JOURNAL OF AERONAUTICS AND SPACE TECHNOLOGIES
JULY 2003 VOLUME 1 NUMBER 2 (73-81)

A NOVEL PROCEDURE AND PARAMETERS FOR DESIGN OF SYMMETRIC QUANTUM WELLS IN TERMS OF NORMALISED PROPAGATION CONSTANT AS A MODEL α IN THE SINGLE MODE

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ABSTRACT

In this work, some design parameters have been obtained, depending on the energy eigenvalue of the carriers such as electrons and holes confined in the quantum well. Some optical power expressions for the active region and cladding layers of the quantum well have been obtained in terms of these parameters and have been theoretically estimated.

Key Words*: Symmetric quantum well, Asymmetric quantum well, Active region power, Loss power, Confinement factor.*

ÖZET

Bu çalışmada, kuantum çukurundaki electron ve delikler gibi taşıyıcıların enerji öz değerlerine bağlı olan bazı tasarım parametreleri elde edilmiştir. Kuantum çukurunun hapsedici tabakaları ve aktif bölgesine ait bazı optik güç ifadeleri elde edilmiş ve teorik olarak hesaplanmıştır.

Anahtar Kelimeler: *Simetrik kuantum çukuru, Asimetrik kuantum çukuru, Aktif bölge gücü, Güç kaybı, Hapsedicilik faktörü.*

1. INTRODUCTION

These days just about everybody has a quantum well (QW) at home. At the heart of every CD player is a layered crystalline structure finely crafted to squeeze laser light from electrons. The scientists create advanced versions of such crystals, producing some of the finest QW material.

Optical devices to understanding the basic principles that govern the operations of the quantum well lasers (QWLs) require a basic comprehension of simple quantum well problem. The QWLs, for example, are around 20-30 atomic layers thick and have been increasingly used to read the information stored on the compact disk. The QWLs are based on the carrier confinement in the QWs as working principle. The single QW is just one of the three basic regions of the quantum devices, which bases on the QW as shown in Fig.1 [1]. The scientists work together to create advanced materials and devices like super fast transistors.

The QWLs produce laser light because of the unique atomic geometry of the layered crystals from which they are fashioned. The regions I, III and II in Fig.1 are called respectively cladding layers (CLs), which are high bandgap layers, and active region (AR). The CLs constitute 2 barriers which are erected by energy [2]. The barriers of energy confine the carriers such as electrons and holes in the AR. For the confinement most of the carriers and photons between the CLs, the QW is realized by the bandgap engineering. When the width $2a$ of the AR is comparable the characteristic length such as Broglie wave length, then the quantum size effect (QSE) occurs [3]. In this case, the carriers introduce new properties and leap a quantum level in energy and release light. This light can read the pattern of pits on a CD or carry information down fibre optic cable in modern high-speed communication networks. By carefully varying crystalline layers to make specialized QWs, scientists can tune lasers to emit optimal wavelengths of light perfectly matched to the transmission properties of a special glass fiber.

The carriers in the AR of the QW are allowed to exist in a certain confined (bound) states, which are described by a wave function such as electric field. That is, the confined states for carriers in the QW can be described by solving the Schrödinger wave equation to solve the quantized electric field wave and energy eigenvalue (EEV) for a carrier. The energy eigenvalues (EEVs) for the carriers in a bulk material [4] are

$$E_n = n^2\pi^2\hbar^2/8m^*a^2, \quad (1)$$

n= 1, 2, 3, ...

and in the AR of the QW

$$E_v = V_o - E_n, \quad (2)$$

n = 1, 2, 3, ...

in which V_o is a barrier potential which is determined by the construction of the semiconductor material used [3], $\hbar$ and m* are normalized Planck constant as $\hbar = h/2\pi$ and effective mass for a carrier, respectively.

