Jet Propulsion Laboratory
California Institute of Technology

Reliability of GaSb-based lasers for space applications

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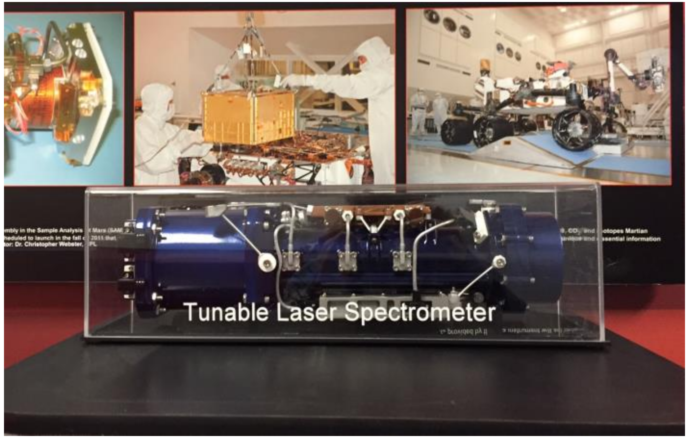
Outline

- Space application
- Importance of GaSb-based semiconductor lasers
- GaSb-based LC-DFB laser fabrication
- Reliability measurements
- Failures
- Packaging and environmental testing
- Conclusion

Space application

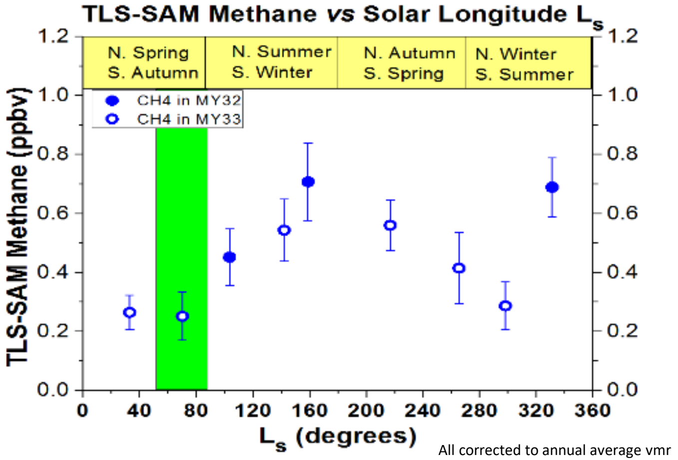
Tunable Laser Spectrometer (TLS) on Mars rover Curiosity



Principal investigator: Dr. Chris Webster, JPL

TLS is a two-channel tunable laser spectrometer using a 2.78 µm diode laser and a 3.27 µm Interband Cascade (IC) laser developed by Rui Q. Yang. These lasers operated at sub-ambient temperatures and required multi-stage coolers.

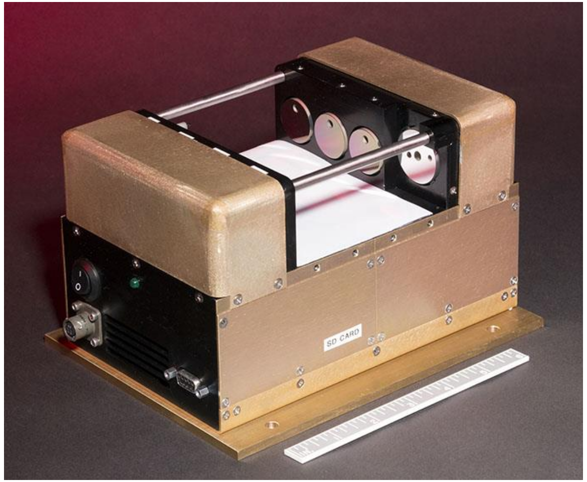
<u>In the Mars atmosphere</u>, TLS measures CH_4, CO_2, H_2O and the isotopic ratios $^{13}C/^{12}C$, $^{18}O/^{17}O/^{16}O$, and D/H



Detection of atmospheric methane at low background levels (~0.5 ppbv) that show a <u>seasonal pattern</u>, and in episodic releases (7 ppbv) show Mars is active - *Webster et al., 2015*

Space application

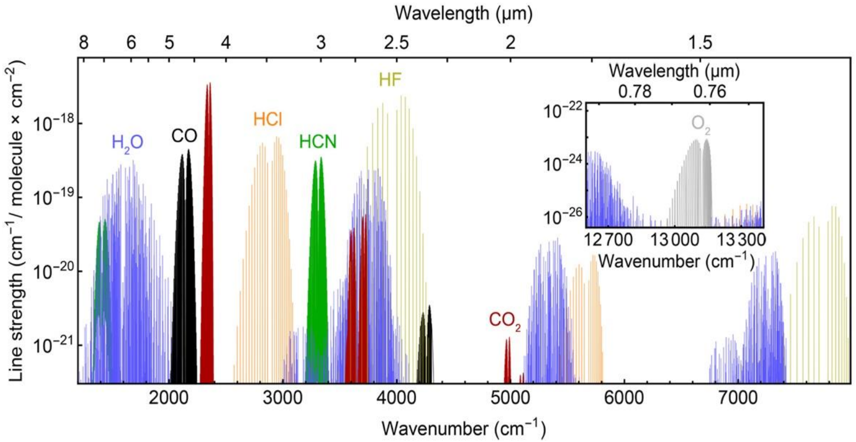
Combustion Product Monitoring
(CPM) Instrument



