Journal of Education for Pure Science- University of Thi-Qar
Vol.10, No.2 (June, 2020)
Website: jceps.utq.edu.iq Email: jceps@eps.utq.edu.iq

DOI: http://doi.org/10.32792/utq.jceps.10.02.08

INVESTIGATION THE DIRECT CURRENT MODULATION IN NANO QUANTUM CASCADE LASERS

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Received 16/6/2020 Accepted 18/02/2020 Published 30/11/2020

Abstract:

In this paper, a theoretical investigation of direct current modulation in Nano quantum cascade lasers is presented. Since the spontaneous emission effect is an important factor in a microcavity the rate equations model has been reconsidered to include the Purcell spontaneous emission enhancement factor F and the spontaneous emission factor. The results indicate that the present rate equation model can be using to study the effect of Purcell spontaneous emission enhancement factor F and the spontaneous emission factor on the direct current modulation in Nano quantum cascade lasers. The results indicate that the effects of Purcell spontaneous emission enhancement factor F and the spontaneous emission factor are very similar to the effects of these factors in traditional semiconductor lasers. It is found that the increase in Purcell factor value leads to increase in photon number and decrease the carrier number in all quantum states. The decreases in enhanced spontaneous emission factor value leads to increases in carrier number and decreases the photon number in all quantum states. This results coming in good agreement with other references.

I – INTRODUCTION:

Since their first realization in 1994, the performance and frequency range of quantum cascade lasers (QCLs) are continually improving. High-performance QCLs are desired for potential applications ranging from molecular detection to telecommunications. Their narrow linewidths, large intensity modulation (IM) bandwidth, high output power and possible ambient temperature operation make them attractive in optical free space data communication and light detection and ranging (LIDAR) applications. QCL consists of a repeating structure in which each repeat unit is made up of an injector and an active region; therefore, electrons are recycled from period to period, contributing each time to the gain and the photon emission. This design leads to high output power and high quantum efficiency. In other words, the carrier density and photon density are proportional to stages number. In QCL, the light emission takes place due to intersubband optical transitions entirely within the conduction band between quantized states in the quantum well (QW) where the carrier lifetime is dominated by nonradiative phonon scattering phenomena. The photon energy that results from a transition is determined by the QW thickness i.e. not dependent on the energy gap of the active material

It is well-known that the mode density increases and the spontaneous emission rate enhances in the microcavity with high Q and small volume due to Purcell effect [1,2]. Due to this effect, the radiative carrier lifetime can be decreased. The main point of the enhancement of the spontaneous emission is that the cavity linewidth is larger than that of the emitter. In nano-lasers, the effects of the combination of the Purcell spontaneous emission enhancement factor F, and enhanced spontaneous emission coupling expressed in the factor β are generally desirable as they tend to enhanced the dynamical performance, lower the injection current and enhanced the utilization of spontaneous emission. Since the semiconductor lasers performance is very sensitive to the perturbations that result from the external optical power such as the optoelectronic feedback, optical feedback, and optical injection, therefore, the enhancement of performance of unidirectionally and mutually coupled lasers have been a subject of interest for many decades [3].

The motivation behind the present paper is that in the many emerging fields that deal with the photonic signal, there is a need for a small, integrated and efficient source with excellent dynamic and static properties. In this paper, a theoretical study of the effects of Purcell effect and enhanced spontaneous emission on direct current modulation in NQCLs is presented for the first time to my knowledge. This paper is organized as follows. Rate equations model is given in section two. Numerical results and discussions are presented in section three. Section four summarizes the main conclusions.

II- RATE EQUATION MODEL:

To investigate the dynamic of NQCLs, it is necessary to study the crucial device parameters and how to further improve them. The crucial device parameters such as saturation photon density, threshold injection current and slope efficiency of the QCLs can be estimated using a rate equation model. QCLs consists of a several repeating structures in which each repeat unit is made up of an injector, a gain region and an injector region coupling two successive active regions and enables the electrons tunneling from an active well to higher energy level in the active region of the next period. Each gain stage incorporates three energy levels labeled |1>, |2>, and |3> with densities N_1, N_2 and N_3, respectively. The optical gain and the carrier dynamics inside gain region for NQCLs can be considered by forming a simplified three-level model for the electrons moving through a three-level system as shown in Fig. 1.

