A Novel Theoretical Procedure to Determine Absorption and Gain Coefficients in a Symmetric Single Step-Index Quantum Well Laser

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Abstract

If the indices n_{II}, $n_{I,III}$ of the regions, the thickness 2a of the active region (AR) and the wavelength λ for a single symmetric step-index quantum well laser (SSSIQWL) are given, the normalized propagation constant (NPC) α is obtained. In this novel method, absorption and gain coefficients for the SSSIQWL have been obtained in terms of the NPCs α in the even and odd fields, directly.

1. Introduction

In double-heterostructure lasers, thickness of the active region (AR) is typically of the order 0.1 to $0.3\mu m$. The thickness $2a$ of the AR is made smaller in a single quantum well, for example, where $2a$ = 50–100 Å [1]. Because the normalized propagation constant (NPC) α is a structural parameter for material, the probability ratios in this novel method are valid for conventional semiconductor and quantum lasers. Furthermore, this method permits one to calculate a lot of parameters for SSSIQWL [2, 3, 4]. In this work, the absorption and gain coefficients for the SSSIQWL have been obtained in terms of the probability ratios, or NPCs α, in the even fields (EF) and odd fields (OF), directly. These are the novelties of this paper.

The notations n_{II} and $n_{I,III}$ in Figure 1 are refractive indices of the regions for the SSSIQWL. The relationship between the indices is $n_{II} > n_{I,III}$ for the SSSIQWL. Propagation constants are [2, 3, 4]

$$\alpha_{II}^2 = \left(\frac{\omega n_{II}}{c}\right)^2 - \beta_z^2 \text{ and } \alpha_{I,III}^2 = \beta_Z^2 - \left(\frac{\omega n_{I,III}}{c}\right)^2 .$$

The carriers are confined in the AR, which is deep between highly thick left and right barriers. The energy states for the carriers in the AR can be described [2, 3, 4] by the EF and OF, respectively:

$$E_{yI} = A_I exp\left[\alpha_I (x + a)\right],$$

$$E_{yII} = Acos\alpha_{II}x = Acos\frac{n\pi x}{2a}, n = 1, 3, 5, ...$$

$$E_{yIII} = A_{III} exp\left[-\alpha_{III}(x - a)\right],$$

$$A = \sqrt{\frac{2\alpha_{II}}{2\zeta + sin2\zeta}}, \quad A_I = A_{III} = A_{I,III} = Acos\zeta$$

and

$$e_{yI} = B_I exp\left[\alpha_I(x+a)\right],$$

$$e_{yII} = Bsin\alpha_{II}x = Bsin\frac{n\pi x}{2a}, n = 2, 4, .6\ldots,$$

$$e_{yIII} = B_{III} exp\left[-\alpha_{III}(x-a)\right]$$

$$B = \sqrt{\frac{2\alpha_{II}}{2\zeta - sin2\zeta}} \quad B_I = B_{III} = B_{I,III} = Bsin\zeta.$$

These fields verify the Schrödinger wave equation [2, 3, 4]. $\zeta = \alpha_{II}a$, $\eta = \alpha_{I,III}a$ are parametric variables of the energy eigenvalues of the carriers in the normalized coordinate system $\zeta - \eta$, $\mathrm{V} = (\zeta^2 + \eta^2)^{1/2}$ is the normalized frequency (NF), NPC is $\alpha = \eta^2/\mathrm{V}^2 = \sin^2\zeta$ [2, 3, 4, 5].

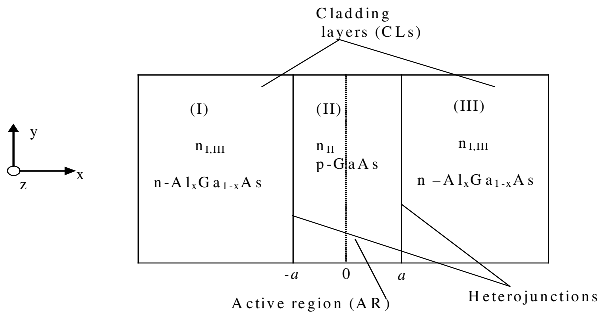

Figure 1. Regions of a SSSIQWL.

A field probability function ratio, $\bar{R}(\bar{r})$, can be defined as the ratio of the total evanescent field function probability I_ℓ (I'_ℓ), in the region I and III to the active field function probability (I_{II}) in the AR in a SSSIQWL. $\bar{R}(\bar{r})$ is expressed as

$$\frac{I_\ell}{I_{II}} = \bar{R} = \frac{1-\alpha}{\eta+\alpha},$$

$$I_\ell = \int_{-\infty}^{-a} |E_{yI}(x)|^2 dx + \int_{a}^{\infty} |E_{yIII}(x)|^2 dx,$$

$$I_{II} = 2\int_{0}^{a} |E_{yII}(x)|^2 dx$$

$$I_i = I_{II} + I_\ell$$

where

$$\bar{r} = \frac{I'_\ell}{I'_{II}} = \frac{1-\alpha}{\eta-\alpha}, \quad I'_\ell = \int_{-\infty}^{-a} |e_{yI}(x)|^2 dx + \int_{a}^{\infty} |e_{yIII}(x)|^2 dx, I'_{II} = 2\int_{0}^{a} |e_{yII}(x)|^2 dx, \quad I'_i = I'_{II} + I'_\ell$$

