EFFECT OF CAPTURE AND ESCAPE TIME CONSTANTS OF ENHANCED PERFORMANCE FOR QUANTUM WELL LASERS IN DIRECT MODULATION

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Abstract

The capture and escape time constants are a small and finite capture and escape time of the carriers between the separate confinement (SCH) region and the quantum well. These time constants are in picosecond time scale and are important in the direct modulated quantum well lasers which these small time constants are effected on the gain compression factor where the gain one from the compression factor is effected on the differential gain . The differential gain is important factors for the enhanced performance for the direct modulated quantum well lasers which the output this lasers are depended on it.

تأثير ثوابت زمن الاسر والهروب على تحسين اداء ليزرات البئر الكمي ذات التضمين المباشر

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الخلاصة

يعرف ثوابت زمن الأسر والهروب بأنه الزمن الصغير والمحدد لأسر وهروب حاملات الشحنة المحصورة بين منطقة الحصر المنفصل والبئر المكمم وتكون قيم هذه الأزمان بالبيكوسكند.تعتبر هذه الثوابت الزمنية مهمة في التضمين المباشر لليزرات البئر الكمي حيث تؤثر على عامل الربح المضغوط الذي يؤثر بدوره على الربح التفاضلي حيث يعد هذا الربح من أحدى العوامل المهمة في تحسين أداء التضمين المباشر لليزرات البئر المكمم كون الخرج الليزري لهذه الليرات يعتمد عليه .

Introduction

Semiconductor lasers have become one of the most important elements in fiber optic links due to their superior modulation characteristics, size and cost efficiency [Agrawal,2002]. The typical laser wavelengths in coherent light communication systems based on semiconductor lasers are 1.3 μm and 1.55 μm, which correspond to the minimum dispersion and attenuation wavelengths, respectively[1,2]. The information is signal can be modulated on semiconductor lasers directly or externally. Direct modulation, involves changing the current input around the bias level above threshold. It is principally a simpler method and is easier to implement rather than the external modulation, but the output light produced depends on internal dynamics of the laser [Pua et al ,1997]. Therefore, in order to improve the modulation characteristics such as obtaining higher modulation bandwidth or enhanced modulation efficiency we need to be able to control some of the intrinsic laser parameters such as optical gain or optical confinement factor. There have been many efforts made to improve direct modulation of semiconductor lasers. This challenge actually began with the invention of new materials such as quantum wells (QWs), quantum wire(QWRs) and quantum dot (QDs) with better carrier and photon confinement that led to higher gain and differential gain and gradually improved by developing better wave guiding and current injections structures[Gareso et al ,2006].

Theory and analysis

A. Resonance Frequency Analysis of Semiconductor Laser:

The analysis of the dynamic behaviour of semiconductor laser starts from the interaction between photon number and carrier number[Pua et al .1997].

$$\frac{dN}{dt}=\frac{I}{eV}-\frac{N}{t_{SP}}-\frac{GP}{(1+eP)} \tag{1}$$

$$\frac{dP}{dt}=\frac{\Gamma GP}{(1+eP)}-\frac{P}{t_P}+\frac{bN}{t_{SP}} \tag{2}$$

where N *is* the carrier density, P is the photon density, I is the injection current, Γ is optical confinement factor, ε is the gain compression factor ,V is the volume of the optical gain medium,τ_{sp} is the carrier recombination lifetime (or spontaneous carrier lifetime) ,*G* is the unclamped material gain, τ_p is the photon lifetime in the cavity ,β represent the fraction of spontaneous emission ,and e is the electronic charge. The photon lifetime,τ_p, is considered as the average time that the photon remains in the cavity before it gets absorbed or emitted through the facets and is related to the cavity loss as

$$\frac{1}{t_P}=n_g(a_i+a_m)=n_g a_{CAV} \tag{3}$$

Where n_g is the group velocity, a_i is the internal loss , a_m is the mirror losses, and a_{CAV} is the cavity loss. At N =N_{th} (N_{th} is the carrier density at threshold), the gain at threshold (G_0) is equal the cavity losses(a_{CAV}) ,{ i.e. $G_0=G(N_{th})=(a_i+a_m)$ }, therefore ,at the steady-state rate equation{(d/dt)=0}, the model gain at threshold [Pua et al .1997] is

$$G_{th}=\Gamma G_0=\Gamma G(N_{th})=\Gamma(a_i+a_m) \tag{4}$$

But the non-linear gain which it is appeared by the gain compression factor, therefore, $G \to \frac{G}{1+eP_0}$ .By using (3) and (4) , we can the get on a relation ship between the model gain at threshold and photon lifetime and is

