

Linewidth enhancement factor of a type-I quantum-cascade laser

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(Received 12 May 2003; accepted 28 July 2003)

Experimental results using the amplified spontaneous emission spectroscopy of a type-I quantum-cascade laser are presented. Using the Hakki–Paoli method, the optical gain spectra of the laser are extracted for the wavelength of 8.2 μm at various subthreshold current levels. The change in refractive index with increased bias current is obtained from the peak wavelength shifts of the Fabry–Pérot spectrum. A low value of -0.5 for the linewidth enhancement factor is found. A group index of around 3.47 has also been determined from Fabry–Pérot modal spacings. © 2003 American Institute of Physics. [DOI: 10.1063/1.1611285]

There has been great interest in mid-infrared (mid-IR) wavelengths covering the range from 3 to 20 μm for infrared absorption spectrometry, IR counter measure, and optical wireless communication. Since the strongest absorption line for molecules, or finger prints, occurs in the mid-IR portion of the spectrum, infrared absorption spectroscopy has been used for trace gas detection and for monitoring the waste released from industries into the atmosphere for environmental protection, combustion diagnostics, and atmospheric chemistry.^{1,2} Both type-I and type-II quantum-cascade (QC) lasers are useful for these applications. In addition, with the transmission window in the range of 3–5 and 8–12 μm , QC lasers have a potential for free space optical wireless communication.^{3,4} For a comprehensive review, see the special feature section issue on QC lasers in Ref. 5.

The linewidth enhancement factor (α_e) plays an important role in determining the spectral linewidth of semiconductor lasers. We focus on determining the α_e spectrum of a type-I QC laser with a lasing wavelength near 8.2 μm . We first measure the amplified spontaneous emission (ASE) spectra at various subthreshold injection current levels. The group index as a function of wavelength is obtained from the modal spacings. The gain and differential gain as a function of the wavelength and current are then obtained using the Hakki–Paoli method.⁶ Similar net modal gain spectra were measured for a type-I QC laser with a lasing wavelength^{7,8} of 4.6 and 11.5 μm . The wavelength shifts due to the increase of the bias current allow us to determine the change in refractive index as a function of wavelength. The results obtained from the differential gain and the incremental change in refractive index are used to determine the linewidth enhancement factor.

The structure of the QC laser sample, D2798, is based on a so-called “three-well vertical transition” design of active

regions with InGaAs quantum wells and AlInAs barriers grown lattice matched to InP substrate.⁹ Thirty-two active regions are alternated with injector regions to form the active waveguide core. The bottom waveguide cladding is provided by the low doped InP substrate. The top waveguide cladding consists of inner low doped AlInAs layers capped by a highly doped InGaAs layer for plasmon-enhanced confinement as described in Ref. 10. During the experiment, the QC laser sample with a cavity length of 1.36 mm is operated in a liquid nitrogen cryostat (78 K) in continuous wave mode with an HP E3631A power supply. The radiation from the QC laser is collected by a concave mirror which focuses it into the emission port of a BOMEM DA8 Fourier transform infrared spectrometer. Finally, the beam is detected by a mercury–cadmium–telluride detector. The ASE spectra of the laser are taken with the current varied from 148 to 160 mA in 2 mA step intervals. Some of these spectra are shown in Fig. 1(a). The peak wavelengths of the Fabry–Pérot (FP) spectrum shift toward the longer wavelength as the bias current increases as shown in Fig. 1(b).

The group index (n_g) is determined by the Fabry–Pérot mode spacings ($\Delta\lambda_{\text{FP}}$) at a wavelength λ and the cavity length L

$$n_g = \frac{\lambda^2}{2L\Delta\lambda_{\text{FP}}}. \quad (1)$$

The value of the group index (Fig. 2) is found to be approximately 3.47, which is slightly higher than the reported value of 3.38 calculated from the Drude model in Ref. 11. The difference may be due to uncertainties in the doping level, hence the group index of our laser sample is likely to be slightly higher than that reported in Ref. 11. The sample in Ref. 11 also had a waveguide which has a very low loss for most wavelengths and had the doping levels adjusted at the lower end farther away from the plasma resonance than usual. This factor also contributes to the lower group refractive index.

The optical gain spectrum is then extracted from the ASE data based on the Hakki–Paoli method.^{6,12} The net

