

# Monolithic high power semiconductor seed lasers near 2.05 $\mu\text{m}$

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**Abstract:** We report on the development and demonstration of a compact 2  $\mu\text{m}$  semiconductor seed laser for CO<sub>2</sub> lidar instruments. Our monolithic high-power fiber pigtailed semiconductor seed laser will greatly enhance the operability and applicability of IPDA lidar systems for high spatial and temporal resolution CO<sub>2</sub> airborne measurements as well as future Earth-orbiting CO<sub>2</sub> measurement missions. The compact semiconductor transmitter has a suitably narrow linewidth (<100 KHz) and enables flexible tuning (>150 GHz) over several CO<sub>2</sub> absorption lines in the 2.05  $\mu\text{m}$  band. The frequency agility and multi-format modulation capability of the this technology, its small size and compatibility with standard DFB lasers at the telecom band paves the way for adoption of the attractive 2.05  $\mu\text{m}$  band for CO<sub>2</sub> profiling and measurements.

**Keywords:** CO<sub>2</sub> lidar, active sensing, semiconductor laser.

## 1. Introduction

The National Research Council's 2007 Earth Science decadal survey has recommended the Active Sensing of CO<sub>2</sub> Emissions over Nights, Days and Seasons (ASCENDS) [1] as a follow-on mission to passive CO<sub>2</sub> measurement missions (e.g., the current AIRS/Aqua and the near-term OCO-2/OCO-3 satellite systems) to determine the location and strength of the source and sinks of atmospheric CO<sub>2</sub>. During the past decade, teams from JPL [2, 3] GSFC [4] and NASA LaRC [5, 6] have developed and flown airborne IPDA lidars for atmospheric CO<sub>2</sub> measurements. The GSFC [4] and LaRC [5] lidar systems operate in the 1.57  $\mu\text{m}$  band, while the JPL [3] and the other LaRC [6] system operate in the 2.05  $\mu\text{m}$  band. A great deal of useful experience and design insight has been gained as a result of the participation of these IPDA lidars in multiple flight campaigns.

The availability of fiber-pigtailed components at the 1.57  $\mu\text{m}$  band allows an implementation of an all fiber-based IPDA lidars with no free-space component [4, 5, 7]. This is preferred for air-borne and space borne systems as it is more compact and robust and less susceptible to environmental fluctuations. Recently, there has been significant progress in the development of high power fiber amplifiers operating at the 2  $\mu\text{m}$  wavelength [8]. However, to-date semiconductor DFB lasers operating in the 2.0  $\mu\text{m}$  wavelength range have remained relatively undeveloped due to lack of telecom or wide-spread metrology applications.

A monolithic fiber-pigtailed semiconductor seed laser operating at 2  $\mu\text{m}$  will greatly enhance the operability and applicability of IPDA lidar systems for high spatial and temporal resolution CO<sub>2</sub> airborne measurements as well as future Earth-orbiting CO<sub>2</sub> measurement missions.

## 2. Fiver-pigtailed semiconductor lasers operating at 2.05 $\mu\text{m}$

Our DFB lasers are based on InGaAsSb strained-quantum wells (QWs) with AlGaAsSb waveguide and cladding layers on GaSb substrates. InP material system, a mature laser platform due to its widespread application in the telecomm industry, has been used for making lasers emitting at 2.0  $\mu\text{m}$ . However, state-of-the-art InP-based semiconductor lasers operating at the 2.0  $\mu\text{m}$  band have limited output power due to increased Auger recombination rates and other loss mechanisms at longer wavelength [9, 10]. Besides, GaSb-based type-I QW diode lasers designed to operate in the spectral region from below 2  $\mu\text{m}$  to above

3  $\mu\text{m}$ , have shown excellent performance as compared to their InP counterpart [11, 12]; GaSb based semiconductor lasers at 2.0  $\mu\text{m}$  and beyond show nearly twice the conversion efficiencies of those of InP-based lasers emitting near 1.9 - 2  $\mu\text{m}$ .