The electric fields, which verify the Schrödinger wave equation, for a carrier are respectively

$$E_{yII} = e_y = A\cos\alpha_{II}x = A\cos\frac{n\pi x}{2a}, \quad (3)$$

n=1, 3, 5,...

in the AR and

$$E_{yI} = A_I \exp\left[\alpha_I(x+a)\right], \quad (4)$$

in the region I and

$$E_{yIII} = A_{III} \exp\left[-\alpha_{III}(x-a)\right], \quad (5)$$

in the region III [5]. In eq.(3) the amplitude A is given by

$$A = \sqrt{\frac{2\alpha_{II}}{2\zeta + \sin 2\zeta}}, \quad (6)$$

and so eq.(3) for a single mode, n=1, becomes

$$E_{yII} = e_y = \sqrt{\frac{2\alpha_{II}}{2\zeta + \sin 2\zeta}}\cos\frac{\pi x}{2a}. \quad (7)$$

The parameter ζ and the propagation constants α_I, α_{II} and $\alpha_{I,III}$ [6] in the equations above are respectively given by

$$\zeta = \alpha_{II}a, \quad (8)$$

and

$$\alpha_I^2 = \beta_z^2 - \left(\frac{\omega n_I}{c}\right)^2 = \beta_z^2 - k_I^2, \; k_I = \frac{\omega n_I}{c} = k_o n_I, \quad (9)$$

$$\alpha_{II}^2 = \left(\frac{\omega n_{II}}{c}\right)^2 - \beta_z^2 = k_{II}^2 - \beta_z^2, \; k_{II} = \frac{\omega n_{II}}{c} = k_o n_{II} \quad (10)$$

$$\alpha_{III}^2 = \beta_z^2 - \left(\frac{\omega n_{III}}{c}\right)^2 = \beta_z^2 - k_{III}^2, \quad (11)$$

$$k_{III} = \frac{\omega n_{III}}{c} = k_o n_{III}, \quad (12)$$

$$k_o = \omega/c = 2\pi/\lambda. \quad (13)$$

where λ is the wavelength of the optical field.

In eqs.(9)-(11) β_z is the phase constant in the z-direction. The parameters above defined belong to the asymmetric quantum well (AQW) shown in Fig.1. If it is taken as $n_I = n_{III} = n_{I,III}$ then the AQW becomes the symmetric quantum well (SQW). Therefore, eqs.(4,5) and eqs.(9,11) become as follows:

$$E_{yI,III} = A_{I,III}\exp\left[\pm\alpha_{I,III}(x \pm a)\right], \quad (14)$$

which are evanescent fields, and

$$\alpha_{I,III}^2 = \beta_z^2 - \left(\frac{\omega n_{I,III}}{c}\right)^2 = \beta_z^2 - k_{I,III}^2, \; k_{I,III} = \frac{\omega n_{I,III}}{c} = k_o n_{I,III}. \quad (15)$$

In eq.(14) the negative sign corresponds to the region III. In this work we will study the SQW in terms of the normalized propagation constant as a model α.

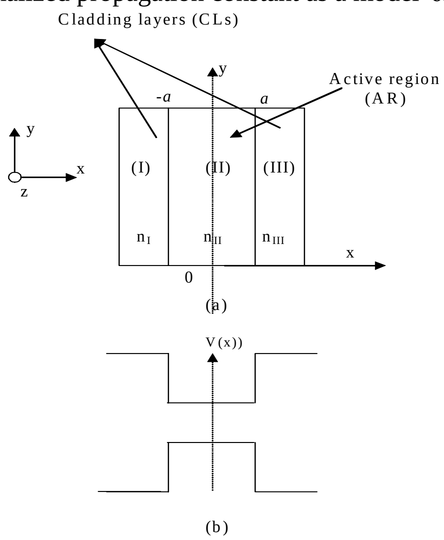

Fig.1 (a) Three basic regions of the AQW, (b) The variation of one-dimensional potential V(x)

2. THE PARAMETER α

For the single mode in the SQW the eigenvalue equation [6] is given by

$$\eta / \zeta = \tan\zeta\,, \quad (16)$$

where η is defined by

$$\eta = \alpha_{I,III} a\,. \quad (17)$$

The parameters $\zeta = \alpha_{II} a = V\cos\zeta$ and $\eta = \alpha_{I,III} a = V\sin\zeta$ are the parametric variables of the EEVs in the normalized coordinate system for the carriers in the AR [6]. The parameters ζ and η form a circle and give normalized frequency (NF) as

