Theory of asymmetric dual quantum well lasers

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(Received 15 April 1991; accepted for publication 5 June 1991)

A basic theory of asymmetric dual quantum well lasers is presented. The lasers consist of two quantum wells of different energy gaps, which are separated by a high and/or thick barrier layer. The barrier layer blocks carrier transport between the wells so that the rate of the transport becomes comparable to the rate of the radiative recombination. It is shown that this leads to novel phenomena of dual-wavelength lasing and wavelength switching with increasing injection current, in agreement with recent experimental results.

Laser diodes (LDs) with a variable emission wavelength λ have wide applications. Conventional optical communication systems may require a tuning range $\Delta\lambda$ of less than 1% of λ, and LDs with a tunable distributed Bragg reflector are widely used.[1] For other applications, such as future optical communication or optical recording systems, a wider $\Delta\lambda$ would be required. A solution is to use an external cavity, which enables us to get $\Delta\lambda/\lambda \sim 13\%$.[2] However, the use of the external cavities places many restrictions on applications to small-size systems such as integrated optoelectronic systems. Hence, it seems important to develop *monolithic* LDs with a wide $\Delta\lambda$. As a new LD with this function, we previously proposed the asymmetric dual quantum well (ADQW) LD,[3–6] for which we have experimentally demonstrated the *discrete* switchings of $\Delta\lambda = 13$ nm (Ref. 4) and 50 nm (Ref. 5), and *quasicontinuous* wavelength tuning of $\Delta\lambda = 22$ nm (Ref. 6), when $\lambda \simeq 800$ nm. The purpose of the present letter is to present a basic theory of the ADQW LDs.[3]

An ADQW LD consists of two quantum wells, well 1 and well 2, of different emission wavelengths λ_1 and $\lambda_2(<\lambda_1)$. The two wells are located in the core of a *single* optical waveguide as shown in Fig. 1, where well 2 of a wider band gap is located on the p-type side.[5] If well 2 is located on the n-type side,[4,6] roles of the electrons and holes should be interchanged in the following discussions. Let us make the thickness d_2 of well 2 larger than the mean-free path of energy relaxation processes of holes. Then, all holes injected from the p-type cladding layer are first trapped by well 2, and they are then thermally activated to be transferred over the barrier into well 1. The point is to block this transfer by making the barrier high and/or thick, so that the rate of the transfer becomes comparable with the recombination rate. This should be contrasted with the case of normal multiple quantum well (MQW) LDs for which barrier layers are usually low and thin to inject carriers uniformly across many wells.[7] If we used such a low and thin barrier in an ADQW LD, most injected carriers would occupy well 1 only, so that the carrier density n_2 of well 2 would not reach its threshold value at a reasonable value of injection current density J. By contrast, the high and/or thick barrier in our case disturbs the increase of the carrier density n_1 of well 1, and n_2 in turn increases. In other words, the quasi thermal equilibration for carrier distributions between the two wells is inhibited, which makes it possible to achieve $n_1 \sim n_2$ at a reasonable value of J, resulting in sufficient optical gains both at λ_1 and λ_2.

As for electrons, well 1 of *narrower* energy gap is located on the n-type side. Hence, unlike the case of holes, the high and/or thick barrier layer tends to *enhance* the imbalance of the electron densities between the two wells. In order to supply well 2 with a sufficient density of electrons, we may make the potential at the edge of separate confinement layer on the n-type side (point A in Fig. 1) equal or higher than that of barrier layer, and also make the thickness d_1 of well 1 smaller than the mean-free path of energy relaxation processes of electrons. Then, a large part of electrons injected from the n-type cladding layer can go over well 1 into well 2, so that we can get sufficient electron densities in both wells. Another way of supplying electrons in well 2 is n^+ doping of the barrier layer.[3] Once the sufficient electron densities are thus obtained in both wells, we can focus on holes and photons, for which we will write down rate equations. Although it is straightforward to extend the theory to include rate equations of electrons, we consider that main physics can be understood by the present simple equations.

Let J_{21} be the hole-current density from well 2 to 1. Taking account of the general case when a part of J, ξJ, is directly injected into well 1, we may write the rate equations for n_1, n_2 and the photon densities s^{λ_1}, s^{λ_2} of the lasing modes at λ_1, λ_2 as

$$\frac{dn_1}{dt} = \frac{\xi J + J_{21}(n_1,n_2)}{ed_1} - G_1^{\lambda_1}(n_1)s^{\lambda_1} - G_1^{\lambda_2}(n_1)s^{\lambda_2} - \frac{n_1}{\tau_{n_1}}, \qquad (1)$$

$$\frac{dn_2}{dt} = \frac{(1-\xi)J - J_{21}(n_1,n_2)}{ed_2} - G_2^{\lambda_2}(n_2)s^{\lambda_2} - \frac{n_2}{\tau_{n_2}}, \qquad (2)$$

$$\frac{ds^{\lambda_1}}{dt} = G_1^{\lambda_1}(n_1)s^{\lambda_1} - \frac{s^{\lambda_1}}{\tau^{\lambda_1}} + \beta_1^{\lambda_1}\frac{n_1}{\tau_{n_1}}, \qquad (3)$$

