Carrier Capture Competition Between Two Different Quantum Wells in Dual-Wavelength Semiconductor Lasers

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***Abstract*— Based on a three-level model, we have numerically shown that a semiconductor gain medium with a structure consisting of two different quantum wells may lead to dual-wavelength laser operation if the balance of carrier capture competition between the two wells can be reached. The major controlling parameters for the operation are the ratio of the carrier quantum capture times of the two wells and the absorption constant of the short-wavelength photons by the long-wavelength quantum well. It is shown that there exists a large parameter space for dual-wavelength operation.**

DUAL-WAVELENGTH semiconductor lasers are useful for the applications such as optical storage, wavelength-division-multiplexing and two-wavelength interferometry [1]. Such a dual-wavelength operation has been implemented using a grating-lens-stripe-mirror setup in an external cavity [2]. Also, compact dual-wavelength laser diodes were fabricated with structures of two different quantum wells [3]–[6], including those of alternating tensile- and compressive-strain quantum wells [6]. In such a device, carriers are captured into both wells and under certain conditions the dual-wavelength oscillation can occur with the two wavelengths corresponding to the two different quantum wells.

The dual-wavelength operation in a structure with two different quantum wells may depend on many conditions; however, an important factor is the competition of carrier capture between the two wells. A balance in the competition is required so that sufficient gain can be provided for either wavelength. In this letter, we use a three-level model to numerically demonstrate that under certain conditions, such a balance is feasible and stable dual-wavelength operation can be achieved if other conditions are favorable. A similar model was proposed to describe the two-wavelength operation in such an asymmetric dual-quantum-well structure [7]. However, the model included many phenomenologic parameters and did not consider carrier quantum capture processes, explicitly. In the model of this letter, we use more fundamental physics parameters and focus at the carrier capture competition between the two wells.

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The basic model we use is depicted schematically in Fig. 1, in which the uncoupled wells 1 and 2 form a quantum well pair. The transition energy between the conduction subband $C1$ and the heavy-hole valence subband $H1$ of well 1 is assumed to be larger than that of well 2. Real structures for laser fabrication may consist of several periods of such a quantum well pair. The carrier injection process in such a quantum-well structure is modeled as a three-level system [8]. The three levels include the confinement region with carrier number N_D, 3-D barrier states with carrier number N_c and subband states with carrier numbers N_{g1}, N_{g2} in wells 1 and 2, respectively. The tunneling between wells is assumed to be negligible. The carrier transport time τ_D is used to describe the diffusion and drift processes across the separate confinement region. The quantum capture times τ_{C1} and τ_{C2} denote the coupling between the continuous 3-D states and ground subbands for wells 1 and 2, respectively. The model can be described with the following six rate equations:

$$\frac{dN_D}{dt} = \frac{I}{q} - \frac{N_D\eta_D - N_C}{\tau_D} - \frac{N_D}{\tau_n} \tag{1}$$

$$\frac{dN_C}{dt} = \frac{N_D\eta_D - N_C}{\tau_D} - \frac{N_C\eta_{F1} - N_{g1}}{\tau_{c1}} - \frac{N_C\eta_{F2} - N_{g2}}{\tau_{c2}} - \frac{N_C}{\tau_n} \tag{2}$$

$$\frac{dN_{g1}}{dt} = \frac{N_C\eta_{F1} - N_{g1}}{\tau_{c1}} - g_1(N_{g1} - N_{t1})S_1 - \frac{N_{g1}}{\tau_n} \tag{3}$$

$$\frac{dS_1}{dt} = \frac{\Gamma_1 g_1(N_{g1} - N_{t1})S_1}{V_1} - \frac{S_1}{\tau_P} + \frac{\Gamma_1 r_1 N_{g1}}{\tau_n V_1} - \Gamma_a \alpha v_g S_1 \tag{4}$$

$$\frac{dN_{g2}}{dt} = \frac{N_C\eta_{F2} - N_{g2}}{\tau_{c2}} - g_2(N_{g2} - N_{t2})S_2 - \frac{N_{g2}}{\tau_n} + \Gamma_a \alpha v_g S_1 V_1 \tag{5}$$

$$\frac{dS_2}{dt} = \frac{\Gamma_2 g_2(N_{g2} - N_{t2})S_2}{V_2} - \frac{S_2}{\tau_P} + \frac{\Gamma_2 r_2 N_{g2}}{\tau_n V_2}. \tag{6}$$

