

The ASTROMUX Project on WDM Technologies For Space

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ABSTRACT

ASTROMUX (Advanced Space Technology for Reliable Optical MULTipleXing) project investigates the feasibility and space-readiness of Commercial-Off-The-Shelf (COTS) Wavelength Division Multiplexing (WDM) Multiplexers/Demultiplexers (MUX/DEMUX) for next-generation inter-satellite optical communication systems. Three device references with 8 channels and 100 GHz channel spacing were selected to undergo a complete characterisation, and a robustness testing campaign. Optical verification confirmed strong compliance with vendor specifications across main parameters: insertion loss, bandwidth, channel isolation, and central wavelength at three temperatures (-20 degC, room temperature, +65 degC). An extensive environmental and lifetime testing activity was performed, which involved random vibrations, pyroshocks, monitored 2500 thermal cycles, monitored damp heat, high temperature storage, and radiation exposure up to 100 krad. Results from the test campaign demonstrated all three device part numbers maintained stable optical behaviour throughout the whole experimental testing, with observed variations and anomalies remaining within acceptable margins. No destructive failures occurred; all device references successfully completed evaluation for space applications.

ASTROMUX also developed two key considerations for future maturation to target space application: mission qualification of existing devices “as-is” – requiring implementation of bake-out and its consequence, outgassing requirements verification, and mission-specific mitigation strategies – and “re-engineering” with supplier participation to produce space-ready device variants.

Overall, ASTROMUX results demonstrate that commercial WDM MUX/DEMUX technologies are promising enablers for high-throughput space optical links and outline the development steps required to advance these devices toward full space qualification.

Keywords: Wavelength Division Multiplexing, Thin-Film Filters, Arrayed Waveguide Gratings, Intersatellite Links, Environmental Testing, Lifetime Testing, Evaluation Test Plan, Fibered Passive Optical Component.

1. INTRODUCTION

In the context of space telecommunications, optical inter-satellite (IS) links are emerging technologies of increasing interest. Wavelength Division Multiplexing (WDM) technologies are considered key enablers for the deployment of very high-throughput satellite optical links. In a WDM link, multiple optical channels are multiplexed/demultiplexed by a single passive optical device.

ASTROMUX (Advanced Space Technology for Reliable Optical MULTipleXing) is focused on analyzing WDM technologies to characterise whether diverse MUX/DEMUX designs available on the market are suitable for space use. Given there is no space-qualified WDM MUX/DEMUX available on the market, the project began by assessing commercially available devices to leverage prior technology developments as a practical baseline.

This paper outlines the main activities (and their respective results) performed within the scope of the project:

- A survey and critical assessment of the State-of-the-Art to assess current WDM-based MUX/DEMUX and to identify commercially available devices for their suitability for space applications.
- An optical characterization and evaluation test plan on three COTS WDM MUX/DEMUX part numbers, selected in line with optical performance, technical requirements, and procurement feasibility. The testing campaign was carried out on the selected devices which included construction analysis, random vibrations, pyroshock, performance in vacuum, steady-state moisture, lifetime (thermal cycling), high temperature storage, and gamma radiations.
- Recommendations for future development, towards mission qualification.

The project has been performed by: ESA as project promoter; ROMATRE for their expertise in WDM MUX/DEMUX to perform market research and select the devices to be tested; POLIMI as optical communication systems experts with lab resources to perform the optical characterisation; UMBRAGROUP with support from SERMS (part of UMBRAGROUP) for their equipped labs to perform environmental and lifetime testing; and RINA Consulting for project coordination and input from their Innovation System Engineering unit with expertise in adapting technologies to satellite scenarios.

2. BACKGROUND

IS links are deemed crucial for communication purposes, particularly for global coverage, as three geostationary satellites, spaced 120° apart in space, can collectively cover the entire globe [1]. Optical links can support high-speed and large bandwidth links, with low power requirements and high efficiency [2]. Further advantages include a broad spectrum with no licensing requirements, highly secure connections, and immunity to electromagnetic and radio frequency interference [3]. However, the narrow beam divergence angle makes acquisition, tracking, and pointing extremely critical: misalignment errors due to satellite vibration, background noise, and electronic equipment disturbance may induce pointing errors that largely degrade link performance. The effect of several parameters on optical links like transmitter/receiver (TX/RX) aperture size, transmitted power, data rate, different wavelengths and modulation formats has been carefully investigated [4][5].

Transmission capacity can be expanded by implementing WDM, and many different approaches have been proposed in literature. S. Chaudhary *et al.* investigated the performance analysis of an optical link based on six channel WDM architecture, with polarization interleaving [6]. Six independent wavelength channels were transported using nonreturn-to-zero modulation, where the odd channels were transported using X-polarization and the even channels were transported using Y-polarization. A. Alipour *et al.* reported the performance comparison of 64-channel WDM-based optical links operated at 10, 20, and 40 Gbps with 250 km of transmission range, using carrier-suppressed return-to-zero, duobinary return-to-zero, and modified duobinary return-to-zero modulation techniques [7]. The performance evaluation of a 32×10 -Gbps dense WDM-based optical link with 150 GHz of channel spacing at 5000 km of transmission range has been reported by P. Kaur *et al.* [8]. A cost-effective 100-Gbps optical link has been proposed by incorporating hybrid spectral amplitude coding-optical code with polarization-division multiplexing under space-turbulence conditions, i.e. pointing error losses [9]. J. Padhy *et al.* reports on a 1.6 Tbps WDM-based optical link using dual-polarization quadrature phase shift keying over 15,600 km of transmission range [10]. The approach is a 16×100 Gbps dense multiplexed IS optical communications. The modelled performance comparison of different operating wavelength in a long-haul optical link shows that the operating wavelength 850 nm performs better as compared to 1550 [11].

The simplified WDM-based optical IS link architecture under evaluation in ASTROMUX is shown in Figure 1, considering 8 TX/RXs operating at wavelengths ranging from 1533.32 nm (195.51 THz) to 1560.52 nm (192.10 THz), spaced of 100 GHz (0.8 nm) apart. The Pseudo-Random Binary Sequence (PRBS) generator produces the electrical signal, which is optically converted by the optical transmitter at different wavelengths. The 8 optical channels are multiplexed and transmitted via the transmitter telescope. At the receiver side, the optical beam is captured by the receiver telescope and demultiplexed. Each received signal is then analyzed by a Bit Error Rate Tester (BERT) to evaluate the overall link performance and signal quality.

The MUX and DEMUX play a key role in the link performance, because it is used to filter the different wavelength at its output port, introducing limited losses and reducing interchannel interference. It is also a single-point failure element in the proposed architecture. Hence, the purpose of ASTROMUX is to investigate the feasibility and space-readiness of COTS WDM MUX/DEMUX for next-generation inter-satellite optical communication systems.

The project decided to focus on two WDM technologies: Arrayed Waveguide Grating (AWG) and Thin Film Filter (TFF) after conducting a state-of-the-art assessment. These technologies have been considered and compared regarding the following parameters: power handling capability; mass, volume, and dimensions; operational/environmental constraints; complexity and scalability; ease of implementation (w.r.t interfaces, connectors, etc.); and suitability for space applications.

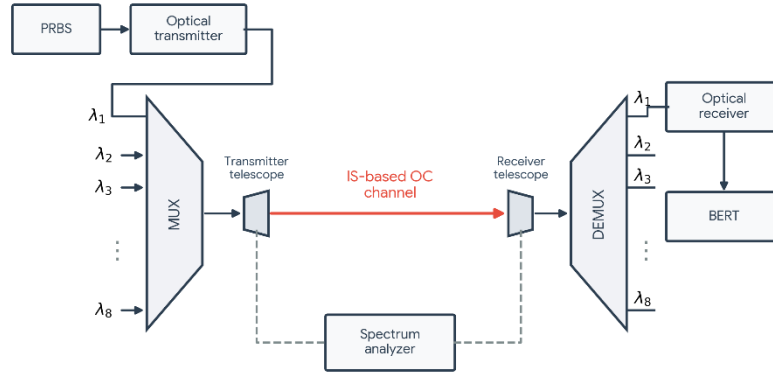


Figure 1. Simplified architecture of an IS optical system, including 8 WDM channels.

