Many-body effects in gain and refractive-index spectra of bulk and quantum-well semiconductor lasers

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Gain and refractive-index spectra for bulk and quantum-well semiconductor lasers are computed using quantum-mechanical many-body theory. The results clearly show the influence of band-gap renormalization, broadening, and Coulomb enhancement on the gain, the absorption, and the refractive-index spectra.

In the standard theory of laser action in semiconductors,[1–3] the electron–hole plasma is treated purely phenomenologically without proper inclusion of the many-body Coulomb effects. To investigate the importance of these effects we recently developed a many-body theory for semiconductor lasers that is valid both for three-dimensional bulk materials and for quasi-two-dimensional quantum-well structures.[4] Our theoretical description of the many-body Coulomb effects is based on the experimental and theoretical studies of passive laser-excited semiconductors of the past 10 years,[5] which show clearly that the optical properties near the fundamental absorption edge are strongly influenced by Coulomb interactions in the electron–hole system. Well-established effects are, e.g., the reduction of the band gap with increasing carrier density, the electron–hole plasma screening of the Coulomb potential, and the enhancement of the optical interband transitions owing to the attractive electron–hole interaction. In this Letter we use the previously developed many-body theory of semiconductor lasers to compute the spectra of the gain and the refractive index at different plasma densities and different temperatures. Taking the material parameters of GaAs as a representative example, we present results for a three-dimensional case of bulk material and a quasi-two-dimensional quantum-well structure.

Using quantum-mechanical many-body theory one can derive the following equation of motion for the interband polarization $P(k)$ between the dipole-coupled valence and conduction band[5–7]:

$$\left[\frac{\partial}{\partial t} + i\Delta\epsilon_{\text{eff}}(k) + \gamma\right]P(k) = i[1 - f_h(k) - f_e(k)] \times \left[d_k E(t) + \sum_{k'\neq 0} V_s(k-k')P(k')\right]. \quad (1)$$

Here $f_{e/h}(k)$ are the distribution functions of electrons and holes in their bands, d_k is the dipole matrix element, $E(t)$ is the light field, V_s is the screened Coulomb potential, and γ^{-1} is the dephasing time. The transition energy $\Delta\epsilon_{\text{eff}}$ is renormalized by screening and intraband exchange effects. The detailed expression is given in Ref. 4.

Recent femtosecond experiments[8] have shown that the dephasing time γ^{-1} in semiconductor lasers is less than 100 fsec. Therefore, by restricting ourselves to a time scale of picoseconds or longer, we can assume that the electron–hole distribution functions $f_{e/h}$ are given by Fermi functions with quasi-chemical potentials defined within the respective bands. In this quasi-steady-state regime we solve the polarization Eq. (1) using a Padé approximation[9] with the result[4]

$$\chi(\omega) = \frac{1}{V}\sum_k \frac{\chi_0(k,\omega)}{1 - q_1(k,\omega)}, \quad (2)$$

where

$$\chi_0(\omega) = \sum_k \chi_0(k,\omega) = \sum_k \frac{d_k[f_e(k) + f_h(k) - 1]}{\omega - \Delta\epsilon_{\text{eff}}(k) + j\gamma} \quad (3)$$

is the susceptibility for electrons and holes without interband Coulomb effects. The factor $1/(1 - q_1)$ in Eq. (2), with

$$q_1(k,\omega) = \frac{1}{d_k}\frac{1}{V}\sum_{k'} V_s(k-k')\chi_0(k',\omega), \quad (4)$$

describes the Coulomb enhancement of the optical transitions caused by the interband attraction of electrons and holes. As discussed in Ref. 4, the enhancement factor has a peak near the quasi-chemical potential and approaches unity for small and large energies.

From the real and imaginary parts of the susceptibility χ we obtain the spectra of absorption (gain) and the index of refraction. Figure 1 shows the computed results for bulk GaAs (Ref. 10) at T = 300 K and various plasma densities, i.e., various injection currents. The gain regime expands with increasing carrier density since (1) the crossover from gain to absorption, i.e., the quasi-chemical potential, shifts to higher energies for higher plasma densities, and (2) the renormalized band gap decreases with increasing plasma density. From Fig. 1(b) we see that the peak of the corresponding refractive-index spectra shifts to higher

