

Gain switching characteristics of quantum well laser in two level rate equations

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Gain switching characteristics of quantum well (QW) lasers diode is described for the first time by using two-level rate equations. Effects of gain switching frequency, some laser diode parameters and dc and rf drive conditions on the full-width half maximum (FWHM) of gain switched pulses are investigated. It is shown that FWHM of pulses decrease as the rf current increased, at a constant frequency. However, the FWHM of pulses increase as the dc bias is increased. FWHM decreases also for small value of gain compression parameter and spontaneous coupling factor whereas the variation in carrier lifetime in the well does not significantly affect the FWHM of generated pulses. It is also shown that as the frequency is increased, FWHM start to increase or decrease depending on the gain compression.

(Received May 29, 2007; accepted June 27, 2007)

Keywords: Quantum well (QW) laser, Gain switching

1. Introduction

The two main techniques for generating picosecond pulses from semiconductor lasers are fast gain switching and mode-locking. Mode-locking, either with active or passive techniques has been shown to produce pulses having durations of 0.56-1.2 ps (passive) and 3-3.5 ps (active) [1-4]. However, the mode-locking of semiconductor lasers requires relatively complex optics, and careful alignment and control of an external cavity. A simple, versatile and reliable method for producing picosecond pulses from semiconductor lasers is the fast gain switching technique [5]. In this method, the gain of the laser diode is modulated by an input rf signal which results in a train of pulses at a repetition rate which is exactly the same as the frequency of the input rf signal. Gain switching pulses are essentially the first peaks of the relaxation oscillations.

A wide range of modulation frequencies can be used in gain switching, unlike in mode-locking. It has been shown that multiple pulses due to relaxation oscillations occur if the modulation frequency is too low [6-7]. By increasing the frequency, the number of relaxation spikes appearing at the output decreases until eventually a single pulse per modulation period is achieved. But the frequency cannot be increased above a certain value known as the cut-off frequency of gain switching. This cut-off frequency is conventionally define in [7] and is different from the usual cut-off for cases of small signal modulation with dc bias above the threshold.

Gain switching of semiconductor laser have already been reported for single mode rate equation in [5] and for multi mode in [8]. However, in this paper, picosecond pulse generation from multi-quantum well laser diode based on two level rate equations by gain switching is investigated for the first time.

2. Theoretical analysis

Quantum well rate equation proposed by Nagarajan et. al. [9] to describe the dynamics of carrier and photon density (N and S) in separate confinement heterostructure (SCH) quantum well lasers is given by

$$\frac{dN_s}{dt} = \frac{I_i}{qV} - \frac{N_s}{\tau_s} - \frac{N_s}{\tau_n} \quad (1)$$

$$\frac{dN_1}{dt} = \frac{N_s}{\tau_s} - \frac{N_1 - N_2}{\tau_c} - \frac{N_1}{\tau_n} - \frac{g(N_1, S_1)S}{\sqrt{1 + \epsilon S}} \quad (2)$$

$$\frac{dN_2}{dt} = \frac{N_1 - N_2}{\tau_c} - \frac{N_2 - N_3}{\tau_c} - \frac{N_2}{\tau_n} - \frac{g(N_2, S_2)S}{\sqrt{1 + \epsilon S}} \quad (3)$$

$$\frac{dN_3}{dt} = \frac{N_2 - N_3}{\tau_c} - \frac{N_3}{\tau_n} - \frac{g(N_3, S_3)S}{\sqrt{1 + \epsilon S}} \quad (4)$$

$$\frac{dS}{dt} = \Gamma(g(N_1, S_1) + g(N_2, S_2) + g(N_3, S_3)) \frac{S}{\sqrt{1 + \epsilon S}} - \frac{S}{\tau_p} + \Gamma\beta \frac{(N_1 + N_2 + N_3)}{\tau_{nQ}} \quad (5)$$

where N_s , N_1 , N_2 and N_3 represent the carriers density in SCH regions, first well, second well and third well respectively, I is the injection current, τ_s is the carrier transport time across SCH region, τ_c is the barrier tunneling time, τ_n is the bimolecular recombination lifetime, Γ is the photon lifetime, β is the optical confinement factor per well, β is the spontaneous emission factor, and ϵ is the gain compression factor and S is the photon population. The rate equations of quantum well (QW) is derived from (1)-(5) following the approach by Tucker [10]. First, it is assumed that $N=N_1+N_2+N_3$ and $g(N,S)=g(N_1,S_1)+ g(N_2,S_2)+ g(N_3,S_3)$, where N is the sum

of each carrier density, and $g(N,S)$ is the sum of the optical gain. By summing up (2)-(4), the QW rate equations is thereby reduced to

$$\frac{dN_s}{dt} = \frac{I_i}{qV} - \frac{N_s}{\tau_s} - \frac{N_s}{\tau_n}$$

$$\frac{dN}{dt} = \frac{N_s}{\tau_s} - \frac{N}{\tau_n} - \frac{\Gamma v_g G(N,S)S}{\sqrt{1+\epsilon S}}$$

$$\frac{dS}{dt} = \frac{\Gamma v_g G(N,S)S}{\sqrt{1+\epsilon S}} - \frac{S}{\tau_p} - \beta \frac{N}{\tau_n}$$

