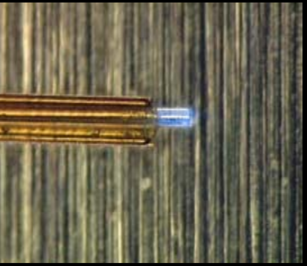


Qualification of Commercial Fiber Optic Components for Space Environments



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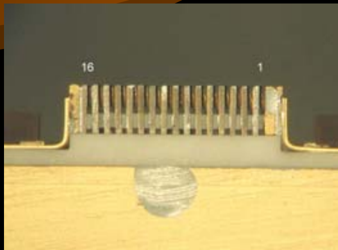
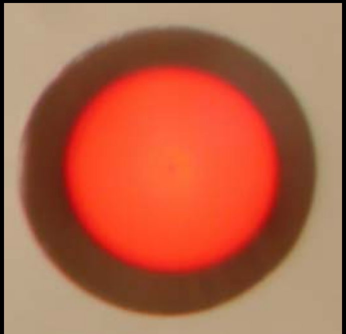
misspiggy.gsfc.nasa.gov/photonics

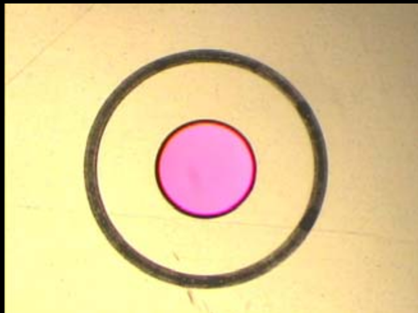


October 6, 2005



ESA/NASA Optoelectronics Workshop

NASA Goddard Space Flight Center



Outline

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- NASA COTS Photonics Validation Approach
- Construction Analysis
- Vacuum Validation
- Vibration Parameters
- Thermal Parameters
- Radiation Parameters
- Examples: Shuttle Return to Flight
- Examples: Mercury Laser Altimeter
- Examples: FODB
- Lessons Learned- Passive
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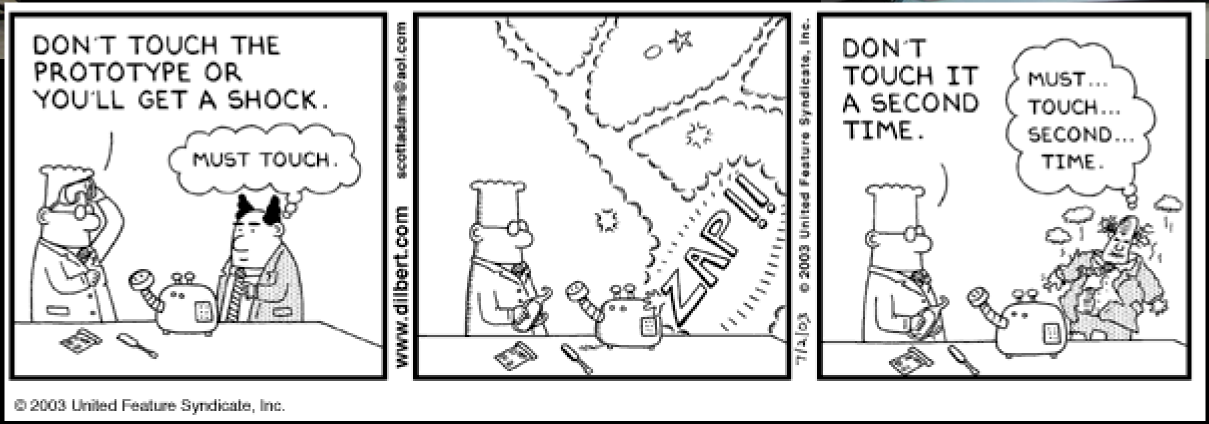
- Lessons Learned- Active
- FAQs
- Conclusion

Our Group

Code 562: Parts, Packaging, & Assembly Technologies Branch



Photonics Group:
Senior Engineers: Dr. Niels Eegholm, Dr. Xiaodan “Linda” Jin, Melanie Ott
Senior Techs: Patricia Friedberg, Shawn Macmurphy, Richard Chuska
Assembler Techs: Mary Malenab, Angie Duany
Directors: Melanie Ott, Dr. Henning Leidecker

Our Focus

Design, development of photonic systems and components; optical fiber assemblies, fiber amps, laser diodes, packaging, testing and qualification of components.

Current projects include:

- Code T Robotic Vision with JHU APL
- Lunar Orbiter Laser Altimeter,
- Instrument Incubation Program,
- Lunar Recon Orbiter,
- Laser Risk Reduction,
- Laser Interferometer Space Telescope,
- NASA Parts and Packaging Prgm.,
- International Space Station,
- Shuttle,
- Sandia National Labs,
- AFRL

Introduction

Changes in Our GSFC Environment
  - Short term projects, low budgets
  - Instruments like GLAS, MLA, VCL, LOLA

Changes to the Mil-Spec system, NASA relied heavily.
Telecommunications products available, state-of-the-art.
Vendors and parts rapidly changing.
Most photonics now COTS.
Qualification not only impossible but far too expensive.
Characterization of COTS for risk mitigation.
Quality by similarity where possible.

Issues to Consider

- Schedule, shorter term
- Funds available,
- Identify sensitive or high risk components.
- System design choices for risk reduction.
- Packaging choices for risk reduction.
- Quality by similarity means no changes to part or process.
- Qualify a "lot" by protoflight method—you fly the parts from the lot qualified, not the tested parts.
- Telcordia certification less likely now.

COTS Technology Assurance Approach For Space Flight

System Requirements (Instrument System Engineer) : Define critical component parameters and the quantity by how each can deviate from optimal performance as a result and during testing -- Performance requirements.

Environmental Requirements (Mechanical, Thermal, Radiation Engineers)
Contamination and materials requirements.
Box level random vibration, double for component
Thermal environment, 10 C higher at extremes
Radiation, worst case conditions.

Failure Modes Study, (Components Engineer)