In this model, the laser transition occurs between |3> and |2> levels. Electrons are injected into level |3> with an injection current Iin and an injection efficiency η, where they either relax to levels |2> and |1> with a total rate $\tau_e^{-1} = \tau_{32}^{-1} + \tau_{31}^{-1}$, where τ_{31} and τ_{32} are the phonon scattering times between levels |3> and |1>, and between levels |3> and |2>, respectively. The phonon scattering times between levels |2> and |1> is τ_{21}, the carriers relax into level |1> by the emission of a longitudinal-optical phonon and tunnel through the exit barrier into the subsequent miniband. All these times are dependent on two parameters; the energy difference between the corresponding states and the phonon energy of scattering process. The rate equations model of nano quantum cascade lasers with direct current modulation can be described as follows [4]

$$\frac{dN_3}{dt} = \eta\frac{I_{in}}{q} + \eta\frac{I_{dc}\sin(\omega t))}{q} - \frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}} - \frac{F\beta N_3 S}{\tau_{sp}} - G(N_3 - N_2)S \quad (1)$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} + G(N_3 - N_2)S \quad (3)$$

$$\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{out}} \quad (4)$$

$$\frac{dS}{dt} = ZG(N_3 - N_2)S_T - \frac{S}{\tau_p} + \frac{F\beta N_3}{\tau_{sp}}(S+1) + ZGN_3S \quad (5)$$

Here q is the charge of electron, N_3 ,N_2 and N_1 are the carrier numbers in levels 3,2 and 1 respectively. η is the injection rate, β is the spontaneous emission factor, G is the gain coefficient, the scattering times of phonon between levels are τ_{31}, τ_{32} and τ_{21}, τ_p is the photon lifetime, τ_{out} is the carriers tunneling time, Z is the gain stages number. Finally, F is the Purcell coefficient, τ_{sp} is the free space spontaneous emission lifetime.

III- Results and Discussions:

The main aim of the paper is to study the performance of direct current modulation in nano quantum cascade lasers giving attention to the role played by the Purcell factor F and the spontaneous emission coupling factor β. The results presented here have been evaluated using the rate equations (1) – (5) and the dynamics of the Nano lasers is analyzed for the device parameters in Table I.

Symbol	Value	Unit
η	0.4	
β	1	
N	10	
F	10	
I_{ac}	1	mA
I_{ac}	0.1	mA
G	1.2×10^5	s^{-1}
τ_{sp}	5	ns
τ_p	0.39	ps
τ_{32}	2.1	ps
τ_{31}	2.6	ps
τ_{21}	0.5	ps
τ_{out}	0.5	ps

Table I: The parameters values in present simulation [7].

Fig. 1. shows the results of direct current modulation in NQCL. As shown in figure, the values of carrier number in quantum states and the photon number are small because the small injection current

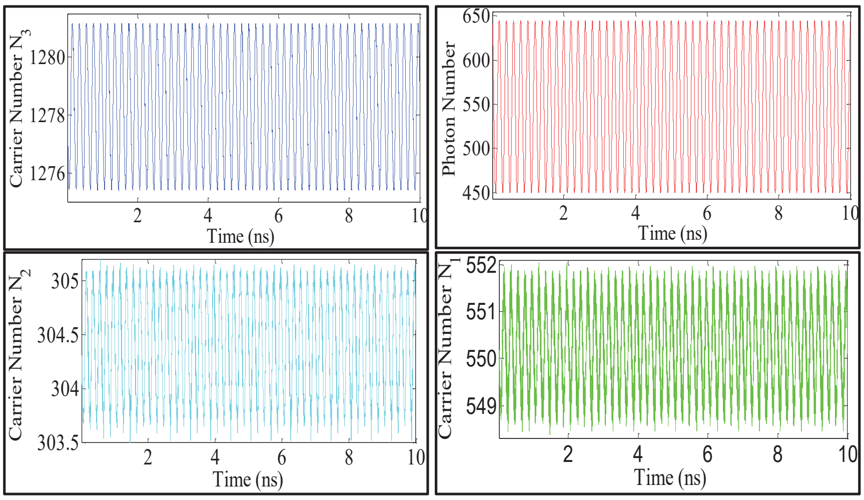

Fig. 3: The carrier number dynamic and photon number dynamic in NQCL under the effect of direct current modulation at F=25.

