

Assessment of reliability in Gallium Arsenide modulators and their realization in SatCom systems

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ABSTRACT

We present the reliability assessment of gallium arsenide (GaAs) optical modulators for space-based optical communication systems. Building on previously reported results, the GaAs modulator technology has demonstrated successful in-orbit operation within a low Earth orbit (LEO) constellation, providing established flight heritage. This paper presents reliability test results supporting continued progress towards qualification for LEO and future geostationary Earth orbit (GEO) applications.

We have achieved broadband data transmission rates from 10 to 220 GBaud, a 3 dB electro-optic bandwidth of 70 GHz, a half-wave voltage (V_π) of 3 V, optical insertion loss (IL) of 5 dB and a static extinction ratio (ER) of 30 dB. These results demonstrate that commercially manufactured GaAs modulators can deliver the performance, reliability and cost advantages required for next-generation space optical communication systems.

Reliability testing has included 2000 hour thermal endurance, temperature cycling between -40°C and 85°C , 100 krad total ionising dose (TID) exposure, proton irradiation to 10^{12} protons/cm², and mechanical shock and vibration using industry-standard MIL and ESCC-derived test methods. Electro-optic characterisation performed throughout the test campaign demonstrated stable device performance.

Keywords: GaAs modulators, electro-optic modulation, space optical communications, inter-satellite links, space qualification, radiation effects, environmental testing, device reliability

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1. INTRODUCTION

The widespread adoption of optical inter-satellite links has created a demand for transmitters and receivers that combine high data rates with the reliability required for long-life satellite communication systems. The ESA *Aidan Next* programme is supporting the development of low-cost gallium arsenide (GaAs) photonic technologies by leveraging commercially established terrestrial manufacturing processes while exploiting the inherent radiation tolerance of GaAs for space applications.¹

Additionally, an impetus towards ever higher data-rates has shifted the emphasis toward coherent optical modulation schemes based on extended phase-shift keying (PSK), especially QPSK and QAM. The basic ‘engine’ of the latter is the ‘IQ’ electro-optic modulator comprising two parallel ‘child’ Mach-Zehnder modulators with onboard optical split from a single input, and recombination to a single output fibre. The same IQ modulator is also useful for single sideband (SSB) modulation.

The Mach-Zehnder Interferometer (MZI) configuration is ubiquitous in such devices due to its high speed, low chirp and well-defined linearity. Its periodic, raised-cosine Light/Voltage characteristic is ideally suited for digital modulation, providing not only a pair of adjacent saturating High and Low amplitude levels but also a repeating set of High levels which alternate in optical phase. This phase-reversal property is the basis of the PSK encoding.

Applications for space have much in common with the military and avionic applications which drove much of the early development of the gallium arsenide (GaAs) electro-optic modulator which is the subject of this paper. GaAs component technology in general has proven credentials of environmental and thermal stability, radiation

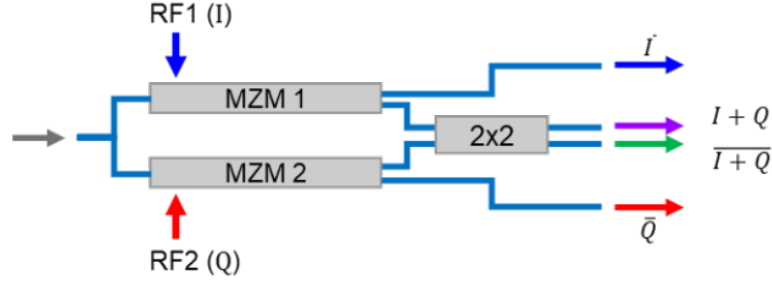


Figure 1. Schematic 'IQ' modulator.

hardness, ruggedness, power-handling and longevity.² Gallium arsenide (GaAs) has long been the material of choice for mm-wave electronic devices and integrated circuits. It has many desirable properties for RF devices which must survive and operate in harsh environments:

- Semi-insulating (SI) GaAs substrates are low-cost and have high-resistivity so can provide low-loss coplanar transmission-lines.
- The electron mobility is high - six times higher than in silicon and almost 60% higher than InP. This enables low optical loss and high RF bandwidth in opto-electronic and electronic devices.
- The bandgap is comparatively large at 1.424 eV (higher still for any AlGaAs layers incorporated). This contributes to the environmental stability and radiation hardness.³
- The related ternary $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is closely lattice-matched to GaAs throughout the range of aluminum-fraction x (the band-gap rises and refractive-index falls with increasing x) conferring considerable freedom in designing AlGaAs/GaAs heterostructures.