$$n_g(a_i + a_m) = \frac{1}{t_P} = \frac{G_{th}}{1+eP_0} \tag{5}$$

At the small-signal analysis[2,4], the injection current (the sinusoidal current variations with a time-varying current) consists on the steady-state input DC current (I_0) is superimposed with a small ac signal and in a simple case of only one angular frequency ω and constant amplitude i_m, the injection current is:

$$I(t) = I_0 + i_m e^{jwt} \tag{6}$$

Similar to the injection current, and by using the complex frequency domain notation, the carrier and photon densities can be also expressed as the sum of their steady-state value plus a small ac component:

$$N = N_0 + n_m e^{jwt} \tag{7}$$

$$P = P_0 + p_m e^{jwt} \tag{8}$$

By substituting equations (6) through (8) into the original rate equations (1) and (2) and considering the terms that are first order in ω , the following relationships are obtained:

$$jwn_m = \frac{i_m}{eV} - \left(\frac{1}{t_{SP}} + \frac{G^{/}P_0}{1+eP_0}\right)n_m - G_0\left(\frac{P_0 e}{(1+eP_0)^2} + \frac{1}{1+eP_0}\right)p_m \tag{9}$$

Where $G'=dG/dN$ is the differential gain. In the photon density rate equation ,besides substituting equations (6) through (8) into the original rate equations (1) and (2) ,we substitute for the inverse photon lifetime using equation (5) and will have:

$$jwp_m = \frac{\Gamma G^{/}P_0}{1+eP_0}n_m + \frac{G_{th}P_0 e}{(1+eP_0)^2}p_m \tag{10}$$

Now from the small-signal solutions to the rate equations we can simply derive the high speed modulation response function for semiconductor lasers is derived as [Chang,2003]:

$$R(w) = \frac{\Gamma G^{/}P_0}{eV(1+eP_0)(w_r^2 - w^2 + jwg)} \tag{11}$$

Where the resonance frequency expression ω_r is :

$$w_r = 2pf_r = \sqrt{\frac{G^{/}P_0}{t_P(1+eP_0)}\left(1+\frac{e}{G^{/}t_{SP}}\right)} \tag{12}$$

The second term can be neglected compared to $1 (e \langle\langle 1)$ and the resonance frequency expression reduces to:

$$w_r = 2pf_r = \sqrt{\frac{G^{/}P_0}{t_P(1+eP_0)}} \qquad (13)$$

And the damping factor γ can be defined as:

$$g = w_r^2(\frac{e}{G^{/}} + t_P) + \frac{1}{t_{SP}} \qquad (14)$$

The damping rate can be expressed as a function of carrier lifetime and *K-factor* where {the *K-factor* can be calculated from the slope of $\sqrt{P_0}$ as a function of resonance frequency(f_r)}, therefore

$$g = Kf_r^2 + \frac{1}{t_P}, \qquad (15)$$
$$where K = 4p^2\left(t_P + \frac{e}{G^{/}}\right)$$

B. Resonance frequency analysis of quantum well Laser:

In quantum well (QW) lasers, carrier transport (including diffusion, tunneling)has a significant effect on the modulation properties of high-speed lasers (i.e. damping rate) via a reduction of the effective differential gain and usually is a significant limit. Therefore in order to obtain a more accurate model it is necessary to include this effect[3,5].

The damping rate exists due to the process of capture and escape of the carriers into and from the QW respectively. Thereby, the damping factor does not necessarily vary linearly with photon density. Therefore this structure of lasers changes the traditional rate equations due to the different carrier densities in the barrier and the well where the transport factor $c = (1+t_{esc}/t_{cap})$ which depends on laser structure{ t_{cap} and t_{esc} are the capture and escape time constants respectively) [Zhang et al ,2001].

This means by the transport factor we can controlled on the damping rate to get on the better enhanced performance for modulated quantum well laser, this is done by the control of the total width of wells(L_q) and the full width of the separate confinement heterostructure (SCH) region(L_{SCH}), this effects are showing in the pumping current density(j_{pump}) where this current density is injection current of the laser.

The carriers in the SCH region is described by the diffusion equation:{$Dd^2 n_b(x)/dx^2 - i\omega n_b(x) = 0$} where $n_b(x)$ is the carrier distribution in the barrier layers. If the width of barrier layer (L_b) is much smaller than the diffusion length ($L_d \equiv (D/\omega)^{0.5}$) (as most often is the case) then $n_b(x)$ is approximately constant and D is the diffusion constant . In this limit, we can derive a relation between the pump current density j_{pump}, the net current density j_{net}, and the active carrier density n_{qc} [5,6]:

$$j_{pump} = j_{net}\left[1 + iw\left(t_{cap}\frac{L_{SCH}}{L_q} + \frac{L_b^2}{2D}\right)\right] + n_{qc}iwL_{SCH}\frac{t_{cap}}{t_{esc}} \qquad (16)$$

