Annealing after irradiation for a duration of 168 hours at room temperature

The TID irradiation was performed at ESTEC.

Before and after the TID test, Chilas B.V and LioniX International performed extensive measurements to fully characterize both technologies.

4 RESULTS

4.1 Ultra-narrow linewidth tuneable laser

Method of analysis

The measurement data provided by LioniX consisted of optical spectrum plots and data files containing the actuator settings and optical power as a function of frequency.

The measured optical spectra were analysed using a Lorentzian fit to extract the central frequency, peak optical power and Full Width at Half Maximum (FWHM). In some configurations, the presence of multiple cavity modes prevented reliable fitting, particularly for FWHM and peak power. These measurements were therefore excluded from the corresponding quantitative analysis.

Performance before radiation testing

The optical measurements were performed at Chilas B.V to validate the performance of the laser after manufacturing. The figures below show representative results for one of the lasers.

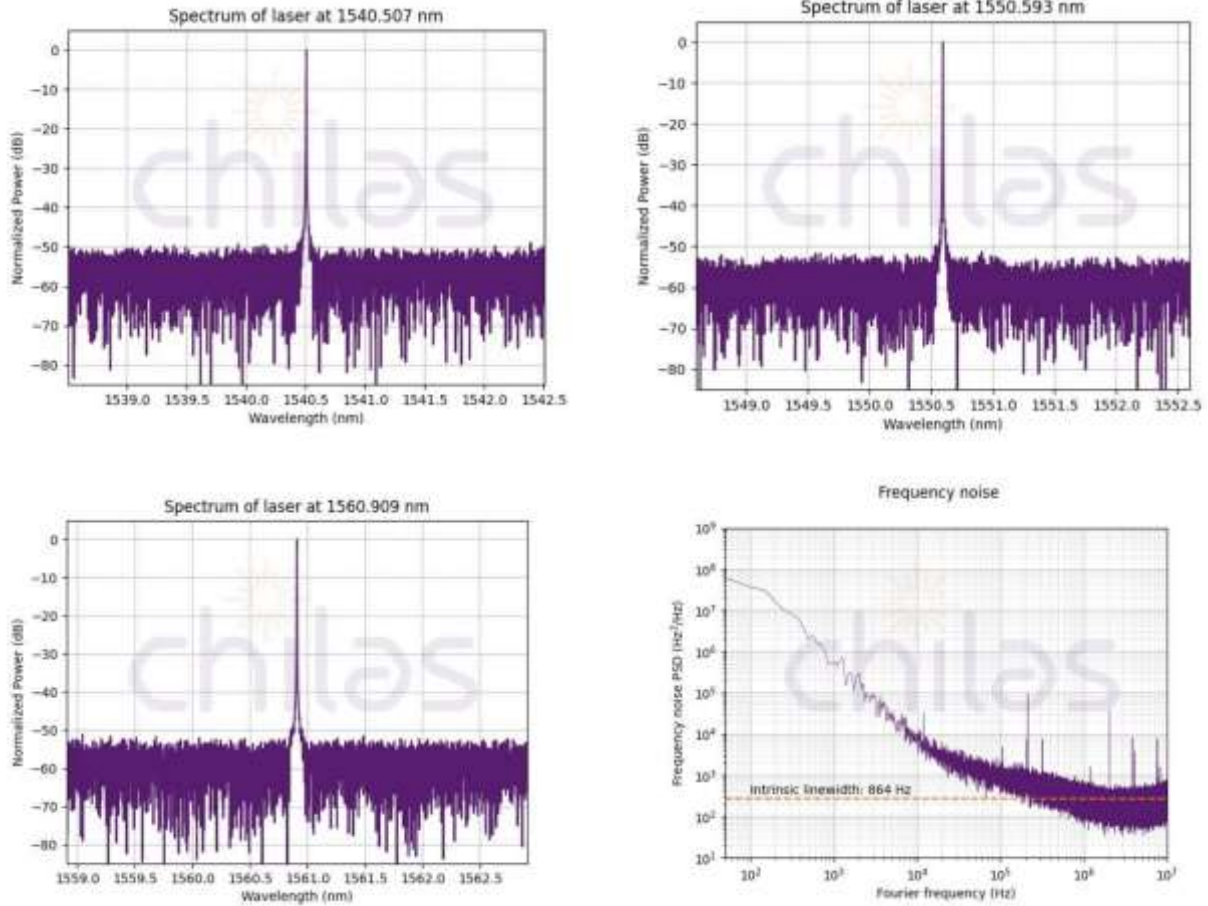


Figure 3 : Laser optical spectrum at 3 wavelengths and frequency noise spectra.

The manufactured lasers meet the specifications, with an optical power exceeding 0 dBm and a linewidth below 10 kHz. However, the optical power is relatively low and varies among the devices. This low power can be attributed to the coupling between the chip and the fiber, which has since been improved. The variations in power can be explained by device-to-device power spread at the chip level. Nevertheless, the power level is sufficient for the OSIP study. All four lasers are tuneable and demonstrate acceptable performance at the three wavelengths.

