Tuning characteristics of InAsSb continuous-wave lasers

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We present a detailed analysis of the tuning characteristics of InAsSb continuous-wave (cw) single-frequency lasers emitting at 3.3 μm (3050 cm^{-1}). The lasers demonstrate a tuning range of -7.5 cm^{-1} by changing the current and -3.5 cm^{-1} by changing the heat sink temperature without mode hopping. The tuning rates are of -0.015 to -0.089 cm^{-1}/mA and -0.11 to 0.27 cm^{-1}/K. The laser tunes to the blue side both with increasing injection current and heat sink temperature. The extended tuning is attributed to the carrier heating effect in the cw operation and the band-filling effect in the presence of strong losses.
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Wavelength tunability is one of the main parameters of diode lasers emitting within the atmospheric transmission window in the mid-infrared spectrum of 3–5 μm. These lasers are being developed for ultrasensitive spectroscopic applications and free space communications. This requires direct and reproducible wavelength tunability for a signal averaging over a specified temporal and spectral interval. At present, the narrow-band-gap semiconductor lasers have strong nonradiative recombination and are being aggressively developed towards improving laser operation temperature and output power.[1–4] Among them a laser tunability and stable single-frequency continuous wave (cw) operation are the subjects of investigations since they are important parameters for the laser applications. A laser tunability over 1.1–1.9 cm^{-1} with a rate of 0.02–0.03 cm^{-1}/mA has been reported for InAsSb cw lasers.[5] A single-frequency tunable cw emission with a side mode suppression ratio (SMSR) down to -29 dB has been obtained at 3.4 μm where the laser tunes over a range of 1.2 cm^{-1} with a rate of 0.032 cm^{-1}/mA.[6] The modulation bandwidth of InAsSb cw laser is compatible with that of available photodetectors.[7] The lasers are optimized for high modal power.[8–9] The application of an external grating-tuned cavity to the InAsSb cw lasers improves the tuning range up to 48 cm^{-1}.[10] The potential for extending the tuning range of Fabry–Pérot devices has been demonstrated under pulsed operation: The tuning without mode hoppings up to 4.4 cm^{-1} with a rate of 0.018–0.078 cm^{-1}/mA was obtained under 0.3–20 μs width current pulses.[11] The 14 μs width pulsed and quasi-cw InAsSb lasers tune over 10 cm^{-1} with a rate of 0.03–0.21 cm^{-1}/mA.[12,13] The pulsed lasers tuned in both the long- and short-wavelength direction. However, detailed data about the temperature and current dependencies of the wavelength tuning of InAsSb cw lasers are still not reported.

In this letter, we investigate a tuning behavior of a continuous-wave InAsSb single-frequency lasers emitting at 3.3 μm. The laser mode shifts and tuning rates are examined against injection current and heat sink temperature. Blue-side tunability of InAsSb cw lasers by both the injection current and the heat sink temperature is discussed.

The lasers used in the tests were a double heterostructure (DH) with a ternary 0.8-μm-thick $InAs_{0.95}Sb_{0.05}$ active layer and 3-μm-thick $InAs_{0.48}Sb_{0.17}P_{0.35}$ cladding layers grown on an (100) oriented InAs substrate by liquid phase epitaxy. The cap was 1-μm-thick InAs layer. The undoped InAsSb active area had *n*-type background electron concentration of lower 10^{16} cm^{-3}. The devices were 10-μm-wide, 250–275-μm-long (5–5.5 cm^{-1} mode spacing), deep-mesa-stripe, and Fabry–Pérot diode lasers in which the active layer thickness and the chip geometry were chosen for a single-frequency operation. The chips were mounted epi-side up on a cooper heat sink block and placed inside a cryogenic laser Dewar (Laser Photonics, L5736). The laser power was measured by an electronically calibrated pyroelectric power meter (Laser Precision, RS5900A, and 1% absolute accuracy). The longitudinal mode structure is investigated by a 1/2 m Czerny–Turner monochromator. The signal was processed by a high dynamic range data acquisition system. The laser tuning was calibrated with a Fabry–Pérot Étalon (0.0307 cm^{-1} free spectral range, 3.0 fitness). Reflective optics were used to minimize back reflections into the laser cavity.