Where

$$L_{SCH} = 2L_b + L_q ,$$

$$j_{net} = j_{cap} - j_{esc} = j_{cap}^{em} + j_{cap}^{ab} - (j_{esc}^{em} + j_{esc}^{ab}) = \left(\frac{\Delta E_f}{K_B T}\right) j_0 \int_0^{\infty} (f^+ - f^-) dk_z^u ,$$

$$\Delta E_f = E_f^u - E_f^c , j_0 = n_0 n_{ph}(n_{ph}+1), n_0 = \frac{m^* K_B T}{p^2 \hbar^2}, n_{ph} = 1/\left\{ e^{\frac{E_{gh}}{K_B}} e^{-\frac{(E_f^u - E_f^c)}{}} - 1 \right\},$$

$$E_z^u = \frac{(\hbar k_z^u)^2}{2m^*}, and f^{\pm} = \frac{1}{\{\exp[\pm E_{ph} - E_f^c + E_z^u)/K_B T] + 1\}}$$

j_{cap} and j_{esc} are the total capture and escape current densities respectively, j_{cap}^{em} and j_{esc}^{em} are the total capture and escape current densities due to longitudinal optical emission respectively , j_{cap}^{ab} and j_{esc}^{ab} are the total capture and escape current densities due to absorption respectively, E_z^u is the energy of unconfined state, E_f^c and E_f^u are the Fermi levels for confined and unconfined states ,E_{ph} is the phonon energy of occupation carriers densities, n_{ph} is the phonon of occupation number, k_z^u is the wave vector of unconfined state in the z-direction, m^* is the effective mass of carriers, ħ=2π/h, h is the plank's constant, K_B is the boltzmann 's constant ,and T is the temperature of the crystal [Tsai, et al,2002].

The capture and escape times constants are

$$\frac{1}{t_{cap}} = \frac{1}{dN_u / dE_f^u} j_0 \frac{1}{K_B T} \int_0^{\infty} (f^+ - f^-) dk_z^u \qquad (17)$$

,and

$$\frac{1}{t_{esc}} = \frac{1}{dN_c / dE_f^c} j_0 \frac{1}{K_B T} \int_0^{\infty} (f^+ - f^-) dk_z^u \, where \Delta E_f \langle\langle K_B T \qquad (18)$$

The ratio $R = \frac{t_{cap}}{t_{esc}} = \frac{dN_u / dE_f^u}{dN_c / dE_f^c}$ (19)

Where N_u and N_c are carriers densities of the unconfined and confined states respectively. If some of carriers are lumped in the SCH region into a single ,$t_{cap} and t_{esc}$ are become $t_{cap}^E and t_{esc}^E$ respectively. Therefore we can written the expression again as[Tsai, et al,2002]:

$$j_{pump} = j_{net}\left[1 + iwt_{cap}^E\right] + n_{qc} iwL_q \frac{t_{cap}^E}{t_{esc}^E} \qquad (20)$$

Where

$$t_{cap}^E = \frac{L_b^2}{2D} + t_{cap}\frac{L_{SCH}}{L_b}, and \frac{t_{cap}^E}{t_{esc}^E} = \frac{t_{cap}}{t_{esc}}\left(\frac{L_{SCH}}{L_q}\right)$$

t_{cap}^E and t_{esc}^E are the effective capture and escape time sonstants.

Therefore, the modulation response function can be expressed as[Zhang, et al ,2001]:

$$R(w) = \frac{\Gamma \frac{G'}{c} P_0}{eV(1+eP_0)(w_r^2 - w^2 + jwg)} \qquad (21)$$

The resonance frequency and damping factor also can be expressed as follows:

$$w_r = 2pf_r = \sqrt{\frac{\frac{G^{/}}{c}P_0}{t_P(1+eP_0)}} \tag{22}$$

$$g = Kf_r^2 + \frac{1}{t_P}, \tag{23}$$

$whereK = 4p^2\left(t_P + \frac{ce}{G^{/}}\right)$ Finally this structure gives rise to the following expression for optical modulation response as a function of frequency:

$$\left|R(f)\right|^2 = \frac{f_r^2}{\left[(f_r^2 - f^2) + (\frac{g}{2p})^2 f^2\right]\left[1 + (2pf_r)^2\right]} \tag{24}$$

Tables (1) and (2) are the parameters values of the InGaAs/InP 5nm-QW[3] and with 1.3µm Buried hetero structure lasers[Agrawal ,2002] respectively

