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Equivalent Circuit-Level Characterization of 1.55 μm Ingan Laser

By Md. Jahirul Islam & Md. Rafiqul Islam
Khulna University of Engineering & Technology (KUET)

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Equivalent Circuit-Level Characterization of 1.55 μm InGaN Laser

Md. Jahirul Islam[α] & Md. Rafiqul Islam[σ]

Abstract- InGaN is one of the most promising group III-V nitride materials recently focused for semiconductor based device fabrication. The advent of long haul optical communication system requires sophisticated and reliable lasing device. InGaN based lasers composited to have 0.8 eV bandgap energy produce coherent light of 1.55 μm. In this paper, the output characteristics of a heterostructured laser with InGaN as active layer is presented systematically. The circuit-level laser modeling is developed by solving the respective rate equations. This includes the conversion of the complete laser system into its equivalent electrical circuits. Thereafter, simulation was carried out using PSPICE to evaluate the electrical quantities e.g. output power, I-V characteristics, slope efficiency and transient response. A bias voltage of 1.2 volts, threshold current of approximately 6 mA, turn on delay time of 3 ns and slope efficiency of 0.368 W/A are found. The findings are summarized in graphical representation and found to be consistent with numerical simulation of the system model.

Keywords: equivalent circuit modeling, rate equations, hetero structure, quantum well laser (QWL), pspice.

I. Introduction

Perhapse, the invention of lasers has been proven to be one of the most significant breakthroughs for technology in the last century [1]. Their applications extend to high speed communications, optical storage (e.g. CDs, DVDs, optical memories), barcode scanners in industrial machines, printers and even in medical science for spectroscopy and imaging, and also in destroying cancer tissues and unnecessary cells in human bodies [1-2]. In addition, modern technology facilitates with distance learning, online education and high speed online entertainment as well as instant communication from each corner of the world. This requires enormously data to be transported within a short period of time. Optical fiber communication system is one of the strongest candidates to overcome the associated problems. The issues with the constraints of noise, bulk volume of data, amount of signal power transmission, interference with other networks and nearby RF electromagnetic fields are greatly settle down with optical fiber system [3-4]. Ideally, 1.55 μm lasers are well suited for long haul communication at higher data rates due to minimal loss [5].

A number of semiconductor alloys such as ternary, quaternary and quintuplet elements are used to fabricate 1.55 μm laser diodes. For instance, materials including AlGaInAs, GaInNAsSb/GaAs, InGaAs/ InGaAs P, and GaInN AsSb/GaNAs [6-8] are the choices for the active layer of the lasers. However, often these ternary, quaternary and quintuplet materials are difficult to grow, and results in lasing problem.

A growing interest on the group III-IV nitride based semiconductor materials has recently been prompted towards light emitting diodes, lasers and solar cells [9-11]. The wider (0.7 – 6.2 eV) and direct bandgap, low electron effective mass, and high theoretical mobilities of these materials made them suitable for device applications [12]. A small amount of Ga in InN results in InGaN composite with 0.8 eV bandgap energy which is compatible with 1.55 μm wavelength.

The equivalent circuit modeling (ECM) is required to clearly understanding the lasers' working conditions and to verify compatibility with associated electrical driver circuits. The ECM using Shockley equation transfers the carrier and photonics numbers into current and voltage quantities, respectively. Numbers of studies investigated the ECM for quantum dot and quantum cascaded lasers [13-15]. However, to the best of authors' knowledge, the ECM of the proposed In GaN based laser is still unreported, and thus requires attention.

In this paper, we investigate the electrical equivalent circuit characteristics of a previously proposed [16] InGaN based heterostructure laser diode. The static current-voltage (I-V), output power-input current (L-I), output voltage, and transient conditions are discussed briefly. PSPICE circuit simulator has been used to demonstrate the lasers' electrical characteristics.

