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Effect of Step Response for Semiconductor Laser

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Abstract

The behavior of the dynamics of semiconductor laser is investigated by simulation and solving numerically the laser rate equations for photon and carrier densities. The rate equations take into account various system parameters such as gain compression factor and carrier recombination mechanisms. The simulation results reviled a step power response and carrier density for various cavity length and facet reflectivity of semiconductor laser.

الخلاصة

درسنا تصرف ديناميكية ليزر شبه موصل بواسطة محاكاة والحل العددي لمعادلات المعدل لكثافة الفوتونات وحاملات الشحنة . معادلات المعدل تأخذ بالحسبان وصف عناصر المنظومة المتنوعة مثل عامل الربح المنضغط وميكانيكية أعادة اتحاد حاملات الشحنة .

نتائج المحاكاة أظهرت استجابة القدرة الخطوية وكثافة حاملات الشحنة لمختلف أطوال الفجوة و انعكاسية الوجه لليزر شبة الموصل .

I. Introduction

Semiconductor lasers are not very different in principle from the light emitting diodes. A p-n junction the active medium, thus to obtain laser action we need only meet the other necessary requirement of population inversion and optical feedback [1]. To obtain simulated emission, there must be a region of the device where there are many excited electrons and holes present together [2].This is achieved by forward biasing a junction formed from very heavily doped n and p material therefore, where semiconductor regions with high doping densities are used in the diode structure the semiconductor regions are said to be degenerated [3].The Fermi level is located above the bottom of the conduction band in the n-type side and at the top of the valence band in the p-type side. when the p-n junction is formed by using this degenerate material the band structure is in equilibrium. when a forward bias is applied to this degenerate diode, the potential hill is occurs. this process occurs because the electrons in the conduction band lose energy by dropping into a holes in valence band, this energy shows up as a photo of energy hυ [4]. When the large photo density is built up many of these transitions, the process is accelerated because of the stimulated emission, and, with reflection feedback occurring, laser action sets in [2].

II. Theory

A. Single-Mode Laser Rate Equation

The single –mode rate equation for a semiconductor laser can be describe as [5].

$$\frac{dP}{dt} = GP + \frac{\Gamma}{V} R_{sp} - \frac{P}{\tau_p} \qquad \textbf{(1)}$$

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_c} - \frac{1}{\Gamma} GP \qquad \textbf{(2)}$$

P: photons density in the active layer.

N: Carriers density in the active layer.

τ_p: photon lifetime.

τ_c: Carrier lifetime.

I: Injected current .

q : Electron charge =$1.6x10^{-19}$ C.

N_t: Transparency value of carrier density.

V: Active layer volume.

G: Net rate of stimulated emission.

R_{sp}: Rate of spontaneous emission coupled to the lasing mode.

Γ :Optical confinement factor.

The net rate of stimulated emission is

$$G = \Gamma \upsilon_g g_m \qquad \textbf{(3)}$$

Where υ_g is group velocity and g_m is the material gain at the mode frequency, g_m varies linearly with N

$$g_m = a(N - N_t) \qquad \textbf{(4)}$$

Where(a) is the differential gain coefficient .Therefore G can expressed as

$$G = G_N (N - N_t)(1 - \varepsilon p) \qquad \textbf{(5)}$$

Where έ is parameter characterizes the strength of the material gain nonlinearity, and G_N can be defined as.

$$.\,G_N = \Gamma \upsilon_g a \qquad \textbf{(6)}$$

The net rate of stimulated emission and the rate of spontaneous emission coupled to the lasing mode R_{sp} are related by.

$$R_{sp} = n_{sp} G \qquad \textbf{(7)}$$

Where n_{sp} is the spontaneous emission factor .

The photon lifetime τ_p is related to the cavity loss α_c.the cavity loss can be splitted into two components :mirror loss α_m and internal loss α_p.

$$\begin{aligned} a_c &= a_i + a_m \\ &= a_i + \frac{1}{2L} \ln\left(\frac{1}{R1R2}\right) \qquad \textbf{(8)} \end{aligned}$$

Where R_1R_2 is the facet reflectivity and L is the effective length of the lasing mode.The photon lifetime τ_p can be expressed as

$$\tau_p = \frac{1}{\upsilon_g a_c} = \frac{1}{\upsilon_g \left(a_i + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)\right)} \qquad \textbf{(9)}$$

It is worth to note here that τ_c is carrier dependent according to the relation

$$\tau_c = \frac{1}{A + BN^2 + CN^2} \qquad \textbf{(10)}$$

A: Nonradiative coefficient .