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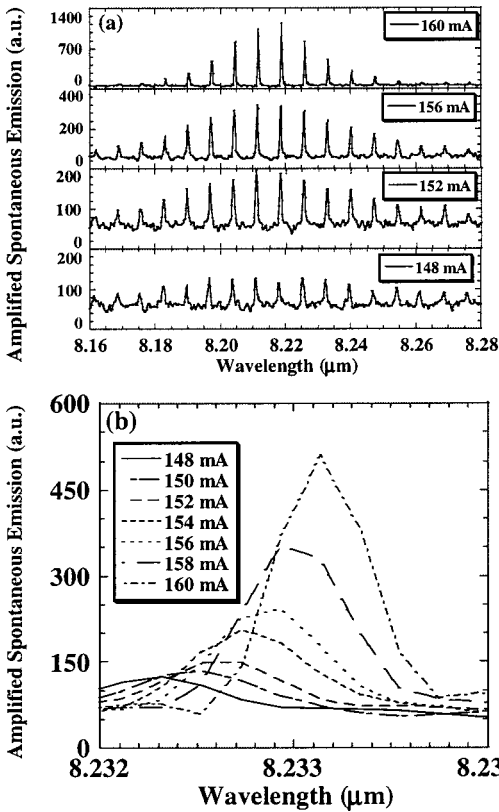


FIG. 1. (a) The amplified spontaneous emission spectrum of a type-I QC laser for injection currents of 148–160 mA with 4 mA intervals. (b) The expansion of the spectrum around 8.232–8.234 μm shows the redshift of the spectra as the current is increased.

modal gain G , plotted in Fig. 3(a), is calculated from the ratio of the maximum (I_{\max}) and minimum (I_{\min}) intensity of the Fabry–Pérot spectra using $S = (I_{\max}/I_{\min})^{1/2}$

$$G = \frac{1}{L} \ln \frac{S-1}{S+1} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right), \quad (2)$$

where L is the cavity length, and R_1 and R_2 are the mirror reflectivities. The mirror loss in the last term of Eq. (2) is approximately 9.25 cm^{-1} , which is scaled by the cavity length from Ref. 13 ($\alpha_m = 5.59 \text{ cm}^{-1}$ for a cavity length of 2.25 mm). Since the gain mechanism of the type-I QC laser is an intersubband process, the line shape of the gain spec-

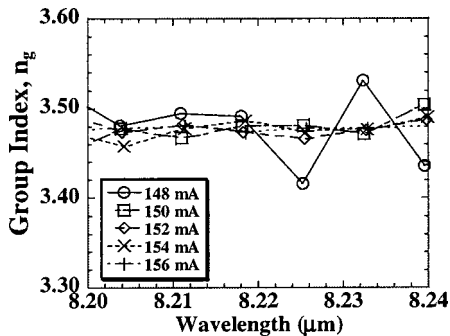


FIG. 2. The group index (n_g) at five bias currents is obtained from the Fabry–Pérot mode spacing ($\Delta\lambda_{FP}$). From the plot, the value of n_g is approximately 3.47.

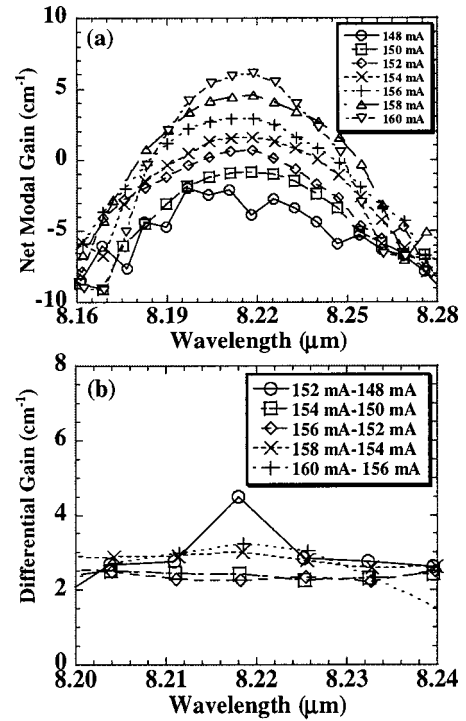


FIG. 3. (a) The optical gain spectra extracted from the Hakki–Paoli method. The line shape of the gain spectra is Lorentzian, since the gain mechanism in the type-I QC laser is intersubband transition. (b) The differential gain spectra of the 4 mA current interval at different current levels.

trum is approximately Lorentzian, as Fig. 3(a) shows. From the ASE spectra, five data points around each maximum intensity are fitted with a cubic-spline method to better determine the peak value and the corresponding peak wavelength. The minimum values are approximate because the signals around the minimum valleys are weak and noisy, but they seem to fluctuate around a mean plateau. The wavelength corresponding to each minimum intensity is obtained by taking the middle wavelength between the peak wavelengths at two maximum intensities. This noise at the minima of the ASE spectra also manifests itself in the differential gain spectra of 4 mA current intervals at different current levels depicted in Fig. 3(b).

The change in refractive index with respect to the change in current¹⁴ is then obtained from the peak wavelength shift ($\Delta\lambda$) with respect to the increase of injected current¹²

$$\Delta n_e = \frac{\partial n_e}{\partial I} \Delta I = \frac{\lambda}{2L} \frac{\Delta\lambda}{\Delta\lambda_{FP}}. \quad (3)$$

The measured peak wavelength shifts are plotted in Fig. 4(a) with an approximate value of 0.27 nm per 4 mA interval or 68 nm/A. Using Eq. (3), Fig. 4(b) shows the corresponding change in refractive index Δn_e , for the 4 mA current interval, which is approximately 1.2×10^{-4} .