The response of the different laser actuators was characterized by LioniX International prior to irradiation. Figure 4 shows one of the ring actuators as a representative example.

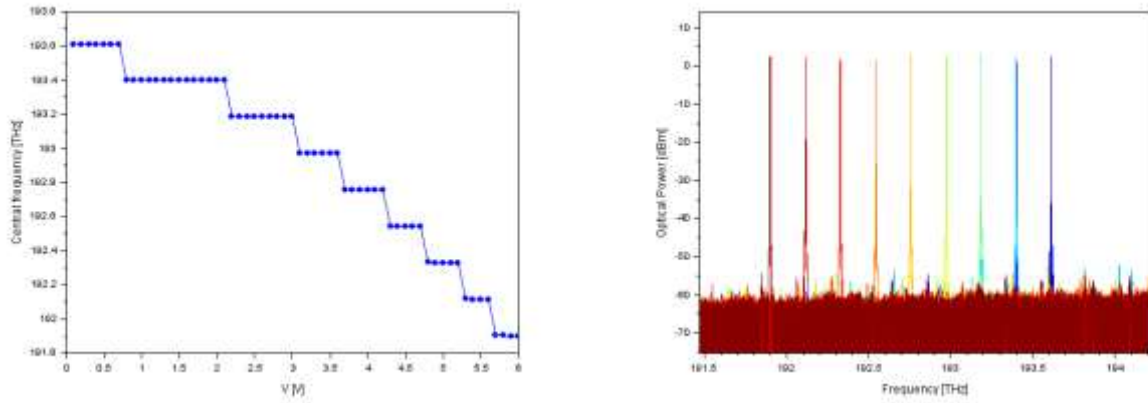


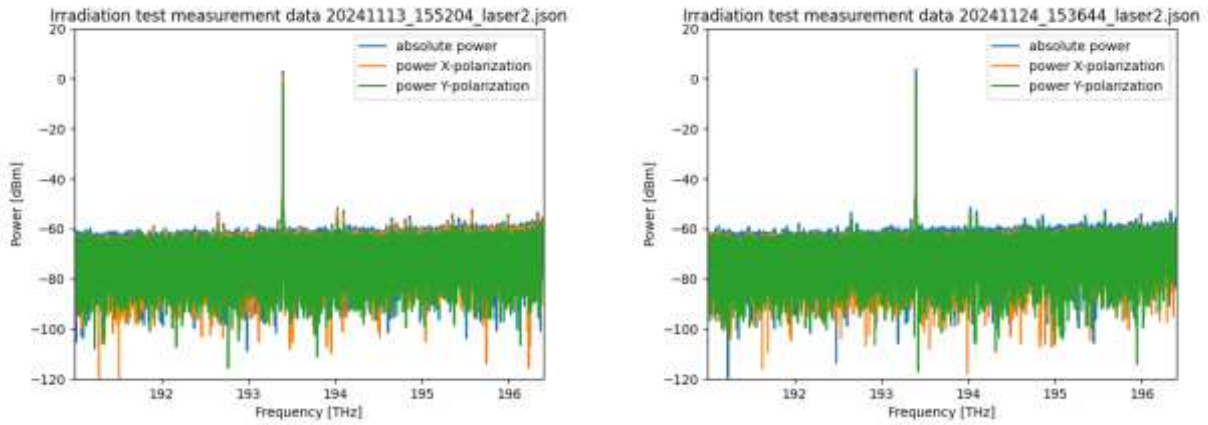
Figure 4 : Scanning actuator 4 (Ring actuator). Left: central wavelength, Right: optical spectrum.

Prior to irradiation, the tuning capability of the lasers was verified over the C-band. Figure 4 shows the response of the laser frequency to the actuator 4 settings: heating the ring resonators changes their refractive index, enabling wavelength tuning of the laser. The characteristic step-like evolution results from transitions between cavity modes. Similar behaviour was observed for the other devices.

These measurements were used as the reference for the post-irradiation characterization.

In-situ radiation testing

During the test 3 lasers have been irradiated up to 100krad(Si), while laser number 4 hasn't and serves as the reference. The performance of each laser was recorded throughout the irradiation: optical power (dBm), central frequency (THz) and Full Width at Half Maximum (THz). The figures below show representative results for one of the lasers.