B: Radiative coefficient .

C: Auger recombination coefficient.

B. Threshold values

To calculate the threshold carrier population N_{th} and the threshold current I_{th}, the following points are followed.

1- The derivation in eqns. (1)and (2) are set to zero.

2- The gain is set equal to the losses.

$$G = \frac{1}{\tau_p} \qquad (11)$$

3- In order to get a particularly simple from of expressions for N_{th} and I_{th}, the spontaneous emission coupled to the lasing mode is neglecting (i.e $R_{sp}=0$). From eqns.(1)and(2)

$$I_{th} = q\frac{N_{th}V}{\tau_c} \qquad \textbf{(12)}$$

From eqn.(11)

$$N_{th} = N_t + \frac{1}{G_N\tau_p} \qquad \textbf{(13)}$$

So the threshold current is then given

$$I_{th} = \frac{qV}{\tau_c}\left(N_t + \frac{1}{G_N\tau_p}\right) \qquad \textbf{(14)}$$

C. Steady-State Solution

The steady state solution can be obtained by setting dP/dt and dN/dt to zero in eqns.(1) and (2)

$$P = -\frac{R_{sp}}{\left(G - \frac{1}{\tau_p}\right)} \qquad (15)$$

$$I = qV\left(\frac{N}{\tau_c} + \frac{GP}{\Gamma}\right) \qquad (16)$$

When the laser operate above threshold, the carrier population is approximately clamped on N_{th},then eqn.(16) can be written as

$$I = I_{th} + \frac{qV}{\Gamma}GP \qquad (17)$$

Then

$$P = \frac{\Gamma\tau_p}{qV}(I - I_{th}) \qquad (18)$$

When G is set to $1/\tau_p$.This equation indicates clearly that the photon population increases linearly with the current I. The emitted power P_e from the front facet R_1 is given by (6).

$$P_e = \tfrac{V}{\Gamma} P \eta_{\text{int}} \upsilon_g a_m h\nu \qquad \text{(19-a)}$$

$$a_m = \tfrac{1}{2L} \ln\left(\tfrac{1}{R\ R_2}\right) \qquad \text{(19-b)}$$

Where hυ is the photon energy and η_{int} is the internal quantum efficiency. When $R_1=R_2$, then eqn.(19-a) is written as(7)

$$P_e = \tfrac{V}{2\Gamma} P \eta_{\text{int}} \upsilon_g a_m h\nu \qquad \text{(20)}$$

Substituting eqns.(9) and(18) into.(20),yields

$$P_e = \tfrac{h\nu}{2q} \eta_d \left(I - I_{th}\right) \qquad \text{(21)}$$

Where $\eta_d$is the differential efficiency.

III. Results and discussion

A-Laser Static Characteristics

Figure(1) shows the dependence of the threshold current I_{th} on laser cavity length L for two values of facet reflectivity $R_1(=R_2)$= 0.32 and 0.8. The threshold current increases almost linearly with L.At L =300µm, L=500µm,I_{th}=40.6 and 58.4 mA, respectively, when $R_1(=R_2)$=0.32.The threshold current reduces to 29.9 and 48.2 mA, respectively, when $R_1(=R_2)$=0.8.