G shows the material gain and v_g is the group velocity. Length of SCH L_s is 300 nm, the longitudinal dimension L_L of the QW is 300 μm , the ridge width is 2.5 μm , and width of the QW is 8 nm. The other model parameters used in simulation are given in Table 1.

3. Results and discussion

The program has been run for the parameter values given in the Table 1. Under these conditions, the laser diode has a threshold current I_{th} of 12 mA.

Table 1. Model parameter values used in the simulation.

Parameter	Value	Unit
τ_s	6	ps
τ_n	2.25	ns
τ_p	3	ps
Γ	0.02	
v_g	7.5×10^7	ms^{-1}
ϵ	1×10^{-17}	cm^3
β	1×10^{-4}	

Fig. 1 represents the variation of the FWHM of the generated pulses, with and without gain compression, as a function of the applied dc bias current. The applied rf current is adjusted at each dc bias current to obtain the minimum pulse duration. Fig. 1 clearly demonstrates the effect of the gain compression parameter on the pulse width of the generated pulses. At a fixed dc bias current of $I_b = I_{th}$, the laser diode with gain compression produces an optical pulse having a duration of 39.23 ps. If the phenomenon of gain compression was not present, 6.71 ps optical pulses at the same value of the dc bias current would have been produced under the otherwise identical conditions. Hence, due to gain compression, the pulse width broadens. As seen in figure dc bias current as large as $2I_{th}$ can be applied to the laser diode without generating a double pulse when the laser diode exhibits gain

compression or no gain compression. Results shown in Fig. 1 indicate that, for the case where gain compression is taken into account, the pulse width decreases if the applied dc bias current is decreased. The same variation in the FWHM of the pulses with dc bias has been shown in [5]. However, the FWHM of the pulses for $\epsilon=0$ is almost insensitive to the variation of dc bias [5].

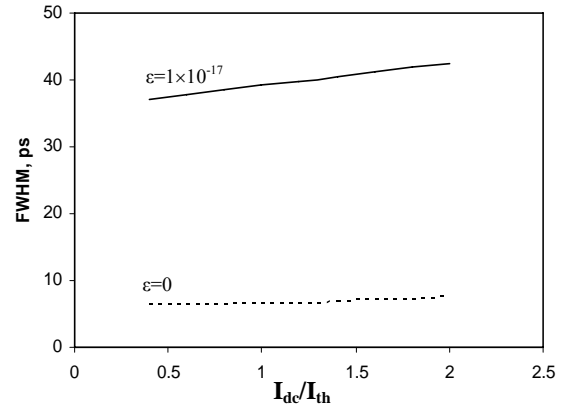


Fig. 1. Variation of the FWHM of pulses with dc bias current.

Fig. 2 shows the variation of FWHM as a function of applied rf current at a fixed dc bias of $1.2I_{th}$ with and without gain compression. The effect of gain compression on the pulse width can clearly be seen from Fig. 2. There is a maximum value of rf current that can be applied to the laser diode without achieving multi-pulsing for the case $\epsilon=0$. From the computer simulations, this maximum value of rf current is found to be $5I_{th}$ for $\epsilon=0$. In both cases, the FWHM of the pulses decrease as the rf current is increased as in [5, 8]. However, for the case with gain compression, there is an optimum rf current of $3.5I_{th}$ after which the FWHM of start to increase again. The same variation of FWHM with rf current has been indicated [5]. For, say, $I_{rf} = I_{th}$, the pulse widths are 18.08 ps for $\epsilon=0$ and 47.47 ps for the gain compression case. The broadening in the pulse width due to gain compression is considerable.

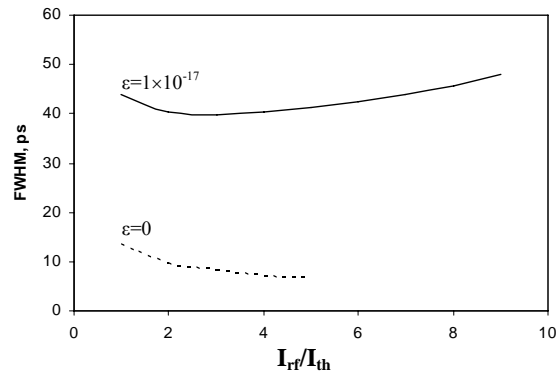


Fig. 2. Variation of the FWHM of pulses with rf current.