2. Some Probability Ratios and Confinement Factors in the SS-SIQWL

Representing the confinement factors Γ_{II} and Λ_{II}, [2, 3, 4, 5] for the EF and OF in the AR, respectively, the ratios $\bar{K}$ and $\bar{q}$ of the loss probabilities to the input probabilities can be obtained as

$$\frac{I_\ell}{I_i} = \bar{K} = \frac{1-\alpha}{\eta+1} = \frac{1}{1+1/R} = 1-\Gamma_{II}, \quad \frac{I'_\ell}{I'_i} = \bar{q} = \frac{1-\alpha}{1+\eta-2\alpha} = \frac{1}{1+\frac{1}{\bar{r}}} = 1-\Lambda_{II},$$

respectively; and the confinement factors Γ_{II} and Λ_{II} in the region II are, respectively given by

$$\Gamma_{II} = \frac{\alpha+\eta}{1+\eta} = \frac{\bar{K}}{\bar{R}}, \quad \Lambda_{II} = \frac{\eta-\alpha}{1+\eta-2\alpha} = \frac{1}{1+\bar{r}} = \frac{\bar{q}}{\bar{r}}$$

for the EF and OF in the SSSIQWL. Thus, we have the relations [4] $\bar{K}+\Gamma_{II} = 1$, $\bar{q}+\Lambda_{II} = 1$.

3. The Novel Absorption Coefficients and Gain Coefficients for The SSSIQWL

F_I (respectively, F'_I), F_{II} (F'_{II}) and F_{III} (F'_{III}) represent the confinement factors of regions I, II and III for the even (odd) field. The parameter g (respectively, g') is the gain coefficient, which is described by the structural properties of the SSSIQWL for the EF (OF). We can define absorption coefficients by k_1, k_3 (k'_1, k'_3) in the ASSIQWL or $k_{1,3}$ ($k'_{1,3}$) in the SSSIQWL, in the EF (OF) in regions I and III. Bhattacharya [1] gives $k_1F_I + k_3F_{III} = gF_{II}$, $k'_1F'_I + k'_3F'_{III} = g'F'_{II}$, where $gF_{II}(g'F'_{II})$ is called the modal gain for the EF (OF). These modal gains are obtained as $g\Gamma_{II} = (1-\Gamma_{II})k_{1,3} = \bar{K}k_{1,3}$, $g'\Lambda_{II} = (1-\Lambda_{II})k'_{1,3} = \bar{q}'_{1,3}$ [1]. So, the novel expressions in this paper for absorption and amplification gain coefficients and their ratios become, respectively,

$$k_{1,3} = \frac{\ln G}{\bar{K}\ell_g}, \quad k'_{1,3} = \frac{\ln G'}{\bar{q}\ell_g}, \quad -k_2 = g = \frac{\ln G}{\ell_g\Gamma_{II}}, \quad -k'_2 = g' = \frac{\ln G'}{\ell_g\Lambda_{II}}$$

$$\frac{g}{k_{1,3}} = \frac{\bar{K}}{\Gamma_{II}} = \bar{R}, \quad \frac{g}{g'} = \frac{\Lambda_{II}}{\Gamma_{II}}, \quad \frac{g'}{k'_{13}} = \frac{\bar{q}}{\Lambda_{II}} = \bar{r}, \quad \frac{k_{1,3}}{k'_{1,3}} = \frac{\bar{q}}{\bar{K}}$$

for the even and odd fields in the same power gain (G = G'), respectively. Here, G and G' are power gains of AR of the SSSIQWL for the EF and OF [1].

For example, for $\lambda = 0.5145\times10^{-6}$ m, $n_{I,III} = 1.55$, $n_{II} = 1.57$ and $2a = 1$ μm = 10000 Å in the SSSIQWL, we have V = 3.0506106640935, $\alpha = 0.851569419263456$, $\alpha_{II} = 2.350598599618280 \times 10^6$ m^{-1}, $\zeta = 1.17529929980914$, $\eta = 2.81511935444115$, $\alpha_{I,III} = 5.630238708882300 \times 10^6$ m^{-1}, $\beta_z = 1.939187568094921 \times 10^7$ m^{-1}, $\bar{K} = 0.03890588129668$, $\bar{R} = 0.04048082340694$, $\Gamma_{II} = 0.96109411870332$, $g/k_{1,3} = \bar{R}$. For given $\ell_g = 0.05$ m and G = 5000 we have g = $1.772395236984149 \times 10^2$ m^{-1} and $k_{1,3} = 4.378357671154261 \times 10^3$ m^{-1}. Note that our result for the NF V is more sensitive than the NF in ref. [6], in which NPC had been defined differently from our definition of α. Since $\zeta < 1.57$ in this example, there are no solutions for the OF and its related parameters, such as $\bar{q}$ and Λ_{II} [5]. Consequently, we are able to calculate absorption and amplification gain coefficients in terms of NPC α for given indices n_{II}, $n_{I,III}$, the thickness $2a$ of the AR and the wavelength λ for the EF and OF in the SSSIQWL.

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