Results and Discussions

A. Effect of the compression gain (ε)

From the **Tables (1) and (2)** and the Eqs.(1) and (2) [at steady state (d/dt =0)], **Figure(2)** shows the differential gain ($G^{/}$ =dG/dt)as the function of the photon density(P) in the InGaAs/InP 5nm-QW Laser compared with 1.3µm Buried hetero structure lasers, we are observed that the differential gain is larger in QW laser compared with the semiconductor laser. Because of the thickness of QW Laser is decreasing compared with the semiconductor laser. Therefore, this leads to increase of the quantum confinement of carriers with increasing the photon density. In addition, the differential gain is reduced due to the nonlinear gain effects that it is represented by the gain compression (ε)where $G \to \frac{G}{1+eP_0}$. From the Eqs. (13) and (22), **Figure(3)**shows the relaxation resonant frequency (f_r) as a function of the square root of the photon density ($\sqrt{P}$) , we can observed from this figure the relaxation resonant frequency in the QW laser is higher than these frequency in the semiconductor laser . Because of the thickness of the QW laser is decreased compared with the thickness of semiconductor laser, and this leads to the quantum confinement of carriers in QW laser is increased with increasing the photon density therefore the differential gain is dominant compared with the nonlinear gain effects .In addition, we can concluded that the damping rate in QW laser is higher than these rate in semiconductor laser as shown in**Figure(3)** where we can calculated the K- factor from **Figure(3)** which it is represented the slope of the curve ,therefore the damping rate as shown in **Figure(4)** (Eqs.(15) and (23)) is higher in QW laser than these rate in semiconductor laser which this rate is a function of the K - factor.

B. Effect of the capture and escape time constants

From the **Table(1)** and Eq.(16) **, Figure(5)** shows the net current density (j_{net}) as a function of the different energies between the Fermi levels for the confined and unconfined states ($\Delta E_f = E_f^{\,u} - E_f^{\,c}$) , and from Eq.(19) , **Figure(6)** shows the ratio R as a function of the ΔE_f. We find that when the net current density is changed from 0 to 2kA/cm^2 (where the value of j_{net} =100A/cm^2 at near threshold operation and j_{net} =2kA/cm^2 at high power operation), the ratio R is almost constant because of the net current density is large, therefore in this range, we can the obtain on the average values of τ_{cap} ,τ_{cap} {from Eq.(16) where $\tau_{cap}=\partial j_{net}/\partial N_u$ and $\tau_{esc} = \partial j_{net}/\partial N_c$}, and R with different confined carrier density N_c (or threshold carrier density)at certain value of V_b. Therefore from Eq.(20), **Figure(7)** shows the ratio R is a function of the quantum wells thickness(L_q) at V_b=0.2eVand $N_c=4\times10^{12}$ cm^{-2},we are observed from this figure the ratio R is depended on the quantum well thickness (i.e is depended on the structure of SCH region),therefore when the ratio R is high (i.e τ_{cap} is high)L_q is low, this means the capture carriers will still confined in the well ,therefore the modulation response will increase compared with the semiconductor laser as shown in **Figure(8)**. But when L_q is high the R and L_b are low ,this means the capture carrier in well will diffusion in SCH region due to $L_d > L_b$.

Conclusions

We can enhance of performance of laser system in direct modulation by increase of the carriers quantum confinement in a optical cavity has small size width (quantum well. This leads to reduce the nonlinear gain effects that it is represented by gain compression due to the enhancement of the differential gain by increasing the carriers quantum confinement). For the control on the gain compression, this is achieving by the control of the capture and escape time constants (i.e the ratio R) ,this means we must change the internal structure of the active region of semiconductor device to the region consists of the confinement and the active regions (separate confinement SCH region) where this regions are represented by the potential barrier and quantum well.

Finally, we can determined the size width of well by selecting the value of the ratio R(when the carriers capture in the well are higher than the carriers escape) but the increasing of carriers capture are limited because the diffusion of carriers capture in the SCH region due to diffusion length is greater than potential barrier length . All this to surety the carriers will confine in the well for reduction of non linear gain effects and enhancement of performance of the laser system in the direct modulation.

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Table(1) Some Parameters values of InGaAsP/InP quantum well laser[3]

Parameter	Symbol	Value
the full width of the separate confinement heterostructure (SCH) region	L_{SCH}	250 μm
Current injection efficiency	η_i	0.86
interaband relaxation time	τ_{in}	0.1×10^{-12} s
Effective mass of electron /Rest mass of electron	$\frac{m_e}{m_0}$	0.11 for x<0.7 0.35 for x>0.7
Effective mass of heavy hole/Rest mass of electron	$\frac{m_{hh}}{m_0}$	0.62+0.05x
Effective mass of light hole/Rest mass of electron	$\frac{m_{lh}}{m_0}$	0.11+0.03x
Quantized energy gap of heavy hole band (confined state)	$E^C = E_g(HH)$ $=E_g(In_{0.49}\ Ga_{0.51})$ $-E_g\ (In_{0.49}\ Ga_{0.51}\ P)$	As shown in Fig.(1)
Quantized energy gap of light hole band (unconfined state)	$E^U = E_g(LH) = 1 - E_g(HH)$	As shown in Fig.(1)
Quantum well size	L_z	5nm
The phonon energy of occupation carriers densities,	E_{ph}	36meV
The phonon emission	ω_o	$0.2ps^{-1}$
Effective barrier height	V_b	0.2 eV