Instrument manager: Dr. Ryan M. Briggs, JPL

CPM is a **six-channel tunable laser** that monitors gas concentrations that are representative of combustion product that would be expected from an on-orbit fire.

Developed for use in the **Saffire experiment inside the Cygnus re-supply vehicle**.



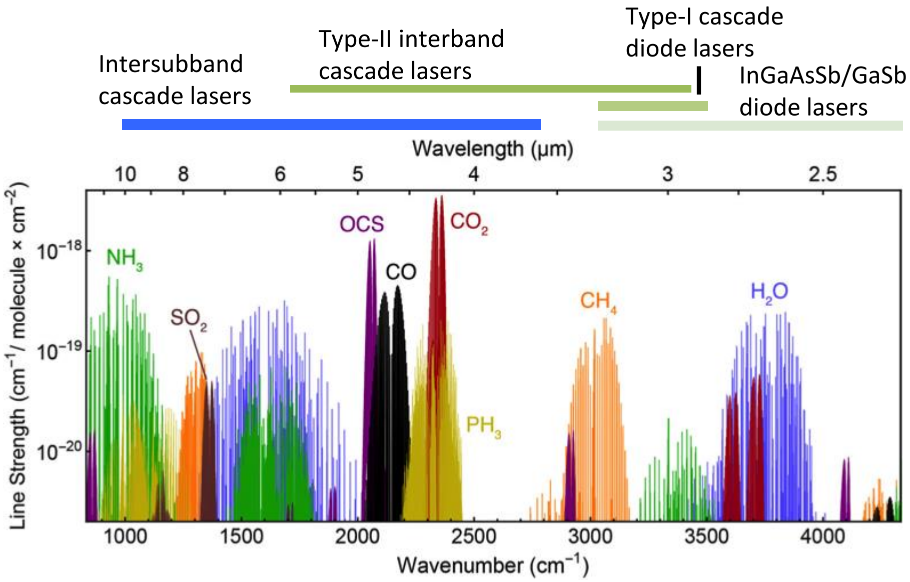
The gases measured are: O_2, CO_2, CO, HF, HCl, and HCN

Concentration range are:

HF, HCl, HCN:	**2 - 50 ppmv**
CO:	**5 - 1,000 ppmv**
CO_2:	**300 - 30,000 ppmv**
O_2:	**14 - 50%**

Fabrication challenges for mid-IR semiconductor lasers

- **Strong fundamental rovibrational modes of target compounds occur in the mud-infrared regime**
  - Absorption measurements require corresponding mid-infrared sources and detectors
- **Lasers in the 2.4-3.6 µm wavelength range can only be addressed by GaSb-based material systems**
- Complex bandgap engineering is required
- GaSb epitaxial growth for semiconductor lasers isn't available at commercial foundries
  - Suppliers are universities or national laboratories
- GaSb material systems not compatible with standard DFB laser fabrication
- Requires unique laterally-coupled feedback gratings
- **Fabrication of reliable sources remains a challenge**

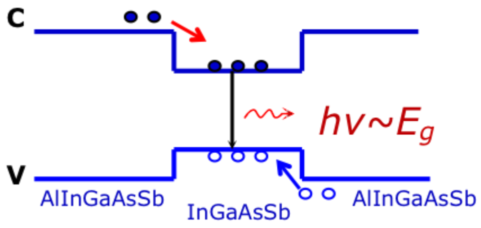


GaSb-based laser

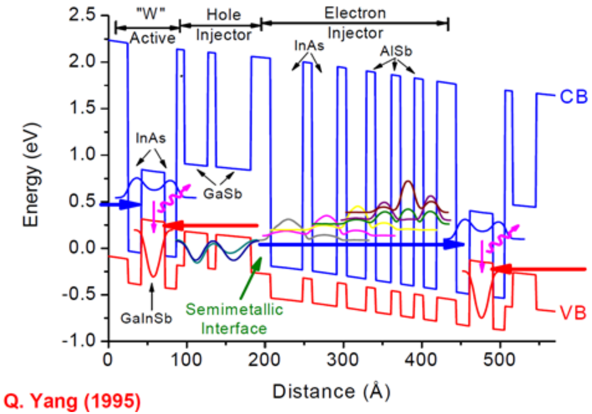
GaSb-based semiconductor lasers can target numerous gas

