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# Effect of Stripe Width on Threshold in Single Quantum Well Laser Diodes

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# 단일양자우물 Laser Diode에서 Stripe 폭이 문턱치에 미치는 영향

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## ABSTRACT

Threshold dependence on stripe width in gain-guided single quantum well lasers has been examined by complex domain effective index method. It is found, in narrow stripe regime, that the lateral optical confinement estimated by newly introduced parameter $\Omega$ decreases very rapidly as the transverse optical confinement factor $\Gamma$ decreases. Thus, in a single quantum well laser with a usually very small $\Gamma$, the optical confinement may become very poor depending on stripe width not only in the transverse but also in the lateral direction, further enhancing the gain saturation and often leading to an anomalously high threshold current. The understanding of rather anomalous threshold dependence on stripe width will be very important in optimization of quantum well laser diode structures.

## 要 約

Gain-guided 구조를 갖는 단일양자우물 laser diode에서, stripe 폭에 따른 threshold의 변화를 복소수 영역 유효굴절률방법을 이용하여 분석하였다. 분석결과 stripe 폭이 좁은 영역에서는, 측방향광집속률을 나타내기위하여 세롭게 도입된 변수 $\Omega$가 수직방향광집속률 $\Gamma$가 감소함에따라 급격하게 감소하는 경향을 알아내었다. 따라서 일반적으로 매우작은 수직방향광집속률 $\Gamma$를갖는 단일양자우물 laser diode에서는, stripe 폭의 크기에 따라서는 광집속률이 측방향은 물론 수직방향으로도 매우 나빠지게 됨으로 이득포화 현상을 더욱 심하시키게되며 경우에 따라서는 문턱전류가 비정상적으로 증가하는 현상으로 이어지게된다. 이와같은 문턱치의 stripe 폭에 대한 약간의 비정상적인 의존성을 이해하는것은 양자우물 laser diode의 구조최적화에 있어서 매우 중요한 일이라고 판단된다.


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## Ⅰ. Introduction

The most remarkable achievements with quantum well (QW) lasers may be the extremely large output power obtained utilizing a long cavity and a wide current injection stripe.[1] However, in applications requiring a relatively low output power which is realized better with a narrow stripe and a short cavity, QW laser diodes may not be as successful. For example, QW lasers with a short cavity usually have anomalously high threshold currents.[2,3] It was also reported that, especially in single quantum well (SQW) lasers with a relatively narrow stripe, the threshold current is often larger than in DH lasers.[4]

In QW lasers, in which the active layer is as thin as the quantum size effect can be observed, the active layer optical confinement factor Γ is extremely small. Even though the active layer optical confinement factor Γ is improved considerably with a separate confinement layer added[5] as shown in Figure 2, it is in general very small compared to in DH lasers. Also in QWs, gain saturation occurs due to rapid band filling,[6] as the theoretically calculated gain-current curve shows in Figure 3. With the feature of both gain saturation and very small active layer optical confinement factor, it is very likely that the threshold active layer gain becomes very high and is in the saturation region. If this occurs, the carrier density will be extremely high activating various non-radiative processes such as Auger recombination, carrier overflow to confinement or cladding layer, and carrier transition to nonradiative bands,[3,7] often leading to anomalously high threshold currents. Thus, in designing QW laser diodes, it is crucial to make the threshold active layer gain as low as possible and minimize the gain saturation.

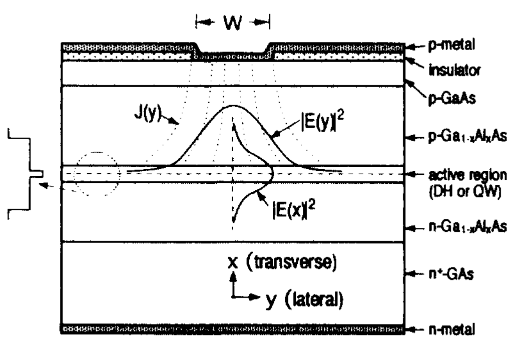


Figure 1. Schematical Cross-sectional view of laser diodes. If not specified otherwise, the refractive indices of active layer and cladding layer are assumed to 3.59 and 3.14, respectively. W : stripe width.

