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Wavelength Switching of Asymmetric Dual Quantum Well Lasers

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An asymmetric dual quantum well laser diode (ADQW LD) is proposed to realize a wide-range tuning capability. Using current injection we have demonstrated wavelength switching over 13 nm in $0.8\mu m$ wavelength region under continuous wave operation for the first time. Simultaneous lasing at dual wavelengths has also been observed.

Monolithic laser diodes (LD's) with wide-range wavelength tunablility have a great deal of possibilities in future electro-optic applications such as multi-wavelength optical communication and/or recording systems. Many studies based on distributed Bragg reflector (DBR) and distributed feedback (DFB) LD's have been done[1]. However, a typical range of their controllable wavelengths is less than 1% of their lasing wavelengths (e.g., $10nm$ for $1.55\mu m$ - DBR LD), because of their Bragg wavelength selectivities in a change of the effective refractive index with carrier injection[1]. To realize a wider tuning range, a method is to control an optical gain spectrum over different transitions between quantized levels in quantum well (QW) LD's. In this paper we propose an asymmetric dual quantum well (ADQW) LD which consists of two *different* quantum wells effectively separated by a barrier layer within a *single* optical cavity as shown in Fig.1(e). We show that it is possible to control gain spectra in both two wells by current injection, thereby changing the lasing wavelength. In this experiment we demonstrate that such an ADQW LD can lase at two wavelengths and switch between them over $13nm$ in $0.8\mu m$ wavelength region.

A remarkable point of well-designed ADQW LD's is that the threshold current can be low. This is because the gain at a shorter wavelength can become equal to that at a longer one with a little injection current. This is different from the case using single quantum well (SQW) LD's, with which Tokuda and coworkers[2] demonstrated wavelength switching over a wide range ($\sim$ 40 nm) between the transition of $n = 1$ and $n = 2$ quantized levels. The schematic band diagram of a SQW and its gain spectra with various carrier injection are shown in Figs.1(a) and 1(b), respectively. The gain for n=2 transition does not increase effectively until the gain for n=1 transition is saturated. In order to make the stimulated emission for n=2 transition possible, the cavity loss has to be increased intentionally so that lasing at n=1 transition is suppressed. In this case the threshold gain increases from g^l_{th} to g^h_{th}, as shown in Fig.1(b). The threshold current, unfortunately, becomes very large due to the increased cavity loss. For this reason lasing in this structure under continuous wave (CW) operation has not been reported yet.

Furthermore not all the ADQW structures enable us to realize low threshold. For example, Matsui et al.[3] also suggested the ADQW structure (see Fig.1(c)), which makes wavelength switching easier by reducing the difference between λ_1 and λ_2. (Here we denote the lasing wavelengths in smaller gap well 1 and larger one well2 by λ_1 and λ_2, respectively.) Since the gain of well 2 cannot be grown until the gain of well 1 is grown as shown in Fig.1(d), the threshold gain should be increased up to g^m_{th}. This results in a large threshold current similar to the above SQW LD.

On the other hand, one of us (A.S.) proposed the following method to get sufficient gain at shorter wavelengths[4]. When well 2 is located near n-type (p-type) semiconductor, the barrier layer should be p^+-doped (n^+-doped) and higher and/or thicker than that of usual multi-QW (MQW) LD's[5]. This is shown in Fig.1(e). With such a high/thick barrier in the ADQW structure, the number of the electrons in well 2 can be increased effectively. Likewise, p^+ doping of the barrier layer (and also of a portion of the n-side separate confinement (SC) layer) assists to supply the holes in well 2. This leads to the sufficient gain in well 2 and thus the nearly equal optical gain at both λ_1 and λ_2 with injection current lower than those in SQW and non-optimized ADQW structures (see Fig.1(f)). Once sufficient gain at both wavelengths is thus obtained, we can switch the lasing wavelength between them by changing injection current, as discussed below. Although further consideration is needed to optimize the above ADQW structure, here we present the preliminary experimental result of our proposed ADQW LD. It is found that the operation is an intermediate case between Figs.1(d) and 1(f).

The ADQW structure described in Table 1 was grown by molecular beam epitaxy on a n-type substrate. The barrier layer was $Al_xGa_{1-x}As$ with $x = 0.3$ and the thickness of $L_B = 150$ Å. Again this ADQW structure and the growth condition were not optimized in the present experiment. For the confinement of an optical field and an electric current, a ridge waveguide was fabricated by the following serial processes: mesa-etching of the wafer; deposition of Si_3N_4; removal of Si_3N_4 from the top of the mesa; evaporation of Au/Cr onto the top layer; lapping; evaporation of Au/Au-Ge onto the bottom of the substrate; and alloying. ADQW LD's with different cavity lengths were obtained by cleaving the wafer and were mounted with p-side up.