- <u>GaSb-based type-I diode lasers</u>
  - InGaAsSb/AlInGaAsSb QWs
  - Viability proven in the 2- to 3.3-µm regime.
  - Both professor Gregory Belenky's group from SUNY at Stony Brook and James Gupta's group from National Research Council of Canada have developed diodes with emission above 3-µm.
  - Driven by mature, low-power consumption, and reliable **3.27 µm source for methane detection**
- <u>GaSb-based type-II interband cascade lasers</u>
  - Developed by Rui Q. Yang
  - Multiple quantum well, hole and electron injector stages to emit multiple photons.
  - Jerry Meyer's group at Naval Research Lab (NRL) and nanoplus GMBH have developed single-mode ICLs near and below 3-µm.
  - Driven by low current threshold, high optical output power at **3.57 µm for HCl detection**

<u>**Diode laser structure**</u>

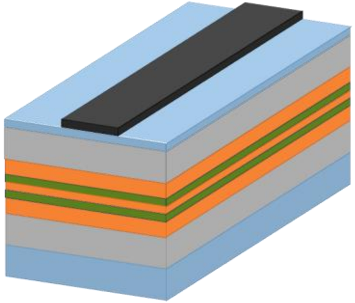


<u>**IC laser structure**</u>

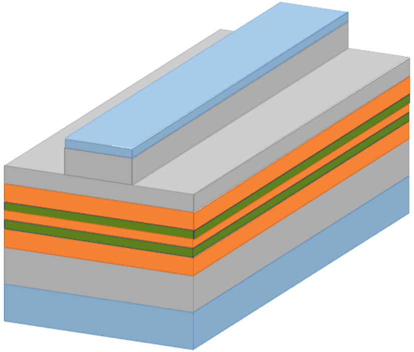


R. Q. Yang (1995)

GaSb-based LC-DFB laser fabrication



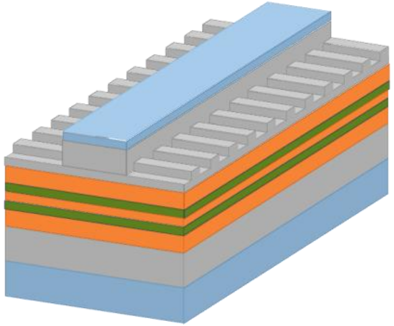
Define 4-µm wide ridge waveguide with optical lithography



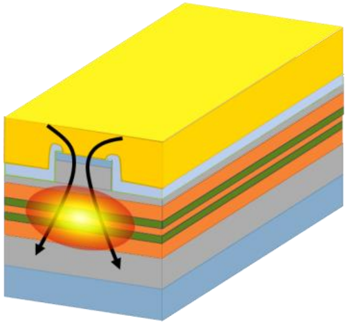
Ridge waveguide etched ~2-µm deep using a BCl_3/Cl_2 plasma

E-beam lithography

Add steps for double-ridge structure



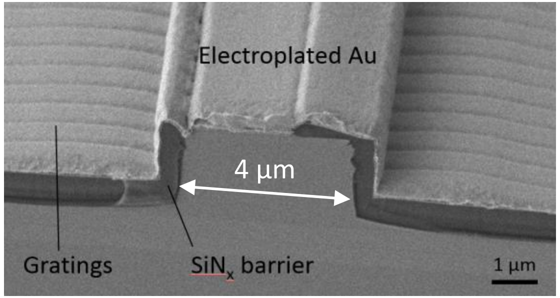
Etching of second order Bragg gratings

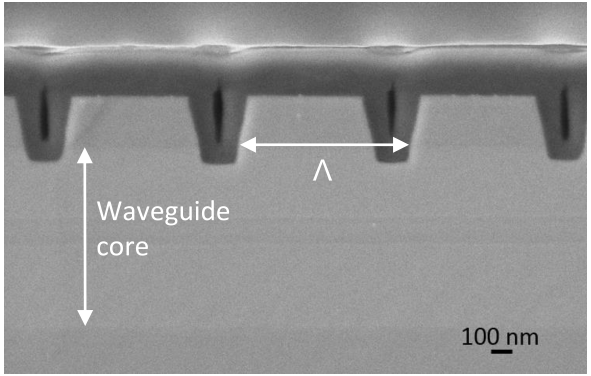


Deposition of SiN_x ~400-nm followed by ~4-µm thick electroplated Au top contact

GaSb-based LC-DFB laser fabrication

LC-DFB diode laser



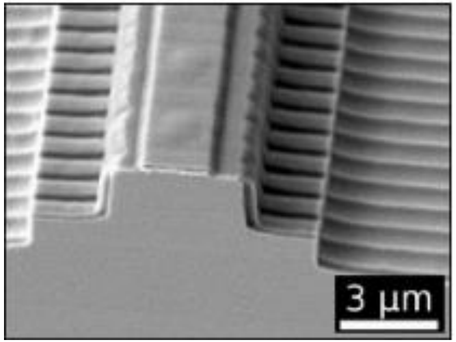


- Fabrication of 4-µm wide ridges, grating pitch $\Lambda = m \bullet \lambda / n_{eff}$ (m=1,2,3,…), duty cycle 30%.

