Linewidth Enhancement Factor and Nonlinear Gain in ZnSe Semiconductor Lasers

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***Abstract*— We have investigated the effects of the Coulomb interaction on the optical gain and the refractive index of ZnSe semiconductor lasers. The Coulomb interaction increases the differential gain, leading to a decrease of the threshold carrier density. Its influence on the linewidth enhancement factor and the nonlinear gain coefficient is relatively small because it increases both the gain and the refractive index simultaneously. We have compared the linewidth enhancement factor α and the nonlinear gain coefficient ε for ZnSe and GaAs lasers with the effects of the Coulomb interaction taken into account. For typical values of total cavity losses, the values of α and ε are higher for ZnSe lasers compared with GaAs lasers.**

I. INTRODUCTION

RECENTLY blue-green lasers have attracted much attention because of their potential applications for optical data storage [1]–[4]. Currently, the main limitation of this kind of lasers is their very short lifetime. For producing reliable CdZnSe–ZnSe lasers, operating continuously at room temperature, further technological improvement and physical understanding of the laser are necessary. Several theoretical papers have studied the linear optical gain in ZnSe lasers [2]–[4]. However, little attention has been paid to the linewidth enhancement factor and the nonlinear gain coefficient [5], which are two important laser parameters influencing many static, dynamic and noise characteristics of semiconductor lasers. In this paper we discuss these laser parameters for ZnSe bulk lasers and compare them with those of GaAs lasers.

The most important difference between ZnSe and GaAs lasers, at least from a theoretical points of view, is that the excitonic effects are much more important for ZnSe, especially at low temperatures [3]. However, as the temperature increases, the importance of the excitonic effects decreases and the role of electron-hole plasma becomes important. For this reason, the model of electron-hole plasma with the Coulomb interaction taken into account seems a reasonable method for studying the optical properties of ZnSe lasers operating at room temperature [4]. We use this model in the following analysis.

II. THEORY

The linear and nonlinear optical susceptibilities for transitions between the conduction and the valence bands with the excitonic enhancement taken into account can be written as [4], [6]:

$$\chi_L(n,E) = \frac{1}{\varepsilon_0}\int_{E_g}^{\infty} F(E_t) \times \frac{R_t^2 D(\omega_t)[f_c + f_v - 1][E - E_t - i\hbar/\tau_{\rm in}]}{[E - E_t]^2 + [\hbar/\tau_{\rm in}]^2}\, dE_t \tag{1}$$

$$\chi_{\rm NL}(n,E) = \frac{E\mathbf{P}[\tau_c + \tau_v]/\tau_{\rm in}}{\varepsilon_0^2 \mu\mu_g}\int_{E_g}^{\infty} F(E_t) \times \frac{R_t^4 D(\omega_t)[f_c + f_v - 1][E - E_t - i\hbar/\tau_{\rm in}]}{\{[E - E_t]^2 + [\hbar/\tau_{\rm in}]^2\}^2}\, dE_t \tag{2}$$

where E and E_t are photon energy and transition energy, respectively, n is the carrier density, E_g is the band gap energy, ε_0 the vacuum permittivity, R_t the dipole moment, $D(\omega t)$ the reduced density of states, f_c and f_v are the occupation probabilities of electrons in the conduction band and holes in the valence band at quasiequilibrium, τ_c, τ_v and $\tau_{\rm in}$ are the intraband relaxation time for electrons, holes, and polarization,. respectively; $\mathbf{P}$ is the photon density, μ and μ_g are the refractive and group index, $\hbar$ is the Planck constant divided by 2π, and $F(E_t)$ is the excitonic enhancement factor given by:

$$F(E_t) = \prod_{j=1}^{\infty}\{1+(2\gamma j^2-\gamma^2)/[(j^2-\gamma)^2+j^2\gamma^2(E_t-E_g)/E_x]\} \tag{3}$$

where E_x is the exciton binding energy and γ is given by (4), shown at the bottom of the next page, where k_B is the Boltzmann constant, μ_c, μ_v and $\mu_{\rm eff}$ are the electron, hole, and reduced effective mass, respectively.

The gain spectrum is obtained from (1) by using the relation $g_L = -[\hbar c/2E]{\rm Im}(\chi_L)$. For a given carrier density, the peak gain $g_{\rm peak}$ is the value of g_L at the peak of the gain spectrum. The linewidth enhancement factor α and the nonlinear gain coefficient ε are obtained from (1) and (2) by using the definitions

$$\alpha = \frac{{\rm Re}(\chi_L)}{{\rm Im}(\chi_L)}; \quad \varepsilon = -\frac{{\rm Im}(\chi_{\rm NL})}{{\rm Im}(\chi_L)\mathbf{P}} \tag{5}$$

III. RESULTS

The band parameters used in our calculation are shown in Table I. The intraband relaxation times τ_c, τ_v, and $\tau_{\rm in}$ are assumed to be the same for both ZnSe and GaAs lasers, with the values of 200 fs, 70 fs, and 100 fs, respectively. The laser

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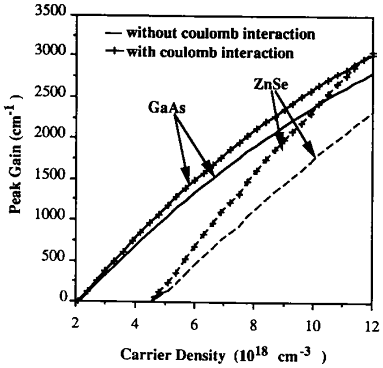

Fig. 1. Comparison of peak gain as a function of carrier density with and without the Coulomb interaction for ZnSe and GaAs lasers.

