Dynamic of quantum Cascade Laser

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Abstract:
The study of quantum cascade laser was carried out using a mathematical model that describes the carriers, in the upper and lower subbands and photon numbers. The Laser output delay time and number of photons affected on by the injection current, relaxation lifetimes of carrier in the upper and lower subbands, the spontaneous emission lifetime and spontaneous emission factor.

Key word : Quantum cascade laser, Upper subband, Lower subband , Photon lifetime ,Output dynamics.

حركيات الليزر التعاقبي الكمي

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الخلاصة :

تمت دراسة حركيات الليزر التعاقبي الكمي مستعملين أنموذج رياضي يصف حركيات كل من تعداد الحاملات في حزام جزئي علوي وحزام جزئي سفلي وعدد الفوتونات المتذبذبة في الليزر تأثر زمن تأخر خرج الليزر ومقدار عدد الفوتونات عند الجزء الثابت من الخرج بكل من تيار الحقن وعمر الحاملات في حزام الجزئي العلوي وحزام الجزئي السفلي وعمر الفوتونات وعمر الانبعاث التلقائي ومعامل الانبعاث التلقائي.

الكلمات المفتاحية : الليزر التعاقبي الكمي،حزام جزئي علوي،حزام جزئي سفلي،عمرالفوتونات،حركيات الخرج.

Introduction :

Quantum cascade lasers (QCLs) are semiconductor lasers (SCLs) that emit in the mid – and long wave infrared (IR) bands, and are finding new applications in precision sensing ,spectroscopy , medical and military applications [1 -5] .

The QCLs are very different from the standard SCls. In the standard lasers, operating on inter-band transitions, if one know the electronic structure , one immediately know the wavelength and can easily calculate the gain profile. Usually one only need to know the energy levels. However, in QC structures the question is much more complicated. The energy levels and wave functions are only a starting point for further calculations and analysis. So, in order to predict correctly the cascade laser performance one need to be able to calculate the electronic structure very accurately [6]

Since the first operational QCL emitted light in 1994 tremendous effort has been put into making them more robust, versatile, and manufactur- able [7 – 11].

In this article we report on the dynamics of QCL under the effect of number of parameters that appeared in the mathematical model that describe its dynamics.

<u>Mathematical model</u> :

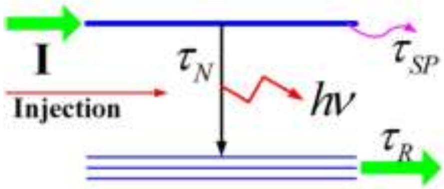
To study the quantum cascade laser dynamics in the autonomous situation we have adopted the model introduced by Wang et al.[12], given by the following three equations describing the carrier number in the upper subband , N_{up} , the carrier number in the lower subbands , N_{low} , and the photon number, S , as

$$\frac{dN_{up}}{dt} = \frac{I}{q} - \frac{N_{up}}{\tau_N} - G_0 \Delta N S \text{ ………………1}$$

$$\frac{dN_{low}}{dt} = \frac{N_{up}}{\tau_N} + G_0 \Delta N S - \frac{N_{low}}{\tau_R} \text{ …………….2}$$

$$\frac{dS}{dt} = (G_0 \Delta N - \frac{1}{\tau_p})S + \beta \frac{N_{up}}{\tau_{sp}} \text{ …………….3}$$

τ_N,τ_R,τ_{sp}, τ_p are respectively relaxation time from the upper sub band , the lower subband, spontaneous emission life time and photon lifetime, β is the spontaneous emission factor, ΔN = N_{UP} - N_{LOW} , G_0 is the gain coefficient, I is the bias current and q is the electronic charge. Fig (1) illustrates the carrier dynamics in the laser. The carriers are injected into the upper subband of the active region by resonant tunneling, while the tunneling time form the injector is ignored since it is external short (N 0.2Ps) [12]. Then, the carrier relax into the lower subband, from which these leave the active region. Neither the carrier absorption process nor the ground level in the active region is taken into account in the simulation.



