On the high speed modulation bandwidth of quantum well lasers

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(Received 26 August 1991; accepted for publication 9 October 1991)

A recent formulation of the gain in conventional three-dimensional double heterostructure (DH) and two-dimensional quantum well (QW) semiconductor lasers has been used to study the high speed modulation in such lasers. The emphasis is on the differential gain and nonlinear (i.e., intensity dependent) gain suppression in these material systems. We conclude that, in variance with earlier predictions, the expectation of higher modulation speed in QW lasers is not warranted at room temperature. The advantage of using multiple QW structure for high speed performance has been analyzed.

Quantum well (QW) lasers have received considerable attention because of the predicted significant improvement in operating characteristics compared to conventional double heterostructure (DH) lasers. Extremely low threshold current and reduced spectral linewidth have been experimentally demonstrated in the QW lasers.[1,2] The differential gain has been theoretically predicted to be enhanced by a factor of 2–4 in the QW lasers.[3] A theoretical consequence of the differential gain enhancement is the improvement of the high speed modulation bandwidth. So far the high speed modulation experiments indicate no significant improvement in the QW laser modulation bandwidth compared to DH lasers.[2,4–7] These experiments also show that the use of multiple quantum wells (MQW), instead of single QW (SQW), as the active region leads to improvement in high speed performance. Is the claim that the QW lasers possess inherently higher modulation bandwidths correct? Does there exist an ultimate modulation speed in the MQW structures? In this letter we try to answer these questions by investigating the modulation dynamics with consideration of different geometrical and dimensional characteristics of carriers in the active region and photons in the waveguide of the QW and the DH structures. We compare the optimized modulation bandwidth in SQW, MQW, and DH lasers and explore the ultimate modulation bandwidth in the QW lasers.

In two-dimensional (2D) QW lasers, for one single QW, the *2D carrier density (N)* and the three-dimensional (3D) photon density (*P*) at the QW are related by rate equations which include the spectral hole burning induced nonlinear gain suppression.[8,9]

$$\frac{dN}{dt}=\frac{J}{e}-\frac{N}{\tau_n}-G_0v_gP+G_1v_g\frac{P^2}{P_s}, \quad (1)$$

$$\frac{dP}{dt}=\Gamma_cG_0v_gP-\Gamma_cG_1v_g\frac{P^2}{P_s}-\frac{P}{\tau_p}, \quad (2)$$

where J is the injection current density, τ_n and τ_p are the carrier and photon lifetimes, v_g is the photon group velocity and P_s is the saturation photon density. The dimensionless 2D material gain coefficients for the QW, G_0^{QW} and G_1^{QW}, are written as

$$G_0(E)=A\sum_{i=l,h}\int\delta\rho_i(f_e+f_h-1)\mathscr{L}d\mathscr{E}, \quad (3)$$

$$G_1(E)=A\sum_{i=l,h}\int\delta_i^2\rho_i(f_e+f_h-1)\mathscr{L}^2d\mathscr{E}, \quad (4)$$

where $\mathscr{L}=(\hbar/T_2)^2/[(\hbar/T_2)^2+(\mathscr{E}-E)^2]$ is the Lorentzian function, $A=E\mu^2T_2/(\hbar^2c\epsilon_0n)$, n is the modal refractive index, T_2 is the interband dephasing time, E is the photon energy of the laser field, μ is the dipole moment matrix element, ρ_i is the step-like 2D reduced density of states for the carriers in the QW, i designates either light holes ($i=l$) or heavy holes ($i=h$), f_e and f_h are the quasi-Fermi distribution functions for electrons and holes, respectively, and δ_i is the polarization modification factor for the dipole moment in the QW structure.[10] The coupling factor Γ_c, which accounts for the separate confinement of the injected carriers in the QW and the photons in the waveguide, is given by

$$\Gamma_c^{SQW}=\int|\psi_e(x)\psi_h(x)|P_p(x)dx\approx\frac{1}{t}, \quad (5)$$

where $\psi_e(x)$ and $\psi_h(x)$ are the normalized wave functions for electrons in the conduction band and holes in the valence bands, respectively, $P_p(x)$ is the normalized optical intensity distribution function and t is the effective optical mode width.

