Extraordinarily wide optical gain spectrum in 2.2–2.5 μm In(Al)GaAsSb/GaSb quantum-well ridge-waveguide lasers

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(Received 28 March 2001; accepted for publication 12 June 2001)

A wide optical gain spectrum with full width at half maximum Δλ=350 nm has been demonstrated in midinfrared (2.2–2.5 μm) room-temperature-operated InGa(As)Sb/GaSb quantum-well (QW) ridge-waveguide diode lasers. A QW width of 200 Å ensured a small energy separation between the first and second quantized states in the QW. Transitions from both quantized states contributed equally to the overall gain spectrum when the optical loss was optimized. © 2001 American Institute of Physics. [DOI: 10.1063/1.1391421]

Easily modulated, easily tuned, single-mode diode lasers are ideal light sources for high resolution, high sensitivity spectroscopy. Such devices find applications in trace-gas monitors,1 isotope and spectrochemical analyzers2 as well as a variety of biomedical applications.3 In order to realize devices with a wide tuning range, a wide optical gain bandwidth is required. In this work, we demonstrate an extraordinarily wide optical gain spectrum in quasiternary InGaAsSb/GaSb quantum-well (QW) lasers operating at wavelengths of 2.2–2.5 μm.

To find the experimental conditions for optimal gain flatness and width, we studied the temperature and current dependencies of the gain spectrum for ridge-waveguide (RWG) lasers with different cavity lengths, L. To achieve the wide and flat optical gain spectrum, the design of the devices as well as their performance conditions were optimized to use both the 1e–1hh and 2e–2hh quantum state transitions. The participation of these transitions in the laser action was discussed earlier.4–8 It was shown experimentally and theoretically,5,6 for AlGaAs single QW lasers that the way to achieve laser action involving the n=2 subbands in the QW is to increase the device losses or raise the heat sink temperature. A decrease in the laser wavelength after threshold was also demonstrated for short cavity midinfrared In(Al)GaAsSb/GaSb lasers and was associated with the participation of optical transitions between the n=2 level in the conduction band and the n=2 heavy hole level in the valence band.7 In the present work we demonstrate that the design of In(Al)GaAsSb/GaSb QW RWG lasers operating at 2.2–2.5 μm produces a wide and relatively flat optical gain spectrum. We measured corresponding values of the device losses, and we present experimental evidence that the wide bandwidth of the optical gain arises from the inequality of the differential gains associated with the first and second electron-hole transitions.

The laser structures were grown by molecular beam epitaxy on GaSb substrates. The laser active region consisted of two heavily strained (1.5%–2%) quasiternary InGa(As)Sb 200-Å-wide QWs surrounded by 0.02-μm-wide Al0.3Ga0.7As0.02Sb0.98 separate confinement layers. The details of the structure have been described elsewhere.7,9 Single-mode 5-μm RWG devices of various cavity lengths were fabricated. Each laser had a neutral coating (R=30%) applied to one facet, and a highly reflective (HR) coating (R=90%) on the other facet. The lasers were mounted p-side down on copper heatsinks. We studied the current and temperature dependencies of the modal gain by the Hakki–Paoli and Cassidy methods10,11 with an accuracy of 1 cm−1. The amplified spontaneous emission spectra were measured with a resolution of 0.125 cm−1 using a Nicolet Magna-860 FTIR spectrometer. To select a single lateral mode we used far-field image filtering techniques12 and the technique based on the selective properties of the Michelson interferometer.13 The value of the total optical loss, αtot, was determined from the long-wavelength region of the gain spectra. The internal loss, αint, and the device internal efficiency, ηint, were calculated using the measured slope efficiency and known device mirror loss, αm.