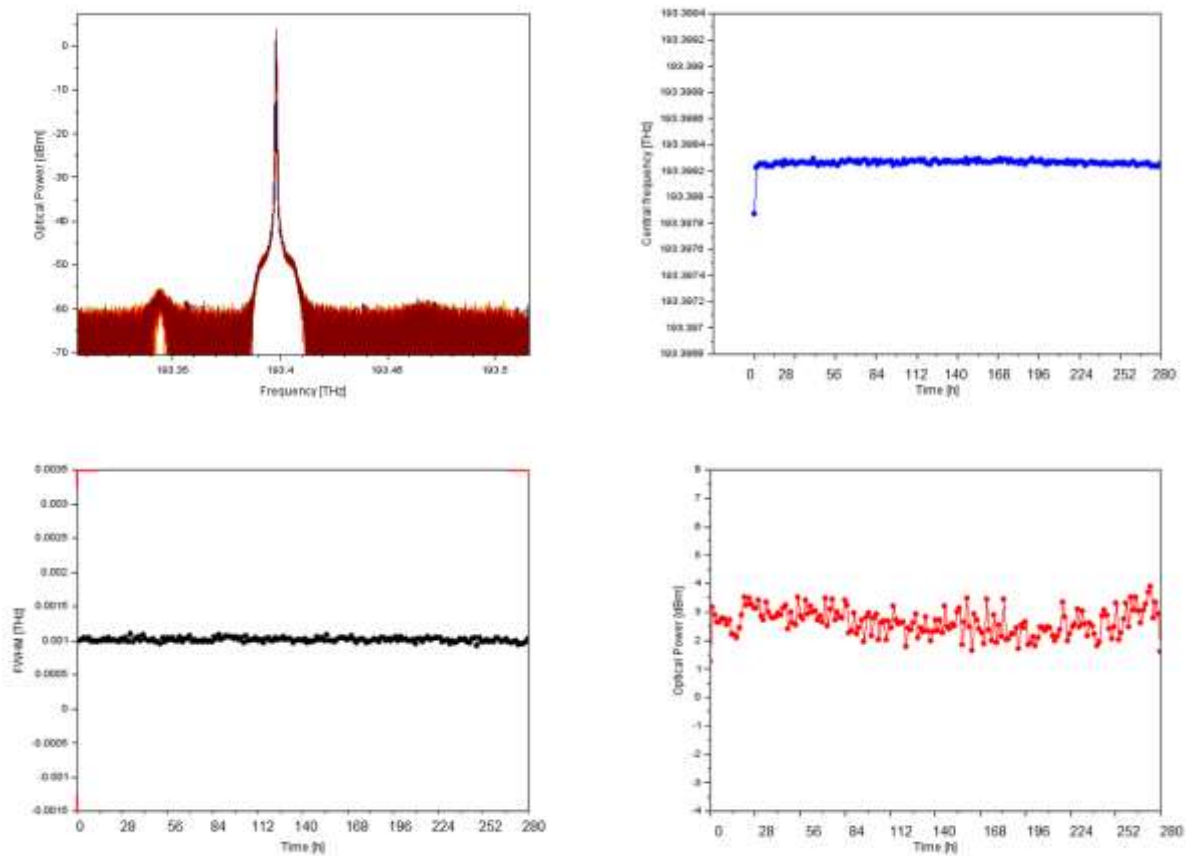


Figure 5 : In-situ measurements during irradiation. Top left: spectrum at beginning of irradiation, Top right : spectrum at the end of irradiation, Middle left : superposition optical spectrum Middle right : central frequency, Bottom left : FWHM and Bottom right : Optical power.

The optical spectra of the lasers remained unchanged during the irradiation testing. The central frequency was not impacted by the total ionising dose (TID). While the optical power exhibited instability, this variation was not dose-dependent. The superposition of the spectra during irradiation did not reveal any changes in laser behaviour.

However, throughout the entire test sequence, we observed performance variations such as changes in optical power. These variations sometimes appeared before the radiation test, between the measurements taken at LioniX and their repeated measurements at ESTEC. It is difficult to determine whether this was due to an issue with the test bench or because the laser parameters were not optimal.

Characterization after irradiation

After the irradiation, LioniX performed a full characterization of the lasers. The spectrum of Laser 2 at 1550 nm is presented below.

