High-power distributed feedback semiconductor lasers operating at 2.05 μm range

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Outline

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Outline

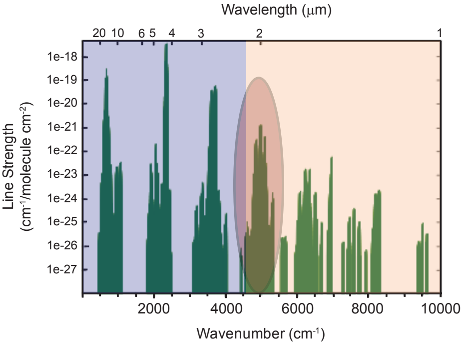
Motivation

- Integrated Path Differential Absorption (IPDA) lidar systems at both the 1.57 and 2.05 μm wavelength bands of CO_2 are being considered for space-born systems monitoring Earth atmosphere CO_2 dynamics
- The 2.05 μm band, with significantly stronger band strength, is more amenable to probing the atmosphere with weighting functions that emphasize the lowest few km above the surface
- The availability of off-the-shelf standard components, including semiconductor DFB lasers and optical amplifiers, has been a major driver in the adoption of 1.57 μm band for CO_2 lidars.
  - ✗ Current 2-μm lidar systems utilize rare-earth ion doped crystal lasers that are diode-pumped
- The recent development of high performance FPAs at mid-IR (1-4 μm) facilitates deployment of 2-μm lidar systems

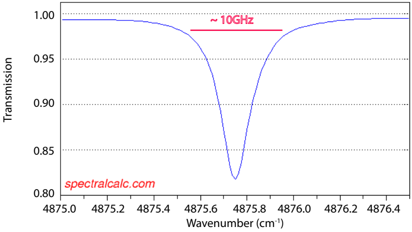
A monolithic semiconductor seed laser operating at 2 μm wavelength bands of CO_2 would greatly enhance the operability and applicability of IPDA 2-μm lidar systems for airborne applications as well as the ASCENDS Earth-orbiting applications.

Active Remote CO_2 Monitoring

CO_2 molecular absorption spectrum



Pressure broadened CO_2 absorption line



Lack of mature components (e.g. optical fiber amplifiers) beyond 2.1 μm

Smaller absorption strength $< 2\ \mu$m

The absorption spectrometer uses an on/off target gas absorption line to infer concentration

Lasers with reproducible tunability larger than absorption line width simplify system design

Semiconductor Lasers for Injection Seeding Applications

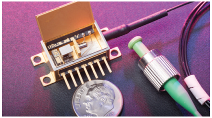
Solid-state lasers

- ✓ High output power
- ✓ Long coherence length (narrow linewidth)
- ✓ Circular beam ($M^2 \sim 1$)
- ✗ Limited tuning range <10 GHz
- ✗ Slow frequency modulation speeds <10 KHz
- ✗ Large thermal budget

Lockheed Martin Coherent Technologies METEOR laser

Semiconductor lasers

- ✓ Compact
- ✓ No moving parts (less susceptible to vibrations)
- ✓ Large tuning range >150 GHz
- ✓ Fast frequency and amplitude modulation speeds >1 GHz
- ✓ Low maintenance cost
- ✗ Larger linewidth



JPL's 2-μm butterfly package

Semiconductor laser's compact size, low thermal mass, and rugged architecture makes it highly suitable for airborne and space applications

DFB Semiconductor lasers for 2.05 μm lidar systems

Laser requirements

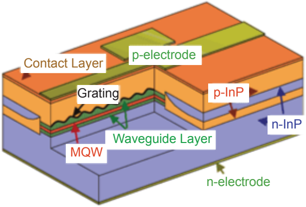
PM fiber output
$\sim$30 mW output power
$<$100 KHz laser linewidth

Strained InP lasers have limited output power

GaSb-based structures: no regrowth techniques

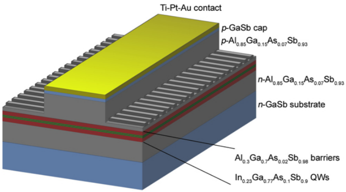
GaSb-based structures enable high power semiconductor lasers at mid-IR

