Reliability of Optical Fiber Modulators for Space Flight Environments

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Abstract:

Optical fiber modulators are of great interest to space flight projects for communications and LIDAR applications. Due to the harsh environments and long duration for most missions, space flight applications have a unique set of demands for photonics parts. This study focuses on the reliability of commercially available optical fiber modulators for space flight environments. General failures modes covered by the Telecordia standards are discussed as well as mitigation techniques for ground based systems. The failure modes that are beyond the mitigation of the Telecordia standards are included as well along with long term reliability and space flight environmental considerations towards the eventual implementation of these devices in space flight instrumentation.

A survey of commercial devices was conducted and a single device was chosen based on the failure mode investigation and taking into account the general requirements of typical space flight components. The details for testing such a device for space flight are included here. Also included are innovative testing methods for making long term reliability assessments for these devices.

1. Introduction

The use of fiber optic networks in communications has exploded since the discovery of its practicality. Glass fiber cables are lightweight, and even durable when used with the correct coating and protection. They are also very high speed because the signal literally travels at the speed of light. Electrical signals also travel close to the speed of light, but an electrical signal loses its strength over a long distance, and it also radiates microwaves at high frequencies. Glass fibers, however, do not lose as much signal strength, and they are electromagnetically insensitive, radiating no EM energy whatsoever. NASA has recently become interested in using high speed digital communication components for on board fiber optic systems. In the past, the use of multimode fiber optic networks was abundant in space-flight missions, but a newer, faster method of data transfer has since been discovered. The use of singlemode fiber, which has been incorporated into the systems of many telecommunications companies, combined with the use of Lithium Niobate ($LiNbO_3$) optical modulators, brings about the capability to transfer data at a rate beyond 10 Gb/s. This extremely rapid data rate makes these systems extremely attractive to the design requirements of space flight applications.

Modulators modify light signals such that they can be used to send data along optical transmission lines. The optical signal is actually modulated by an electrical signal through the use of the $LiNbO_3$ crystal. The crystal's indices of refraction depend proportionally on the strength of the electrical field being passed across the crystal. Thus, the extent to which the crystal modulates the phase of the light depends on the electrical signal. Basically, this means that any electrical signal, for any application, can be transformed into an optical signal simply by running the signal across the $LiNbO_3$ crystal. Even though, the electrical field does modulate the phase of the light propagating through the crystal, a process is necessary to provide intensity based modulation from the phase based modulation. To do this, the light signal is separated into two waveguides inside the crystal. After modulation, whether conducted on one waveguide or both the end result by joining them at the output is an intensity based modulation due to the interference of the two paths of light. The optimum situation would suggest that no optical power be present for a digital "0," and that the maximum optical power be present for a digital "1." This would require either complete constructive interference, or complete destructive interference. Ideally, constructive interference occurs when the light is modulated by p radians and destructive interference occurs when the light is not modulated at all. Therefore, it is desirable to put the crystal in a state that modulates the phase so that a "1" would require $V_{p + p/2}$ and a "0" would require $V_{p - p/2}$ (directly in between the two extremes). This state is called quadrature, sometimes called V_p and it results in the best extinction ratio because complete negative voltage causes destructive interference and complete positive voltage causes constructive interference.

There are three different types of commercially available $LiNbO_3$ modulators. The differences depend on the orientation (or cut) of the crystal, and the method of waveguide fabrication. The crystals themselves are available in wafers of X-cut, Z-cut, and Y-cut orientations, with the axis of the cut being perpendicular to substrate surface. Z-cut modulators typically use titanium ions for waveguide fabrication, while X-cut modulators can use either titanium ions or hydrogen ions (protons). The Y-cut orientation does not yield high enough electro-optic coefficients for an effectively functioning modulator. Modulators that are X-cut proton waveguides typically do not require much (if any) DC bias voltage to achieve quadrature.

Though the effectiveness of these devices is extremely high for commercial applications, space flight environmental specifications are unique. Launch conditions determine the vibration survival specification and the orbits determine what the thermal cycling parameters will be. The missions are of long duration where hardware repairs are unlikely. Therefore, the parts that comprise a space flight system must be well understood for reliability concerns.

2. Background

The reliability of modulators has been investigated for space flight missions. The goal of this work was to provide innovative and effective methods of testing modulators for feasibility and reliability such that they may be incorporated into space flight systems. In the first section of this report a basic survey of available literature was conducted and summarized in the form of a discussion of failure modes and reliability testing conducted in the past. A comparison is made between some of the requirements of space flight and industry. It is important to fully understand what has been considered acceptable in the past in industry as well as in space flight such that new procedures could be developed through the investigation of what information these traditional tests provide. After the failures modes and traditional testing schedules were examined, the tests that seemed to be the most significant for exposing failure modes were identified.

For purposes of this paper and further discussion the following terminology must be defined:

V_p RF or V_{RF} ; RF signal voltage, The amount voltage from an alternating current of an input analog data stream (RF) that causes the $LiNbO_3$ crystal to modulate the phase of the light by p radians.

V_p DC or V_p : DC bias voltage, the voltage applied to the $LiNbO_3$ modulator from a direct current source that causes the $LiNbO_3$ crystal to modulate the phase of the light by p radians.

Quadrature: The status of the crystal when a DC voltage is applied that causes the crystal to modulate the phase of the light by radians.