$$V = \sqrt{\zeta^2 + \eta^2}\,, \quad (18)$$

which is also given by

$$V = (a/\hbar)\sqrt{2m^* V_o}\,, \quad (19)$$

or

$$V = \frac{2\pi}{\lambda} a \sqrt{n_{II}^2 - n_{I,III}^2}\,, \quad (20)$$

in the another alternative forms [7], as the radius of the circle as shown in Fig.2 [5,6]. The parameter α is defined as

$$\alpha = \eta^2 / V^2 = \sin^2\zeta\,, \quad (21)$$

which is the normalized propagation constant (NPC) [5,6,7]. Because the NPC is nonlinear, α was expressed as

$$\alpha = (1.1428V - 0.9960)^2 / V^2\,, \quad (22)$$

by Rudolf and at al. in the ref.[8] for linearity in the range of $1.5 \langle V \langle 2.5$.

The NPC α gives the another parameter L, which describes the depth of the QW as shown in Fig.2, as

$$L = 1 - \alpha = \zeta^2 / V^2 = \cos^2\zeta\,. \quad (23)$$

The parametric variables ζ and η are also given by

$$\zeta = V\sqrt{1-\alpha} = V\sqrt{L} \quad (24)$$

and

$$\eta = V\sqrt{\alpha}\,, \quad (25)$$

in terms of α and the parameter L [5,6] .

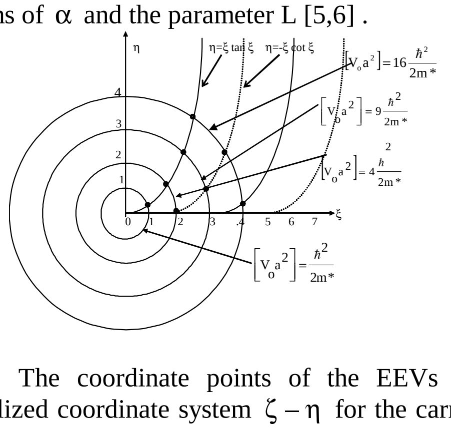

Fig. 2 The coordinate points of the EEVs in the normalized coordinate system $\zeta - \eta$ for the carriers in the QWs (dotted lines belong to the odd field).

3. THE PROPERTIES OF THE NPC α

Another defining of the NPC α_e [6] for the AQW is given by

$$\alpha_e = \frac{\beta_z^2 - k_I^2}{k_{II}^2 - k_I^2} = \frac{n_{ef}^2 - n_I^2}{n_{II}^2 - n_I^2} = \frac{\eta^2{}_e}{V_e^2} = \frac{2(\eta_I^2 + \eta_{III}^2)}{V^2(1+\sqrt{1+a_p})^2}\,, \quad (26)$$

where the parameters $\eta_I = a\alpha_I$ and $\eta_{III} = a\alpha_{III}$ for the CLs are the ordinates of the EEVs for carriers for the regions I and III in the AQW and one can write as

$$\eta_e = \sqrt{(1/2)[\eta_I^2 + \eta_{III}^2]} = V_e\sqrt{\alpha_e}\,, \quad (27)$$

where

$$V_e = \sqrt{\zeta_e^2 + \eta_e^2}\,, \; \zeta_e = \zeta = \alpha_{II} a\,, \quad (28)$$

$$a_p = (n_I^2 - n_{III}^2)/(n_{II}^2 - n_I^2)\,, \quad (29)$$

which is the asymmetric factor [9]. Note that eq.(27) for the AQWs yields $\eta_I = \eta_{III} = \eta_{I,III}$ for the SQWs.

The parametric coordinates ζ_e, η_e define an elipse. Here η_e is the ordinate of the energy eigenvalue point on the ellipse for a carrier and V_e is the normalized frequency corresponding to this ordinate. If $\eta_e = V_e\sqrt{\alpha_e}$ due to eq.(25) is used in eq.(26), α_e is obtained. This means that, in order to get the NPC, η_e and V_e change in such a way that the ratio η_e / V_e remains as the NPC (as a constant). In eq.(26) $n_{ef} = \beta_z / k_o$ is effective index. If it is taken as $n_I = n_{III} = n_{I,III}$ then a_p=0 and thus eq.(26) becomes