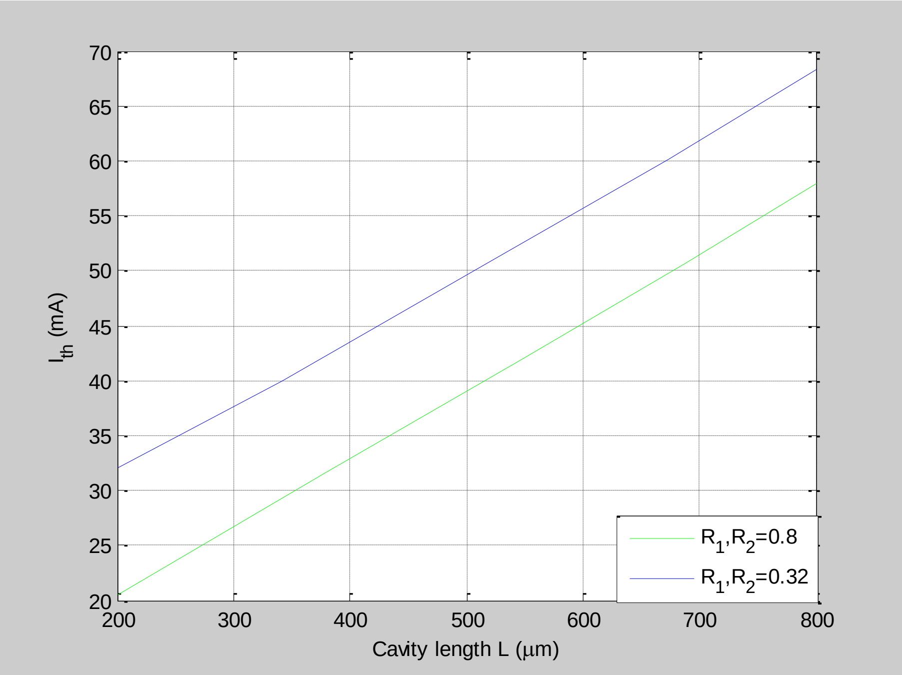


Fig.(1) Dependence of threshold current on cavity length

Figure(2) shows the dependence of I_{th} on facet reflectivity for two values of L=300µm.The threshold current decrease strongly with R.The results in Fig.(1) and (2) can be explained with aid of eqn.(3.14).This equation can be rewritten as.

$$I_{th} = \frac{qwd}{\tau_c}\left(N_t + \frac{\upsilon_g a_i}{G_N}\right)L - \frac{qwd}{2\tau_c}\frac{\upsilon_g}{G_N}\ln R_1 R_2 \qquad (22)$$

This expression reveals that I_{th} increase linearly with L and decreases with In(R_1R_2).This results hold true when is assumed independent of .

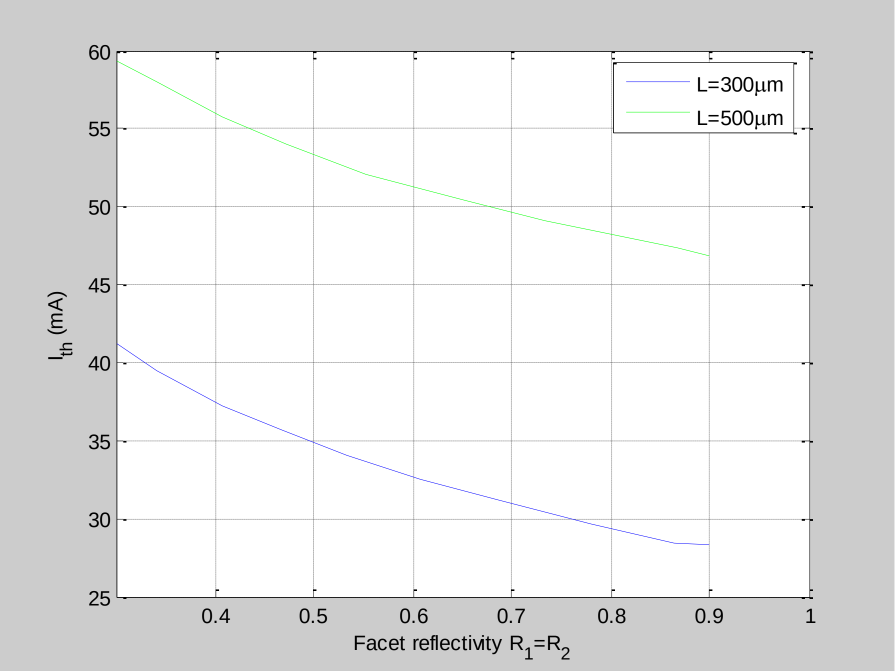
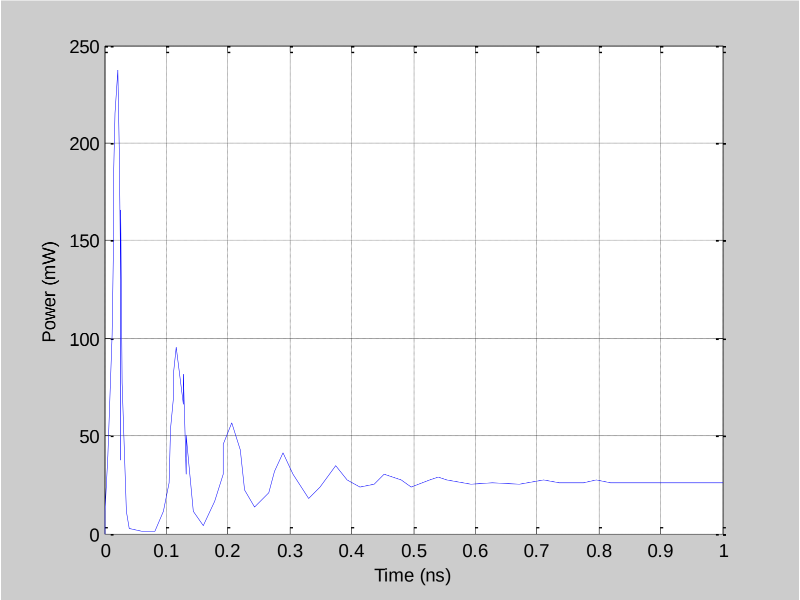