Author α σ : Department of Electrical and Electronic Engineering, Khulna University of Engineering & Technology (KUET), Khulna-9203, Bangladesh. e-mail: jahirul_kuet@yahoo.com

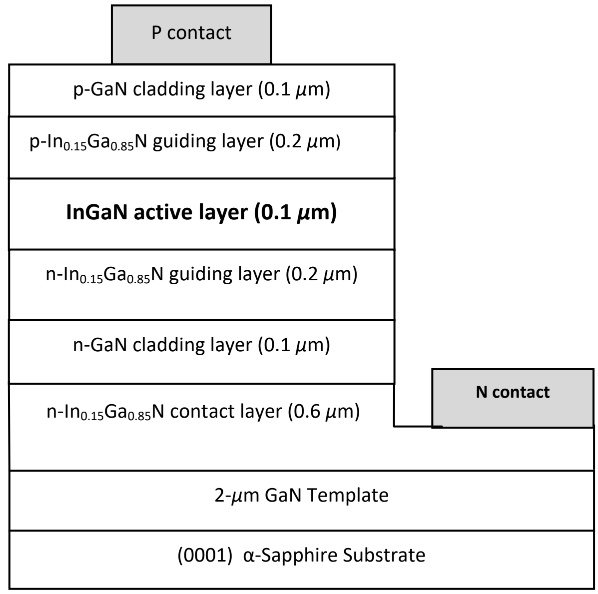

Fig.1: Schematic structure of the proposed InGaN based Quantum Well Laser (After Ref. [16]).

II. Proposed Laser Structure

The schematic structure of the proposed 1.55 μm quantum-well hetero structure lasers using InGaN is shown in Fig.1. A c-plane sapphire wafer is used as the substrate. The LD structure consists of 0.6 μm thick n-$In_{0.15}Ga_{0.85}N$ contact layer, 0.1 μm thick GaN cladding layer, 0.2 μm thick $In_{0.15}Ga_{0.85}N$ guiding layer, and a 0.1 μm thick InGaN active layer.

III. Mathematical Model

The rate equations for quantum well lasers are given by [17-18]

$$\frac{dN(t)}{dt} = \eta_i \frac{I(t)}{eV_a} - \frac{N(t)}{\tau_n} - g_0 \frac{N(t)S(t)}{1+\varepsilon S(t)} \tag{1}$$

$$\frac{dS(t)}{dt} = -\frac{S(t)}{\tau_p} + \frac{\beta N(t)}{\tau_n}\Gamma_c + \frac{g_0 N(t)S(t)}{1+\varepsilon S(t)}\Gamma_c \tag{2}$$

$$\frac{S}{P_f} = \frac{\lambda \tau_p}{\eta_c V_a hc} = \vartheta \tag{3}$$

where N = equilibrium carrier concentration; I = injection current; $\frac{N(t)}{\tau_n}$ = the carrier recombination rate = $AN+BN^2+CN^3$, where A, B, and C are the unimolecular, radiative, and Auger recombination coefficients, respectively; S = photon density = S_{tot}/V_a, where, S_{tot} is again the total number of photons in the active volume; $\beta = \beta_A AN+\beta_B BN^2+\beta_C CN^3$, where β_A, β_B, and β_C are coupling coefficients; P_f = the output power, V_a = is the volume of a single QW; η_i = is the current-injection efficiency; Γ_c = is the optical confinement factor of one QW; g_0 = is the carrier dependent gain coefficient; τ_p = is the photon lifetime; λ= is the lasing wavelength; η_c = is the output-power coupling coefficient; and $\frac{1}{1+\varepsilon S(t)}$ = the gain saturation term.

IV. Model Implementation

To convert the rate equations into circuit model, multiplying Eqn. (1) by $\frac{eV_a}{\eta_i}$ and then simplifying we get

$$I = \frac{1}{\eta_i} I_n + \frac{\tau_n}{\eta_i}\frac{dI_n}{dt} + g_0 \frac{eV_a}{\eta_i} \frac{N_e \exp\left(\frac{eV}{nkT}\right) S(t)}{1+\varepsilon S(t)} \tag{4}$$

where, $I_n = \frac{eV_a N(t)}{\tau_n}$ and $N = N_e \exp\left(\frac{eV}{nkT}\right)$.

