Recent Development of Component Technologies for 2 μm LIDAR at JPL

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LIDARs for Active Sensing of CO2

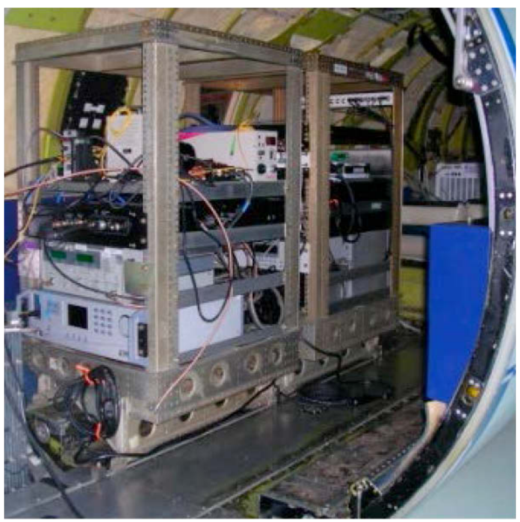
Objective:

- Global-scale atmospheric measurements of Carbon Dioxide (CO_2) and other Green House Gases with full diurnal, full latitude, all season coverage capability

Implementation:

- Use of the laser- based Integrated Path Differential Absorption (IPDA) method at 1.57 and 2.05 μm

- Airborne lasers are needed to demonstrate instrument capabilities, risk reduction and satellite measurement validation.



CO2 DIAL- Lear Jet NASA GSFC (2008- present) 1.5 μm Fiber Laser

CO2 Absorption Spectrometer- JPL(2006 - present) 2 μm CW Laser

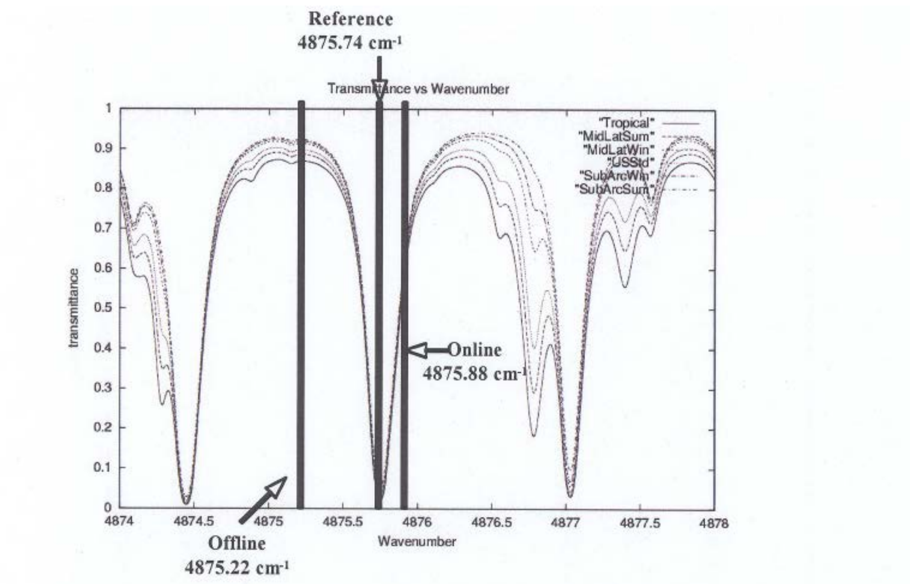
CO2 DIAL-King Air / Lear Jet NASA LaRC (2004- present) 1.5 μm Fiber Laser

Approach for Active Sensing of CO2

- CO2 Laser Absorption Spectrometers (LAS) for high accuracy measurements for detection of CO2 mixing ratio and its variability in the atmosphere.

- The 2.05 µm CO2 band is considered optimal for both strong CO_2 absorption and minimal sensitivity to variations in temperature and water vapor concentration

- Three laser Instrument
  1- Absolute frequency reference locked to a CO2 line
  2- On-line laser (Offset frequency locked to the reference laser)
  3- Off-line laser (Offset frequency locked to the reference laser)



Critical Components & Their Requirements for LAS Instrument at 2 μm

System options:

- Transmitter: Pulsed or CW
- Receiver: Direct or Coherent detection

Components and required specs:

- Airborne transmitter
  - λ ->2.05097 μm, R(30) line center
  - power -> 180 mW
  - linewidth <200KHz in 0.5 msec
  - Frequency stability 2MHz
  - tunable over 12 GHz
- Injection seed
  - λ ->2.05097 μm, R(30) line center
  - power -> 50 mW
  - linewidth <200KHz in 0.5 msec
  - Frequency stability 1MHz
- Local oscillator
  - λ ->2.05097 μm
  - power -> 50 mW
  - linewidth <200KHz in 0.5 msec
  - Frequency stability 1MHz
- Reference oscillator
  - λ ->2.05097 μm
  - power -> 30 mW
  - Frequency stability in lock loop <100KHz

- Laser amplifier (or fiber amplifier for modulated CW system)

