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Tuning a conventional quantum well laser by nonresonant laser field dressing of the active layer

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ABSTRACT

Tunable semiconductor lasers may be considered as a critical technology for optical communications. We investigate the theoretical feasibility of tuning a conventional GaAs/Al$_{0.2}$Ga$_{0.8}$As quantum well laser emitting at 825 nm by non-resonant laser-dressing of the active layer. Conduction and valence subbands are sensitive to the intense dressing field and this effect can be used to blueshift the active interband transition. The laser-dressed electron and hole states are calculated in the effective mass approximation by using the finite difference method. Emitted wavelength, threshold current and characteristic temperature are discussed as functions of the dressing laser parameter and cavity length.

1. Introduction

Achieving frequency tuning in semiconductor laser systems is not a trivial task [1]. In the last decades, several types of tunable semiconductor lasers (TSLs) have been designed and commercialized, such as the selectable distributed-feedback (DFB) array, grating-coupled external-cavity (GCEC) laser, vertical-cavity surface-emitting laser with external micro-electromechanical mirror (MEMs/VCSEL), grating-coupled sampled-reflector (GCSR), sampled-grating distributed-Bragg-reflector (SGDBR) [2] or integrated ring mode-locked lasers [3]. All these lasers are based on some additional mode selection systems, therefore being less suitable for a high-speed tuning of the frequency. Instead of selecting a single frequency from a multimodal emission spectra, one may imagine a method for actively changing the band gap of the semiconductor. Generally the band gap depends on the chemistry of the composed semiconductor, and much less on various physical conditions, such as temperature, pressure and external static or dynamic fields. However, in low-dimensional materials, such as semiconductor quantum wells (QWs), wires (QWWs) and dots (QDs), the effective bandgap exceeds the bandgap of the bulk semiconductor by some quantity much more susceptible to be changed by the structure geometry and external factors [4]. This extra energy is due to the quantization of the carrier dynamics in the nanostructures. For example, the single mode quantum laser diodes operate at a precise frequency and the emission wavelength is determined by the effective bandgap of the quantum well [5]. The effective bandgap depends on the discreet energy levels of the carriers in the QW and can be modified by changing the quantum well width in the fabrication process or actively by using external fields. The electrons and holes energy levels may be shifted by intense fields, for example by quantum confined Stark effect [6]. There are other interesting processes as well, involving not static but dynamical fields and our work will make use of such an effect, known as the laser-dressing of the quantum wells. The dressing of the electronic states in a quantum structure means a modification of the energies and wave functions of the confined electrons under a non-resonant intense laser radiation [7–9]. We will demonstrate that in a QW laser's active layer the effective band gap could be actively modified by a non-resonant laser-dressing of the subband states. This implies the possibility of tuning the emission wavelength of the QW laser in real time by changing the intensity of the dressing radiation. Such an optoelectronic system would lead to very interesting applications, such as accordable semiconductor laser sources and fast optical modulators capable to "translate" an intensity-modulated optical signal into a frequency-modulated one.

We consider a conventional QW laser grown by an epitaxial method on a GaAs substrate. The cladding layers are made of Al$_{0.4}$Ga$_{0.6}$As, the optical confinement layer (OCL) material is Al$_{0.2}$Ga$_{0.8}$As and the active layer is a GaAs square quantum well (SQW) [10] (Fig. 1). In the absence of external fields, the confinement potentials for electrons and holes have the typical square shape (black curves). If the semiconductor heterostructure is irradiated with a THz non-resonant intense laser field (ILF), it has

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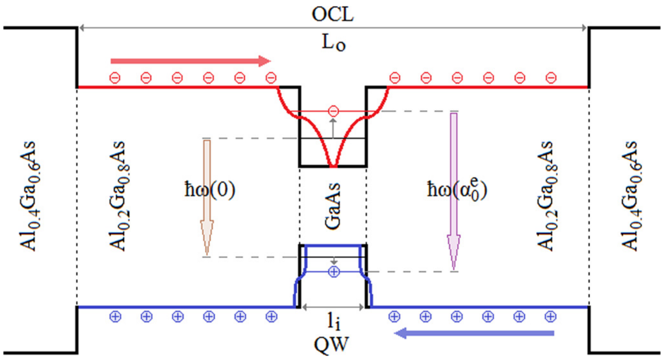

Fig. 1. (Color online) Schematic of a GaAs/$Al_{0.2}Ga_{0.8}$As quantum well structure under intense laser field. QW denotes the active layer and OCL is the optical confinement layer. Dressed confinement potentials of the electron (red line) and hole (blue line) are illustrated.

been stated [11] that the electrons and holes will "see" different time-averaged laser-dressed confinement potentials (red and blue curves, respectively). The conduction subbands of the QW will be raised in energy by the increase of the laser dressing parameter α_0^e (see theory section), while the valence subbands will be lowered. As a direct consequence, the effective band-gap of the nano-heterostructure will be increased by the ILF and the active optical interband transition (IBT) of the QW laser will be blue-shifted: $\hbar\omega(\alpha_0^e) > \hbar\omega(0)$. Since the dressing laser parameter depends not only on the frequency Ω but also on the intensity I_d of the driving laser, one may obtain a significant tunability of the QW laser by modulating the amplitude of the ILF.