$$\alpha_e = \frac{n_{ef}^2 - n_{I,III}^2}{n_{II}^2 - n_{I,III}^2} = \frac{\eta^2{}_c}{V_c^2} = \frac{\eta^2{}_{I,III}}{V_{I,III}^2} = \alpha_{I,III} = \alpha\,, \quad (30)$$

$$(\zeta = \zeta_c = \zeta_{I,III}, \eta = \eta_c = \eta_{I,III}, V = V_c = V_{I,III})$$

where α represents the NPC for the SQWs. The parameters $\zeta_c = \alpha_{I,III} a = V_c\cos\zeta$ and $\eta_c = \alpha_{I,III} a = V_c\sin\zeta$ give a circle with the radius V=V_c for the even field. If the circle is schematically plotted in Fig.3, then from the figure one obtains $\sin^2\gamma = \eta_c^{\,2}/V_c^{\,2}$, in which η_c and V_c are respectively the ordinate of the point on the circle and the normalized frequency corresponding to this ordinate η_c for the energy eigenvalue of a carrier.

So, the NPC α_c for this circle with the radius V_c is given by

$$\alpha_c = \sin^2\zeta_c = \sin^2\gamma = \eta_c^{\,2}/V_c^{\,2}. \quad (31)$$

If the equation $\eta_{I,III} = V_{I,III}\sqrt{\alpha} = V\sqrt{\alpha}$ or $\eta_c = V_c\sqrt{\alpha} = V\sqrt{\alpha}$ substitutes in eq.(31), it is also seen that $\alpha_c = \alpha$, as shown in eq.(30). Here, α represents the NPC for the circle. This states that the NPC is independent of the angle γ and a constant, corresponding to normalized frequency V_c and the ordinate η_c.

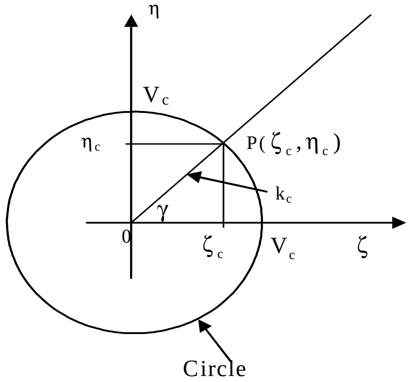

Fig.3 Effective index surface given by the circle for ordinary wave

The circle in Fig.3, represents an ordinary wave and OP can be considered a wave number such as k_c. In such a medium, according to normalized wave number $\dfrac{k_c}{k_o}$, the formula

$$\frac{k_o^{\,2}}{k_c^{\,2}} = \frac{1}{n_c^{\,2}} \quad (32)$$

expresses the effective index surface for the ordinary wave and is independent of the angle γ [2].

From Fig.4, one obtains the parametric equations of the ellipse as

$$\zeta_e = R_1\cos\gamma = R_1\cos\zeta_e, \quad (33)$$

$$\eta_e = R_2\sin\gamma = R_2\sin\zeta_e \quad (34)$$

where R_1 and R_2 are the radii of the ellipse. This ellipse is formed by the effective index of the AQW. Fig.4 has also Fig.3, and represents the index surface for the AQWs. Triangles $0P\zeta_c$ and $OE\zeta_e$ are similar triangles, as shown in Fig.4. So, for the AQW and SQW, respectively, the normalized propagation constants α_e and α_c are equal to each other [cf.eq.(31)]. As a matter of fact, one gets

$$\alpha_e = \sin^2\zeta = \sin^2\gamma = \eta_e^{\,2}/V_e^{\,2}, \quad (35)$$

or from eqs.(33,34),

$$\alpha_e = \eta_e^{\,2}/R_2^{\,2}. \quad (36)$$

Once the free wave number k_o and the length *a* of the QW are selected for a working point as certain values, the both parameters η_e and V_e change with respect to each other in such a way that the NPC α_e remains as a constant. But, to get the changing radii for ellipse, according to the effective index surface, the indices must change with wavelength λ [2].

