Simulation modulation of laser diode by coupling TCAD with MATLAB

R. A. ABDULLAH*, K. IBRAHIM
Nano-Optoelectronics Research and Technology Laboratory (N.O.R), School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia

ISE TCAD (Integrated System Engineering Technology Computer Aided Design) software simulation program has been coupled with popular MATLAB program as a new idea to help analyses the small signal of pulse response for digital modulation purposes. ISE TCAD software simulation program has been employed to build a laser structure and extract its output to select the desired operating points from the output. While, MATLAB has been utilized to create the state-space model which has been applied to Jacobian matrix of the rate equations of laser diode (LD). And the pulse response for digital modulation has been studied through the state-space model itself.

(Received July 08, 2009; accepted April 11, 2010)

Keywords: Laser diode, TCAD, MATLAB program, Simulation

1. Introduction

LDs are important optical sources in optoelectronic integrated circuits for high-speed long-distance optical-fiber communication systems [1]. The typical characteristics of the LD modulation can be gained by determining the LD response to small signal modulation, which measures the amplitude of the modulated signal relative to that of unpopulated signal [2]. For design of such systems, it is essential to accurately predict the dynamic behaviors of the laser transmitters under specific operating conditions [3]. For this purpose, computer-aided simulation techniques based on behavioral models of laser diodes have been developed and validated for a variety of applications [4,5]. In this paper, coupling ISE TCAD with MATLAB has been made to help study the modulation response. Fig. 1 is the block diagram of coupling TCAD with MATLAB.

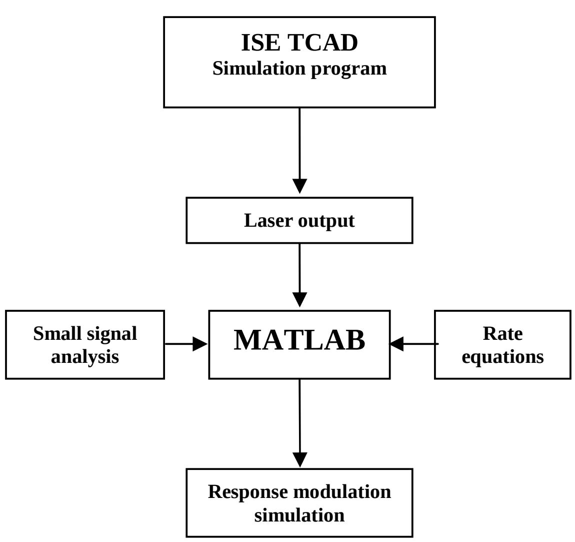

Fig. 1. Block diagram of coupling TCAD with MATLAB.

2. Laser diode structure and parameters

The two-dimensional ISE TCAD simulation program is utilized. Carrier drift-diffusion model and Newton method are used. The ISE TCAD self-consistently solves electronic and optical equations in a quantum well laser [6]. The electronic equations are the Poisson and the continuity equations of both free and bound electrons and holes. A scalar Helmholtz equation is used to solve the optical problem, and a photon rate equation is used to calculate the photon spectrum of each mode [6]. The electronic band structure of quantum well is calculated using k.p theory of wurtzite semiconductors [7]. Spontaneous and stimulated optical recombinations are calculated in the active region according to Fermi's golden rule. As a result, the coupling between the optical and electronic equations leads to convergent problems of the Newton method [7].