To exploit these advantages, well qualified foundry processes have been developed over many decades for the fabrication of GaAs discretes and monolithic microwave integrated circuits (MMICs). Thus, one further considerable benefit of GaAs for space applications is that it is already formally qualified to an appropriate standard for aerospace systems.

2. GAAS ELECTRO-OPTIC MODULATORS

$\text{Al}_x\text{Ga}_{1-x}\text{As}$ has similar properties to GaAs up to $x \approx 0.4$ where the fundamental energy gap becomes indirect; higher aluminum fractions than this are rarely used. In addition to the basic properties listed above, the AlGaAs material system has optical properties which enable it to be used for electro-optic modulators:

- As a non-elemental III-V compound, the crystal is non-centrosymmetric. This provides a linear electro-optic effect, which is a small change in refractive-index in response to an applied electric field.
- For wavelengths longer than the band-edge (> 900 nm) the intrinsic (undoped) absorption is very low meaning that low-loss optical waveguides can be made.
- The optical refractive-index is high (≈ 3.4) and is similar to the equivalent microwave parameter (≈ 3.6). This means that velocity-matched travelling wave configurations can be engineered.

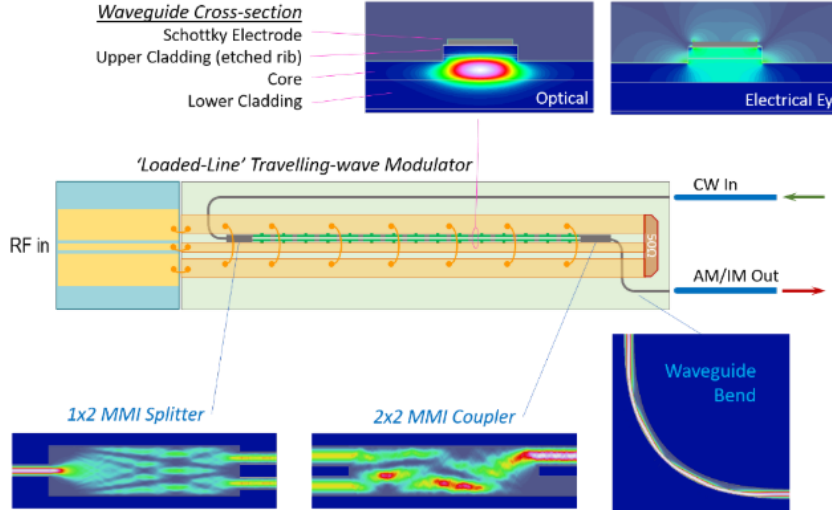


Figure 2. Schematic of a GaAs folded 'MZ' modulator.

2.1 Optical Folding and Splitting

A fundamental facility of the GaAs optical waveguides is the relative ease with which tight, low-loss bends can be realized.⁴ This is partly a consequence of the GaAs foundry dry-etching process which is able to yield very smooth and vertical, deep-etched waveguide walls with high conformity to the CAD dimensions. This enables 90° and 180° bends to be realized with very low loss penalty; thus the optical path can be folded so that optical and RF interfaces are segregated to opposite ends of the modulator chip (Figure 2). This means that the RF input path can be made short, straight and direct for best high frequency performance.

Optical split and recombine functions are implemented using Multimode Interference (MMI) structures⁴ (see Figure 2). These are somewhat sensitive to wavelength but can be acceptable in terms of loss over a 60 nm range extended C band (1520 nm – 1580 nm). Their major sensitivity is to the width of the MMI section, which determines the intermodal beat-lengths. This is also a beneficiary of the high-precision foundry process. Neither bends nor MMI structures have much sensitivity to temperature or other environments.