Therefore, $$\frac{eV_a}{\eta_i}\frac{dN(t)}{dt} = \frac{\tau_n}{\eta_i}\frac{dI_n}{dt} \tag{5}$$

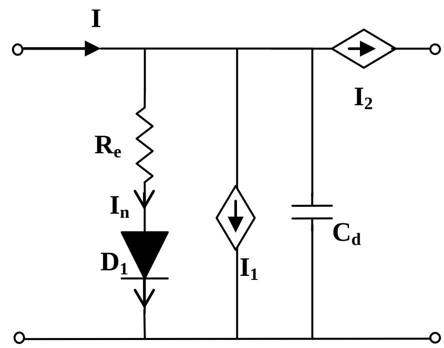

Fig. 2: PSP CE circuit model of Eqn. (4).

Current I of Eqn. (4) is equal to three related current components at quantum well regions i.e. I_n, $I_1 = \frac{\tau_n}{eV_a}\frac{dI_n}{dt}$ and the stimulated emission component I_2. The p-n heterojunction voltage V_j can be represented by one ohmic resistance R_e, series-connected with Shockley p-n junction diode (shown in Fig.2). $C_d = C_0\left(1-\frac{V_j}{V_d}\right)^{-\frac{1}{2}}$, a junction depletion capacitance is added to the circuit, where C_0 is the zero bias depletion capacitance, V_j is the junction voltage, V_d is the build-in potential.

Now, multiplying Eqn. (2) by eV_a we get,

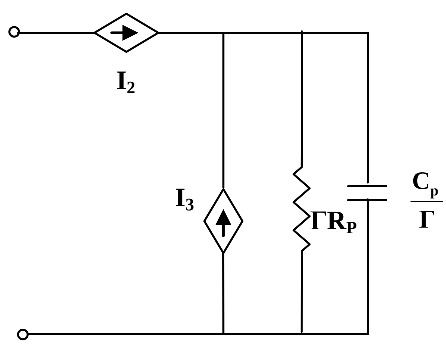

Fig. 3: PSPICE circuit model of Eqn. (8).

$$eV_a\frac{d\,S(t)}{dt} = -eV_a\frac{S(t)}{\tau_p} + eV_a\frac{\beta N(t)}{\tau_n}\Gamma_c + eV_a\frac{g_0 N(t)S(t)}{1+\varepsilon S(t)}\Gamma_c \quad (6)$$

which later reduces to

$$C_p\frac{d\,S(t)}{dt} + \frac{S(t)}{R_p} = G_0\frac{N(t)S(t)}{1+\varepsilon S(t)}\Gamma_c + \beta I_n\Gamma_c \quad (7)$$

Rearranging Eqn. (7), one can get

$$\frac{S(t)}{\Gamma_c R_p} + \frac{C_p}{\Gamma_c}\frac{d\,S(t)}{dt} = G_0\frac{N(t)S(t)}{1+\varepsilon S(t)} + \beta I_n \quad (8)$$

Where the parameters R_p and G_0 are defined by [19],

$$R_p = \frac{\tau_p}{C_p},\ G_0 = D\left(J_{nom} - 2\times10^{13}\right)^2 .$$

Also, D= a constant and $J_{nom} = \frac{I_n}{V_a}$.

In Eqn. (8), the first two terms represent a resistance (in parallel) and a capacitance. Again, the optical emission consists of a spontaneous component stimulated component $G_0\frac{N(t)S(t)}{1+\varepsilon S(t)}$. These two components are modeled by two (I_3 and I_2) current sources as shown in Fig.3. Thus, the light output is proportional to the output node in voltage representation. The voltage representation is applicable if transmission channel and receiver circuit are included in the simulation.

Now from Eqns. (4) and (8), the total equivalent circuit for a single QW laser has been illustrated in Fig.4.