Fig(1): Simplified carrier dynamics model

Simulation results and discussion:

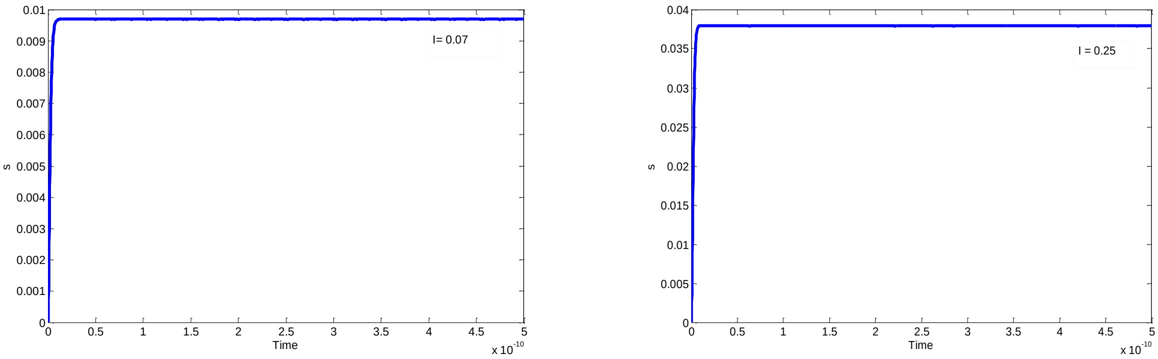
To obtain the dynamics of the quantum cascade laser we have solved the model (1 -3) using the fourth order Runge - Kutta numerical method of integrating with the help of Mat Lab. Initial conditions and numerical values of the parameters appeared in the (1 – 3) model given in table

Table (1): parameter values used in the simulation

Symbol	Description	Value	Unit
τ_N	Carrier relaxation time from upper subband	1.5×10^{-12}	Sec
τ_R	Carrier removal time from lower subband	1.2×10^{-12}	Sec
τ_P	Photon life time	1×10^{-12}	Sec
τ_{SP}	Spontaneous life time	1×10^{-9}	Sec
β	Spontaneous emission factor	1×10^{-5}	………
G_0	Gain coefficient	2.5×10^{5}	sec^{-1}
q	Electronic charge	1.602×10^{-9}	Coul.

Fig(2)represents sample results of variation of output produced from QCL against time for five chosen injection current while the figures (3 – 8) shows the effect of injection current ,I, carrier relaxation time from upper sub band,τ_N, carrier relaxation time from lower subband, τ_R, photon life time, τ_P, spontaneous emission life time, τ_{SP}, and spontaneous emission factor, β , respectively.

As the injection current increased the carriers population inversion increased hence the photon number increases and the laser signal delay time decreased with the reduction of the transient region length,see fig (3).Increasing the carrier relaxation time, τ_N , from the upper sub band decreased the probability of stimulation emission although increases the carriers in the upper sub band so that the photon number decreases, see fig (4) while increasing the carrier relaxation time, τ_R , from the lower sub band decreases the population and decreasing the photon numbers, see fig (5). Increasing the photon life time, τ_P , i.e increasing the time for the photons in the cavity hence decreases the photon numbers as show in fig (6). Both the spontaneous emission lifetime and factor have no clear effect on the photon number as can be seen in figures (7) and (8).



Fig(2):variation of delay time(t) and photon numbers as a function of injection current, I: a=0.07, b=0.25, c=0.7, d=1.0, e=2.0