Both bends and MMIs use a deep-etched waveguide (etched fully through the GaAs core layer) while other regions of the Photonic Integrated Circuit (PIC) are required to use the shallower-etched waveguide. Transition tapers connecting the two types are low-loss.⁴

Figure 3 illustrates the 'IQ' implementation used for the environmental analysis of this paper.

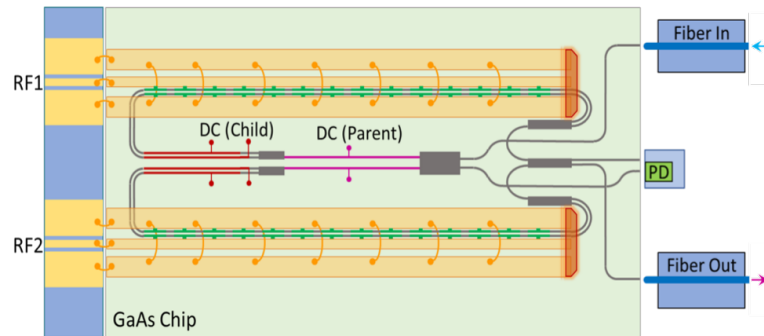


Figure 3. Schematic of a GaAs folded 'IQ' modulator.

2.2 RF Properties

Bandwidths have been measured up to 70 GHz for GaAs 'MZ' modulators, see Figure 4. The subject of this paper addresses packaged IQ modulators of a design which have measured 3 dB bandwidths around 40 GHz, extending to typically -4.5 dB at 50 GHz. We have previously reported on well balanced I and Q channels in the GaAs 'IQ' optical modulator.^{1,4}

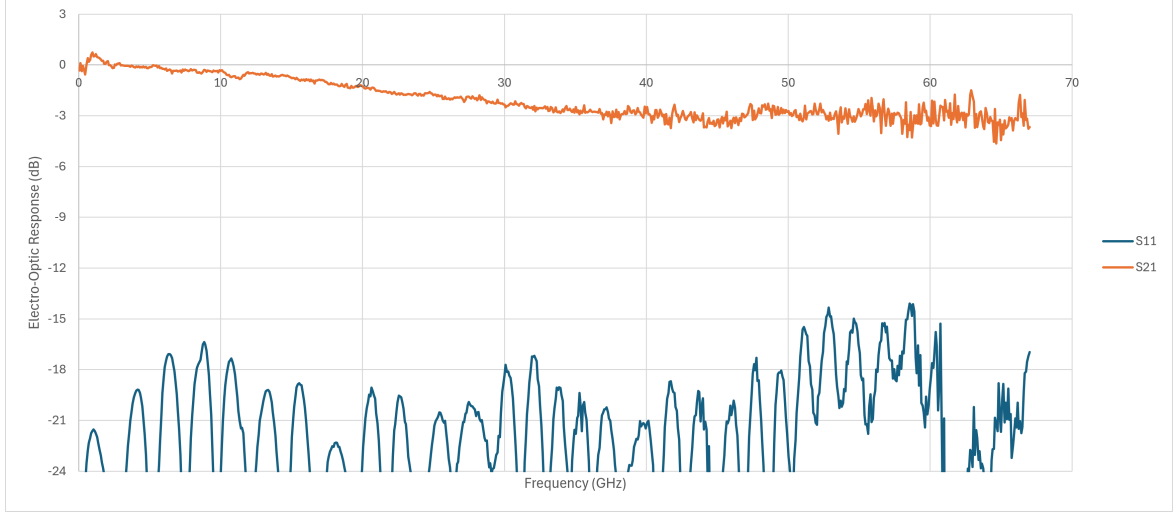


Figure 4. Measured Electro-Optic response (S_{11} and S_{21}) of a GaAs 'MZ' optical modulator achieving a 3-dB bandwidth approaching 70 GHz.