Optical Power: Radiant power that is in the form of optical waves, i.e., electromagnetic waves that have a wavelength in the optical spectrum portion of the electromagnetic frequency spectrum.

Thermal Optical Environment: Temperature under which the component can function properly.

Wavelength: the distance between points of corresponding phase of two consecutive crests.

Speed: Speed at which the modulator processes data, measured in Gb/sec.

S_{11}: Voltage Standing Wave Ratio (VSWR), the ratio of electrical power incident to electrical power reflected from the modulator electrodes. This is frequency dependent.

S_{21}: Frequency response of modulator as signal is applied to electrodes.

IL (Insertion Loss): The power loss that results from the insertion of a device such as a connector or coupler into a fiber optic system.

R_e (Extinction Ratio): The ratio of the average received optical energy of a logic “1” pulse to the average received optical energy of a logic “0” pulse.

Return Loss: The optical power that is reflected back toward the source by another component in fiber optic system or an imperfection (break, splice, etc.) in the system.

3. Investigation of Failure Modes:

Based on a thorough literature search, a listing of potential failure modes has been identified. In Table 1 the failure modes for optical modulators are presented in a summary along with the testing necessary that will bring out the failure mode in these devices. A discussion of each failure mode is presented below. It is important to notice that the majority of these documented failure modes can be induced through thermal testing.

Table 1 – Identified Failure Modes

Failure Mode	Corresponding Test
DC Drift	Raised Thermal Operating Temperature
Fiber Buckling (break)	Thermal cycling, Vibration Testing
Hydrogen Diffusion (APE modulators)	Raised Thermal Operating Temperature
Material Expansion (OTE) Mismatching	Thermal cycling
Degradation of Coupling Material	Increased Optical Power

3.1 DC Bias Drift

In order to attain the highest possible extinction ratio, the substrate must be at quadrature. This means that complete destructive interference will result in a logic "0" and complete constructive interference will result in a logic "1." To get the substrate to "quadrature," a bias voltage field must be applied to it. This optimum voltage, known as V_π DC, often drifts back and forth over a period of time. This causes problems because it diminishes the extinction ratio (the difference between a logic "1" and a logic "0"). If the extinction ratio diminishes, the optical receiver cannot differentiate as well between "on" and "off" and the bit error rate increases. Studies have shown that V_π DC drifts as a result of age and is accelerated by heightened temperatures [6]. Studies have also shown that a higher V_pDC results in a higher rate of change of V_pDC [8]. Conversely, a lower V_pDC results in a lower rate of change, making it more desirable to have a modulator whose V_pDC is near zero. Not only does it require less power, but it also will dampen the effect of the V_pDC drift. It is also desirable to have a near-zero V_p because a large drift may require more voltage than the available voltage from a given power source. For the purpose of a space flight application, near-zero voltage operation is extremely desirable because only a finite amount of power can be used. This power budget tends to be quite small, so too much bias voltage can easily exceed it.

3.2 Material Expansion (OTE) Mismatch

OTE mismatching results when the packaging materials do not similarly react to temperature changes. This failure mode can be encountered when a thermal cycling test is performed. The end result is often a break in the hermetic seal or a crack in the epoxy. These problems are encountered because the changing temperature causes the materials to expand and contract at high rates. This failure mode can be avoided by using high quality approved epoxy and seals.

3.3 Fiber Breakage

Fiber breakage generally occurs when the mechanical integrity of the modulator as a whole is compromised. This failure mode is often encountered while performing fiber pull, vibration, and drop shock testing. The fiber does not need to completely break to cause failure. Small cracks on the surface or throughout the fiber can cause enough signal degradation to produce a continuity problem.

3.4 Hydrogen Diffusion

Hydrogen diffusion is a failure mode that is only encountered when using modulators with annealed proton-exchanged (APE) waveguides. At temperatures above 95° C, the hydrogen ions (or protons) in the waveguide react with the Lithium ions in the substrate, altering its indices of refraction. This alteration of the indices of refraction causes distortion of the light signal. This failure mode is not of the catastrophic type and is more of a slow degradation that may be simulated through accelerated aging. Even at a temperature of 125° C, the modulator can perform sufficiently for up to 13 years.

3.5 Degradation of Coupling Materials

Degradation of Coupling Material is the result of an application of high optical input. The increased power causes a chemical change in the coupling material and thus changes its optical properties. This occurs at the entrance to the crystal (from fiber to waveguide) and at the exit of the crystal (from waveguide to fiber). The transparency of the coupling material is compromised. This opacity does not allow enough of the optical signal to the crystal. In Figure 1 an example of this failure mode is shown. This failure occurred at NASA Goddard Space Flight Center when the device was used in a Q-switched fiber laser. The coupling material was exposed to approximately 200mj/cm^2 from the result of Q-switching a laser coupled to the device.