Equations (1)–(6) describe the dynamics of various carrier numbers and photon densities S_1 and S_2, corresponding to the transition photon wavelengths, λ_1 and λ_2, respectively, from wells 1 and 2. The effects of nonlinear gain are neglected for mathematical simplicity. Since we have assumed that the photon energy of well 1 is larger than that of well 2, a part of the photons in S_1 is expected to be absorbed by well 2.

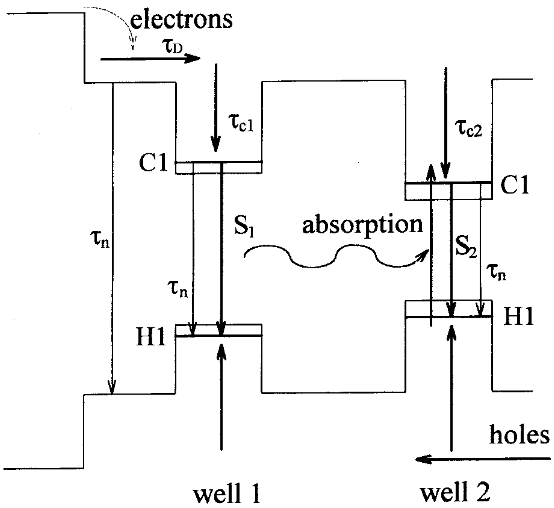

Fig. 1. Schematic diagram of the two-quantum-well pair. The transition energy $C1$–$H1$ of well 1 is assumed to be larger than that of well 2. Thus, a part of the photons emitted from well 1 is absorbed by well 2.

This photon loss from S_1 is represented by the terms with the absorption constant a in (4) and (5). Because the absorption is not at band extrema and its value depends on the carrier density inside well 2, accurate α value cannot be available. In the following, we assume that α has the same order of magnitude as its value of linear absorption near the band extrema. Also, we define a parameter B as the ratio of the fourth term over the second term on the right-hand side of (4), i.e., B represents the ratio of the absorbed photon density over that due to output and other internal loss:

$$B = \Gamma_a \alpha v_g \tau_p. \tag{7}$$

As can be seen in (2), the carriers supplied by the injection current is shared by the two different wells. The dependence of carrier quantum capture time on the depth and/or width is quite complicated [9]–[11]. It is actually possible to have the carrier quantum capture time of the well of the shorter wavelength either larger or smaller than the one of the longer wavelength. For the well with a shorter carrier capture time, its higher capture rate may lead to a larger photon density S_1 and hence dominates the oscillation of the laser cavity. As will be seen in the following, two major parameters controlling the oscillation conditions are τ_{c2}/τ_{c1} and B. Those parameters in (1)–(6) not defined yet are explained on Table I.

We have numerically solved (1)–(6) at the steady state with reasonable parameter values (listed on Table I) [12]. Fig. 2 shows the L–I curves of wavelengths λ_1 [Fig. 2(a)] and λ_2 [Fig. 2(b)] with $\tau_{c1} = 1$ ps and $\tau_{c2} = 5$ ps for various B values. In the case $B = 0$, because $\tau_{c2} > \tau_{c1}$, the oscillation of λ_1 dominates at the threshold current 63 mA until the injection current increases up to 123 mA beyond which both wavelengths oscillate. Although λ_2 can also oscillate, its power is much lower than that of λ_1 and its differential output is smaller than that of λ_1. As B increases, i.e., the transfer of photons of λ_1 into carriers for λ_2 becomes significant, the dominance of carrier capture for λ_1 is canceled by the λ_1 photon absorption, leading to a larger S_2 and a smaller S_1. As can be seen in the figure, when $B = 0.5$, the L–I curves for λ_1 and λ_2 are nearly identical, both with a higher threshold current at 106 mA. When $B = 1$, within the considered injection current range λ_2 dominates the oscillation.

