Islamic Azad University

Journal of
Optoelectronical Nanostructures

Spring 2020 / Vol. 5, No. 2

Analysis of Kirk Effect in Nanoscale Quantum Well Heterojunction Bipolar Transistor Laser

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(Received 17 Apr. 2020; Revised 19 May 2020; Accepted 25 May 2020; Published 15 Jun. 2020)

Abstract: In this paper, we present an analytical model to analysis the kirk effect on static and dynamic responses of quantum well heterojunction bipolar transistor lasers (HBTLs). Our analysis is based on solving the kirk current equation, continuity equation and rate equations of HBTL. We compare the performance (current gain, output photon number and small signal modulation bandwidth) of the transistor laser with different levels of the kirk current. We show that, at high collector currents, the static and small signal behavior of HBTL depend on kirk current level. The results indicate that, the level of kirk current affect current gain, output photon number and modulation bandwidth From simulation results, it can befound that, kirk effect has destructive influence on HBTL performance. It was found that lower modulation bandwidth and lower current gain occurs at lower kirk current level. For increasing kirk current, the high collector-base voltage and high collector length was proposed.

Keywords: Quantum well, Heterojunction Bipolar Transistor lasers (HBTLs), Kirk Effect, Saturation Velocity

1. NTRODUCTION

The recent invention of heterojunction bipolar transistor lasers (HBTLs) marks a great advance in semiconductor device research because the transistor laser monolithically integrated the functionality of a laser and a bipolar transistor. Indeed, HBTL operates simultaneously as a transistor and laser [1-4].

One of the mechanisms that affect the transistor performance is kirk effect. At high collector current levels, the traveling electron modifies the electrical field profile in the collector space charge region of bipolar transistors.

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Indeed, at high collector current, the electrical field of collector region near the base, decreases to zero, therefore there is no more field to prevent the holes from spilling into the collector. Indeed, base push out is said to occurs. The effective base thickness is the sum of the physical base thickness plus the hole spilling distance. Therefore at high collector current, the current gain decreases, as the transit time associated with the thickened base layer increases. The device characteristics as a result of base pushout are refereed to kirk effect. The kirk effect in homojunction bipolar transistor and single heterojunction bipolar transistor (SHBT) have been reported[5].
N . G. Tao et al[6] studied the kirk effect mechanism in type II InP/GaAsSb/InP npn double heterojunction bipolar transistors. They found that the large valance band discontinuity at base/collector heterojunction does not allow hole spilling into collector as is the case in homojunction collectors. D. Cohen Elias et al [7] studied the kirk effect mechanism in bipolar transistors with a nonuinform dopant profile in the collector. By using gummel method [8] They found that threshold current was enhanced by more than 50% compared to the uniform doping case. It is observed that transistor laser has lower threshold voltage in comparison with quantum dot laser[9-10]. Also recently npn AlGaInAs/Inp transistor laser with a thin base layer to suppress unnecessary recombination between electrons and holes, was proposed[11]. Also the other work shows the narrower bandgap for base region, improves the current gain [12]. For simulation and analysis of the device, a large signal model with multiple quantum well is introduced, based on rate equations [13] and charge control model. Also, in another research paper, the frequency response and modulation bandwidth of transistor laser was investigated [14]. The effect of kirk current on the characteristics of photodiodes were investigated [15-16].
In this paper, we analytically investigate the kirk effect on static and dynamic performance of HBTL. To our knowledge, for the first time this paper describes the kirk effect in HBTL. Our analysis is based on continuity equation, rate equations, and kirk current equation. By using these equations, we investigate the kirk effect on main characteristics of HBTL such as, current gain, output photon numbers, and modulation response. The organization of paper is as follows: In section 2 we introduce the main formulation of HBTL, in section 3 the kirk effect mechanism is presented. In section 4 results are discussed, and in section 5 conclusion are presented.