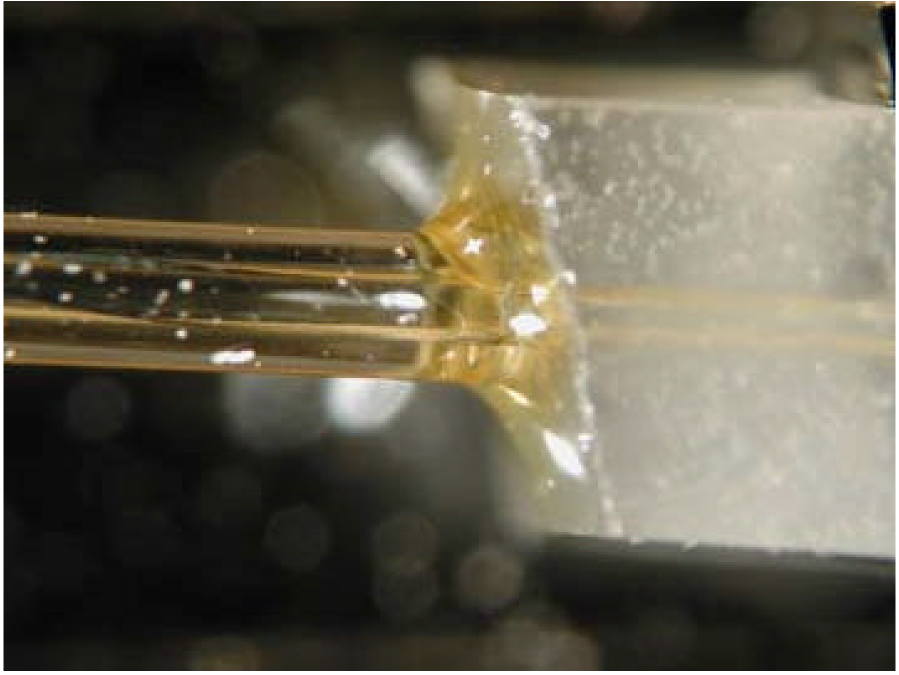
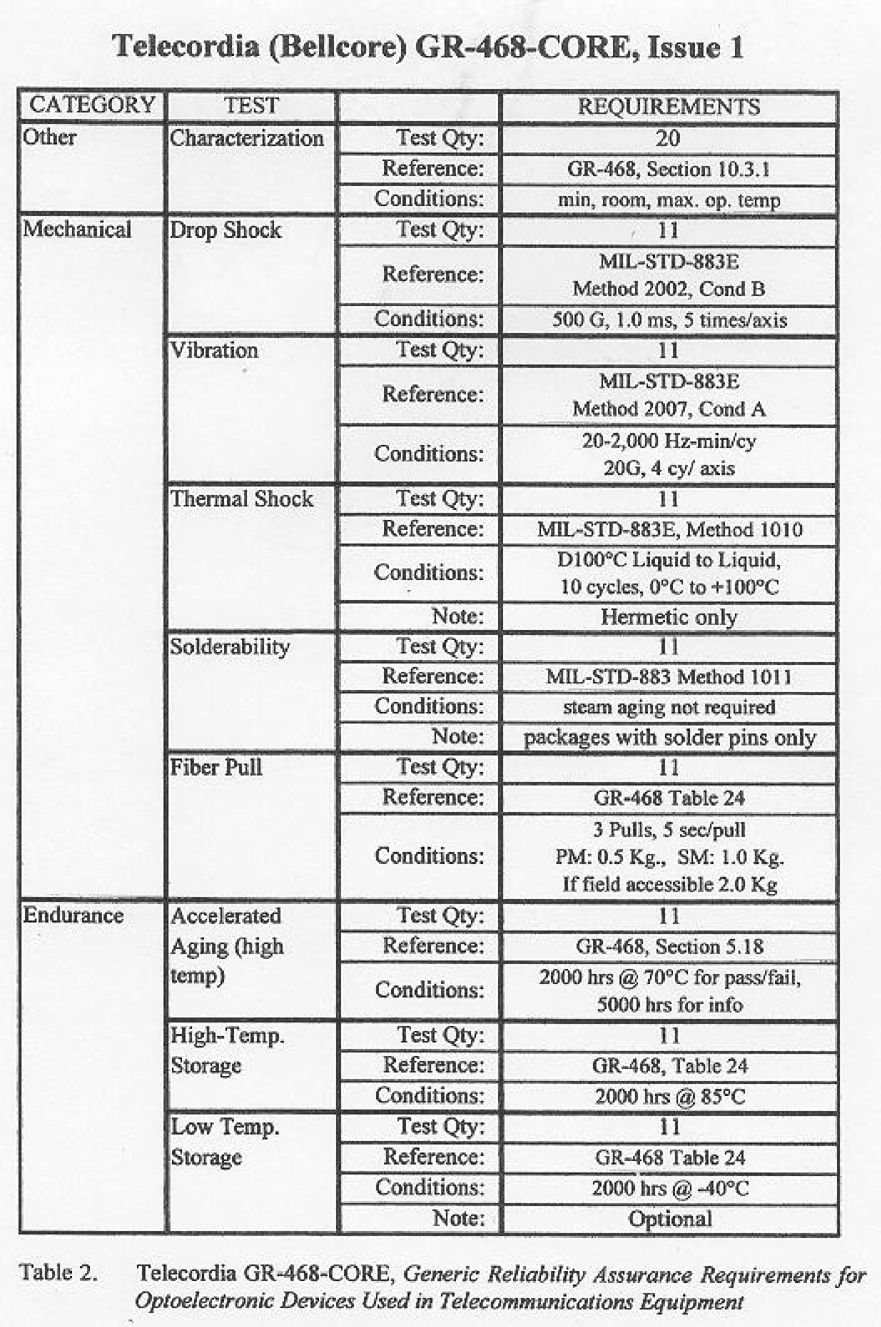


Figure 1: Degradation of coupling material in optical modulator package.