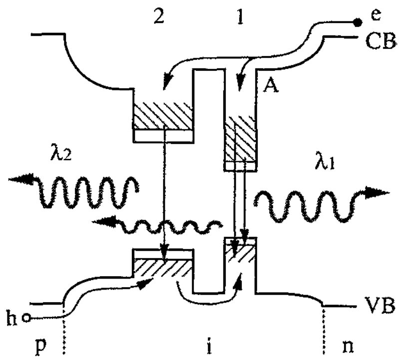

FIG. 1. Schematic band diagram of an ADQW LD. The shaded regions in the wells indicate the accumulated carriers.

$$\frac{ds^{\lambda_2}}{dt}=[G_1^{\lambda_2}(n_1)+G_2^{\lambda_2}(n_2)]s^{\lambda_2}-\frac{s^{\lambda_2}}{\tau^{\lambda_2}}+\beta_1^{\lambda_2}\frac{n_1}{\tau_{n_1}}+\beta_2^{\lambda_2}\frac{n_2}{\tau_{n_2}}, \tag{4}$$

where τ_{n_1} and τ_{n_2} are the recombination lifetimes in well 1 and 2, respectively, and τ^{λ_1} and τ^{λ_2} are the lifetimes of the λ_1 and λ_2 photons. The $G_1^{\lambda_1}$, $G_1^{\lambda_2}$, and $G_2^{\lambda_2}$ ($\beta_1^{\lambda_1}$, $\beta_1^{\lambda_2}$, and $\beta_2^{\lambda_2}$) respectively denote the optical gain coefficients (the spontaneous emission factors) of λ_1 from well 1, λ_2 from well 1, and λ_2 from well 2. For example,

$$G_1^{\lambda_2}=\Gamma_1^{\lambda_2}cg_1^{\lambda_2}(n_1)/N^{\lambda_2}, \tag{5}$$

where $\Gamma_1^{\lambda_2}$ is the confinement factor of the λ_2 light with respect to well 1, c the light velocity, $g_1^{\lambda_2}$ the optical gain of well 1 at λ_2, and N^{λ_2} the effective refractive index for the λ_2 lasing mode. The other factors, $G_2^{\lambda_1}$ and $\beta_2^{\lambda_1}$, do not enter the equations because well 2 has no quantum states at λ_1.

The above set of equations can describe both static and dynamic properties of ADQW LDs. To demonstrate that wavelength switchings indeed occur as a result of peculiar features of the above equations, we here present a solution for the static properties. Note that the equations do *not* take account of any effects of thermal heating, so that the wavelength switching is *not* due to the thermal heating. This means that the switching speed is *not limited* by slow times ($\sim\mu$s or longer) of thermal processes. The switching in the absence of the thermal heating has been experimentally confirmed by a recent time-resolved experiment.[5]

To analyze the static properties, we set $d/dt=0$ in Eqs. (1)–(4), and we may drop the spontaneous-emission terms in Eqs. (3) and (4). We also assume that $\xi=0$. As for J_{21}, although its rigorous functional form is unknown at present, we can say that J_{21} would depend only on n_2 when n_1 is not too large, because the thermal activation energy for n_1 is much larger than that for n_2. We also note that J_{21} is an increasing function of n_2. Wavelength switchings occur for any functional forms of J_{21} which satisfy these properties. For simplicity, we here assume the following form:

$$J_{21}\simeq evn_2, \tag{6}$$

where v is the effective velocity of holes moving over the barrier. The barrier must be high and/or thick enough so that v becomes much slower than that in normal MQW LDs. From Eq. (13) below, we find that v must be as small as $\sim 10^3$ cm/s to achieve a reasonable value of $J_{\rm th}^{\lambda_2}$.

By noting that $G_1^{\lambda_1}$, $G_1^{\lambda_2}$, and $G_2^{\lambda_2}$ are also increasing functions of n_1 or n_2, we can easily find the following solution. Below the lasing threshold, $s^{\lambda_1}=s^{\lambda_2}=0$, and

$$n_1=v\tau_{n_1}n_2/d_1, \tag{7}$$

$$n_2=J/e(v+d_2/\tau_{n_2}). \tag{8}$$

We here consider the case when the barrier is not too high so that the λ_1 light first starts lasing as J is increased.[4–6] The threshold value of J is found to be

$$J_{\rm th}^{\lambda_1}=e(v+d_2/\tau_{n_2})d_1n_{1\rm th}/v\tau_{n_1}, \tag{9}$$

where the threshold hole density $n_{1\rm th}$ is given by

$$G_1^{\lambda_1}(n_{1\rm th})=1/\tau^{\lambda_1}. \tag{10}$$

When $J_{\rm th}^{\lambda_1}\leqslant J<J_{\rm th}^{\lambda_2}$ [see Eq. (13)], $s^{\lambda_2}=0$ and s^{λ_1} increases as

$$s^{\lambda_1}=\frac{v\tau^{\lambda_1}(J-J_{\rm th}^{\lambda_1})}{ed_1(v+d_2/\tau_{n_2})}. \tag{11}$$

