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An equivalent circuit-level model for dual-wavelength quantum cascade lasers

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ABSTRACT

We introduce an equivalent circuit model for dual-wavelength quantum cascade lasers (QCLs) using the four-level rate-equations. We examine the validity of the proposed circuit model by comparing the simulated results with the theoretical results available in the literatures. By using the proposed equivalent circuit-level model, the effects of injection current on dual-wavelength QCL static and dynamic behaviors are investigated. We show that the proposed circuit-level model can accurately predict the operating characteristics of the dual-wavelength QCLs.

1. Introduction

The quantum cascade lasers (QCL) are optical sources with small sizes, large intensity modulation bandwidth, narrow linewidth and high operating temperatures [1–4]. They are attractive for different applications, such as chemical sensors [5], pollution monitoring, environmental sensing [6], free space optical communication systems, coherent applications, infrared spectroscopy [7], and so on. Recently, the multi-wavelength QCLs has attracted much attention mainly due to potential applications in areas such as trace-gases sensing [8], ranging (LIDAR) [8,9], generation of terahertz radiation using of nonlinear mixing of two wavelengths [10]. The numerical approaches used to analyze the multi-level rate-equations of QCLs are accurate, but very computationally intensive. Thus, these models aren't suitable for system-level designs and optimizations. Instead, it is possible to form an equivalent circuit-level model and reduce drastically the complexity of the analysis. Actually, the most important advantage of the laser circuit-level modeling is that it allows a complete simulation of lasers embedded in electronic circuits. In this paper, we propose an equivalent circuit-level model for dual-wavelength QCLs based on a transformed four-level rate-equations. The proposed model, for any arbitrary initial conditions, can be used for both steady-state and dynamic responses. The proposed model is verified using analytical results from hamadou et al. [11] for the steady state and transition time responses. The simulation results show an excellent agreement in all the comparisons. Furthermore, using the proposed circuit model the modulation responses of the both modes in different operatiing regions are investigated. The paper is organized as follows: In Section 2, the standard four-level rate-equations-based model of the dual-wavelength QCLs is presented. In Section 3, the derivation of the equivalent circuit-level model based on the transformed four-level rate-equations is demonstrated. Verification of presented dual-wavelength QCL circuit-level model is presented in Section 4.

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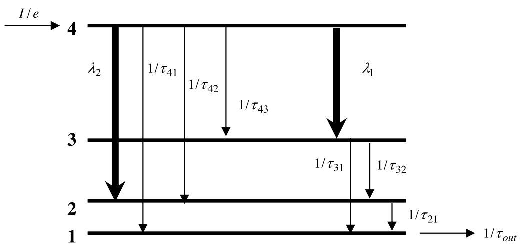

Fig. 1. Schematic structure of energy levels in a dual-wavelength QCL.

2. The four-level rate-equations-based model of the QCLs

The four-level model system of the bound to continuum stage in a dual-wavelength QCL is shown schematically in Fig. 1. The dynamics of carrier and photon numbers in a four-level QCL, neglecting optical nonlinearities, can be described in terms of the following six first-order differential equations [11]

$$\frac{dN_4}{dt}=\frac{I}{e}-\frac{N_4}{\tau_4}-\Gamma^{(1)}\frac{c'\sigma^{(1)}}{V}(N_4-N_3)S^{(1)}-\Gamma^{(2)}\frac{c'\sigma^{(2)}}{V}(N_4-N_3)S^{(2)}, \tag{1}$$

$$\frac{dN_3}{dt}=\frac{N_4}{\tau_{43}}-\frac{N_3}{\tau_3}+\Gamma^{(1)}\frac{c'\sigma^{(1)}}{V}(N_4-N_3)S^{(1)}, \tag{2}$$

$$\frac{dN_2}{dt}=\frac{N_4}{\tau_{43}}-\frac{N_3}{\tau_{32}}-\frac{N_2}{\tau_{21}}+\Gamma^{(2)}\frac{c'\sigma^{(2)}}{V}(N_4-N_3)S^{(2)}, \tag{3}$$