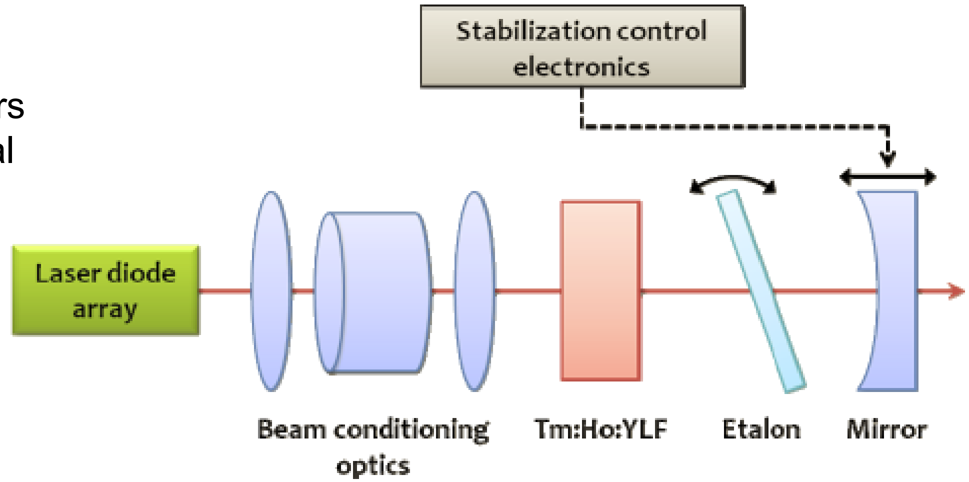
- Detectors with high gain low noise for direct detection

- Detectors with high quantum efficiency, high bandwidth for heterodyne detection

Current Technology for Lasers and JPL Approach

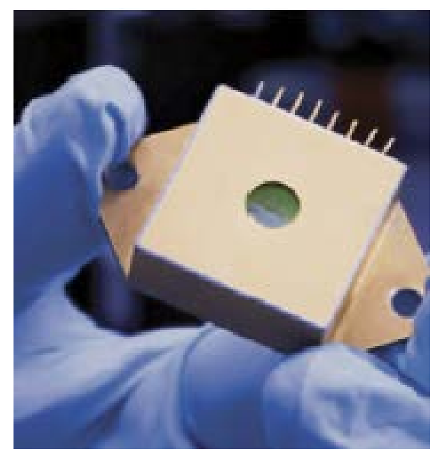
Current technology:

Diode pumped solid-state crystal lasers each in a cavity that comprises several optical elements and a piezo-electric transducer



JPL approach:

- Replace the diode pumped solid-state-laser with monolithic diode lasers at 2 μm
- Depending on the performance: Potential replacement for injection seed, master oscillator, reference oscillator, air borne transmitter, and local oscillator
- Benefit from JPL extensive experience in space qualification of semiconductor lasers and detectors (MSL)

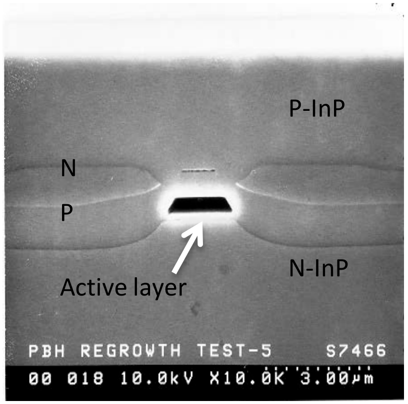


State-of-the-art Diode Lasers @ 2 μm

Choice of semiconductor laser material @ 2μm

Indium Phosphide (InP) material system

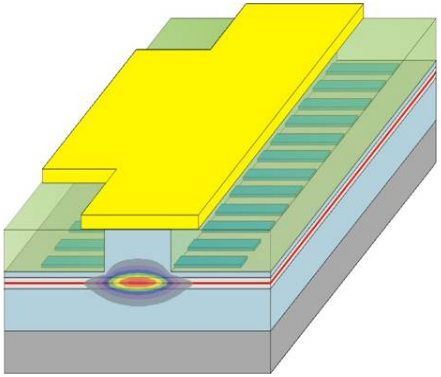
- mature technology (use in telecom) +
- suitable for monolithic architecture +
- auger recombination limits the maximum output power ~10 mW -



SEM crss-section of an InP single frequency laser.
Very advanced designs

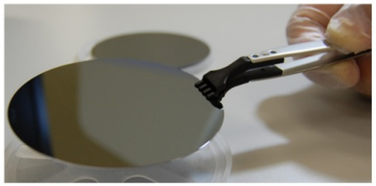
Gallium Antimonide(GaSb) material system

- higher optical power (100s of mW in multimode structure) +
- less developed material system requiring extensive fabrication development -
- difficult to fabricate single frequency lasers at high power. Max power 5-10 mW -

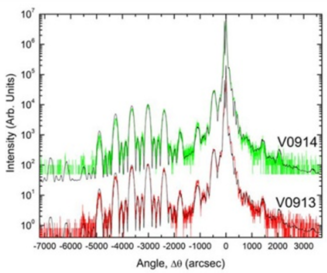


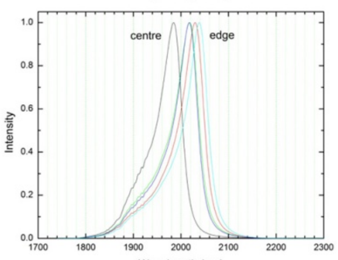
Schematic diagram of GaSb single frequency laser.
Material issues limits the design to ridge waveguide architecture