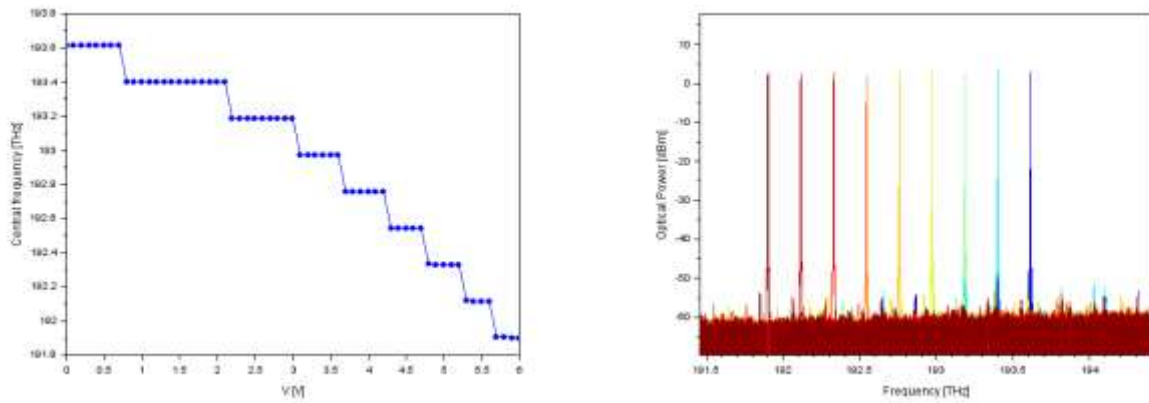
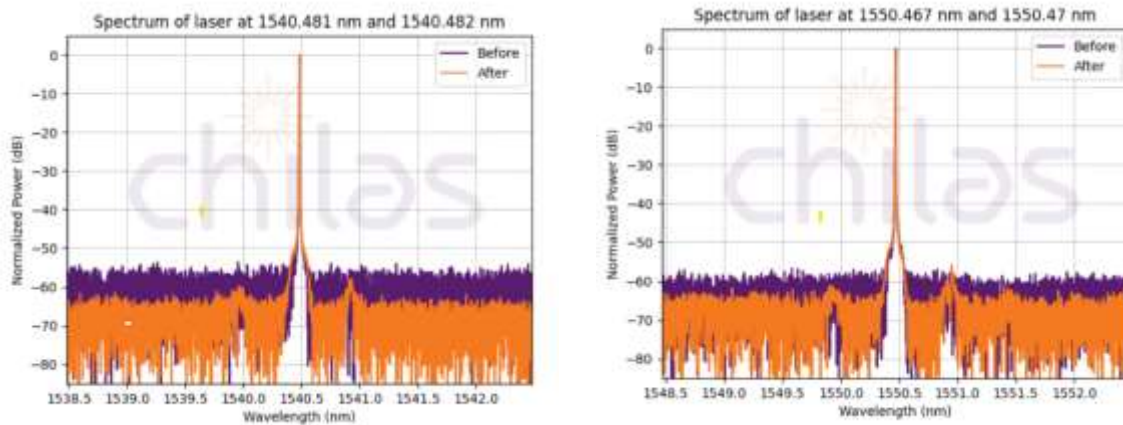


Figure 6 : Post-irradiation Scanning actuator 4 (Ring actuator). Left : central wavelength, Right : optical spectrum

Post-irradiation characterization showed that the response of the different laser actuators remained consistent with their respective pre-irradiation behaviour. Figure 6 illustrates the response of the ring actuator as a representative example. Its characteristic step-like frequency response was preserved, and the laser remained tuneable over the investigated range. Similar behaviour was observed for the other lasers. No radiation-induced change in the actuator response was identified.

Following irradiation, the lasers underwent 168 hours of room temperature annealing. No significant evolution of the optical spectra, central frequency or FWHM was observed during this period. Since no measurable degradation was observed during irradiation, no significant annealing effect was identified.

To complete the final characterization, the lasers were returned to Chilas for comparison with the initial pre-irradiation measurements. Measurements were conducted at three wavelengths in the C-band: 1540 nm, 1550 nm, and 1560 nm. The datasheet contains optical spectra at each wavelength and frequency noise spectra. The spectrum of Laser 1 is presented below.



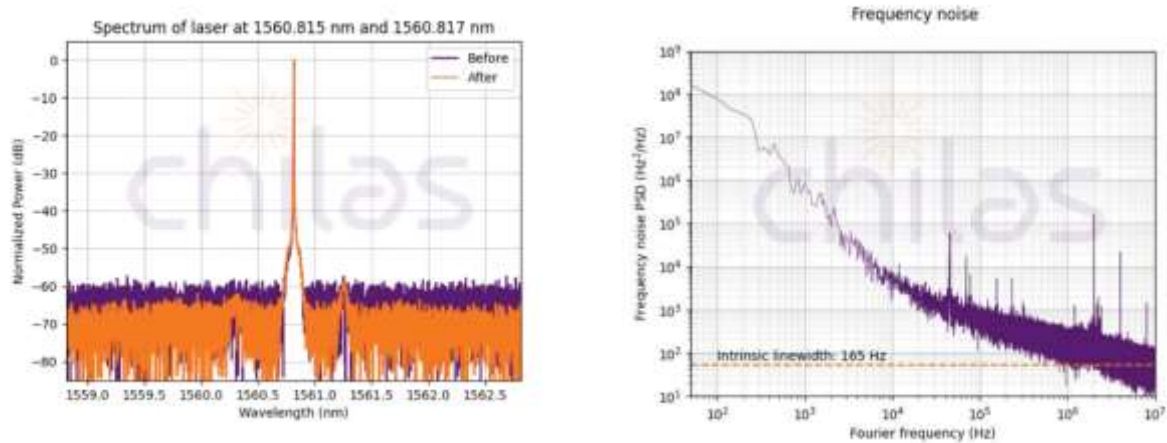


Figure 7 : Laser 1 (MAP539) optical spectrum at 3 wavelengths and frequency noise spectra.