2. MAIN FORMULATION OF HBTL

Fig.1 shows the conduction energy band of the base and dc excess minority carrier distribution $\left[\delta N(x)\right]$, in the base region. The carriers injected from the emitter, diffuse across the base and reach the quantum well (QW). We assume that, there is only one quantum well that is located in the middle of the base region and act as a source for the laser emission. The base QW governs and enhances the charge recombination. The QW adds another recombination region in the base that has a variable recombination rate (spontaneous emission below laser threshold and stimulated emission above laser threshold). The carriers entering the virtual states have two possibilities: falling in the QW states or diffusing to the collector.

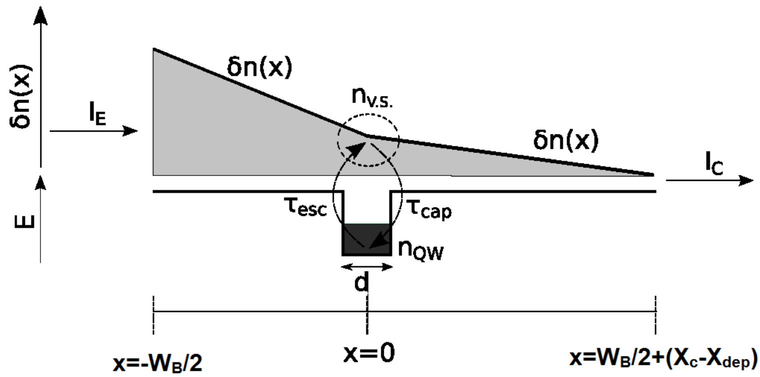

Fig. 1. Schematic of carrier diffusion and quantum capture in the quantum wells, and the conduction band energy of the base region.

$$j_E = n_{V.S}\frac{qD_n}{L_D}\left(\sinh\left(\frac{W_B}{2L_D}\right)+\left(\frac{\cosh\left(\frac{W_B}{2L_D}\right)\cosh\left(\frac{W_B}{2L_D}+\frac{X_C-X_{dep}}{L_D}\right)}{\sinh\left(\frac{W_B}{2L_D}+\frac{X_C-X_{dep}}{L_D}\right)}\right)\right)+j_{V.S}\cosh\left(\frac{W_B}{2L_D}\right) \quad (1)$$

$$j_C = n_{V.S}\frac{qD_n}{L_D}\left(\frac{1}{\sinh\left(\frac{W_B}{2L_D}+\frac{X_C-X_{dep}}{L_D}\right)}\right) \quad (2)$$

$$\frac{j_{QW}}{qd}=\frac{n_{V.S}}{\tau_{cap}}-\frac{n_{QW}}{\tau_{esc}} \quad (3)$$

$$\frac{dn_{V.S}}{dt}=\frac{j_{V.S}}{qd}-\frac{j_{QW}}{qd}-\frac{n_{V.S}}{\tau_s} \quad (4)$$

$$\frac{dn_{QW}}{dt} = \frac{j_{QW}}{qd} - \frac{n_{QW}}{\tau_s} - G_0\left(n_{QW} - n_{tr}\right)S \tag{5}$$

$$\frac{dS}{dt} = \left(\Gamma G_0\left(n_{QW} - n_{tr}\right) - \frac{1}{\tau_p}\right)S + \frac{\Gamma\beta n_{QW}}{\tau_s} \tag{6}$$

In above equations, j_C is the collector current, j_E is the emitter current, j_B is the base current, W_B is the base width, $n_{V.S}$ is the virtual states carrier concentration, and $j_{V.S}$ is the current to the virtual states due to diffusion. j_{QW} is the current from the virtual states to the 2D bound states within the QW, D_n is the diffusion coefficient in the base , n_{QW} is the QW carrier density, S is the photon concentration, Γ is the optical confinement factor, d is the QW width, n_{tr} is the carrier density at optical transparency, τ_{cap} is the capture lifetime for the carriers falling from the virtual states to the QW states, τ_{esc} is the escape lifetime from the QW to the virtual states, τ_s is the spontaneous emission lifetime, τ_p is the photon lifetime, G_0 is the optical gain, L_D is diffusion length, X_c is collector length, and X_{dep} is depletion region in Collector.