JPL Design & Fabrication flow for Diode Lasers @ 2 μm



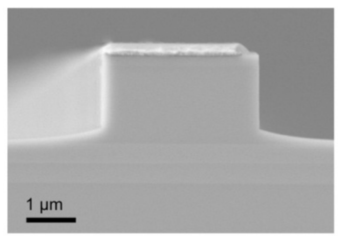
Epitaxial growth and characterization (x-ray diffraction, photoluminescence)

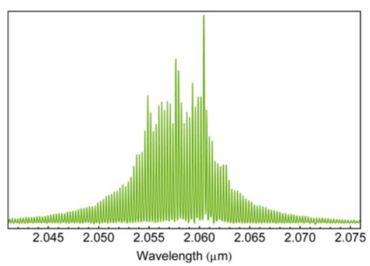




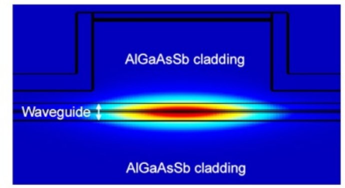
MBE grown Gallium Antimonide(GaSb) material system for laser development

Fabry-Perot laser fabrication, waveguide mode characterization

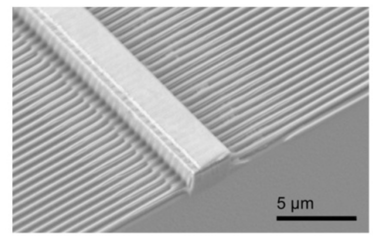


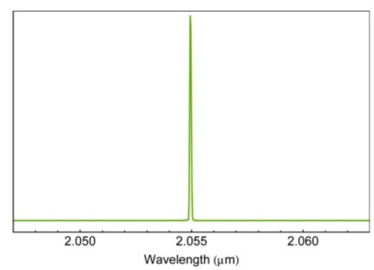


Ridge waveguide design for laser characterization and optimization



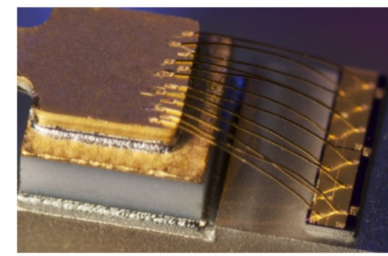
Waveguide and grating modeling, DFB laser fabrication

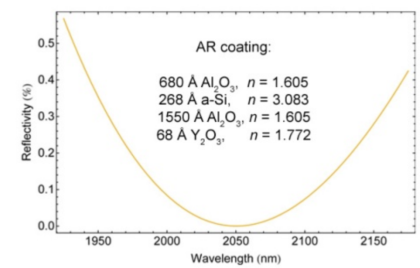




Laterally coupled grating architecture for single frequency operation

Facet coating, die attachment, and wire bonding

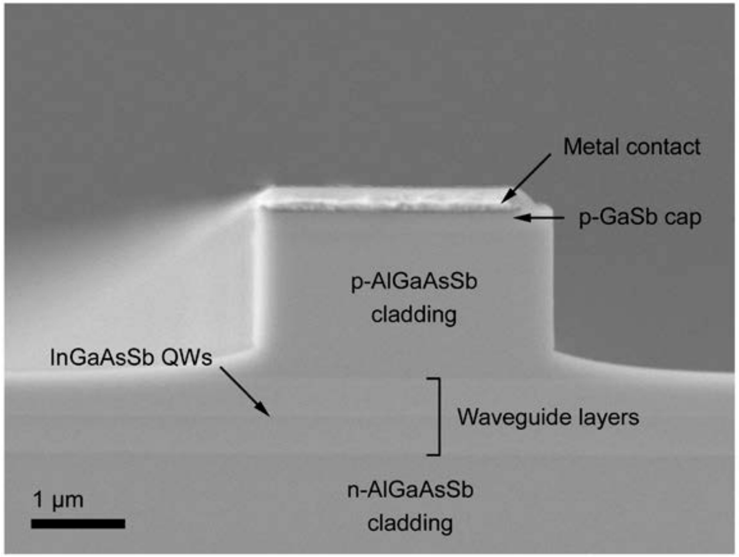




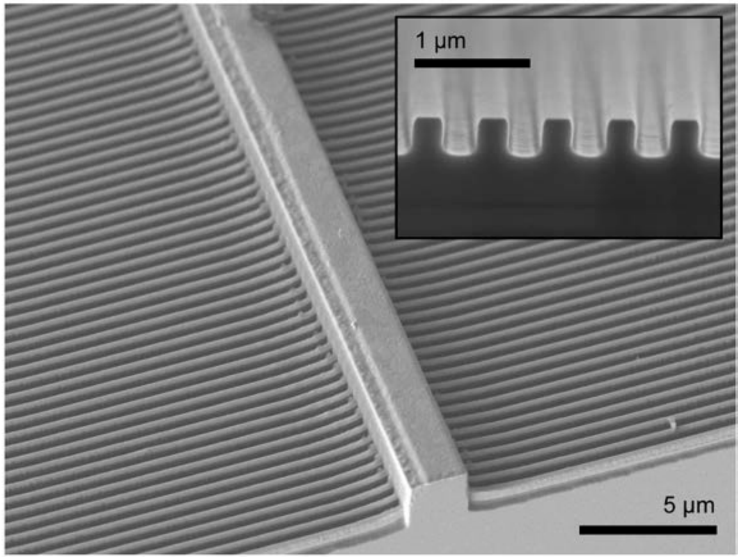
Laser mirror coating to suppress Fabry-Perot modes. Hard solder die attach

