Laterally Coupled Distributed-Feedback GaSb-Based Diode Lasers for Atmospheric Gas Detection at 2 µm

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Abstract: We demonstrate single-mode laterally coupled distributed-feedback diode lasers at 2.05 µm employing low-loss etched gratings. Single-facet CW output exceeds 50 mW near room temperature with linewidth below 1 MHz over 10-ms observation times.
OCIS codes: (140.5960) Semiconductor lasers; (140.3490) Lasers, distributed-feedback; (280.1910) DIAL, differential absorption lidar.

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1. Introduction

The National Aeronautics and Space Administration has committed to deploying airborne and space-based lidar systems to measure the spatial and temporal distribution of atmospheric CO_2 to better understand the carbon cycle and predict its future impact on global warming and climate change [1]. These studies will employ laser-based integrated-path differential-absorption lidar methods using the CO_2 bands centered at either 1.57 or 2.05 µm [2]. Due to optimal optical depth and minimal sensitivity to water vapor concentration, the 2.05 µm band is preferred for probing the Earth's atmosphere in the lowest few kilometers above the surface where carbon sources and sinks exist [3]. Furthermore, high-performance detection systems operating from 2.0 to 2.5 µm can also be used to measure concentrations of aerosols, ozone, methane, and other important atmospheric gases.

Effective CO_2 detection systems are predicted to require seed lasers producing at least 50 mW of CW optical power, with narrow linewidth and frequency jitter on the order of 1 MHz [4]. Typical lidar transmitter architectures consist of a frequency-stable solid-state seed laser with a high-power optical amplifier; however, by replacing the solid-state light source with a semiconductor laser of comparable performance, the form factor and reliability of the transmitter can be substantially improved for airborne applications. Semiconductor lasers emitting at 2 µm have been demonstrated on InP, but Auger recombination and other loss mechanisms at longer wavelengths have limited single-mode InP-based diode lasers to output powers on the order of 10 mW [5]. While 2-µm diode lasers have been fabricated using GaSb-based alloys [6], GaSb-based distributed-feedback (DFB) lasers with the narrow linewidth required for gas detection are not widely available. In particular, the difficulty of epitaxial regrowth on GaSb has been a significant impediment to fabrication of conventional DFB structures with buried gratings. Alternatively, Bragg gratings can be patterned alongside a ridge waveguide to form a laterally coupled distributed-feedback (LC-DFB) laser [7], which has the potential to enable narrow-linewidth, single-longitudinal-mode lasers without additional epitaxial growth processes. Prior to the work reported here, GaSb-based LC-DFB laser designs have incorporated deposited metal gratings that enable narrow-linewidth operation but generate additional absorption loss in the laser cavity, limiting output power to approximately 10 mW [8].

2. GaSb-based LC-DFB laser fabrication

We demonstrate GaSb-based LC-DFB diode lasers with low-loss etched gratings. The lasers were fabricated from a wafer with two $In_{0.23}Ga_{0.77}As_{0.1}Sb_{0.9}$ quantum wells (QWs) centered within an $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ waveguide layer and surrounded by $Al_{0.85}Ga_{0.15}As_{0.07}Sb_{0.93}$ cladding, all grown on a GaSb substrate by molecular-beam epitaxy. As shown in Fig. 1(a), waveguide ridges 3 to 4 µm wide were etched into the top cladding layer, and second-order gratings were etched alongside the ridges. The lasers were then coated with a thick SiN_x layer using plasma-enhanced chemical vapor deposition, and the SiN_x was etched away from the top of the ridges for deposition of electrical contacts. Based on numerical analysis of the fabricated waveguide structure, the grating coupling constant, κ, for the second diffraction order is approximately 4 cm^{-1}. The lasers were cleaved into bars with a cavity length of L = 2 mm to achieve $\kappa L \sim 1$. Various facet-coating schemes were explored, with an anti-reflection (AR) coating on the output facet combined with either an AR, high-reflection (HR), or simple passivation coating on the back facet. Individual lasers were soldered epitaxy-side up onto gold-coated copper mounts for testing.

