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Monte Carlo Simulation of Time-Dependent Operation of Quantum Cascade Lasers

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Abstract

A Monte Carlo method has been used to investigate the dynamics of a terahertz quantum cascade laser. The simulator follows the evolution of both electrons and photons and makes use of a special weighting procedure in order to cope with the huge variations in the number of photons. The laser turn-on time is found to be much longer than the time needed to establish the electron population inversion. Moreover, it presents an important statistical dispersion which reflects the "rare events" statistics of photon emissions during the initial stage. The response to a modulation of either optical losses or injected current has been investigated and the laser turn-on delay appears as the main factor that limits the response at high frequency.

1 Introduction

Unipolar Quantum Cascade Lasers (QCLs) based on intersubband transitions in heterostructures have attracted a great deal of interest since the first successful realization in 1994 [1]. In mid-infrared, QCLs have already reached the commercial stage and QCLs operating at THz frequencies, although still at laboratory stage, are experiencing continuous improvements, thanks to an enormous research effort. Owing to the great complexity of such devices, the development of efficient simulators is crucial.

The most frequent description of laser dynamics is based on a simple analysis in term of balance equations for a few levels. It leads to a set of three or four differential equations which are easily solved by standard methods, and may serve as a starting point for SPICE models [2]. However, this approach relies on severe assumptions and, more importantly, it makes use of time constants which, generally, can only be obtained on phenomenological grounds. More sophisticated simulation tools, based on quantum Green functions formalism or on semi-classical Monte Carlo approach [3, 4, 5], have been used in order to describe electron transport across the QCL structure, thus providing an estimation of the optical gain. However, these models are unable to provide any information on the dynamics of the laser, because they disregard the coupling between electrons and light in the optical cavity[1]. In this paper we propose to overcome this limitation by developing a Monte Carlo model which follows both electrons and photons accounting for their mutual interaction.

[1]A noticeable exception by which we have been inspired can be found in [4]

2 The Model

Electrons are treated along the lines described in [5]. The QCL structure is made of a sequence of identical “stages”. Electron states and scattering probabilities are calculated assuming an ideal infinite periodicity. Accordingly, when an electron undergoes an ”inter-stage” transition it is reinjected in the central stage and the current is incremented. The following scattering mechanisms are accounted for: polar optic and acoustic phonons, alloy disorder, impurity, and carrier-carrier.
Electromagnetic modes and photonic density of states could be obtained from electromagnetic simulation of the resonant cavity. For the moment, we take the results from the existing literature. We account for the following events that photons can encounter: emission (spontaneous or stimulated) and absorption by electrons, annihilation (optical losses), escape from the cavity (contribution to the emitted laser light).
An important feature of the model is the use of a special weighting procedure that allows us to cope with the enormous variation in the number of photons. The weight of electrons and photons, thereafter denoted as α_e and α_p respectively, can here be simply defined as the number of real particles corresponding to one simulated particle. α_e is kept constant whereas α_p varies as a function of photon population P. When the cavity is empty or contains only a few photons $\alpha_p = 1$. When P is large, α_p is varied so that the number of simulated particles remains fixed to a given value. In the treatment of electron-photon interaction, the difference in the weight of the two kinds of particles is counterbalanced by a rejection technique.

3 Results

As a first example, we have considered a “resonant phonon” QCL structure designed to operate at 3.4 THz [6, 7]. We have assumed that the resonator is a simple Fabry Perot of dimensions $1.22\,\mathrm{mm} \times 23\,\mu\mathrm{m}$ and we have considered a strict monomode operation. The optical losses have been assumed to correspond to a photon lifetime in the cavity $\tau_p = 10\,\mathrm{ps}$.
To begin with, we have investigated the turn-on dynamics of the laser. Fig. 1 shows the evolution of electron population inversion ΔN and photon population P for two different ”simulated experiences”, *i.e.* two different sequences of random numbers, assuming initial conditions $P = 0$, $\Delta N = 0$. We see that electron population inversion is established in less than 10 ps whereas the build-up of photon population takes more than 50 ps. Moreover, this ”laser delay time”τ_d is affected by a large statistical dispersion. This is because, as is well known, laser operation starts from spontaneous emissions occurring randomly in the initially empty cavity. In the initial stage, emissions are rare events and this results in a very noisy behaviour of photon population and leads to large fluctuations of τ_d.
We have then investigated the response of the laser to a modulation of either (*i*) optical losses or (*ii*) pump current, illustrated by Fig. 2 and 3 respectively.
In case (*i*), we have considered that the photon lifetime in cavity changes abruptly from $\tau_p = 10\,\mathrm{ps}$ (low optical losses) to 0.1 ps (high optical losses). We have not observed any kind of overshoot of light intensity or relaxation oscillations. This is consistent with previous reports and is explained by the fast response of the electron gas [8]. The laser

response is clearly affected by the delay time τ_d, which is here non-negligible compared to the period and presents some statistical dispersion.