TABLE I
PARAMETER VALUES USED IN CALCULATIONS

PARAMETER	SYMBOL	VALUE
Carrier transport time accross the separate confinement region	τ_D	5ps
Equilibrium factor between N_C and N_D	η_D	1.0
Equilibrium factor between N_C and N_{g1}	η_{F1}	1.0
Equilibrium factor between N_C and N_{g2}	η_{F2}	1.0
Photon lifetime	τ_p	1.6ps
Gain constant of λ_1	g_1	1.8382×10^{-4} cm^3s^{-1}
Gain constant of λ_2	g_2	1.8382×10^{-4} cm^3s^{-1}
Carrier lifetime	τ_n	2.2ns
Cavity volume of λ_1	V_1	6.0×10^{-10} cm^3
Cavity volume of λ_2	V_2	$6.0\times10^{-10}cm^3$
Confinement factor of λ_1	Γ_1	0.6
Confinement factor of λ_2	Γ_2	0.6
Transparent carrier population of λ_1	N_{t1}	2.14×10^8
Transparent carrier population of λ_2	N_{t2}	2.14×10^8
Spontaneous emission factor of λ_1	r_1	1.0×10^{-5}
Spontaneous emission factor of λ_2	r_2	1.0×10^{-5}
Group velocity	v_g	—

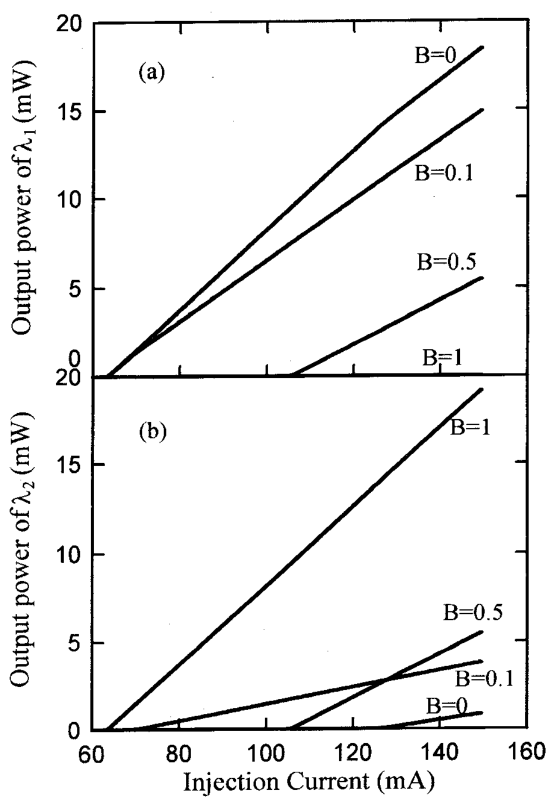

Fig. 2. L–I curves for λ_1 and λ_2 with various B values. (a) Output power of λ_1. (b) output power of λ_2. Note that $\tau_{c1} = 1$ ps and $\tau_{c2} = 5$ ps.