TABLE 1. Layer structure of the ADQW LD.

Layer	Al content	Thickness (nm)	Carrier (cm^{-3})
Substrate	0.0	——	$n = 2 \times 10^{18}$
Buffer	0.0	500	$n = 2 \times 10^{18}$
Clad	0.5	1500	$n = 1 \times 10^{17}$
SCH(GRIN)	0.5 - 0.3	25	non-doped
SCH(flat)	0.3	10	$p = 1 \times 10^{18}$
Well2	0.08	16	non-doped
Barrier	0.3	15	$p = 1 \times 10^{18}$
Well1	0.0	8	non-doped
SCH(flat)	0.3	10	$p = 1 \times 10^{18}$
SCH(GRIN)	0.3 - 0.5	25	$p = 1 \times 10^{18}$
Clad	0.5	1500	$p = 1 \times 10^{18}$
Cap	0.0	500	$p = 1 \times 10^{19}$

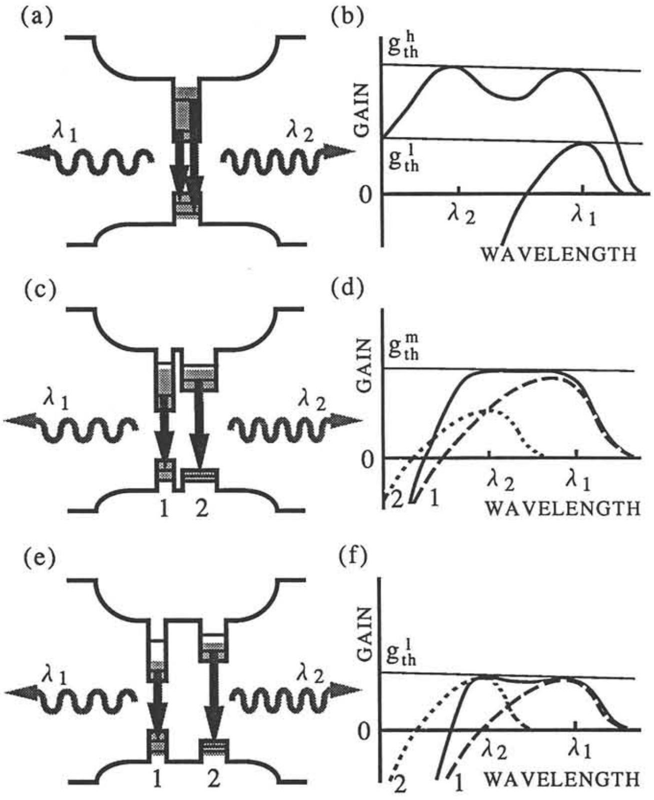

FIG.1. Schematic band diagrams of a SQW, a non-optimized ADQW and an optimized ADQW structure are shown in (a), (c) and (e), respectively, and corresponding gain spectra are schematicaly shown in (b), (d) and (f). The shaded region in the wells indicate the carriers accumulated in each well. The wavelength for lower quantized energy gap and higher one are λ_1 and λ_2, respectively. (b) shows the gain at low and high current injection levels, and the threshold gain g_{th}^l (g_{th}^h) with low (high) cavity loss. The total gain (solid line), the gain in well 1 (dashed lines) and the one in well 2 (dotted lines) are shown in (d) and (f). The threshold gain with middle cavity loss are denoted as g_{th}^m in (d).

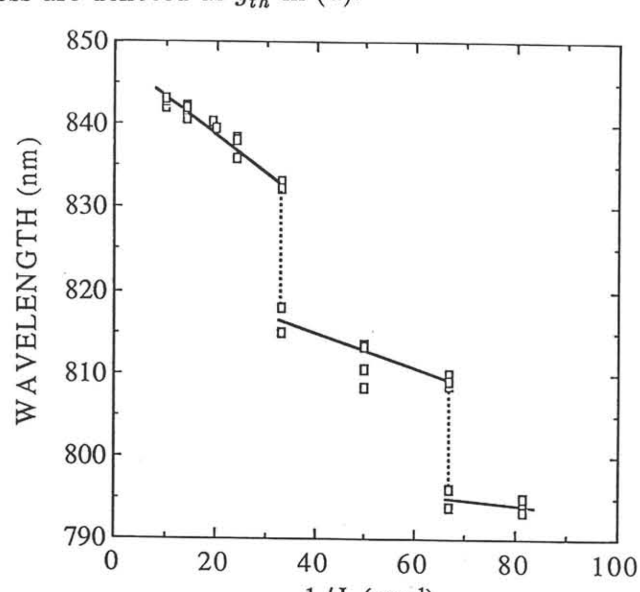

FIG.2. Lasing wavelength at the lasing threshold as a function of the reciprocal of the cavity length.