3. RELIABILITY QUALIFICATION AND RESULTS

3.1 Qualification Methodology

The qualification programme was developed to assess the reliability of commercially manufactured gallium arsenide (GaAs) optical modulators for space optical communication applications. The programme was designed to demonstrate that the devices can withstand the thermal, radiation and mechanical environments encountered during launch and operation while maintaining their electro-optic performance.

The qualification methodology was based on established practices, with environmental tests selected to represent the principal stresses experienced throughout the mission lifecycle. Test conditions and acceptance criteria were developed with reference to MIL⁵ and ESCC⁶ standards, providing a structured framework for evaluating device robustness under representative operational conditions. The qualification campaign comprised thermal endurance, temperature cycling, total ionising dose (TID) radiation, proton irradiation, vibration and mechanical shock testing.

Electro-optic characterisation was integrated throughout the qualification programme to assess the effect of environmental exposure on device performance. Measurements of key parameters were performed before and after each environmental test. These are explained in more detail in section 3.2. The measurements provided a direct assessment of the ability of the devices to retain their operating characteristics following environmental stress. The following sections describe each qualification test and the corresponding experimental results.

Devices spanning a wide range of insertion losses and extinction ratios were deliberately selected for qualification to capture the expected variation associated with the manufacturing and assembly processes.

3.2 Electro-optic Characterisation

Electro-optic characterisation was performed to establish the baseline performance of the GaAs optical modulators prior to environmental qualification and to provide a reference for comparison following completion of the qualification programme.

DC Loss-Voltage (LV) measurements were performed to characterise the static optical performance of the devices, including optical insertion loss, extinction ratio and DC V_π . DC measurements were performed using a polariser attached to the device output. The insertion loss presented includes connector losses, but removes the loss associated with the polariser. RF characterisation was performed using S-parameter measurements to determine the high-frequency response of the modulators and extract the 3 dB electro-optic bandwidth.

These measurements were repeated following environmental qualification testing to assess any changes in device performance resulting from thermal, radiation and mechanical stresses.

3.3 Thermal Endurance Testing

A thermal life test was performed to assess the long-term stability of the GaAs optical modulators under elevated temperature exposure. The test was designed to evaluate potential degradation mechanisms associated with prolonged thermal exposure and to provide confidence in device reliability for extended-duration space communication missions.

Devices were subjected to thermal exposure at 85 °C for a total duration of 2000 hours. Electro-optic characterisation was performed prior to the start of the test, at intermediate intervals, and following completion of the test campaign. Thermal exposure was continuous, with an exception during intermediate measurements when devices were reduced to room temperature. Monitoring at intermediate stages enabled the identification of any gradual changes in device performance that may not have been apparent from only pre- and post-test measurements.

Table 1. Electro-optic performance of GaAs optical modulator device 1 before, during and after thermal endurance testing.

Time elapsed (hours)	Insertion Loss (dB)	Extinction Ratio (dB)	V_π (V)	3 dB BW - I Channel (GHz)	3 dB BW - Q Channel (GHz)
0	6.17	34.4	9.79	36.2	32.3
456	6.43	32.8	9.52	39.0	31.3
864	6.61	37.7	9.48	35.8	32.4
1700	6.25	31.5	9.47	37.4	30.2
2340	6.25	31.5	9.47	41.4	32.4

Table 2. Electro-optic performance of GaAs optical modulator device 2 before, during and after thermal endurance testing.

Time elapsed (hours)	Insertion Loss (dB)	Extinction Ratio (dB)	V_π (V)	3 dB BW - I Channel (GHz)	3 dB BW - Q Channel (GHz)
0	7.71	17.2	10.01	38.7	34.1
456	7.58	19.7	9.95	45.4	38.2
864	7.13	20.6	9.97	41.6	34.5
1700	6.87	21.3	9.99	42.1	32.4
2340	6.74	21.8	9.95	41.1	34.3

The devices demonstrated stable electro-optic performance throughout the 2000-hour thermal endurance test at 85 °C. No degradation in extinction ratio or V_π was observed. One device exhibited a reduction in insertion loss during the test; although the origin of this change has not been established, the change represents an improvement in optical performance and does not indicate degradation of the device. Overall, the results demonstrate that the devices maintained their electro-optic performance during prolonged exposure to elevated temperature.