4. Telecordia Standards for Optoelectronics

While NASA has established environmental test parameters for components used in space flight hardware, it is important to take into account the Telcordia (Bellcore) Standards (GR-468-CORE). These standards are widely used in the telecommunications industry to test for mechanical reliability and endurance of various optoelectronic devices. Only modulators that have been tested to the Telecordia standards will considered for usage in space flight environments Figure 2 and Figure 3 show a listing of the Telecordia specified tests.

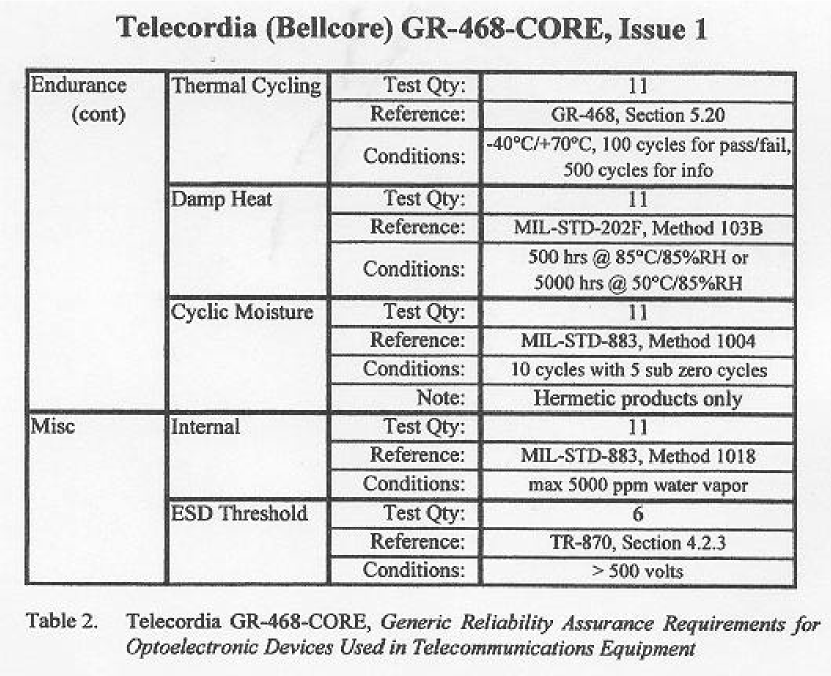


Telecordia (Bellcore) GR-468-CORE, Issue 1

CATEGORY	TEST		REQUIREMENTS
Other	Characterization	Test Qty:	20
		Reference:	GR-468, Section 10.3.1
		Conditions:	min, room, max. op. temp
Mechanical	Drop Shock	Test Qty:	11
		Reference:	MIL-STD-883E Method 2002, Cond B
		Conditions:	500 G, 1.0 ms, 5 times/axis
	Vibration	Test Qty:	11
		Reference:	MIL-STD-883E Method 2007, Cond A
		Conditions:	20-2,000 Hz-min/cy 20G, 4 cy/ axis
	Thermal Shock	Test Qty:	11
		Reference:	MIL-STD-883E, Method 1010
		Conditions:	D100°C Liquid to Liquid, 10 cycles, 0°C to +100°C
		Note:	Hermetic only
	Solderability	Test Qty:	11
		Reference:	MIL-STD-883 Method 1011
		Conditions:	steam aging not required
		Note:	packages with solder pins only
	Fiber Pull	Test Qty:	11
		Reference:	GR-468 Table 24
		Conditions:	3 Pulls, 5 sec/pull PM: 0.5 Kg., SM: 1.0 Kg. If field accessible 2.0 Kg
Endurance	Accelerated Aging (high temp)	Test Qty:	11
		Reference:	GR-468, Section 5.18
		Conditions:	2000 hrs @ 70°C for pass/fail, 5000 hrs for info
	High-Temp. Storage	Test Qty:	11
		Reference:	GR-468, Table 24
		Conditions:	2000 hrs @ 85°C
	Low Temp. Storage	Test Qty:	11
		Reference:	GR-468 Table 24
		Conditions:	2000 hrs @ -40°C
		Note:	Optional

Table 2. Telecordia GR-468-CORE, *Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment*

Figure 2: Table on Telecordia Testing (Bellcore Standards) for Optoelectronics Part 1.[8]



Telecordia (Bellcore) GR-468-CORE, Issue 1

Endurance (cont)	Thermal Cycling	Test Qty:	11
		Reference:	GR-468, Section 5.20
		Conditions:	-40°C/+70°C, 100 cycles for pass/fail, 500 cycles for info
	Damp Heat	Test Qty:	11
		Reference:	MIL-STD-202F, Method 103B
		Conditions:	500 hrs @ 85°C/85%RH or 5000 hrs @ 50°C/85%RH
	Cyclic Moisture	Test Qty:	11
		Reference:	MIL-STD-883, Method 1004
		Conditions:	10 cycles with 5 sub zero cycles
		Note:	Hermetic products only
Misc	Internal	Test Qty:	11
		Reference:	MIL-STD-883, Method 1018
		Conditions:	max 5000 ppm water vapor
	ESD Threshold	Test Qty:	6
		Reference:	TR-870, Section 4.2.3
		Conditions:	> 500 volts

Table 2. Telecordia GR-468-CORE, *Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment*

Figure 3: Continuation of the Telecordia Tests Part 2.[8]

Table 2 shows a comparison of the requirements of NASA and Telcordia specifications for thermal and vibration, two tests that are typically used to validate technology for space environments. These two tests are also known for bringing out failure modes of typical fiber optic devices. Due to the usage of MIL-STD-883 in the Telecordia specifications, the random vibration environmental parameters and duration are of greater intensity than is required for space flight launch vehicles. Based on this the probability is high that the device will pass typical space flight launch specifications.

