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Analysis of strain effects on the dynamic spectra of a quantum well semiconductor optical amplifier using quantum well transmission line modelling method

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ABSTRACT

This paper studies the strain (i.e. compressive (CS) and tensile (TS)) effects on the dynamic spectra of an amplified femtosecond pulse in a quantum well semiconductor optical amplifier (QW-SOA) using quantum well transmission line modelling (QW-TLM) method. Based on the analysis of band structure, the gain spectrum as well as the spontaneous spectrum of quantum well (QW) in the CS, unstrained (US) and TS are investigated using QW-TLM and it was found that in the CS QW, the magnitude ratio of the gain spectrum and the spontaneous emission spectrum is the largest. Furthermore, QW-TLM is adopted to investigate the dynamic spectral evolution of femtosecond pulse amplification in QW-SOAs and it was found that as the femtosecond pulse approaches the amplifier output, the centre frequency of the amplified femtosecond pulse spectra decreases and its bandwidth decreases. The output spectra of the amplified femtosecond pulse in QW amplifiers under the CS, US and TS cases are compared and the simulation results show that in a CS QW-SOA the spectral shape exhibits the largest magnitude and the smallest fluctuation due to the largest gain and the largest ratio between the gain and noise.

1. Introduction

Quantum well semiconductor optical amplifiers have been studied for applications in the long haul optical communications and all optical signal processing technology due to the small size, direct current pumping and wide nonlinear effects [1–6]. Compared with bulk SOAs, the increased dimensional confinement of carriers in the active region of QW amplifiers can reduce the gain recovery time [7,8]. Since the coupling among the heavy hole band, light hole band and the spin–orbit spilt-off band in the presence of strain becomes strong, the strain has a significant influence on the band structure and the refractive index of QW amplifiers. Existing theoretical and experimental work shows that both compressively stained (CS) and tensile strained (TS) QW amplifiers have superior characteristics as compared with the unstrained (US) QW amplifiers [9–11]. Some previous work studied the dynamic temporal and spectral characteristics of QW structures using the analytical expression method. The strain effects on the dynamic gain spectra in quantum well lasers were studied using the carrier and photon rate equations [12–14] and it was found that the bi-axial strain can effectively improve the gain characteristics and reduce the threshold current of quantum well lasers. The optical signal amplification in strained QW amplifiers suffers from the gain saturation effects [15–19], which leads to the temporal and spectral distortion due to the dynamic variations of the gain and spontaneous emission spectrum. In addition, many body effects induced by the carrier Coulomb interaction influences the gain and spontaneous emission spectra of strained quantum wells [20,21].

The quantum well transmission line modelling (QW-TLM) method [22] is an effective technique for analysis of semiconductor optical devices. It is based on the actual physical process of photon–electron interaction within the cavity which can be used to accurately study the properties of semiconductor optical devices both in the time and frequency domain. In the QW-TLM method, the electron transitions from the conduction band to the valence band in the wave vector space are represented by the parallel QW-TLM units. In each QW-TLM unit, two parallel RLC stub filters and the corresponding weight coefficients are adopted to model the electron transitions from the conduction band to the heavy hole band and the light hole band at a given vector. The method can provide the accurate description of optical processes by modelling the electron transition in semiconductor optical devices.

In this paper, the QW-TLM method is used to establish a model

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for strained QW amplifiers. The model consists of transmission line, transmission coefficient, spontaneous emission source and scattering module. The spontaneous emission and stimulated emission processes in QW amplifiers are represented by the spontaneous emission source and the scattering module. The band structures of QW amplifiers in the CS, US and TS cases have been analysed by considering the strain-dependent coupling between the heavy hole band, light hole band and spin–spilt off band. The different distributions of valence sub-bands are compared. The gain spectrum of the scattering module and the spontaneous emission spectrum of the spontaneous emission source in the model are obtained and compared in both strained and US cases. The evolution of the dynamic spectral shape of an amplified femto-second pulse along the amplifier cavity in the presence of compressive strain has been further investigated. Also, effects of strain on the output spectra of the amplified femto-second pulse have been studied based on QW-TLM.

The following paper is organized as: The theoretical model is introduced in Section 2. The strain effect on the band structure, gain and spontaneous emission spectrum of quantum well using QW-TLM is presented in Section 3. Comparisons of the dynamic spectra of the amplified pulse in the presence of CS, US and TS QW amplifiers are explained in Section 4 and conclusion is given in Section 5.

2. Theory

Fig. 1 shows the structure of the QW amplifiers model based on QW-TLM. The amplifier model is divided into m sections, each of which consists of scattering module, spontaneous emission source, transmission line and transmission coefficient α.

The input signal electric field $E_1(z, t)$ and that of the amplified spontaneous emission $E_2(z, t)$ propagate along the transmission line and arrive at the scattering module where the electric field stimulates the electron transitions. The spontaneous emission source and the scattering module describe the photon spontaneous and stimulated emissions processes. The internal structure of the scattering module is shown in Fig. 2.