- Conditions and Parameters,

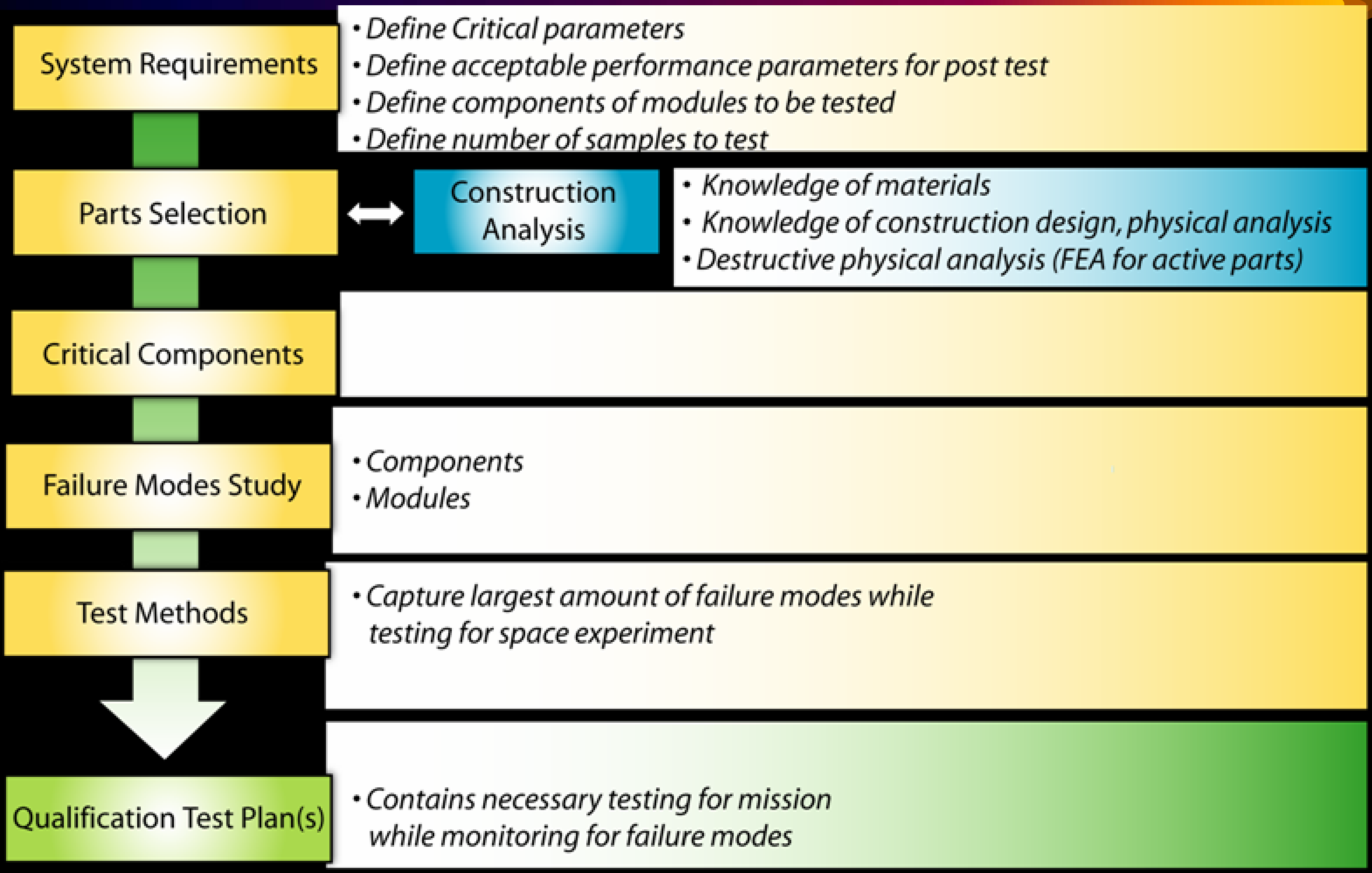
Test Methods

- Tailored to capturing the largest amount of failure modes while testing for space environment.

Test Plan

- Contains necessary testing for mission while monitoring for failure modes.

COTS Technology Assurance Approach



System Requirements

- Define Critical parameters
- Define acceptable performance parameters for post test
- Define components of modules to be tested
- Define number of samples to test

Parts Selection ⟷ Construction Analysis

- Knowledge of materials
- Knowledge of construction design, physical analysis
- Destructive physical analysis (FEA for active parts)

Critical Components

Failure Modes Study

- Components
- Modules

Test Methods

- Capture largest amount of failure modes while testing for space experiment

Qualification Test Plan(s)

- Contains necessary testing for mission while monitoring for failure modes

Flow chart courtesy of Suzzanne Falvey, Northrup Grumman, based on M Ott reference:

* *Photonic Components for Space Systems*, M. Ott, Presentation for Advanced Microelectronics and Photonics for Satellites Conference, 23 June 2004.

Qualification Plan

Define critical parameters that must be stable during testing.

Define acceptable changes in performance parameters as a final result of testing and testing (dynamic and permanent). Acceptance criteria

Choose parts or system to be tested.

How many samples (sample size) can you afford to test (considering time, equipment, materials)?

Materials Analysis,

- Outgas testing for anything unknown, take configuration into account.
- Packaging!
- Destructive Physical Analysis is crucial to formulation of testing plan

Vibration Survival and “Shock” (larger components) Test

- Use component levels as defined by system requirements
- Define parameters to monitor during testing

Thermal Cycling/Aging Test or Thermal Vacuum (depends on materials analysis)

- Define which parameters will indicate which failure mode
- Monitor those parameters during testing.

Radiation Testing

- Accelerated dose rate, extrapolation model use if possible, worst conditions

Addition tests based on specific mission requirements?

COTS Space Flight “Qualification”

Materials Analysis	• *Outgas testing for anything unknown* • *Take configuration into account*
Vibration Survival and “Shock Test”	• *Use components levels as defined by system requirements* • *Define parameters to monitor during testing*
Thermal Cycling / Aging Test	• *Define which parameters will indicate which failure mode* • *Monitor those parameters during testing*
Radiation Testing	• *Acclerated dose rate* • *Extrapolation model use if possible* • *Worst conditions*
Additional Tests	• *Based on specific mission requirements*
Qualification Assurance Plan	• *Continued reliable performance over life of mission*

Flow chart courtesy of Suzzanne Falvey, Northrup Grumman, based on M. Ott reference:

* *Photonic Components for Space Systems*, M. Ott, Presentation for Advanced Microelectronics and Photonics for Satellites Conference, 23 June 2004.

Construction/Materials Analysis

Destructive Physical Analysis
    Identify packaging issues
Gases analysis, hermetic?
Materials identification,
    Packaging: wirebonds, die attach materials
Identify non metallic materials for vacuum exposure
    Potential contamination issues.

Construction Analysis is crucial!
    Long Term Reliability
    Will it survive harsh environments?

Environmental Parameters

- Vacuum requirements
  - (Materials Analysis or Vacuum Test or both)
- Vibration requirements
- Thermal requirements
- Radiation requirements

Environmental Parameters: Vacuum

Vacuum outgassing requirements:

- ASTM-E595,
  - 100 to 300 milligrams of material
  - 125°C at 10^{-6} Torr for 24 hours
  - Criteria: 1) Total Mass Loss < 1%
    2) Collected Volatile Condensable Materials < 0.1%
  - Configuration test
  - Optics or laser nearby, is ASTM-E595 enough?
    -ask your contamination expert

1) Use approved materials
2) Preprocess materials, vacuum, thermal
3) Decontaminate units: simple oven bake out, or vacuum?
4) Vacuum test when materials analysis is not conducted and depending on packaging and device.

Space environment; vacuum is actually 10^{-9} torr, best to test as close as possible for laser systems. Many chambers don't go below 10^{-7} torr.