Fig.(2) Dependence of threshold current on facet reflectivity

B- Laser Step Response

This section present simulation results for the dynamics of a semiconductor .The results are obtained by solving numerically the laser rate eqns. (1) and (2) using fourth- order rung-kutta method.

Figures(3-a) and(3-b) show, the power dynamic response of the laser in the absence and presence of the gain compression factor respectively .The laser current is assumed to be a step function (switched from I_{off} to I_{on} at t=o).The results in the these figures indicate clearly that the presence of the compression factor in the model will damp the transient response. When the laser dynamics settled down, the output power approaches (34.4mW) for both cases.



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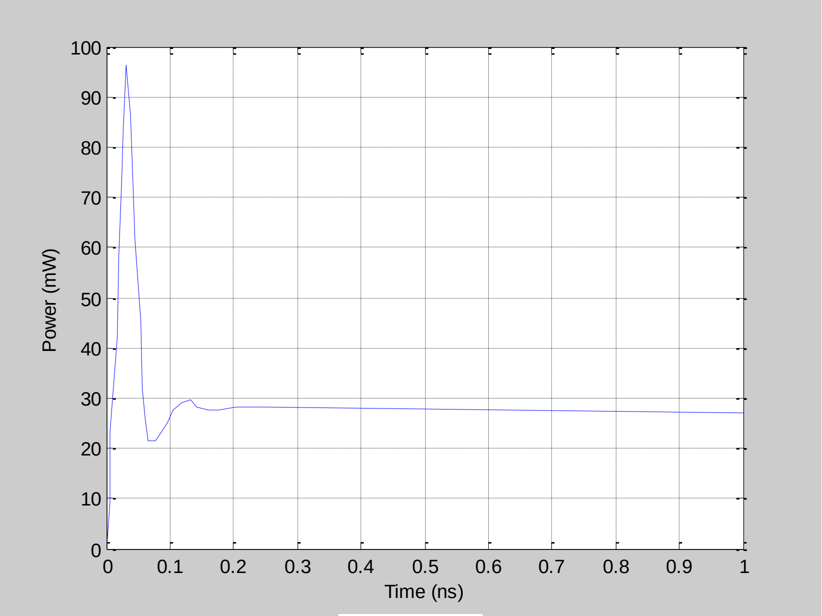