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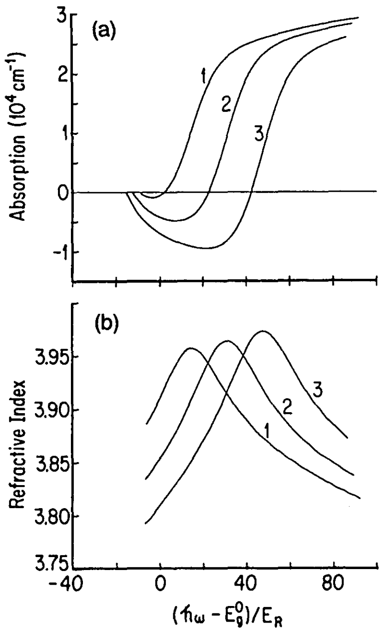

Fig. 1. (a) Gain/absorption and (b) refractive-index spectra for bulk GaAs at room temperature and plasma densities of 2×10^{18} (curve 1), 5×10^{18} (curve 2), and 1×10^{19} cm^{-3} (curve 3).

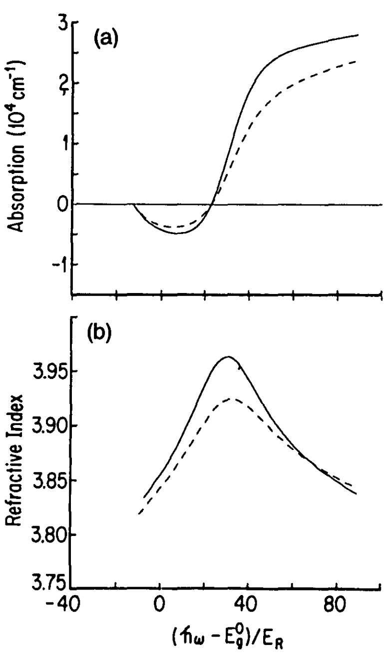

Fig. 2. (a) Gain/absorption and (b) refractive-index spectra for room-temperature bulk GaAs at a density of 2×10^{18} cm^{-3}. The dashed curves are the results without Coulomb enhancement.

energies, causing negative refractive-index changes in the gain regime.

Figure 2 presents a comparison between the spectra obtained using Eqs. (2) and (3), i.e., with and without the Coulomb enhancement factor. Even though the enhancement is not pronounced in the gain regime, Fig. 2(b) shows that the index of refraction is significantly modified since the refractive-index changes are related to the total changes in the gain/absorption spectrum.

The optical spectra for a quasi-two-dimensional GaAs quantum well[11] at $T = 300$ K (Fig. 3) also exhibit increasing chemical potential and band-gap renormalization. The shape of the gain spectra [Fig. 3(a)] deviates significantly from that of bulk GaAs, express-

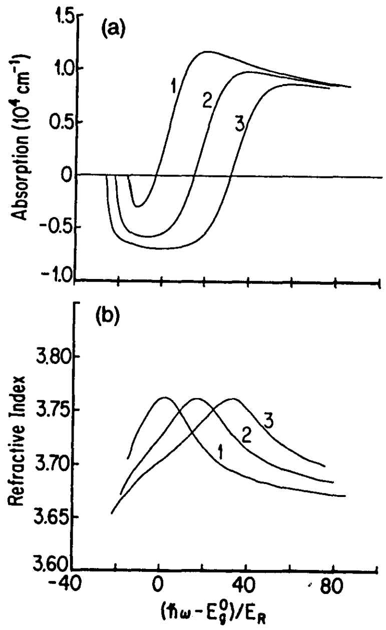

Fig. 3. (a) Gain/absorption and (b) refractive-index spectra for quasi-two-dimensional GaAs at room temperature for the plasma densities of 2×10^{12} (curve 1), 4×10^{12} (curve 2), and 6×10^{12} cm^{-3} (curve 3).

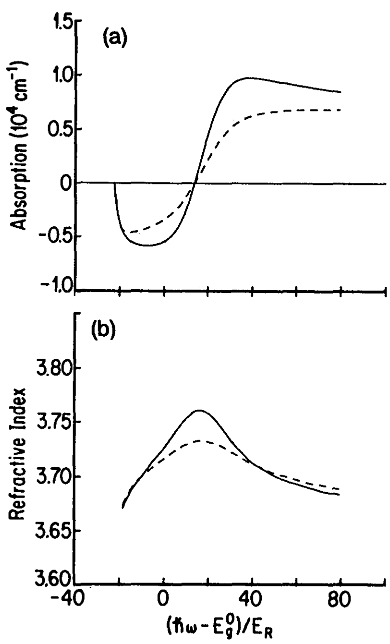

Fig. 4. Quasi-two-dimensional GaAs (a) gain/absorption and (b) refractive-index spectra for room temperature and a plasma density of 4×10^{12} cm^{-3}. The dashed curves are the results without Coulomb enhancement.