Environmental Parameters: Vibration

Launch vehicle vibration levels for small subsystem (established for EO-1)

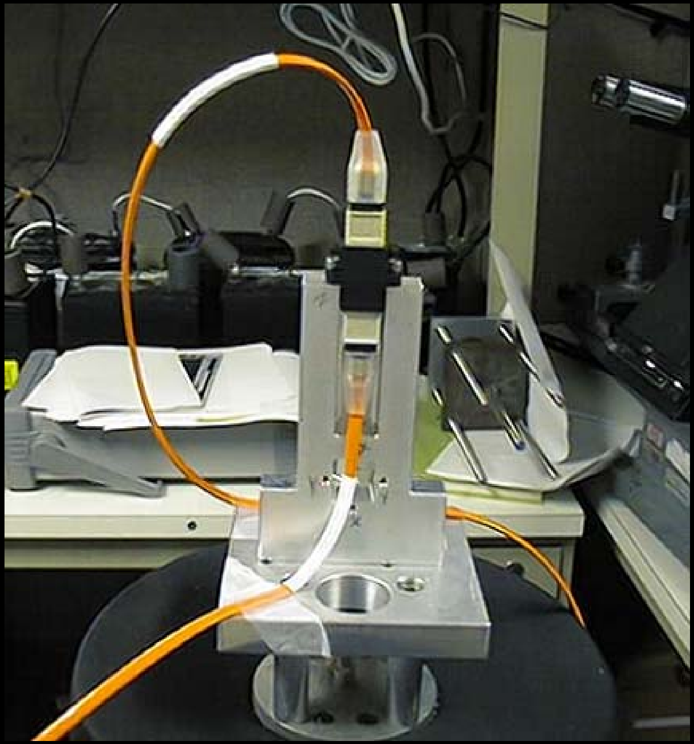
Frequency (Hz)	Protoflight Level
20	0.026 g^2/Hz
20-50	+6 dB/octave
50-800	0.16 g^2/Hz
800-2000	-6 dB/octave
2000	0.026 g^2/Hz
Overall	14.1 grms

However, this is at the box level, twice the protoflight vibration values establish the correct testing conditions for the small component.

Environmental Parameters: Vibration

Launch vehicle vibration levels for small component (based on box level established for EO-1) on the “high” side.

Frequency (Hz)	**Protoflight Level**
20	**0.052 g^2/Hz**
20-50	**+6 dB/octave**
50-800	**0.32 g^2/Hz**
800-2000	**-6 dB/octave**
2000	**0.052 g^2/Hz**
Overall	**20.0 grms**



3 minutes per axis, tested in x, y and z

Environmental Parameters: Thermal

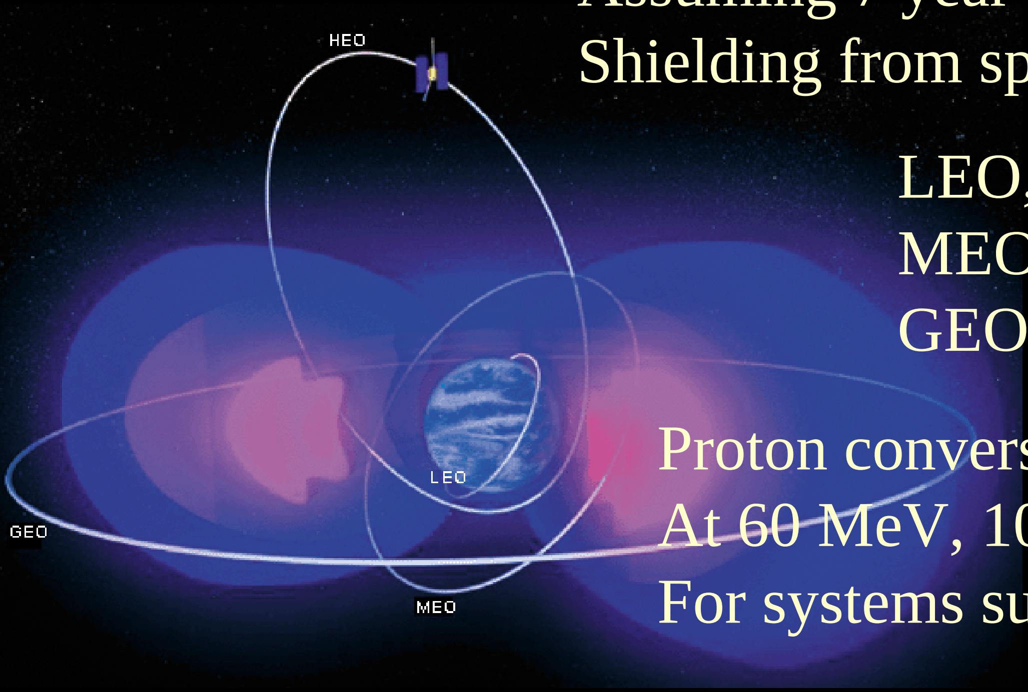
There is no standard, typical and benign –25 to +85 C.
Telcordia is –45°C to +80°C.

Depending on the part for testing;
- Insitu testing where possible
- Add 10°C to each extreme for box level survival

Thermal cycles determined by part type
- 60 cycles for assemblies for high reliability
- 30 cycles minimum for assemblies, high risk
- 100 or more, optoelectronics.
- More for high power systems

Knowledge of packaging and failure modes really helps with cycles determination.

Environmental Parameters: Radiation



Assuming 7 year mission,
Shielding from space craft

LEO, 5 – 10 Krads, SAA
MEO, 10 –100 Krads, Van Allen belts
GEO, 50 Krads, Cosmic Rays

Proton conversion to Total Ionizing Dose (TID)
At 60 MeV, 10^{10} protons/Krad for silicon devices
For systems susceptible to displacement damage

Testing for displacement damage: 3 energies in the range ~ 10 to 200 MeV.
If you have to pick one or two energies stay in the mid range of 65 MeV and lower. Less probability of interaction at high energies.
Ballpark levels: 10^{-12} p/cm^2 LEO, 10^{-13} p/cm^2 GEO, 10^{-14} p/cm^2 for special missions (Jupiter).

Environmental Parameters: Radiation

Typical space flight background radiation total dose
30 Krads – 100 Krads over 5 to 10 year mission.

Dose rates for fiber components:
- GLAS, 100 Krads, 5 yr, .04 rads/min
- MLA, 30 Krads, 8 yr, .011 rads/min (five year ave)
- EO-1, 15Krads, 10 yr, .04 rads/min

Any other environmental parameters that need to be considered? For example, radiation exposure at very cold temp, or prolonged extreme temperature exposure based on mission demands.

Shuttle Return to Flight: Construction Analysis

Optical Fiber Pigtailed Collimator Assemblies

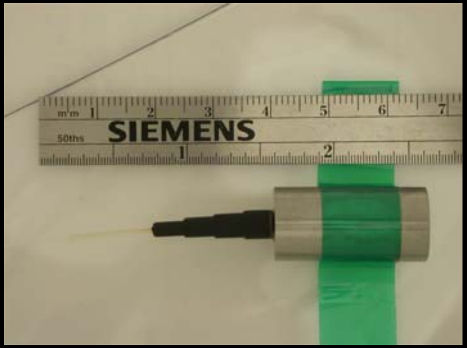
Lightpath: pigtailed fiber to collimator lens and shell

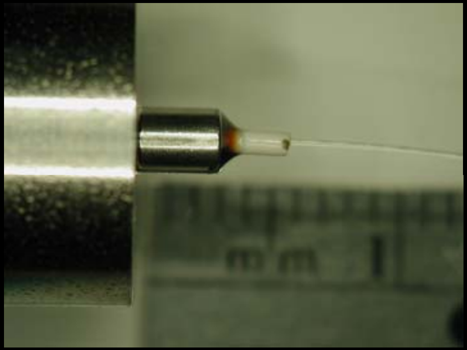
GSFC: upjacket (cable), strain relief and termination, AVIMS, PC, SM