Table 3. Electro-optic performance of GaAs optical modulator device 3 before, during and after thermal endurance testing.

Time elapsed (hours)	Insertion Loss (dB)	Extinction Ratio (dB)	V_{π} (V)	3 dB BW - I Channel (GHz)	3 dB BW - Q Channel (GHz)
0	5.26	23.8	9.57	38.7	34.1
456	5.26	24.8	9.70	35.6	32.0
864	5.17	27.3	9.72	39.0	30.8
1700	5.05	27.2	9.74	36.1	32.4
2340	5.11	29.6	9.70	34.1	30.1

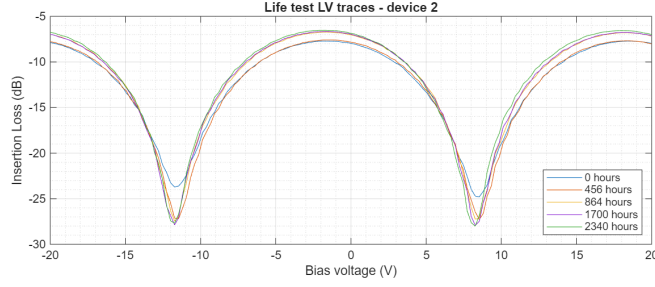


Figure 5. LV traces measured for device 2 included in the thermal endurance test.

3.4 Thermal Cycle Testing

Thermal cycling was performed to assess the robustness of the GaAs optical modulators when subjected to repeated temperature extremes representative of the thermal stresses experienced during spacecraft operation. The test was intended to evaluate potential degradation mechanisms associated with repeated thermal expansion and contraction of the device package, optical interfaces and internal structures.

Devices were subjected to 50 thermal cycles between -40°C and 85°C . DC electrical measurements were performed at both temperature extremes during each cycle to monitor any changes in device behaviour throughout the test sequence. These measurements were used to identify trends or potential degradation during thermal stressing; the devices were not required to meet their full electro-optic performance specifications while operating at the temperature extremes. No bake-out was performed prior to testing.

Table 4. Electro-optic performance of two GaAs optical modulators before and after thermal cycle testing.

Device	IL before (dB)	IL after (dB)	V_{π} before (V)	V_{π} after (V)	ER before (dB)	ER after (dB)
1	4.24	4.87	8.66	8.48	32.1	31.8
2	6.41	6.65	9.55	9.50	33.1	32.9

3.5 Mechanical Qualification

Our GaAs optical modulators were submitted to mechanical testing to evaluate the robustness of the devices under mechanical stress representative of a launch environment. The modulators were subjected to sine and random vibration and mechanical shock. External visual inspection was performed before and after test. In all cases, two modulators were used.

3.5.1 Sine Vibration

Sine vibration testing was performed to assess the mechanical robustness of the packaged GaAs optical modulators under vibration levels representative of the launch environment. The test was conducted in accordance with the