3. Laser performance

The light output and current-voltage characteristics of a typical AR/HR-coated LC-DFB laser are shown in Fig. 1(b). The lasers exhibit threshold current between 30 to 40 mA near room temperature, with maximum output power

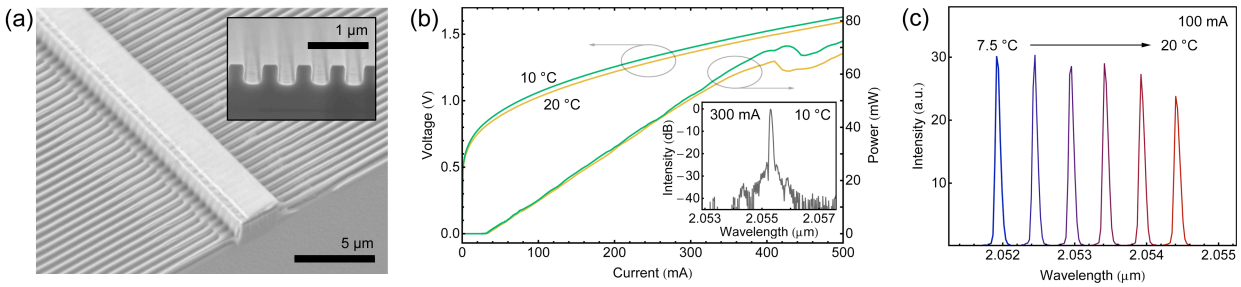

Figure 1. (a) Scanning electron micrograph of a laterally coupled DFB laser with etched gratings. (b) Light-current-voltage performance of a DFB laser with AR/HR-coated facets. The inset shows the laser emission spectrum, indicating single-mode operation with side-mode suppression of 25 dB. (c) Thermal dependence of the emission wavelength for the same AR/HR-coated laser measured in increments of 2.5 °C, showing characteristic DFB tuning of 0.2 nm/°C.

from the AR-coated facet exceeding 50 mW prior to the onset of thermal roll-off. Accounting for facet losses, sub-threshold Hakki-Paoli measurements for the LC-DFB devices revealed internal waveguide loss of 5 cm^{-1} at wavelengths near 2 µm, comparable to the loss measured for Fabry-Perot devices without gratings. The linewidth of the LC-DFB lasers was determined from the frequency-noise power-spectral density using a Fabry-Perot interferometer, resulting in a measurement of the upper bound of the linewidth. For observation times of 10 ms and 500 ms, we measured linewidths of 900 kHz and 1.4 MHz, respectively.

Spectral measurements of the laser output show single-mode operation with tuning to longer wavelength at a rate of 0.2 nm/°C with respect to heat-sink temperature, as shown in Fig. 1(c). The tuning rate for Fabry-Perot lasers fabricated with the same dimensions, but without gratings, was found to be nearly 1.4 nm/°C, indicating the relatively strong characteristic temperature dependence of the gain spectrum generated by the GaSb-based QWs [9]. The nearly order-of-magnitude lower thermal tuning rate of the spectral output for DFB lasers demonstrates the dependence of the Bragg-grating reflectivity on the thermo-optic coefficients of the materials that comprise the laser cavity. The higher thermal tuning rate of the gain spectrum relative to the LC-DFB grating reflectivity eventually leads to multimode laser operation as the junction temperature increases, which can be caused by increasing the heat-sink temperature or the operating current. By reducing the heat-sink temperature to -10 °C to compensate for current-induced heating, we observe single-mode DFB operation for current levels exceeding 500 mA with AR/passivation-coated devices, corresponding to single-mode output in excess of 80 mW.

In this work, we demonstrate single-longitudinal-mode lasers at 2.05 µm with the highest output power reported for any GaSb-based DFB laser. We attribute this record performance to high-quality epitaxial growth, effective thermal management of mounted devices, and low internal optical loss with etched LC-DFB gratings. The realization of high-power, frequency-stable semiconductor lasers at 2 µm is a significant step toward creating compact and reliable transmitters for remote detection of CO_2 and other atmospheric constituents.

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