Materials & Construction Analysis

- Non compliant UV curable adhesive for mounting lenses to case
  - Solution 1: replace with epoxy, caused cracking during thermal cycling
  - Solution 2: replace with Arathane, low glass transition temp. adhesive

  Lesson: coordinate with adhesives expert, care with adhesive changes.
- Hytrel, non compliant as an off the shelf product (outgassing, thermal shrinkage)
  - Thermal vacuum preconditioning (145°C, <1 Torr, 24 hours)
  - ASTM-E595 outgas test to verify post preconditioning.
  - Thermal cycling preconditioning (30 cycles, -20 to +85°C, 60 min at +85°C)



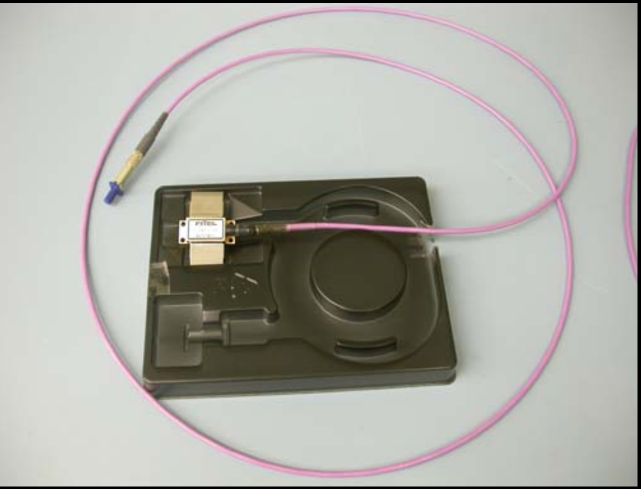


Shuttle Return to Flight

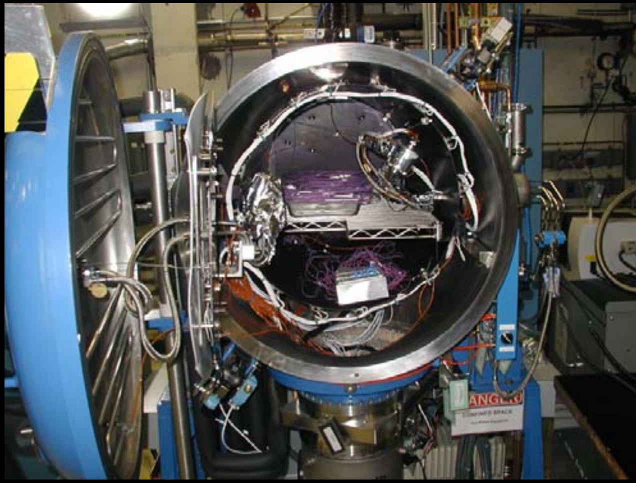
Laser Diode Assemblies

Fitel: laser diode pigtails
GSFC: Upjacket (cable), strain relief, termination, AVIMS APC SM
Fitel uses silicone boot, non-compliant!
Too late in fabrication process, schedule considerations to preprocess.

Cable: Thermal preconditioning, 30 cycles
Hytrel boots: Vacuum preconditioning, 24 hours
Kynar heat shrink tubing, epoxy: approved for space use.



Post manufacturing decontamination of entire assembly required
Laser diode rated for 85°C processing performed at 70°C



Mercury Laser Altimeter (MLA): Construction Analysis

Optical Fiber Assemblies

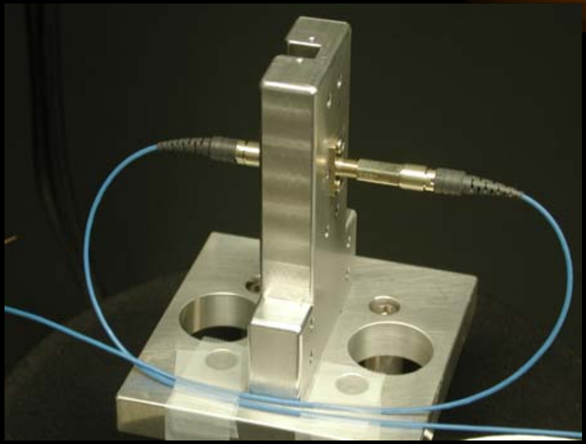
Diamond AVIMS connector / W.L. Gore Flexlite
Polymicro Technologies FIA 200/220
Performance: < 0.4 dB loss

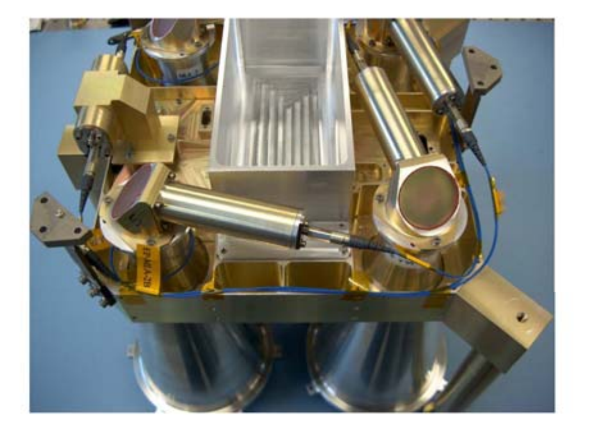
Preconditioning of non metallic materials and failure modes knowledge of construction

Hytrel boots: Thermal vacuum precondition: 140°C, 24 hrs, 1 Torr
Flexlite cable: Thermal preconditioning, 8 cycles, -20 to +60°C, 60 min at 60°C
Epotek 353ND: approved for space.

Post processing decontamination of assemblies @ 50°C (To bake out but not to age)
- Cure schedule on outgassing database is very high temp.
- Best to use close to usage temp cure, with a post cure bake out