Unique and Well Controlled Fabrication

Laser ridge cross section



Laterally coupled Design



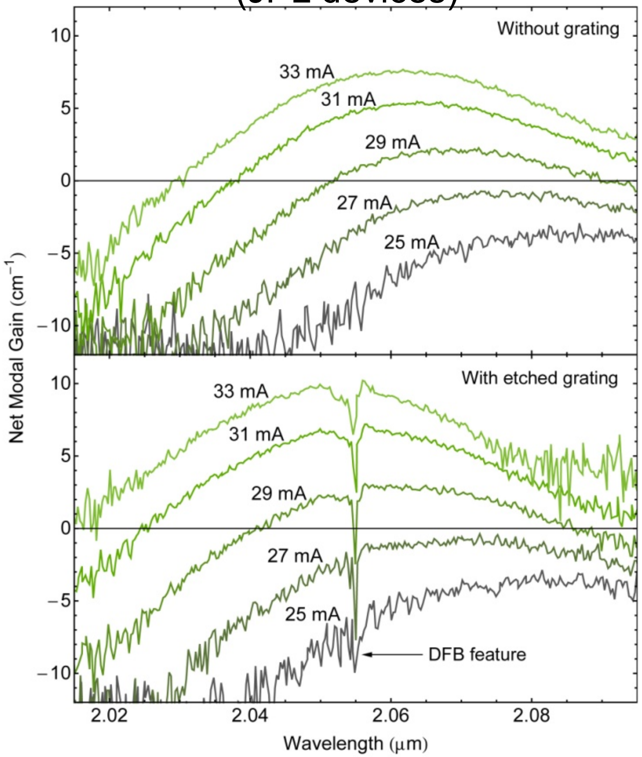
Forouhar, *et al.* APL **100**, 031107 (2012)

- High quality fabrication of Single-mode ridges etched into waveguide cladding layer

- DFB diffraction grating patterned by electron-beam lithography
- Grating dimensions are carefully controlled to set the DFB laser emission wavelength

Index-coupled (JPL) vs. Loss-coupled (conventional) Lasers

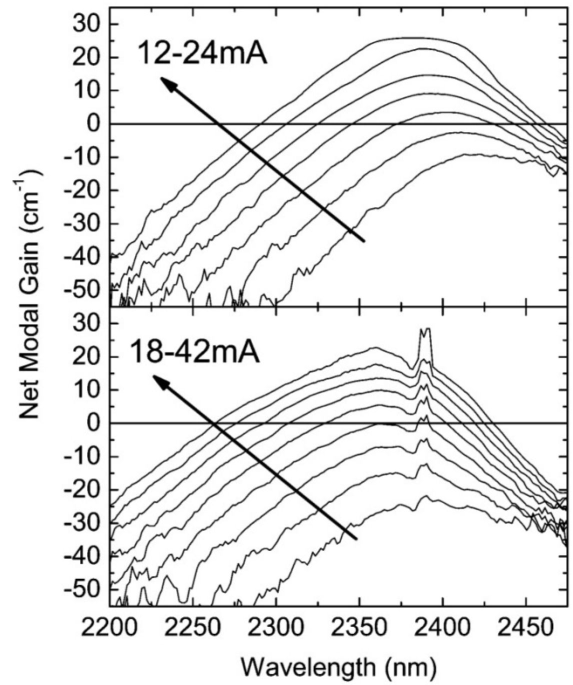
Laser gain with etched gratings (JPL devices)



- No observed increase in waveguide loss with the addition of etched gratings (loss is ~ 5 cm^{-1})
- Net gain clamps at 13 cm^{-1} (equal to facet losses)

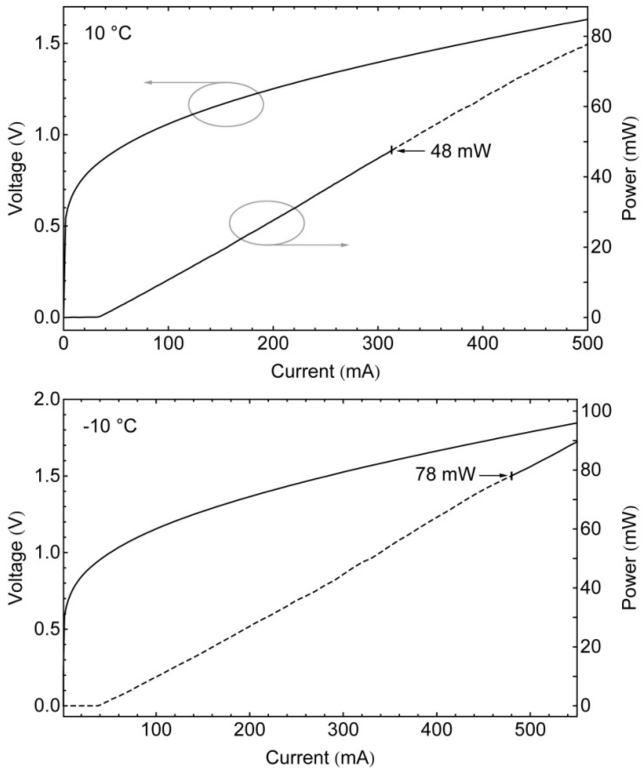
Laser gain with deposited metal gratings