A schematic diagram of the violet InGaN laser diode structure under study is shown in Fig. 2. In this simulation, it is assumed that the InGaN laser diode is grown on the n-type GaN layer whose thickness is 2 µm. On the top of this GaN layer is a 0.1- µm-thick n-type $In_{0.05}Ga_{0.95}N$ compliance layer and a 0.45- µm-thick n-type $Al_{0.7}Ga_{0.93}N$ cladding layer, followed by a 0.1-µm-thick n-type GaN guiding layer. The active region consists of double $In_{0.12}Ga_{0.88}N$ undoped quantum wells where the thickness of every well is 2.5 nm, and every well is sandwiched between two 5-nm-thick $In_{0.01}Ga_{0.99}N$ barriers. A 0.02-µm-thick p-type ternary $Al_xGa_{1-x}N$ blocking layer is grown on top of the active region, followed by a 0.1-µm-thick p-type GaN guiding layer and a 0.45-µm-thick p-type $Al_{0.7}Ga_{0.93}N$ cladding layer. Finally, a 0.1-µm-thick p-type GaN cap layer is grown over p-type cladding layer to complete the structure. The doping concentrations of n-type and p-type are equal to $5 \times 10^{18} cm^{-3}$ and $1 \times 10^{18} cm^{-3}$ respectively. The active region is 1 μm in width and 750 μm in length. The reflectivities of the two end facets are 50% for each one. The L-I curve of this LD is shown in Fig. 3.

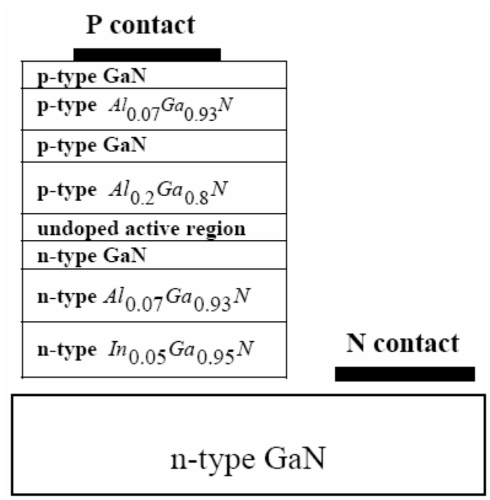

Fig. 2. The schematic diagram of violet InGaN laser diode under study.

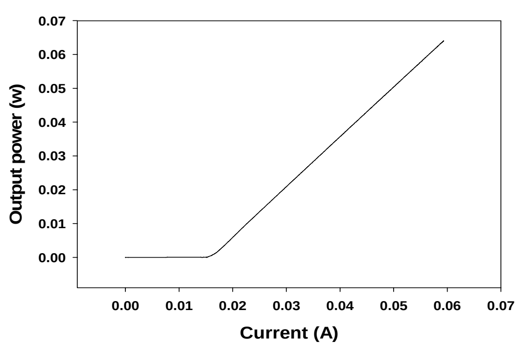

Fig. 3. The L-I curve of LD.

The refractive indices of $Al_xGa_{1-x}N$ and $In_{xy}Ga_{1-x}N$ are given by Eq. 1 and Eq. 2 respectively as [8]:

$$n(Al_xGa_{1-x}N) = 2.5067 - 0.43x \tag{1}$$

$$n(In_xGa_{1-x}N) = 2.5067 + 0.91x \tag{2}$$

The band gap energies of $Al_xGa_{1-x}N$ and $In_{xy}Ga_{1-x}N$ are given by Eq. 3 and Eq. 4 respectively as [8]:

$$E_{g,In_xGa_{1-x}N} = x.E_{g,InN} + (1+x).E_{g,GaN} - 1.43x.(1-x) \tag{3}$$

$$E_{g,Al_xGa_{1-x}N} = x.E_{g,AlN} + (1-x).E_{g,GaN} - 1.3.x.(1-x) \tag{4}$$

The laser parameters which have been used in ISE TCAD simulation program are listed in the table 1 below [9, 10,11]:

Table 1. The laser parameters which have been used in ISE TCAD simulation program.