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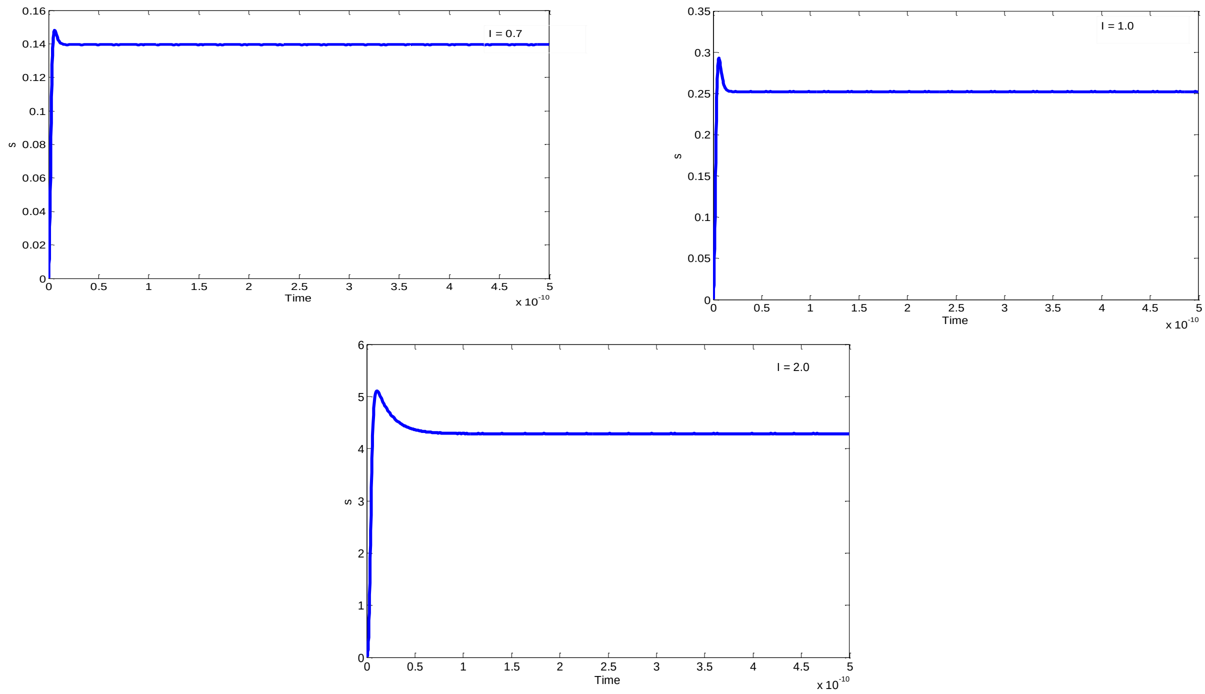