After characterization and an initial reliability test, the submounts are soldered onto a temperature controlled heat sink and packaged inside a standard 14-pin butterfly package with a PM1950 Nufern output optical fiber (polarization maintain optical fiber with transmission between 1850-2200 nm). A single element optical lens is used to image the mode of the laser onto the facet of the optical fiber. An integrated single-stage optical isolator and anti-reflection (AR) coated optical elements are used to suppress and minimize optical feedback into the laser cavity and avoid potential instabilities and maintain laser spectral linewidth[13]. Figure 1(a) shows the output power and the corresponding voltage across the PN junction of a semiconductor DFB laser measured at the end of the output optical fiber measured at different heat sink temperatures. The lasers show a threshold current density of  $450 \text{ Acm}^{-2}$ , that indicates the high quality of material growth and device fabrication. The extracted slope efficiency from the end of the optical fiber is  $0.055 \text{ mWmA}^{-1}$  that corresponds to a 40% fiber coupling efficiency considering a measured  $0.135 \text{ mWmA}^{-1}$  slope efficiency from the emitting laser facet.

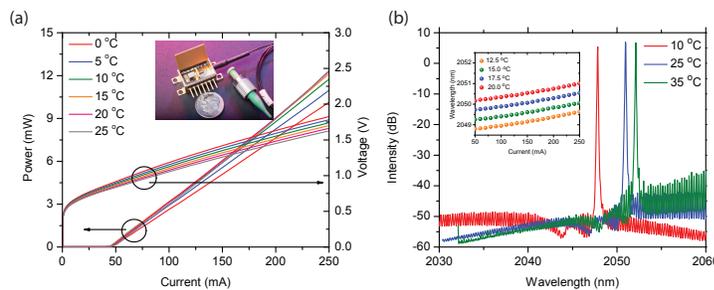


Figure 1. (a) LIV curve of the packaged module with the package layout as inset. (b) Lasing spectra of the packaged laser at different heat sink temperature at 250 mA input current, current and temperature tuning characteristics are shown as an inset showing more than 1 nm continuous tuning.

Figure 1(b) shows optical output spectra collected from the optical fiber end measured at different heat sink temperature at 250 mA input current with current and temperature tuning characteristics shown as an inset. The DFB lasers show single mode behavior with better than 50 dB of side-mode suppression ratio (SMSR). The lasers exhibit stable and constant wavelength ( $\lambda$ ) tuning by  $d\lambda/dT = 0.18 \text{ nmK}^{-1}$  over a large current and temperature range with excellent side-mode suppression ratios and over 150 GHz mod hop free tuning capability.

The current tuning capability enables a variety of high-speed frequency sequencing and switching formats. This is important for high precision  $\text{CO}_2$  lidar measurement schemes that require near-simultaneous measurements at multiple wavelengths in the vicinity of the target absorption line in order to infer column  $\text{CO}_2$  concentration. The optical output shows a linear polarization along the slow axis of the optical fiber with better than 20 dB extinction over the operating current and temperatures.

The Schawlow-Townes linewidth of these lasers was measured using the coherent frequency discriminator technique with a fiber Mach-Zehnder interferometer [14]. The block diagram of the frequency discriminator measurement setup is depicted in Fig. 2(a). It consists of a fiber-based Mach Zehnder interferometer. By using a slow thermal phase modulator (<10 Hz bandwidth), the interferometer is locked at one of its quadrature points and the optical frequency variations are linearly converted into intensity modulations that are then detected using a fast detector [15]. Polarization drifts are suppressed by using polarization maintaining optical fibers in the interferometer.