Paramete	symbol (unit)	GaN	AlN	InN
Lattice constant	a_o (A^o)	3. 189	3.112	3.545
Spin-orbit split energy	Δ_{so} (A^o)	0.017	0.019	0.005
Bandgap energy	E_g (ev)	3.42	6.2	0.77
Elastic stiffness constant	C_{33} (GPa)	398	373	224
Elastic stiffness constant	C_{13} (GPa)	106	108	92
Electron effective mass	$m_e (m_o)$	0.2	0.4	0.11
Heavy hole effective mass	m_{hh} (m_o)	1.595	3.53	1.44
Light hole effective mass	m_{lh} (m_o)	0.26	3.53	0.157

It is noteworthy that some parameters are sensitive to the technological processes such as the Shockley Read–Hall (SRH) recombination lifetime of electrons and holes; while other so that they can be neglected in nitride materials such as Auger recombination (C) of GaN. However, it is assumed that the values are 1 ns and 1×10^{-34} $cm^6 s^{-1}$, for (SRH) and (C), respectively[12]. The L-I of this design is shown in Fig.3.

3. Laser diode rate equations

The LD dynamics are modeled by coupled rate equations [13] which describe the relation between the carrier density N(t) and the photon density S(t):

$$\frac{dN(t)}{dt} = \frac{I(t)}{q \cdot V_a} - g_o \frac{[N(t) - N_o] \cdot S(t)}{1 + \varepsilon \cdot S(t)} - \frac{N(t)}{\tau_n} \tag{5}$$

$$\frac{dS(t)}{dt} = \Gamma \cdot g_o \frac{[N(t) - N_o] \cdot S(t)}{1 + \varepsilon \cdot S(t)} - \frac{S(t)}{\tau_p} + \frac{\Gamma \cdot \beta}{\tau_n} \cdot N(t) \tag{6}$$

where Γ is the optical confinement factor which describes how much of the mode is confined in the active region, N_o is the carrier density at transparency for which the net gain is zero, τ_p is the photon lifetime, τ_s is the carrier lifetime, *I(t)* is the injection current, *β* is the spontaneous emission factor, q is the electron charge, V_a is the active region volume which can be omitted if the equations are to be interpreted in terms of carrier and photons numbers, g_o slope gain constant, α is the linewidth enhancement factor and ε is the gain compression factor.

These rate equations represent a large-signal mode model that describes the laser diode behavior in both the spontaneous emission and stimulated emission region. From the equations above, it is possible to derive a set of steady state and small signal equations to help in further understanding the static and dynamic behaviors of laser diodes (InGaN multi quantum wells laser diode). To calculate some parameters MATLAB program has been used (see Table 2).

Table 2. The LD parameters which have been used in the rate equations.

parameter	symbol	value
optical confinement factor	Γ	0.00745
active region volume	V_a	$1.5\times 10^{-11}\ cm^{3}$
spontaneous emission factor	β	10^{-5}
photon lifetime	τ_p	$8.5\times 10^{-12}\ s$
carrier lifetime	τ_s	$2\times 10^{-10}\ s$
slope gain constant	g_o	$4.36\times 10^{-7}\ cm^{-3}s^{-1}$
carrier density at transparency	N_o	$1\times 10^{18}\ cm^{-3}$
Quantum efficacy	η	0.5
gain compression factor	ε	3.5×10^{-17}

4. Steady state solution

Steady state solution occurs when Gain = Losses, therefore in this case [14]:

$$\frac{dN(t)}{dt}=0,\quad \frac{dS(t)}{dt}=0 \tag{7}$$

Hence, the couple rate equations above will be:

$$\frac{I}{q\cdot V_a}-g_o\frac{(\bar{N}-N_o)\cdot\bar{S}}{1+\varepsilon\cdot\bar{S}}-\frac{\bar{N}}{\tau_n}=0 \tag{8}$$

$$\Gamma\cdot g_o\frac{(\bar{N}-N_o)\cdot\bar{S}}{1+\varepsilon\cdot\bar{S}}-\frac{\bar{S}}{\tau_p}-+\frac{\Gamma\cdot\beta}{\tau_n}\cdot\bar{N}=0 \tag{9}$$

where $\bar{N}$ and $\bar{S}$ are the values of the carrier and photon densities at steady state.