Fig. 4 and Fig. 5, show the effect of enhanced spontaneous emission factor β on the direct current modulation in nano quantum cascade lasers at two different values of enhanced spontaneous emission factor, β =0.5 and β =0.1 respectively. As shown in Fig.4 and Fig.5, the decreases in enhanced spontaneous emission factor value leads to increases in carrier number and decreases the photon number in all quantum states. This results coming in good agreement with other references. The decreases in enhanced spontaneous emission factor means that the fraction of spontaneous emission that contributes in lasing mode is decreases and hence increases the carrier number and decreases the photon number. On the other hand, the effect of Purcell factor on the general behavior of direct current modulation is very clear in comparison with enhanced spontaneous emission factor. We can see sharp changes in carrier number in all states with the increase the Purcell factor while the general distribution of carrier number in all states is unaffected with the decrease in enhanced spontaneous emission factor.

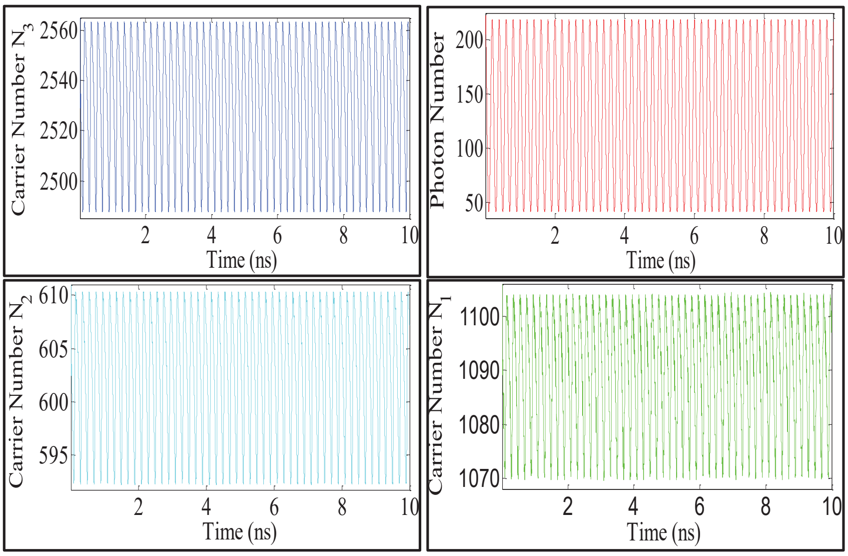

Fig. 4: The carrier number dynamic and photon number dynamic in NQCL under the effect of direct current modulation at β=0.5.

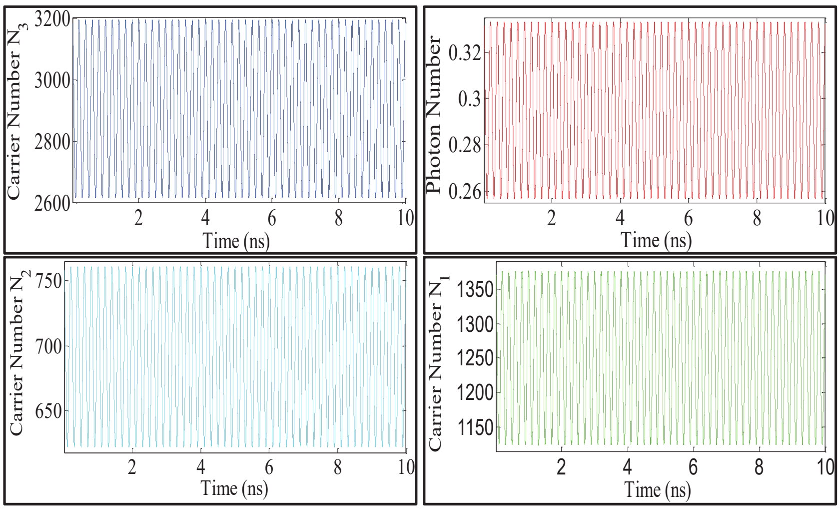

Fig. 5: The carrier number dynamic and photon number dynamic in NQCL under the effect of direct current modulation at β=0.1.

4- CONCLUSIONS:

Direct current modulation is theoretically investigated using Nano quantum cascade lasers. In this study, simple rate equations model with Purcell factor and enhanced spontaneous emission factor has been presented to investigate the Direct current modulation and the impacts of Purcell factor and enhanced spontaneous emission factor. The theoretical investigation is concentrate to study the impacts of Purcell factor and spontaneous emission factor on the direct current modulation quality. It is found that the increase in Purcell factor value leads to increase in photon number and decrease the carrier number in all quantum states. The decreases in enhanced spontaneous emission factor value leads to increases in carrier number and decreases the photon number in all quantum states. This results coming in good agreement with other references.

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