By measuring the PSD of the Mach-Zehnder interferometer output photocurrent, the frequency independent part of the measured spectrum is due to the laser spontaneous emission or Schallow-Townes

laser linewidth. Figure 2(a) shows three PSD spectra of the frequency fluctuations of a fiber-pigtailed 2.05  $\mu\text{m}$  laser measured at 60 mA, 70 mA and 120 mA corresponding to a linewidth of 170 KHz, 70 KHz and 25 KHz, respectively. The spectra in figure 2(a) demonstrate three distinct regions. The frequency range between 3-10 MHz where the spectrum is flat is used to extract laser linewidth due to spontaneous emission noise. The nulls at 185 MHz correspond to a 5.4 ns delay ( $\tau_0$ ) between the arms of the interferometer. Figure 2(b) shows the extracted laser linewidth as a function of input current at three different laser heat-sink temperatures.

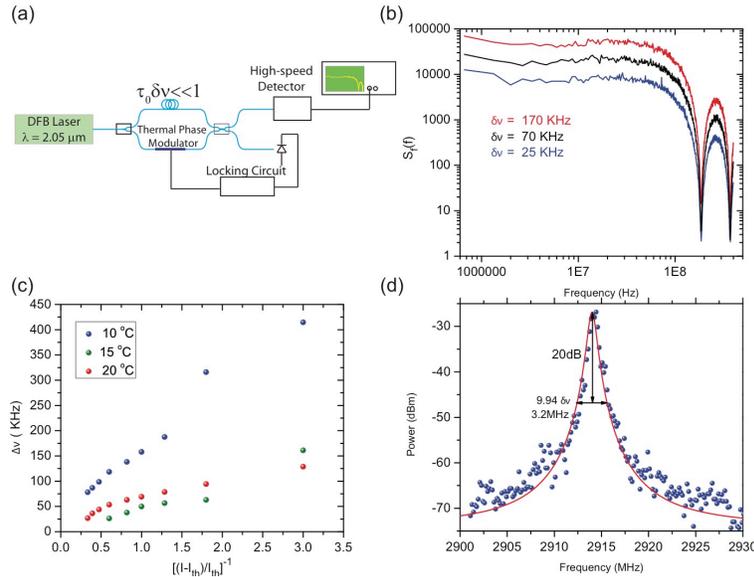


Figure 2. (a) The coherent optical frequency-discriminator setup. (b) Measured FM noise of the DFB laser at different bias levels at 15°C. (c) Extracted laser linewidth at different bias levels and heat sink temperatures. (d) Measured beat note of the free-running semiconductor laser with a solid-state laser locked to a CO<sub>2</sub> gas cell on an electrical spectrum analyzer.

Also, the total linewidth of the DFB laser was measured using a heterodyne beat-note measurement setup [15]. In this setup, the output of the DFB laser was mixed with the output of a fiber-coupled Tm,Ho:YLF reference laser using a fiber beam combiner. The reference laser is locked to line center of a carbon dioxide (CO<sub>2</sub>) absorption cell [16]. The DFB laser frequency offset from the reference laser is adjusted using its temperature and input current. The beat note is detected using a high bandwidth fiber-coupled InGaAs detector and is then analyzed on an electrical spectrum analyzer. Figure 2(a) shows the measured beat note measured on an electrical spectrum analyzer with a 10 KHz resolution bandwidth. A Lorentzian fit to the line shape yielded a 321 KHz FWHM linewidth. An independent measurement of the reference laser has indicated a FWHM linewidth 150 KHz. Therefore, the total FWHM linewidth of the DFB laser was estimated to be 171 KHz.

### 3. Conclusion

We demonstrated a versatile 2.05  $\mu\text{m}$  DFB semiconductor laser. The compact semiconductor transmitter has a suitably narrow linewidth and enables flexible tuning and versatile modulation formats that enables high precision airborne and space CO<sub>2</sub> measurements. The significantly stronger band strength at this wavelength, is more amenable to probing the atmosphere with weighting functions that emphasize the lowest few km above the surface, where the CO<sub>2</sub> sources and sinks of interest exist, while maintaining optimum differential absorption optical depth for high precision and low bias. Due to its compact size, low thermal mass, and rugged architecture, this module will significantly improve the current lidar systems performance.