In order to determine the total cavity loss appropriate for switching operation, we measured the dependence of the cavity length L upon the lasing wavelengths λ_L at the threshold, which is shown in Fig.2. They were measured under pulsed operating condition (pulse width 300 ns and repetition frequency 100 kHz) at room temperature. With the decrease of L, a smooth decrease and two abrupt changes (at $L \simeq 300\mu m$ and $L \simeq 150\mu m$) in λ_L are seen. The $\lambda_L's$ around $840nm$, $810nm$ and $795nm$ are consistent with the calculated transition energies between n = 1 quantized levels in well 1, n = 1 levels in well 2, and n = 2 levels in well 2, respectively. As is discussed later[4], λ_L at the threshold should be λ_1 (a longer wavelength) for wavelength switching. In fact, wavelength switching was not observed for the LD's with $L < 300$ μm. Thus, we have to use the LD's with $L \geq 300$ μm. Especially ADQW LD with $L \approx 300$ μm is most desirable because the optical gain is almost equal at both λ_1 and λ_2 when $L \approx 300$ μm is chosen, as seen from Fig.2.

By using ADQW LD with $L = 301$ μm, we could obtain wavelength switching under CW operation at $5°C$ for the first time. The output power P versus injection current I in this sample is shown in Fig.3. In this figure the square represents the total light output, whereas the circle and triangle denote the light output at wavelength $\lambda_1 \simeq 831$ nm and $\lambda_2 \simeq 818$ nm, respectively. Emission spectra at three different injection levels are also shown in the inset of the figure. At the threshold, lasing is seen only at λ_1. With the increase of I, P_1 at λ_1 increases until lasing at λ_2 takes place. With the further increase of I, P_1 decreases after taking the maximum. On the other hand, P_2 at λ_2 increases linearly with I.

In what follows, we briefly discuss a possible mechanism for the observed wavelength switching. Figure 4 shows the schematic band diagrams (Figs.4(a), 4(c) and 4(e)) and the gain spectra (Figs.4(b), 4(d) and 4(f)) at different injection levels corresponding to Figs.3(1), 3(2) and 3(3), respectively. Here the threshold currents at λ_1 and λ_2 are denoted by I_{th1} and I_{th2}, respectively. For $I_{th1} \leq I < I_{th2}$, lasing at λ_1 takes place (as shown in Figs.4(a) and 4(b)), so that the electron density

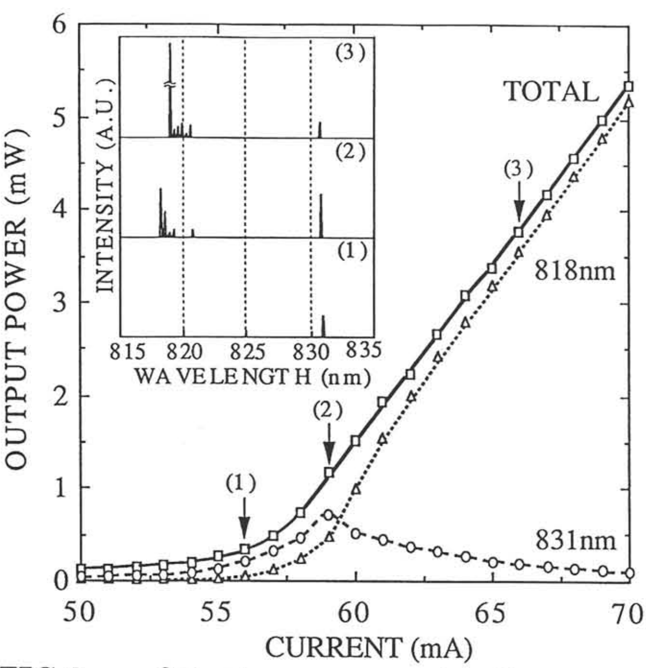

FIG.3. Output power vs. injection current characteristics of the ADQW LD with $301\mu m$ cavity length under CW operation at $5°C$. The output power of $831nm$ light (circles) and $818nm$ light (triangles) are shown as well as the total power (squares). The emission spectra at three different injection levels are also shown in the inset.