- Laterally-coupled distributed feedback gratings were developed to avoid etching through the active structure due to reliability concerns.

- Gratings do not penetrate into the top barrier close to the ridges, but do so far from it.

LC-DFB IC laser



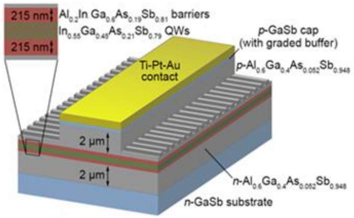
DFB laser architecture for IC lasers used a double-ridge design due to current spreading in the active region.

It reduces threshold current by a factor 6.

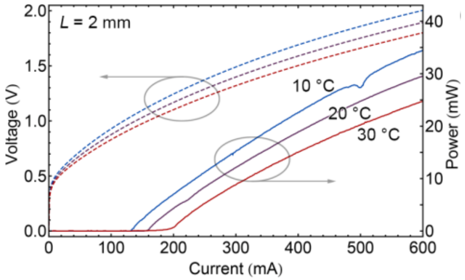
Hybrid configuration where the active region is etched all the way through, but this is done far from where the optical mode is generated

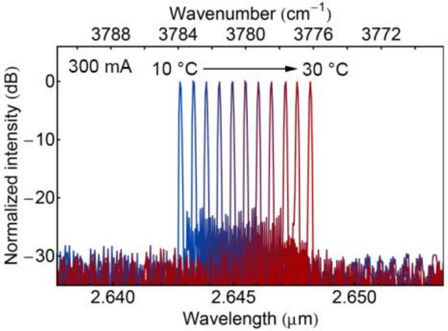
Diode performance

2.65 µm



Seven 6.6 nm InGaAsSb QWs separated by **20 nm quinary AlInGaAsSb barriers** and a 215 nm thick SCH layer between the upper and lower cladding layers and the QWs.

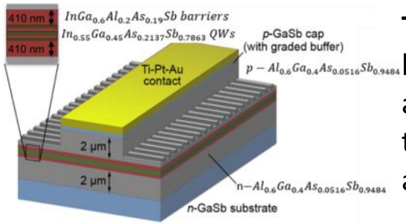




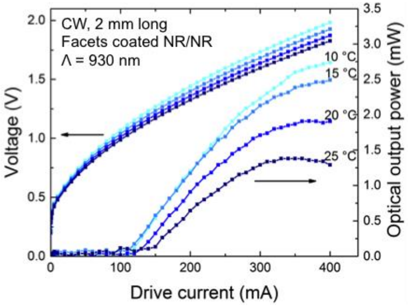
Briggs *et al.*, Optics Express 21 (2013)

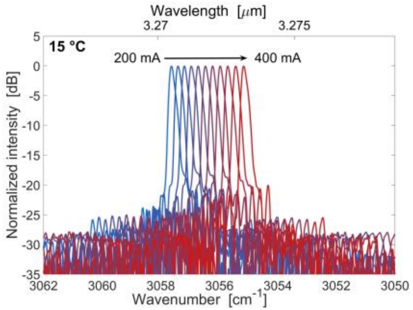
Current threshold 160 mA at 20 °C, and a tuning rate of 0.27 nm/°C
The optical spectra measured with a FTIR shows a side-mode suppression ration (SMRS) over 25 dB

3.27 µm



Three 17 nm InGaAsSb QWs separated by **30 nm quinary AlInGaAsSb barriers** and a 410 nm thick SCH layer between the upper and lower cladding layers and the QWs.





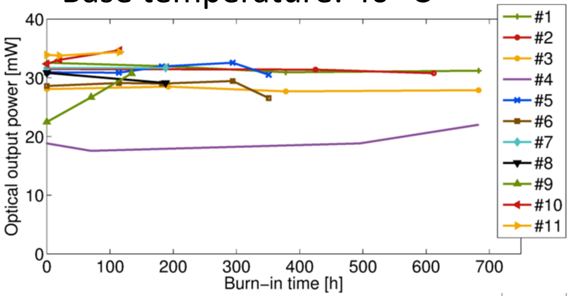
Current threshold 110 mA at 20 °C, and a tuning rate of 0.33 nm/°C
The optical spectra measured with a FTIR shows a side-mode suppression ration (SMRS) over 25 dB