$$\frac{dN_1}{dt}=\frac{N_4}{\tau_{41}}+\frac{N_3}{\tau_{31}}+\frac{N_2}{\tau_{21}}-\frac{N_1}{\tau_{out}}, \tag{4}$$

$$\frac{dS^{(1)}}{dt}=N_P\Gamma^{(1)}\frac{c'\sigma^{(1)}}{V}(N_4-N_3)S^{(1)}-\frac{S^{(1)}}{\tau_p^{(1)}}+N_p\beta^{(1)}\frac{N_4}{\tau_{sp}^{(1)}} \quad \text{and} \tag{5}$$

$$\frac{dS^{(2)}}{dt}=N_P\Gamma^{(1)}\frac{c'\sigma^{(2)}}{V}(N_4-N_3)S^{(2)}-\frac{S^{(2)}}{\tau_p^{(2)}}+N_p\beta^{(2)}\frac{N_4}{\tau_{sp}^{(2)}}, \tag{6}$$

where N_1, N_2, N_3 and N_4 are the instantaneous numbers of electrons in each of the four levels, respectively, $S^{(1)}$ and $S^{(2)}$ denote the photon numbers for modes 1 of wavelength λ_1 and 2 of wavelength λ_2, respectively. V denotes the whole volume of the active region, e is the magnitude of electronic charge, and I is the injection current. Furthermore, $\Gamma^{(i)}$ is the mode confinement factor for wavelengths λ_i (i = 1, 2), $c' = c/n_{eff}$ is the average velocity of light in the system, in which n_{eff} and c are the effective refractive index of the cavity and the speed of light in vacuum, respectively. In addition, $\beta^{(i)}$ define the respective proportions of spontaneous emission when a photon is emitted into the corresponding cavity mode and $\sigma^{(i)}$ represent the stimulated emission cross section for the transition corresponding to wavelengths λ_i and are given by

$$\sigma^{(i)}=\frac{4\pi(ez^{(i)})^2}{\varepsilon_0 n_{eff}\lambda_{(i)}(2\gamma^{(i)})},\quad i=1,\ 2 \tag{7}$$

where $ez^{(i)}$ are the dipole matrix elements of the transition i, ε_0 is the vacuum permittivity and $2\gamma^{(i)}$ represent the full-width at half maximum (FWHM) of the respective electroluminescence spectrum for transition i. In the above equations, τ_{43}, τ_{42}, τ_{41}, τ_{32}, τ_{31} and τ_{21} are non-radiative scattering times due to LO-phonon emission, τ_{out} represents the electron escape time between two adjacent stages and $\tau_{sp}^{(i)}$ are radiative spontaneous relaxation times for both involved transitions and are given by

$$\frac{1}{\tau_{sp}^{(i)}}=\frac{8\pi^2 n_{eff}(ez^{(i)})^2}{\varepsilon_0\hbar\lambda_{(i)}^3},\ i=1,\ 2 \tag{8}$$

where $\hbar$ is the reduced Plank constant. Furthermore, τ_3 and τ_4 are introduced as $1/\tau_4=1/\tau_{43}+1/\tau_{42}+1/\tau_{42}$ and $1/\tau_3=1/\tau_{32}+1/\tau_{31}$, respectively. $\tau_p^{(i)}$ are the photon lifetimes that can be expressed as $\tau_p^{(i)}=\left(c'(\alpha_w^{(i)}+\alpha_m^{(i)})\right)^{-1}$, where $\alpha_w^{(i)}$ and $\alpha_m^{(i)}$ are the losses of waveguide cavity and mirrors, respectively. The mirrors loss can be given by $\alpha_m^{(i)}=-\ln(R_1^{(i)}R_2^{(i)})/(2L)$, where $R_1^{(i)}$ and $R_2^{(i)}$ are the reflectivity of the facets 1 and 2, respectively, and L is the lateral length of the cavity.