Arrayed waveguide grating

AWGs are mature integrated photonic devices widely used in WDM optical networks. They consist of two planar star couplers connected by an array of waveguides with progressively increasing path lengths, creating wavelength-dependent constructive interference that directs different wavelengths to different output ports. AWGs are compact, passive, highly scalable, and can support a large number of channels with low loss, making them attractive for high-capacity optical communications. Their main limitation for space applications is the wavelength shift caused by temperature-dependent refractive index variations, which can require thermal stabilization when using conventional AWGs. Alternatively, athermal AWGs can be used, which have been designed and developed with a reduced temperature dependence. Overall, AWGs are well suited to space applications due to their compact size, light weight, and no power consumption. Athermal AWGs could be preferred for their robustness and reliability in harsh environmental conditions.

Thin film filters

TFFs use multilayer dielectric thin-film cavities acting as Fabry-Perot interferometers to selectively transmit one wavelength while reflecting others. By cascading multiple filters, wavelength channels can be multiplexed or demultiplexed with low insertion loss and sharp spectral selectivity. TFF technology has been extensively deployed in WDM systems and is particularly effective for channel spacings of 100 GHz or greater. However, insertion loss increases with channel count, limiting scalability for large-channel systems. TFFs can be used in space applications, but their suitability may depend on specific design considerations and environmental requirements. They are generally more sensitive to temperature variations compared to AWGs.

3. METHODOLOGY

Following a study on commercially available WDM MUX/DEMUXs based on AWG and TFF technologies, three device references were selected for the characterisation procedure as these WDM technologies and devices were most compliant to project requirements reported in Table 1 and were also feasible w.r.t auxiliary aspects such as costs and delivery times.

Table 1. Optical requirements for the WDM MUX/DEMUX

Parameter	Value
Operational centre frequency	1533,32 nm (195.51 THz) and 1560,52 nm (192.10 THz)
Number of multiplex channels	1 x 8
Channel centre accuracy	< ±10 GHz
Channel spacing	0.8 nm (100GHz)

Parameter	Value
Channel bandwidth	> spacing x 0.48
Insertion loss	< 3 dB
Insertion loss uniformity	<0.5 dB
Polarisation dependent loss	< 0.5 dB
Return loss	> 45 dB
Isolation at adjacent channel	> 30 dB
Isolation at non-adjacent channel	> 40 dB
Passband ripple	< 0.3 dB
Power handling	> 300 mW

1. **Device A: WDM TFF MUX/DEMUX:** device behavior matches almost all relevant optical requirements. While the standard version does not comply with the required operating temperature range, the industrial version does.
2. **Device B: athermal AWG MUX/DEMUX:** while this device does not have the same optical performance as the other devices, it was nonetheless selected due to no wavelength shift expected in the required temperature range, as well as a lack of thermal cooling requirement to operate. Among all analyzed devices, this was found to be the best athermal AWG device in terms of optical characteristics.
3. **Device C: WDM TFF 3-port MUX/DEMUX:** this device has good optical performance and it has the smallest size among the MUX/DEMUX devices. It is not athermal, however, the supplier assured a guaranteed performance in the entire operating temperature range.

From each device reference, a sample size of 8 devices per suppliers was purchased to undergo constructional analyses, optical characterisation, and finally environmental and mechanical tests during the ASTROMUX test campaign. Each test condition was applied to a single device (meaning, tests were not applied to the same sample sequentially). The procedures followed for the device evaluation are reported in Figure 2 and outlined in the remainder of this Section.

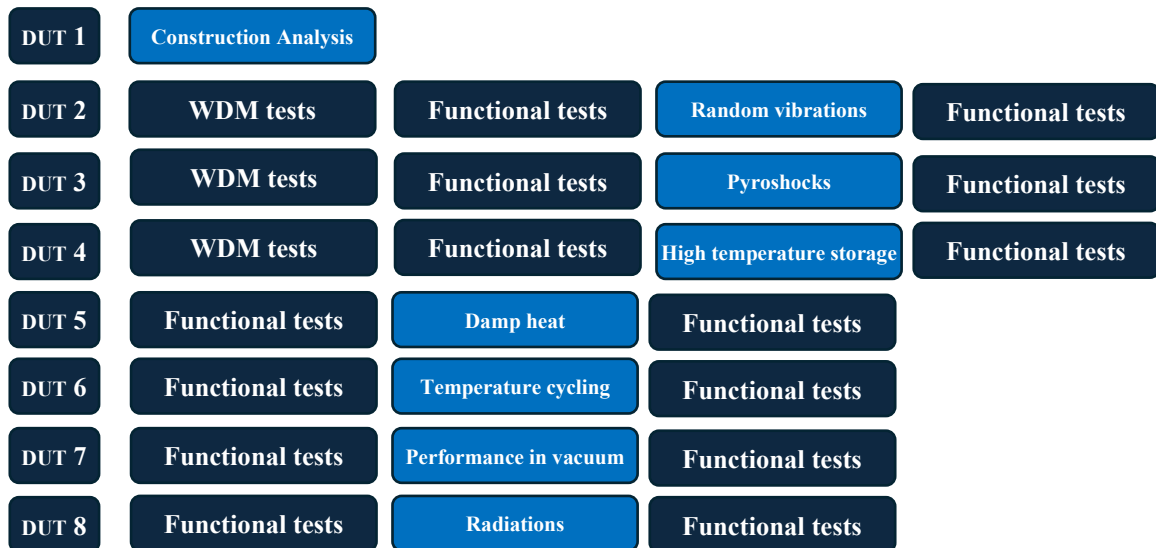


Figure 2. Overall testing campaign on DUTs.

3.1 Test Campaign

As an essential procedure, a preliminary verification of DUT optical characteristics was performed, including a detailed analysis of the performance in case of simultaneous transmission of the 8 WDM channels. This ensured that device performance is in line with supplier datasheets and to get an idea on how they perform with high power (250 mW) and in a WDM configuration. The set of functional tests at the three temperatures provides a baseline to identify the changes

during the subsequent testing campaign for space characterisation. All the WDM channels are with OOK modulation at 10 Gbaud and co-propagate over 2-km SMF without chromatic dispersion compensation.

The subsequent test campaign included random vibrations, pyroshock, performance in vacuum at the three temperatures, damp heat, lifetime (thermal cycling), high temperature storage, and radiations.

In order to have a reference for detecting meaningful changes in the device's performances, at the beginning and at the end of all the tests, all the devices underwent functional checks (in DEMUX configuration) in climatic chamber at ambient pressure and at ambient temperature (+20°C), in hot (+60°C) and cold (-20°C) conditions. The optical characteristics measured during the functional tests were the parameters of the output power spectra, i.e.: operational centre frequency, number of operative channels, channel centre accuracy, channel spacing, channel bandwidth, insertion loss, insertion loss uniformity, isolation at adjacent and non-adjacent channel and passband ripple.

The functional test were performed with 1 mW optical input. Moreover, the data acquired in the initial test were compared with the data measured in post-test phase. In order to determine any failure of the devices, initial, post-test and drifts measurements were compared to specification (see Table 1) and to the chosen drifts limits as reported in Table 2.

Table 2. Optical parameters used as main pass/fail criteria

Measured Performance	Max. Allowed Drift
Channel Central Frequency	+/- 25 GHz
Insertion Loss	Increase > 1.5 dB

The evaluation test procedures are outlined in the following Sections.