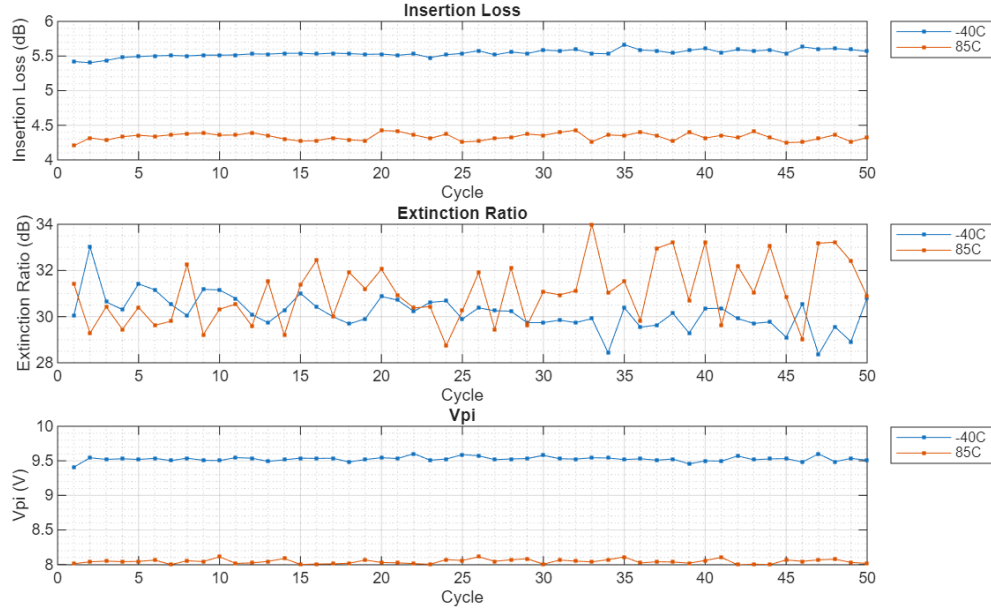


Figure 6. The progression of insertion loss, extinction ratio and V_{π} for device 1 through 50 temperature cycles.

customer-specified vibration profile, with a single upward frequency sweep from 30 to 200 Hz. A vibration level of 30 g was applied from 30–100 Hz, reducing to 15 g from 100–200 Hz, with a sweep rate of 1 octave/min.

Following completion of the vibration test, the devices were inspected for evidence of mechanical damage and subsequently subjected to electro-optic characterisation. The post-test measurements were compared with the pre-test results to assess any changes in optical and electrical performance resulting from the applied vibration environment.

No mechanical damage or degradation in electro-optic performance was observed.

Table 5. Electro-optic performance of two GaAs optical modulators before and after sine vibration testing.

Device	IL before (dB)	IL after (dB)	V_{π} before (V)	V_{π} after (V)	ER before (dB)	ER after (dB)
1	7.83	8.09	7.863	7.886	20.76	28.55
2	4.79	5.26	7.886	7.723	24.41	26.54

Comparison of the electro-optic performance before and after sine vibration exposure showed no significant change in insertion loss, extinction ratio or V_{π} . No evidence of mechanical damage was observed in external visual inspection following the test. The measured results demonstrate that the packaged GaAs modulators retained their electro-optic performance following exposure to the specified sine vibration environment.

3.5.2 Random Vibration

Random vibration testing was performed to assess the mechanical robustness of the packaged GaAs optical modulators under launch-induced vibration. Two devices were subjected to random vibration testing using different test conditions. The test conditions are summarised in Table 6.

Device 1 was subjected to a single-axis test in the Z direction, with a total vibration level of 19.7 g_{RMS} over a 20 s duration. Device 2 was subjected to a more demanding multi-axis profile, comprising 33.8 g_{RMS} in the X and Y axes for 5 min per axis and 70 g_{RMS} in the Z axis for 5 min. The applied profiles covered the frequency range from 20 to 2000 Hz, with the specified acceleration spectral density and frequency slopes as detailed in Table 6.

Following random vibration exposure, the devices were inspected for evidence of mechanical damage and electro-optically characterised. Insertion loss, extinction ratio and V_π were measured before and after testing to assess any change in device performance resulting from the applied vibration environment.

The results for both devices are presented in Table 7. No significant degradation in the measured electro-optic parameters was observed following random vibration exposure. In particular, Device 2 retained its electro-optic performance following the higher-level, multi-axis vibration profile, providing additional evidence of the mechanical robustness of the packaged modulator.

Table 6. Test conditions for random vibration testing on two GaAs optical modulators.

Device	Axis	Frequency	PSD level	Total	Duration
1	Z	20-80-800-2000 Hz	0.28 g^2/Hz	19.7 g_{RMS}	20 s
2	X, Y	20-100-800-2000 Hz	0.78 g^2/Hz	33.8 g_{RMS}	5 min/axis
2	Z	20-80-800-2000 Hz	3.54 g^2/Hz	70 g_{RMS}	5 min

Table 7. Electro-optic performance of two GaAs optical modulators before and after random vibration testing.