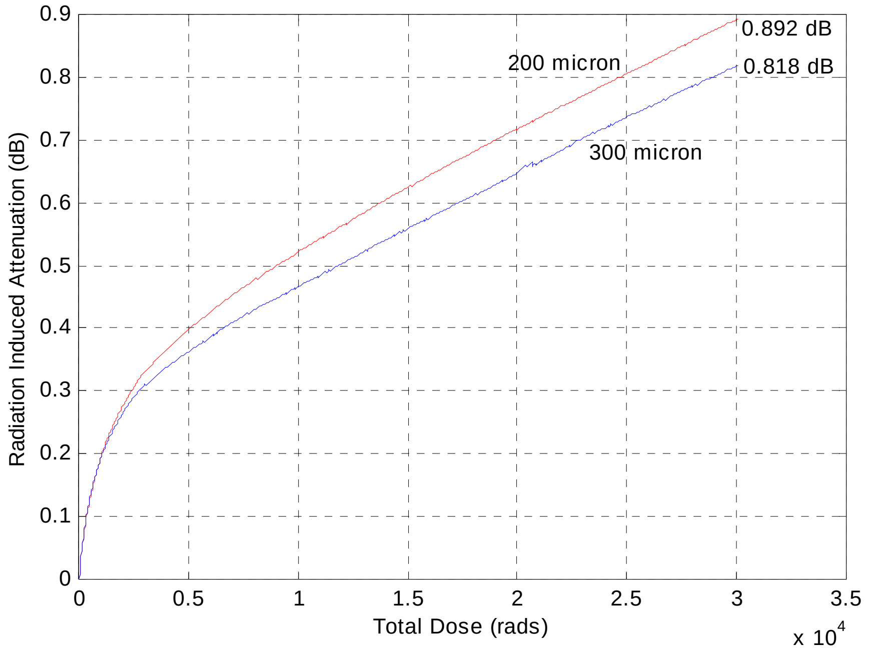
MLA Assembly Environmental Validation



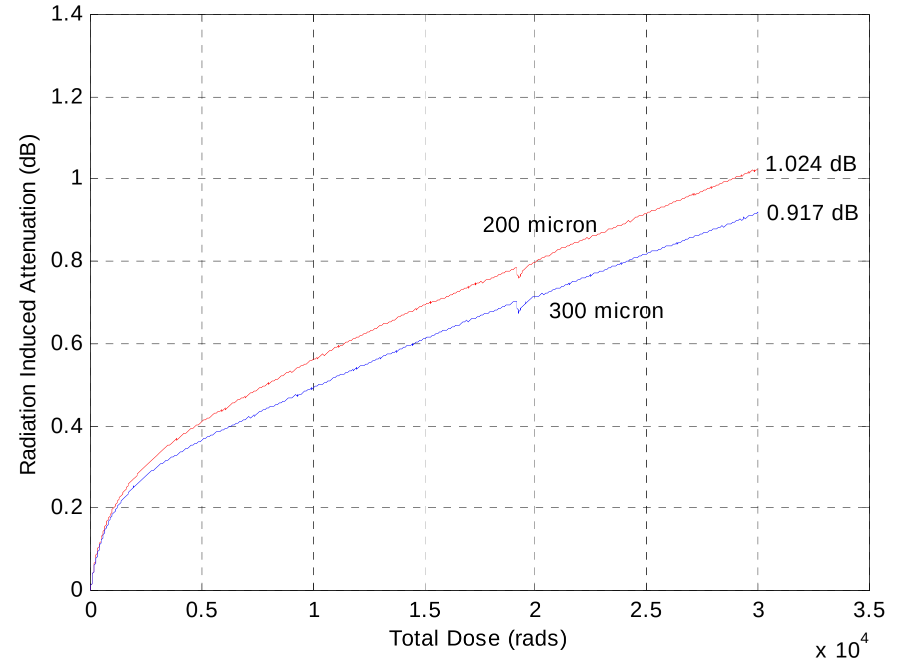


Requirements/Testing: Performance < .4 dB for all, 850 nm
Vibration 14.1 grms, 3 min/axis
Because box level @ 10 grms
Thermal: -30°C to +50 °C, 90 cycles, last 42 monitored
25 minute soak, 2 °C/min ramp rates.
Radiation: two dose rate model, -20°C,
11.2 and 22.7 rads/min to 30 Krads
(Actual dose rate .011 rads/min)

MLA Assembly Environmental Validation



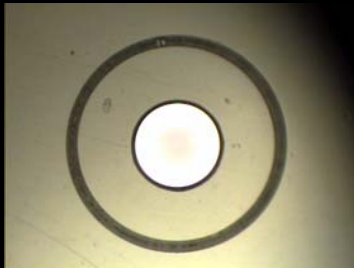
Flexlite Radiation Test, 22.7 rads/min at –18.3°C



Flexlite Radiation Test, 11.2 rads/min at –24.1°C

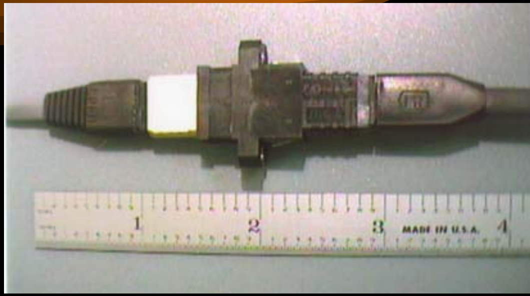
Radiation Conclusion: < .07 dB, using 11.2 rads/min, -24.1°C, 26.1 in, “dark”
Results for 10 m, at 30 Krads, -20°C, 850 nm, 23 rads/min ~ 1 dB or 0.10 dB/m

Random Vibration and Thermal Cycling: no registered losses
</= .04 dB power increase



FODB Validation Activities

Fiber Optic Data Bus based on EO-1 requirements

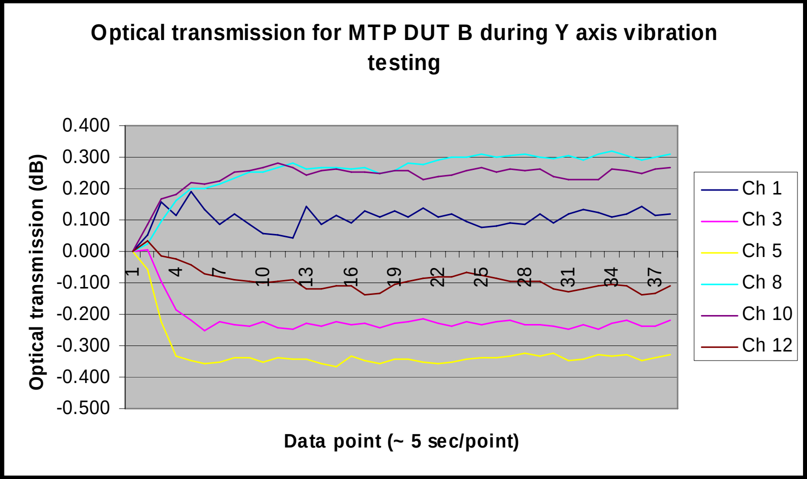


USConec MTP Array Connector / W.L.Gore 12 Fiber Ribbon Cable
For functionality and termination of existing design, 125 um ferrules
For functionality and environmental validation:
Spectran/OFS 100/140/250 commerical grade optical fiber
new boots, 140 micron ferrules.

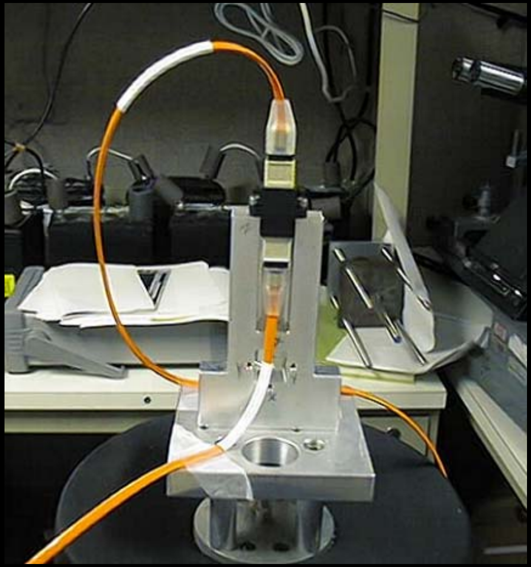
Random Vibration: 20 grms, 3 min/axis
Thermal: -20°C to +85 °C, up to 38 cycles,
25 minute dwell, 1 °C/min rate
Radiation (gamma): Two dose rate model:
4 rads/min to 62 Krad
27 rads/min to 403 Krad
< 1 microwatt CW 1310 nm

Optivision/ONI,
PFOTX12 Transmitter
PFORX12 Receiver
for Vibration, Radiation.