3. KIRK EFFECT MECHANISM

The electrical field in practically the entire collector exceeds the critical field beyond which the electron carriers travel at a constant saturation velocity (v_{sat}). Such a velocity is much greater than the diffusion velocity, so the carriers travel in collector mainly by drift (although in the base they travel mainly by diffusion). Therefore the carrier concentration and poisson equation can be defined as [6-7]:

$$n(x) = \frac{j_C}{qv_{sat}} = \text{constant} \tag{7}$$

$$\frac{d\varepsilon}{dx} = \frac{1}{\varepsilon_s}\left(\frac{j_C}{v_{sat}} - qN_c\right) \tag{8}$$

Table 1: Parameters of the transistor laser [7-12]

Symbol	Description	Value
τ_S	Spontaneous emission lifetime	200ps
τ_B	Carrier recombination lifetime in base	200ps
τ_{capi}	Intrinsic Carrier capture time in QW	1ps
τ_{esc}	Carrier escape time from QW	10ps
τ_p	Photon lifetime in the cavity	4ps
τ_{sp}	Spontaneous emission lifetime	1ns
W_B	Width of the base	100nm
G_0	Differential optical gain	10^{-5} cm^3s^{-1}
W_{ba}	Width of barrier	40nm
Γ	Optical confinement factor	0.05
ε	Gain compression factor	1.5×10^{-17} cm^3
Area	Area of the TL	16µm
β	Spontaneous emission factor	10^{-5}
V_{sat}	Saturation velocity	8×10^6 cm/s
X_c	Collector length	105 nm

Where v_{sat} is saturation velocity, and N_c is the collector doping concentration. As, the current density increases, the mobile electron concentration becomes significant and the slope of the field decreases. While the current density increases, the junction voltage drop on BC junction ($V_{cb} + \varphi_{cb}$) and the area under the field profile is unchanged [8]. The simultaneous requirements of the decreasing field slope and the constant area imply that the depletion thickness increases until it reach $x=X_c$, the full collector thickness. As the current density increases a level such that $n=N_c$, the net charge inside the junction becomes zero, and the field profile stays constant. When current density increases further such that $n \succ N_c$, the electrical filed takes on a negative slope. As the trend progress, the magnitude of the filed eventually diminishes to zero. When there is no more filed to prevent the holes from, spilling into the collector, the effective base thickness increases. Indeed the filed in collector region near the base decreases to zero at the kirk current density is defined as [6]:

$$j_{kirk} = \frac{2\varepsilon_s v_{sat}\left(v_{cb} + \varphi_{cb}\right)}{X_c^2} + qv_{sat}N_c \qquad (9)$$

$$j_C = \frac{2\varepsilon_s v_{sat}\left(v_{cb} + \varphi_{cb}\right)}{X_{dep}^2} \qquad (10)$$

For our analysis, we consider a typical TL with material and geometrical parameters as given in Table 1[2-4].

4. RESULTS

A. Steady-state analysis

DC analysis is done by solving Eqs.(1-6) and Eq.(10), while all time derivations are zero. The modified base width is :

$$W = W_B + (X_c - X_{dep}) \qquad (11)$$

By solving mentioned equations, depletion width X_{dep} can be found. The modified base width as a function of collector current for different kirk current is plotted in Fig.2.

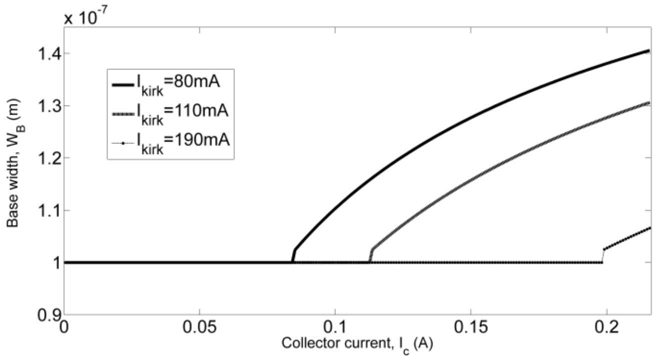

Fig. 2. Modified base width versus collector current, for different kirk current.