The differential gain and the change of the refractive index are used to extract the linewidth enhancement factor¹⁵

$$\alpha_e = -\frac{4\pi}{\lambda} \frac{\Delta n_e}{\Delta g} = -\frac{4\pi}{\lambda} \frac{n_e(I_2) - n_e(I_1)}{g(I_2) - g(I_1)}. \quad (4)$$

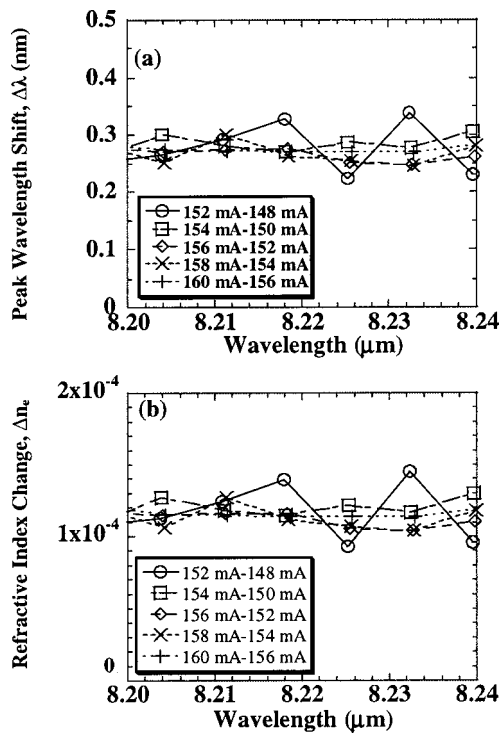


FIG. 4. (a) The wavelength shift of 0.27 nm per 4 mA interval ($= 68 \text{ nm/A}$) taken at the current range of 148–160 mA. (b) The change in refractive index with a current interval of 4 mA extracted from the wavelength shift and the Fabry–Pérot mode spacing.

The linewidth enhancement factor for a 4 mA current interval is plotted as a function of wavelength in Fig. 5 where the average value is approximately -0.5 (at 78 K) at the lasing wavelength of $8.22 \mu\text{m}$, which is slightly larger than the reported value of 0.1 (at 15 K) for the type-I QC laser with a lasing wavelength⁷ of $4.6 \mu\text{m}$. The larger α_e we observed can be due to a few factors. First, the extraction of α_e in Ref. 7 was based on the Kramers–Kronig using the measured gain spectrum at 15 K, while our method here is a direct

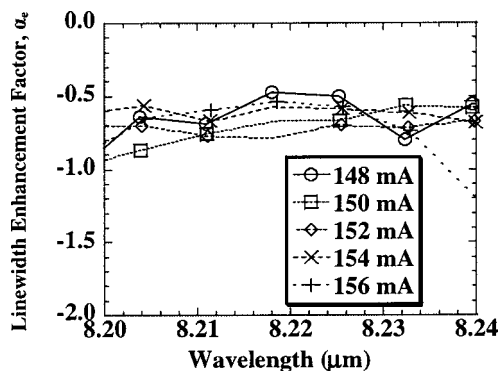


FIG. 5. The linewidth enhancement factor (α_e) is calculated from the measured change in refractive index and the differential gain with a current interval of 4 mA at various current levels. From the plot, the value of α_e is approximately -0.5 at the lasing wavelength of $8.22 \mu\text{m}$ near threshold.

measurement of α_e using the peak wavelength shift at 78 K. (The Kramers–Kronig relation requires accurate measurement of a broad gain spectrum which is affected by the noisy background when ASE is weak.) In addition, there is a strong contribution of lattice temperature component to the measured α_e which is notable since the power efficiency is low and the threshold current is high. This thermal tuning in a QC laser was measured to be about $28\text{--}48 \text{ nm/A}$. Since the operating currents are quite low, the actual wavelength shift after deducting thermal tuning is about $20\text{--}40 \text{ nm/A}$, which makes our α_e value even smaller than -0.5 . It should be noted that another effect due to the carrier temperature induced change in refractive index¹⁶ for intersubband lasers deserve further study for intersubband lasers.

In summary, the Lorentzian-like gain spectra of a type-I QC laser are extracted using the Hakki–Paoli method. With the results obtained from differential gain and the change in the effective refractive index as a function of wavelength and current, we find the linewidth enhancement factor, a parameter which plays an important role in the linewidth of semiconductor lasers, to be approximately -0.5 at a lasing wavelength of $8.22 \mu\text{m}$. We also found a group index value of approximately 3.47.

This work at UIUC was supported by DARPA (Optoelectronics Center) under Grant No. MDA972-00-1-0020 and ARO (MURI) under Grant No. DAAD 19-01-1-0591. The work performed at Bell Laboratories was partly supported by DARPA/U.S. ARO under Contract No. DAAD19-00-C-0096.

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