Random Vibration:
20 grms, 3 min/axis
Radiation:
62.5 MeV protons,
30 Krad, 85 Krad
BER & power
parameters



MTP Array/Ribbon Cable Assemblies



Vibration Summary

Dynamic test: 3 axis test, 3 min/axis, channel six of each DUT, 9 dynamic tests total. Losses < 0.1 dB, DUT A on X axis test highest loss @ 1.2 dB

Static test: < .4 dB

Thermal Summary

38 cycles: DUT A ave loss: 1.48 dB, DUT B ave loss 1.4 dB

18 cycles: DUT C ave loss: 1.38 dB

Radiation Summary

DUT A: 4 rads/min, 6.18 dB/ 5.24 m mated pair

DUT B: 27 rads/min, 15.18 dB/ 5.24 m mated pair

Extrapolated to 0.1 rads/min, .75 dB for 10 Krads, 4.75 dB for 100 Krads.

FODB TX & RX Prototype Test

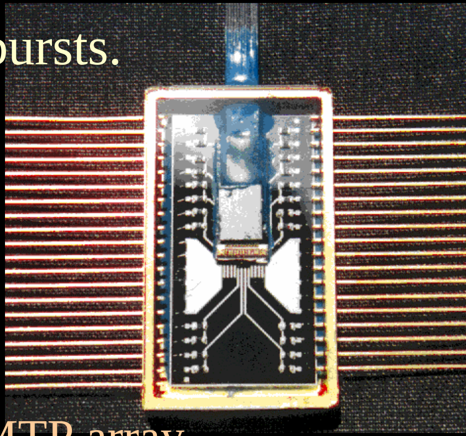
Post protoflight RV visual inspection: one broken wire.

Radiation: no BERs upto 30 Krad

@ ~ 85 Krad, RX Icc increased by 1.4 mA, some BER bursts.

BERs only during irradiation.

Remained functional after 100 Krads



Assembly reports:

Ott et al. SPIE Proceedings Vol. 3440 & Vol. 4732,
“Characterization of a twelve channel optical fiber, ribbon cable and MTP array connector assembly for space flight environments,” SPIE Vol. 4732, April 2002,
misspiggy.gsfc.nasa.gov/photonics

TX-RX reports:

O’Bryan et al., “Single Event Effect and Radiation Damage results from Candidate Spacecraft Electronics,” IEEE Radiation Effects Data Workshop, July 1998. (radhome.gsfc.nasa.gov)

Test report: radhome.gsfc.nasa.gov/radhome/papers/d020498.pdf

Lessons Learned and Learning: Passive Components

- Always perform materials analysis which may include a destructive physical analysis.
- If materials analysis is not performed please plan to do thermal cycling vacuum testing.
- Failure mode of delamination for LD coupled fiber or gain fiber may not show up during insitu monitoring as a degradation or failure mode.
- Final inspections on termini end faces shall be performed at 200 X prior to shipment for integration and inspected prior to integration for cleanliness.
- Cure schedules for larger core graded index fibers especially should be as close the lower bound of the operation temperature range as possible. High temp cure sets up a high stress situation.
- Just because you see a cure schedule in the outgassing.nasa.gov database that passes TML and CVCM requirements, doesn't mean you have to follow the cure schedule listed.
- Graded index 100/140 is extremely brittle..special care required during termination and integration.

Geoscience Laser Altimeter (GLAS): Fiber, Assemblies, Diodes

- Fiber
  - Variety of candidates, radiation analysis based on previously published data, quality by similarity.
  - Database funded by NEPP,
    - IEEE NSREC Data Workshop 2002 (misspiggy.gsfc.nasa.gov/photonics)
  - Electron testing for scintillation effects.
- Cable Assemblies (AVIMS, Flexlite)
  - Quality by similarity, tested by Lockheed-Martin.
- Laser Diodes
  - Never performed a construction analysis and devices failed in space flight.

Laser Diode Packaging Issues

GLAS, MOLA, MLA, Calipso use high power laser diode bar arrays for pumping of solid state lasers.

Indium creep (shorting, intermetallics)

Cracking of semiconductor from wedgebonds

Diffusion layer pinholes

Dendrite growth of tin/lead solder

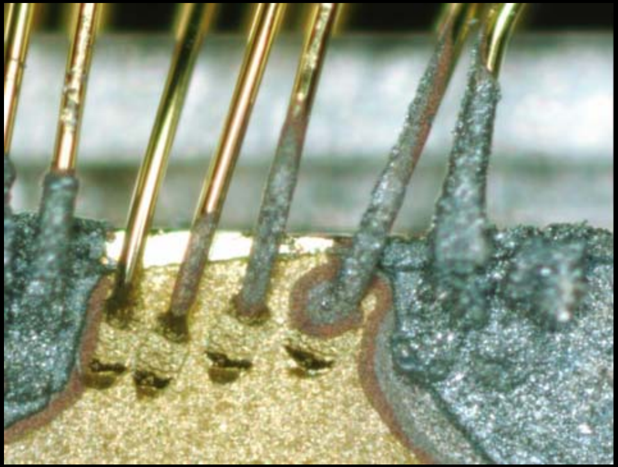
Contamination related failure (hermetic packaging)

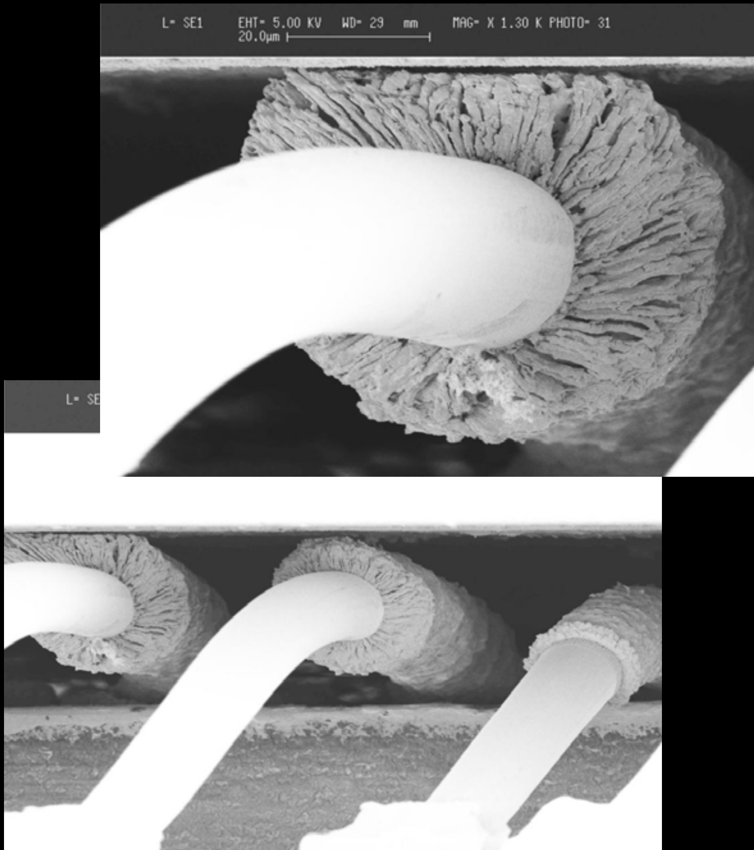
Workmanship Issues (application of indium solder)