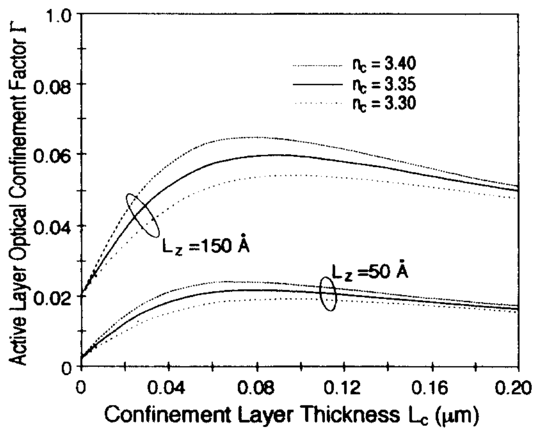


Figure 2. Active layer optical confinement factor Γ as a function of confinement layer thickness $L_c$. $L_z$ : QW thickness, $n_c$ : confinement layer refractive index.

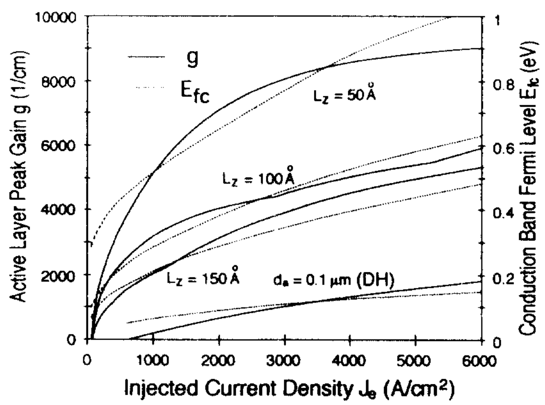


Figure 3. Active layer peak gain g and conduction band quasi-Fermi level $E_{fc}$ (measured from the bulk conduction band edge) as a function of the injected current density. $d_a$ : active layer thickness in DH structure.

In QW lasers with the feature of gain saturation, the threshold in general depends much more sensitively on geometry parameters such as cavity length L and the stripe width W. The threshold dependence on stripe width have been studied very rarely compared to the threshold dependence on cavity length. It is very important, however, to understand how the threshold depends on stripe width, since in most practical applications a relatively narrow stripe, which is to better stabilize the lateral modes, is required. In addition, in QW lasers the differential mode gain may become extremely small in the saturation region. In this case, even a very small amount of mode loss change, for example, as a result of stripe width change will have a much more serious effect than in DH lasers with virtually no gain saturation. In this work, the threshold dependence on stripe width W is analyzed by using the complex domain effective index method.[8]

## Ⅱ. Theory

The evaluation of threshold dependence on stripe width begins with a proper estimation of mode gain G. In most of the previous studies, mode gain G has been estimated by

$$G = \Gamma g \qquad (1)$$

where Γ and g are the transverse active layer optical confinement factor and the active layer gain, respectively. In reality, however, the gain G estimated by equation (1) is the mode gain for the transverse mode with an infinite lateral width. When the current injection stripe W is relatively small, the mode profile will not overlap well with the gain profile in the lateral direction. In this case, the mode gain is estimated better by

$$G = \int_{-\infty}^{\infty} \int_{act} g(y)\,|E(x, y)|^2\,dxdy \Big/ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x, y)|^2\,dxdy \qquad (2)$$

where E(x, y) is the modal electric field. However, the equation (2) is not easily applicable because in general the modal field E(x, y) is not very well defined in y-direction.

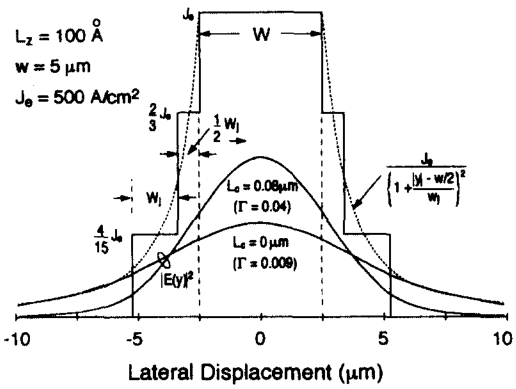


Figure 4. Approximated current density and lateral mode profiles when stripe width W is 5 μm and uniform injected current density $J_e$ in the stripe region is 500 A/cm². $L_c$ : confinement layer thickness, Γ : transverse optical confinement factor, $W_j$ : characteristic current spreading length.