At 82 K, the cw threshold current I_{th} was 19–21 mA, corresponding to a threshold current density of 700–750 A/cm^2. The temperature dependence of the threshold current reveals a characteristic temperature of 21 K (between 78 and 100 K). An output power is in the range of 0.3 mW. The laser emits in the vicinity of 3.28 μm (3047 cm^{-1}). Figure 1 represents the three-dimensional-contour lasing spectra versus the injection current at a temperature of 82 K. Between 1.6 and 5.5 of the threshold, the side mode suppression ratio (SMSR) is of -23 to 27 dB and corresponds to a single-frequency operation. In the vicinity of the mode hopping and in the presence of a sufficient side mode, the SMSR is at

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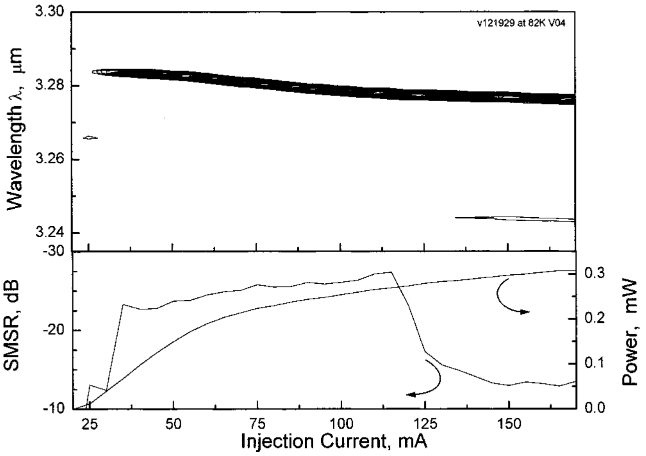

FIG. 1. The three-dimensional-contour cw lasing spectra at 82 K. CW output power and side mode suppression ratio (SMSR) vs injection current present at the bottom. The threshold current is 21 mA dc.

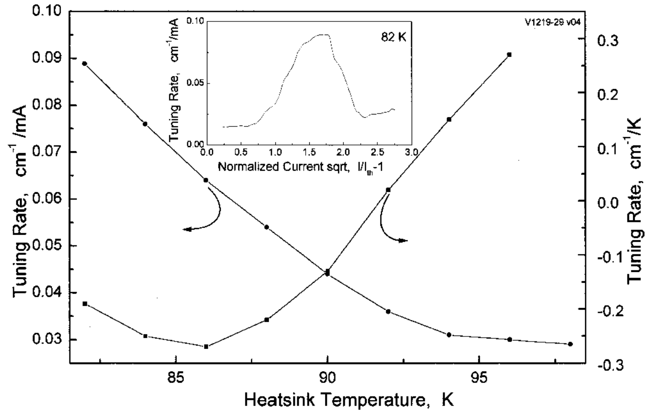

FIG. 3. The temperature dependence of the laser temperature tuning rate taken at 100 mA dc and the temperature dependence of maximal current tuning rate. The dependence of the laser tuning rates vs the normalized injection current taken at 82 K shown in the inset.

least -13 to 15 dB. As the injection current changes between 1 and 8 I_{th}, the main longitudinal, mode shifts from 3.2834 to 3.2763 μm.

