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

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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 Erbium doped fiber amplifiers (EDFA), 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 2 µm MCT APDs as well as Thulium doped fiber amplifiers (TDFA) facilitate deployment of 2-µm lidar systems

A monolithic semiconductor seed laser operating at 2.05 µm wavelength is extremely relevant for airborne and future Earth-orbiting CO$_2$ IPDA lidars.
Active Remote CO₂ Monitoring

CO₂ molecular absorption spectrum

Pressure broadened CO₂ absorption line

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.

Smaller absorption strength < 2 µm
Semiconductor Lasers for Injection Seeding Applications

Solid-state lasers

✓ High output power
✓ Long coherence length (narrow linewidth)
✓ Circular beam (M² ~ 1)

✗ Limited tuning range ~ 10 GHz
✗ Slow frequency modulation speeds <10 KHz
✗ Large thermal budget

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

Lockheed Martin Coherent Technologies METEOR laser

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.
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
DFB Semiconductor Lasers for 2.05 $\mu$m Lidar Systems

**Motivation**

High Power Semiconductor Lasers

**Introduction**

Fiber-pigtailed Laser Modules

**Conclusion**

**Laser requirements**

PM fiber output

$\sim$30 mW output power

$<100$ KHz laser linewidth

**A conventional DFB structure**

Strained InP lasers have limited output power

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

GaSb-based laser diodes enable a wide spectral range in the mid-IR (diodes: 2-3 $\mu$m, ICLs 3-6 $\mu$m)

**Laterally coupled DFB structure**

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 \( \mu \text{m} \) Lidar Systems

Calculated optical mode

- Single-mode optical waveguides are etched into low-index cladding layer
- Second order gratings are etched along side ridges
  
  Helps suppress second DFB mode
- Lithographically defined grooves control the emission wavelength
- Standard III/V processing techniques
Laterally Coupled GaSb-based Semiconductor DFB Lasers

LC-DFB laser after SiN\textsubscript{x} deposition and electroplating

- SiN\textsubscript{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

Wavelength tuning versus input current

Lasing spectrum vs. bias current and temperature
2.05 µm Laser Butterfly Packages

2.05 µm semiconductor laser butterfly package

2.05 µm butterfly components with integrated optical isolator

40% coupling efficiency is demonstrated

>60% coupling efficiency can be achieved using double acylindrical lens with a focusing lens (3 lens scheme)
2.05 \( \mu m \) 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

![Diagram of frequency noise spectrum measurement setup]

DFB Laser \( \lambda = 2.05 \mu m \)
\[ \tau \Delta \nu \ll 1 \]
Thermal Phase Modulator
Locking Circuit
High-speed Detector

\[ S(0) = \Delta \nu / \pi \]
Laser Linewidth Measurement

Measured frequency noise spectrum at different bias current

**\( S_i(f) = (2\pi \tau_0 \Delta i)^2 \text{sinc}(\tau_0 f)^2 S_v(f) \)**

**\( S_v(f) = \frac{\delta \nu}{\pi} \)**

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 \( \kappa L \).
Laser Linewidth Measurement: Heterodyne setup

**Beating a experiment setup**

- 2.05 µm diode
- Inline optical isolator
- Tm,Ho:YLF laser locked to CO2 line center
- High speed detector
- Spectrum Analyzer
- Oscilloscope

**Beating spectrum (left) and Fast Fourier Transform (FFT) of time traces**

- Frequency (MHz) range: 2900 to 2930
- Power (dBm) range: -30 to -70
- Frequency (MHz) range: -2 to 2
- Power (a.u.) range: 0.0 to 1.0

*Details:
- 9.94 δν
- 3.2MHz
- 20dB
JPL Semiconductor Laser Capabilities

Figure: 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
- Beyond 4 µm, demonstrated QCLs with record low power consumption (<1 W)

- 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
✓ Mid-IR semiconductor lasers operating in the 2-5 μm wavelength range offer a compelling technology for remote sensing lidar applications

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