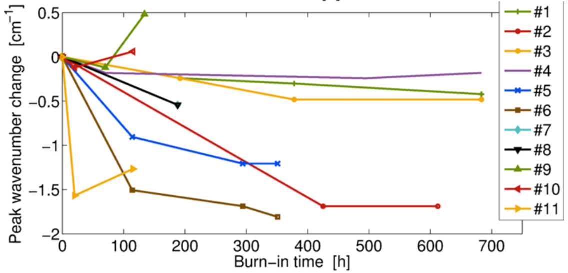
Diode performance

2.65 µm

Constant current mode: 500 mA

Base temperature: 40 °C



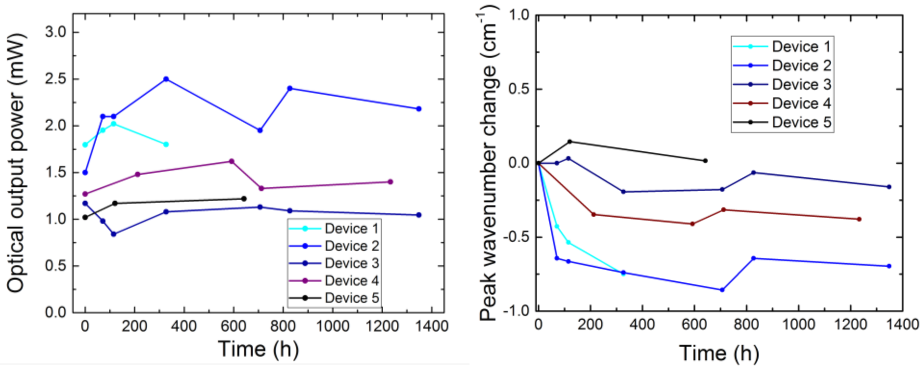


- **Peak wavenumber stabilizes after 100-200 hours**
- The change in peak wavenumber is less than 2 cm^{-1}
- Measured red-shift in wavelength emission
- Resistance increased of 3 mOhm across the laser

3.27 µm

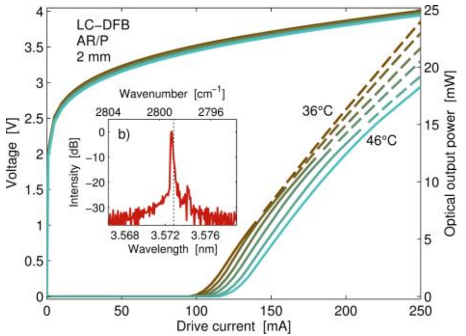
Constant current mode: 350 mA

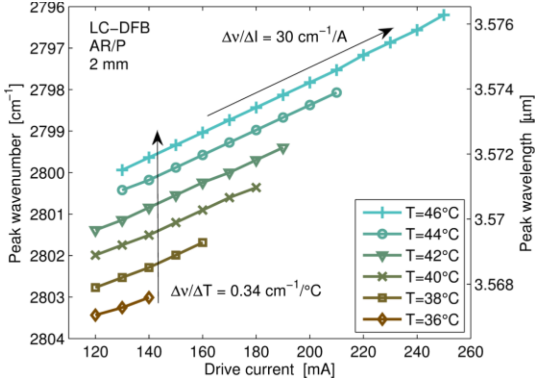
Base temperature: 30 °C



- **Peak wavenumber stabilizes after 100-300 hours**
- The change in peak wavenumber is less than 1 cm^{-1}
- Measured red-shift in wavelength emission
- Resistance increased of 17 mOhm across the laser

IC laser emitting near 3.57 µm performance

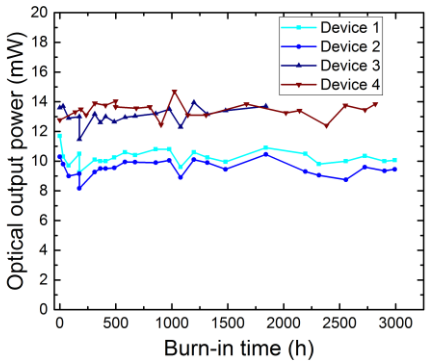


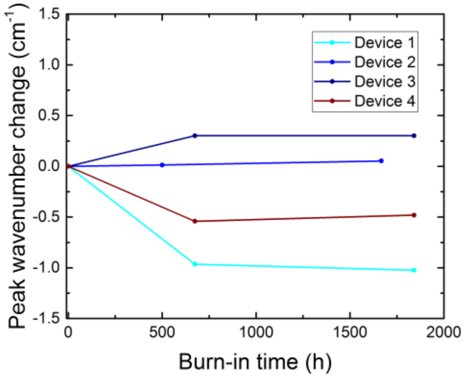


Forouhar *et al.*, Appl. Phys. Lett. 105 (2014)