3.1.1 Construction Analysis

The Construction Analysis as defined in ECSS-Q-ST-60C [12] is a sequence of non-destructive and destructive tests conducted to determine the design and technologies used in the construction of the device, identify the various materials and assess the interfaces robustness in an early stage of the Evaluation campaign. The output of this step could lead to change test sequences or could simply show a total inadequacy of the devices to space application. The tests performed were:

External Visual Inspection, X-Ray Inspection, Cable Retention Test, Internal Visual Inspection, SEM (scanning electron microscopy) and material analysis, Cross Section followed by visual inspection, SEM and material analysis.

3.1.2 Mechanical load testing procedures

The vibration test campaign was performed to verify the structural integrity and to assess the capability of the WDM MUX/DEMUX devices when subjected dynamic mechanical loads expected during launch, and pyroshock tests to evaluate the structural robustness and functional integrity when subjected to high-frequency, high-acceleration mechanical shocks representative of launch separation events.

All devices were tested using dedicated fixtures designed to reproduce representative mechanical boundary conditions. Functional optical checks were performed before and after each test to assess possible performance degradation induced by the applied mechanical stresses and to verify if the potential performance drift is within the pass-fail criteria.

Random vibrations: Each device was subjected to random vibration profiles along the three orthogonal axes (X, Y, Z), using an electrodynamic shaker system and control accelerometers to ensure compliance with the specified Power Spectral Density (PSD) levels. Detailed test conditions are outlined in Table 3. Additional intermediate checks were executed while a complete post-test functional verification was carried out after the conclusion of the vibration sequence on all axes.

Table 3. Detailed test conditions: random vibrations testing

Parameter	Test conditions
Spectrum	20-2000 Hz
Overall acceleration	10; 20
Exposure time	15 Minutes

Pyroshock: The test campaign was performed using a calibrated pyroshock simulator. Each device was subjected to a references of shock pulses along the three orthogonal axes, in accordance with the test profiles and Shock Response Spectrum (SRS) levels outlined in Table 4. Intermediate optical checks were performed during the test sequence to identify a structural damage in-between tests, while a full post-test functional verification was executed upon completion of the shocks on all axes. Visual inspections were also conducted to identify any structural damage or anomalies.

Table 4. Detailed test conditions: pyroshock testing

Frequency (Hz)	Shock response spectrum (g)
100	100
2000	1000
10000	1000

3.1.3 Environmental testing procedures

The environmental test campaign was performed to verify the functional stability and long-term reliability of the WDM MUX/DEMUX devices when subjected to environmental conditions representative of on-ground storage, launch preparation and in-orbit operation. The objective of the thermal tests was to identify potential degradation mechanisms related to thermo-mechanical stress, material ageing and environmental effects, while ensuring compliance with the project requirements. The tests included exposure to combined temperature and humidity conditions, high-temperature storage, lifetime/thermal cycling and vacuum performances when temperature changed.

For all environmental tests, functional optical measurements were carried out before and after the environmental exposure, and, where applicable, during the test execution, to monitor the device performance and detect any drift of the main optical parameters.

Moisture: conducted to assess the resistance of the WDM MUX/DEMUX devices to prolonged exposure to high temperature and high relative humidity conditions, representative of severe on-ground storage environments. The devices underwent to controlled temperature and humidity conditions within a climatic chamber, as outlined in Table 5. The test aimed at evaluating the potential impact of moisture ingress on optical performance, materials and assembly integrity.

Table 5. Detailed test conditions: moisture testing

Parameter	Test condition
Storage temperature	85°C +3/-0°C
Relative humidity	85% (+/- 3%)
Dwell time	500 hrs

High temperature storage: performed to evaluate the stability and long-term behaviour of the WDM MUX/DEMUX devices when exposed to elevated temperature conditions for extended durations. The objective of the test was to assess potential ageing effects, material degradation and thermo-mechanical stress phenomena that could affect the optical performance during prolonged on-ground storage or non-operational mission phases. The devices were stored in a controlled thermal environment at the specified temperature and duration (see Table 6).

Table 6. Detailed test conditions: high temperature storage testing

Parameter	Test condition
Storage temperature	85°C +3/-0°C
Dwell time	2000 hrs

Lifetime: this test procedure was performed to investigate the long-term reliability and durability of the WDM MUX/DEMUX devices when subjected to repeated thermal stresses representative of in-orbit mission scenarios. The test campaign consisted of prolonged thermal cycling under controlled environmental conditions outlined in Table 7. The objective was to identify potential degradation mechanisms associated with thermo-mechanical fatigue, material ageing and cumulative stress effects over the expected operational lifetime.

Table 7. Detailed test conditions: lifetime testing

Parameter	Test conditions
T max.	85°C +3/-0°C
T min.	-40°C -3°C/+0°C
Gradient	15°C/min
Dwell time	15 minutes
Number of cycles	2500

Thermovacuum: performed to verify the functional performance and stability of the devices when operating under combined thermal and vacuum conditions representative of the space environment. The test consisted of subjecting the devices to temperature variations between the specified minimum and maximum operational limits in vacuum conditions (see Table 8). The objective of the test was to assess the influence of vacuum and thermally induced stresses on the optical performance, as well as to verify the correct operation of the devices in the absence of convective heat transfer. Each device was mounted on a dedicated conductive interface fixture and tested individually inside a thermal vacuum chamber.

Table 8. Detailed test conditions: thermovacuum testing

Parameter	Test Conditions
Hot operating temperature	60°C +4/-0°C
Min. operating temperature	-20°C -4°C/+0°C
Pressure	<1 e-5mbar (+/-80%)
N° of cycle	1
Dwell time	2 hrs
Temperature rate	<1°C/min
Stabilization criteria	<1°C/hr

3.1.4 Radiation test procedure

Radiation tests were performed to evaluate the tolerance of the WDM MUX/DEMUX devices to ionizing radiation effects representative of the space environment. The objective of the test was to assess the susceptibility of the devices to Total Ionizing Dose (TID) effects and to verify the stability of the optical performance after exposure to the specified radiation levels. The irradiation campaign was conducted at the Calliope Gamma Irradiation Facility of the ENEA Casaccia Research Centre (Rome, Italy), using a *Co-60* gamma radiation source with a mean photon energy of approximately 1.25 MeV. The devices were irradiated in air, at room temperature and ambient pressure, and positioned inside a dedicated lead bunker within the irradiation cell.

The irradiation was performed incrementally until reaching a total absorbed dose of 1 kGy (Si). The dose rate applied during the campaign was monitored and updated daily to account for the natural decay of the *Co-60* source. Absorbed dose measurements were carried out using a Fricke dosimetry system, in compliance with ENEA internal procedures and applicable ASTM standards, ensuring traceability and accuracy of the delivered dose. The irradiation campaign started on 12 January 2026 and ended on 27 January 2026, for a total irradiation time of approximately 337 hours. The absorbed dose was delivered through multiple irradiation steps to achieve the target total ionizing dose under controlled conditions.

Functional optical measurements were performed before irradiation to establish reference performance. Additional optical verifications were conducted after each irradiation step, at the completion of the irradiation campaign and after the post-irradiation 24-hours annealing period, to assess any permanent degradation or drift of the main optical parameters.

Table 9. Detailed test conditions: radiation testing

Parameter	Test condition
Total absorbed dose	100 krad
Dose rate	0.1 rad/sec
Dose step	0-5-10-15-25-35-55-75-100
Time for functional test at each step	<= 2 hrs

3.2 Outgassing analysis

A research-based outgassing analysis was conducted on the bill of materials (BoM) of each device references. This analysis consisted of searching public ESA and NASA outgassing databases for the specified materials in the following databases: ESA Outgassing Database; NASA Outgassing Database; Space Materials Database (SPACEMATDB). According to ECSS-Q-70-02C [13], outgassing is almost always associated with polymeric materials, adhesives, paints, resins, plastics, elastomers, and organic coatings. These materials can release plasticizers, residual solvents, unreacted monomers or oligomers, additives, and/or absorbed water. Specific limits for Total Mass Loss, Recovered Mass Loss, and Collected Volatile Condensable Material parameters are defined in the standard, however each mission can specify more stringent requirements to be met depending on the expected sensitivity to the contamination released in orbit.