From equation (8) we can obtain:

$$g_o\frac{(\bar{N}-N_o)\cdot\bar{S}}{1+\varepsilon\cdot\bar{S}}=\frac{I}{q\cdot V_a}-\frac{\bar{N}}{\tau_n} \tag{10}$$

By substituting Eq. (10) into Eq. (9), we obtain:

$$\Gamma\left(\frac{I}{q\cdot V_a}-\frac{\bar{N}}{\tau_n}\right)-\frac{\bar{S}}{\tau_p}+\frac{\Gamma\cdot\beta}{\tau_n}\cdot\bar{N}=0 \tag{11}$$

By rearranging Eq. (11), we will obtain the carrier density as a function of the driven current and photon density at steady state:

$$\bar{N}=\frac{\frac{\tau_n}{q.V_a}-\frac{\tau_n.\bar{S}}{\Gamma.\tau_p}}{\beta-1} \tag{12}$$

The output power of laser diode from one facet is given in terms of the steady-state photon density as [15]:

$$p(t)=\frac{v_a\eta h\nu}{2\Gamma\tau_p}s(t) \tag{13}$$

From this equation, we can obtain the photon density as a function of the laser output power:

$$\bar{S}=\frac{2\Gamma P\tau_p}{v_a\eta h\nu} \tag{14}$$

Fig. 4 stands for Eq. (14); while Fig. 5 stands for Eq.(12).

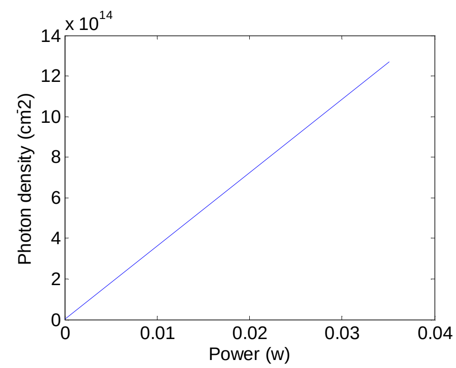

Fig. 4. The photon density as of the laser output power.

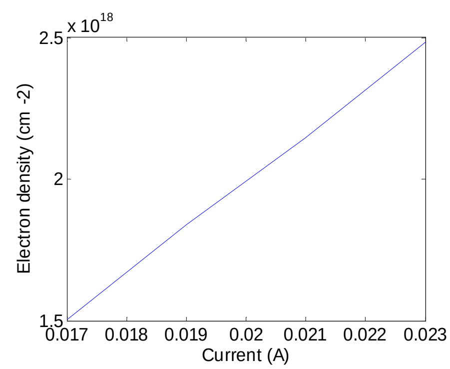

Fig. 5. The Carrier density as a function of the driven current.

5. State-space model

A state-space representation is a mathematical model of a physical system as a set of input-output state variables related to first-order differential equations. Moreover, this form is better suited for a computer simulation than n^{th}-order input-output differential equations [16]. State space refers to the space whose axes are the state variables. The state of the system can be represented as a vector within that space. In order to enter a state-space model into MATLAB, the variables must be given a numerical value.

In order to obtain values to simulate the small signal response, the non-linear rate equations are linerarized by taking the partial derivative of each time-dependent term with respect to the photon and electron densities [17]. This model allows the results of the large signal response to be used in simulating the small signal response. The process of selecting operating point is explained below[17]: the researchers have chosen an arbitrary operating point close to the threshold, therefore, the gain saturation term $1/(1+\varepsilon S(t))$ will approach 1 for values of $\varepsilon S(t)\langle\langle 1$. This term has a negligible effect on Eq.1 and Eq.2. Consequently, the partial derivatives of Eq. (5) and Eq. (6) with respect to N(t) and S(t) are:

$$\frac{\partial\left(\frac{dN(t)}{dt}\right)}{\partial N(t)} = -\frac{1}{\tau_p} - g_o \cdot S(t) \tag{15}$$

$$\frac{\partial\left(\frac{dN(t)}{dt}\right)}{\partial N(t)} = -g_o \cdot [N(t) - N_o] \tag{16}$$

$$\frac{\partial\left(\frac{dS(t)}{dt}\right)}{\partial S(t)} = \Gamma \cdot g_o \cdot S(t) + \frac{\Gamma \cdot \beta}{\tau_n} \tag{17}$$

$$\frac{\partial\left(\frac{dS(t)}{dt}\right)}{\partial S(t)} = \Gamma \cdot g_o \cdot [N(t) - N_o] - \frac{1}{\tau_p} \tag{18}$$

The state-space model of couple rate equations are:

$$\begin{bmatrix} \dot{N} \\ \dot{S} \end{bmatrix} = A \begin{bmatrix} N \\ S \end{bmatrix} + Bf(t) \tag{19}$$

$$y = C \begin{bmatrix} N \\ S \end{bmatrix} + Df(t) \tag{20}$$

The first row of A and the first row of B are the coefficients of the first state equation for $\frac{dN(t)}{dt}$. Likewise, the second row of A and the second row of B are the coefficients of the second state equation for $\frac{dS(t)}{dt}$. C and D are the coefficients of the output equation for y where y is the desired output for the photon density.

Jacobin's matrix in state-space model will be applied to the following equations:

$$\begin{bmatrix} \dot{N} \\ \dot{S} \end{bmatrix} = \begin{bmatrix} \frac{\partial\left(\frac{dN(t)}{dt}\right)}{\partial N(t)} & \frac{\partial\left(\frac{dN(t)}{dt}\right)}{\partial S(t)} \\ \frac{\partial\left(\frac{dS(t)}{dt}\right)}{\partial N(t)} & \frac{\partial\left(\frac{dS(t)}{dt}\right)}{\partial S(t)} \end{bmatrix} \cdot \begin{bmatrix} N \\ S \end{bmatrix} + \begin{bmatrix} \frac{1}{qV_a} \\ 0 \end{bmatrix} \cdot I(t) \tag{21}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} N \\ S \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} \dot{N} \\ \dot{S} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_n} - g_o.S(t) & -g_o.[N(t)-N_o] \\ \Gamma.g_o.S(t)+\frac{\Gamma.\beta}{\tau n} & \Gamma.g_o.[N(t)-N_o]-\frac{1}{\tau_p} \end{bmatrix} \begin{bmatrix} N \\ S \end{bmatrix} + \begin{bmatrix} \frac{1}{qV_a} \\ 0 \end{bmatrix} I(t) \tag{23}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} N \\ S \end{bmatrix} \tag{24}$$

Therefore,

$$A = \begin{bmatrix} -\frac{1}{\tau_n} - g_o.S(t) & -g_o.[N(t)-N_o] \\ \Gamma.g_o.S(t)+\frac{\Gamma.\beta}{\tau n} & \Gamma.g_o.[N(t)-N_o]-\frac{1}{\tau_p} \end{bmatrix} \tag{25}$$

$$B = \begin{bmatrix} N \\ S \end{bmatrix} \tag{26}$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{27}$$

$$D = \begin{bmatrix} 0 \end{bmatrix} \tag{28}$$

By selecting four operating points from L-I curve (Fig. 1) and using Eq. (12) and Eq. (14), we can obtain the electron and photon densities as functions of LD bias current (see Table 3).

Table 3. Electron and photon densities of four operating point selected from L-I curve.

Pumping current (mA)	Electron density (cm^{-3})	Photon density (cm^{-3})
17	1.5×10^{18}	2.79×10^{13}
19	2.185×10^{18}	8.15×10^{13}
21	2.352×10^{18}	1.268×10^{14}
23	2.5×10^{18}	1.811×10^{14}

6. Response simulation result

The LD under study has been modulated with 1 mA above the operating points whose details are described in Table 3. The injected modulation signal starts at (zero ns) and ends at (8 ns) with duration of (3 ns).