Consequently, the effective index does depend on the form of ellipse as shown in Fig.4 and this index surface corresponds to the extraordinary wave [2] and is given by

$$\left[\frac{k_o}{k_e}\right]^2 = \frac{1}{n_{ef}^{\,2}} = \frac{\cos^2\gamma}{n_1^{\,2}} + \frac{\sin^2\gamma}{n_2^{\,2}}, \quad (37)$$

which describes an ellipse[2]. The phase constants for the ordinary waves are not equal for $\gamma \neq 0$. This fact plays a critical role in the nonlinear optics. OE in Fig.4 can be regarded as the wave number k_e for extraordinary wave. In eq.(37), for $\gamma = 0$ and $\gamma = 90^o$ note that the effective indices are respectively equal to the indices n_1 and n_2, respectively.

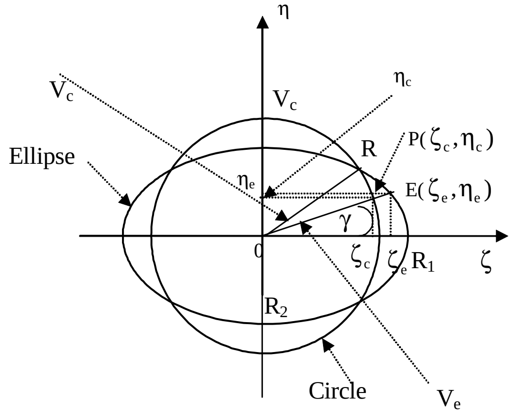

Fig.4 Effective index surfaces on the circle and ellipse for ordinary and extra ordinary waves

In coclusion, the NPC for the material used about any QW is dependent of indices of the regions of the QW and also dependent of structural parameters of material used and barrier potential V_o and the length *a* of the

QW. As a matter of fact, some of these are implied by the expressions [4] as follows for a single mode, $\nu = 1$:

$$\alpha = \frac{E_\nu}{V_o} = \frac{E_1}{V_o}, \; E_1 = \frac{\hbar^2\pi^2}{8m^* a^2}, \quad (38)$$

In eq.(38) V_o, and, m* represent the barrier potential, the width of the QW and the effective mass for a carrier, respectively.

Consequently, the NPC α belonging to the QW for given k_o, n_I, n_{II} and n_{III} is obtained as only one value. For this NPC, the parametric coordinates of the EEVs for carriers constitute an elipse in the AQWs, while they form a circle for the SQWs ($n_I = n_{III} = n_{I,III}$) for the single mode.

4. POWER FOR THE AR IN THE QW

In the AR the power P_{II} is requested as a unity, after loss power $P_{I,III}$ flows through the CLs, is shown in Fig.5.

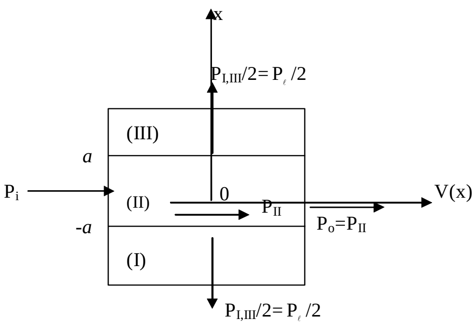

Fig.5 Different powers in the QW in the model α

Denoting the complex conjugate with (*), the power P_{II} of the AR [6] in Fig.5 is defined as

$$P_{II} = \int_{-a}^{a} e_y(x) e_y(x)^* dx = A^2 W, \quad (39)$$

for the AQW or

$$\begin{aligned} P_{II} &= 2\int_0^a e_y(x) e_y(x)^* dx \\ &= 2\int_0^a \left| e_y(x) \right|^2 dx \end{aligned}, \quad (40)$$

for the SQW. From eqs.(3,40) in the SQW, one gets

$$P_{II} = 2A\int_o^a \cos^2 \alpha_{II} x dx = A^2 \left(a + \frac{\sin 2\zeta}{2\alpha_{II}}\right) \quad (41)$$

and so

$$W = a + \frac{\sin 2\zeta}{2\alpha_{II}} \quad (42)$$

which is called effective optical mode width [10].

Eqs.(6,41) give P_{II}=1. The input power P_i in the SQW is given by

$$P_i = P_{II} + P_{I,III}. \quad (43)$$

In this α model, one assumes that $P_i \rangle P_{II}$ and

$$P_o = P_{II} = P_i - P_{I,III} = P_i - P_\ell. \quad (44)$$

in which $2P_\ell$ is the loss power.