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#### 5. References

- [1] [National Research Council. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond], The National Academies Press, Washington DC (2007).
- [2] Menzies, R. T. and Tratt, D. M., "Differential laser absorption spectrometry for global profiling of tropospheric carbon dioxide: selection of optimum sounding frequencies for high-precision measurements," *Applied optics* 42(33), 6569-6577 (2003).
- [3] Spiers, G. D., Menzies, R. T., Jacob, J., Christensen, L. E., Phillips, M. W., Choi, Y., and Browell, E. V., "Atmospheric CO<sub>2</sub> measurements with a 2 μm airborne laser absorption spectrometer employing coherent detection," *Applied optics* 50(14), 2098-2111 (2011).
- [4] Abshire, J. B., *et al.*, "Airborne measurements of CO<sub>2</sub> column concentration and range using a pulsed direct-detection IPDA lidar," *Remote Sensing* 6(1), 443-469 (2013).
- [5] Dobler, J. T., *et al.*, "Atmospheric CO<sub>2</sub> column measurements with an airborne intensity-modulated continuous wave 1.57 μm fiber laser lidar," *Applied optics* 52(12), 2874-2892 (2013).
- [6] Singh, U., *et al.*, "Column CO<sub>2</sub> measurement from an airborne solid-state double-pulsed 2-micron integrated path differential absorption lidar," in [International Conference on Space Optics], 10 (2014).
- [7] Johnson, W., Repasky, K., Nehrir, A., and Carlsten, J., "Development of an eye-safe micro-pulse differential absorption lidar (DIAL) for carbon dioxide profilings," AGU Fall Meeting Abstracts 1, 0097 (2011).
- [8] Phillips, M. W., "Thulium-doped fiber amplifier development for power scaling the 2 micron coherent laser absorption instrument for ASCENDS," Lockheed Martin Coherent Technologies, Louisville, CO, Tech. Rep.
- [9] Phelan, R., *et al.*, "In<sub>0.75</sub>Ga<sub>0.25</sub>AsInP multiple quantum-well discrete-mode laser diode emitting at 2 μm," *IEEE Photon. Technol. Lett.*, 24(8), 652-654 (2012).
- [10] Mitsuhashi, M., Ogasawara, M., Oishi, M., Sugiura, H., and Kasaya, K., "2.05-μm wavelength InGaAs-InGaAs distributed-feedback multi-quantum-well lasers with 10-mw output power," *IEEE Photon. Technol. Lett.*, 11(1), 33-35 (1999).
- [11] Forouhar, S., Briggs, R. M., Frez, C., Franz, K. J., and Ksendzov, A., "High-power laterally coupled distributed-feedback gasb-based diode lasers at 2 μm wavelength," *Applied Physics Letters* 100(3), 031107 (2012).
- [12] Briggs, R. M., *et al.*, "Single-mode 2.65 μm InGaAsSb/AlInGaAsSb laterally coupled distributed-feedback diode lasers for atmospheric gas detection," *Optics express* 21(1), 1317-1323 (2013).
- [13] Bagheri, M., Frez, C., Kelly, B., Gupta, J., and Forouhar, S., "High output power, fibre-coupled distributed feedback lasers operating near 2.05 μm wavelength range," *Electronics Letters* 49(24), 1552-1553 (2013).
- [14] Bagheri, M., Spiers, G. D., Frez, C., Forouhar, S., and Aflatouni, F., "Linewidth measurement of distributed-feedback semiconductor lasers operating near 2.05 μm," *IEEE Photon. Technol. Lett.*, 27.18 (2015): 1934-1937.
- [15] Baney, D. M. and V., S. W., [Fiber optic, Test and measurement], ch. High resolution optical frequency analysis, 169-218, Prentice-Hall, Inc (1998).
- [16] Spiers, G. D., Menzies, R. T., Tratt, D. M., and Phillips, M., "The laser absorption spectrometer for carbon dioxide sink and source detection," in [Second Earth Science Technology Conference.], 11 {13 (2002).