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Gain switching characteristics of InAs-InP(113)B quantum dot laser

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In this study, gain switching characteristic of quantum dot (QD) lasers is described by using rate equations. The effect of some laser diode parameters on the output pulse of gain switching is investigated. The numerical results indicate that carrier recombination time in QD and spontaneous coupling factor strongly affect the system operation, whereas there is no significant effect of gain compression factor or of the carrier recombination in the wetting layer or of the carrier emission from the QD to the wetting layer or of the relaxation time from the wetting layer to the QD.

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1. Introduction

There are several techniques to generate picosecond optical pulses. Two main techniques to produce picosecond pulses from semiconductor lasers are gain switching and mode-locking.In most of the pulsed-mode applications mode-locking is preferred because higher repetitions rates are available if compared to gain switching technique [1-4]. However, the mode-locking of lasers involve comparatively complex optics and control of external cavity. Therefore, the gain switching seems to be the simplest technique of the short pulse generation requiring neither external cavity nor saturable absorber [5-6]. Indeed, in order to perform gain switching only to drive the gain of the laser diode by an input rf signal [4]. Gain switching pulses are essentially the first peaks of the relaxation oscillations.

Recently, the use of quantum dot (QD) semiconductor lasers has attracted much more attention due to superior performance such as fast carrier dynamics, broadband gain, low-spontaneous emission levels and a low-threshold current density[7, 8–13]. Therefore, in this paper, the effect of the carrier dynamics on the output pulse is investigated for InAs-InP(113)B quantum dot (QD) laser when laser is under the gain switching condition.

Here, gain compression factor (ε), the carrier recombination (radiative and nonradiative) in the QD (τ_r), the carrier emission from QD to the wetting layer (τ_e), the carrier relaxation time into QD (τ_d), the carrier recombination (radiative and nonradiative) in the wetting layer (τ_{wr}) are investigated. Furthermore, the results are compared with those of a mode-locked quantum dot hybrid soliton pulse source (QD-HSPS) laser.

2. Theoretical analysis

In our simulation, 1.55 μm InAs QD laser grown on InP substrate InAs-InP(113)B suitable for telecommunications is used. The schematic of QD laser structure is given in Fig. 1. Here, the excited state in the QD and Pauli blocking of the ground state (GS) levels are neglected. As seen in the figure, the QD laser includes a wetting layer (WL) and one confined state, that is, GS. The WL state acts as a common reservoir [14–16, 17], and the dot state couples to the WL.

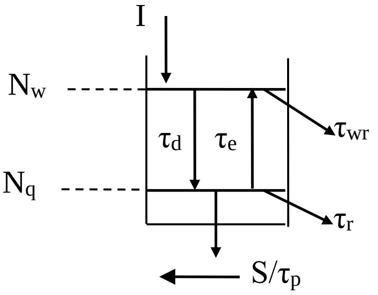


Fig. 1. Schematic energy band diagram of the QD laser

Three rate equations for QD laser are given below:

$$\frac{dN_w}{dt}=\frac{I}{qV_A}-\frac{N_w}{\tau_d}-\frac{N_w}{\tau_{wr}}+\frac{N_q}{\tau_e} \tag{1}$$

$$\frac{dN_q}{dt}=\frac{N_w}{\tau_d}-\frac{N_q}{\tau_e}-\frac{N_q}{\tau_r}-\left(\frac{N_B\Gamma v_g a\left(\frac{N_q}{N_B}-1\right)S}{1+\varepsilon S}\right) \tag{2}$$

$$\frac{dS}{dt} = \left(\frac{N_B \Gamma v_g a \left(\frac{N_q}{N_B} - 1\right) S}{1 + \varepsilon S}\right) - \frac{S}{\tau_p} + \beta \frac{N_q}{\tau_r} \qquad (3)$$

Where I is the injected current , V_A is the active region volume, N_w is the carrier density of wetting layer, N_q is the carrier density of ground state (quantum dot-QD), S is the photon density, τ_d is the carrier relaxation into QD, τ_{wr} is the carrier recombination (radiative and nonradiative) in the wetting layer, τ_r is the carrier recombination (radiative and nonradiative) in the QD, τ_e is the carrier emission from QD to the wetting layer, β is the spontaneous coupling factor, Γ is the confinement factor, v_g is the group velocity, a is the differential gain, N_B is the quantum dot density (cm^{-3}). The escape rate of photons from the cavity is resulted from the photon lifetime τ_p and is defined as

$$\frac{1}{\tau_p} = V_g \left(\alpha_{\text{int}} + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right)$$

where α_{int} is the internal loss and $R_{1,2}$ are the facet reflectivities.