5. LOSS POWER IN THE QW

In the AQW the loss power [6] for the CLs in Fig.5 is generally defined as follows:

$$P_I = \int_{-a}^{0} E_{yI}(x) E_{yI}(x)^* dx, \quad (45)$$

$$P_{III} = \int_0^a E_{yIII}(x) E_{yIII}(x)^* dx, \quad (46)$$

$$P_\ell = P_I + P_{III}. \quad (47)$$

The loss in eq.(47) in the AQW becomes as

$$P_\ell = P_{I,III} = 2\int_0^a E_{yI,III}(x) E_{yI,III}(x)^* dx \quad (48)$$

in the SQW or

$$P_\ell = 2\int_0^a \left| E_{yI,III}(x) \right|^2 dx = \frac{A^2_{I,III}}{\alpha_{I,III}} \quad (49)$$

where

$$A_{I,III} = A\cos\zeta, \quad (50)$$

and so

$$P_\ell = \frac{A^2\cos^2\zeta}{\alpha_{I,III}} = \frac{2\zeta}{\eta}\frac{L}{2\zeta + 2\cos\zeta\sin\zeta}, \quad (51)$$

or

$$P_\ell = \left(\frac{L}{\eta}\right)\frac{1}{1+\eta/V^2} = \frac{L}{\eta+\alpha}. \quad (52)$$

Eq.(39) yields

$$\begin{aligned} P_{II} &= \frac{A^2_{I,III}}{\alpha_{I,III}}\left(\frac{\eta}{\cos^2\zeta} + \frac{\eta}{2\zeta}\frac{\sin 2\zeta}{\cos^2\zeta}\right) \\ &= P_\ell\left(\frac{\eta}{\cos^2\zeta} + \frac{\eta}{2\zeta}\frac{\sin 2\zeta}{\cos^2\zeta}\right) \end{aligned}, \quad (53)$$

or eqs.(40,41,49,53) give

$$P_{II} = P_\ell\left(\frac{\eta}{L} + \frac{\eta^2}{\zeta^2}\right) = 1, \quad (54)$$

or from this equation one gets

$$P_\ell = \frac{1}{\frac{\eta}{L} + \frac{\eta^2}{\zeta^2}} = \frac{L}{\eta + \alpha}, \quad (55)$$

with the help of eqs.(24,25). Note that this different procedure is also in agreement with eq.(52).

6. INPUT POWER IN THE QW

The input power P_i [6] in the AQW in Fig.5 is defined as

$$P_i = \int_{-a}^{a} e_y(x) e_y(x)^* dx + \int_{-a}^{0} E_{yI}(x) E_{yI}(x)^* dx + \int_{0}^{a} E_{yIII}(x) E_{yIII}(x)^* dx, \quad (56)$$

or in the SQW

$$P_i = 2\int_0^a e_y(x) e_y(x)^* dx + 2\int_0^a E_{yI,III}(x) E_{yI,III}(x)^* dx$$

$$= 2\int_0^a \left|e_y(x)\right|^2 dx + 2\int_0^a \left|E_{yI,III}(x)\right|^2 dx, \quad (57)$$

or from eq.(43)

$$P_i = 2\int_0^a \left|e_y(x)\right|^2 dx + P_\ell, \quad (58)$$

or the power for the AR

$$P_{II} = P_i - P_\ell = 2\int_0^a \left|e_y(x)\right|^2 dx, \quad (59)$$

or from eq.(3)

$$P_{II} = P_i - P_\ell = 2A^2 \int_0^a \cos^2(\alpha_{II} x) dx$$

$$= A^2\left(a + \frac{\sin 2\zeta}{2\alpha_{II}}\right) = A^2 W, \quad (60)$$

and from eq.(51).

$$P_{II} = P_i - P_\ell = P_\ell\left(\frac{\eta}{L} + \frac{\eta^2}{\zeta^2}\right), \quad (61)$$

or

$$P_i = P_\ell + P_\ell\left(\frac{\eta}{L} + \frac{\eta^2}{\zeta^2}\right). \quad (62)$$