We apply our analysis to the GaAs/AlGaAs material system. We assume a typical QW laser structure with symmetric 4000 Å $Al_{0.5}Ga_{0.5}As/Al_{0.2}Ga_{0.8}As$ graded index (GRIN) separate confinement heterostructure (SCH) and a 100 Å quantum well located at its center. The coupling factor is evaluated as $\Gamma_c^{SQW}=3.56\times10^4\ cm^{-1}$ for this SQW structure. The computed peak 2D material gain coefficients G_0^{QW}, corresponding G_1^{QW}, differential gain coefficients $G_0^{QW'}=dG_0^{QW}/dN$ and $G_1^{QW'}=dG_1^{QW}/dN$ as functions of *2D carrier density (N)* at room temperature ($T=300$ K) are shown in Fig. 1. We have taken the following values for the relevant parameters in the calculation, $\mu=5.2\times10^{-29}$ C m, $T_2=0.1$ ps, $\tau_n=3$ ns, and $n=3.4$ for the TE mode. We assume that all subbands are parabolic and $m_e=0.067m_0$, $m_{hh}=0.45m_0$, $m_{lh}=0.082m_0$ have been used.

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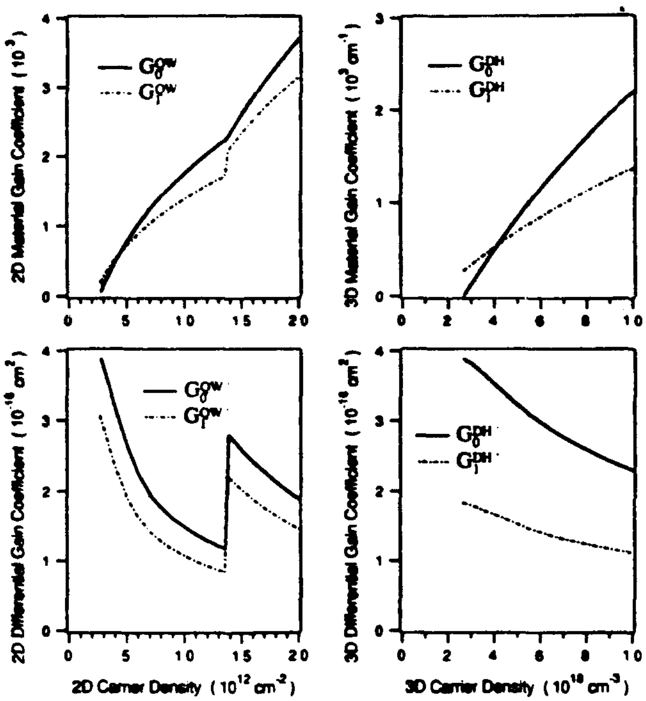

FIG. 1. Peak material gain coefficients for 2D QW and 3D DH and corresponding differential gain coefficients as functions of carrier density.

Performing a standard small-signal analysis we find the 3 dB modulation bandwidth

$$f_{3\mathrm{dB}}=\sqrt{f_r^2-\frac{\gamma^2}{8\pi^2}+\sqrt{\left(f_r^2-\frac{\gamma^2}{8\pi^2}\right)^2+f_r^4}}, \tag{6}$$

where f_r is the relaxation resonance frequency

$$f_r^2=\frac{v_g^2\Gamma_c}{4\pi^2}\left[\left(G_0-2G_1\frac{P_0}{P_s}\right)\left(G_0'-G_1'\frac{P_0}{P_s}\right)+\frac{G_1}{P_s}\left[\frac{1}{v_g\tau_n}+\left(G_0'-G_1'\frac{P_0}{P_s}\right)\right]\right]P_0, \tag{7}$$

P_0 is the stationary photon density at the QW active region. Note that if we neglect gain suppression, i.e., $G_1=0$, we get the conventional result $2\pi fr = \sqrt{v_g G_0' P_0/\tau_p}(1/\tau_p = \Gamma_c G_0 v_g)$. The damping rate γ is given by

$$\gamma=\frac{1}{\tau_n}+v_g\left[\left(G_0'-G_1'\frac{P_0}{P_s}\right)+\frac{\Gamma_c G_1}{P_s}\right]P_0. \tag{8}$$

. For the 3D DH lasers we assume a typical $Al_{0.35}Ga_{0.65}As/GaAs$ DH with GaAs active layer thickness 0.1 μm. The 3 dB modulation bandwidth is also described by Eqs. (6)–(8) but the coupling factor for the DH structure is

$$\Gamma_c^{\mathrm{DH}}=\int_{\text{active region}}P_p(x)dx\simeq\frac{d}{t}, \tag{9}$$

where d is the active layer thickness and it is evaluated as $\Gamma_c^{\mathrm{DH}}=0.328$ for the assumed DH structure. The conventional 3D material gain coefficients for DH lasers, G_0^{DH} and G_1^{DH}, are also written as Eqs. (3) and (4) but ρ_i is the 3D