In the scattering module, the input electric field $E_{in}(z, t)$ is converted into the input voltage signal V_{in} by the equation

$$V_{in} = E_{in}(z, t)\Delta L \tag{1}$$

where, ΔL is the length of the transmission line between two adjacent scattering modules. The input voltage propagates into the parallel QW-TLM units and scatters in the node of each stub filter. The amplified electric field $E_d(z, t)$ is obtained by the sum of the outputs of the parallel QW-TLM units multiplied by the gain coefficient G_0. The gain coefficient G_0 can be expressed as [23]:

$$G_0 = \frac{\Gamma q^2}{\pi h n_r c\varepsilon_0 m_0^2 L_z \gamma} \tag{2}$$

Where, Γ is the optical confinement factor, q is the magnitude of the electron charge, h is the Plank constant, c is the speed of light in free space, n_r and ε_0 are the refractive index and the permittivity in free space, m_0 is the electron rest mass in free space, L_z is the quantum well width, γ is the linewidth of the QW-SOA. The output electric field of the scattering module is given as

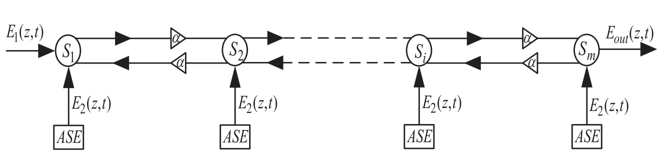

Fig. 1. The QW-TLM model.

$$E_{out}(z, t) = E_{in}(z, t) + E_d(z, t) \tag{3}$$

Each QW-TLM unit consists of two parallel RLC stub filters and the corresponding weight coefficients. In the ith QW-TLM unit, the first branch consists of the resistor Z_{ai}, the capacitor Z_{Cai} and the inductor Z_{Lai}, which are used to model the electron transition from the conduction band to the heavy hole band at a given wave vector while in the second branch the resistor Z_{bi}, capacitor Z_{Cbi} and inductor Z_{Lbi} are used to represent the electron transition from the conduction band to the light hole band at the wave vector $k_t(i)$. In the QW-TLM unit, the capacitors and inductors in the RLC filter have been modelled using the open-circuit and short-circuit transmission line [24]. The admittance expressions for the resistors (Y_{ai},Y_{bi}), capacitors (Y_{Cai},Y_{Cbi}) and inductors (Y_{Lai},Y_{Lbi}) can be expressed as [25]:

$$Y_{ai} = Y_{bi} = 1 \tag{4}$$

$$Y_{Cai} = \frac{1}{Z_{Cai}} = \frac{Q}{\tan(\pi f_1(k_t(i))\Delta T)} \tag{5}$$

$$Y_{Lai} = \frac{1}{Z_{Lai}} = Q\tan(\pi f_1(k_t(i))\Delta T) \tag{6}$$

$$Y_{Cbi} = \frac{1}{Z_{Cbi}} = \frac{Q}{\tan(\pi f_2(k_t(i))\Delta T)} \tag{7}$$

$$Y_{Lbi} = \frac{1}{Z_{Lbi}} = Q\tan(\pi f_2(k_t(i))\Delta T) \tag{8}$$

where

$$f_1(k_t(i)) = (E_n^c(k_t(i)) - E_{\sigma,m}^h(k_t(i)))/h \tag{9}$$

$$f_2(k_t(i)) = (E_n^c(k_t(i)) - E_{\sigma,m}^l(k_t(i)))/h \tag{10}$$

Q is the Q-factor of the stub filter, ΔT is the propagation time between two adjacent scattering modules ($\Delta T = 1/f_{sam}$ where f_{sam} is the sampling frequency), $E_n^c(k_t)$, $E_{\sigma,m}^h(k_t)$ and $E_{\sigma,m}^l(k_t)$ are the conduction band, the heavy hole band and the light hole band, respectively, which are obtained by solving the following Schrodinger equations [26,27]:

$$H^c\varphi_n(z;\, k_t) = E_n^c(k_t)\varphi_n(z;\, k_t) \tag{11}$$

$$\sum_{\upsilon=HH,LH} H_{3\times3,i\upsilon}^{\sigma} g_{m,\upsilon}^{\sigma}(z;\, k_t) = E_{\sigma,m}^{\upsilon}(k_t) g_{m,i}^{\sigma}(z;\, k_t) \tag{12}$$

where, H^c and $H_{3\times3,i\upsilon}^{\sigma}$ are the Hamiltonians for the conduction and valence bands, $\varphi_n(z;\, k_t)$ and $g_{m,\upsilon}^{\sigma}$ are the envelope functions of the nth conduction sub-band and the mth valence sub-band. In each QW-TLM unit, the weight coefficients A_i and B_i are given as [22]:

$$A_i = \frac{1}{f_1(k_t(i))}\left|\hat{e}M_{nm}^{\sigma\eta}(k_t(i))\right|^2 \times (F_n^c(k_t(i)) - F_{\sigma m}^h(k_t(i)))k_t(i)dk_t \tag{13}$$

$$B_i = \frac{1}{f_2(k_t(i))}\left|\hat{e}M_{nm}^{\sigma\eta}(k_t(i))\right|^2 \times (F_n^c(k_t(i)) - F_{\sigma m}^l(k_t(i)))k_t(i)dk_t \tag{14}$$

where, $M_{nm}^{\eta\sigma}(k_t(i))$ is the momentum matrix element for the stimulated emission in the wave vector $k_t(i)$, $F_n^c(k_t(i))$, $F_{\sigma m}^h(k_t(i))$ and $F_{\sigma m}^l(k_t(i))$ are the values of the Fermi–Dirac distribution function