Table (2) The parameters values of 1.3μm Buried hetero-structure laser [1]

Parameter	Symbol	Value
Active-layer thickness	D	0.2 μm
Cavity length	L	250 μm
Active-region width	W	2 μm
Group velocity	c/μ_g	
Effective refractive index	$\overline{m}$	3.4
Group refractive index	μ_g	5
Carriers recombination lifetime	t_{SP}	2.2ns
Photon lifetime	t_P	1.6ps
Confinement factor	Γ	0.3
Threshold current	I_{th}	15.8mA
Fraction of spontaneous emission entering the lasing mode	β	$10^7\ s^{-1}$
Gain compression factor	ε	$3\times10^{-12}\ m^2/s$

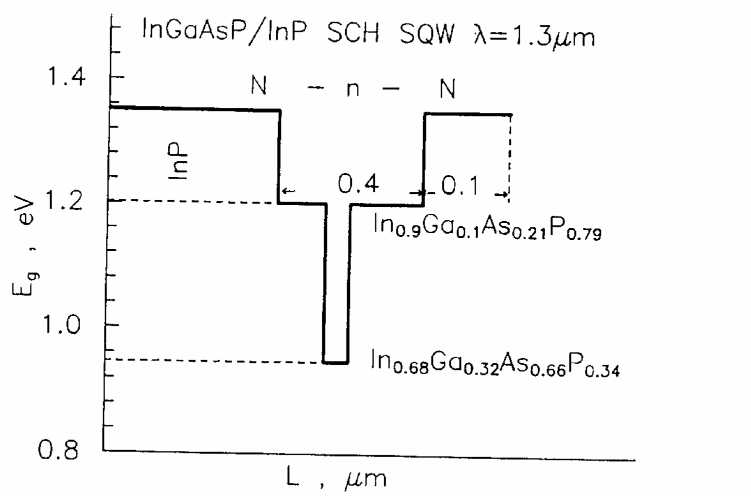

Figure 1. Band schemes of N-n-N InGaAsP/lnP SCH SQW structures .