Laser Diode Packaging Issues

Device Short
Indium creep
into bolt holes

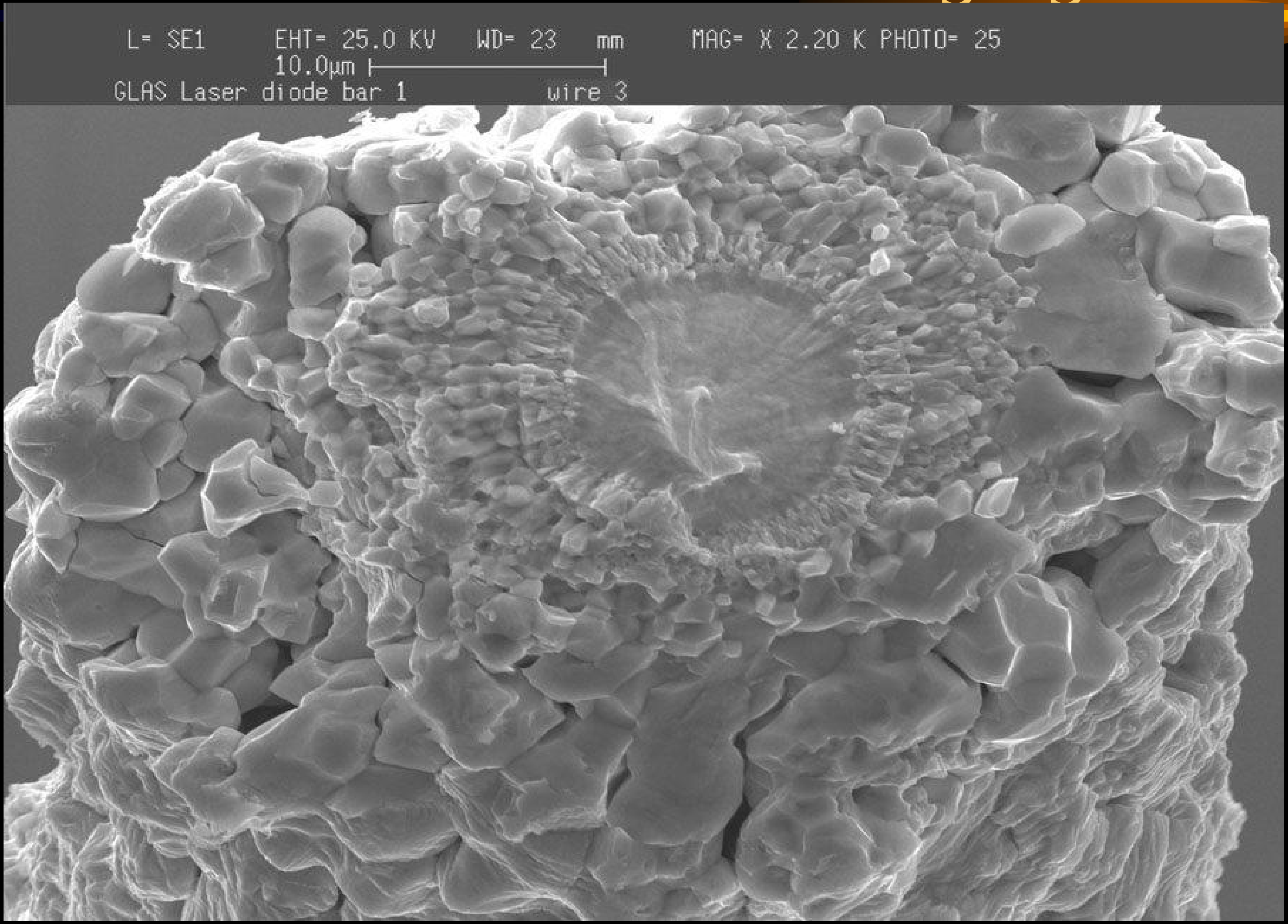
Indium creep
onto the gold
wires
Intermetallic
Gold/indium





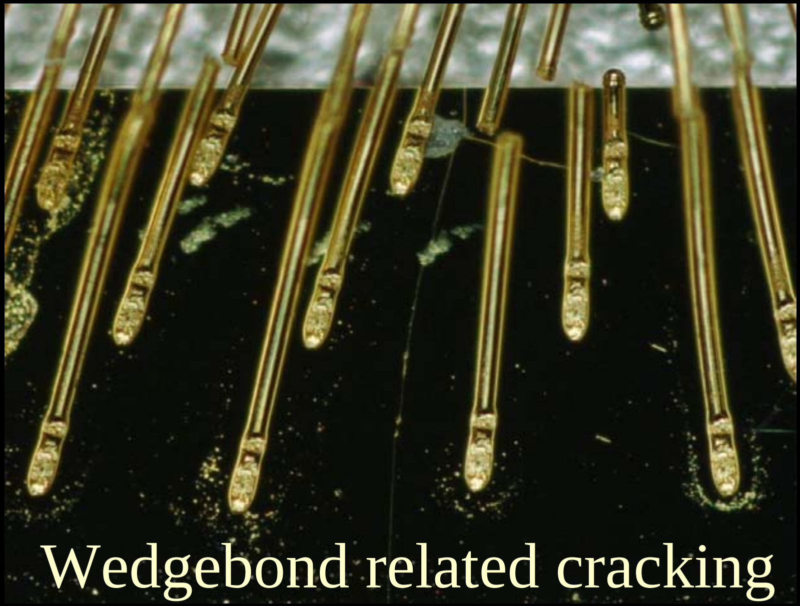
Pictures from Dr. Henning Leidecker’s presentation “Failure Analysis of GLAS Laser Diode Arrays,” Community Forum on Laser Diode Arrays in Space-Based Applications, 2004

Laser Diode Packaging Issues



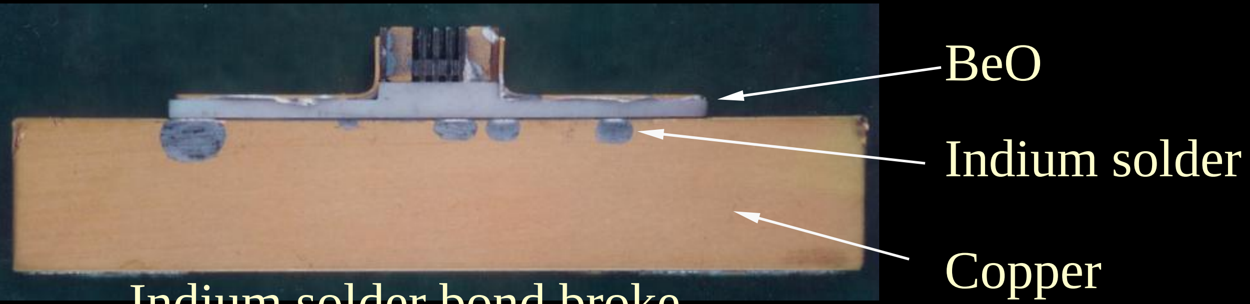
Intermetallic-Indium attack of gold wire