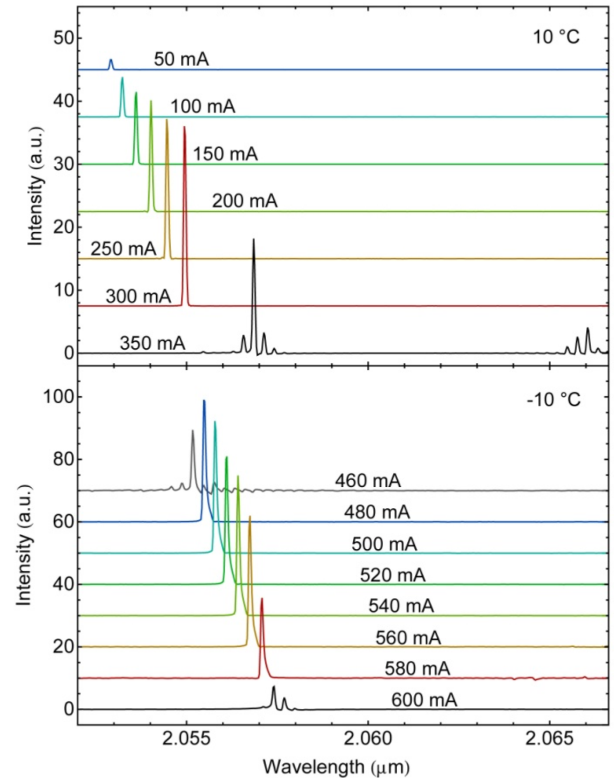
Gupta, *et al.* PTL **21**, 1532 (2009)



- Waveguide loss increases by > 10 cm^{-1} with the addition of metal gratings
- Increased threshold, decreased output power

2-μm DFB laser Performance preliminary results





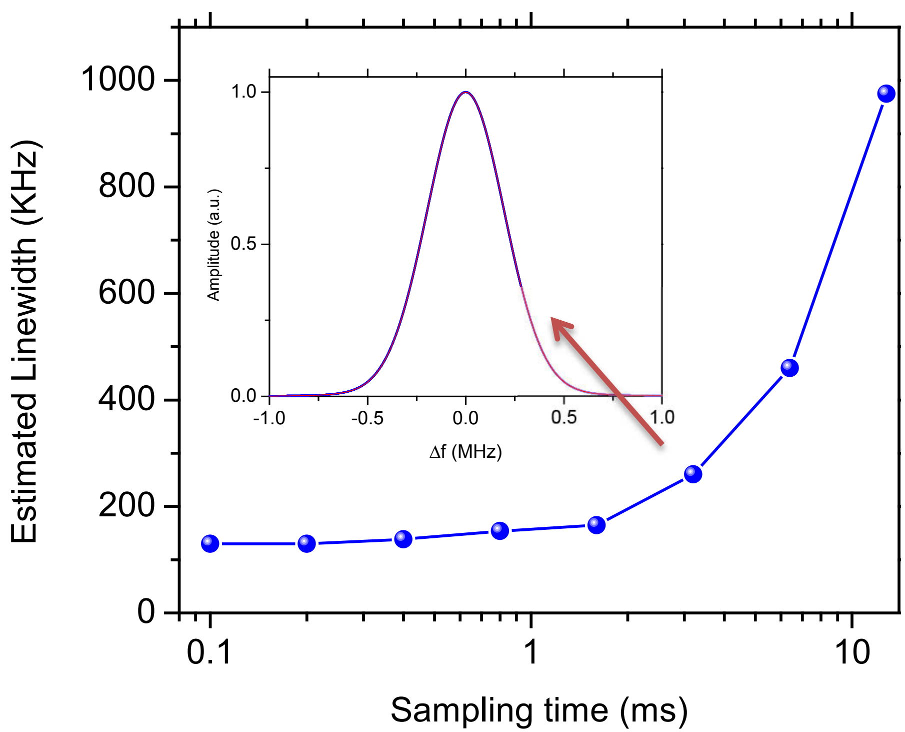
Light-current-voltage performance
Regimes of single-mode (solid line) and multimode (dashed line) emission are observed

Laser spectra vs current

- **Single-mode output exceeds 80 mW at -10 °C**
- **DFB emission wavelength tunes continuously with increasing current or temperature**
- **Thermal tuning rate is 0.20 nm/°C ~15 GHz/°C**

2-μm DFB laser Performance preliminary results cont.