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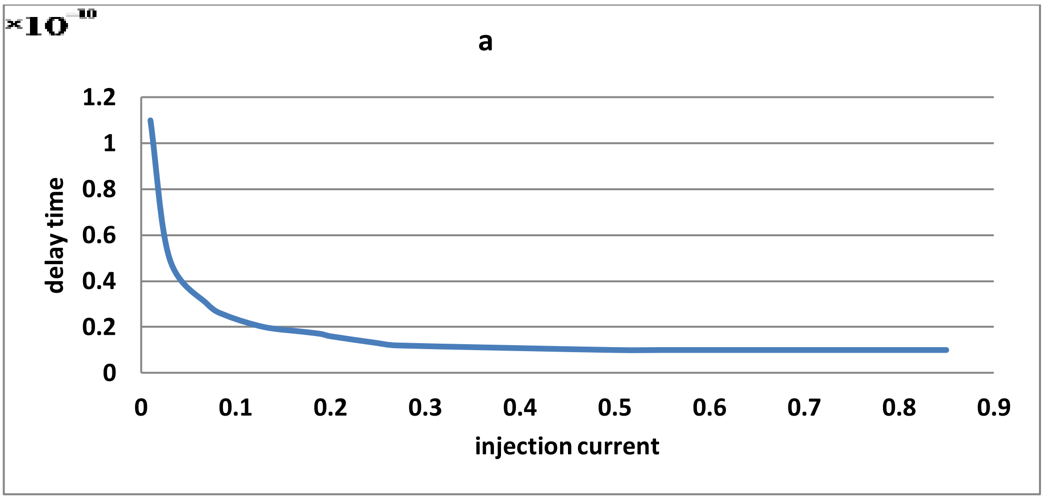
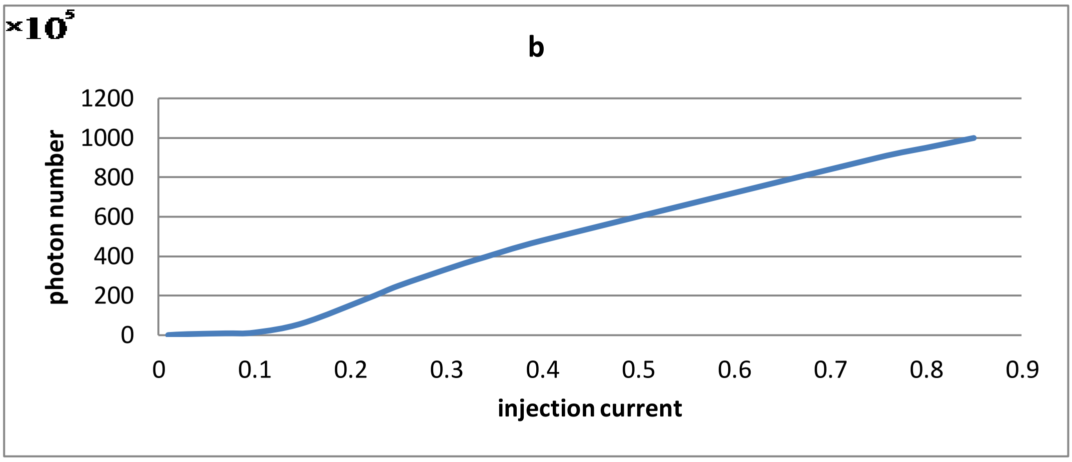
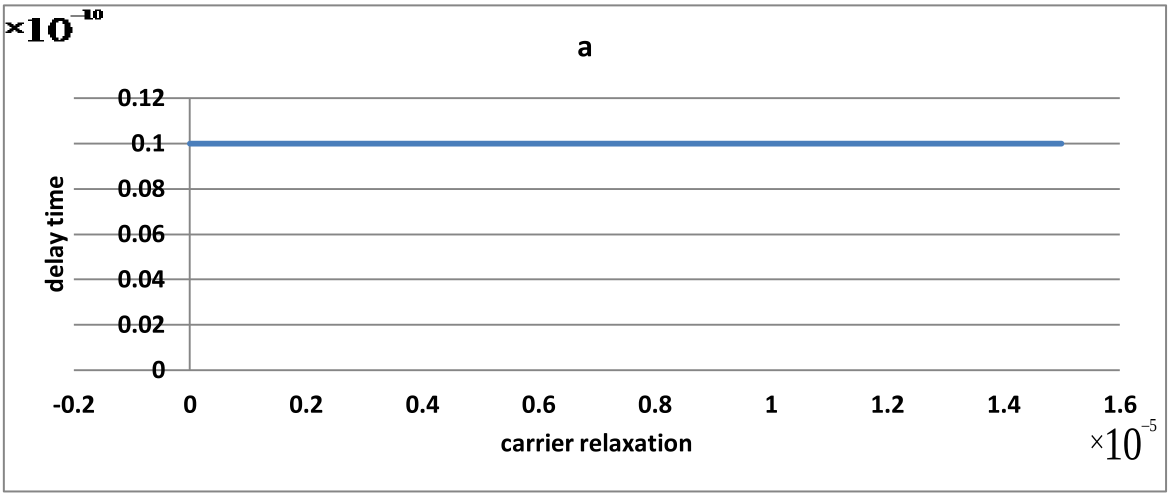
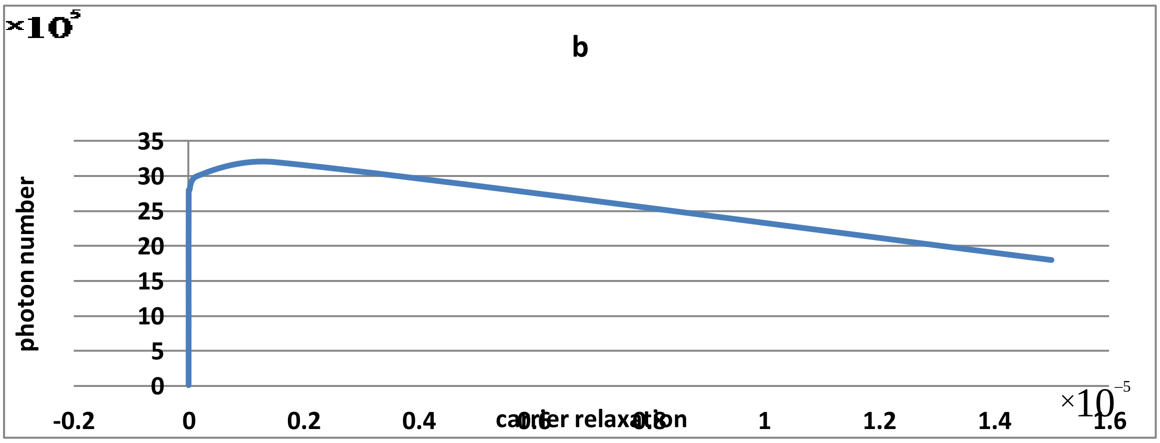