4. RESULTS

4.1 Optical performances verifications

This section presents the two types of optical tests performed on the procured references (WDM tests in Figure 2).

4.1.1 Preliminary Optical Assessment in a WDM System

The first step in the testing campaign was to analyze the performance of the MUX/DEMUX in a WDM application, and in a second step to identify if high optical power could be detrimental.

In this paragraph we report the experimental results achieved by employing a pair of device of the same vendor with one operating as MUX and the other operating as DEMUX. The BER performance of the channel CH33 with the co-existence of the 100-GHz spaced adjacent channels CH32 and CH34 is reported in the following figures, showing the OSA spectrum and the BER.

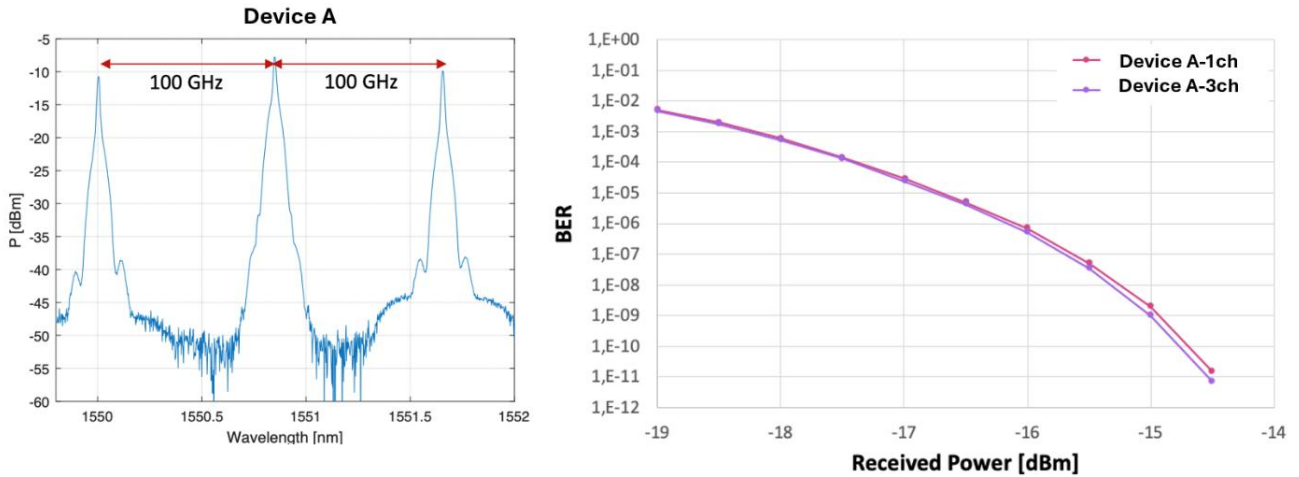


Figure 3.

Left. Measured OSA spectrum with the two adjacent channels.

Right. Measured BER curves with receiver sensitivity tested: Red curve, CH33 only; Purple curve, co-existence of the adjacent CH32 and CH34.

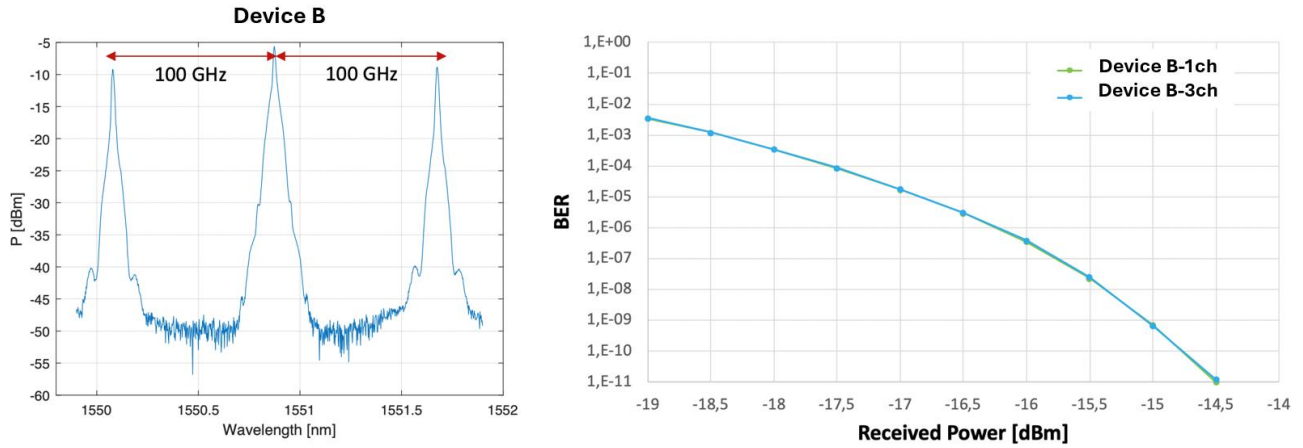


Figure 4.
 Left. Measured OSA spectrum with the two adjacent channels.
 Right. Measured BER curves with receiver sensitivity tested: Green curve, CH33 only; Blue curve, co-existence of the adjacent CH32 and CH34.'

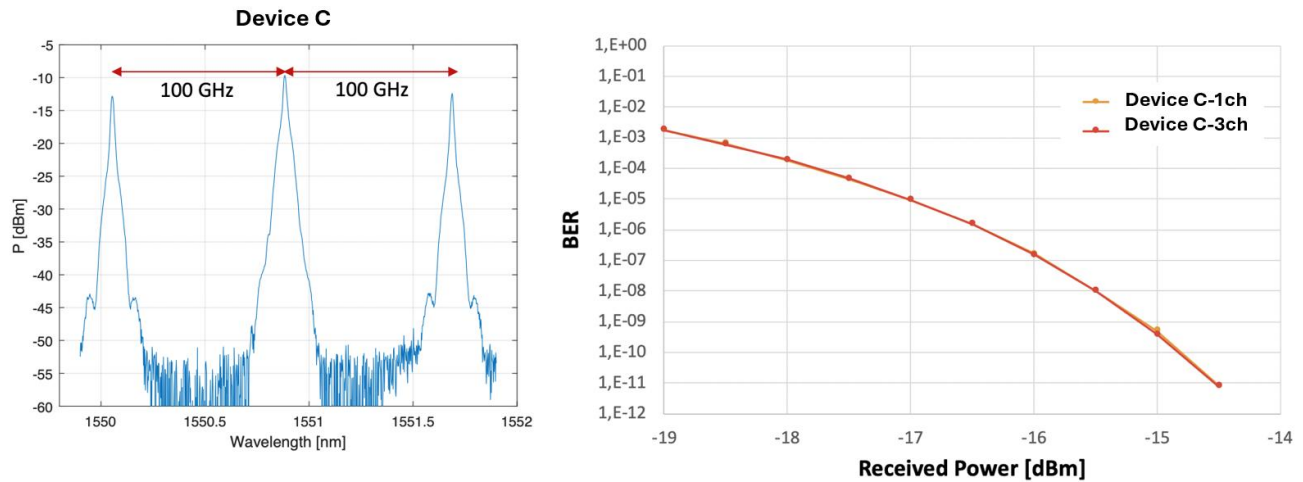


Figure 5.
 Left. Measured OSA spectrum with the two adjacent channels.
 Right. Measured BER curves with receiver sensitivity tested: Orange curve, CH33 only; Red curve, co-existence of the adjacent CH32 and CH34.