At first when the collector current increases up to kirk current, the base width is constant. But for collector current above kirk current, the base width increases.This is because, when the collector current is lower than kirk current, the collector width (X_c) is equal to depletion width (X_{dep}). When the collector current exceeds the kirk current, base pushout is occur and depletion width become smaller than collector width $(X_{dep} \prec X_c)$. Therefore according to Eq. (11), the base width becomes higher. Fig.3 shows the dependency of the dc current gain (β_{dc}) on the base current as a function of kirk current. As shown in the figure, when the base current increases, thedc current gain is constant at first (below the base threshold current), and then decreases. Indeed, laser stimulated emission above threshold leads to the decrease of collector current, and consequently the degradation of dc current gain. Furthermore smaller kirk current leads to a lower current gain at high base current due to increment of base width. Indeed, for small base current (that collector current is lower than kirk current) the dc current gain curves are identical. But for high base current (that collector current is higher than kirk current) the dc current gain decreases as kirk current decreases. Fig. 4 shows the light-current characteristics for different kirk currents. It can be found that, higher kirk current leads to the higher L-I slope and therefore higher quantum efficiency. At first when the base current increases up to critical value (that collector current becomes equal to kirk current), the slope of curves are identical. But for the base current above critical value (that collector current is above kirk current), the slope of curves decreases. This is because, when the collector current reaches to kirk current the base width increases. Therefore the recombination outside of quantum well becomes higher and recombination inside the quantum well becomes lower. By decreasing kirk current, the base pushout phenomenon occurs at lower collector current level, and consequently leads to a lower L-I slope. To compare our resultswith previous ones, Fig.5 shows the current gain at different carrier recombination τ_S lifetime in quantum well, calculated at previous research [3]. From the figure, it can be found that the effect of τ_S below the

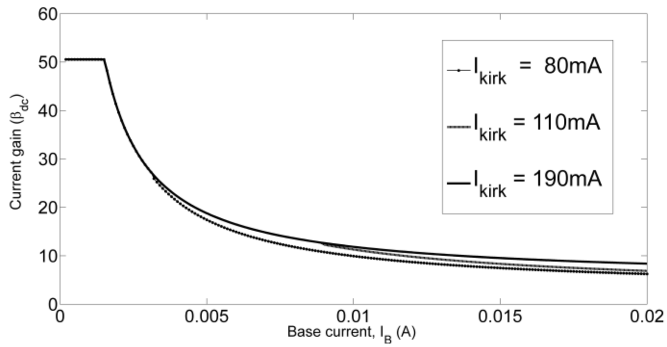

Fig. 3. DC current gain versus base current for different kirk current.

base threshold current is remarkable while kirk effect has no considerable effect below the base threshold. Indeed, it changes current gain after base threshold according to Fig.3. Also in the research [3], the photon numbers versus base current for different quantum capture efficiency, was calculated. From Fig.6, we can find that different, leads to threshold current change. In comparison with Fig.4, kirk current has no considerable effect on threshold current and only changes the slope of the curve. In other research, the effect of additional quantum well in the device was investigated [4]. Fig.7 indicate that similar to kirk current, the number of quantum wells in the base region changes the slope of light-current characteristics named quantum efficiency. In another research [15], the kirk effect in photodiode was investigated. In that research, by using a type-II ($GaAs_{0.5}Sb_{0.5}$/InP)absorption-collector interface and inserting an n-type charge layer in the collector, the kirk effect was minimized. In other research [16], a vertical PIN photodiode was investigated. It was shown that low doing in the N-collector leads to the reduction of current gain due to kirk effect. To reduce the kirk effect a highly doped N-type layer for PIN was recommended.