3. Results and discussion

In our simulations, the threshold current was found 22 mA and operating frequency was taken to be 400 MHz. In order to obtain gain switching pulses, the current modulation is in the form of a positive half of a sinusoidal curve with an amplitude *rf* and a frequency *f*, with no dc current (dc=0) [18].

$$i(t) = \frac{rf}{2}\left(\left| \cos(2\pi ft) \right| - \cos(2\pi ft) \right)$$

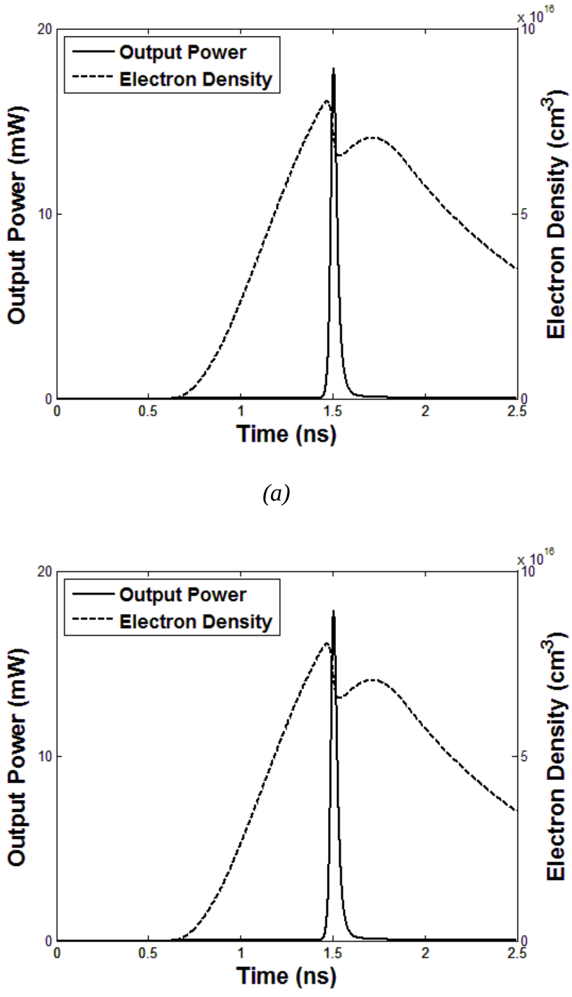
Here, rf is taken to be 52 mA and this current value was used in the following results unless otherwise stated. The length and width of the cavity are assumed to be L= 2.45 mm and W=120 µm, respectively. The values of the other parameters can be found in Table 1. The values of these parameters were obtained from [17, 19].

Our results showed that when standard values given in Table 1 are used, pulsewidth is obtained 39 ps giving an output peak power of 18 mW. The short pulses were generated between 1.5 and 2 GHz giving a pulsewidth range from 67.3 to 61.3 ps for $\beta = 1x10^{-4}$ in [17] under the mode-locked condition.

Fig. 2a and Fig. 2b shows the variation of the output power of the generated pulses and carrier density, with and without gain compression factor (ε) respectively. As seen in the figures, the results are the same with and without ε. Therefore, ε has an insignificant effect on the output pulses.

Table 1. Laser diode parameters

Parameter	Value	Unit
τ_d(carrier relaxation into QD)	2.5	ps
τ_{wr}(carrier recombination in the LW)	500	ps
τ_e (carrier emission from QD to WL)	1.1×10^{-7}	s
τ_p (photon lifetime)	8.9	ps
Vg (group velocity)	9.17×10^{9}	cm/s
β (spontaneous coupling factor)	10^{-4}	
Γ (confinement factor)	0.025	
ε (gain compression factor)	3×10^{-18}	cm^3
a (differential gain)	4.6×10^{-14}	cm^2
f (frequency)	400	MHz
L (length)	2.45	mm
W (width)	120	µm
Nr (refractive index)	3.27	
α_{int}(internal losses)	6	cm^{-1}
R_1(facet reflectivity)	0.95	
R_2(facet reflectivity)	0.05	
N_B(quantum dot density)	$6*10^{16}$	cm^{-3}