4.1.2 Compliance with vendors' data sheets (optical requirements)

The optical characterisation performed on the devices showed that the IL, central frequency, 3dB bandwidth, isolation from adjacent WDM channels at 100GHz spacing, and isolation from non-adjacent WDM channels at 200GHz spacing were consistent with the values declared in the vendors' test sheets. One incoming unit (TFF-based) exhibited abnormally high insertion loss in one single channel prior to any project testing. The affected unit was returned to the supplier and promptly replaced by a compliant one. The event highlights the importance of systematic incoming optical verification of commercial devices prior to integration or testing, while also confirming the value of a responsive technical support from the supplier.

The characterization related to standard operation for all devices was achieved by using an optical power in input to the WDM DUT of around 0 dBm (1 mW). In case of high power handling, the characterization was achieved by using an optical power in input to the WDM DUT of around 24 dBm (250 mW), lower than 24.77 dBm (300 mW), in order to

preserve the not-angled LC/PC connectors. Note that TFF-based devices are in the so-called “twin” configuration, including the MUX and DEMUX. Thus, measurements related to the characterisation for Device A and C are reported for the DEMUX and MUX configuration separately.

For each device series, three devices underwent the optical characterization (see Figure 2). A single representative DUT has been chosen as the representative device, for which results have been reported below.

4.1.2.1 Optical Characterisation Device A (TFF)

Optical requirements testing results for Device A report the measurement related to the characterization from the common TX to the RX direction (for the DEMUX) and from the common RX to the TX direction (for the MUX).

Figure 6 reports the optical spectral transfer function measured for all 8 ports when the radiation at the input port sweeps from 15548 nm to 1556.5 nm.

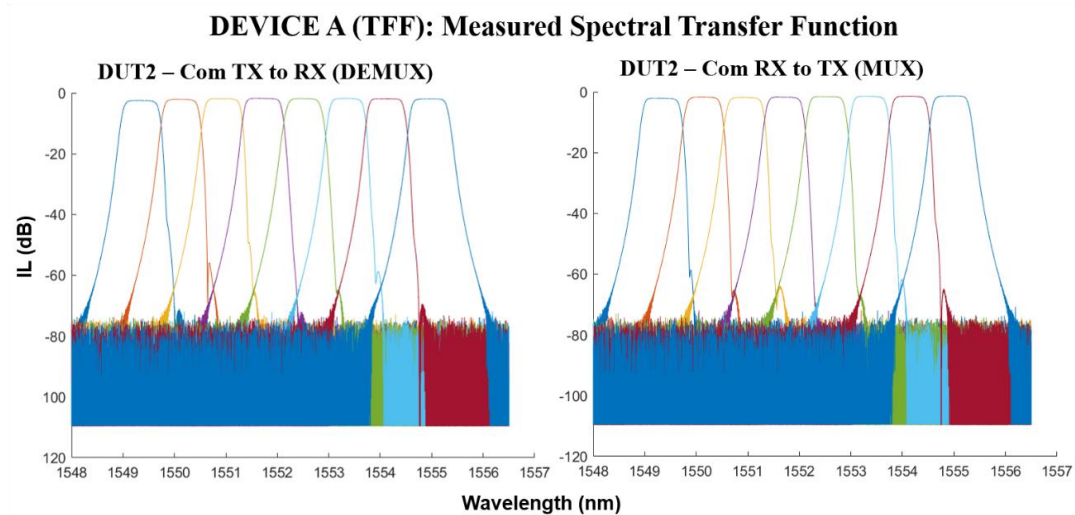


Figure 6. Measured spectral transfer function of Device A in configuration common TX to RX (DEMUX) and common RX to TX (MUX).

From the measured spectra, the optical characteristics were deduced as reported in **Error! Reference source not found.** which also reports the optical performance values and high-power handling of the device for a single channel.

Table 10. Optical performance of Device A across all channels, and optical characteristics and high power handling for channel 33.

	Device A (TFF)	
	DEMUX	MUX
Optical Performance (All Channels)		
Insertion Loss Uniformity	0.7 dB	0.7 dB
Passband Ripple	0.1 dB	0.1 dB
Polarization Dependent Loss	0.1 dB	0.1 dB
Return Loss	> 45 dB	> 45 dB
Optical Characteristics (CH33)		
Operation centre frequency (GHz)	193.297	193.296
CH band @0.5dB (GHz)	67.44	64.28
CH band @3dB (GHz)	85.28	83.88
Insertion Loss	1.87	1.83

Adjacent isolation - left CH (dB)	54.13	54.16
Adjacent isolation – right CH (dB)	68.13	68.16
Non- Adjacent isolation - left CH (dB)	88.13	78.16
Non-Adjacent isolation – right CH (dB)	78.13	88.16
High Power Handling (CH33)		
Insertion Loss	1.45 dB	1.64 dB
CH bandwidth @ 0.5 dB	64.25 GHz	56.96 GHz
CH bandwidth @ 3 dB	84.43 GHz	83.50 GHz
Adjacent Isolation	> 50 dB	> 50 dB
Non-adjacent Isolation	> 75 dB	> 75 dB

4.1.2.2 Optical Characterisation Device B (AWG)

Optical characterisation for Device B has not been performed in separate DEMUX and MUX configurations (as has been done for TFF-based devices), as AWG devices are reciprocal, single chip/module. Therefore, a single transfer-function characterization has been performed.

Figure 7 reports the optical spectral transfer function measured for all 8 ports when the radiation at the input port sweeps from 15545 nm to 1554 nm.

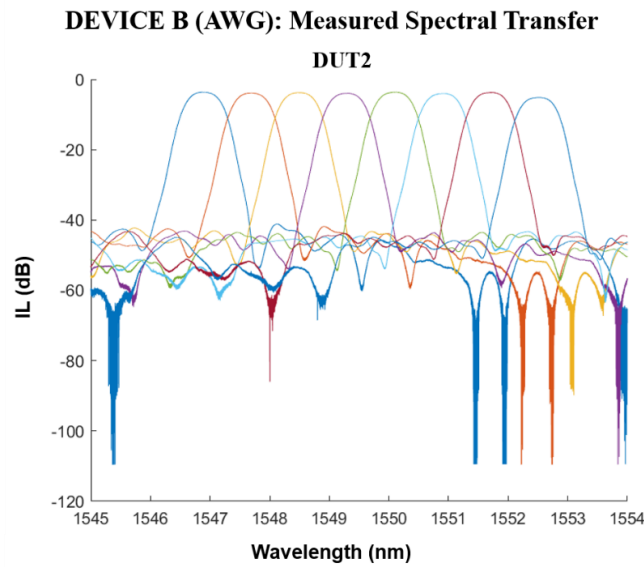


Figure 7. Measured spectral transfer function of Device B.

From the measured spectra, the optical characteristics were deduced as reported in Table 11. which also reports the optical performance values and high-power handling of the device for a single channel.

Table 11. Optical performance of Device B across all channels, and optical characteristics and high power handling for channel 33.

Device B (AWG)	
Optical Performance (All Channels)	
Insertion Loss Uniformity	1.49 dB
Passband Ripple	0.3 dB
Polarization Dependent Loss	0.2 dB
Return Loss	> 45 dB
Optical Characteristics (CH33)	
Operation centre frequency (GHz)	193.303
CH band @0.5dB (GHz)	37.13
CH band @3dB (GHz)	73.28
Insertion Loss	4.03
Adjacent isolation - left CH (dB)	34.25
Adjacent isolation – right CH (dB)	42.67
Non- Adjacent isolation - left CH (dB)	42.67
Non-Adjacent isolation – right CH (dB)	42.87
High Power Handling (CH33)	
Insertion Loss	3.88 dB
CH bandwidth @ 0.5 dB	35.25 GHz
CH bandwidth @ 3 dB	73.05 GHz
Adjacent Isolation	> 30 dB
Non-adjacent Isolation	> 40 dB

4.1.2.1 Optical Characterisation Device C (TFF)

Optical characterisation for Device C has been performed for both DEMUX and MUX configuration (reported for port D and port M, respectively).