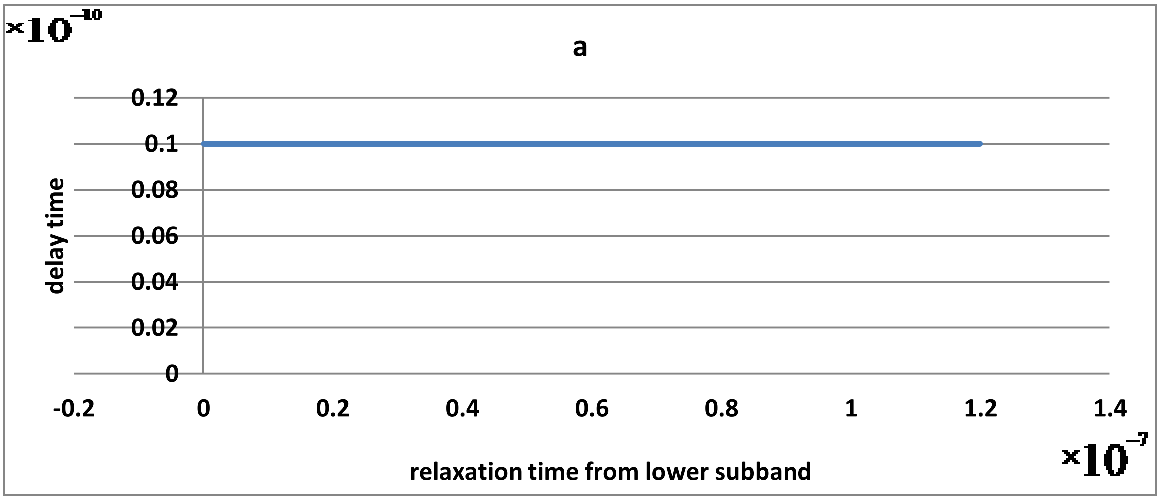


Fig(3)(a) Delay time,(b)photon number of quantum cascade laser against inject current.





Fig(4)(a) Delay time,(b) photon number of quantum cascade laser against carrier relaxation time from upper subband.