Estimated laser linewidth vs. sampling time measured at 40 mW output power
(Lineshape at 6 ms sampling time as inset)



The measured lineshape profile fits very well to a voigt-profile with $w_{Gaussian}$ = 230 KHz and $w_{Lorentz}$ = 23 KHz.

- Less than <u>**100 KHz**</u> white frequency noise (Schawlow-Townes linewidth) has been measured for these DFB lasers.
- Gaussian linewidth contribution to overall lineshape is due to large contributions from 1/f noise (flicker) sources. This effect has been confirmed in frequency noise spectra.
  - The 1/f noise sources are not all internal to the laser itself. Other factors such as measurement instrument and electronics contribute to flicker noise.
- Removing flicker noise sources will significantly stabilize frequency noise fluctuations.
- Locking laser emission wavelength to a reference cell (CO_2 cell) will cancel out some of the flicker noise sources and help stabilize wavelength.
- A stabilization feedback loop will help achieve wavelength stabilities better than white frequency noise limit (< 100 KHz).

Summary- Diode Lasers @ 2 μm

- Laterally Coupled DFB GaSb-based semiconductor lasers at 2 μm wavelength meet all the performance requirements of injection seeds, local oscillators, and reference frequency lasers

- Monolithic structures with high reliability that could easily be qualified for space

- III-V semiconductor materials are inherently radiation hard

- They may meet the performance requirement of coherent laser transmitter for airborne and space borne missions

State-of-the-art Detectors @ 2 μm

The key performance parameters for the lidar application are Detectivity D*, Quantum Efficiency QE, and speed/bandwidth

InGaAs/InP detectors

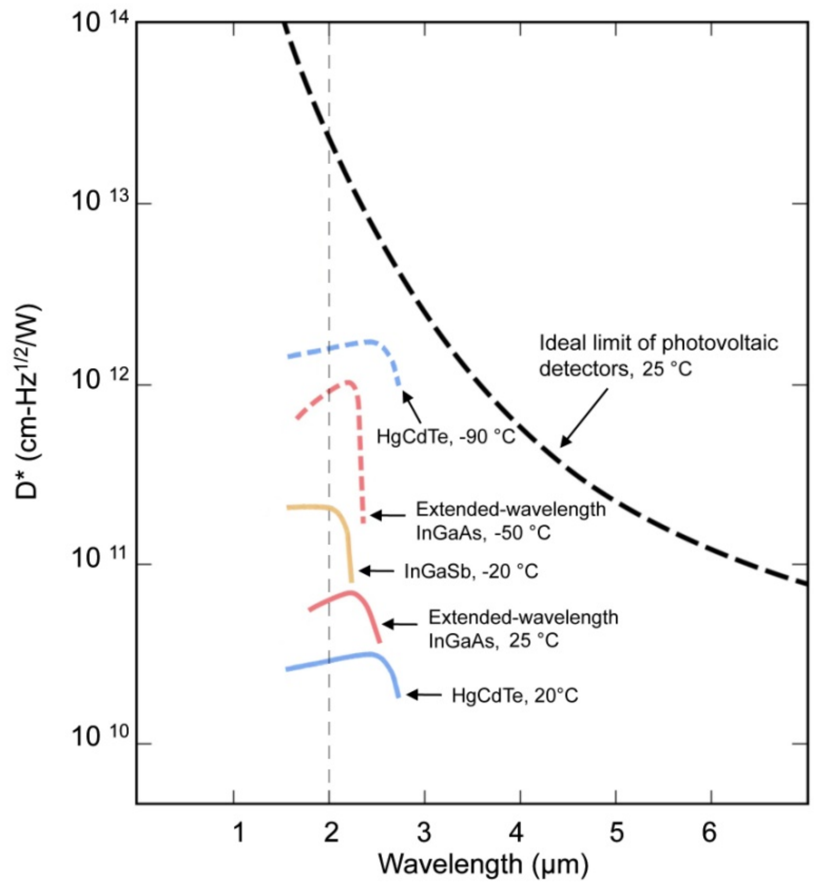
- Based on telecom technology
- Available commercially
- Wavelength extended beyond 1.57 μm by introducing strained absorption layer
- D*< 1E12 @ -50 °C