Figure 8 reports the optical spectral transfer function measured for all 8 ports when the radiation at the input port sweeps from 15545 nm to 1554 nm.

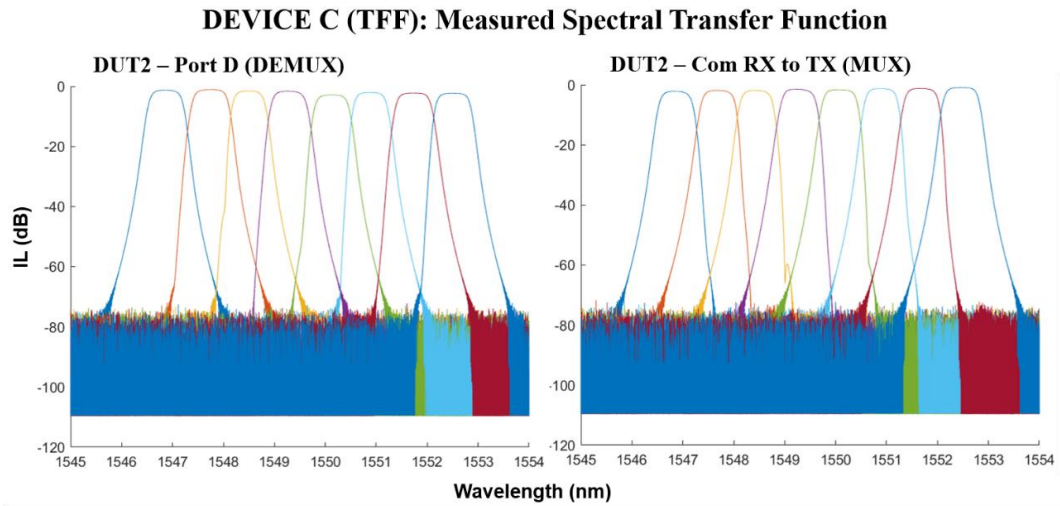


Figure 8. Measured spectral transfer function of Device C in DEMUX and MUX Configuration.

From the measured spectra, the optical characteristics were deduced as reported in Table 12 which also reports the optical performance values and high-power handling of the device for a single channel.

Table 12. Optical performance of Device C across all channels, and optical characteristics and high power handling for channel 33.

	Device C (TFF)	
	DEMUX	MUX
Optical Performance (All Channels)		
Insertion Loss Uniformity	1.65 dB	1.26 dB
Passband Ripple	0.3 dB	0.3 dB
Polarization Dependent Loss	0.1 dB	0.05 dB
Return Loss	> 45 dB	> 45 dB
Optical Characteristics (CH33)		
Operation centre frequency (GHz)	193.304	193.302
CH band @0.5dB (GHz)	50.76	49.65
CH band @3dB (GHz)	75.39	74.48
Insertion Loss	2.07	1.26
Adjacent isolation - left CH (dB)	67.92	53.74
Adjacent isolation – right CH (dB)	57.92	78.74
Non- Adjacent isolation - left CH (dB)	77.92	78.74
Non-Adjacent isolation – right CH (dB)	77.92	78.74
High Power Handling (CH33)		
Insertion Loss	1.99 dB	1.15 dB
CH bandwidth @ 0.5 dB	47.93 GHz	45.37 GHz
CH bandwidth @ 3 dB	73.81 GHz	73.69 GHz
Adjacent Isolation	> 50 dB	> 50 dB
Non-adjacent Isolation	> 75 dB	> 75 dB

4.2 Vibration testing results

The vibration and pyroshock tests did not reveal any significant degradation in the optical performance of the three devices under investigation. The differences observed between pre- and post-test measurements were limited to minor and occasional variations in insertion loss, most likely attributable to connector handling and cleaning rather than to structural effects induced by the tests. The absence of any measurable shift in observed resonance peaks before and after vibration testing confirmed the mechanical stability of the devices.

As it can be observed in Figure 9, in the case of the athermal AWG device, a small central frequency shift of approximately 4–6 GHz for all 8 WDM channels under test was observed in the pyroshock testing and was interpreted as an effect of the internal thermo-mechanical compensator. It is worth noting that the measured shift was not critical for device performance (being less than 10% of the WDM channel spacing) and did not impact IL or adjacent-channel isolation, thus the observed effects were not considered indicative of any functional failure.

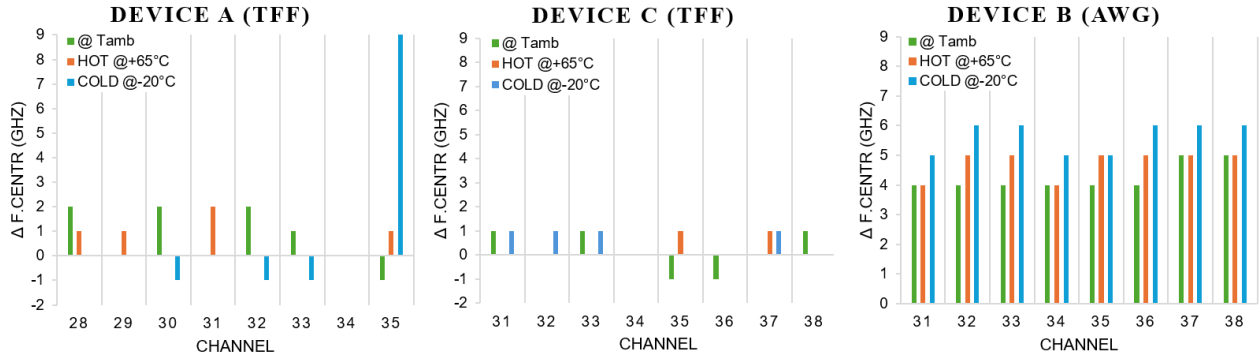


Figure 9. Variation of the measured central frequency pre- and post-pyroshock testing for the three device series, at three different reference temperatures.

4.3 Environmental testing results

Independent of the environmental tests performed, pre- and post-test optical characterisations showed that the TFF-based 3-port MUX/DEMUX devices tend to exhibit IL degradation at low temperatures for specific channels. Some of these channels showed IL values exceeding 3 dB at $T = -20^{\circ}\text{C}$ (a trend also confirmed during vacuum thermal testing). A less pronounced IL degradation under cold conditions was also observed in several devices. In all cases, IL degradation is observed both pre- and post-test.

These additional losses could not be attributed to a spectral shift of the transfer function, as the measured central frequencies remain essentially unchanged. A possible explanation may be related to the stiffening of the epoxy adhesive used in the Device C construction at low temperatures. However, it should be noted that this behaviour affected only selected channels. The observed IL degradation was temporary, with measured IL values only slightly exceeding 3 dB.

Moisture tests: did not reveal any significant degradation in the optical performance of the three devices under investigation with generally negligible deviations and a single minor insertion loss anomaly on one channel of Device C under cold conditions, plausibly related to the solidification of the filling resin.

High temperature storage tests: demonstrated overall stable behaviour for all devices. Overall, no adverse effects attributable to the high temperature tests were identified.

TFF-based devices showed no significant post-test variations. Device A presented insertion loss differences on the order of 0.5–0.6 dB attributed to connector effects and, in some cases, a slightly improved performance.

Device B, based on AWG technology, also maintained stable performance, although one channel displayed an insertion loss slightly exceeding the manufacturer's declared limit under hot conditions. This behaviour was consistent with the inherently higher baseline insertion loss of AWG technology and did not indicate test-induced degradation.

Lifetime tests: confirmed the long-term stability of the devices. Overall, no significant performance degradation attributable to the lifetime tests was observed.