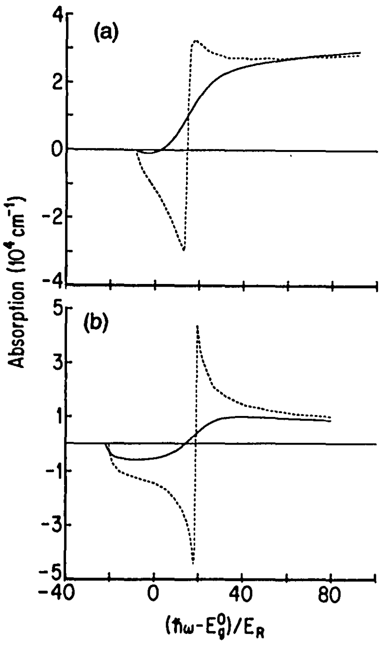

Fig. 5. (a) Bulk GaAs and (b) quasi-two-dimensional GaAs gain/absorption spectra for a density of 2×10^{18} (a) and 4×10^{12} cm^{-3} (b) and temperatures of $T = 10$ K (dotted curves) and $T = 300$ K (solid curves).

ing the difference in the density of states in two and three dimensions and the stronger electron–hole Coulomb correlation in two dimensions. To illustrate this fact further we show in Fig. 4 a comparison between the results of Eqs. (2) and (3) for the two-dimensional case. The combined influence of the Coulomb enhancement and the constant density of states in two dimensions leads to a gain spectrum with a broad flat maximum.

Figure 5 shows the influence of the temperature on the absorption spectra obtained from Eq. (2) in both two and three dimensions. At low temperatures the Coulomb enhancement causes sharp peaks below and above the quasi-chemical potential. Note that in bulk material the spectral region of optical gain expands significantly with decreasing temperature, whereas the expansion is almost negligible in two dimensions.

In conclusion, we have presented a comprehensive study of the influence of many-body effects on gain, absorption, and refractive-index spectra in bulk and quantum-well GaAs. The Coulomb effects are by no means negligible for a quantitative analysis and have to be included in any systematic study of laser action in semiconductors.

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References

1. A. Yariv, *Optical Electronics*, 3rd ed. (Holt, Rinehart & Winston, New York, 1985).
2. G. P. Agarwal and N. K. Dutta, *Long-Wavelength Semiconductor Lasers* (Van Nostrand Reinhold, New York, 1986).
3. G. H. B. Thompson, *Physics of Semiconductor Laser Devices* (Wiley, Chichester, UK, 1980).
4. H. Haug and S. W. Koch, Phys. Rev. A **39**, 1887 (1989).
5. See, e.g., H. Haug, ed., *Optical Nonlinearities and Instabilities in Semiconductors* (Academic, New York, 1988); H. Haug and S. Schmitt-Rink, Prog. Quantum Electron. **9**, 3 (1984); J. Opt. Soc. Am. B **2**, 1135 (1985); L. Banyai and S. W. Koch, Z. Phys. **B63**, 283 (1986); S. Schmitt-Rink, C. Ell, and H. Haug, Phys. Rev. B **33**, 1183 (1986).
6. J. R. Müller, R. Mewis, and H. Haug, Z. Phys. **B69**, 231 (1987).
7. M. Lindberg and S. W. Koch, Phys. Rev. B **38**, 3342 (1988).
8. M. P. Kessler and E. P. Ippen, Appl. Phys. Lett. **51**, 1765 (1987).
9. P. R. Gaves-Morris, ed., *Padê Approximants and Their Application* (Academic, New York, 1973).
10. The material parameters for bulk GaAs are $E_R = 4.2$ meV, $a_0 = 12.4$ nm, $m_e = 0.0665m_0$, $m_h = 0.52m_0$, and $\hbar\gamma = 1E_R$ ($0.1E_R$) for $T = 300$ K (10 K). $E_g = 1522$ meV $- 0.58T^2/(T + 226$ K) meV/K according to C. K. Kim, P. Lautenschlager, and M. Cardona, Solid State Commun. **59**, 797 (1986).
11. For quasi-two-dimensional GaAs we take the bulk parameters, except that E_g is increased by 120 meV. The energies are scaled to the three-dimensional Rydberg energy.