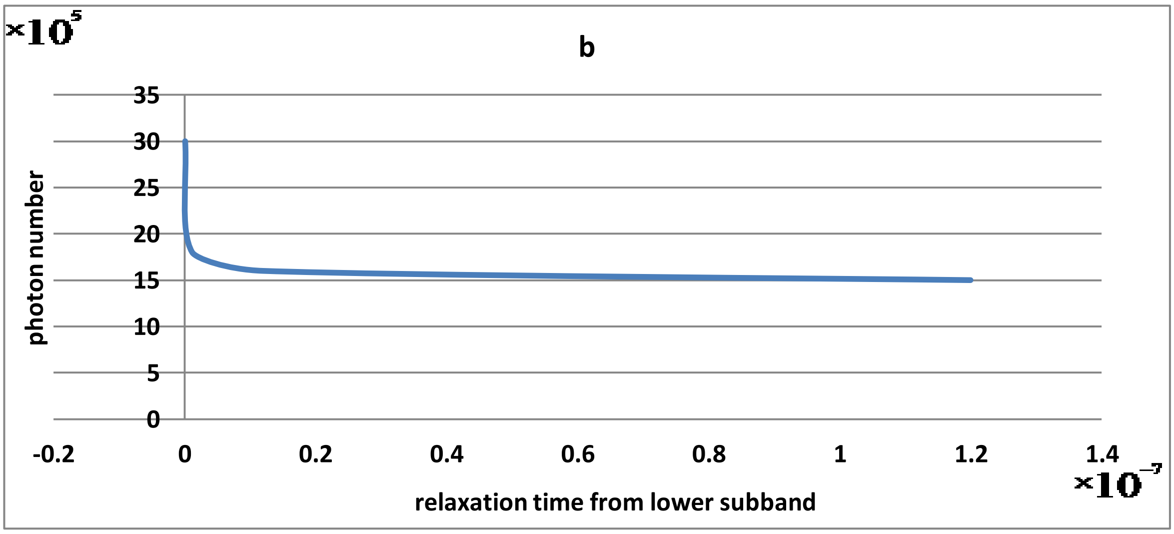
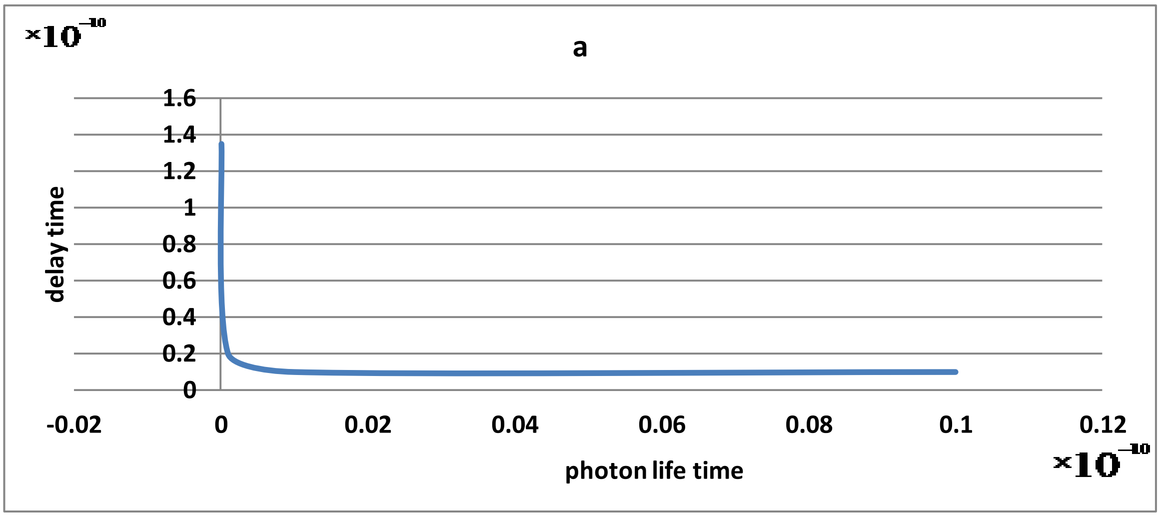
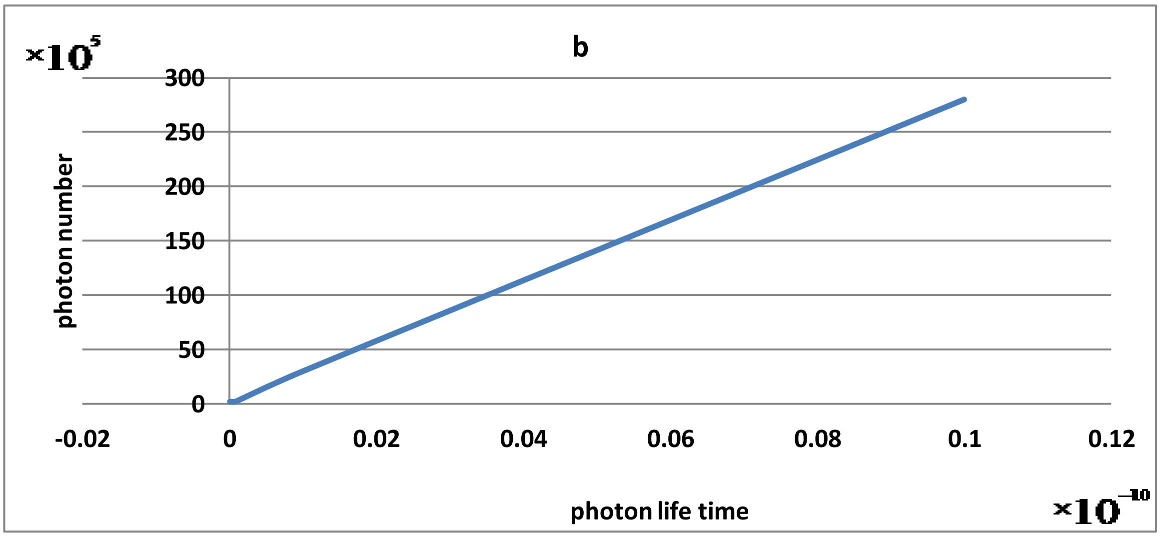
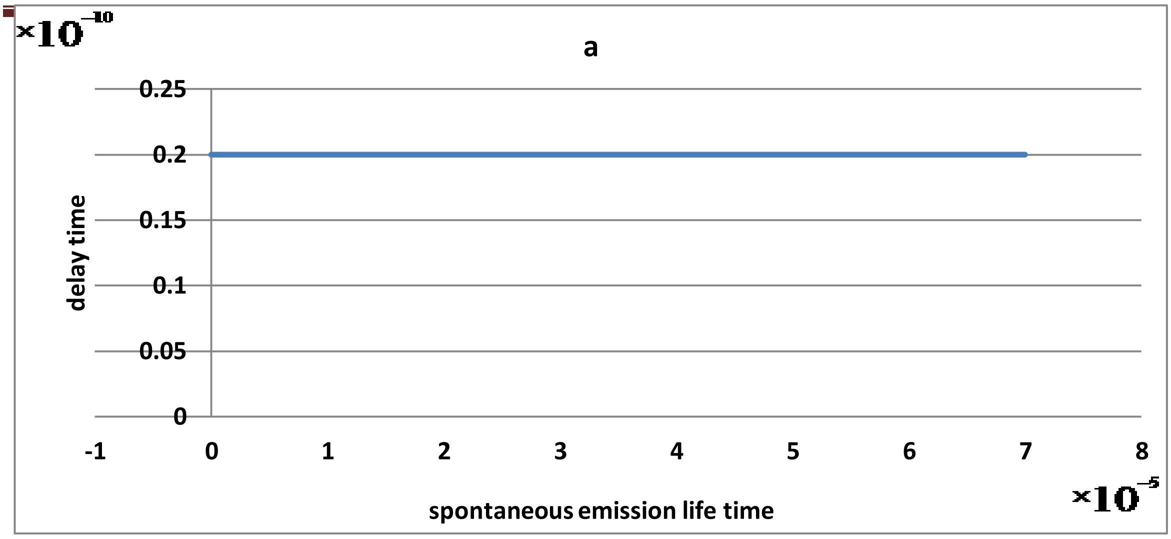