Figure 2 shows the lasing wave number against the injection current at heat sink temperatures in the range of 82–98 K. At each temperature over the entire current range, the wave number exhibits a nonlinear shift with increasing current to the blue side. Below 92 K, the current tuning exceeds the temperature tuning and *vice versa* above 92 K. The current tuning range decreases linearly with an increasing of temperature from 7.5 to 2.2 cm^{-1} at 82 and 98 K, respectively. The temperature tuning depends on the current. At lower currents, the wave number shifts with the temperature to the blue side. At higher currents, the shift is observed to the red side at temperatures below 92 K and to the blue side above. In the inset in Fig. 2, the shift of wave number with temperature at constant current of 90 mA, changes direction: The red side is observed below 90 K, but the blue side above 92 K. The small temperature tuning range was a result of a large band filling as a result of the increase in I_{th} with temperature and very small T_0. The dependence taken at constant pumping above the threshold ($2I_{\mathrm{th}}$) demonstrates a linear shift towards the blue side.

The current tuning rates change nonlinearly against the current (the plot at 82 K is presented in the inset in Fig. 3) and consist of three regions. Below the 1.5 I_{th} rate and above 3.6 I_{th}, the rates slightly increase with current in the range of 0.015–0.017 cm^{-1}/mA. The maximum rate of 0.089 cm^{-1}/mA is obtained at 4.1 I_{th}. The similar current dependences are observed at higher temperatures but the maximum rate (Fig. 3) is decreased with temperature from 0.089 to 0.029 cm^{-1}/mA at 82 and 98 K, respectively. Figure 3 demonstrates the dependence of the temperature tuning rate at 100 mA dc versus the heat sink temperature. The redshift below 92 K has a rate of -0.19 to -0.27 cm^{-1}/K at 82 and 86 K, respectively. The blueshift above 92 K has a rate up to 0.27 cm^{-1}/K at 98 K. Note that a rate of the red-side temperature tuning is less than the tuning to blue side and the temperature dependence of the band gap (-2.8 cm^{-1}/K).

The most important feature of the laser is the blue-side tuning around 1.5–5 I_{th} (at 82 K). This allows us to extend the continuous tuning range over the Fabry–Pérot mode spacing, from a value of 2 cm^{-1} typically reported for InAsSb cw lasers[5,6] to above 7 cm^{-1}.[14] The blue-side tuning by current in InAsSb DH cw laser is commonly explained by the bandfilling. Band filling has been observed in III–V diode lasers with a high level of internal losses and low characteristic temperature T_0 even above the threshold.[15] The current tuning to the blue side was observed previously in pulsed[11–13] and cw[5] InAsSb lasers. It is explained by intervalence band absorption (IVBA) which caused an increase in the carrier density and, hence, decreased the effective refractive index in the active region above the threshold.[5,11,13,16] Recently the shift was attributed to the forming of a smooth optical waveguide across the laser cavity that radiation flux oscillates maintaining its own frequency and intensity.[12]

Figure 4 shows the differential quantum efficiency η_d versus current. The efficiency is a nonlinear function of a current and reaches a maximum at $\sim$1.5–1.6 I_{th}, decreases rapidly, and saturates at currents over 4 I_{th} at 82–92 K. Above 92 K, η_d decreases to negative values without saturation. Over the entire region the η_d is below 1%–2%. This low value is due to the narrow stripe geometry of the laser cavity and long interband relaxation time of 0.1–0.6 ps[9] which was applied to obtain a single frequency lasing with a high SMSR. For comparison, a η_d as high as 30%, a mode

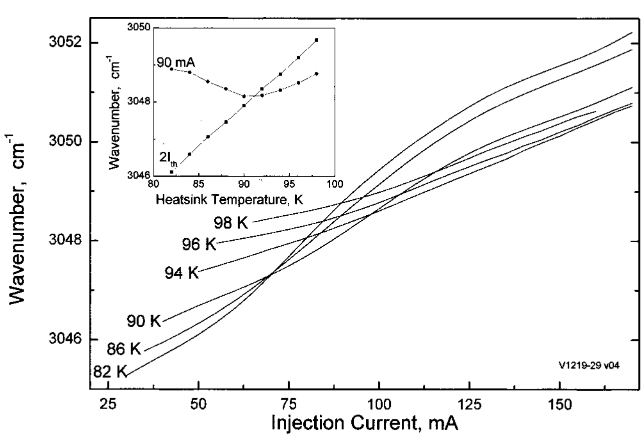

FIG. 2. Shift of the lasing mode vs injection current at 82–98 K heat sink temperatures. The temperature dependence of the laser mode shift taken at 90 mA dc and at $2I_{\mathrm{th}}$ shown in the inset.