Schematic representation of a conventional DFB structure using regrowth



T. Sato *et al. IEEE photon. Technol. Lett.* 20 (2008).

JPL's solution: laterally coupled DFB structure

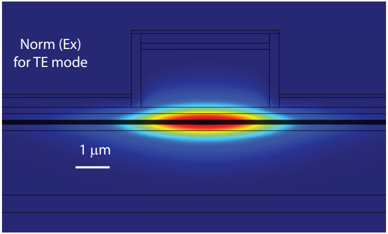


S. Forouhar *et al. Applied Physics Letters.* 100 (2012).

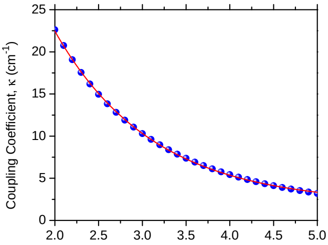
Laterally-coupled DFB InGaAsSb/AlGaAsSb multiple quantum well structures on GaSb was chosen as an alternative approach to achieve power requirements.

DFB Semiconductor lasers for 2.05 μm lidar systems

Calculated optical mode

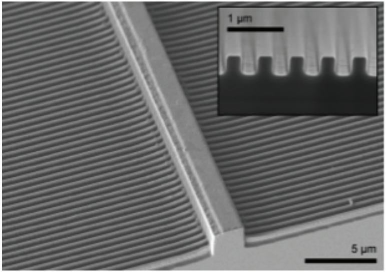


Calculated effective coupling strength



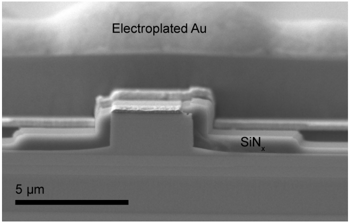
- Single-mode optical waveguides are etched into low-index cladding layer
- Second order gratings are etched along side ridges

  Helps suppress second DFB mode



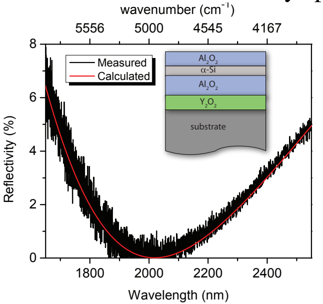
Laterally coupled GaSb-based semiconductor DFB lasers

LC-DFB laser after SiNx deposition and electroplating

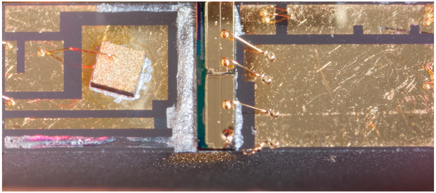


- SiN_x isolation layer deposited by PECVD, followed by electroplating of thick Au top contacts
- Anti-reflection coating layer is applied to front facet
- Back facets are protected by passivation layers