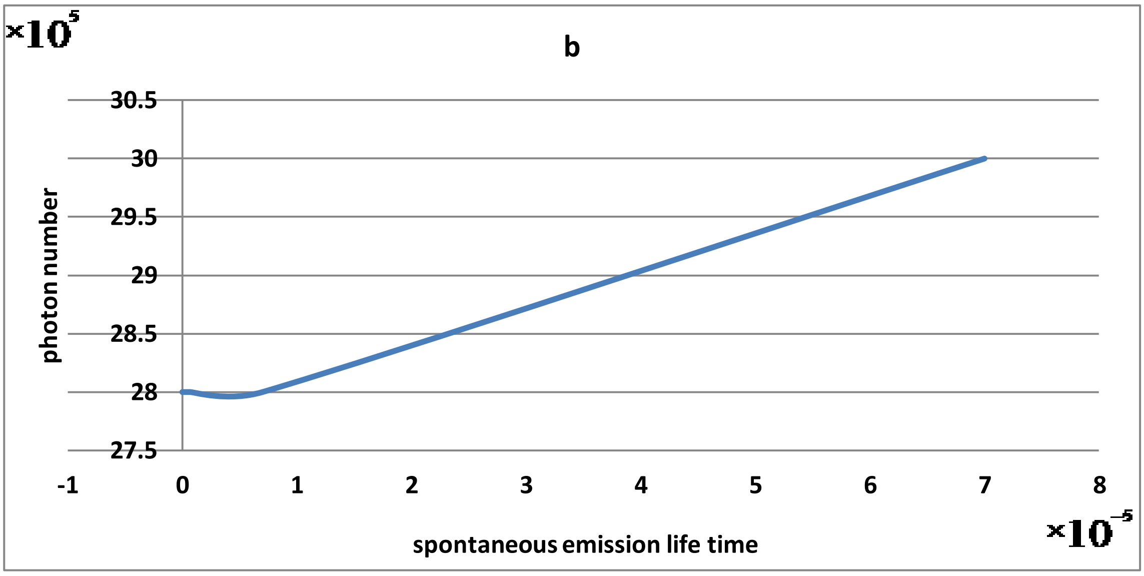
Fig (5)(a) Delay time ,(b) photon number of quantum cascade laser against relaxation time from lower subband.