Fig. 6 shows the pulse response of LD at the bias operating point 17 mA. It is obvious from this figure that the pulse is very clean; whereas the relaxation oscillation, preshoot and overshoot do not appear clearly in the pulse response. The examination of the pulse response with the other operating points at 19, 21 and 23 mA are presented in Fig.7, Fig. 8 and Fig. 9, respectively.

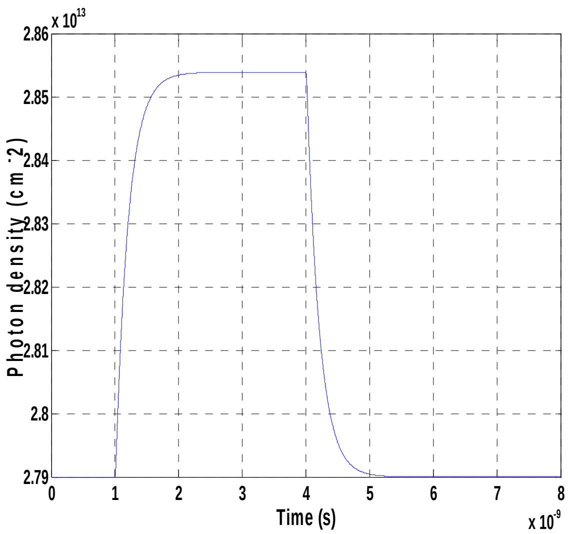

Fig. 6. Pulse response to 3 ns with 1 mA injected modulation current above the bias operating point 17 mA.

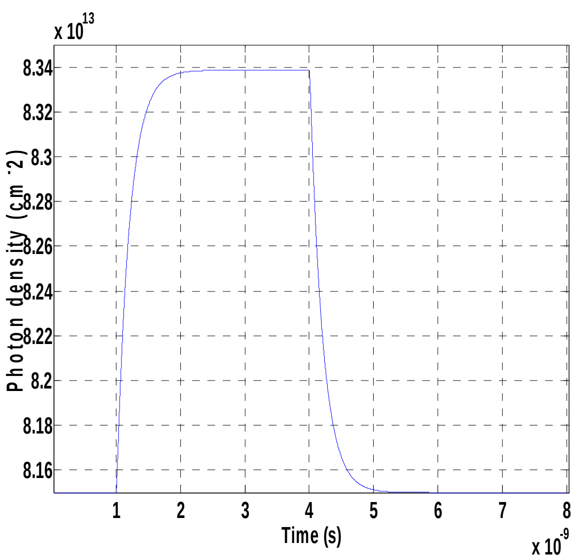

Fig. 7. Pulse response to 3 ns with 1 mA injected modulation current above the bias operating point 19 mA.

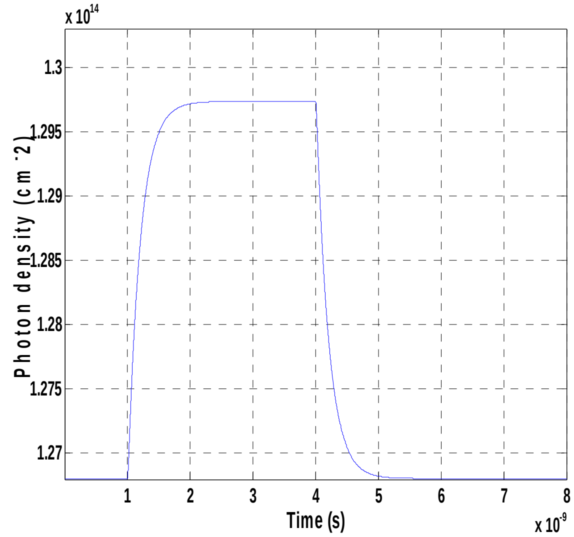

Fig. 8. Pulse response to 3 ns with 1 mA injected modulation current above the bias operating point 21 mA.

