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Simulation of well-barrier hole burning in QW lasers

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Abstract

A circuit model to include the effect of well-barrier hole burning that is responsible for additional damping in quantum well laser is derived from the rate equations. This model is implemented using the circuit analysis program SPICE2 and the results of the dc analysis for a QW laser with and without WB hole burning are compared.

Keywords: Circuit modelling, well-barrier hole burning, quantum well lasers.

1. Introduction

Semiconductor laser (SL) is an important light source for high bit-rate fiber optics communications and integrated optics systems[1–4] because of simple construction, small size, high efficiency and direct modulation capability up to GHz range[5]. Hence a detailed analysis of the performance of SL is crucial to the design of integrated circuits and systems. Various types of laser models and their methods of construction have been developed in parallel with the progress in laser diodes. These models are broadly classified as static and dynamic models. Dynamic models provide an understanding of the modulation response of the laser for high-speed communication and signal processing applications. However, the models derived from the above methods suffer from the limitation of non-inclusion of substrate and package parasitics and device–circuit interactions in calculations. An alternate approach that overcomes these limitations is to transform the rate equations into a circuit model which can then be solved using standard circuit analysis techniques. More recently, attention has been focussed on modelling and study of the quantum well (QW) lasers because they exhibit many interesting properties not obtained in conventional double-heterostructure lasers such as low threshold, high modulation bandwidth, narrow spectral linewidth, etc[6,7]. In this paper, a circuit model of QW laser that takes into account the effect of well barrier (WB) hole burning which can be used to

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explain observed large damping in certain QW laser is presented. The model is simulated using circuit simulation program SPICE2 and the results of the dc analysis for a QW laser with and without WB hole burning are compared.

2. Well-barrier hole burning in quantum well lasers

Investigation of nonlinear gain in semiconductor lasers is important since this property plays an important role in certain laser characteristics such as modulation dynamics[8], laser amplification[9] and phase conjugate wave generation[10]. The nonlinear gain effect is enhanced in QW lasers, which is due to the quantum confinement of electrons[11]. In addition, the differential gain is reduced by the nonlinear gain effect which significantly affects modulation dynamics of semiconductor lasers under high photon density conditions. The main mechanisms for the gain nonlinearity, include the spectral hole burning[12,13], spatial hole burning[14] and carrier heating[15,16]. Among these, the spectral hole burning is the most intrinsic mechanism which directly reflects the quantum confinement effect of electrons. In analogy with spectral hole burning, where the photon density changes the distribution between the number of carriers contributing to the gain at the lasing wavelength and those not contributing at that wavelength, in well barrier hole burning, photon density changes the distribution between the number of carriers in the wells and those in the barriers/confinement region. The size of this additional gain suppression depends on two critical parameters: 1) the capture time of carriers moving between wells and barrier /confinement region, and 2) the ratio of the number of carriers at equilibrium in the barrier/confinement region to those in the wells. Since both these factors (capture time and equilibrium distribution) depend on the QW laser's particular structure, this damping is in turn also structure dependent[17]. This additional damping rate adds to the damping already caused by spectral hole burning or carrier heating, giving the possibility of even greater damping in QW lasers than in bulk lasers, thereby severely limiting the maximum achievable modulation bandwidth.

3. Modelling of well-barrier hole burning

Well-barrier hole burning incorporates certain features of the spatial inhomogeneities in perpendicular carrier transport. This inhomogeneity is supposed to redistribute or segregate carriers in such a way that the lasing mode experiences different levels of gain. In a multiple QW laser, carriers which contribute to gain, must first diffuse along the confinement and barrier region[18,19] and then be captured, with a finite quantum mechanical probability into the well[18,20-22]. The diffusion rate and capture rate influence the carrier injection efficiency and hence the gain nonlinearity[23]. As Fig. 1 illustrates schematically, after injection, electrons and holes diffuse and drift through the separate confinement heterostructure (SCH) region to within a few hundred Angstroms of the QW where they may be captured quantum mechanically by the quantum wells. At high-injection levels required for lasing, the densities of electrons and holes in excess of equilibrium values are equal and the diffusion-dominated regions spread away from the contacts throughout the entire intrinsic region. Thus these excess densities play the role of an effective mobile carrier density across the p-i-n region of the device. The WB hole burning is argued to result from the build up of these mobile-carrier density in the SCH