The current dependencies of the modal gain spectra for λ=2.45 μm In(Al)GaAsSb/GaSb RWG lasers measured at room temperature for TE polarization are presented in Fig. 1. The shaded area marks the value of total loss estimated from the long-wavelength region of the gain spectrum measured at a current of 10 mA. In broadened-waveguide lasers with two QWs the value of total loss does not depend on current since the contribution of in-well free carrier absorption into the total loss is small. For a 1 mm cavity length device with...
neutral/HR coatings, $\alpha_m$ is estimated to be 6 cm$^{-1}$, resulting in calculated values of $\alpha_{\text{int}} = 20$ cm$^{-1}$ and $\eta_{\text{int}} = 0.45$. As can be seen from Fig. 1, the room temperature gain spectra for the 2.45 $\mu$m lasers with a cavity length of 1 mm and $\alpha_{\text{tot}}$ of 26 cm$^{-1}$ are characterized by a narrow peak with full width at half maximum (FWHM) $\Delta \lambda = 165$ nm at threshold.

The shape of the gain spectrum is changed drastically for devices with a 0.5 mm cavity length. Figure 2 presents the family of modal gain spectra for 0.5 mm cavity length lasers with $\lambda = 2.45$ $\mu$m at different injection currents at room temperature. The value of $\alpha_{\text{tot}}$ estimated for this device from the long-wavelength part of the spectra was $\alpha_{\text{tot}} \geq 60$ cm$^{-1}$. With increasing current, a new peak develops on the high-energy shoulder of the gain spectra. At threshold, $\Delta \lambda \approx 350$ nm. The corresponding transformation of the modal gain spectrum in the case of RWG lasers with $\lambda = 2.35$ $\mu$m was not achieved at room temperature, since generation at $\lambda = 2.35$ $\mu$m appears before the gain broadening phenomenon. The effect of gain broadening with an injection current increase was demonstrated for these devices at 33 °C. At this temperature (see Fig. 3) the laser with an estimated $\alpha_{\text{tot}}$ of 45 cm$^{-1}$ is characterized at threshold by $\Delta \lambda = 300$ nm.

The shift of the laser wavelength associated with optical transitions between $n = 2$ level in the conduction band and $n = 2$ heavy hole level in the valence band was observed in the case of short cavity AlGaAs and In(Al)GaAsSb/GaSb QW RWG lasers. At high injection conditions the effect of the band filling of the higher quantum subbands leads to a corresponding population inversion. Below the device threshold, when the contributions of these two optical transitions to the device gain become comparable, we can observe the transformation of the gain spectrum with current as shown in Figs. 2 and 3. A combination of several factors makes this transformation possible: a small difference between transition energies (~40 meV); a high electron concentration caused by high optical losses; a nonequilibrium car-
rier distribution between the first and second electronic states in the QW; and finally the differential gain inequality for the $1e-1hh$ and $2e-2hh$ optical transitions.

Figure 4 shows the modal gain maximum for the 2.35 $\mu m$ device as a function of the energy of quasi-Fermi level separation, $\Delta \varepsilon_F = \varepsilon_F^o - \varepsilon_F^p$. Assuming that the total losses are the same at all injections, the $\Delta \varepsilon_F$ value (transparency energy) can be estimated from intersection of the high-energy tail of the gain spectra and shaded strip (see Fig. 3). Since change of $\Delta \varepsilon_F$ is approximately proportional to the change of the carrier concentration, data in Fig. 4 present the behavior of the differential gain within a wide range of injection. These data show that the modal gain peak for the second (higher energy) transition rises more rapidly with injection than does the peak for the first (lower energy) transition.

Summarizing, we have demonstrated an In(Al)GaAsSb/GaSb 2.2–2.5 $\mu m$ ridge-waveguide quantum-well diode laser with an extraordinarily wide ($\Delta \lambda = 350$ nm) and reasonably flat optical gain spectrum. This laser structure can be used to develop a single-chip external-cavity laser with a record-setting continuous tuning range.

This work was supported by the United States Air Force Office of Scientific Research under Grant No. F-49620-98-10133.