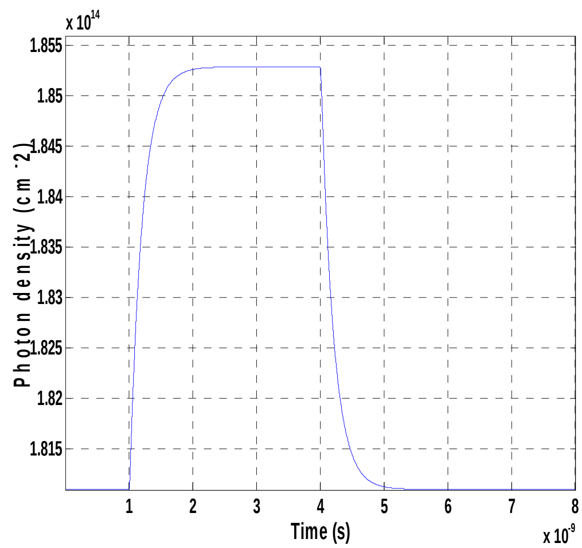

Fig. 9. Pulse response to 3 ns with 1 mA injected modulation current above the bias operating point 23mA.

7. Conclusions

It was found that coupling TCAD with MATLAB is suitable for studying the modulation response of LDs. TCAD was used to build the a structure; while MATLAB was used to build state-space model. A combination of TCAD and MATLAB is recommended to study the response modulation for digital modulation of multi quantum wells InGaN LD. This method can also be used for any type of laser diodes.

References

[1] G. Jianjun, G. Baoxin, L. Chunguang, Microwave and Optical Technology Lett. **30**, 270 (2001).
[2] O. Kjebon, R. Schatz, S. Lourdudoss, S. Nilsson, B. Stalnacke, L. Backbom, Electronics Letters **33**, 488 (1997).
[3] F. Habibullah, W.-P. Huang, Optics communications **258,** 230 (2006).
[4] S. Kobayashi, Y. Yamamoto, M. Ito, T. Kimura, IEEE J. Quantum Electron. **18**, 582 (1982).
[5] J. Wang, K. Peterman, IEEE J. of Lightwave Technology **10**, 96 (1992).
[6] ISE TCAD user's manual release 10.0, Zurich, Switzerland, 2004.
[7] S. L. Chuang, C. S. Chang, Phys. Rev. B **54**, 2491 (1996).
[8] S. Nakamura, S. Pearton, G. Fasol, New York, 2000.
[9] I. Vurgaftman, J. R. Meyer, J. Appl. Phys. **94**, 3675 (2003).
[10] D. Fritsch, H. Schmidt, M. Grundmann, Phys.Rev. B **67,** 235205 (2003).
[11] Michael E. Levinshtein, Sergey L. Rumyantsev, Michael S. Shur, John Wiley & Sons, Toronto, Canada, 2001.
[12] S. M. Thahab, H. Abu Hassan, Z. Hassan, Opt. Express, **15**, 2380 (2007).
[13] S. Nakamura, S. Pearton, G. Fasol, New York, 2000.
[14] I. Vurgaftman, J. R. Meyer, J. Appl. Phys. **94**, 3675 (2003).
[15] D. Fritsch, H. Schmidt, M. Grundmann, Phys.Rev. B **67,** 235205 (2003).
[16] W. C. Messner, D. M. Tibury, J. Smoker, I. H. Tseng, Addison-Wesley Publishing Company, 1998.
[17] M. Dehghan, P. Derakhshan-Barjoi, Progress in Electromagnetic Research **3**, 105 (2008).

*Corresponding author: rafid_alabdali@yahoo.com