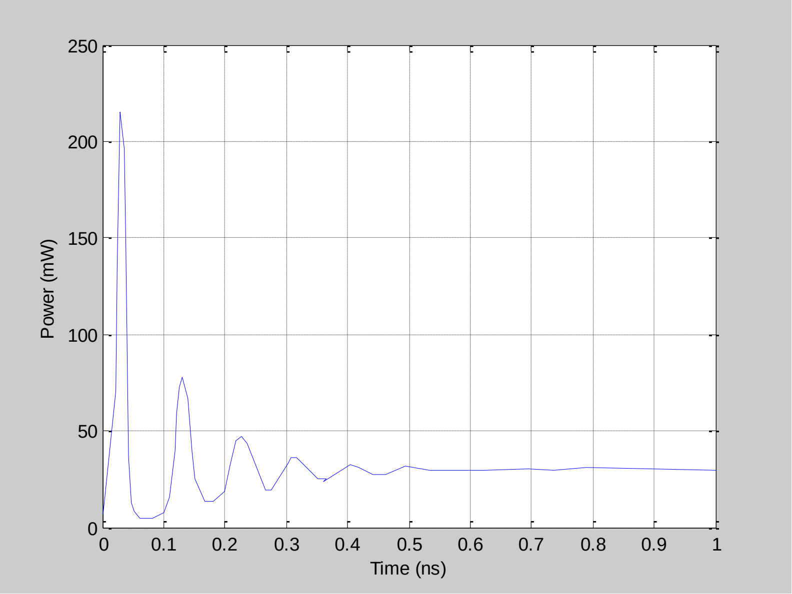
-b-

Fig.(3) Step power response of 300 µm (a) E=0 (b) E=1.5E -17 cm^3

The calculation is repeated for L=500µm,and the results are depicted in Figs.(4-a) and (4-b) .Note that increasing L from 300µm to 500µm reduces the overshoot peak, this is illustrated in Table (1) when έ is absent and present ,respectively.

Table (1) Overshoot Power With Cavity Length

Cavity Length L (mm)	**Overshoot Power (mw)**	
	E=0	**E=1.5E-17 cm^{+3}**
300	**235.2**	**96.8**
500	**213.1**	**91.5**



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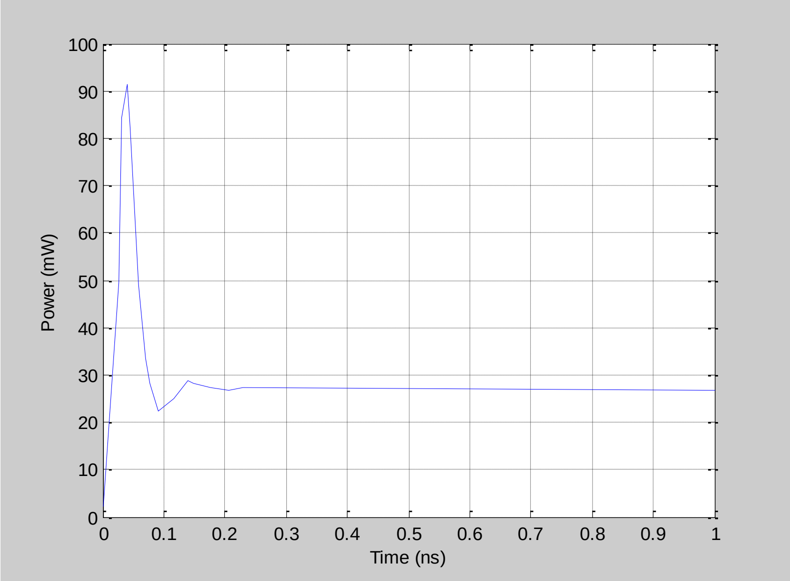
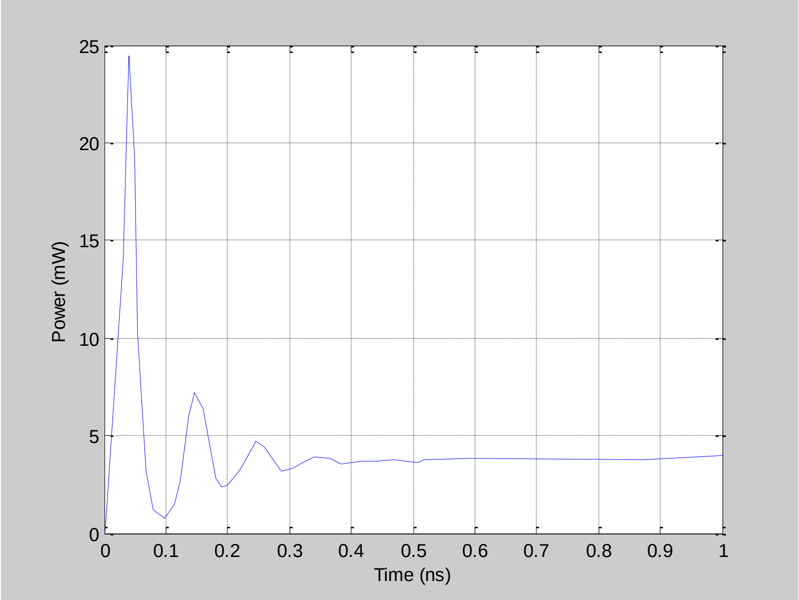


