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Original research article

Circuit-level modeling of quantum cascade lasers: Influence of Kerr effect on static and dynamic responses

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ABSTRACT

The three-level rate-equations-based QCL models, considering the Kerr nonlinearity term, possess multiple DC solution regimes for nonnegative values of injection currents. We show that by giving the proper initial conditions, the DC bias point simulation results of the proposed QCL circuit-level model will converge to the physical positive output powers. We also show that the proposed model can accurately predict the influence of the Kerr effect on static and dynamic behaviors of the QCLs.

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1. Introduction

The quantum cascade lasers (QCLs) have gained widespread attention due to their small sizes, large intensity modulation bandwidth, narrow linewidth, high operating temperatures and robust fabrication [1–3]. These advantages make them attractive for different applications, such as chemical sensors [4], anesthetic gas detecting, pollution monitoring, free-space optical communication systems, infrared spectroscopy [5], and so on. The operation of QCLs can be modeled and analyzed numerically using the multi-level rate-equations-based theoretical models. The used numerical approaches are accurate, but very computationally intensive and aren't suitable for system-level designs and optimizations. Instead, it is possible to form a rate-equations-based equivalent circuit model and reduce drastically the complexity of the analysis [6–11]. We have shown that in the equivalent circuit model of QCLs, which are based on three-level rate-equations, considering the Kerr nonlinearity term, multiple solution regimes are obtained. It has been shown that the optical Kerr nonlinearity in QCLs can lead to some significant issues, such as mode locking and photon number dependency of the losses, hence, studies of QCL with optical Kerr nonlinearity are very important [12]. In this investigation, we propose a new equivalent circuit model for QCLs based on three-level rate-equations, which can predict the influence of the Kerr nonlinearity on the QCLs operations. We show that by giving the initial conditions, which can be obtained from a DC sweep simulation or an analytical expression, the proposed model can be used for both steady-state and dynamic responses. The proposed model is verified using the analytical and also numerical results from hamadou et al. [12] for the dynamics of electrons, in different energy levels, and photons in the cavity. The simulation results show an excellent agreement in all the comparisons. The paper is organized as follows: In Section II, the solution regimes of a three-level rate-equations-based model of the QCLs, considering the influence

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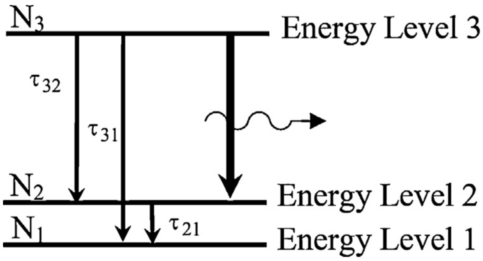

Fig. 1. Schematic of a three-level QCL.

Table 1
The used parametres for evaluating the solution regimes of the three-level rate-equations of the QCLs. The model parameters are from Hamadou et al. [12].

Symbol	Description	Value
τ_{32}	Lifetimes representing the transitions from level 3 to 2	2.1×10^{-12} (s)
τ_{31}	Lifetimes representing the transitions from level 3 to 1	4.2×10^{-12} (s)
τ_{21}	Lifetimes representing the transitions from level 2 to 1	3×10^{-13} (s)
τ_{sp}	Spontaneous lifetime between level 3 and 2	3.55×10^{-9} (s)
τ_{out}	Electron escape time	10^{-12} (s)
τ_p	Photon lifetime	3.36×10^{-12}(s)
τ_3	Electron lifetime in the upper level	1.4×10^{-12} (s)
η_0	Power output coupling efficiency	0.19136
λ	Free space wavelength	9×10^{-6} (m)
N	Number of gain stages	48
L	Lateral length of the cavity	10^{-3} (m)
R_1	Reflecting power of facets 1	0.29
R_2	Reflecting power of facets 2	0.29
n_{eff}	Effective refractive index of the cavity	3.27
G	Gain coefficient per stage	744 (1/s)
β	Fraction of spontaneous emission entering into lasing mode	2×10^{-3}
I_{th}	Threshold current	1.1108 (A)
α_m	Mirrors loss	1240 (1/m)
α_w	Waveguide loss of the cavity	2000 (1/m)

of Kerr nonlinearity, is presented. In Section III, the derivation and verification of the proposed equivalent circuit model of QCLs, that is based on the three-level rate-equations, with adding Kerr nonlinearity term, is demonstrated.

2. Solution regimes of the three-level rate-equations-based model of the QCLs, considering the influence of Kerr effect

The rate equations of a three-level QCL, corresponding to Fig. 1, can be described in terms of the following three first-order differential equations [12–14]

$$\frac{dN_3}{dt} = \frac{I}{e} - \frac{N_3}{\tau_3} - (N_3 - N_2)GN_{ph}, \tag{1}$$

$$\frac{dN_2}{dt} = \left(\frac{1}{\tau_{32}} + \frac{1}{\tau_{sp}}\right)N_3 - \frac{N_2}{\tau_{21}} + (N_3 - N_2)GN_{ph}, \tag{2}$$

$$\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{out}}, \tag{3}$$

$$\frac{dN_{ph}}{dt} = N(N_3 - N_2)GN_{ph} + N\beta\frac{N_3}{\tau_{sp}} - \frac{N_{ph}}{\tau_p}(1 - \gamma_0 N_{ph}), \tag{4}$$

where N_1, N_2 and N_3 are the instantaneous numbers of electrons in energy level 3, i.e. the upper lasing state, energy level 2, i.e. the lower lasing state, and energy levels 1, i.e. the ground state, respectively. N_{ph} denotes the photon numbers in the cavity, N is the number of cascade stages, G is the gain coefficient, and γ_0 is the dimensionless coefficient, which describes the magnitude of nonlinear effects. β denotes the spontaneous emission coupling coefficient, e is the magnitude of electronic charge and I is the injection current. τ_{32}, τ_{31} and τ_{21} are the lifetimes representing the transitions from level 3 to 1, 3 to 2 and 2 to 1, respectively, and τ_{out} represents the electron escape time between two adjacent stages. τ_{sp} denotes the radiative spontaneous relaxation time between levels 3 and 2, and τ_3 is the electron lifetime in the upper level and is given by $1/\tau_3 = 1/\tau_{32} + 1/\tau_{31} + 1/\tau_{sp}$. Furthermore, τ_p is photon lifetime that can be expressed as $\tau_p = (c'(\alpha_w + \alpha_m))^{-1}$, where α_w and α_m are the losses of waveguide cavity and mirrors, respectively, and $c' = c/n_{eff}$ is the average velocity of light in the

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