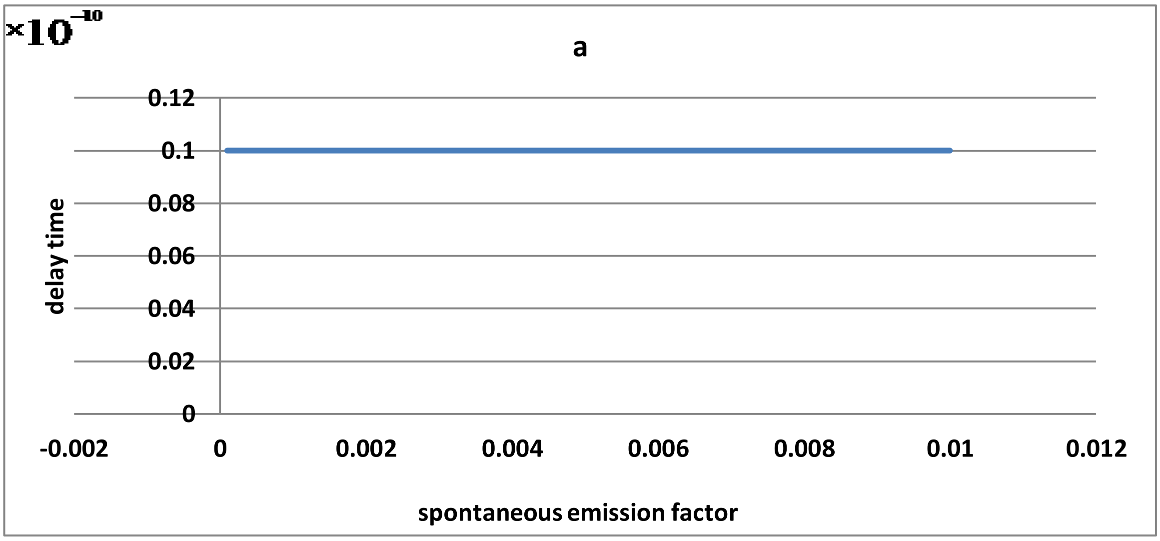


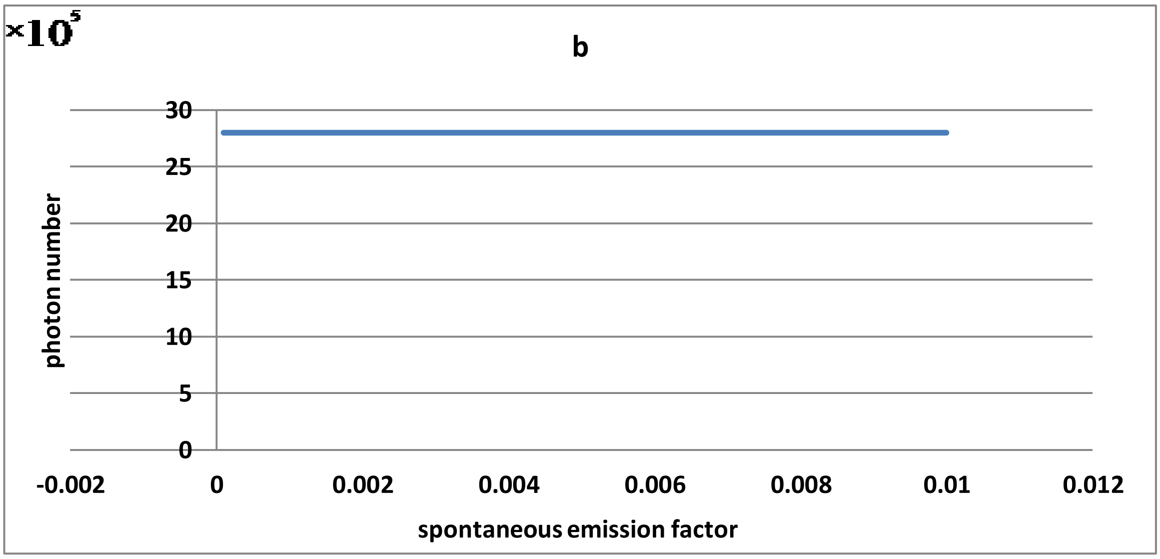
Fig(6)(a)Delay time ,(b)photon number of quantum cascade laser against photon life time.





Fig(7) (a)Delay time,(b) photon number of quantum cascade laser against spontaneous emission life time.





Fig(8) (a) Photon number, (b) Delay time of quantum cascade laser against spontaneous emission factor .

Conclusion :

The turn on dynamic of a quantum cascade laser is studied. The increase of (a) injection current decreases the delay time of the laser signal while it increases the photon number in the steady state region(b) relaxation time of carriers in the upper subband increase does not affect the delay time while it decreases the photon number (c) so does the increase of relaxation time of carriers in the lower subband .(d) The photon lifetime increase increases the delay time and decrease the photon number. (e)Both the spontaneous emission lifetime and factor do not affect both delay time and number if photons as they both increases.

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