Some of the parameters are varied from their standard values given in the Table 1 to investigate their effect on pulse width. Carrier lifetime τ_n in the well can be changed slightly. The effect of changing the value of τ_n from 2.25 ns to 1.5 ns on FWHM of the pulses is shown in Fig. 3 as a function of dc bias both with and without the gain compression parameter. As can be seen in figure, the variation in τ_n does not significantly affect the FWHM of the generated pulses.

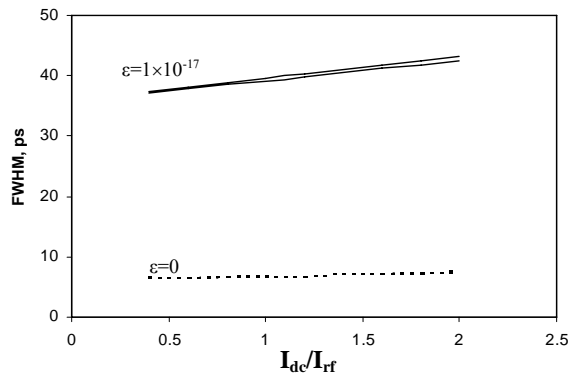


Fig. 3. Effect of the variation of carrier lifetime τ_{nQ} on the FWHM of pulses.

The second parameter which is changed from its standard value is the value of β , that is, the spontaneous emission into the mode. The effect of a decrease of β , from 10^{-4} to 10^{-5} on the pulse width is shown in Fig. 4 where it is seen to decrease the pulse width. At a fixed dc bias current of $I_b = I_{th}$, the width is decreased from 37.36 ps to 35.44 ps with gain compression and from 6.33 ps to 6.23 ps without gain compression. This shows that the variation in the value of β affects the pulse width of the pulses generated by gain switching.

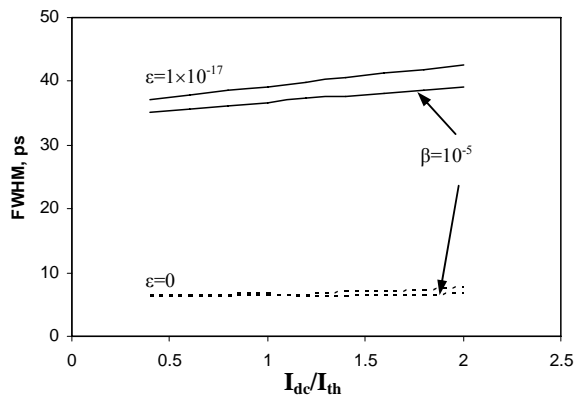


Fig. 4. Effect of the variation of spontaneous coupling factor β on FWHM of pulses.

Effect of gain switching frequency on pulse width is given in Fig. 5 when the laser diode is driven at $I_b = 1.2I_{th}$ and $I_{rf} = 3I_{th}$. The FWHM of output of laser diodes increases as the frequency increased without gain compression whereas it decreases with gain compression case. This figure also shows how the parameters affect the maximum and minimum gain switching frequencies that can be applied to laser diode. Multi-pulsing occurs at frequencies below 2.5 GHz for standard parameters and no gain compression cases. The highest cut-off frequency is calculated to be 4.5 GHz for standard parameters with and without gain compression cases.

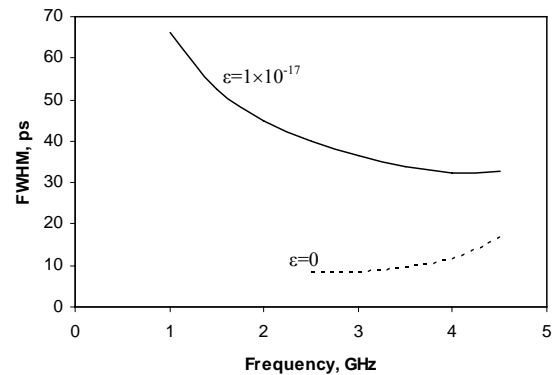


Fig. 5. Effect of the gain switching frequency on the FWHM of pulses.

4. Conclusion

The generation of picoseconds pulses by gain switched using two level rate equations of quantum well laser diode has been discussed. It has been found that the main limitation for obtaining short pulses is gain compression parameter, as expected. The pulse width broadened due to gain compression. It has been also found that the carrier lifetime τ_{nQ} in the well has little effect in gain switching. It is clear from the simulation that the spontaneous emission factor β will affect the width of the generated pulses. In order to have shorter pulses, the laser diode structure should be designed so as to give rise to a small β . FWHM of laser output decreases as the frequency increases for laser diodes with high gain compression, whereas the behavior is opposite for laser diodes with no gain compression.

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