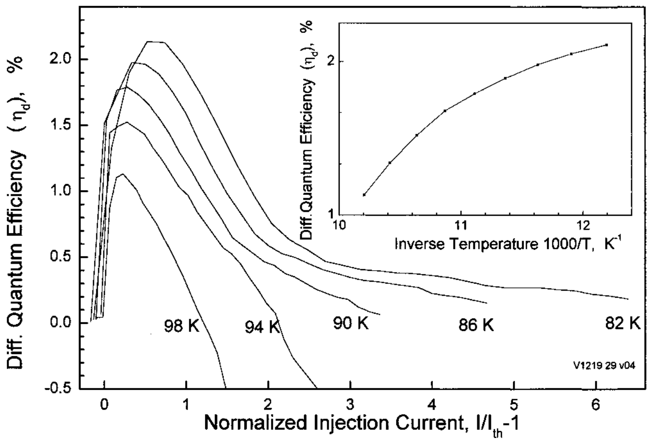

FIG. 4. The cw differential quantum efficiency against normalized injection current taken at heat sink temperatures between 82 and 98 K. The dependence of η_d vs inverse temperature taken at maximum is included in the inset.

power as high as 2 mW/facet and a temperature limit of about 20 K higher is observed for InAsSb cw multimode lasers based on similar DH.[8] Nonlinear mechanisms such as carrier heating, gain saturation, IVBA and Auger recombination are primary factors in reducing the maximum operating temperature of laser by 20 K relative to the multimode device and affect the efficiency more than the threshold. For a low η_d, most of the current becomes heat. From Fig. 4, the carrier heating can be roughly estimated to be as high as 0.8–1.5 K/mA (between 1.5 and 4 I_{th} at 82 K). As the heating reduces the gain, increases the IVBA and enhances Auger recombination, it makes the η_d nonlinear. A reduction of the efficiency is observed above 1.7 I_{th}. As the efficiency drops above $2I_{\mathrm{th}}$, the effective carrier temperature saturates at high pumping rates. Therefore, in cw operation with the heating under saturation, a change in a pumping rate changes a carrier concentration above the threshold. Thus it affects the band filling and the refractive index. Carrier heating gives rise to a blue-side tunability which quickly increases with the current. The tunability is limited by the generated heat. A simplified calculation of the tuning, resulting from thermal expansion of the laser crystal and the tuning, resulting in a variation of the refractive index,[17] show that under the heating they would be of similar magnitude at 0.085 cm^{-1}/mA but opposite in the tuning direction and counteract each other. From Figs. 1–4, we can see that the current tunability is low in the regions corresponding to the mode competition and a low SMSR. The most significant tunability was achieved in the region of a decrease of η_d (at 82 K, between 1.5 and 4 I_{th}) where strong heating occurs.

In summary, we present a detailed analysis of the tuning characteristics of InAsSb continuous-wave single-frequency lasers emitting at 3.3 μm (3050 cm^{-1}) versus current and temperature. The lasers demonstrate a continuous tuning range of $-7.5\ \mathrm{cm}^{-1}$ by changing the current and $-3.5\ \mathrm{cm}^{-1}$ by changing the heat sink temperature without mode hopping over the mode spacing. The laser tunes to the blue side with increasing both injection current and heat sink temperature with rates of -0.015 to $-0.089\ \mathrm{cm}^{-1}$/mA and -0.19 to 0.27 cm^{-1}/K. The laser can tune to the red side by changing the temperature only inside a narrow temperature interval. The extended tunability is attributed to the carrier heating effect in the cw operation and the band-filling effect in the presence of strong losses.

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