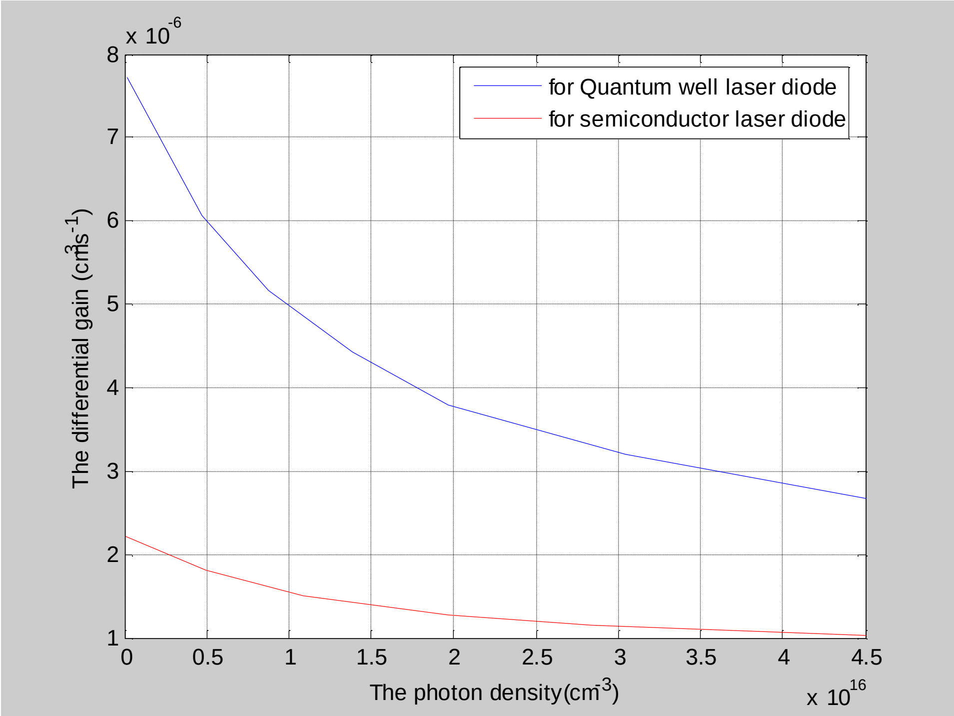

Figure 2 The differential gain with respect to the photon density

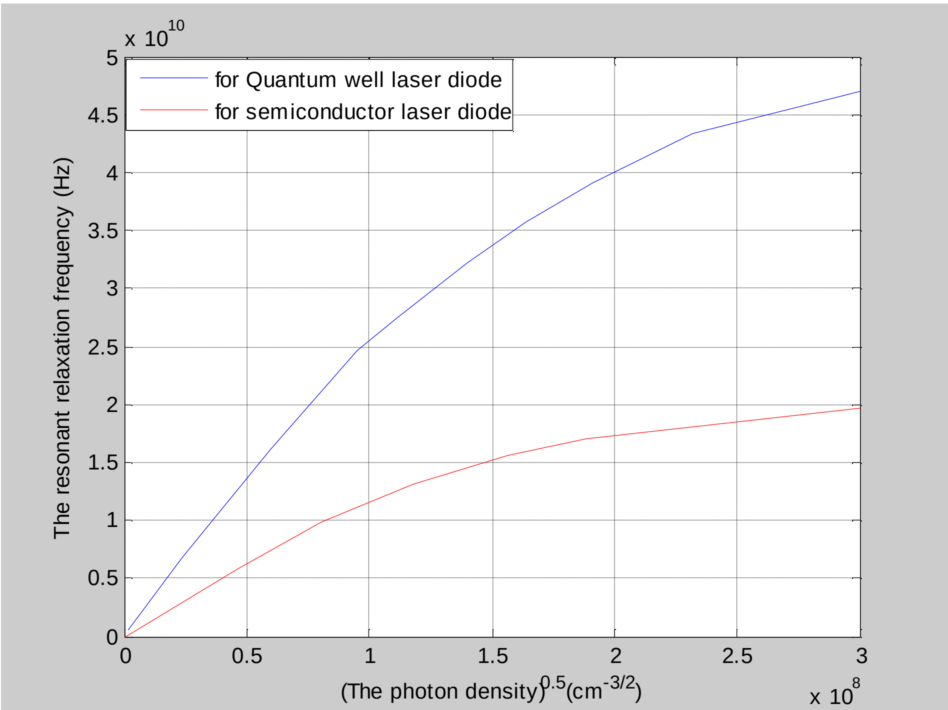

Figure 3 The resonant relaxation frequency with respect to (the photon density)$^{0.5}$