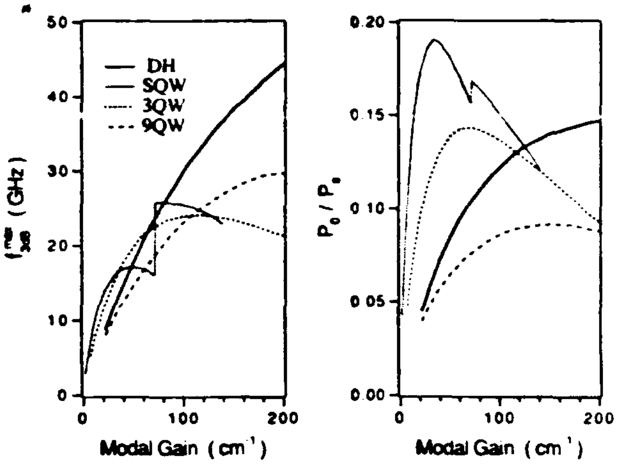

FIG. 2. Maximum 3 dB modulation bandwidth and corresponding photon density as functions of modal gain for different structures.

reduced density of states for the carriers in the active layer of the DH structure.

The computed peak 3D material gain coefficients G_0^{DH}, corresponding G_1^{DH}, differential gain coefficients $G_0^{\mathrm{DH}'}=dG_0^{\mathrm{DH}}/dN$ and $G_1^{\mathrm{DH}'}=dG_1^{\mathrm{DH}}/dN$ as functions of *3D carrier density (N)* in the active region are shown in Fig. 1 for $T=300$ K. Figure 1 shows that there is no differential gain enhancement in QW structures compared to DH structure at room temperature. This conclusion differs from that of previous theoretical predictions and is in agreement with the fact that no significant improvement in the high speed modulation bandwidth of QW lasers has been reported to date.

The definition of Γ_c^{SQW} [Eq. (5)] shows that Γ_c^{SQW} does not depend on the QW width. Γ_c^{SQW} can only be changed by changing the SCH structure, which changes the optical mode width. Another way to change the coupling factor is to employ MQW in the active region. We simply assume the coupling factor is increased as $\Gamma_c^{\mathrm{MQW}} \approx N_{\mathrm{QW}}\Gamma_c^{\mathrm{SQW}}$ for the MQW structure with N_{QW} uncoupled quantum wells in the following analysis. Γ_c^{DH} is the conventionally defined confinement factor and the different definition for Γ_c^{SQW} stems from the different dimensionality of the confined carriers in the QW . The coupling factor Γ_c reflects the impact of carrier dimensionality on the coupling between the injected carriers and the stimulating photons. Both above defined 2D and 3D material gain coefficients do not depend directly on the laser device parameters and are material and dimensionality (i.e., 3D or 2D) dependent.

From Eqs. (6)–(8) we find that the intrinsic 3 dB modulation bandwidth $f_{3\mathrm{dB}}$ depends on the stationary photon density P_0 and there exists a value of P_0 that maximizes $f_{3\mathrm{dB}}$, $f_{3\mathrm{dB}}=f_{3\mathrm{dB}}^{\max}$. In Fig. 2 we show $f_{3\mathrm{dB}}^{\max}$ and corresponding photon density as functions of the modal gain ($G_{\mathrm{modal}}=\Gamma_c G_0$) for a SQW, three QW (3QW), nine QW (9QW), and DH lasers. We find that as the number of quantum wells N_{QW} increases the *maximum* $f_{3\mathrm{dB}}^{\max}$ increases but this increase "saturates". In other words, there seem to exist an ultimate limit to the modulation speed attainable

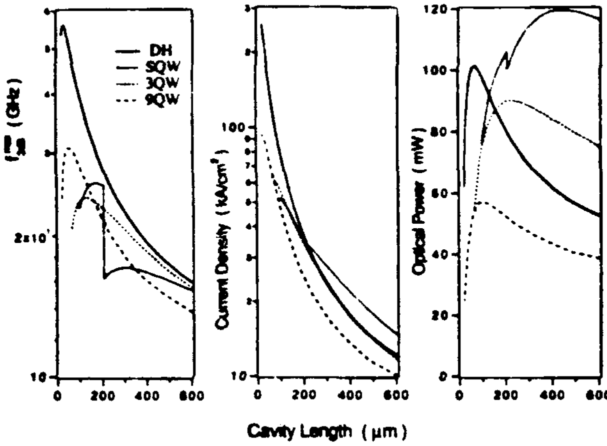

FIG. 3. Maximum 3 dB modulation bandwidth, corresponding injection current density and optical output power as functions of cavity length for different structures.

with MQW structures. Fig. 2 also shows that the photon density, at which $f_{3\,\mathrm{dB}} = f^{\max}_{3\,\mathrm{dB}}$, is reduced as N_{QW} increases.