-b-

Fig.(4) Step power response of 500 µm (a) E=0 (b) E=1.5E -17 cm^3

Figures(5-a) and(5-b) examine, respectively, the laser dynamic when L=300µm and $R_1=R_2=0.8$ in the absence and present of the gain compression factor έ. Increasing R reduces the output power without affecting much to the dynamic behavior.



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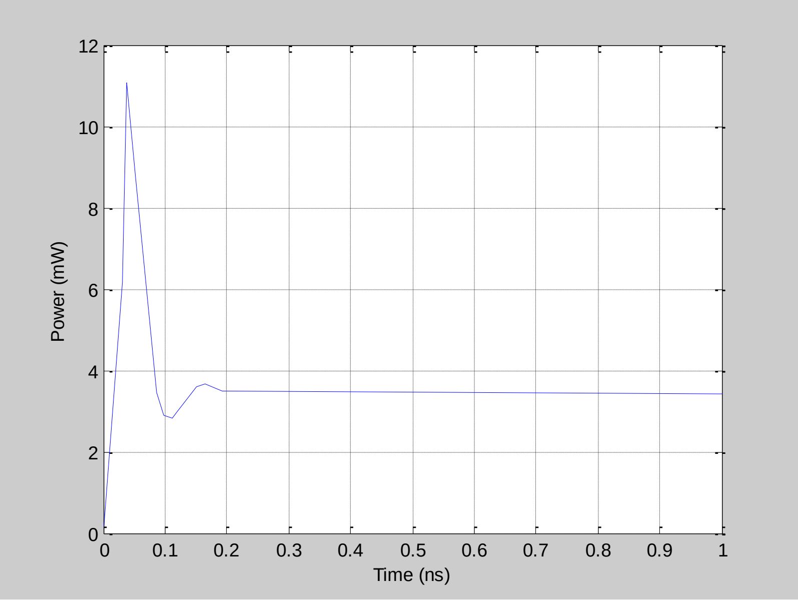

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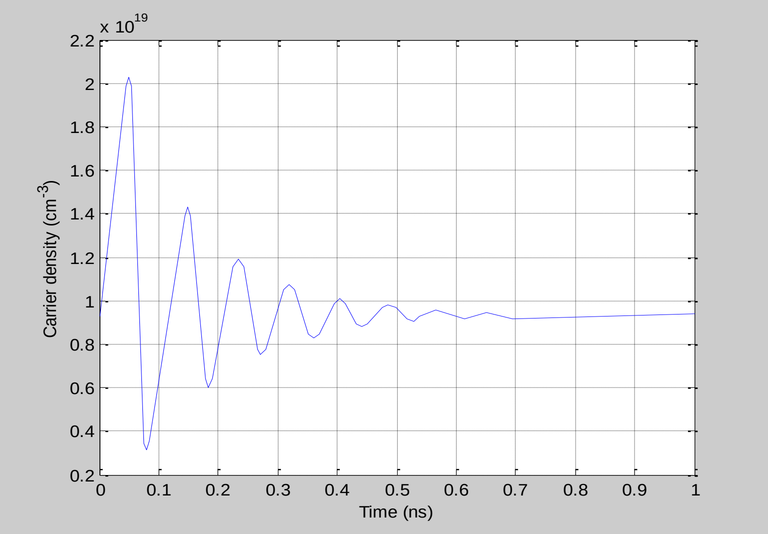
Fig.(5) Step power response of 300 µm when $R_1=R_2=0.8$ (a) E=0 (b) E=1.5E -17 cm^3

Figures (6 – 8) show the carrier dynamic response corresponding to the Figs(3 -5),respectively. Investigating these figures reveals the finding.

