Excited-State Absorption in High-Power Mid-Infrared Quantum Cascade Lasers

Yamac Dikmelik and Jacob B. Khurgin
Johns Hopkins University, Department of Electrical and Computer Engineering, Baltimore, MD, 21218, USA
yamac@jhu.edu

Anthony J. Hoffman, Scott S. Howard, Kale J. Franz, and Claire F. Gmachl
Princeton University, Department of Electrical Engineering, Princeton, NJ, 08544, USA

Abstract: The loss due to excited-state absorption into the continuum was calculated for high-power mid-infrared quantum cascade lasers. We find this loss to be a significant fraction of the gain at the laser wavelength.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.3070) Infrared and far-infrared lasers

1. Introduction

Continuous wave operation of mid-infrared quantum cascade lasers (QCLs) has been demonstrated at room temperature by several groups [1-3]. Waveguide loss is a parameter that remains relatively unexplored for high-power QCLs and is important for improving the wallplug efficiency. Recent experimental measurements have suggested that waveguide loss can be attributed primarily to resonant intersubband absorption in the active region [4]. In this work, we investigate absorption from the upper laser level into the continuum as a potential source of waveguide loss. The high-power QCL structure analyzed here is an example of the double-phonon resonant design first reported in 2001 [5]. This particular QCL is a strain-compensated $Ga_{0.41}In_{0.59}As/Al_{0.56}In_{0.44}As$ heterostructure demonstrated to emit at a wavelength of 6.1 μm [6].

2. Analysis

We perform the analysis by numerically solving Schrodinger's equation to find both the bound and the continuum state wavefunctions, taking into account band nonparabolicity. Continuum states are evaluated by discretizing the energy axis above the lowest energy AlInAs barrier and solving for the wavefunction for each energy level. The loss due to absorption from the upper laser level to extended states in the continuum is calculated using [7]

$$\alpha = \frac{4\pi e}{\varepsilon_0 n \lambda} \frac{1}{2L_p} \frac{K(\omega)}{eF_{\text{bias}}} \langle \psi_K | z | \psi_3 \rangle^2 \eta_i \tau_3 \tag{1}$$

where L_p is the length of one period of the structure, F_{bias} is the bias electric field, ψ_K is the extended state wavefunction indexed by wavenumber K, and ψ_3 and τ_3 are the wavefunction and the lifetime of the upper laser level, respectively. The wavenumber indexing the extended state that corresponds to a transition frequency ω is given by

$$K(\omega) = \frac{\sqrt{2m^*(E_3 + \hbar\omega - V_b)}}{\hbar} \tag{2}$$

where E_3 is the energy of the upper laser level and V_b is the barrier height. The loss calculated from Eq. (1) includes the correction for the redistribution of the density of states under an applied bias.

3. Results and Discussion

Figure 1(a) shows the conduction band profile, bound state wavefunctions, and the continuum state wavefunctions as a false-color image overlaid on the band profile, for one active region sandwiched between two injector regions of the QCL structure under analysis. The continuum states above the active region show a minigap between two quasi-bound states at an energy range above all the active region and injector bound states. The absorption at the laser transition energy falls in this minigap as shown by the gain and the loss curves in Figure 1(b). However, the residual loss due to the continuum states above the injector region in this energy range is about 12% of the peak gain for a linewidth of 14 meV, a significant fraction that corresponds to a waveguide loss of 2.3 cm^{-1} at an operating current of 4 kA/cm^2. This is almost an order of magnitude higher than the free carrier absorption in the cladding for a carrier density of 2×10^{16} cm^{-3}.