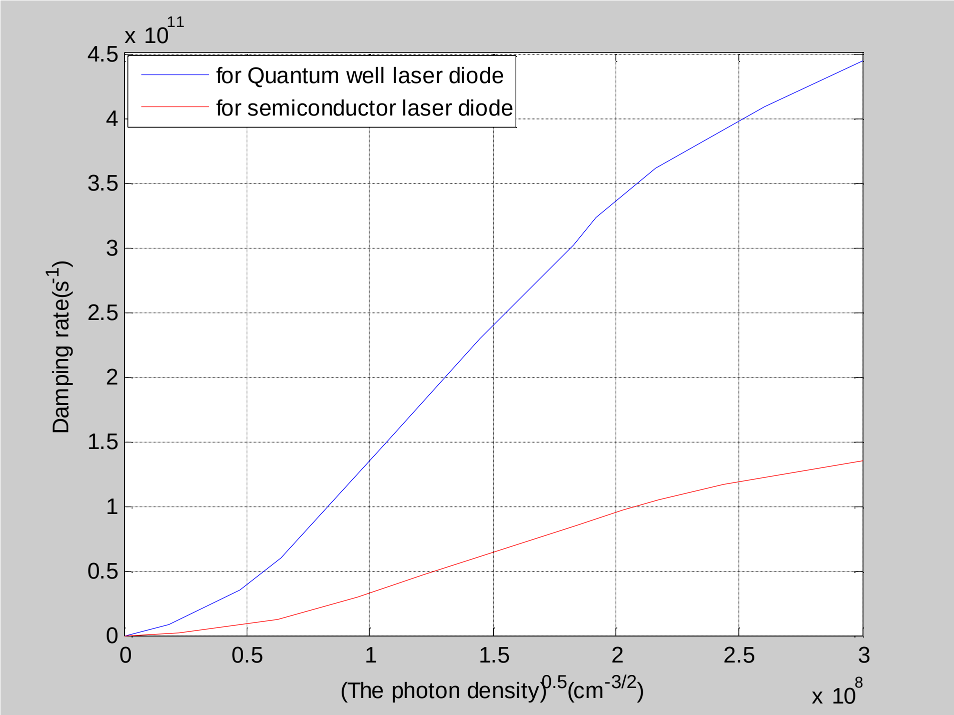

Figure 4 The damping rate with respect to (the photon density)$^{0.5}$

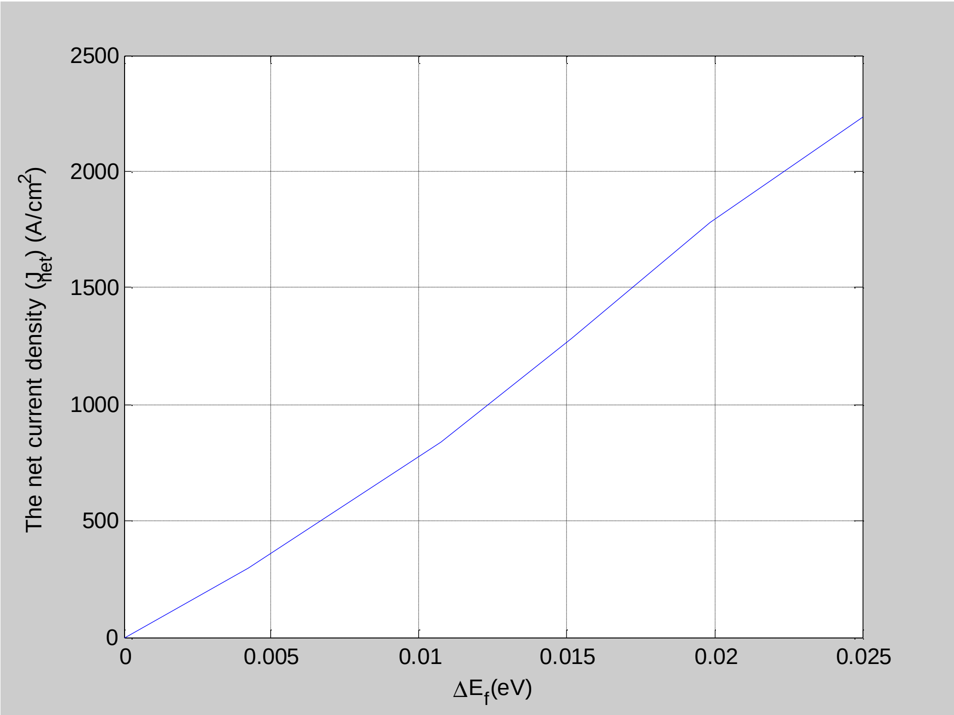

Figure 5 the net current density as a function ΔE_f

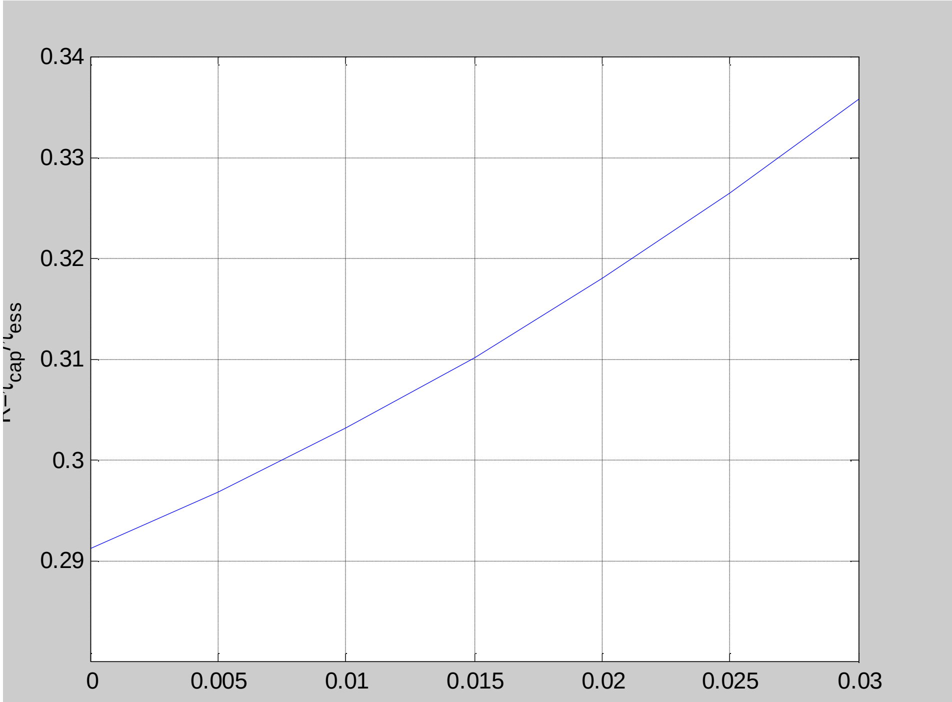