Device	IL before (dB)	IL after (dB)	V_π before (V)	V_π after (V)	ER before (dB)	ER after (dB)
1	8.09	8.72	7.886	8.003	28.55	27.55
2	5.26	4.78	7.723	7.816	26.54	26.52

No significant degradation in insertion loss, extinction ratio or V_π was observed following random vibration testing. Both devices retained their electro-optic performance following exposure to their respective vibration profiles. In particular, device 2 demonstrated stable performance following the more demanding multi-axis vibration exposure, providing additional evidence of the mechanical robustness of the packaged modulator.

3.5.3 Shock

Shock testing was conducted to verify the mechanical robustness of the device against transient high-frequency shock environments representative of launch vehicle and spacecraft separation events. The specified shock spectrum comprised a peak acceleration of 30 g at 100 Hz, increasing to 200 g at 500 Hz and 1000 g from 3000 Hz to 10,000 Hz. A quality factor of 10 was applied, with three shocks performed in the Z-axis.

Table 8. Electro-optic performance of two GaAs optical modulators before and after shock testing.

Device	IL before (dB)	IL after (dB)	V_π before (V)	V_π after (V)	ER before (dB)	ER after (dB)
1	7.83	7.97	7.863	7.956	20.76	26.61
2	5.42	4.79	7.653	7.886	28.18	24.41

The modulators showed no significant change in insertion loss, extinction ratio or V_π following shock testing. Device 2 loss improves after shock. This may be considered an artefact of measurement uncertainty. No mechanical damage was identified during post-test visual inspection. The results demonstrate that the packaged GaAs modulators can withstand the specified shock environment without significant degradation.

3.6 Radiation Testing

3.6.1 Total Ionising Dose

Total ionising dose (TID) testing was performed using gamma irradiation to assess the radiation tolerance of the GaAs optical modulators under cumulative ionising radiation exposure. The devices were exposed at a dose

rate of 3.6 krad/h. Electro-optic characterisation was performed prior to irradiation, followed by intermediate measurements at accumulated doses of 20 krad and 100 krad. Following completion of the irradiation, the devices were subjected to room-temperature annealing and subsequently re-characterised to assess any recovery or further changes in performance following removal from the radiation environment. The results are presented in Table 9.

Table 9. Electro-optic performance of one GaAs optical modulator before, during and after TID (gamma) testing.

	Pre radiation	20 krad	100 krad	Post annealing
IL (dB)	10.48	13.74	11.70	8.90
ER (dB)	21.05	21.19	25.70	22.66
V_π (V)	10.82	9.23	9.31	10.40

The electro-optic performance remained stable throughout the gamma irradiation test, with no significant degradation in insertion loss, extinction ratio or V_π observed up to the maximum accumulated dose of 100 krad. The measurements taken at 20 krad and 100 krad showed no significant adverse trend with increasing dose. Following room-temperature annealing, the measured parameters remained consistent with the pre-irradiation performance, indicating no significant persistent degradation resulting from the applied TID exposure.

3.6.2 Displacement Damage

High-energy proton irradiation was used to assess displacement damage associated with energetic particle exposure in the space radiation environment, with the GaAs optical modulators exposed to 60 MeV protons at progressively increasing fluence levels up to 10^{12} protons/cm².

Electro-optic characterisation was performed prior to irradiation to establish the baseline device performance, followed by measurements at accumulated fluences of 10^{10} , 10^{11} and 10^{12} protons/cm². This enabled changes in device performance to be monitored progressively with accumulated radiation exposure.

Table 10. Electro-optic performance of the first GaAs optical modulator before and during proton irradiation at dosage of 10^{10} , 10^{11} and 10^{12} protons/cm².

Device 1	Pre radiation	10^{10} p/cm ²	10^{11} p/cm ²	10^{12} p/cm ²
IL (dB)	10.18	9.34	9.48	10.09
ER (dB)	25.74	22.42	27.07	22.31
V_π (V)	10.57	10.57	10.40	9.57

Table 11. Electro-optic performance of the second GaAs optical modulator before and during proton irradiation at dosage of 10^{10} , 10^{11} and 10^{12} protons/cm².