1- The initial carrier density is equal to the threshold value N_{th}, since $I_{off}=I_{th}$ is used in the simulation .N_{th} is equal to 1.644 E18 cm^{-3} when L=300µm and $R_1=R_2=0.32$.The value of N_{th} reduces to 1.475E18cm^{-3} when $R_1=R_2$ increase to 0.8.



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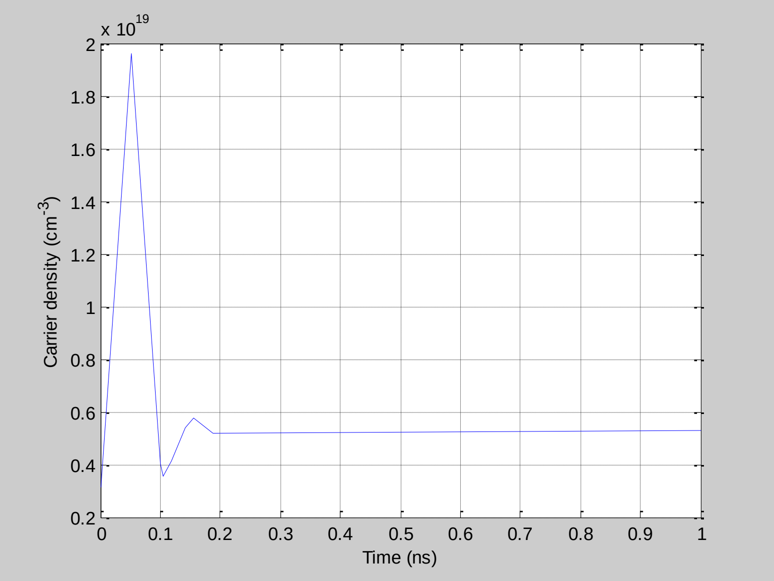

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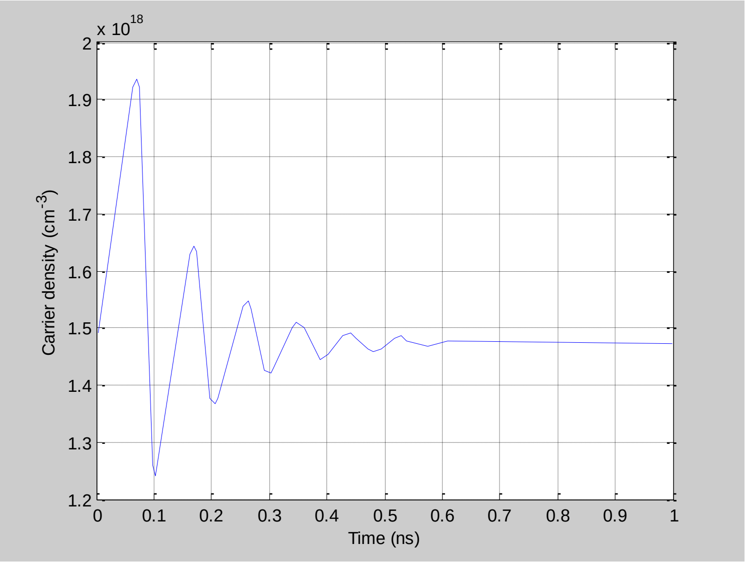
Fig(6) Step carrier response density of a 300 µm-laser
(a) E=0 (b) E=1.5 E -17 cm^3