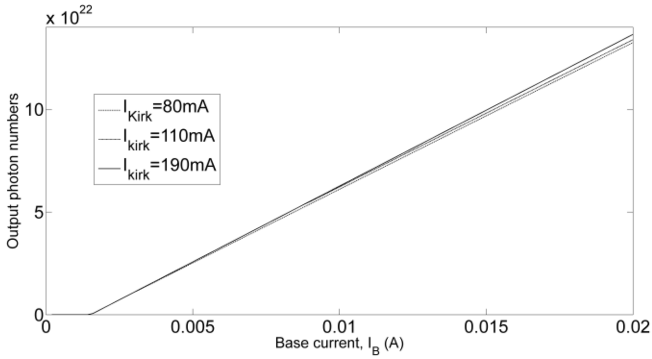

Fig.4 Light-current characteristics versus base current for different kirk current.

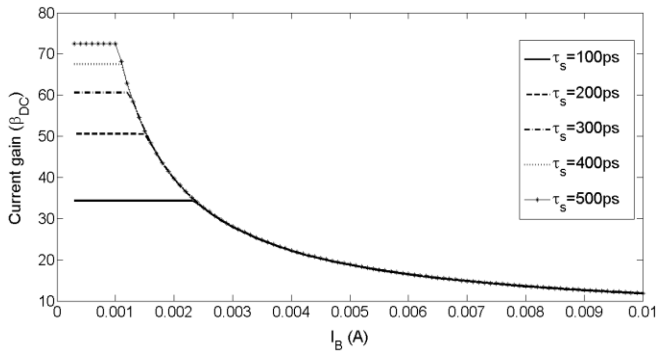

Fig.5 Small signal modulation response for different kirk current.

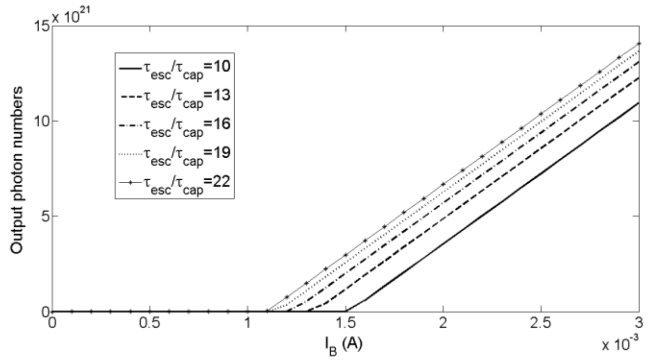

Fig.6 Light-current characteristics versus base current for different quantum capture efficieny

B. Small signal analysis

The small signal analysis of transistor laser in the common base (CB) configuration is done by calculating the CB modulation transfer function $[s(jw)/j_e(jw)]$. The small signal relationship between photon density and the emitter current, is found by linearization [10] Eqs(1)-(6), and Eq(10) and applying appropriate manipulation. Fig.8 illustrates the small signal modulation responses of HBTL for different kirk current. From the figure, it can be observed that, higher kirk current level, leads to higher modulation bandwidth.
Indeed, by decreasing kirk current the base width increases, which leads to degradation of output power and consequently the decrement of modulation bandwidth. The result indicate that by reducing the kirk current from 190mA to 80mA the bandwidth increase from 50GHz to 65GHz.Indeed, when the collector current exceeds the kirk current, base pushout is occured and depletion width becomes smaller than collector width. By increasing base width, output photon number decreases.