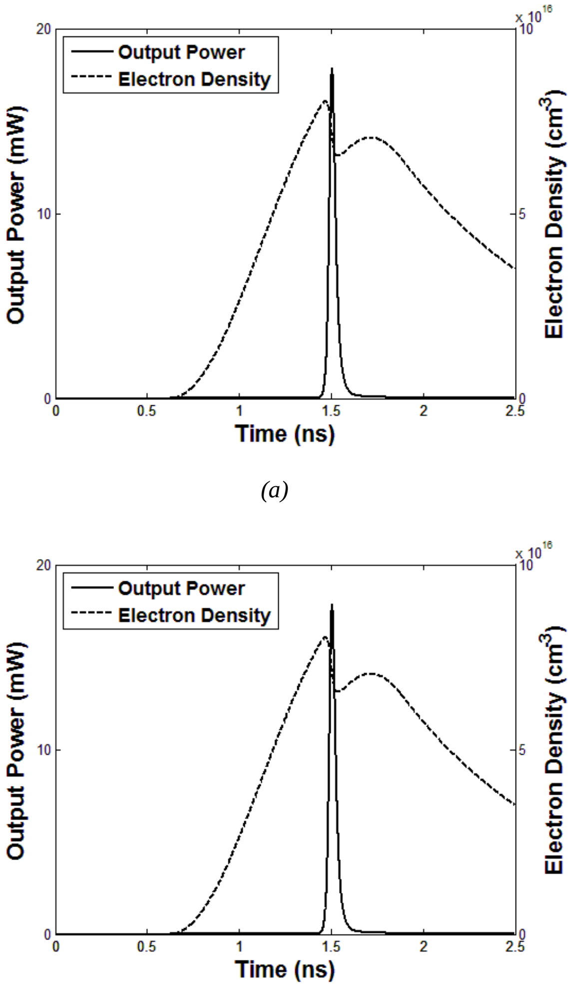


(a)

(b)

Fig. 2. Effect of the ε on output power and carrier density. The solid line indicates output power and the dashed line indicates electron density for (a) $\varepsilon= 3\times10^{-18}$ cm^3, b) $\varepsilon = 0$

The effect of τ_{wr} and τ_e on the output power and electron density is given in Fig. 3a, b. It can be observed in the figures that whether the value of τ_{wr} and τ_e are assumed to be the standard values or to be infinitely large, the results are the same.



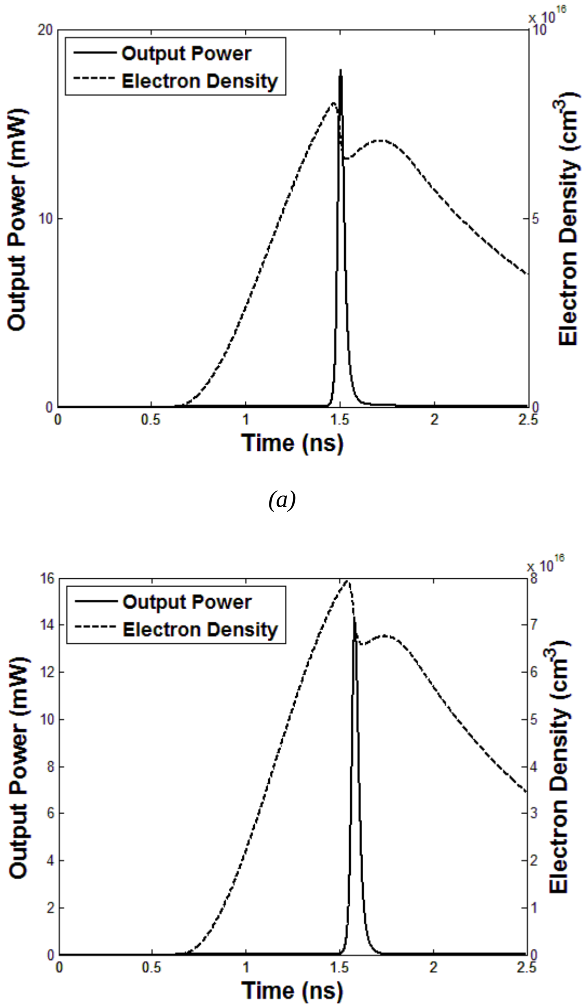
(a)

(b)

Fig. 3. Effect of the τ_{wr} and τ_e on output power and carrier density. The solid line indicates output power and the dashed line indicates electron density for (a) τ_{wr} = 500 ps, $\tau_e = 1.1*10^{-7}$ s and (b) $\tau_{wr} = \infty$, $\tau_e = \infty$

The results show that carrier recombination (radiative and nonradiative) in the wetting layer (WL) τ_{wr} and carrier emission from quantum dot (QD) the wetting layer (WL) τ_e have no significant effect on the gain switching output pulses. Similar results were found in [17].