So, the parameter K [6] is

$$\frac{P_\ell}{P_i} = K = \frac{1}{\frac{\eta}{L} + \frac{\eta^2}{\zeta^2} + 1} = \frac{L}{\eta + \alpha + L}, \quad (63)$$

or from eq.(23)

$$K = \frac{1-\alpha}{\eta + 1}. \quad (64)$$

The confinement factor [6] is defined by

$$F_{II} = \frac{P_{II}}{P_i} = 1 - K = \frac{\eta + \alpha}{\eta + 1}. \quad (65)$$

In the same way from eq.(54) one gets the parameter R [6] as

$$\frac{P_\ell}{P_{II}} = R = \frac{1}{\frac{\eta}{L} + \frac{\eta^2}{\zeta^2}} = \frac{1-\alpha}{\eta + \alpha}. \quad (66)$$

The power for the AR from eqs.(55,61) is obtained as

$$P_{II} = P_i - P_\ell = \frac{L}{\eta + \alpha}\left(\frac{\eta}{L} + \frac{\eta^2}{\zeta^2}\right) = 1, \quad (67)$$

which is in agreement with power of the AR defined as a unity. The constant A in eq.(6) due to eq.(42) becomes

$$A = 1/\sqrt{W}. \quad (68)$$

Eqs.(60,68) shows the agreement in eq.(54,67) as a result.

7. THRESHOLD CONDITION AND GAIN

Threshold coefficient (threshold gain) [2] for the SQWs is determined by the requirement that the round-trip gain is equal to 1:

$$(R_1 R_2)^{1/2} e^{g_o \ell_g} = 1. \quad (69)$$

which gives the threshold gain as

$$g_{th} = \frac{1}{2\ell_g} \ln \frac{1}{R_1 R_2}. \quad (70)$$

If one considers only mirror losses, this implies that for the amplifying the gain coefficient g must be sufficiently large, so that

$$(R_1 R_2)^{1/2} e^{g\ell_g - g_o \ell_g} \geq 1 \quad (71)$$

or

$$g = g_o + g_{th} \quad (72)$$

where ℓ_g and g_o are respectively the length of the cavity and the only mirror losses.

8. ESTIMATION PROCEDURE BY MEANS OF THESE DESIGN PARAMETERS IN THE SINGLE QWs AT THE NEAR THRESHOLD LEVEL

For a=5 A°, $\lambda = 1.55\ \mu m$, $n_{I,III}$=3.350 and n_{II}=3.352, one gets V=1.6592, which is in the range of the linearity. Therefore, eq.(22) gives $\alpha = 0.2995$ and so L=0.7005. The parametric coordinates ζ and η of the EEVs in Fig.2 are respectively ζ = =1.38868 and $\eta = 0.90802$ according to eqs.(24,25). The loss power P_ℓ in eq.(51) becomes 0.5801. In order to remain as a unity of the power P_{II} for the AR, the input power $P_i = 1 + P_\ell$ according to eqs.(43,48) must be 1. 5801 and the confinement factor F_{II} in eq.(65) is 0.6329.

The absorption coefficients within the regions I and III of the AQWs give the relation with the confinement factor F_{II} [11] as

$$F_{II} + k_I + k_{III} = 1\,, \quad (73)$$

where k_I and k_{III} are respectively absorption coefficients for the regions I and III. From eqs.(65,73) one gets

$$K = k_I + k_{III} \quad (74)$$

in the AQWs and taking $k_I = k_{III}$

$$k_I = k_{III} = K/2, \quad (75)$$

in the SQWs. So, one can get as [11]

$$g_{th} F_{II} = (1 - F_{II}) k_I = K^2/2 \quad (76)$$

at the threshold. The threshold condition of the cavity at the situation of small-signal power gain becomes

$$G = e^{g_{th} F_{II}} = e^{K^2/2}, \quad (77)$$

which gives $1.0697 \cong 1$ according to the parameters given above and value of K in eq.(64). This implies the working in the immediate at the threshold level.