Table 2: NASA Vibration and Thermal Parameters vs. Telcordia Parameters

	NASA Requirements		**Telcordia Requirements**
Vibration Testing	Vibration conducted on each of three axes	3 minutes / axis	
	Frequency (Hz)	Protoflight Level	20-2,000 Hz-min/cycle
	20	.052 g2 / Hz	
	20-50	+6 dB / Octave	
	50-800	.32 g2 / Hz	
	800-2000	-6 dB / Octave	20G, 4 cycles/axis
	2000	.052 g2 / Hz	
	Overall	20.0 grms	
Thermal Cycling Testing	-20°C/+85°C, 30 cycles for pass/fail, 42 cycles for info		-40°C/+70°C, 100 cycles for pass/fail, 500 cycles for info

The thermal specification is also of longer duration for accessing the long term reliability or aging of the component. The NASA requirement is focused on performance for the duration of the mission assuming that the part has already been screened to industry statndards. Therefore, in this case, the thermal and vibration testing used to characterize parts for space flight are used for verification for mission life. Based on the fact that the Telecordia specification requires a rigorous set of testing, there is a good probability that if a part has been qualified properly using the Telecordia test schedule than it will withstand space flight thermal and vibration environments. This is the reason for choosing a modulator that is qualified to the Telecordia standards. Therefore, in addition to noting which modulators have adequately addressed the typical failure modes discussed previously, the other criteria for a reliable modulator is Telecordia qualification.

4.1 Telecordia Testing Summary

Table 3 shows a summary of the Telecordia testing and the quality function if performs or which aspect of the device is being tested given a specific test. It is important to note that x-cut devices do not require hermetic packaging and therefore testing for hermeticity is not necessary for those components. By examining the table below it is apparent that these tests take into account many aspects for producing reliable components. Therefore, it is a logical assumption that any component that has been Telecordia qualified should be a highly reliable component if all the tests listed here are conducted to the Telecordia standards. Based on the summary of testing required to bring out known degradation and failure modes listed in section 3 (Table 1), the testing listed in Table 3 certainly includes testing that would be required to assess the reliability of a device.

Table 3: Summary of Telecordia Tests and Quality Functions

Telecordia Test	Quality Function
Drop Shock	Wirebond quality.
Vibration	Mechanical resonance, flaws in subcomponents.
Thermal Shock (hermetic)	Hermetic seal, fiber breakage.
Solderability	Mechanical integrity.
Fiber Pull	Fiber breakage, hermetic package.
Accelerated Aging (high temp)	Overall long term reliability, V_{dc} drift.
High Temp Storage	If aging is performed at this temp, it is redundant.
Low Temp Storage	Not usually performed unless requested.
Thermal Cycling	All aspects of the packaging design, materials, seal etc.
Damp Heat	Not performed on hermetic unless exposed epoxy.
ESD Threshold	Electrodes.
Internal Moisture (hermetic)	Hermetic packaging.

Revalidation of all the Telecordia testing upon procurement would be a very expensive venture. Therefore, to validate that a part is in fact reliable in a more efficient manner may require only performing those tests that bring out the majority of degradation and failure modes as a means of technology validation. Based on the study summarized in section 3 this would indicate that elevated thermal testing, thermal cycling and vibration testing should be the main focus if only an abridged testing schedule were to be performed for technology validation. Since the references used for the failure and degradation modes study summarized in section 3, post date the Telecordia standards it could be assumed that many of these degradation and failure modes were discovered during Telecordia qualification, something that all commercial vendors who produce modulators need to achieve to have a component considered reliable among the telecommunications community. These are the largest users of this technology. The degradation mode of coupling compound darkening, although of interest involves putting more energy into a device than is validated by the manufacturer specification and should be not be considered a reliability issue. It should only be noted that propagation of more power than is specified could result in this type of malfunction.

The most time consuming test of the Telecordia required testing is the accelerated aging reliability test which requires 2000 minimum hours of testing and 5000 hours for gathering information on the expected lifetime of the part. The test requires prolonged exposure to 70 degrees C. In other studies that have been conducted temperatures of 85ºC and 100ºC have been used for accelerated aging especially for monitoring the drift of Vdc in bias devices. With higher temperature, the swing variation in the Vdc increases. The part is driven at the maximum modulation rate and fully characterized during testing.

5. Characterization and Testing of Modulators

In general, to fully characterize an optical fiber modulator the following instrinsic parameters are necessary to gather information: S_{11}, S_{21}, Vrf, Vdc, phase shift away from quadrature (for non bias devices), optical insertion loss, optical return loss (power in/power reflected), and extinction ratio which is the optical intensity maximum/optical intensity minimum. However, if a “system” approach is applied than many of these parameters are monitored simultaneously by substituting a BER measurement. The accelerated aging test is the most significant for bringing out a majority of degradation and failure modes. Therefore during this test instead of testing all the parameters listed previously, titanium waveguide or bias devices (X or Z cut) two tests are required to monitor the performance. The first is by maintaining constant quadrature and using the “system” approach, monitoring the change in the bias voltage Vdc, the insertion loss and BER. The second test would entail keeping the bias voltage constant while monitoring phase changes, insertion loss and BER. If a proton waveguide device (meaning no bias is necessary) is under test, only the phase changes, insertion loss and BER are required for full characterization during an accelerated life test. Therefore, to avoid running two long term tests, a non bias device would be better suited to space flight applications where multiple long term tests are not feasible for technology validation due to budget and time concerns.