Figure 6 the ratio R is a function of ΔE_f

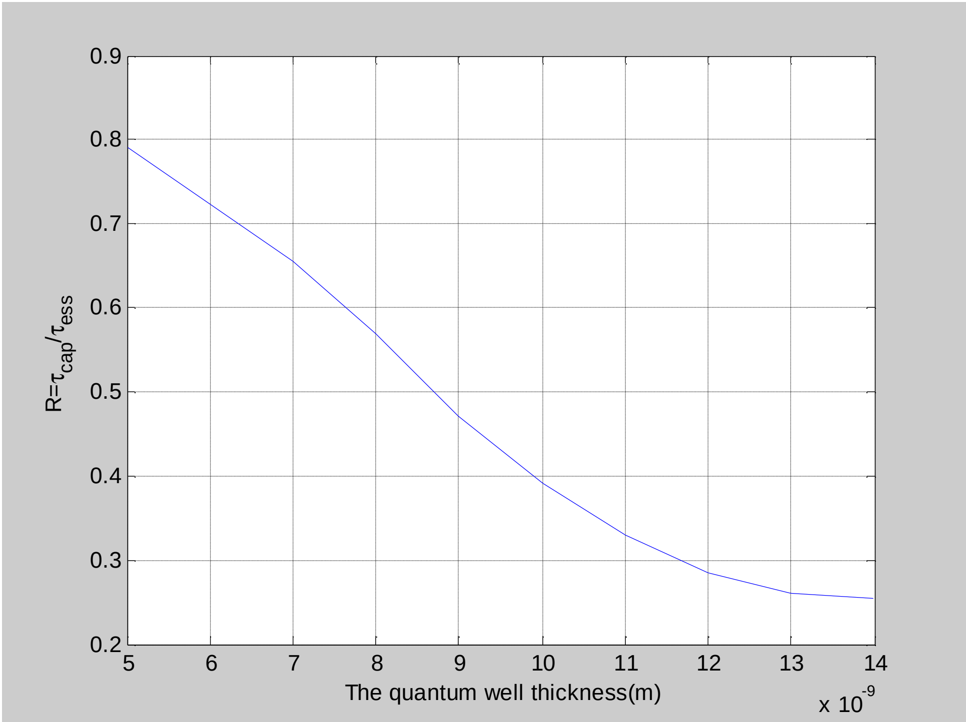

Figure 7 The ratio R is a function of the quantum wells thickness

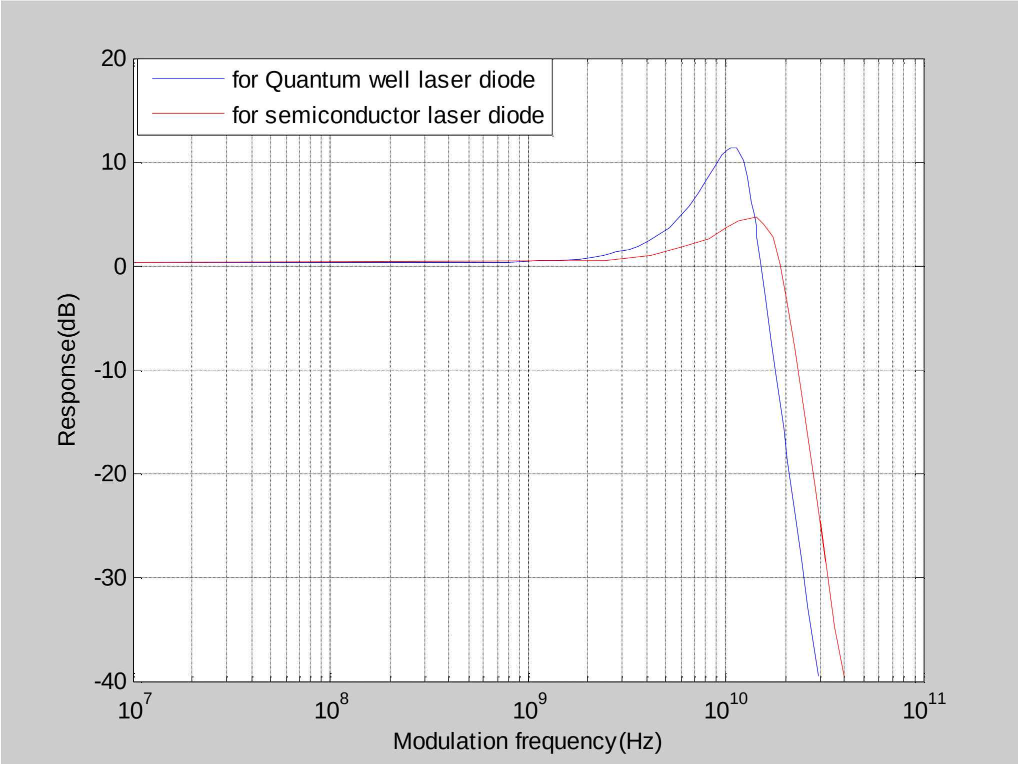

Figure 8 The Response a function of the Modulation frequency