For a better understanding of the modulation bandwidth improvement and the ultimate limit, we consider the 0 dB modulation bandwidth instead of the 3 dB bandwidth employed above

$$f_{0\,\mathrm{dB}} = \sqrt{2\left(f_r^2 - \frac{\gamma^2}{8\pi^2}\right)}. \qquad (10)$$

$f_{0\,\mathrm{dB}}$ is the frequency at which the power response to current modulation is equal to the low frequency limit. It is straight forward to show that $f_{0\,\mathrm{dB}}$ has a maximum value

$$f^{\max}_{0\,\mathrm{dB}} = \frac{1}{2\pi}\ \frac{v_g G_0 G_0'}{G_0'/\Gamma_c + G_1/P_s}, \qquad (11)$$

at a photon density

$$P_0 = \frac{1}{\Gamma_c}\ \frac{G_0 G_0'}{(G_0'/\Gamma_c + G_1/P_s)^2}. \qquad (12)$$

We find that as the coupling factor increases the modulation bandwidth is enhanced. This improvement is due to the relative fading of the damping effect caused by the differential gain. We also find that there exists a limit

$$f^{\mathrm{ultimate}}_{0\,\mathrm{dB}} = \frac{1}{2\pi}\ \max\left(\frac{G_0 G_0'}{G_1}\right) v_g P_s \qquad (13)$$

for the improvement due to increase of Γ_c. Equation (12) indicates that the optical power level, at which modulation bandwidth is optimized, is reduced as the coupling factor increases.

In Fig. 3 we show the calculated $f^{\max}_{3\,\mathrm{dB}}$, corresponding bias current density and optical power as functions of cavity length L for the different structures. We have assumed internal loss constant $\alpha_i = 2\ \mathrm{cm}^{-1}$ for each QW and $\alpha_i = 15\ \mathrm{cm}^{-1}$ for the DH structure. We have taken active stripe width $w = 2\ \mu\mathrm{m}$ and mirror reflectivity $R = 0.3$ for the QW and the DH lasers. The MQW structure are superior to the SQW structure in the terms of operating injection current density and optical power. Very high injection current density will cause the thermal degradation of differential gain and finally reduce the modulation bandwidth. The operating optical power reduction in MQW structures will give reduction in the damage to the laser structures under high optical intensity. The use of MQW as active region makes the QW lasers much easier to approach their optimized high speed bandwidth limits.

Figure 3 shows that, ideally, the DH lasers have larger $f^{\max}_{3\mathrm{dB}}$ than the SQW lasers, but this conclusion is also subject to the corresponding operation conditions to reach $f^{\max}_{3\mathrm{dB}}$. Generally the thermal degradation is very severe if the injection current density is beyond 10 kA/cm^2 in a semiconductor laser. Comparing the operation current density to reach $f^{\max}_{3\mathrm{dB}}$ in the DH and the SQW lasers, we find the DH lasers are superior to the SQW lasers at long cavity length ($L > 200\ \mu\mathrm{m}$). The abrupt increase of $f^{\max}_{3\mathrm{dB}}$ for $L < 200\ \mu\mathrm{m}$ in the SQW lasers is due to the onset of the second quantized state lasing. The high speed operation lasing at the second quantized state is not healthy due to the severe thermal degradation. We notice that $f^{\max}_{3\mathrm{dB}}$ has a peak at $L \simeq 300\ \mu\mathrm{m}$ for the SQW lasers operating at the first quantized state. At $L \simeq 300\ \mu\mathrm{m}$ the DH lasers have larger $f^{\max}_{3\mathrm{dB}}$ and lower injection current density than the SQW lasers.

In conclusion, at variance with previous theoretical predictions we find at room temperature there is no differential gain enhancement in the QW structure lasers. This leads to no significant improvement on the modulation bandwidth in the QW lasers. We show that the modulation bandwidth in the QW lasers can be enhanced by enlarging the coupling factor and there exists an ultimate for this improvement. In practice the modulation bandwidth improvement is strongly limited by the thermal degradation and optical degradation. In QW lasers, the use of MQW as active region makes the high speed operation of the lasers practical and reliable.

The authors are grateful DAPPA, the Office of Naval Research, and the Air Force Office of Scientific Research who supported this work.

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