Laser Diode Packaging Issues



Wedgebond related cracking

Crack resulted in low res. Path to wires



Indium solder bond broke

Workmanship:
application of
Indium solder

Pictures from Dr. Henning Leidecker’s presentation
“Failure Analysis of GLAS Laser Diode Arrays,”
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Laser Diode Operation

Project	Pulse width	Rep. Rate	Peak Current	Stress ~(I^2*PW)	Damage/Pulse ~(Stress^8)	Damage Rate ~(D/P * RR)
MOLA	150 µs	10 Hz	60 Amp	$5.4*10^5$	$7.23*10^{45}$	$7.23*10^{46}$
GLAS	200 µs	40 Hz	100 Amp	$2.0*10^6$	$2.56*10^{50}$	$1.02*10^{52}$
Calipso	150 µs	20 Hz	60 Amp	$5.4*10^5$	$7.23*10^{45}$	$1.45*10^{47}$
MLA	160 µs	8 Hz	100 Amp	$1.6*10^6$	$4.30*10^{49}$	$3.44*10^{50}$

Why did the GLAS laser 1 fail while others did not?

Components, Laser Diodes Lessons Learned and Learning

- Telcordia vibration spectrum is not as intense as possible launch conditions, however, thermal testing is rigorous.
- Modulators should be hermetically sealed for vacuum environments!
- Telcordia does not cover qualification of high power diodes devices over 100 mW. Fiber amp pumps are not included ~ 3 to 5 Watts.
- Hermetic packaging of high power laser diodes; single emitter or bar arrays required for vacuum environments. Packaged with some oxygen.
- No epoxies in high power packages. JDS makes for Lucent a high power LD for fiber amp pump applications for space.
- For these devices never by-pass thermal vacuum testing unless DPA analysis shows no potential for failure modes without doubt.
- Question to answer for space flight lidar systems that use low repetition rate systems; will the hard solder packages be able to handle the lower rep rates (power cycling) such that indium can be avoided completely….stay tuned.
- We are currently writing a high power laser diode array qual document.

Radiation Testing at GSFC on Optical Fiber Candidates

Radiation Testing @ 1300 nm, OFS optical fiber

Part	Dose Rate	TID	Temp	Attenuation
BF05444 100/140/500	0.1 rads/min	100 Krad	25°C	0.0048 dB/m
BF05202 100/140/172 RH	14.2 rads/min	5.1 Krad	-125°C	0.14 dB/m
BF05202 100/140/172 RH	42 rads/min	100 Krad	-125°C	1.5 dB/m
CF04530 100/140/172 S	14.2 rads/min	5.1 Krad	-125°C	0.053 dB/m
CF04530 100/140/172 S	42 rads/min	100 Krad	-125°C	0.064 dB/m
BF04431 62.5/125/250	0.1 rads/min	100 Krad	-25°C	0.91 dB/m
BF04431 62.5/125/250	0.1 rads/min	100 Krad	25°C	0.59 dB/m

“Radiation Effects Data on Commercially Available Optical Fiber,” M. Ott, IEEE NSREC 2002

Radiation Effects on Rare Earth Fiber for Lasers Paper Survey

Aluminum content increases radiation induced effects [1]

Yb (mol %)	Al_2O_3 (mol %)	P_2O_5 (mol %)	TID Krad	Rad Induced Atten.
0.13*	1.0	1.2	14	1 dB/m
0.18	4.2	0.9	14	12 dB/m

*** Fiber also contains 5.0 mol% Germanium. Data at 830 nm, 180 rads/min.**

Rare Earth dopant (Er) does not dominate over radiation performance [2]

Part	Er Content	Al (%mol wt)	Ge (%mol wt)	Sensitivity 980 nm, dB/m Krad	Sensitivity 1300 nm, dB/m Krad
HE980	$4.5\ 10^{24}\ /m^3$	12	20	.013	.0041
HG980	$1.6\ 10^{25}\ /m^3$	10	23	.012	.0038

84 rads/min upto 50 Krad, 3 m under ambient

[1] H. Henschel et al., IEEE Transactions on Nuclear Science, Vol. 45, Issue 3, June 1998, pp. 1552-1557.
[2] T. Rose et al., Journal of Lightwave Technology, Vol. 19, Issue 12, Dec. 2001, pp. 1918-1923.

Radiation Effects on Rare Earth Fiber for Lasers Paper Survey

Low Dose Rate, .038 rads/min extrapolation for HE980

Wavelength	Total Dose	Radiation Induced Attenuation
980 nm	100 Krad	**0.91 dB/m**
1300 nm	100 Krad	**0.26 dB/m**
1550 nm	100 Krad	**0.14 dB/m**

Also shows wavelength dependence, consistent with other COTS fiber.

Yb and Er doped fibers are equivalent in terms of sensitivity.

Lanthanum doped fibers are extremely sensitive at ~10's dB/m.

Yb and Er doped fibers exhibit saturation behavior.

Proton and gamma exposures show similar results.

To compare sensitivity to typical 100/140 at 100 Krads

Temp	λ nm	Dose rate	Sensitivity	Reference
25°C	1310	.01 rads/min	1.7 10^{-4} dB/m	M. Ott, SPIE Vol. 3440.
50°C	850	.032 rads/min	2.0 10^{-4} dB/m	M. Ott, IEEE NSREC Data Workshop 2002.

Frequently Asked Questions

- Gamma vs Protons? Gamma for fiber, protons for laser diodes
- Chemical vs. Mechanical strip for fiber coatings? SEM imaging -- some thermal-mechanical stripping methods do not score or nick the optical fiber. Example: process used by USCONEC
- Hermetic packaging for laser diodes? YES, please.
- Hermetic packaging for modulators? YES, please.
- What to do with LD's: DPA, Materials analysis, Thermal Vacuum, Proton Testing.
- Testing Fiber? Don't test acrylate for outgassing, it fails, but in a configuration doesn't add a lot to the total.

Conclusion

Performance Requirements (System Engineer, Top level Spec)

Environmental Requirements
- Thermal Engineer
- Contamination Engineer
- Radiation Physicist

Physics of Failure
- Components Engineer
- Materials Experts
- Can save $$$$

Materials Analysis (crucial!)

Test Plan tailored to above,
- Define criteria or range of performance allowable.
- Quality by similarity for environmental testing.

Choose Telcordia qualified when you can, plan additional testing

Plans for Fiscal Year ‘06

- Fiber amplifier qualification of components for several programs. Includes low dose rate radiation testing.
- Fiber failure analysis and long term reliability of cracked end faces.
- MTP optical fiber array and ribbon cable assembly qualification with thermal vacuum testing.
- Imaging Fiber Array development.
- LIDAR imaging assemblies
- More Shuttle assemblies.
- Laser Diode Packaging Guidelines and Qualification Document; High Power Arrays, Single Emitters, Low power Single Emitters.

Thank you
for the invitation!

For more information please visit the website:

misspiggy.gsfc.nasa.gov/photonics