We observed a superposition of the spectra before and after radiation. This test confirms that the laser behaviour remains unchanged after radiation. In this final measurement, we observe a general improvement in optical power. This is because the power was monitored directly on the output fiber this time, rather than on another fiber in the beam path. However, we noted changes in the linewidth, which remained acceptable. These measurements confirm that the laser's performance is acceptable after irradiation testing.

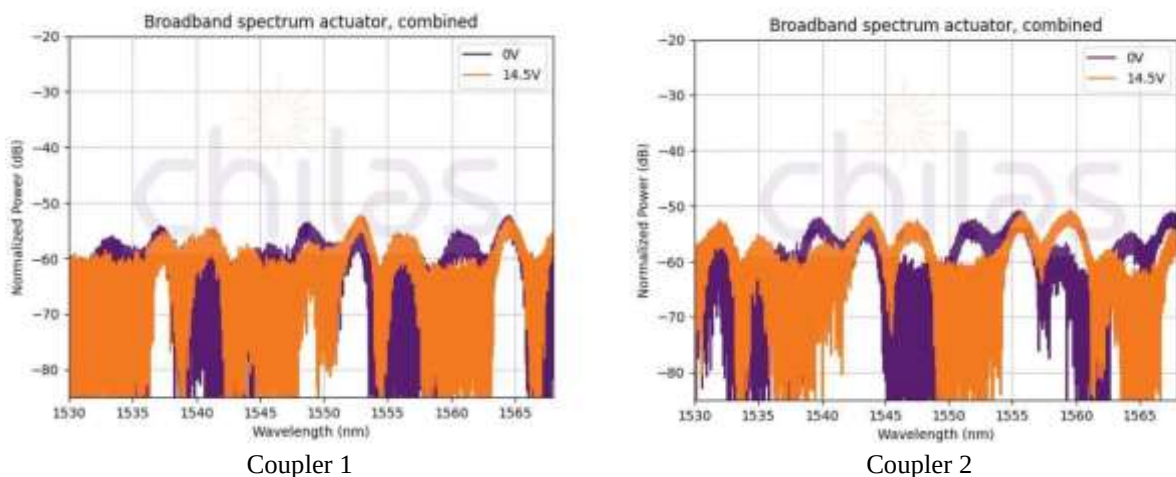
The results are sufficient to confirm that the component remained functional and exhibited qualitatively similar behaviour before and after TID irradiation. However, it is challenging to identify TID impact on optical power due to both the relatively low laser output power and the test-to-test variations observed independently of irradiation.

It should be noted that LioniX International reported improvements in the coupling ratio between the Semiconductor Optical Amplifier (SOA) and the external cavity. Consequently, the actual laser from LioniX demonstrates improved optical performance.

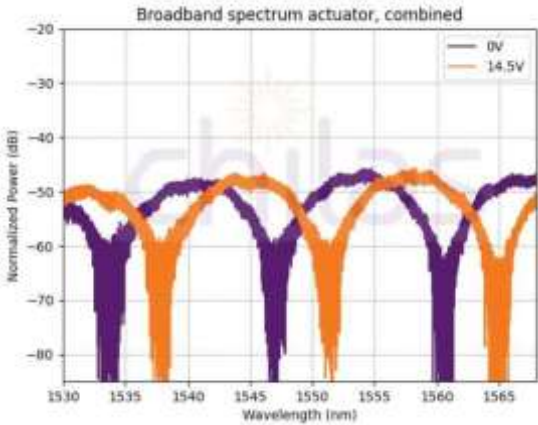
4.2 Tuneable Coupler

Performance before radiation testing

The optical measurements were performed at Chilas to validate the performance of the coupler after manufacturing.



No spectrum for Coupler 3 (3086)

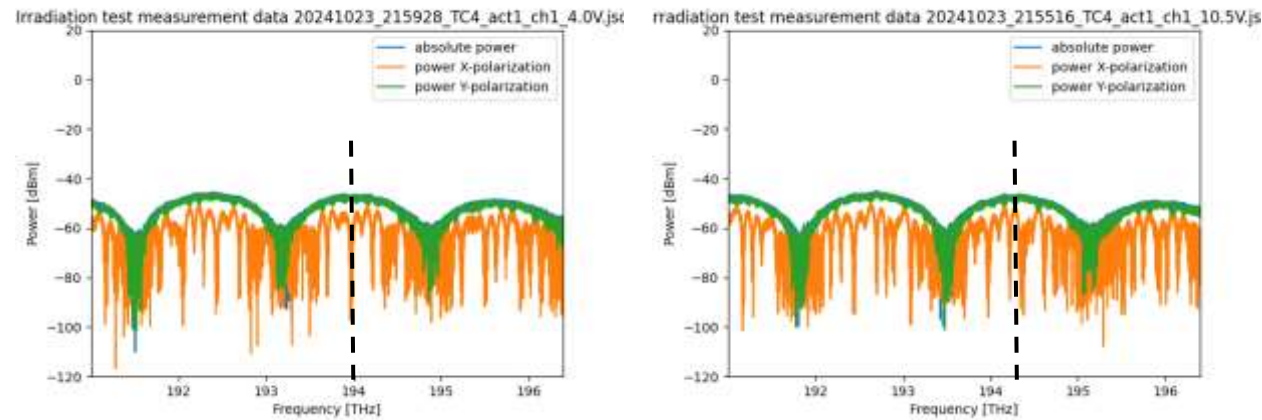


Coupler 4

Figure 8 : Couplers optical spectrum at 2 configurations.