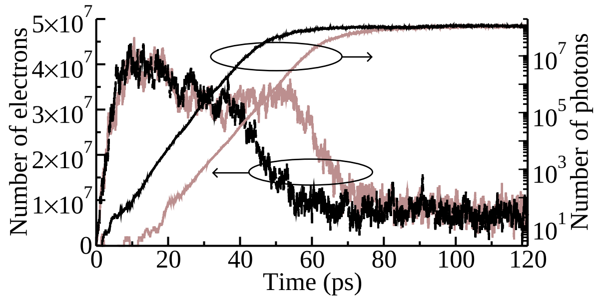

Figure 1: Time evolution of electron population inversion and photon number for two different simulated experiments. The considered device is the QCL of Ref. [6] and the temperature is $\theta = 44$K.

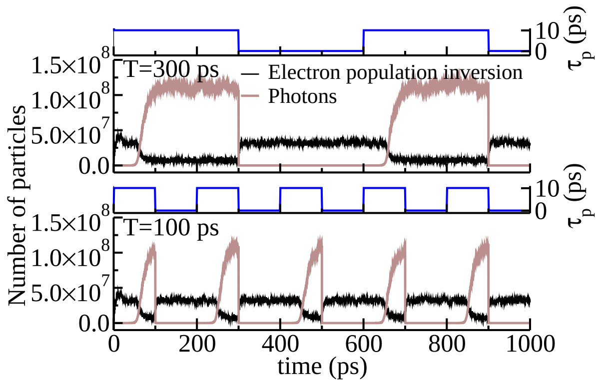

Figure 2: Time evolution of population inversion and photon number in response to a periodic modulation of the photon lifetime in cavity τ_p. (same device as in Fig. 1)

In case (*ii*), we have considered that the current is abruptly switched from an above-threshold value to zero. For simplicity we have assumed that the applied voltage, and thus conduction band profile and electron states, are kept unchanged. Once again, one observes that electron population inversion responds very fast whereas photon number varies on longer time scales: laser delay time for switching on and photon lifetime for switching off. We have also considered the interesting case of a very high frequency modulation (33 GHz). In that case, the period of the signal is of the same order as the laser delay time τ_d. We observe a slight reduction of the maximum value of the photon number. During the first periods, the laser does not start at all, because the "on-state" of the current does not last long enough. However, once the photon population has built

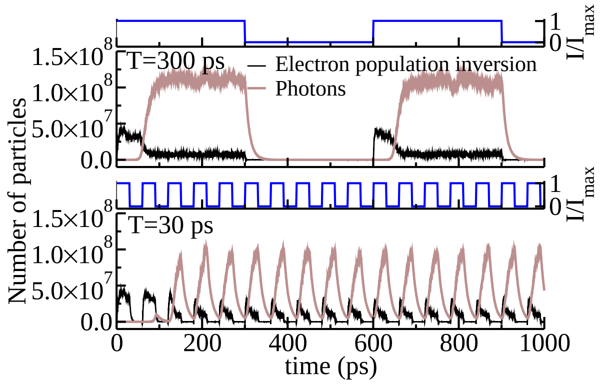

Figure 3: Time response of to a periodic modulation of the injected current I, which is switched from an above-threshold value I_{max} to 0. (same device as in Fig. 1)

up, it does not return to zero because the current never remains off for long enough, therefore the turn-on delay time does not come into play anymore.

4 Conclusion

We have developed a Monte Carlo simulator of QCLs that treats electrons and photons on the same footing. We have used it to investigate the time-dependent operation of a terahertz QCL. We have verified that electrons evolve much faster than photons. We have also found that the main factor that slows down the laser response is the "delay time" related to spontaneous emission.

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