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Original research article

Particle Swarm Optimization approach to identify optimum electrical pulse characteristics for efficient Gain Switching in Dual Wavelength Quantum Cascade Lasers

P. Ashok*, M. Ganesh Madhan

Department of Electronics Engineering, Madras Institute of Technology, Anna University, Chennai, India

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ABSTRACT

Numerical simulation of Gain Switching in Dual Wavelength QCLs (DW-QCLs) for short pulse generation in the mid-Infrared region is reported. A four-level rate equation model is used to investigate the QCL which consists of 48 periods of injector and active regions, emitting at 10.5 µm and 8.9 µm. The device is simulated for various inputs such as square, haversine and tangential hyperbolic electrical pulses. The optimum parameters of electrical pulse pertaining to generation of short pulses with maximum power and minimum pulse width for single wavelength and simultaneously at both wavelengths are determined using Particle Swarm Optimization (PSO) technique. The physical nature of drive current and its time period dictates the duration and peak power in both the wavelengths. It is found that square pulse of amplitude 11.12 mA and 0.1 ns produces short optical pulses of width 15.89 ps with peak power of 2.2 mW at 10.5 µm. Similarly, short optical pulses with peak power 1.8 mW and width 15.92 ps are generated by square pulse of amplitude 13.12 mA at 8.9 µm. It is also observed that tangential hyperbolic pulse of amplitude 10.79 mA and 8.47 mA produces short optical pulses with equal power and equal pulse width respectively in both the wavelengths at 0.1 ns.

1. Introduction

Multi-wavelength operation of Quantum Cascade Lasers (QCLs) have been more attractive in the recent years due to many potential applications. The two main features which are unique to QCLs are unipolarity (optical transition between sub bands) and a cascading scheme (electron recycling to produce more photons per electron). The first demonstration of a QCL was reported in 1994 from Bell Laboratories using an $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ heterostructure [1]. A cascade inter-sub band laser operating at 830 nm was demonstrated by Garcia et al. [2] in 1997. Multistage cascade scheme is evident in QCLs where electrons recycled from period to period contribute every time to gain and photon emission. Each electron injected above threshold generates photons proportional to the number of stages leading to differential efficiency and hence the optical power is proportional to the number of stages. There is no dependence of band gap on the emission wavelength in QCLs. Various models for the design of QCLs have been investigated [3–9]. An in-depth study on the impact of device parameters on the performance of QCLs was reported by Ashok et al. [10].

Numerous short pulse generation techniques are available for semiconductor lasers namely gain switching, external modulation and mode locking [11,12]. Among the various methods, gain switching is preferred for its compactness, efficiency and ease of current

* Corresponding author.
E-mail addresses: ashokp2k4@gmail.com (A. P.), mganesh@annauniv.edu (G.M. M.).

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injection [13,14]. Gain switching generates short pulses by impressing a periodic electrical modulation on a DC biased semiconductor laser diode without the need for high speed external modulator [15,16]. Lin et al. [17–20] generated 50 ps short pulses by fast gain switching in simple injection lasers using an impulse comb generator. By injecting 4.4 GHz sinusoidal signal to a DFB laser, Takada et al. [21] generated short pulses of 30 ps width. Jukam et al. [22], Jianfeng et al. [23] and Capasso et al. [24] devised various experimental methods to generate short pulses by gain switching in QCLs. A detailed investigation of gain switching based optimum short optical pulse generation in QCLs is presented in [25]. Rate equation-based modelling [26] is most commonly used for analysis of DW-QCLs. Alternatively, equivalent circuit model for DW-QCLs is also devised by Mohsen et al. [27]. Multi-wavelength QCLs are mainly used in applications such as trace-gases sensing, LIDAR based ranging and non-linear mixing of two wavelengths to generate terahertz radiation. The device considered for the study is a 48-stage mid infrared DW-QCL emitting at two wavelengths 10.5 μm and 8.9 μm respectively. The device operates in single mode and bi-mode with threshold current of 5.5 mA and 8.25 mA respectively. The rate equations of DW-QCL are numerically solved by Runge Kutta method using ODE solver in MATLAB, to study gain switching.

PSO is a computational method that optimizes a problem by iteratively improving a solution with regard to a given measure of quality [28]. It solves a problem by having a population of candidate solutions, called as particles, and moving these particles around in the search-space to provide the best solution. Each particle's movement is influenced by its local best-known position, but is also guided toward the best-known positions in the search-space, which are updated as better positions, found by other particles. This is expected to move the swarm towards the best solution. To improve the convergence accuracy, a double potential well and share-learning is proposed by Su-hui Xu et al. in [29]. PSO is also used to enhance the accuracy of determining the relationship between RFID signals and position of a tag in RFID based positioning system as in [30]. The usage of PSO is visible in non-linear dynamic systems as in [31]. PSO based optimization of nano-particles shape and size has been implemented in [32]. PSO algorithm has been updated with adaptive mutation with dynamic non-linear changed inertia weight as in [33]. Even though various applications of PSO are reported in the literature, this approach to identify the optimum electrical pulse characteristics for dual wavelength gain switching process in a QCL has not been carried out so far. The paper is organized as follows. Section 2 explains the DW-QCL structure and analysis of transient and steady state responses. Section 3 provides the analysis on the gain switching based time evolution of the electron distribution in different levels and the optical power output in the cavity for various electrical drive signals under bi-mode lasing region. Section 4 summarizes the findings of the PSO based optimization of Gain Switching in DW-QCLs. Section 5 concludes the findings.

2. Gain Switching in DW-QCLs

2.1. DW-QCL structure

A four-level model is used to characterize DW-QCLs operating simultaneously on two laser lines having a common upper level. Fig. 1 shows the energy-level diagram of one stage of the active region. The upper and lower states for emission at $\lambda_1 = 10.5\,\mu m$ will be levels 4 and 3 respectively while those for $\lambda_2 = 8.9\,\mu m$ will be levels 4 and 2 respectively. It is interesting to note that inter-subband phonon scattering also occurs between levels 4 and 1, 4 and 2, 4 and 3. The active region is stacked up into two stages. The first stage uses double phonon resonance design [34–36] while the second stage is based on bound to continuum design [8,36], with the free space emission wavelength designated as λ_1 and λ_2.

DW-QCLs are modeled using four-level rate equations neglecting optical non-linearities [27]. They are as follows:

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

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

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

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

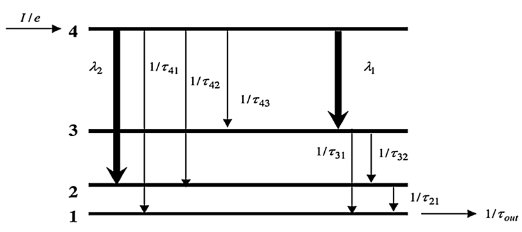

Fig. 1. Four-level model system of DW-QCLs [26].