Constant current mode: 200 mA

Base temperature: 40 °C





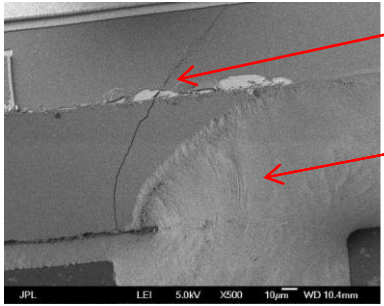
Current threshold 100 mA at 36 °C, and a tuning rate of 0.43 nm/°C

The optical spectra measured with a FTIR shows a side-mode suppression ration (SMRS) over 25 dB

- **Peak wavenumber stabilizes after 100-300 hours**
- The change in peak wavenumber is less than 1 cm^{-1}
- Measured red-shift in wavelength emission
- Resistance decreased of 6 mOhm across the laser

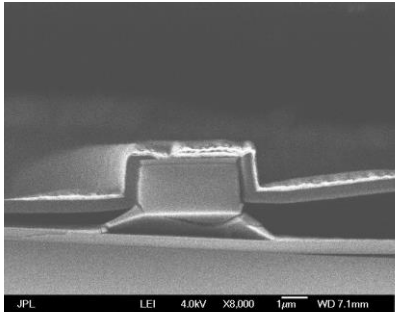
Failures

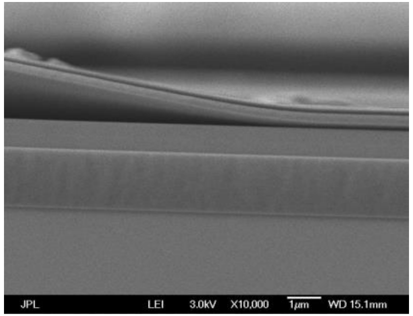
Stress due to CTE mismatch and poor solder flow



- CTE mismatch between submount and laser due to requirement in submount material.
- Poor solder flow, and the use of eutectic AuSn (hard solder) caused the device to break due to the CT mismatch between the laser and submount.
- Problem was solved using indium solder (soft solder).

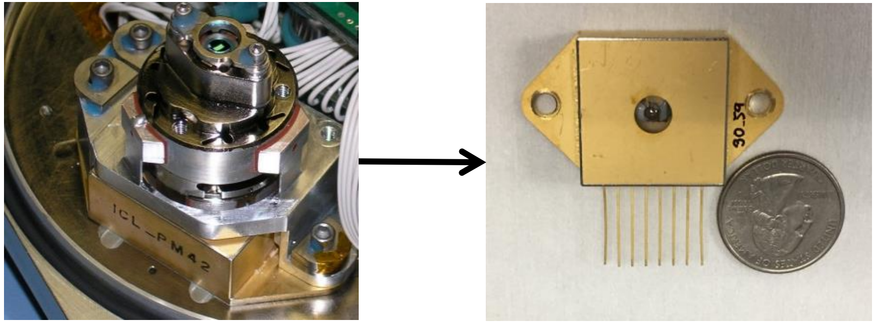
Device oxidation





- High aluminum content in cladding layers.
- Great laser performances.
- Reliability issues due to rapid oxidation of high aluminum-content layers causing delamination.
- Reduced aluminum content in cladding layers solved the oxidation issues.

Packaging of 3.27 µm laser

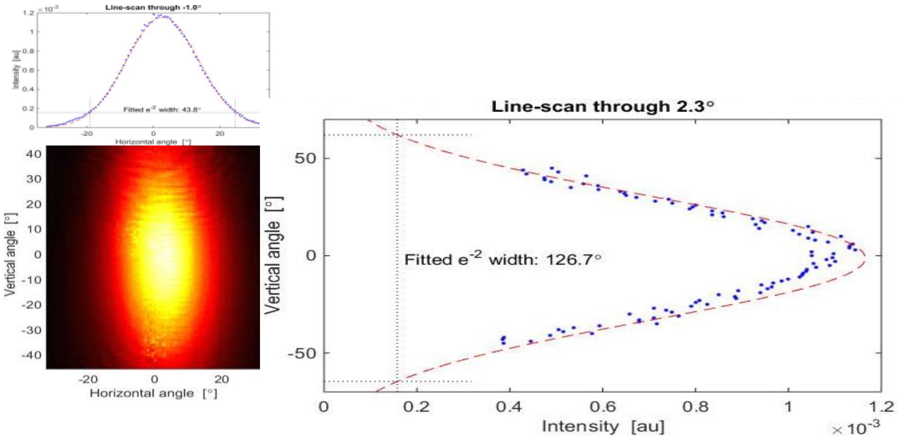


Effort in reducing size and alignment complexity, replaced 3 lens collimator with a single lens inside a package with same form factor through a collaborative effort with Achray Photonics.

Highly divergent and asymmetric beam.