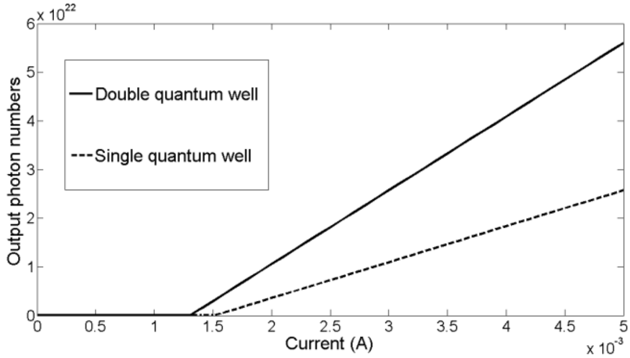

Fig.7 Output photon numbers versus base current for transistor laser with single and double well

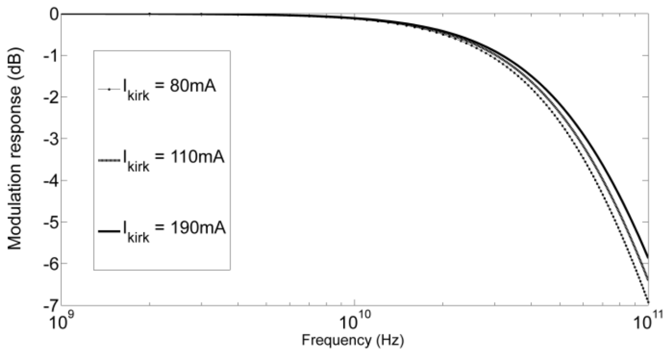

Fig.8 Modulation response versus frequency for transistor laser with different kirk currents.

Therefore lower modulation bandwidth occurs. From static and dynamic simulation results, it can be found that, kirk current has destructive effect on laser performance. Indeed, it is preferred to occur kirk effect in high base current over low base current. Therefore, high kirk current is ideal. According to Eq.(9), the kirk current increases by increasing V_{cb} and X_c. Although increasing N_c leads to increasing kirk current, but also it increases collector resistive, that is not desirable.

5. CONCLUSION

At Based on solving kirk current equation and rate equations of HBTL we simulated the kirk effect in HBTL. The modulation bandwidth of TL and effect of quantum capture and escape time for carrier on modulation bandwidth is studied during the analysis.

We show that, at high collector current, the static and small signal behavior of HBTL depend on kirk current level. It was found that, by decreasing kirk current, the base pushout phenomenon occurs at lower collector current level, and consequently leads to a lower L-I slope and lower. Also, lower modulation bandwidth and lower current gain occurs at lower kirk current. For increasing kirk current, the high collector-base voltage and high collector length was proposed. Also the investigation of kirk effects on Vertical Cavity Surface Emitting lasers (VCSELs) [17,18] are proposed for future works.

REFERENCES

[1] W. Liu, *Fundamentals of III-V Devices, HBTs, MESFETs, and HFETs/HEMTs* John Wiley & Sons. New York, 1999.

[2] B. Faraji B, W. Shi, D L. Pulfrey, and L. Chrostowski. *Analytical modeling of the transistor laser*, IEEE J. Sel. Topics Quantum Electron. 15(3) (1992, Aug.) 594-603. Available: https://ieeexplore.ieee.org/document/4839011

[3] A. Horri , S.Z. Mirmoeini, and R. Faez. *Analysis of carrier dynamic effects in transistor laser*, Optical Engineering. 51(2) (2012.) 024202. Available: https://spie.org/Publications/Journal/10.1117/1.OE.51.2.024202?SSO=1

[4] A. Horri , and R. Faez. *Large signal analysis of double quantum well transistor laser,* Optical and Quantum Electronics. 45(5) (2013.) 389-399. Available: https://link.springer.com/article/10.1007/s11082-012-9641-5

[5] M.S. Shirokov , S.V. Cherepko , D. Xiaohang , J.C.M Hwang , and D.A. Teeter. *Large-signal modeling and characterization of high-current effects in InGaP/GaAs HBTs,*. IEEE Trans. Microwave Theory and Techniques 50(4) (2002.) 1084-1094. Available: https://ieeexplore.ieee.org/document/993410