TABLE I
BAND PARAMETERS USED IN NUMERICAL CALCULATIONS

parameters	GaAs	ZnSe
m_c/m_0	0.067	0.145
m_v/m_0	0.48	0.60
E_g (eV)	1.42	2.71
Δ (eV)	0.35	0.43
μ	3.6	2.9
μ_g	4.2	3.5
E_x (meV)	4	17

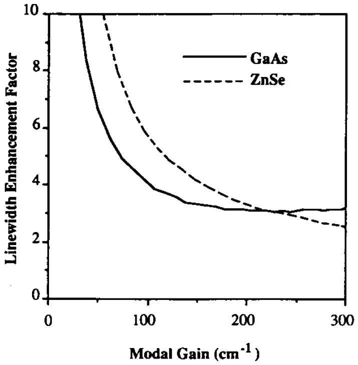

Fig. 2. Linewidth enhancement factor at the peak gain wavelength as a function of modal gain for GaAs and ZnSe lasers.

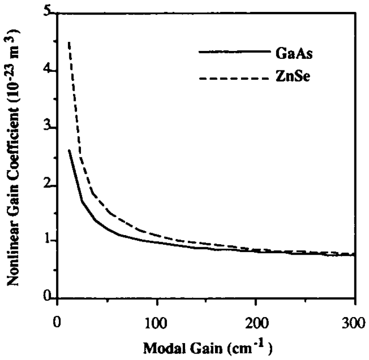

Fig. 3. Nonlinear gain coefficient at the peak gain wavelength as a function of modal gain for GaAs and ZnSe.

operating temperature is 300 K. The calculated peak gain is shown in Fig. 1 as a function of carrier density for both GaAs and ZnSe lasers. For comparison, the results obtained without including the Coulomb interaction are also shown in this figure. The Coulomb interaction increases peak gain at a given carrier density and this increase is more important for ZnSe lasers because of a larger exciton binding energy. The differential gain is also enhanced by the coulomb interaction. Because of the larger band gap, the carrier density at transparency n_0 is larger for ZnSe lasers, and the Coulomb interaction does not influence n_0. Note that the gain enhancement seen in Fig. 1 relates to the gain peak, which itself shifts with increasing carrier density. This is different than the enhancement factor calculated by comparing the gain at a given frequency.

Fig. 2 shows the linewidth enhancement factor as a function of the modal gain, defined as $g_{\text{mod}} = \Gamma g_{\text{peak}}$ with the confinement factor $\Gamma = 0.1$, for both GaAs and ZnSe lasers. The linewidth enhancement factor α decreases with the modal gain for both types of lasers. As compared to GaAs lasers, α is larger in ZnSe lasers for $g_{\text{mod}} < 230$ cm^{-1} and smaller for higher modal gains. The nonlinear gain coefficient ε as a function of modal gain is shown in Fig. 3. ε decreases with the modal gain and its value is about 10–20% higher in ZnSe than in GaAs lasers for typical values of the modal gain. The ε parameter has previously been calculated for strained quantum wells but without including the Coulomb-interaction effects [5].

In order to show quantitatively the effects of the Coulomb interaction on laser parameters, Table II gives the values of the carrier density at transparency, the maximum gain at a carrier density of 6.6×10^{18} cm^{-3}, the differential gain, the linewidth enhancement, and the nonlinear gain coefficient at the peak gain wavelength for ZnSe lasers. The Coulomb interaction does not change the carrier density at transparency, but increases the peak gain and the differential gain by about 50%. Both α and ε are reduced, but the decrease is relatively small (about 4%) because the Coulomb interaction increases both the real and imaginary parts of the optical susceptibility, and both the linear and nonlinear gain, at the same time.

Supposing an internal loss of 40 cm^{-1}, a cavity length of 400 μm and the reflectivity of 30% for both mirrors

$$\gamma = \sqrt{\frac{\pi k_B \mathrm{T} \mathrm{E}_x^{1/2}}{4}} \times \left\{ \int_{E_g}^{\infty} (E_t - E_g)^{1/2} dE_t \sum_{i=c;v} (m_i/m_{\text{eff}})^{3/2} f_i(1 - f_i) \right\}^{-1/2} \tag{4}$$

TABLE II
EFFECT OF THE COULOMB INTERACTION ON CALCULATED GAIN PARAMETERS FOR A ZnSe LASER AT A CARRIER DENSITY OF $6.6\times10^{18}\mathrm{cm}^{-3}$

parameters	without Coulomb interaction	with Coulomb interaction
n_0 (10^{18} cm^{-3})	4.8	4.8
g_{peak} (cm^{-1})	666	1000
dg/dn (10^{-16} cm^2)	3.3	4.9
α	6.1	5.8
ε (10^{-23} m^3)	1.15	1.1

for both GaAs and ZnSe lasers, the $\alpha = 4.0$ and 5.8 and $\varepsilon = 0.95 \times 10^{-23}$ m^3 and 1.1×10^{-23} m^3, respectively. Therefore, both α and ε are larger for ZnSe laser compared with GaAs laser.

In conclusion, the Coulomb interaction increases both the peak gain and the differential gain, leading to a decrease of the laser threshold carrier density. Its influence on the linewidth enhancement factor and the nonlinear gain coefficient is relatively small. Because of the large band gap in ZnSe lasers, the values of α are higher in ZnSe lasers than in GaAs lasers under typical operating conditions. The nonlinear gain coefficient is also larger by about 10% for ZnSe lasers.

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