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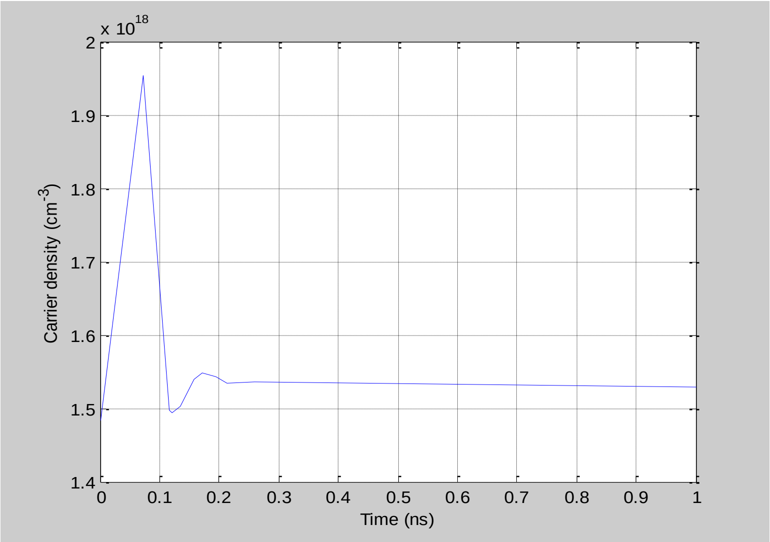
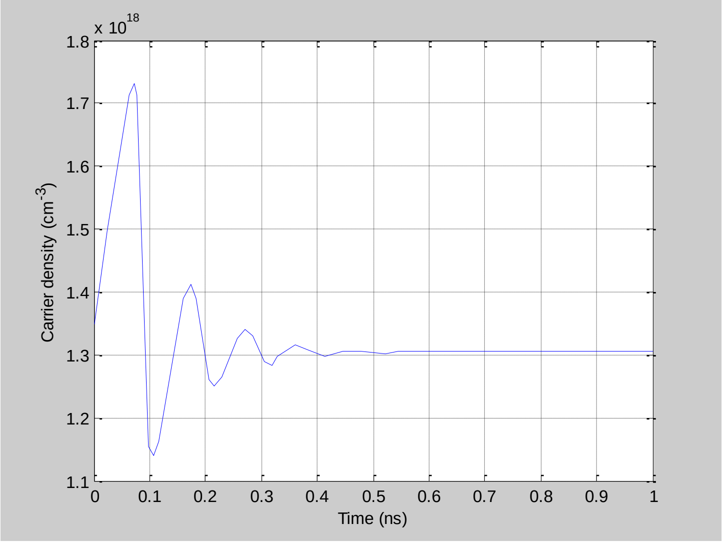


-b-

Fig.(7) Step carrier response density of a 500 µm-laser
(a) E=0 (b) E=1.5 E -17 cm^3

When the laser dynamic settled down, the threshold carrier density is approximately clamed to N_{th}.



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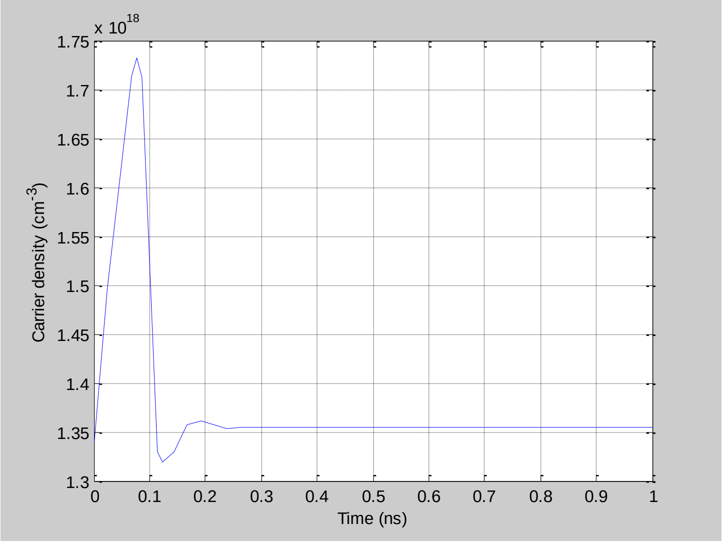

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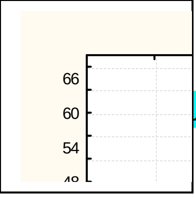
Fig.(8) Step carrier density response of a 300 µm-laser when R_1=R_2=0.8 (a) E=0 (b) E=1.5 E -17 cm^3

Conclusion

Simulated results have been presented the dynamic characteristic of a scenario laser operating so the main conclusions drawn from this study are:

1. This expression reveals that I_{th} increases linearly with L and decreases with In(R_1R_2).This results true when τ_c is assumed independent of L.
2. The results indicate clearly that the presence of the compression factor in the model will damp the transient response. When the laser dynamic settled down ,the output power is the same for both cases.
3. When increasing the cavity length peak power overshoot was reduced. The output power was reduced when increasing the facet reflectivity without affecting much to the dynamic behavior.
4. The initial carrier density is equal to the threshold value Nth.



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