The characterization revealed performance limitations among the tested couplers. Coupler 3 was not functional and was therefore excluded from the irradiation study. Couplers 1,2 and 4 exhibit optical responses, but with output power levels significantly below the expected performance. Among them, Coupler 4 provided the clearest demonstration of tuning behaviour, with a shift of the wavelength corresponding to maximum transmission when the actuator voltage was changed. Similar effects were observed for Couplers 1 and 2, although the low optical power limited the quality of the characterization. These components were studied to assess the impact of radiation on the coupler’s tuning effect. However, the low power level poses a challenge for the study, as detecting any potential decrease in power is challenging.

LioniX measured the optical spectrum of the couplers in different configurations, applying varying voltages to each actuator. Figure 9 shows actuator 1 as a representative example.



Cross Bare actuator 1

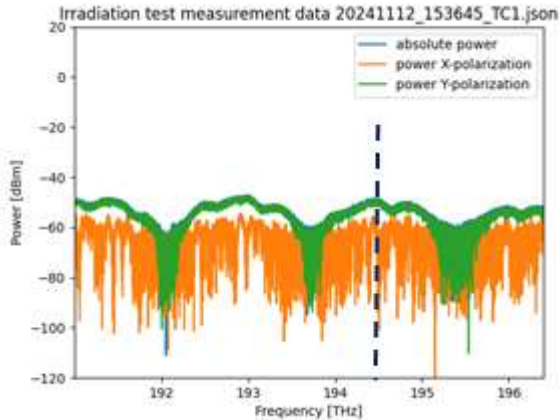
Figure 9 : Scanning of actuator 1 at different voltages.

We observed that applying different voltages to the actuator causes a shift in the frequency at which maximum power occurs. There is no significant impact on the optical power, although the low optical power limited quantitative characterization.

In-situ radiation testing

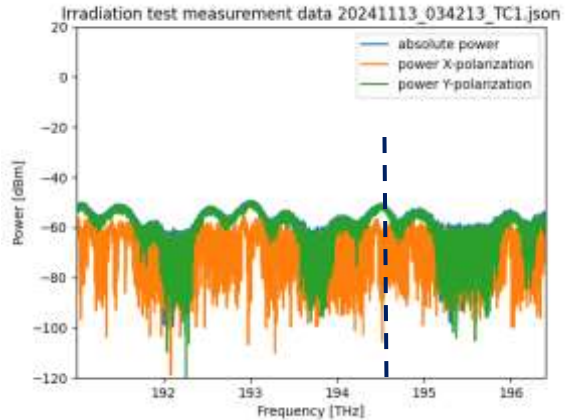
During the test 2 couplers have been irradiated up to 100krad(Si), while one coupler hasn't and serves as the reference. The optical spectra of the couplers were measured during the radiation testing. The figures below show as example the result for one of the couplers. The dot line represents one of the maximal power over the C-band.