The Device A (TFF-based) sample exhibited no measurable changes in either insertion loss or central frequency. Device C (also TFF-based) displayed minimal variations after test completion, with some channels marginally exceeding the declared insertion loss limit. These deviations were explained by the channel-by-channel measurement procedure, which is sensitive to connector alignment and residual contamination.

Within the AWG-based Device B, a pre-existing issue was confirmed on one channel at cold temperature, characterised by an insertion loss exceeding 3 dB; this behaviour was therefore considered intrinsic to the device and not related to ageing. A slight central frequency shift observed on another channel was also confirmed to have been present prior to testing.

Thermovacuum tests: indicated that none of the devices experienced significant degradation attributable to the test environment, thus the behaviour of all devices was considered stable.

Figure 10 shows that TFF-based devices showed stable insertion loss, central frequency, and bandwidth, with variations limited to the instrumental resolution. Device C showed no effects directly induced by the thermal vacuum conditions, while confirming a sensitivity to low temperatures, with some channels exhibiting insertion loss increases greater than 3 dB under cold conditions.

AWG-based Device B, although characterised by higher insertion loss values consistent with AWG technology, did not show degradation after testing; the presence of an internal thermal compensation component may explain possible oscillations during rapid temperature transitions.

Furthermore, a difference between AWG and TFF technologies was observed, with respect to the compensation of the change in temperature, where AWG devices presented a delay in comparison to the TFF devices.

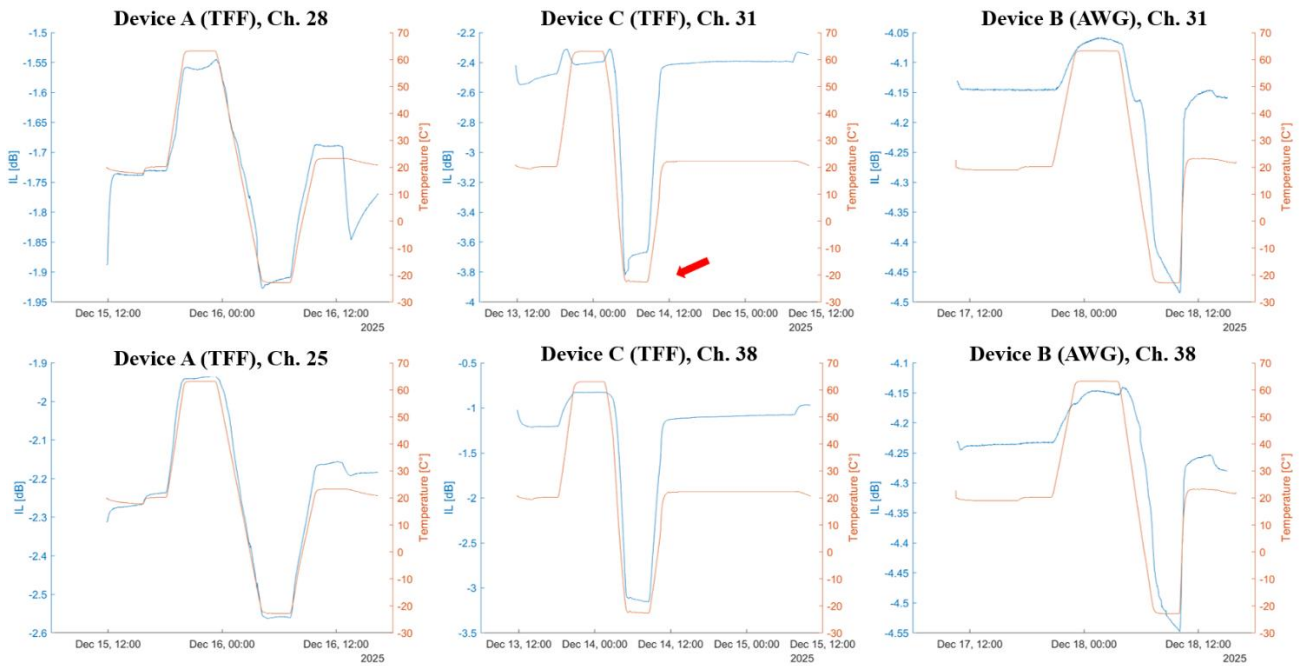


Figure 10. Measured Insertion Loss (IL) during thermo-vacuum testing for the three device references, presenting two representative channels each. The red arrow points out Device C sensitivity to low temperatures present in some channels.

4.4 Radiation testing results

Regarding radiation exposure, two TFF-based devices exhibited a progressive IL increase for the outermost spectral WDM channels (channels 34 and 35 for one; channels 31 and 32 for the other) for radiation doses exceeding 500Gy, as it is evident in Figure 11. After 24 hours, IL values returned to nominal levels, as confirmed by post-test measurements. This behaviour was not observed in the device based on AWG technology, which was virtually insensitive to radiation, with

insertion loss variations below 0.5 dB and no measurable impact on central frequency or bandwidth, a behaviour attributed to shorter internal optical paths and reduced channel differentiation.

The observed degradation cannot be attributed to a spectral shift of the device transfer function, as the corresponding central frequencies remain unchanged. A possible explanation may be related to the longer optical path experienced by the outermost channels (involving a higher number of mirrors, lenses, and fibre segments) in case of thin-film technology, making them more susceptible to radiation-induced transient absorption effects. Since the effect was limited in magnitude (IL values remained below 4 dB), temporary and the central frequencies remained unchanged, the result is best interpreted as technology-specific radiation sensitivity information to be considered in future mission-dependent acceptance and design activities.

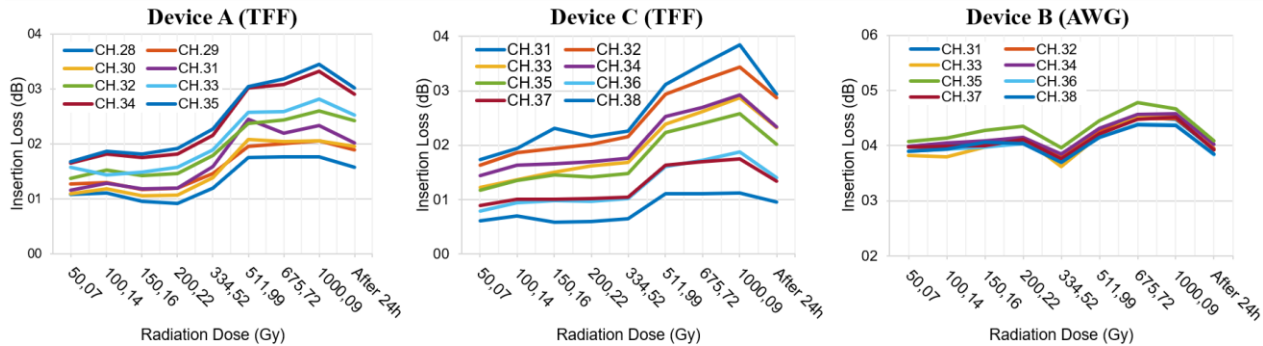


Figure 11. Measured Insertion Loss (IL) during radiation exposure of all three device series. Notable is the increase found in outer channels of TFF device A (channels 34 and 35), and device C (channels 31 and 32).

4.5 Outgassing analysis results

The outgassing analysis revealed that each device references contains several components and materials which were either classified as non-compliant organics or were unknown. It is worth noting that the depth and precision of this qualitative analysis depended largely on the information provided by the manufacturer, and, in some cases, materials were mostly unknown due to a lack of description found in the BoM, difficulty in linking the materials to products in the outgassing databases, or classified chemical elements listed for the materials. Furthermore, it was not always possible to link a component/material to a precise commercial match in the outgassing databases, in which case outgassing thresholds were inferred from aggregated values found in similar entries.

Non-compliant organics, which could be precisely identified within the outgassing databases, were largely made up of adhesives, coatings, absorbants, and optical fiber (connectors).