Device 2	Pre radiation	10^{10} p/cm ²	10^{11} p/cm ²	10^{12} p/cm ²
IL (dB)	8.90	8.83	7.91	8.76
ER (dB)	18.99	18.07	16.94	22.26
V_π (V)	10.24	9.40	8.89	8.89

No significant change in insertion loss, extinction ratio or V_π was observed for either device with increasing proton fluence. The IL of device 2 briefly improves at 10^{11} p/cm² and returns to original performance at 10^{12} p/cm², so this may be judged as an artefact of measurement uncertainty due to the lack of clear relationship between radiation dose and IL. This otherwise indicates good tolerance to displacement damage under the tested conditions.

4. CONCLUSIONS

The qualification results demonstrate robustness across the environmental stresses considered in this qualification programme. Thermal endurance, thermal cycling, radiation and mechanical testing were completed without significant degradation of the measured electro-optic parameters. This shows that device performance was maintained under the tested conditions.

The 2000-hour thermal life test at 85°C provides evidence of stability under prolonged elevated-temperature, while the 50-cycle temperature test demonstrates robustness to repeated thermal cycles between –40°C and 85°C. The mechanical tests similarly showed that the packaged devices maintained their electro-optic performance following sine vibration, random vibration and shock exposure. The results from the multi-axis random vibration test, in particular, demonstrate retention of performance following exposure to a more demanding vibration environment than the single-axis test applied to the other device.

The radiation test results demonstrate the robustness of the GaAs modulator technology to both total ionising dose and displacement damage. No significant degradation was observed following gamma irradiation to 100 krad following room temperature annealing. Similarly, proton irradiation to a fluence of 10^{12} protons/cm² produced no degradation in the measured parameters. Together, these results provide confidence in the ability of the devices to maintain their functional performance under the combined radiation environments expected during extended space operation.

An important aspect of the qualification programme is that device performance was assessed directly through electro-optic measurements rather than relying solely on post-test visual or electrical inspection. Monitoring during thermal and radiation tests also provided evidence of performance stability throughout the applied exposure, while the pre- and post-test characterisation enabled permanent changes to be distinguished from reversible environmental effects and measurement artefacts. This provides a direct link between environmental robustness and the performance required for high-speed optical communication.

The results support the use of GaAs optical modulators in future LEO optical communication systems and provide the basis for ongoing work on qualification for GEO applications. The use of established terrestrial manufacturing and assembly processes, combined with the demonstrated environmental robustness, offers the potential for scalable production of high-performance modulators while retaining the reliability required for space deployment.

ACKNOWLEDGMENTS

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REFERENCES

- [1] Walker, R. G., Cameron, N., Zhou, Y., and Clements, S., “Electro-optic modulators for space using gallium arsenide,” in [*International Conference on Space Optics — ICSO 2016*], *Proceedings of SPIE* **10562**, 105621A, SPIE (2016).
- [2] Baca, A. G. and Ashby, C. I. H., [*Fabrication of GaAs Devices*], The Institution of Electrical Engineers, London, United Kingdom (2005).
- [3] Claeys, C. and Simoen, E., [*Radiation Effects in Advanced Semiconductor Materials and Devices*], Springer-Verlag, Berlin, Heidelberg, New York (2002).
- [4] Walker, R. G., Cameron, N. I., Zhou, Y., and Clements, S. J., “Optimized gallium arsenide modulators for advanced modulation formats,” *IEEE Journal of Selected Topics in Quantum Electronics* **19**(6), 138–149 (2013).
- [5] U.S. Department of Defense, “MIL-STD-883: Test Method Standard, Microcircuits,” military standard, U.S. Department of Defense (2004).
- [6] European Space Agency, “ESCC 23202: Validation and Lot Acceptance Testing Guidelines for Laser Diodes,” escs specification, European Space Agency (2018).