InGaAsSb/GaSb detectors

- Laboratory demonstration
- Complicated fabrication
- D*< 5E11 @ -20 °C

MCT detectors

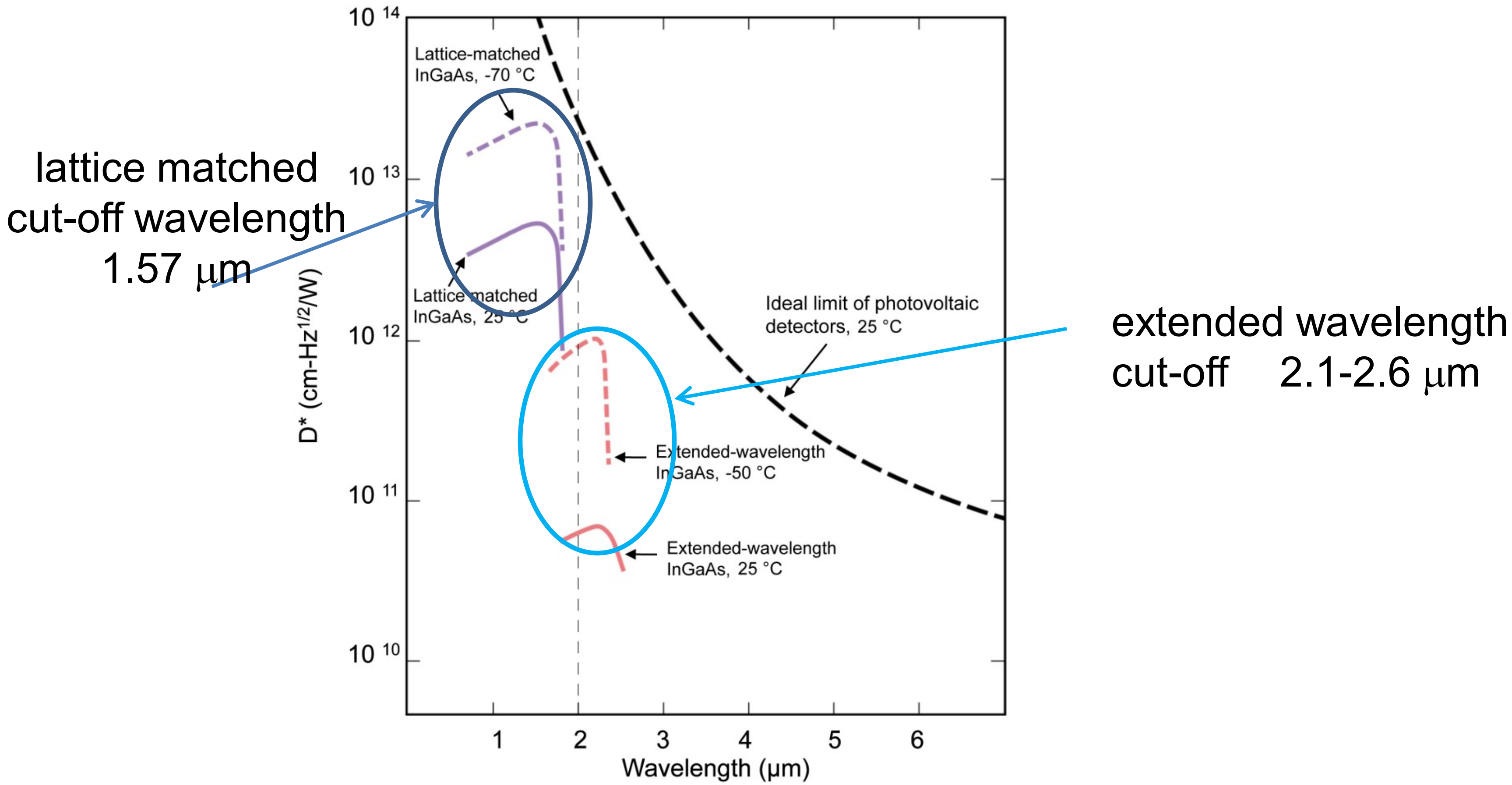
- Available commercially
- Large array format
- Low operating temperature
- D*< 2E12 @ -90 °C



Detectivity D* vs λ for available detectors

InGaAs Detector Performance

lattice matched VS extended wavelength



The performance degradation of InGaAs extended wavelength detectors at 2 μm and beyond is due to lattice mismatch between the active detector material (for absorption at 2 μm) and the InP substrate upon which it is fabricated.

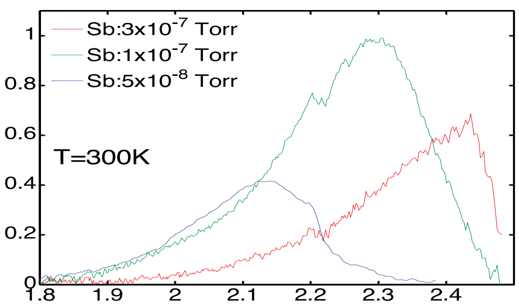
Innovative Material for 2 μm Detectors

InGaAsNSb lattice matched to InP

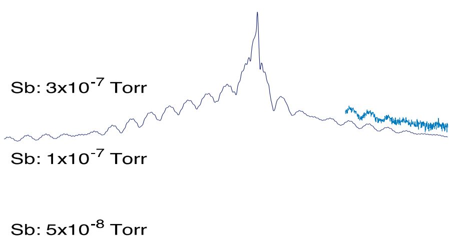
(Stanford University)

Add nitrogen N and antimony Sb to the InGaAs compound semiconductor alloy resulting in GaInNAsSb compound

Effect: Shrink the bandgap to extend the wavelength response while keeping the material lattice matched to the InP substrate