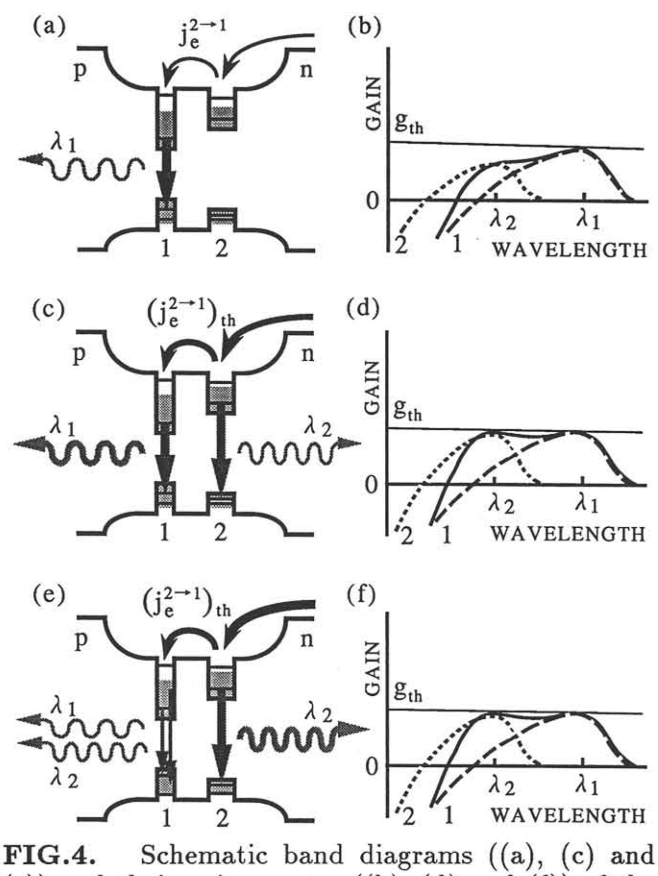

FIG.4. Schematic band diagrams ((a), (c) and (e)) and their gain spectra ((b), (d) and (f)) of the ADQW LD at different injection levels corresponding to (1), (2) and (3) in Fig.3, respectively. The solid arrows in the band diagrams represent the electron flows $j_e^{2\rightarrow1}$ from well 2 to well 1, and the shaded regions in the wells indicate the carriers accumulated in each well. $j_e^{2\rightarrow1}$ in (c) and (e) are fixed at $(j_e^{2\rightarrow1})_{th}$. In (b), (d) and (f), dashed lines and dotted lines show the gain in well 1 and well 2, respectively, and solid lines the total gain.

n_1 in well 1 is fixed independent of I. On the other hand, the electron flow $j_e^{2\to1}$ from well 2 to well 1 increases with the increase of I. Since the magnitude of $j_e^{2\to1}$ is determined mainly by the electron density n_2 in well 2 (because the electrons are transferred from well 2), n_2 should also increase with the increase of I, until lasing at λ_2 occures at its own threshold I_{th2} (Figs.4(c) and 4(d)). For $I \geq I_{th2}$, both n_1 and n_2 are fixed while P_2 increases with I. A rough calculation on the gain spectra of the present ADQW structure indicates that the optical gain at λ_2 is positive[6] not only in well 2 but also in well 1 at $I = I_{th2}$. Consequently, the electrons injected into well 1 participate in generating λ_2 photons as well as λ_1 photons as shown in Fig.4(e). Since the magnitude of $j_e^{2\to1}$ is fixed at a threshold value $(j_e^{2\to1})_{th}$ for $I \geq I_{th2}$ (because both n_1 and n_2 are fixed), the total number of photons generated from well 1 is also fixed. On the other hand, the stimulated emission rate of λ_2 photons from well 1 is proportional to P_2 and grows with the increase of I, because λ_2 photons generated from well 2 increases with I. As a result, P_1 in turn decreases for $I > I_{th2}$. This explains the observed behaviour. On the other hand, wavelength switching in the SQW LD was explained as mainly due to carrier heating by increased current injection and partly due to multimode coupling[2]. Carrier heating may also contribute to the switching behaviour in our ADQW LD. The above-mentioned switching mechanism is important for the case of high/thick barriers, whereas the carrier heating becomes significant in thin well structures. More detailed studies are necessary to clarify the wavelength switching mechanism for the present ADQW LD. Furthermore the optimization of ADQW structure may prevent carrier heating, thus results in more stable switching operation.

Finally, it should be noted that the lasing wavelengths of 831 nm and 818 nm are slightly shifted from the lasing wavelengths of 840 nm and 810 nm expected from the quantized levels. This is probably due to the fact that the overall optical gain is the sum of that for each well and thus the net gain peaks are shifted from each peak for each well. For a larger separation between the two lasing wavelengths, the following improvement can be thought: much higher and/or thicker barrier (which results in larger n_2 and smaller n_1); much thicker wells; larger gap difference between the two wells.

In conclusion, we have proposed a novel ADQW structure for a wide-range wavelength tunability, and have demonstrated the first experiment on wavelength switching. With increasing injected current, wavelength switching from 831 nm to 818 nm, as well as simultaneous lasing at both wavelengths has been observed under CW operation at $5°C$. We expect that better device efficiency and larger wavelength separation are obtainable by optimizing the ADQW structure and the growth condition.

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