The effect of the relaxation time (τ_d) from the WL to the QD is shown Fig. 4a and 4b. Our results showed that pulse width slightly increase with increasing τ_d giving a pulse width change from 39.18 ps to 43.47 ps as τ_d is increased from 2.5 to 30 ps. Therefore, τ_d has an insignificant effect on the gain switching output pulses as found in [17].

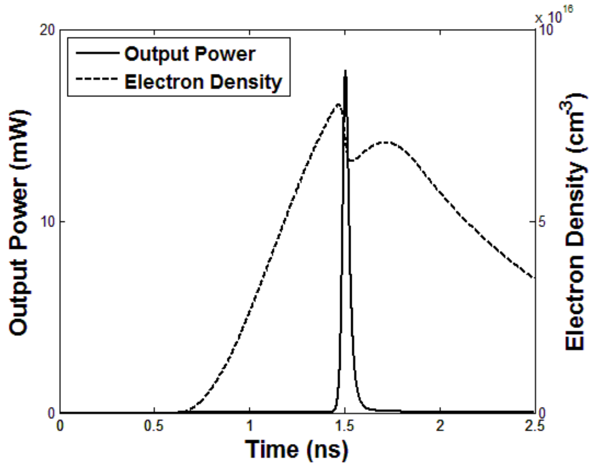


(a)

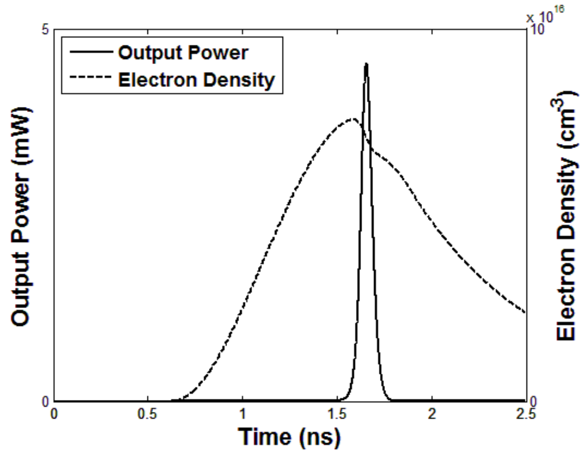
(b)

Fig. 4. Effect of the τ_d on output power and carrier density. The solid line indicates output power and the dashed line indicates electron density for (a) τ_d =2.5 ps. and (b) τ_d =30 ps

The effect of the carrier recombination in the QD (τ_r) is given in Fig. 5a and Fig. 5b. The numerical results showed that τ_r has a significant effect on the output pulses. The pulse width changes from 39.18 ps to 68.04 ps giving an output power of from 17.89 mW to 4.53 mW as τ_r is decreased from 1 to 0.7 ns. Similar results were observed in [17].



(a)



(b)

Fig. 5. Effect of the τ_r on output power and carrier density. The solid line indicates peak power and the dashed line indicates electron density for (a) τ_r =1 ns (b) τ_r =0.7 ns

Our results also showed that spontaneous coupling factor (β) has significant effect on the output pulses giving a pulse width change from 45 to 35.6ps and peak power from 14 to 21 mW as β is decreased from 10^{-3} to 10^{-5}. Similar results were also obtained in [20]. Dogru et. al. [17] also found that β strongly affected the operation of the mode-locked QD-HSPS. The mode-locking frequency range increased and short pulses were generated for a β value of zero.

4. Conclusions

In this study, the effect of carrier dynamic on the output pulse of gain switching QD laser was investigated and results were compared with the mode-locked QD-HSPS. The obtained results indicated that the output pulses are affected by several parameters in the following way: spontaneous coupling factor and carrier recombination time in the QD strongly affected the system operation, whereas there was no significant effect of gain compression factor, of the carrier recombination in the WL or of the carrier emission from the QD to the WL or of the relaxation time from the WL to the QD. The obtained results are very good agreement in [17].

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