Initially, when laser starts, the gain may be much larger than the threshold gain. After a few oscillations in the value of the round trip gain, the laser action reaches a steady state and the gain obtains a steady-state value. Finally, it should be noted that the efficiency of a laser not only depends on the gain, but also on the pumping of efficiency [3]. Taking the mirror losses and the other cavity losses into account [2,12], one obtains

$$g = g_o + \frac{1}{2\ell_g} \ln \frac{1}{R_1 R_2} = g_o + g_{th} = K^2/2\,, \quad (78)$$

where g_o, and the each of R_1, R_2 are respectively total of the mirror losses, other cavity losses, and reflectivity of the each of mirror as shown in Fig.6. The gain profile and loss level are depicted in Fig.7, in which $\omega_o = 2\pi f_o$, where f_o is resonant frequency.

A few round-trips through the cavity are sufficient to the field quite large. For example, one generally supposes that the net gain

$$(R_1 R_2)^{1/2} e^{(g - g_o)\ell_g} = 4\,. \quad (79)$$

So, eq. (78) for given above parameters yields g=0.76. That is, for example, after just 5 round trips, the intensity will have grown by a factor of $4^{2x5} \cong 1.05x10^6$ with the amplifying of

$$G = e^{g} = 2.13\,, \quad (80)$$

provided that the gain coefficient g stays constant as 2.13 [13].

The real value of eq.(78) must be 1 not 1.0697. Because, the NPC α could not be exactly determined due to non-linearity in eq.(21) and thus has obtained approximately, as 1.0697.

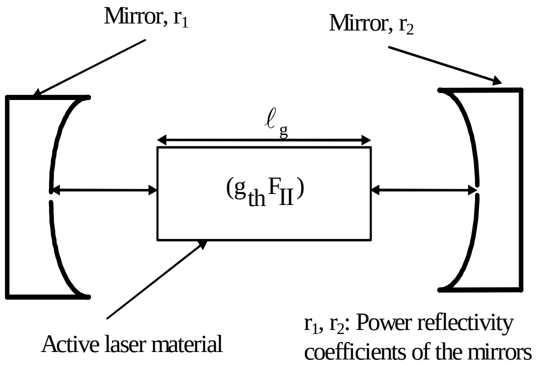

Fig.6 A simple laser resonator at the threshold

If the QW structure repeats itself in a periodic manner, it is known as a multiple quantum well (MQW) such as super lattices and quantum cascade lasers. The MQW structure leads to direct the emitted light along the layers. The optical confined of carriers occurs in the QWs all across the device. Some photons exist from the MQW layers of the gain section, some get absorbed by the material and some stimulated the emission of the other photons. The change of the stimulated emission increases as we inject more carriers. Transparency occurs when material loss equals gain and at higher pumping power, the MQW stack becomes a gain medium [14].

The optical feedback essential for a laser is obtained by reflecting part of the light through the gain medium, using the mirrors to create a laser cavity. For example, limiting together many of the three QW structures in descending staircase of energy levels results in one electron emitting as many coherent photons as, there are active regions. This is how laser light is produced in the quantum cascade lasers [9].

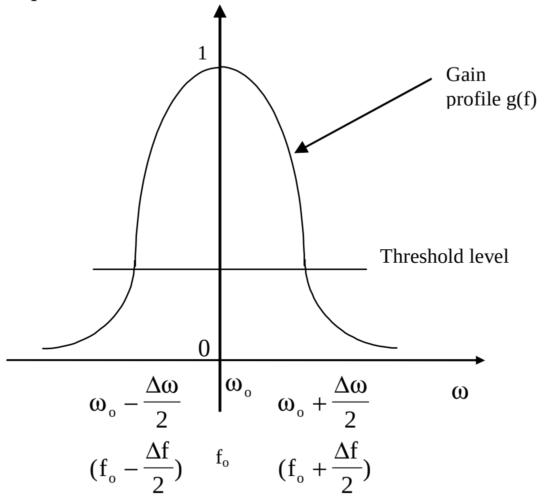

Fig.7 The gain profile and threshold level

9. RESULTS

The effective masses of carriers of the material used for the QWs are functions of the carrier velocities which depend on the indices of the regions of the QWs. The indices vary with the wavelength of the field. The NPC α also depends on the wavelength, indices and the velocities of carriers. Consequently, the carrier mass and the NPC α must be accurately determined under these circumstances.

The greater accuracies of the calculated values for effective mass of the carrier and the NPC α in the SQW are, the greater accuracies of the parameter values obtained by this theoretical approach are olso.

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