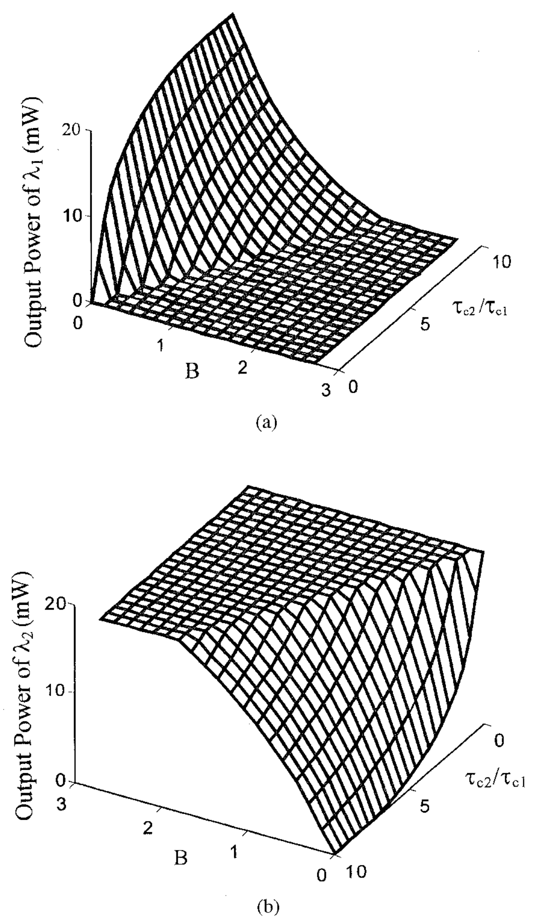

Fig. 3. Output powers of λ_1 (a) and λ_2 (b) with various $(\tau_{c2}/\tau_{c1}, B)$ pairs. The injection current is 150 mA and $\tau_{c1} = 1$ ps.

Fig. 3 demonstrates the 3-D curves for output power as functions of τ_{c2}/τ_{c1} and B. The injection current is set at 150 mA and τ_{c1} is chosen to be 1 ps. As can be seen in the figure, although it is difficult to always make the output powers of λ_1 and λ_2 the same, there exists a quite large region in the $\tau_{c2}/\tau_{c1} - B$ space for λ_1 and λ_2 to oscillate simultaneously. If we define the lasing condition as that the output power is larger than 10 μW, the shaded region between the two solid lines in Fig. 4 represents the situation in which both λ_1 and λ_2 can oscillate for the parameter values considered in Fig. 3. This large region of simultaneous oscillation implies that it might not be difficult to fabricate a semiconductor gain medium with two different types of quantum well for dual-wavelength operation. In Fig. 4, we also plot two dashed lines to form the shaded region in which dual-wavelength oscillation is possible when the injection current is reduced to 70 mA. We can see that a larger injection current leads to a larger region for dual-wavelength oscillation.

We have also studied the stability of the dual-wavelength operation with a typical perturbation method. We solved the linearized equations for a small perturbation and found that the perturbation diminished in a manner similar to relaxation oscillations for both wavelengths. This observation assures the

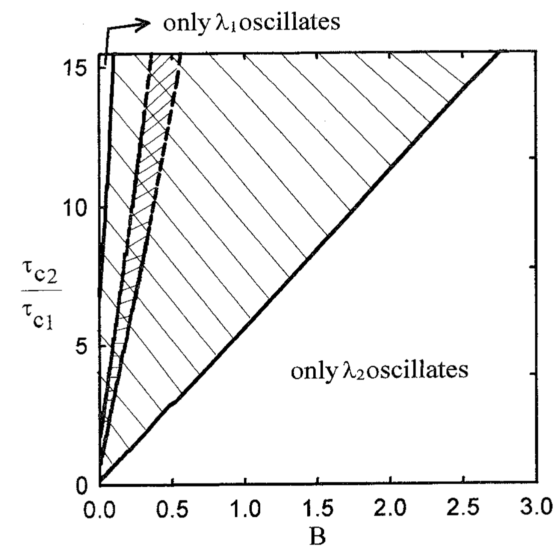

Fig. 4. Oscillation conditions of λ_1 and λ_2. The injection current is 150 mA (solid lines) or 70 mA (dashed lines). The shaded region for dual-wavelength oscillation lies between the two solid (dashed) lines.

feasibility of stable dual-wavelength oscillation in a structure with two different quantum wells. In summary, we have numerically shown that there existed a quite large parameter space in which a semiconductor gain medium with two different quantum well structures could lead to stable dual-wavelength oscillation.

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