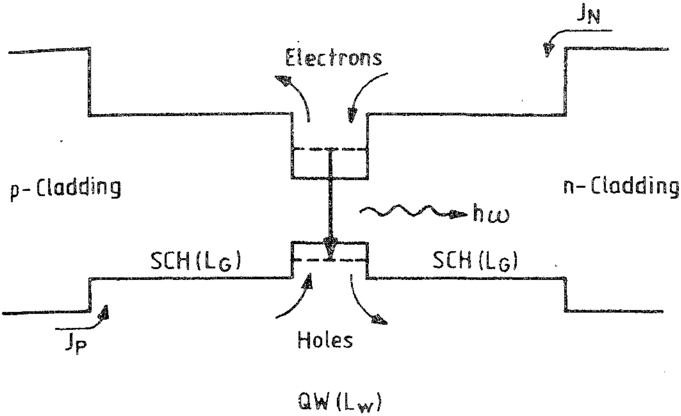

FIG. 1 Schematic diagram of carrier transport in a InGaAs–GaAs QW laser illustrating the capture and release processes for electrons and holes. L_w and L_G are the thicknesses of InGaAs QW and GaAs SCH layers, respectively.

during capture and release of carriers by the quantum wells. The WB model postulates that the photon-carrier resonance results from the coupled nonlinear interaction between a photon reservoir of density P and two carrier reservoirs: a collector with density N_b, and a gain reservoir of density N_W. As shown in Fig. 2, the collector receives carriers remotely from the pump current source, loses the carriers to the environment by spontaneous recombination in the barrier region and supplies carriers as needed to the gain reservoir. The gain reservoir captures and releases carriers from and to the collector reservoir and loses carriers by spontaneous emission into the lasing mode as well as by spontaneous recombination to the environment. The photon reservoir loses photons by internal and mirror losses in the lasing cavity. The gain medium and photon reservoir interact *via* stimulated absorption and emission. The conservation chart (Fig. 2) contains the essential rate processes for the nonlinear rate equations given by[24]

$$\frac{dN_b}{dt} = \frac{J}{e} - \frac{N_b}{t_{sb}} - \frac{(N_b - \eta N_w)}{t_c}; \tag{1}$$

$$\frac{dN_w}{dt} = \frac{(N_b - \eta N_w)}{t_c} - \frac{N_w}{t_{sw}} - \Gamma v_g\, G(N_w) P; \tag{2}$$

$$\frac{dP}{dt} = \Gamma V_g\, G(N_w) P - \frac{P}{t_{ph}} + \beta \frac{N_w}{t_{sw}}; \tag{3}$$

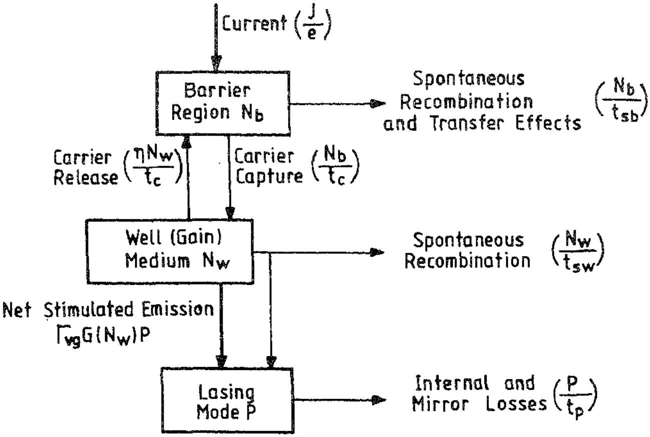

FIG. 2. Conservation chart for the WB hole burning model indicating the dominant rate processes for the WB model.