6. Testing for Failure Modes

Several tests are necessary to bring out the known failure modes but most of the failure modes discussed here involve elevated thermal conditions. Under elevated thermal conditions several parameters are monitored based on the actual type of modulator under investigation. As summarized in Table 1, DC drift, and hydrogen diffusion (X-cut proton waveguides only) a prolonged thermal test with elevated levels is used to bring out the failures. For fiber breakage, and material mismatch a thermal cycling test is used to simulate the stressful conditions that result in a failure of this type. Therefore four out of the five failures list in Table 1 require a thermal test. Optical degradation of the coupling materials is only an issue if the modulator is in a high energy application. However, that is not satisfied by a thermal test but would be simulated with a high power source.

Reliability studies to investigate the performance of modulators and to simulate accelerated life conditions typically use elevated thermal level testing. In many cases, the Bit Error Rate (BER) is monitored as well as the insertion loss over a prolonged period of time of anywhere from 5000 to 10000 hours (30 weeks to more than a year). Obviously it would be very difficult and expensive to run a BER test for nearly a year for a full reliability study. The minimum requirement from the Telecordia standards is 2000 hours although many studies conducted in the past go beyond this. Besides testing for BER the intrinsic parameters would be monitored for a full device assessment when possible which includes: V_{rf}, Vp, ? phase from quadrature (for nonbiased devices), insertion loss, return loss, Re (extinction ratio), ratio of electrical power in vs power reflected, and frequency response. However as mentioned previously in section 5, BER and insertion loss and phase monitoring can take the place of measuring all the intrinsic parameters by providing enough information about the device to make appropriate assessments. The only challenge here is that BER testing equipment tends to be some of the more expensive pieces of equipment known for telecommunications device characterizations.

7. Innovative Test Methods for Failure Modes

In order to decrease the amount of testing necessary to bring out a majority of the failure modes discussed here several innovative test methods are proposed to accomplish the same results as by the methods discussed in section 6. Based on the research conducted during this task, we propose to use a pseudo random binary sequence (PRBS) extinction ratio eye pattern diagram in place of the BER measurement typically used. Using the NIST method with some modifications to typical experimental arrangements, this can provide data about a 10 Gb/s device using the same method originally performed on 2.5 Gb/s devices. The test will then be performed with the devices exposed to a stressed environment.[8,10]. However, even for this testing the stressed environment requires an elevated thermal level test. Therefore, in addition to using the eye diagram method we propose to use a thermal cycling test in place of a prolonged thermal test at high temperatures. To complete the characterization, an insertion loss test will be conducted as well. The eye diagram monitoring will allow for intrinsic parameters to be accessed simultaneously. The thermal cycling will provide stresses that will affect many failure modes simultaneously. In many cases with packaging of optical fiber devices failure modes respond more quickly to thermal cycling than to prolonged high temperature exposure. Therefore, if we apply this type of validation on a part that has been Telecordia qualified than a majority of failure modes will be accounted for.

7.1 Justification for Thermal Cycling

In the case of semiconductor devices the dopants are placed in very specific locations for very specific purposes. Any diffusion of these dopants could result in the component becoming nonfunctional. Elevated thermal testing will expedite this diffusion thus accelerating the time to failure. This is typically a very effective method of predicting time to failure or catastrophic failure for typical semiconductor devices. In the case of ceramics the main form of failure tends to be cracking or crack growth over time which results in the degradation and failure of the part over time. In crystals, cracking certainly dominates as a catastrophic failure mode and with diffusion being perhaps a slow degradation mode. Although elevated thermal exposure will expedite the diffusion, thermal cycling will expedite material stresses that will end up in crack growth. For lithium niobate modulators it may be more beneficial to use a thermal cycling test for expediting the catastrophic failure mode of cracking. For testing the phase and bias voltage stability, the high thermal testing is useful.

Since most space flight missions do not last more than 10 years and most less, it is more prudent to spend the time and effort to test a component such as a modulator in a cycling thermal environment. Most space flight environments are unique compared to industry and do not have the luxury of maintaining a constant thermal condition. So thermal cycling is very helpful in determining a components packaging robustness, functionality and stability over a wide variety of thermal conditions. Such thermal extremes are not a typical condition with the exception of storage for industry components.

8. Space Flight Environmental Requirements

Typical thermal and vibration environments are listed in Table 2 where the NASA requirements are compared to the Telecordia standards.

Vibration: At the component level in a space flight instrument and for typical launch vehicles the vibration level are commonly 10 grms(component level, survival), 14.1 grams (component level, prototype or part level, survival) or 20 (part level, prototype) grms. A fiber optic modulator is actually a small component due to the coupling of several types of piece parts which include a crystal, wire bonds, optical fiber and electrical and optical fiber connectors. Therefore, a vibration test to a 14.1 grms level should be adequate to assuring survival for launch conditions and for stimulating vibration induced failure modes such as fiber breakage or even wire bond failure. For research information 20 grms could still be used although 14.1 grms is adequate. However, both failure modes should have been more than mitigated through choosing a Telecordia qualified product.