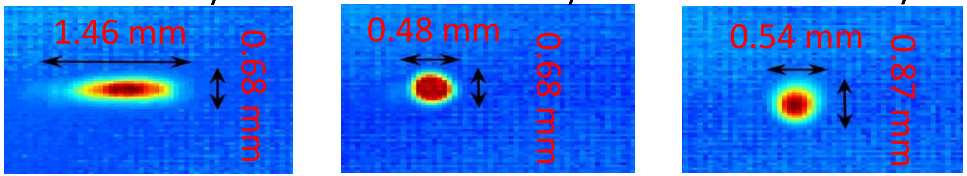
Single-lens collimator delivers outstanding beam profile measured from lensed package at Heriott cell entrance to the far mirror!

Laser far-field emission profile **before packaging**



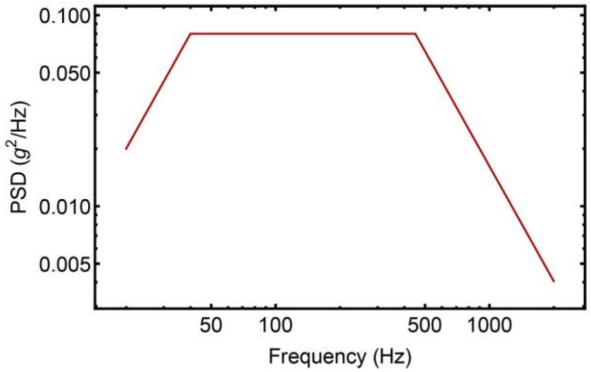
Laser far-field emission profile **after packaging**

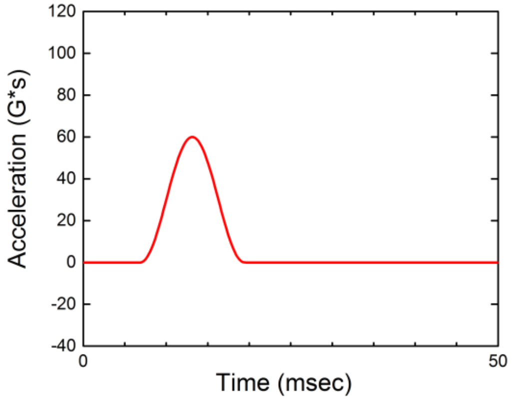
2 cm away | 12 cm away | 20 cm away



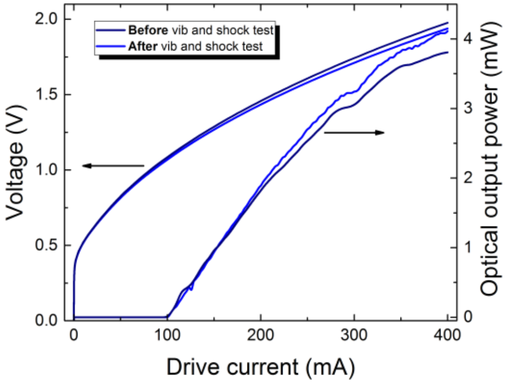
Performance – Vib and shock testing

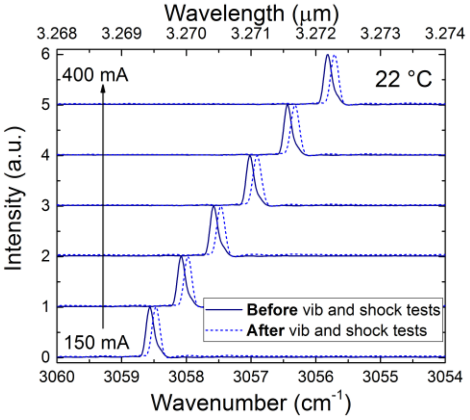
- Thermal Cycling
  - -40 °C to +80 °C, 8 cycles
- Leak Testing
  - Leak rate of 1.5 x 10^{-8} cc He/s after thermal cycling
- Random vibration based on TLS requirements
  - 20 to 40 Hz, +6 dB/octave
  - 40 to 450 Hz, 0.08 g^2/Hz
  - 450 to 2000 Hz, -6 dB/octave
- Shock loading to 60 g
  - 60 g, 10 ms, half-sine pulse
  - 3 tests per direction, 2 directions per axis
  - 18 shock loads total





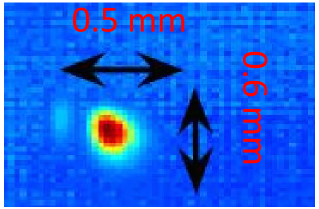
Performance – Vib and shock testing of 3.27 µm laser