978-1-55752-859-9/08/$25.00 ©2008 IEEE

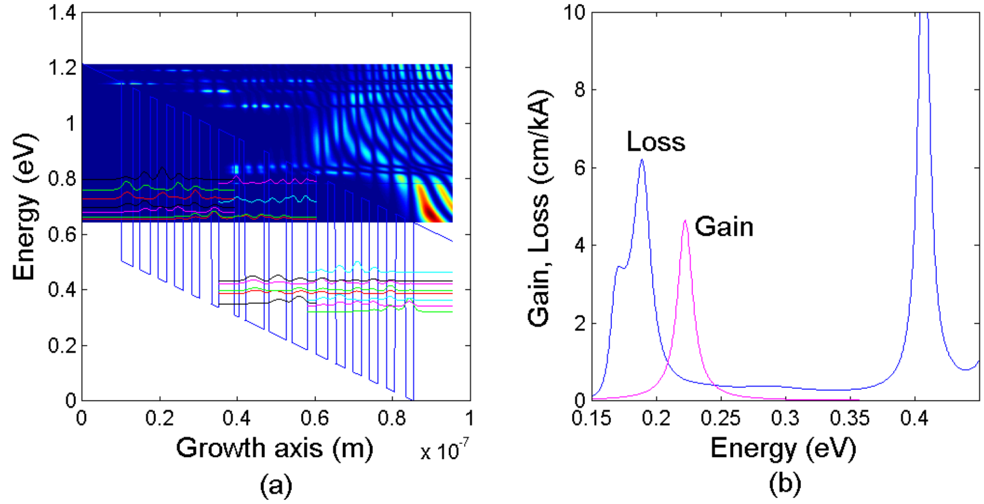

Fig. 1. (a) Conduction band profile, bound state wavefunctions, and continuum state wavefunctions as a false-color image for the QCL under analysis; (b) loss due to absorption into the continuum and gain coefficient as functions of the transition energy.

Figure 2(a) shows the bound and continuum state wavefunctions obtained by solving for two stages of the QCL structure. Solving for two stages reveals four quasi-bound states above the injector in the energy range for which a minigap exists above the active region. Using Eq. (1) underestimates the loss in this case because the energy spread of each quasi bound state is much narrower than the line broadening typically observed in QCLs. Figure 2(b) shows the loss calculated by considering transitions from the upper laser level to each quasi-bound state, taking into account line broadening with the same linewidth as the gain. This loss curve illustrates the contribution of individual quasi-bound states to the total absorption, but the loss at the laser wavelength ends up being quite similar to the result shown in Fig. 1(b) for this particular QCL.

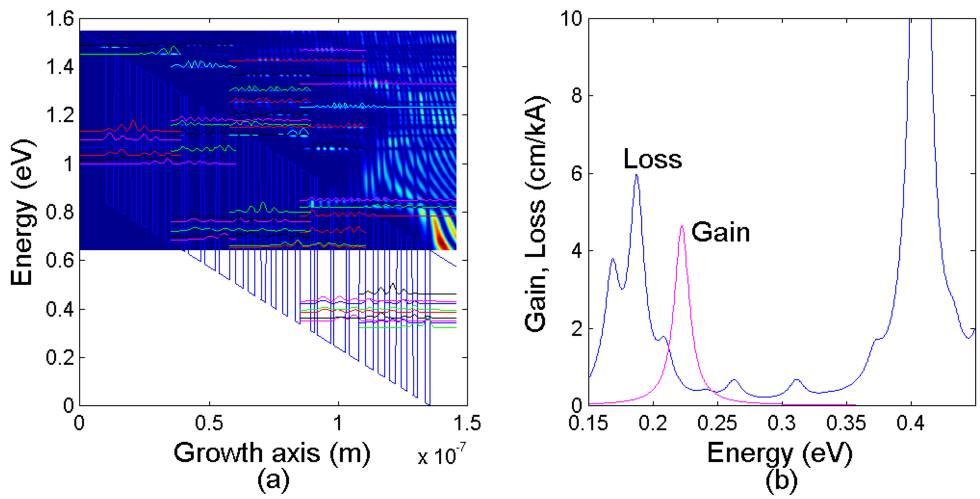

Fig. 2. (a) Bound, quasi-bound, and continuum state wavefunctions for two stages of the QCL structure; (b) loss due to transitions from the upper laser level to the quasi-bound states and gain coefficient as functions of the transition energy.

References

1. A. Evans, J. S. Yu, S. Slivken, and M.Razeghi, *Appl.Phys. Lett.*. **85**, 2166 (2004).
2. Z. Liu, D. Wasserman, S. S. Howard, A. J. Hoffman, C. F. Gmachl, X. Wang, T. Tanbun-Ek, L. Cheng, and F. S. Choa, *IEEE Photon. Technol. Lett.*, **18,** 1347 (2006).
3. L. Diehl, D. Bour, S. Corzine, J. Zhu, G. Hofler, M. Loncar, M. Troccoli, and F. Capasso, *Appl. Phys. Lett.*, **89**, 081101 (2006).
4. Z. Liu, G. Silva, J. J. Paulose, C. F. Gmachl, L. Cheng, F. S. Choa, R. Leavitt, F. J. Towner, X. Wang, and J. Fan, *CLEO/QELS 2007 Technical Digest*, CTuO4.
5. D. Hofstetter, M. Beck, T. Aellen, and J. Faist, *Appl.Phys. Lett.*, **78**, 396 (2001).
6. S. Slivken, A. Evans, J.David, and M.Razeghi, *Appl.Phys. Lett.*. **81**, 4321 (2002).
7. V. V. Mitin, V. A. Kochelap, and M. A. Stroscio, *Quantum Heterostructures,*(Cambridge, 1999).