Coupler 1



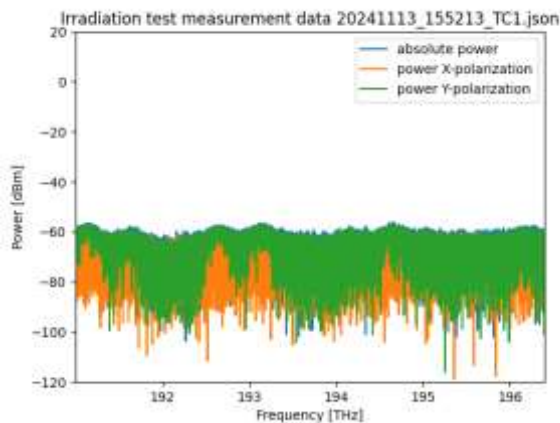
Maximal output power at 194.5 THz

Before Irradiation

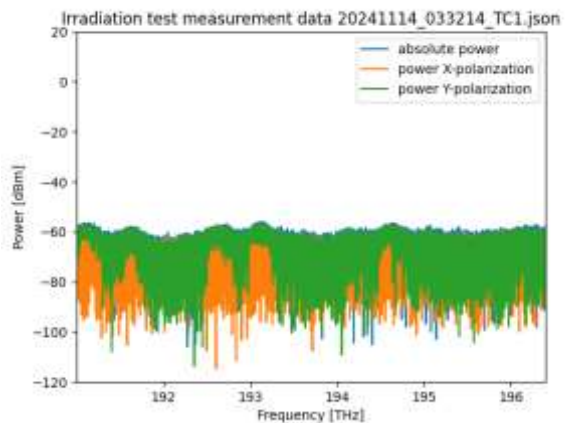


Maximal output power at 194.5 THz

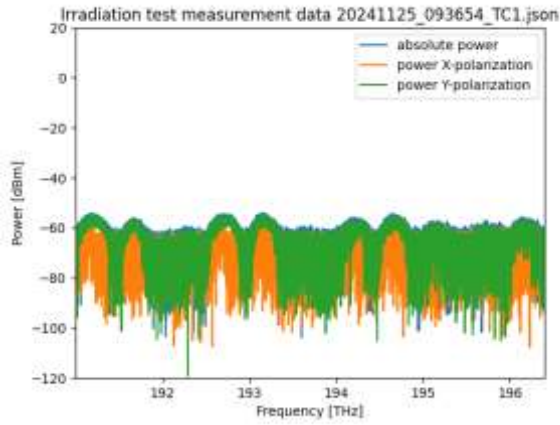
Beginning of Irradiation ~3.5 krad



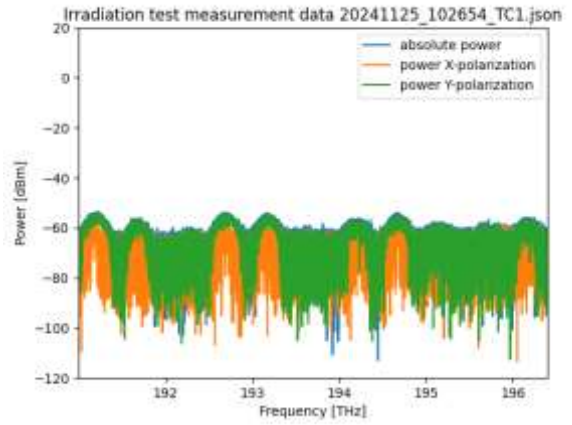
~7.7 krad



~12.2 krad



End of Irradiation



No curing effect

Figure 10 : In-situ radiation testing Coupler 1 – Optical spectrum.

Table 1 : Coupler 1 variation of optical power during radiation.

Time of measurement	Frequency at maximal output power (THz)	Optical power (dBm)	$\Delta P = P_{\text{max}} - P_{\text{min}}$ (dB)
Before Radiation	194.5	-49	13.7
~3.5 krad	194.5	-49.2	13.3
~7.7 krad	194.5	-53.1	8.8
~12.2 krad	191.1	-53.6	8.7
112.6 krad	191.0	-54	7.5
1 hour post irradiation	191	-53.8	7.9

During irradiation, a decrease in optical power and a reduction of the spectral modulation depth were observed. For Coupler 1, ΔP decreased from 13.7 dB before irradiation to approximately 7.5 dB at the end of the test, indicating a degradation of the tuning contrast. No curing effect was observed in the hour following the end of irradiation. Both Coupler 1 and Coupler 2 exhibited significantly low optical power levels prior to irradiation. However, due to the very low initial optical power of the tested devices, the radiation-induced contribution cannot be quantitatively isolated from measurement limitations.

The observed power and contrast degradation is consistent in order of magnitude with the TID-induced losses (up to 1 dB/cm) and effective index shifts ($\sim 1 \times 10^{-3}$) reported for SiN waveguides at comparable doses [5], though geometry and dose-rate differences limit direct comparison.

Characterization after irradiation

Following irradiation, the couplers underwent 168 hours of room temperature annealing. A slight recovery in optical power was observed between the end of irradiation and the first annealing measurement, performed 29 hours later. No significant evolution was subsequently observed during the 168 hours monitoring period. Therefore, a partial recovery during the first 29 hours cannot be excluded.

As for earlier steps, a final characterization involved a complete scan of the couplers in various configurations. LioniX measured the optical spectrum of the couplers by adjusting the values applied to the different actuators. An extract of the spectra for Coupler 1 is presented below in two configurations: Cross/Cross and Bar/Cross. The dot line represents one of the maximal powers over the C-band.