As for the hole densities, $n_1=n_{1\rm th}$ is fixed, whereas n_2 continues to increase as Eq. (8), until it reaches the threshold value $n_{2\rm th}$ given by

$$G_2^{\lambda_2}(n_{2\rm th})=1/\tau^{\lambda_2}-G_c \tag{12}$$

at the second threshold current density

$$J_{\rm th}^{\lambda_2}=e(v+d_2/\tau_{n_2})n_{2\rm th}. \tag{13}$$

Here, $G_c\equiv G_1^{\lambda_2}(n_{1\rm th})$ is the optical gain coefficient of well 1 at λ_2 (not λ_1) for $n_1=n_{1\rm th}$, which plays a crucial role in determining the switching characteristics,[3] as shown below. When $J_{\rm th}^{\lambda_2}\leqslant J<J_{\rm th}^{\lambda_1\prime}$ [see Eq. (16)], s^{λ_2} increases with J as

$$s^{\lambda_2}=\frac{(J-J_{\rm th}^{\lambda_2})}{ed_2(1/\tau^{\lambda_2}-G_c)}. \tag{14}$$

On the other hand, $n_1=n_{1\rm th}$ and $n_2=n_{2\rm th}$ are both fixed, and thus the hole supply to well 1, J_{21}, is also fixed. This constant J_{21} should be balanced with the λ_1 emission plus the stimulated emission of the λ_2 photons from well 1 when $G_c>0$ (or, when $G_c<0$, *minus* the carrier generation in well 1 due to the absorption of the λ_2 photons). That is,

$$s^{\lambda_1}=\frac{v\tau^{\lambda_1}(J_{\rm th}^{\lambda_2}-J_{\rm th}^{\lambda_1})}{ed_1(v+d_2/\tau_{n_2})}-G_c\tau^{\lambda_1}s^{\lambda_2}. \tag{15}$$

Since s^{λ_2} increases with J, s^{λ_1} in turn *decreases* when $G_c\equiv G_1^{\lambda_2}(n_{1\rm th})>0$, which is a condition for the nonthermal switching of the emission wavelength.[3] In fact, s^{λ_1} continues to decrease when $G_c>0$ until it vanishes at $J=J_{\rm th}^{\lambda_1\prime}$, where the third threshold current density

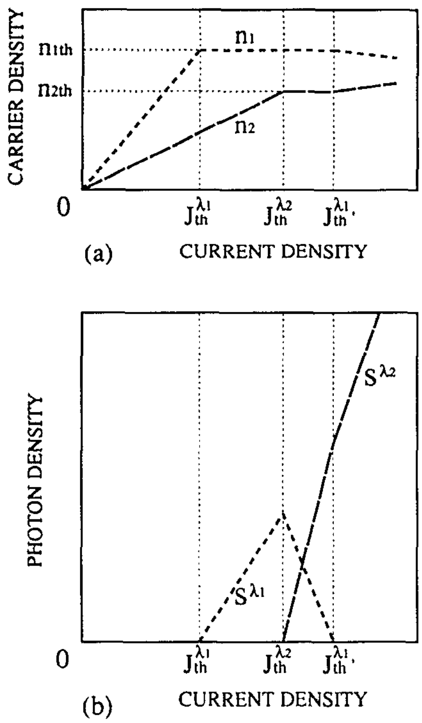

FIG. 2. Schematic plots of (a) the carrier densities and (b) the photon densities, as functions of the current density.

$$J_{th'}^{\lambda_1} = J_{th}^{\lambda_2} + \frac{v d_2 (1/G_c \tau^{\lambda_2} - 1)(J_{th}^{\lambda_2} - J_{th}^{\lambda_1})}{d_1 (v + d_2/\tau_{n_2})}. \qquad (16)$$

When $J > J_{th'}^{\lambda_1}$, by expanding n_1, n_2, and s^{λ_2} around their values at $J = J_{th'}^{\lambda_1}$, we can easily see that s^{λ_2} continues to increase with J, and n_1 starts to decrease, whereas n_2 in turn starts to increase. The decrease of n_1 is because n_1 is consumed by the increasing stimulated emission of the λ_2 light [the third term in the right-hand side of Eq. (1)]. On the other hand, n_2 increases to compensate for the decrease of n_1 in order for the total optical gain at λ_2, $G_1^{\lambda_2}(n_1) + G_2^{\lambda_2}(n_2)$, to be kept constant. Since a small part of J is consumed for this increase of n_2, the gradient $\partial s^{\lambda_2}/\partial J$ becomes slightly smaller than that for $J < J_{th'}^{\lambda_1}$. We have thus achieved a complete switching of the emission wavelength from λ_1 to λ_2, as schematically shown in Fig. 2.

In summary, we have presented the basic operation principles and the basic equations (1)–(4) of ADQW LDs. The high and/or thick barrier between two wells of different emission wavelengths blocks the carrier transport between the wells, resulting in dual-wavelength lasing and wavelength switching with increasing the injection current. Since this switching does not rely on any effects of thermal heating, the switching speed is not limited by slow times of thermal processes. The present theory agrees with recent experimental results.[4–6]

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