We will calculate/discuss the wavelength range of tunability, saturation modal gain, radiative recombination inside and outside the active region, lasing condition and lasing threshold density of carriers. We will present threshold current density and characteristic temperature of the QW laser as functions of the emitted wavelength and laser cavity length. It should be mentioned that our work is based on a very simple prototype of QW laser since its aim is not to discuss the efficient design of semiconductor lasers but to propose a method for achieving tunability of such devices. Conventional QW lasers may be significantly improved by bandedge-engineering as it was shown by several authors [10,12]. Therefore the principle exposed in the current study is expected to be further extended and generalized for more complex and efficient laser devices.

The paper is organized as follows. In Section 2 the theoretical framework is described. Section 3 is dedicated to the results and discussion, and finally, our conclusions are summarized in Section 4.

2. Theoretical framework

2.1. Laser-dressed electronic states in the QW

We assume an electron (e) or a heavy hole (h) subjected to the confinement potential of a square quantum well (SQW):

$$V_{e(h)}(z) = V^0_{c(v)}\Theta\big(|z| - l_i/2\big), \tag{1}$$

where $V^0_{c(v)}$ is the conduction (valence) band off-set, Θ is the Heaviside step function and l_i is the QW width (Fig. 1). The carrier is also under the action of a nonresonant laser field of frequency Ω, linearly polarized on the growing direction of the QW, described by the vector potential $A_z(t) = A_0\cos(\Omega t)$. We will further denote by $\mp e$ and $m^*_{e(h)}$ the electric charge and the effective mass of the electron (hole), respectively. By using the translations $z \to z \pm eA_z(t)/(m^*_{e(h)}\Omega)$ in the time-dependent Schrödinger equation describing the interaction dynamics:

$$\left\{-\frac{\hbar^2}{2m^*_{e(h)}}\left[\frac{\partial}{\partial z} \pm i\frac{eA_z(t)}{\hbar}\right]^2 + V_{e(h)}(z)\right\}\psi(z,t) = i\hbar\frac{\partial}{\partial t}\psi(z,t), \tag{2}$$

the temporal dependence may be transferred from the kinetic energy operator to the potential energy term [13]:

$$\left\{-\frac{\hbar^2}{2m^*_{e(h)}}\frac{\partial^2}{\partial z^2} + V_{e(h)}\big(z \pm \alpha^0_{e(h)}\sin(\Omega t)\big)\right\}\psi(z,t) = i\hbar\frac{\partial}{\partial t}\psi(z,t), \tag{3}$$

where $\alpha^0_{e(h)} = eA_0/(m^*_{e(h)}\Omega)$ is the laser-dressing parameter for the electron (hole). In the high-frequency limit [14,15] the laser-dressed eigenstates are solutions of the time-independent Schrödinger equation:

$$\left[-\frac{\hbar^2}{2m^*_{e(h)}}\frac{\partial^2}{\partial z^2} + V^d_{e(h)}(z)\right]\phi(z) = E\phi(z), \tag{4}$$

where $V^d_{e(h)}(z)$ is the laser-dressed confining potential, with the general form [16]:

$$V^d_{e(h)}(z) = \frac{\Omega}{2\pi}\int_0^{2\pi} V_{e(h)}\big(z \pm \alpha^0_{e(h)}\sin\varphi\big)d\varphi. \tag{5}$$

For the SQW potential given by Eq. (1), it was shown that the integral in Eq. (5) can be analytically solved [17] to:

$$V^d_{e(h)}(z) = \frac{V^0_{c(v)}}{2\pi}\Re e\left\{\sum_{\sigma=\pm 1}\Theta\big(2\alpha^0_{e(h)} + 2\sigma z - l_i\big)\arccos\left(\frac{l_i - 2\sigma z}{2\alpha^0_{e(h)}}\right)\right\}. \tag{6}$$

In order to solve Eq. (4) with the potential given by Eq. (6), a finite difference method (FDM) will be used. We will denote by $E_1^{e(h)}$ the energies of the lowest electron (hole) subband edges in the QW, which will be functions of the laser dressing parameter. By noting that $\alpha_0^h = \alpha_0^e m_e^*/m_h^*$, we may use a single, more convenient dependence on α_0^e, for all quantities which are dependent on the laser dressing. Therefore, the IBT energy in the QW will be written as:

$$E_i(\alpha_0^e) = E_g^i + E_1^e(\alpha_0^e) + E_1^h(\alpha_0^e), \tag{7}$$

where E_g^i is the bandgap of the QW material (we will further denote by $E_g^o = E_g^i + V_c^0 + V_v^0$ the bandgap of the barrier material).

It is known that the laser-dressing of the confinement potential of a QW induces a delocalization of the carriers [18]. Thus, the probability of finding the electron (hole) inside the QW:

$$P_1^{e(h)}(\alpha_o^e) = \int_{-l_{QW}/2}^{+l_{QW}/2}\big|\phi_1^{e(h)}(z)\big|^2 dz \tag{8}$$

will depend on the laser parameter. Here, by $\phi_1^{e(h)}(z)$ we denote the first subband wave functions of the electron (hole).

The overlap integral of the ground state wave functions of the electron and hole [19,20] will also be an implicit function of α_o^e:

$$I_{eh}(\alpha_o^e) = \int_{-\infty}^{+\infty}\phi_1^e(z)\phi_1^h(z)dz. \tag{9}$$