5. DISCUSSION

Results from the testing campaign demonstrated all three device references maintained stable optical behaviour throughout the whole procedure, when comparing performance prior and after testing, with observed variations and anomalies remaining within acceptable margins. No destructive failures occurred and all device references were assessed to have successfully been tested for evaluation for space use.

Anomalous test results (though non-critical) and lessons learned include the following:

- **Compliance with vendors' data sheets** (optical requirements): one unit exhibited abnormally high insertion loss in one single channel prior to any project testing. This highlights the need for systematic optical verification of all unique devices.
- **Mechanical stress**: one AWG device's pyroshock testing induced small central frequency shifts for all eight WDM channels under test.
- **Low-temperature behaviour**: one TFF device references presented IL degradation at low temperatures for specific channels. This degradation is temporary and expected to be due to epoxy adhesive stiffening.

- **Radiation effects:** TFF technologies exhibited progressive increase in IL for the outermost spectral WDM channels when radiation exceeded 500Gy. This effect was temporary and limited in magnitude, leaving the central frequencies unchanged.
- **Outgassing:** all three-device references contain materials with outgassing behaviour (primarily adhesives, polymer boots, and encapsulants).

These findings suggest that first and foremost, testing every unique device is crucial before use in space application, as device performance can deviate significantly from supplier specifications and keeping an open communication stream with suppliers is greatly advantageous when dealing with COTS devices. Lastly, the largest finding to address in future developments is the clarification of outgassing behaviour, as the devices were not built with space applications in mind and thus all contain materials known to have outgassing risks.

With respect to the specific technologies (TFF and AWG), TFF device references represented a good trade-off between cost and performance, proving to be simple, cost-effective, and sufficiently robust under the tested environmental conditions. However, it is better suited to systems with a limited number of WDM channels, as IL tends to increase significantly with channel count. On the other hand, AWG technology appears more complex and expensive, but highly robust to all tested environmental stresses. It is particularly suitable for applications requiring a high number of WDM channels (e.g., 64 or 128 channels).

5.1 Recommendations for future development

The ideal continuation of the ASTROMUX project's activities consists of evaluating the devices to achieve the next substantial step towards potential full space qualification, with the possibility of enabling demonstration within an actual mission context to reach the highest levels of technology maturity. Any follow-up activity requires more complete visibility of the device BoM and relevant sub-elements, to support material assessment, identify potential outgassing drivers, and define any additional verification activity needs. This requires direct supplier engagement and product data beyond what is typically available from commercial datasheets alone.

If the observed low temperature and radiation-related behaviours confirmed, specific mission-level requirements may be needed to ensure proper mitigation. Although temporary, these anomalies indicate that environmental conditions can modify the device behaviour. Since the in-orbit devices lifespan must be guaranteed up to 5 years for new CubeSat-like constellations and more for LEO and GEO constellations, further investigations may be needed to better characterise these aspects. The devices not only have to function, but they need to do so reliably enough that there is a high level of confidence that they will continue to function in space, despite being terrestrial by design.

In line with space product-assurance practices, further progression requires a structured approach combining additional evidence generation, supplier involvement, materials and process visibility, and mission-dependent acceptance criteria. There are two possible options for increasing the devices' readiness with respect to space application:

5.1.1 Approach 1: To use the devices “as-is”

The first approach is to use the devices “as-is” in their current configuration, capitalizing on the good performance demonstrated by the small sample evaluated during ASTROMUX: there were no failures or critical breakages; the deviations found were minimal. Future activities would focus on confirming the repeatability of these results on a large sample of devices, while clarifying remaining BoM-related uncertainties, outgassing behaviour (i.e. through a bakeout procedure), low-temperature sensitivity, and radiation effects. Once these aspects are better characterized, part of the residual risk could be managed through direct supplier involvement and low-impact product quality controls, such as tighter process control, cold acceptance testing, systematic verification of IL uniformity, and radiation-effect characterization on production runs. The remaining risk could be addressed at mission/user level through mitigation measures such as maintaining a minimum operating temperature, introducing radiation shielding, assigning more robust or less critical signals to the most radiation-sensitive channels, and applying stricter IL margins. This would be the most direct continuation of ASTROMUX, accepting current device limitations while using a delta-evaluation strategy to exploit existing results with more supplier involvement, extension or adjustment of testing where gaps remain, and limited additional (development) efforts.

5.1.2 Approach 2: Re-engineering the devices for space application

This second approach entails re-engineering the devices starting from a defined set of device performance requirements, which could also involve a change in the physical characteristics of the product and assembling them into a dedicated space-compliant version (assigning a new P/N). Although ASTROMUX findings can be leveraged to reduce some development efforts, this approach relies heavily on supplier involvement, product adaptations, repeated characterisation, and evaluation testing of the modified devices, this approach incurs significantly more time and development efforts. Furthermore, as in Approach 1, the lack of complete component clarity and discovered outgassing issues can still have major impacts depending on the extent of re-engineering. The main benefit of directly re-engineering the devices for greater space compliance is that any testing anomalies and uncertainties introduced by the initial outgassing analysis would be clarified and dealt with, and the products would be assured to be compliant with all space product assurance requirements. Furthermore, taking this approach would avoid the necessity of the user adapting mission requirements (i.e. to put constraints on the mission) based on the specific device behaviour found in testing, and establishes a robust baseline for eventually reaching commercially available space-grade devices.

6. CONCLUSIONS

The ASTROMUX project has generated a comprehensive experimental dataset on commercially available WDM MUX/DEMUX technologies, providing a solid basis for the characterisation of their optical performance and environmental robustness under a broad range of test conditions.

The results confirm that both TFF and AWG technologies exhibit a generally stable functional behaviour when exposed to thermal, mechanical and radiation-related stresses representative of potential space applications. This demonstrates a significant level of technological maturity at system-relevant level and supports the continued interest in these technologies as enabling elements for future high-throughput optical satellite communications. Nevertheless, this robustness should not be interpreted as a formal qualification or readiness status of the tested commercial devices. The obtained results are to be understood as a structured characterisation and evidence-generation activity that identify both strengths and remaining gaps to be addressed for any future space utilisation, and highlighted issues are not unexpected for commercial products originally designed for terrestrial applications.

Based on these findings, ASTROMUX also developed key considerations for future maturation beyond characterisation, towards eventual space qualification. Primarily, the results must be repeated on a larger sample of devices through a comprehensive evaluation campaign. Furthermore, additional tests and analyses should be conducted to address the technological gaps found, particularly with respect to outgassing risks.

Outgassing risks must be mitigated through supplier-supported list of materials clarification, material testing for outgassing, or re-design. Additionally, certain temperature-dependent behaviours in TFF devices suggest the use of devices in space applications is bound to mission constraints that must be set by the user, matching the device performance. To address these topics, two suggestion routes for future development were defined:

1. **Comprehensive evaluation of existing devices “as-is”**, requiring test sequences as done in ASTROMUX on a larger sample of devices, including a complete BoM analysis, more comprehensive outgassing assessment (i.e. with a bakeout procedure), and a detailed performance envelope definition.
2. **Re-engineering** with supplier participation to produce space-ready device variants, leveraging ASTROMUX results as a basis for data review determining the extent of device re-engineering. As opposed to defining the performance envelope when using the devices “as-is”, performance requirements are set a priori, and devices are modified to meet them. Once devices are re-engineered, they must undergo a similar comprehensive evaluation to be used in space applications.

Overall, ASTROMUX results demonstrate that commercial WDM MUX/DEMUX technologies are promising enablers for high-throughput space optical links and outline the development steps required for a reliable use of advanced optical multiplexing technologies in future space systems. In this perspective, the results of ASTROMUX represent a key enabling step towards the controlled and reliable use of advanced optical multiplexing technologies in future space systems.

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