[6] N.G Tao and C.R Bolognesi, *Kirk effect mechanism in type-II InP/GaAsSb double heterojunction bipolar transistor,*. Journal of applied physics 102(6) (2007.) 064511. Available: https://aip.scitation.org/doi/10.1063/1.2783764

[7] D. Elias and D. Ritter, *Kirk effect in bipolar transistors with a nonuniform dopant profile in the collector,*. IEEE Electron Device Letters, 27(1) (2006.) 25-27. Available: https://ieeexplore.ieee.org/document/1561444

[8] H.K. Gummel, *A self consistent iterative scheme for one-dimension steady state transistor calculation,*. IEEE Transactions on Electron Devices, 11(10) (1964.) 455-465. Available: https://ieeexplore.ieee.org/document/1473752

[9] M. Feng, R. Bambery, and Jr Holonyak, *Bandfilling and photon-assisted tunneling in a quantum-well transistor laser,*. Applied Physics Letters, 98(12) (2011.) 123505.

Available: https://aip.scitation.org/doi/10.1063/1.3569949

[10] A. Horri, S.Z. Mirmoeini, and R Faez, *The noise equivalent circuit model of quantum dot laers,*. Journal of Russian Laser Research, 33(3) (2012.) 217-226. Available: https://link.springer.com/article/10.1007/s10946-012-9275-x

[11] T. Kaneko, T. Yoshida, S. Tadano, N. Nishiyama, and S. Arai, *Improvement in the current-gain of a 1.3 µm npn-AlGaInAs/InP transistor laser using a thin p-GaInAsP base layer* ,. Japanese Journal of Applied physics, 55(3) (2012.) 217-226. Available: https://link.springer.com/article/10.1007/s10946-012-9275-x

[12] A. Horri, S.z. Mirmoeini, R. Faez, *Large Signal Circuit Model of Two-Section Gain Lever Quantum Dot Laser,*. Chinese Physics Letters, 29(11) (2012.) 114207. Available: https://iopscience.iop.org/article/10.1088/0256-307X/29/11/114207

[13] I. Taghavi, B. Namvar, M. Hosseini, and H. Kaatuzian, *Large signal analysis of multiple quantum well transistor laser: Investigation of inbalanced carrier and photon density distribution* ,. Journal of Applied physics, 127(13) (2020.) 133102. Available: https://link.springer.com/article/10.1007/s10946-012-9275-x

[14] Y. Li, and J.P Leburton, *Base transport factor and frequency response of transistor lasers*, Journal of Applied physics, 126(15) (2019.) 153103. Available: https://aip.scitation.org/doi/abs/10.1063/1.5099041?journalCode=jap

[15] J. Wun, R. Chao, Y. Wang, Y.Chen, and J. Shi, *Type-II GaAs 0.5Sb0.5/Inp Uni-traveling carrier photodiodes with sub-terahertz bandwidth and high power performance under zero bias operation* , Journal of Lightwave Technology, 35(4) (2017.)711-716,Available: https://ieeexplore.ieee.org/abstract/document/7562455

[16] R. Swoboda, K. S. Hormstein, H. Wile, G. Langguth, and H. Zimmermann, *Bicmos-integrated photodiode exploiting drift enhancement*, Optical Enginnering, 53(8),(2014.),087103,Available:https://spie.org/publications/journal/10.1117/1.OE.53.8.087103

[17] A. Ghadimi, and M. Ahmadzadeh, *Effect of variation of specification o quantum well and contact length on performance of InP-based Vertical Cavity Surface Emitting Laser (VCSEL)*, JOURNAL of OPTOELECTRONICAL NANO STRUCTURES,5(1),(2020.),19-34,Available: http://jopn.miau.ac.ir/article_4031.html

[18] M. Riahinasab, and E. Darabi, *Analytical Investigation of Frequency Behavior in Tunnel Injection Quantum Dot VCSEL* , JOURNAL of

OPTOELECTRONICAL NANOSTRUCTURES, 3(2), (2020.), 65-86, Available: http://jopn.miau.ac.ir/article_4031.html