Calculated/measured reflectivity spectra

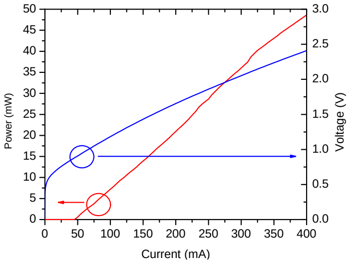


Mounted laser on submount

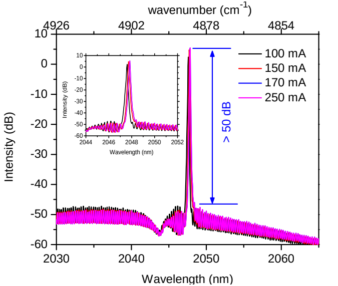


DFB Laser Performance

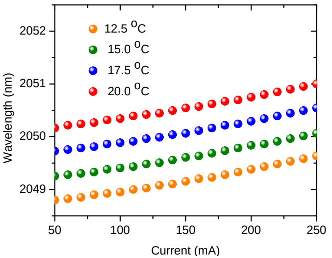
Output power versus input current

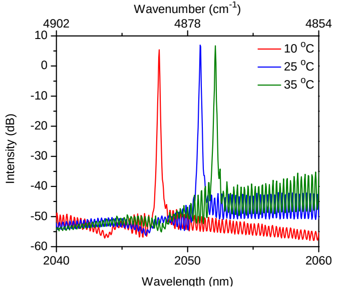


Lasing spectrum vs. bias current and temperature



Wavelength tuning versus input current





2.05 μm Linewidth Measurement Techniques

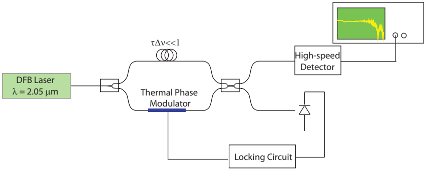
Heterodyne technique

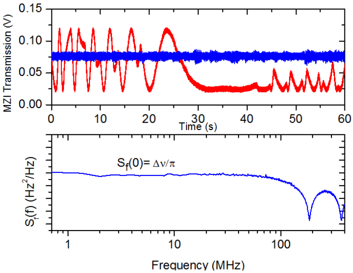
- ✓ Beat two similar laser with small frequency offset and look at the beating spectrum
- ✓ Relatively simple to implement
- ✗ Requires very stable lasers to minimize frequency drift

Self-delayed homodyne technique

- ✓ Beat one laser with its delayed replica
- ✓ Is insensitive to frequency jitter
- ✓ Simple to implement
- ✗ Requires long (>20 km) of single mode optical fiber

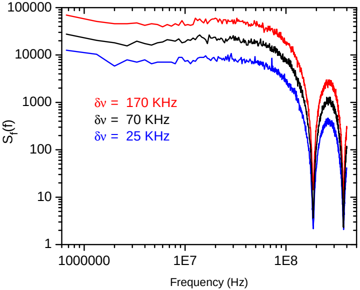
Frequency noise spectrum measurement setup



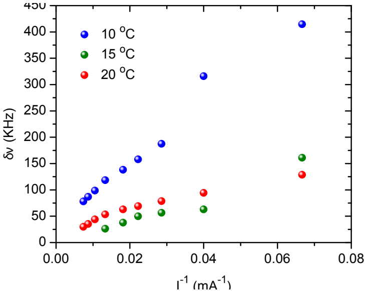


Laser Linewidth

Measured frequency noise spectrum at different bias current



Extracted Schallow-Townes linewidth versus injected current



$$S_i(f) = (2\pi\tau_0\Delta i)^2 sinc(\tau_0 f)^2 S_v(f)$$
$$S_v(f) = \frac{\delta\nu}{\pi}$$

Linewidth $<$ 30 KHz was measured for these lasers. The spectral purity is due to the small linewidth enhancement factor of this material system, long optical cavity and close to unity κL.

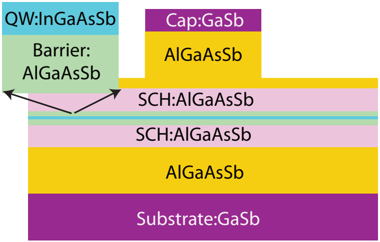
Fiber-based Transmitters for Lidar Applications

All-fiber lidar architecture

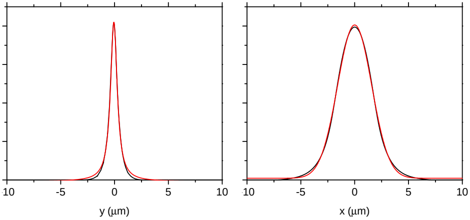
- More compact and robust transmitter
- Easier to maintain (no optical alignment needed)
- Less susceptible to environmental vibrations
- Allows to use fiber amplifiers
- Using polarization maintaining optical fibers minimizes polarization drifts resulting in more sensitive measurements

Laser Output Farfield Pattern

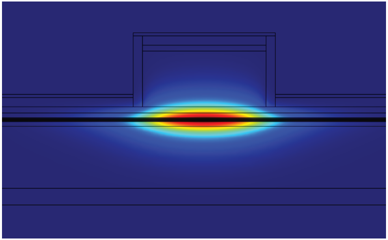
Heterostructure composition



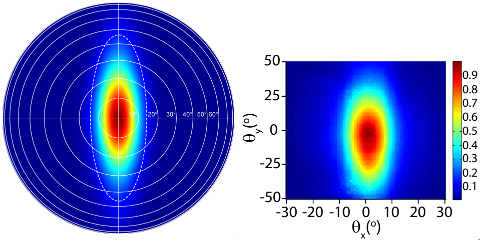
Laser mode near-field parallel (left) and orthogonal (right) to growth direction