In this study, instead of using the equation (2) directly, the complex domain effective index method has been used.[8] In this method, the current density profile estimated by Yonezu et al.[9] was piecewise-uniformly approximated into seven lateral layers as shown in Figure 4, and the active layer gain profile g(y) was then calculated using the equations by Yan et al.[10] Appropriate loss or gain, in addition to active layer gain g, should be also assumed in a waveguide. We have also included the effect of the gain induced refractive index change Δn by

$$\Delta n = \alpha \frac{\Delta g}{2k} \qquad (3)$$

where $\alpha$, $\Delta g$, $k=2\pi/\lambda$, and $\lambda$ are the line width enhancement factor assumed to $-0.5$,[6] gain change, free space propagation constant, and wave length, respectively. Then the net mode gain $G_n$ is given by

$$G_n = 2\mathrm{Im}(\beta_y) \tag{4}$$

where $\beta_y$ is the complex mode propagation constant for the lateral mode. It is noted that the gain by equation (4) is the net mode gain, since the internal mode loss due to either the lateral radiation[8] or the absorption is automatically taken into account. The threshold will be achieved when the net mode gain is equal to the output mirror loss, $1/L\cdot\ln(1/R)$ where L and R are the cavity length and reflectivity, respectively. In this study, a very useful parameter $\Omega$, named the lateral optical confinement factor, is defined by

$$G_n = \Omega\cdot G_{xe} = \Omega\cdot(2\mathrm{Im}(\beta_{xe})) \tag{5}$$

where $G_{xe}$ and $\beta_{xe}$ is the transverse mode gain and the transverse mode propagation constant, respectively, in the stripe region in which uniform current density $J_e$ is assumed as shown in Figure 4. It is noted that the equation (5), in reality, is obtained by extending the relationship in equation (1) into the lateral direction.[8]

## Ⅲ. Computational Results

Figure 5 shows the lateral optical confinement factor as a function of the stripe width W at a current density $J_e = 500$ A/cm$^2$. It is quite obvious that as the stripe width decreases the lateral optical confinement factor $\Omega$ decreases, because not only the mode spreads more but also the lateral radiation increases.[8] Another very important observation in Figure 5 is that the lateral optical confinement factor $\Omega$ decreases as the transverse optical confinement factor $\Gamma$, since in general the gain-induced lateral guiding or optical confinement effect decreases as the active layer

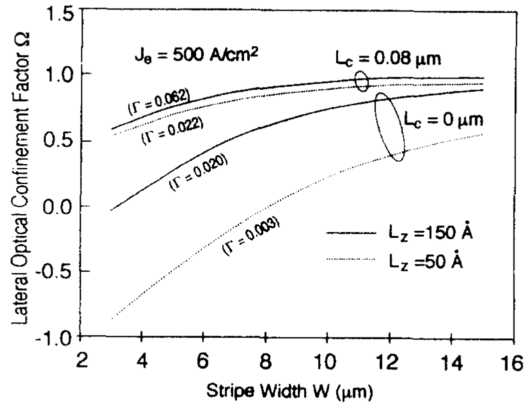


Figure 5. Lateral optical confinement factor $\Omega$ as a function of the stripe width at a injected current density $J_e = 500$ A/cm$^2$.

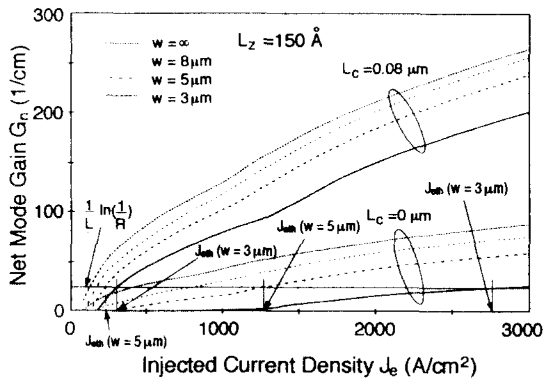


Figure 6. Net mode gain $G_n$ as a function of the injected current density for various stripe width. $J_{eth}$ : threshold current density at a given mirror loss $1/L\cdot\ln(1/R)$.

optical confinement factor $\Gamma$.[11] This point can also be observed in Figure 4. The lateral mode spreads more in a simple QW structure ($L_c = 0$ $\mu$m) with smaller $\Gamma$, compared to in a separate confinement heterostructure (SCH) with improved $\Gamma$. Similarly, compared to in DH lasers with a lager $\Gamma$, the optical confinement in QW lasers is in general very poor not only in the transverse but also in the lateral direction. The seriously de graded lateral optical confinement factor $\Omega$ can easily move the threshold active layer gain into the saturation region, thereby increasing the threshold current significantly.