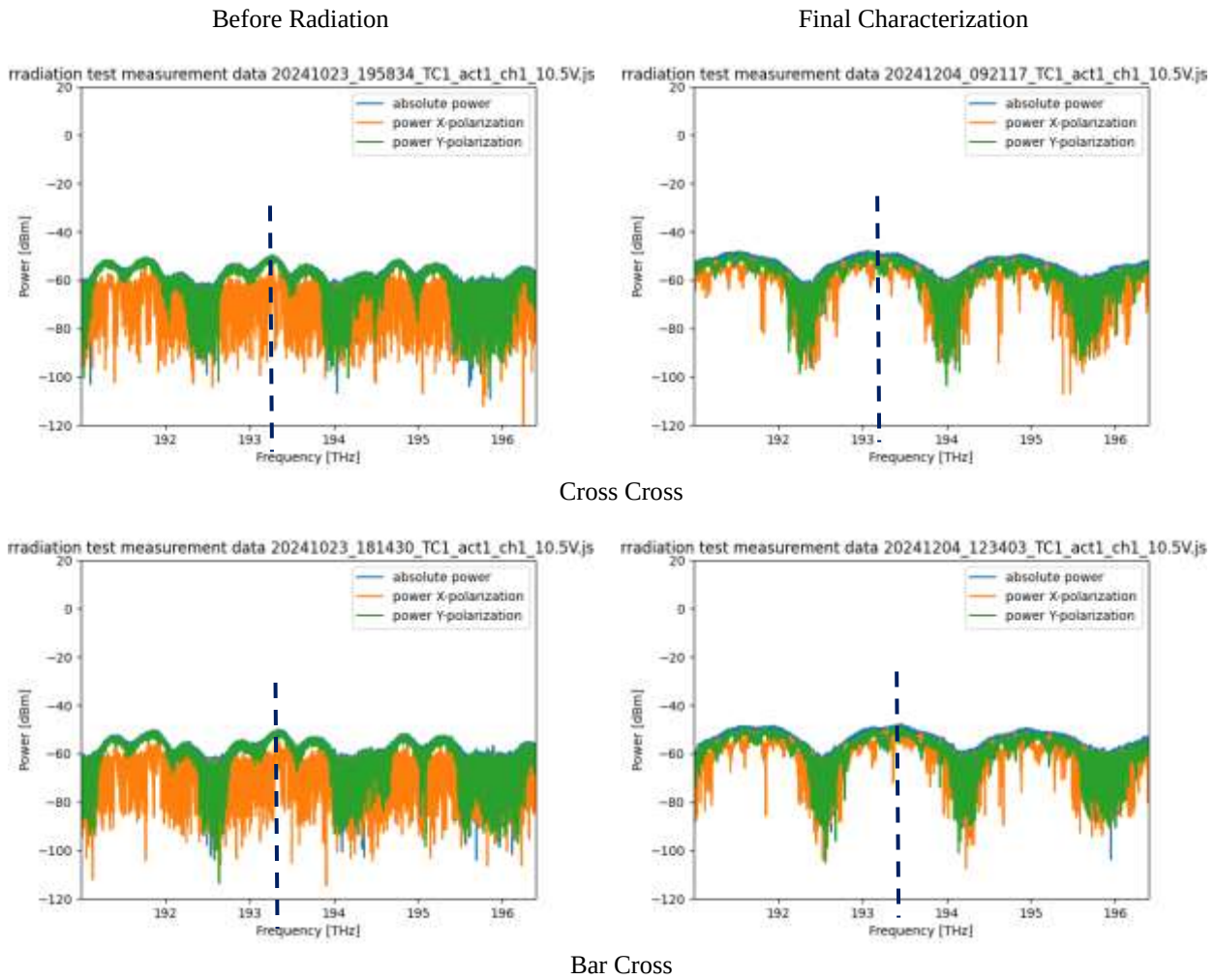


Figure 11 : Coupler 1 Comparison of different configurations before/after irradiation.

Figure 11 compares the pre- and post- irradiation responses of Coupler 1 for two representative actuator configurations. Differences in the spectral shape are observed after irradiation, while the tuning contrast remains comparable to the pre-

irradiation measurements. However, due to the low optical power of the device, the radiation-induced contribution to the power variation cannot be reliably quantified.

The couplers exhibited changes in the optical power and tuning contrast during irradiation, suggesting sensitivity to TID. The couplers employed were standard building blocks rather than components specifically designed for this application. Consequently, the relatively high optical losses observed in the wavelength range of interest restricted the depth of the analysis. Further testing on devices with improved optical performance is therefore required to establish the TID sensitivity of the coupler technology.

5 CONCLUSION

The manufactured lasers are tuneable and demonstrated acceptable performance at the three wavelengths. During irradiation testing, the laser did not exhibit any significant variations, and its parameters (central frequency, optical power, FWHM) remained compliant with specifications. The superposition of the laser's behaviour during irradiation testing showed that the laser was stable. Thus, we can conclude that the radiation testing did not affect the component's functioning. However, it is challenging to identify TID impact on optical power due to both the relatively low laser output power and the test-to-test variations observed independently of irradiation.

The manufactured couplers did not meet the requirements in terms of optical power, and one coupler was non-functional. These were standard components not specifically optimized for the specific application of this test scenario. Characterization performed by LioniX demonstrated that the couplers are tuneable along the C-band. However, the limited initial performance of the components restricted the quantitative assessment of radiation-induced degradation on optical power. The two couplers irradiated up to a total ionising dose (TID) of 100 krad(Si) showed a quick decrease in performance with a decrease in power at the very beginning of the irradiation. No curing effect was observed in the hour following the end of irradiation.

The results obtained in this study indicate that the tuneable laser, based on an external InP Semiconductor Optical Amplifier (SOA) and an external cavity in Silicon Nitride (TriPleX), exhibited no significant TID-induced degradation up to 100krad(Si) within the measurement accuracy. The study highlights the complexity of assembling PIC components, but the results support further investigation of this technology for space applications.

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