Thermal: The thermal test requirement for typical LEO and GEO could be between 85ºC to –25ºC for components. The thermal operation environment for the Codeon Mach 10 modulator is 0ºC to 70ºC and the storage temperature is –45ºC to + 85ºC. The fact that it has been Telecordia qualified indicates that it has been tested from –40ºC to + 70ºC for thermal cycling aging, thermal shocked from 0ºC to 100ºC and operated during thermal exposure as high as 85ºC for 500 hours during a damp heat endurance test. It is not unlikely that the modulator would survive a space flight environmental thermal test and since the test is of a wider thermal range, the stress should be adequate for stimulating the failure modes.

Outgassing: All materials shall require investigation as to which are appropriate for a space flight vacuum environment. Those materials that can not be identified as either space flight approved or not approved will be subject to testing to ASTM 595E. It is also possible that a configuration test can be conducted using the ASTM 595E environmental constraints but with the entire component being exposed. In many cases this provides a more expedient means by which a group of materials that make a component can be validated. However, if the buffer on the cable is not a thermally stable type, the fiber will pull out of the package during testing resulting in a catastrophic failure of the device. Therefore special consideration needs to be taken when making the decision to test in configuration or by individual materials analysis testing. It is in fact highly likely that this is where the device itself will require enhancements before being exposed to a space flight vacuum environment. A materials analysis on a few key items such as the fiber buffer or cable, epoxies etc. should further clarify if this is true. Once a material has been shown to be a none "outgasser" than an alternative material must be chosen for replacement.

Radiation: Data on modulators tested in a radiation environment does exist.[12-16]. Typical space flight environments involve gamma radiation dose rates of less than .1 rad/min. Total doses of 10K to 100K are also typical depending on the orbit and the mission duration. Models exist for testing optical fiber at higher dose rates to extrapolate to lower dose rates but a present no established model exists for testing of lithium niobate modulators. Therefore, for gamma testing a higher dose rate will need to be used to attain at minimum 10 Krads for investigating radiation induced effects.
Previous data has shown that in general, titanium diffused and proton exchanged waveguide lithium niobate devices are not very susceptible to radiation induced effects up to a 1 Mrad during high dose rate exposures. To summarize the results of the survey paper reference 12, modulator materials perform similar to optical fiber for lower dose rates and at higher dose pulses show a reaction that resembles photorefraction as well. There is no definitive indication that these devices are susceptible to displacement damage such that proton or neutron radiation would be necessary therefore, gamma exposure should be appropriate for simulating radiation induced effects.

9. Innovative Test Plan Outline for Space Flight Validation

1. Optical inspection and validation of performance parameters
    a. Measured eye pattern.
2. Inspection of all material for outgassing. Materials analysis and test to ASTM 595E for those materials not already contained in the NASA outgassing database.
3. Vibration testing.
    a. Levels are as follows for components at the protoflight level

Table 4: Vibration Profile Levels for Component Testing

Frequency (Hz)	Protoflight Level
20	.052 g^2/Hz
20-50	+6 dB/octave
50-800	.32 g^2/Hz
800-2000	-6 dB/octave
2000	.052 g^2/Hz
Overall	20.0 grms

    b. Using Table 4, vibration exposure should be conducted for 3 minutes per axis, x, y and z. Component is tested insitu if possible by eye pattern monitoring.

4. Thermal testing
    a. Levels are as follows using eye pattern monitoring insitu. –45 to +85 using 2 ºC/min ramp rates and 40 minutes minimum for dwell at extremes. The test should be conducted for 100 cycles minimum.
    b. Stress electrodes test, test should be conducted at the maximum modulation rate possible by specification or by available equipment and at maximum rating for voltage for the duration of the test.
5. Radiation testing, unless otherwise specified by the project radiation is only necessary when any radiation induced change in phase is intolerable. In most cases due to the size and materials used in most modulators, radiation testing has shown that lithium niobate modulators are quite insensitive to typical space flight environment total doses and dose rates.

10. Criteria for Commercial Modulators

For this study several criteria were used to choose from the variety of optical modulators available commercially. The following list was formulated for choosing a group of modulators to consider for this study based on bandwidth. The next step was to choose the most suitable device based on the other criteria which included testing to Telecordia standards, device designs that mitigated failure, and low power consumption.

10.1 Space Flight Utilized Bandwidth

In cases of optical fiber communication buses the rule of thumb for increasing the reliability of space flight sub-systems is to utilize 10% of the rated system bandwidth. In this case since a system is not specified. Therefore the assumption will be used at the device level. In order to assure a 1 Gb/s data rate, 10 Gb/s would be the specified data rate of a device to satisfy this requirement. Although a few modulators do exist at the 40 Gb/s data rate, the 10 Gb/s devices have more heritage at this time.

10.2 Telecordia Qualified

As a way of insuring a highly reliable system based on commercial standards the only modulators that can be seriously considered for usage must be Telecordia qualified. This criteria assumes that most failure modes which do appear in the documention of the past 10 years were probably taken into account when the Telecordia standards were developed. This of course, is the assumption based on failure modes that occur on ground based systems and not space flight systems. However, the comparison of the thermal and vibration environment in section 4 does illustrate that a high probability exists for the devices once Telecordia qualified, to withstand space flight thermal and vibration environments. Radiation and outgassing were addressed in Section 8 on space flight testing to be performed for validation.