Figure 6 shows the net mode gain as a function of the current density $J_e$. For a same stripe width, the SCH-QW structure with larger $\Gamma$ and $\Omega$ have a larger net mode gain and a lower threshold current density $J_{eth}$ than a simple QW ($L_c = 0$ $\mu$m) structures. In addition, in the SCH-QW structure, the threshold current density depends much less sensitively on stripe width. For example, when the stripe width changes from 5 $\mu$m to 3 $\mu$m but with the mirror loss fixed as indicated in the figure, the threshold current density $J_{eth}$ changes from 230 A/cm$^2$ to 310 A/cm$^2$ for the SCH-QW lasers while for the simple QW lasers it changes much more significantly from 1250 A/cm$^2$ to 2750 A/cm$^2$. Similarly, in a DH laser with both much larger $\Gamma$ and $\Omega$, the threshold current density will have a much less sensitive dependence on stripe width.

In our calculation, we have neglected the effect of the non-radiative processes which will become active under severe band filling. As shown in the Figure 3, the conduction band quasi-Fermi level $E_{fc}$ rises significantly as the current density increases. For example, in the case of GaAs QW of $L_z = 100$ Å at current density $J_e = 2000$ A/cm$^2$, the $E_{fc}$ is about 0.38 eV and is larger than the conduction band offset $\Delta E_c$ which is about 0.28 eV between GaAs active layer and $Ga_{0.65}Al_{0.35}As$ confinement layer.[12] This implies that a considerable amount of injected carriers would overflow to confinement layer degrading the carrier injection efficiency significantly.[7] The effect of the carrier overflow will become more serious as the stripe width decreases, since the lateral optical confinement factor $\Omega$ decreases as the stripe width, leading to more severe band filling and gain saturation. With this effect included, the actual threshold current density will depend on stripe width W more sensitively than expected in our calculation.

## Ⅳ. Summary and Discussion

In summary, the lateral optical confinement factor $\Omega$ in gain-guided QW lasers has been estimated by using the complex domain effective index method. The result reveals that as the stripe width decreases the lateral optical confinement factor $\Omega$ becomes closely related with the transverse optical confinement factor $\Gamma$, and in general, as the $\Gamma$ decreases the $\Omega$ also decreases. As a result, in gain-guided QW lasers with a usually very small $\Gamma$, the lateral optical confinement factor $\Omega$ may become very small depending on stripe width W, further enhancing the gain saturation and often leading to anomalously high threshold current. By the same token, in QW lasers, the smaller the stripe width, the larger the critical cavity length below which the threshold current increases anomalously.

Based on the above understanding, a fundamental guide line for optimization of QW laser diodes in terms of especially threshold and output power is made as below.

1) Narrow Width Regime ($W <$ for example 5 $\mu$m):
In this low output power regime, the single quantum well (SQW) structure may hardly complete with the conventional DH structure in terms of especially threshold current and temperature characteristics. One possible approach may be to employ either a strongly index-guided or a multiple quantum well (MQW) structure in order to improve the $\Omega$ or both the $\Gamma$ and $\Omega$, respectively. In the case of MQW structure, however, the external quantum efficiency may converge to that of DH structure as the number of wells N increases.

2) Intermediate Width Regime ($5\,\mu m < W < 20\,\mu m$):
In htis medium output power regime, depending on cavity length L and stripe width W, either a SQW or a MQW ($N = 2$ or 3) structure may be employed, However, a strongly index guided structure may be inevitable.

3) Wide Width Regime (W > 20 $\mu$m):

In this high output power regime, a SQW structure is preferred over either DH or MQW structure, especially in terms of output power and efficiency.

Lastly, we believe that the above conclusions will hold equally well for other material systems, such as InGaAsP/InP and InGaP/InGaAlP.

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