Room-temperature PL spectra of GaInNAsSb/InGaAs QW samples



(004) ω/2θ XRD scans and simulations of the GaInNAsSb/InGaAs QW samples

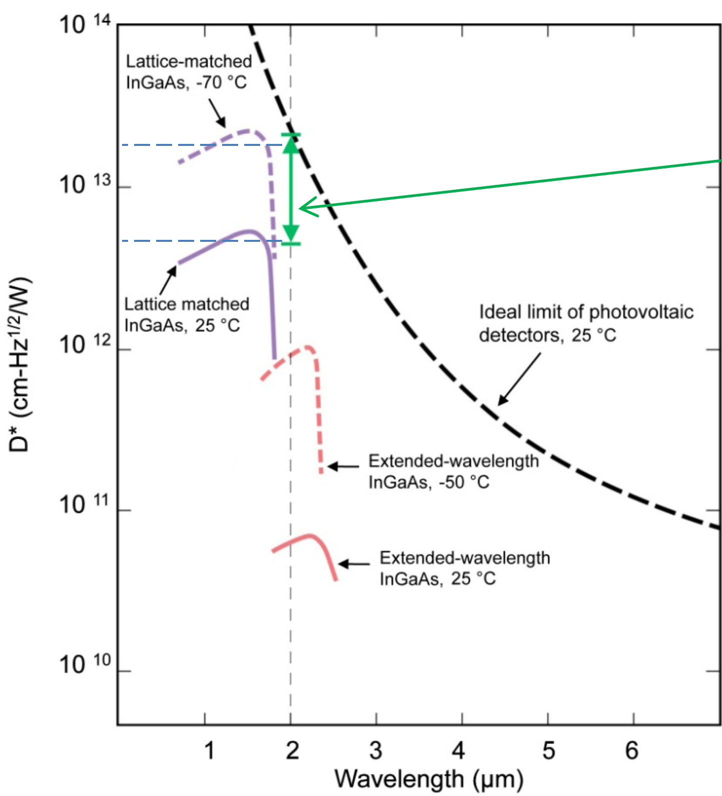
A unique property of GaInNAsSb is the band anti-crossing effect at the conduction band edge caused by degeneracy splitting between the electron energy levels of the bulk crystal and impurity levels from the nitrogen.

Potential to have a high gain Avalanche Photodiodes at 2.0-2.5 μm !!!!

Stanford University/JPL Approach

Develop detector technologies for both direct and heterodyne detection lidars in the 1.7-2.5 μm wavelength range using lattice-matched GaInNAsSb layers on InP substrates

- Demonstrate a single element GaInNAsSb *pin* detector with cutoff wavelength in the 2.0-2.5 μm range.
- Demonstrate an optimized single element 2.0-2.5 μm GaInNAsSb *pin* detector with high quantum efficiency and low dark current



Predicted performance for lattice matched GaInNAsSb detectors

$D^* > 10^{12}$ Cm-Hz$^{1/2}$W/Hz$^{1/2}$ @ 25C
NEP< 1×10^{-14} W/Hz$^{1/2}$
Detector active area diameter> 500 μm
Detector bandwidth > 200 MHz

$D^* > 10^{13}$ Cm-Hz$^{1/2}$W/Hz$^{1/2}$ if the detector is cooled via TEC

Summary and Concluding Remarks

- The component technology at 2.0 um is maturing very fast to be used for space

- Laterally Coupled DFB GaSb-based semiconductor lasers at 2 μm wavelength meet all the performance requirements of injection seeds, local oscillators, and reference frequency lasers

- They may meet the performance requirement of coherent laser transmitter for airborne and space borne missions

- Under development:

  Long term frequency stability and space qualification of the diode Lasers

  Innovative material system (GaInNAsSb) to significantly improve the performance of Coherent and Direct receivers

Thank you

Publication

1. Menzies and Tratt, "Differential laser absorption spectroscopy for global profiling of tropospheric carbon dioxide: selection of optimum sounding frequencies for high-precision measurements", Applied Optics, V42, 33, 6569-6577, (2003)
2. Spiers et al., "Atmospheric CO2 Measurements with a 2-micrometer Airborne Laser Absorption Spectrometer Employing Coherent Detection", Applied Optics, V50, 14, 2098-2111, (2011)
3. Christensen et al., "Spectroscopic Investigation of CO2 near 2.05 µm: Potential Biases Induced by Line-Mixing", accepted for publication in J. Quant. Spectroscopy.
4. Siamak Forouhar, Ryan M. Briggs, Clifford Frez, Kale J. Franz, and Alexander Ksendzov, "High-power laterally coupled distributed-feedback GaSb-based diode lasers at 2µm wavelength", Appl. Phys. Lett. 100, 031107 (2012); doi: 10.1063/1.3678187
5. "GaSb-based high-power single-spatial-mode lasers at 2.0 µm", Kale J. Franz[1], Clifford Frez[1], Jianfeng Chen[2], Yueming Qiu[1], Daniel V. Freilich[1], Leon Sterengas[2], Gregory L. Belenky[2], Siamak Forouhar[1], Conference on Lasers and Electro-optics Baltimore 2011
6. "Laterally Coupled Distributed-Feedback GaSb-Based Diode Lasers for Atmospheric Gas Detection at 2 µm", Ryan M. Briggs, Clifford Frez, Alexander Ksendzov, Kale J. Franz, Mahmood Bagheri, and Siamak Forouhar, May 2012, Conference on Lasers and Electro-optics, San Jose, 8-10 May 2012