10.3 Mitigated Failure Modes

During this survey interviews with each vendor regarding their modulator technology were conducted in addition to reviewing all documented specifications provided by the vendors on their respective devices. The objective of this review was to compare the collected information on failure modes to the current 10 Gb/s designs to identify those parts that has been specifically designed in a way that would mitigate the risk of any of the mentioned failure modes. In addition to providing a more reliable device, this process could also eliminate the need for costly testing in the future once it is verified that the failure mode was indeed mitigated through design.

10.4 Low Power Requirement.

Typical space flight missions require low power consumption instruments and subsystems. Therefore devices and systems that have the lowest power consumption requirements will provide a more suitable option for a space flight mission. This again is one reason for chosing a device that has no bias requirement.

10.5 Amount of Testing Required

In order to reduce the costs associated with usage and technology validation of a device for a space flight mission it is important to consider devices based on how much testing is required to attain a reasonable assessment. Titanium devices require twice the testing than the proton devices require for the accelerated life assessment as discussed in section 5.

10.6 Other Considerations

In addition to the criteria listed above are the other specifications that are desirable such as low insertion loss, high extinction ratio, low return low, maximum optical power input and broad optical wavelength bandwidth. There issues although taken into account are more significant when a specific application is necessary as opposed to a general study as conducted here. However, a large extinction ratio will allow for a larger signal to noise ratio and a larger input power could mitigate against the failure modes related to higher input power. Lastly, the responsiveness of the vendor has been taking into consideration as well. Technical support is very important to the proper use of any device.

11. Summary of Commercial Survey

Several devices were chosen for this study based on commercial availability and were categorized by data rate. Table 5 illustrates the specifications of the candidates. All of the considered modulators have data processing rates of 10.0 Gb/s, and all of them have thermal operating temperatures of $0 < C° < 70$. Several companies, such as Canadian Instrumentation & Research Ltd., Cleveland Crystals Inc., Fujitsu Compound Semiconductor Inc., IntraAction Corp., LINOS photonics Inc., MVM Electronics Inc., Nippon Electric Glass America, OKI Semiconductor, CyOptics Inc., Flextronics, and Lightwaves2020 Inc., were considered, but do not provide the specific type of Lithium Niobate modulator necessary for this study.

Table 5: Specifications of Commercially Available Optical Modulators at 10 Gb/s

	Vp	V_{RF}	Optical Power	Wavelength (nm)	Insertion loss	Ext. Ratio	Return Loss
Codeon Corp ** part # 10GXBO-S-S	0 V*	< 5.5 V	50 mW	1525-1605	< 5.0 dB	> 20 dB	-40 dB
JDS Uniphase ** part # 21012957	< 8.0 V	< 6.8V	50mW	1525-1565	< 5.0 dB	> 20 dB	-45 dB
Agere Systems ** part # 2623CSA	< 4.0 V	< 5.0V	30 mW	1525-1620	< 5.5 dB	> 27 dB	-35 dB
Micro Photonix	< 6.0 V	< 5.5V	50mW	1510-1590	< 5.0 dB	> 15 dB	-50 dB
Srico Inc. part # 400-03-C	< 5.0 V	15.0V	30 mW	1550	Not Avail.	> 20 dB	Not Avail
EOSpace	< 4.5	< 10.0V	Not Tested	1550	< 3.0 dB	> 13 dB	-45 dB
Aeroflex Trilink M10P	< 6.0	< 7.0 V	Not Tested	1520- 1580	< 4.5 dB	> 20 dB	-45 dB

* Actual specification is –3.0 V to + 3.0 V.
** Indicates that the device has been Telecordia qualified

From the results of the commercial survey, it can be concluded that the Codeon Mach 10 $LiNbO_3$ modulator (part # 10GXBO-S-S) with integrated variable optical attenuator is the best commercially available device. It has been tested to the Telcordia Standards (GR-468) for reliability in telecommunications applications, while Aeroflex Trilink, EOSpace, Srico, and Micro Photonix have not. Agere and JDS Uniphase have, however, been tested to these standards. Although the Agere 2623CSA and the Mach 10 are both available with integrated optical attenuators, specification table 5 shows the Codeon Mach 10 has a 50mW maximum rating for optical input power, while the Agere has a 30 mW maximum rating for optical input power, an increase of 66%. The JDS Uniphase modulator also has a 50mW input optical power max, but it is not offered with an integrated optical attenuator. An increased max power rating creates a lesser chance of degradation of coupling material between the fiber and the waveguide, a failure mode that is caused by excessive optical input power. All devices surveyed have bandwidths of 10 Ghz. The JDS Uniphase and Agere modulators require at most 9.0V for operation at quadrature. However, the Codeon Mach 10 features trimmed bias which allows near-zero volt operation (namely-3.0V and 3.0V) at quadrature, making it more energy efficient than its competitors, neither of which offer the trimmed bias. Finally, the cost of the Codeon Mach 10 is more sensible ($3,000) given the inclusion of the integrated attenuator, with the JDS Uniphase modulator costing $2800 without the optical attenuator. The shipping times for all of the modulators are about 6 weeks. Although we contacted Microphotonix several times they appear to be unresponsive to requests for more information.

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