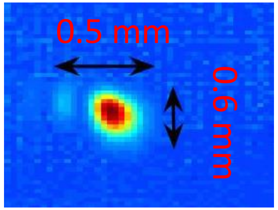


Optical beam 12 cm away from the laser package

Before environmental testing



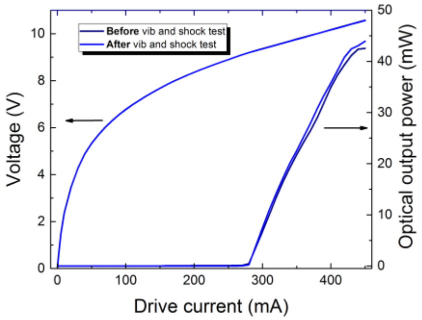
After environmental testing

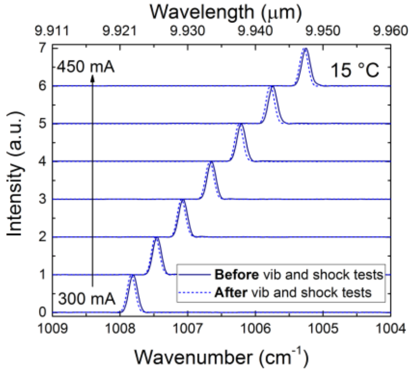


- Current threshold, voltage, and output power do not change with environmental testing
- Emitted wavelength as a function of drive current remained constant
- Optical beam wasn't affected by the environmental testing meaning the lens mounting scheme isn't affected by typical environmental conditions

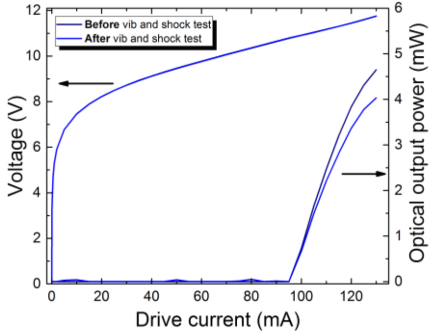
Intersubband cascade lasers up to 10 µm

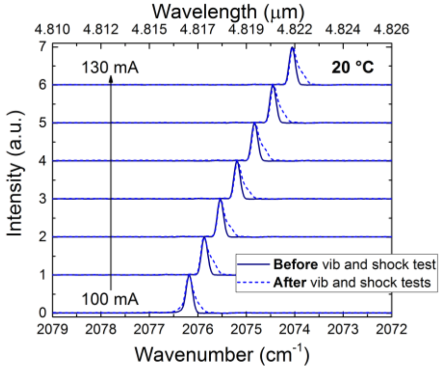
9.92 µm laser





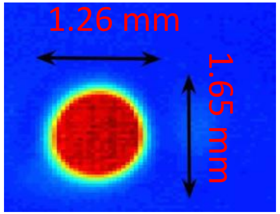
4.82 µm laser



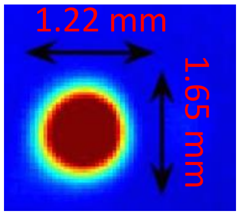


Optical beam 12 cm away from the laser package

Before environmental testing



After environmental testing



We developed semiconductor laser sources up to a wavelength of 10 µm that are suitable for space applications

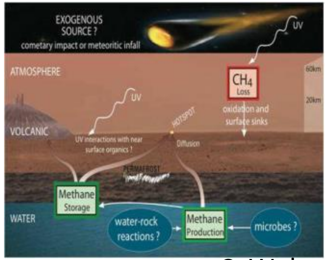
Conclusion

- We have fabricated and tested reliable lasers at 2.65 µm, 3.27 µm, and 3.57 µm
- We have developed and tested 3.27 µm semiconductor lasers that are suitable for space applications
- We have developed semiconductor lasers for space applications that covers a wide mid-IR wavelength range

Future work

- Space qualification of IC lasers
- Lifetime measurements of lasers
- Development of Venus and Saturn probes
- Development of gas sensors for the ISS and Orion
- Development of novel gas sensors for Earth and climate sciences

Planetary structure and evolution

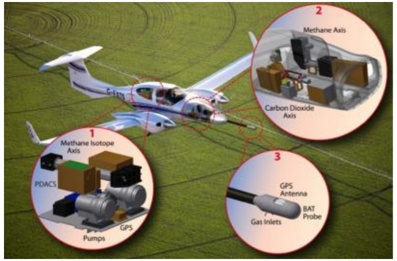


C. Webster, JPL

Human spaceflight operations

NASA

Earth and climate sciences



J. Anderson, Harvard Univ.

Liz Moyer, Univ. Chicago

Acknowledgement

- **Dr. James Gupta** and his group at the National Research Council of Canada
  - **Design and growth of GaSb-based diode lasers**
- **Dr. Jerry Meyer** and his group at the Naval Research Laboratory
  - **Design and growth of GaSb-based interband cascade lasers**
- JPL's Advanced Microfabrication and Optoelectronics group
  - **Ryan M. Briggs, Clifford Frez, Mahmood Bagheri, and Siamak Forouhar**
- The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

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