Corrugated-Sidewall Interband Cascade Lasers Emitting > 50 mW cw in a Single Spectral Mode

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BIOGRAPHY

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TECHNICAL ABSTRACT

Mid-IR interband cascade lasers (ICLs) incorporating “carrier rebalanced” designs \[1\], epitaxial-side-down mounting, and other improvements have recently displayed pulsed threshold current densities as low as 134 A/cm\textsuperscript{2} at 300 K and maximum cw operating temperatures as high as 119 \textdegree C. However, the application of these devices to trace gas sensing based on laser spectroscopy will also require operation in a single spectral mode, with output in a narrow line whose wavelength can be tuned, \textit{e.g.}, by varying the injection current and/or thermoelectric cooler temperature. While the powers required by some detection systems are quite modest (\(\leq 1 \text{ mW}\)), remote sensing will generally require somewhat higher single-mode laser powers. In previous work, we reported the etching of a corrugated pattern into the sidewalls of narrow ICL ridges to serve the dual purpose of suppressing higher-order lateral lasing modes, by increasing their loss, and also forming a 4\textsuperscript{th}-order distributed feedback (DFB) grating to select a single longitudinal mode \[2\]. Devices employing this approach emitted up to 12 mW cw in a single spectral mode at room temperature and 45 mW at -20\textdegree C with a tuning range of 11 nm.

Here we discuss the unexpected spectral performance of a series of ICL narrow ridges with corrugated sidewalls having a pitch not specifically designed to match a given DFB resonance. Light-current (\(L-I\)) and far-field characterizations confirmed that the ridges having corrugated sidewalls could generate more power in a good than sister devices having straight sidewalls, since the ridges could be wider before higher-order lateral modes became dominant. For example, the corrugated-sidewall devices reported here lased in a single lateral mode despite having a ridge width of 13.2 \(\mu\)m. The narrow ridges were fabricated by optical lithography and Cl-based inductively coupled plasma dry etching. The etch proceeded to the GaSb separate-confinement layer below the active region, and was followed by a wet phosphoric-acid-based clean-up etch. The optical lithography mask patterned a lateral grating with period 2 \(\mu\)m into both sides of the ridges. A 200-nm-thick conformal Si\textsubscript{3}N\textsubscript{4} layer was next deposited by plasma-enhanced chemical vapor deposition, followed by sputtering of 100 nm of SiO\textsubscript{2} to fill occasional pinholes in the Si\textsubscript{3}N\textsubscript{4}. Windows were opened by contact lithography, followed by e-beam evaporation of the Ag/Ti/Pt/Au contact metallization. Gold was electroplated on top of the structure to a thickness of 5 \(\mu\)m, cavities were cleaved to a length of 4 mm, high-reflection (HR) and anti-reflection (AR) coatings were deposited on the facets, and mounting was either epitaxial-side-up or epitaxial-side down. The emission spectra were obtained with a Bomem DA-8 FTIR.

Figure 1 illustrates the emission spectra from an epi-up device when operated at \(T = 25 \text{ \degree C}\) just below (55 mA, black) and just above (65 mA, red) the lasing threshold. Most of the ridges display single-mode emission with narrow linewidth at some temperatures and currents, although that behavior was more robust for some than others. Figures 2-4 summarize the spectral and \(L-I\) characteristics for an epi-down device whose output remains single-mode over an extended range of operating conditions. Figure 2 indicates that the wavelength of the single-mode output shifts by 2 nm
when the current is varied from 150 mA to 400 mA at the fixed temperature of 25 °C. The measured spectral linewidth of ≤ 0.15 nm is limited by the spectrometer resolution. The sidemode suppression ratio of ≈ 17 is somewhat lower than for earlier devices [2], presumably because the grating was not designed or optimized for DFB operation. Figure 3 illustrates the spectral shift with temperature when the current is held fixed at 250 mA. The temperature range of 20-35 °C is seen to provide a wavelength tuning range of 6 nm. Figure 4 plots the L-I characteristics for the same device at 10, 25, and 40 °C, showing only the current ranges over which the output is single-mode at each temperatures. Note that the single-mode cw output is up to 55 mW at 25 °C and > 70 mW at 10 °C. The ambient-temperature result is by far the highest reported single-mode cw power to be generated by an interband lasers emitting beyond 3 μm. A second epi-down device performs similarly to the results shown in Figs. 2-4, while two epi-up devices show similar spectral properties with somewhat lower maximum cw output powers.

Figure 1. Cw output spectra for an epitaxial-side-up ridge with corrugated sidewalls at currents just below (55 mA) and just above (65 mA)

Figure 2. Cw output spectra for a corrugated-sidewall epi-down ridge at a series of currents and a fixed threshold temperature of 25 °C.

Figure 3. Cw output spectra for the same epi-down device as in Fig. 2, at a fixed current of 250 mA and a series of temperatures.

Figure 4. Cw L-I characteristics for the same device as in Figs. 2 and 3, over the range of currents for which single-mode output is maintained at each temperature.

Keywords: Interband cascade lasers, mid-infrared diode lasers, distributed-feedback lasers, chemical sensing.