where t_{sb} is the effective carrier lifetime in the barriers, t_{sw}, the carrier lifetime in the wells, t_{ph}, the photon lifetime, t_c, the quantum capture time, Γ, the confinement factor, v_g, the group velocity, G, the optical gain, β, the spontaneous emission factor, J/e, the pumping rate of the constant current source and η, the ratio of the capture and release times for the carriers into and out of the well region. Multiplying the above equations by qv_a (where q is electron charge and v_a, the volume of the active region) and rearranging the terms, the equations reduce to the following form

$$t_{sb}\frac{dI_{D1}}{dt} = I - I_{D1} - \left[I_{D1}\frac{t_{sb}}{t_c} - \eta I_{D2}\frac{t_{sw}}{t_c}\right] \tag{4}$$

$$t_{sw}\frac{dI_{D2}}{dt} - \left[I_{D1}\frac{t_{sb}}{t_c} - \eta I_{D2}\frac{t_{sw}}{t_c}\right] - I_{D2} - I_{st} \tag{5}$$

$$C_p\frac{dp}{dt} = I_{st}\frac{P}{R_p} + \beta I_{D2} \tag{6}$$

where $I_{D1} = q\ v_a N_b/t_{sb}$, $I_{D2} = q\ v_a N_w/t_{sw}$

$I_{st} = q\ v_a \Gamma G\ (N_w)\ p$, $C_p = q\ v_a$, $R_p = t_{ph}/C_p$ and $t_{sb} = t_{sw}(1 + L_G/L_z)$.

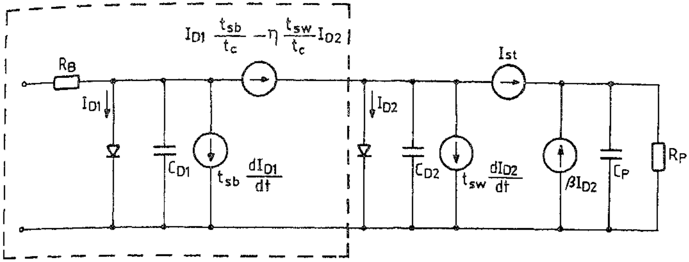

FIG. 3 Equivalent circuit of WB hole burning in a QW laser

Following the methodology of Tucker[25], the above equations are transformed into an equivalent circuit as shown in Fig. 3. The equivalent circuit can be divided into two parts. The first portion models the barrier/confinement region represented by eqn 4 (enclosed within dashed lines) and the second part is the model for the QW laser diode alone represented by eqns 5 and 6. The circuit model is simulated by applying dc sweep to it. The plot of input current *versus* output light intensity is shown in Fig. 4 for different values of η. For each value of η, simulations are performed for different number of wells ($N_w = 1,...5$). A large change in threshold current density is observed in all these cases compared to that of a QW laser without any hole burning effect. From the simulation results it is observed that the threshold current density is low for $N_w = 2$ compared to that of $N_w = 1$ and it increases for higher values of N_w ($N_w > 2$). This is in agreement with the results of Arakawa and Yarive[26].

4. Conclusion

We have studied the additional damping that is observed in certain QW lasers by introducing the concept of WB hole burning, and have obtained a threshold current of

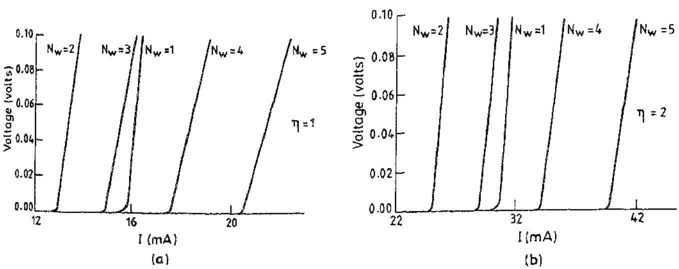

FIG. 4. Simulated response to a dc sweep for different number of wells, and a) η = 1, b) η =2.

approximately 15.8 and 30.6 mA for $\eta = 1$ and $\eta = 2$, respectively, whereas the corresponding value obtained from the QW laser model without any hole burning effect is only 10 mA.

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