Calculated optical mode

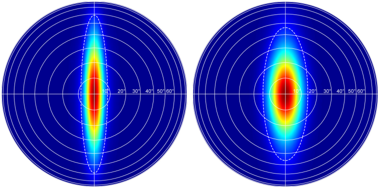


Laser mode far-field pattern

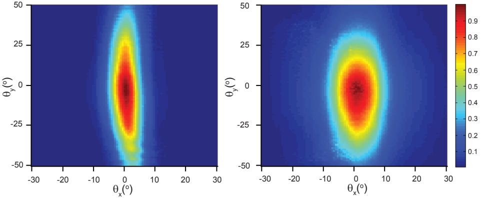


Laser Farfield Optimization

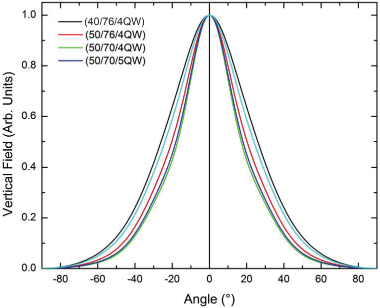
Calculated farfield pattern for epi-structures with different Al content



Measured garfield pattern for lasers with epi-layers with different Al content



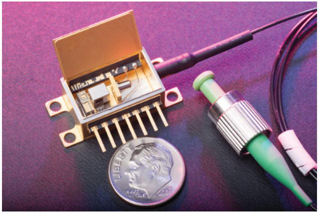
Calculated farfield pattern for epi-structures with # of QWS / SCH layer thickness/composition



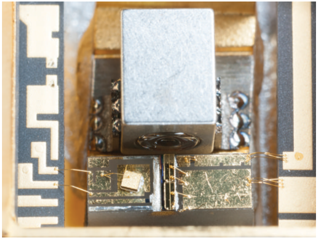
Laser fast axis can be engineered by modifying separate confinement heterostructure (SCH) layer thickness and composition.

Butterfly

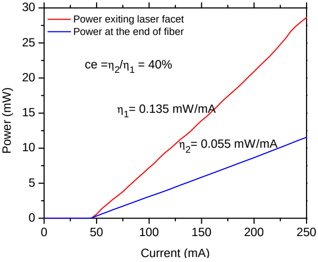
2.05 μm semiconductor laser butterfly package



2.05 μm butterfly components with integrated optical isolator



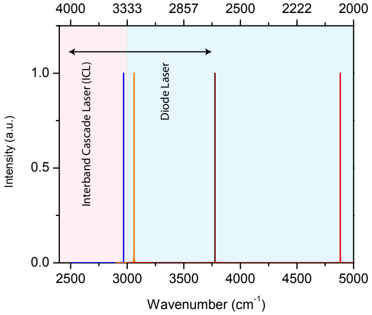
Measured coupling efficiency



40% coupling efficiency is demonstrated
>60% coupling efficiency can be achieved using double acylindrical lens with a focusing lens (3 lens scheme)

JPL Semiconductor Laser Capabilities

JPL semiconductor laser inventory



- The GaSb based diode lasers cover a wide spectral range (2-3.5 μm)
- Beyond 3 μm, GaSb-based interband cascade lasers (ICLs) perform better (higher power)

- We have successfully fabricated and delivered semiconductor lasers to a variety of different NASA missions
- End-to-end laser fabrication capability
- Space-qualification for semiconductor lasers
- Record high output power single mode semiconductor lasers in the mid-IR range
- Reliability measurement for semiconductor lasers

Conclusion

- ✓ High power fiber-pigtailed semiconductor lasers at 2.05 μm range have been realized
- ✓ The lasers show excellent side-mode suppression and spectral purity
- ✓ The lasers have less than 100 KHz natural linewidth
- ✓ The butterfly package modules with fiber-coupled output power facilitates implementation of fiber-based optical transmitters for airborne and space applications
- ✓ The polarization maintaining (PM) output fiber removes uncertainties associated with polarization drifts and improve measurement sensitivity

Acknowlegements

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