V. PSPICE CIRCUIT SIMULATION RESULTS

Unlike electronic devices that are usually characterized by current and voltage, optoelectronic devices are normally characterized by light intensity and current. Since light intensity cannot be represented by any physical circuit quantities, modeling optoelectronic devices by PSPICE circuit model is certainly not physically transparent.

The results of PSPICE circuit model for InGaN based laser developed according to the electrical equivalent circuit discussed in section IV, is presented in this section. The parameters used for the PSPICE simulation are listed in Table 1.

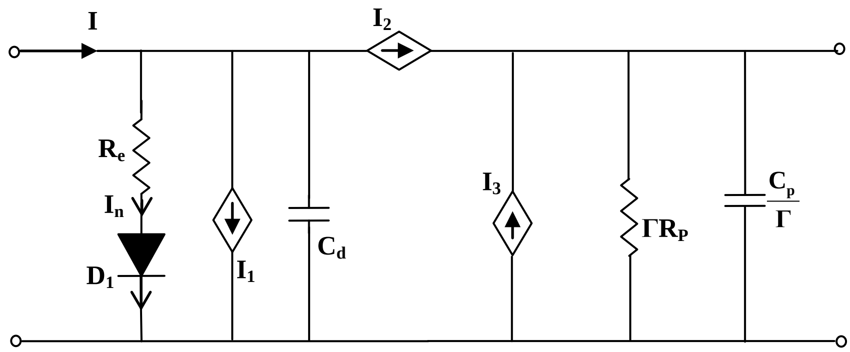

Fig. 4: Equivalent circuit model of a single quantum well laser.

Table 1: Parameters used in PSPICE circuit simulations [20].

Parameter	Unit	Value
R_e	Ω	0.468
R_p	Ω	29.4
R_s	Ω	2.0
τ_{ns}	ns	2.25
τ_{np}	ns	3
C_p	pF	0.102
C_d	pF	10
S_c	m^{-3}	10^{18}
D	$V^{-1}A^{-1}m^6$	1.79×10^{-29}
β_s	-	10^{-5}

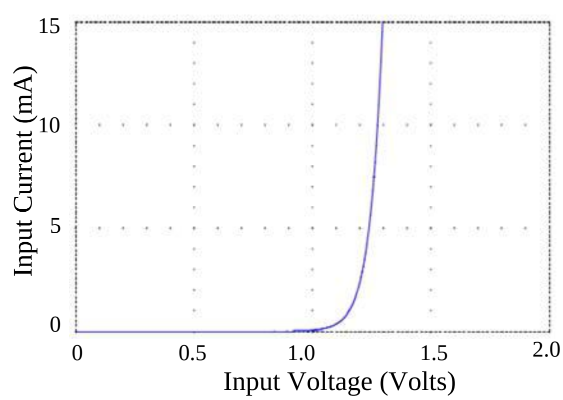

Fig.5: Current vs. voltage relationship for InGaN laser.

The PSPICE circuit simulation evaluates the electrical characteristics such as current-voltage, transient response of the laser equivalent circuit. Figure 5 depicts the I-V response of the laser. As it is shown in the figure, the current initiates to flow at an applied voltage of approximately 1.20 volts and then increases abruptly. The threshold value of the voltage is approximately 1.20 volts.

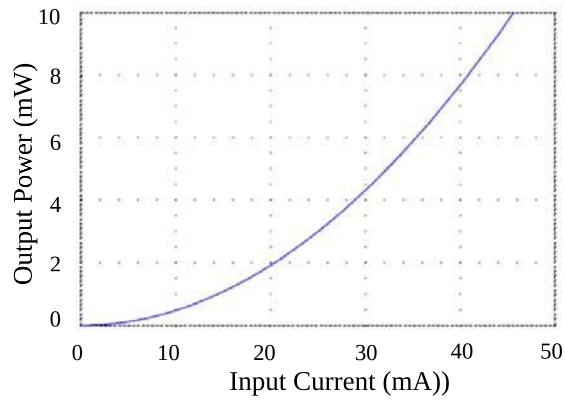

Fig.6: Output power-input current (L-I) characteristic of the proposed laser.

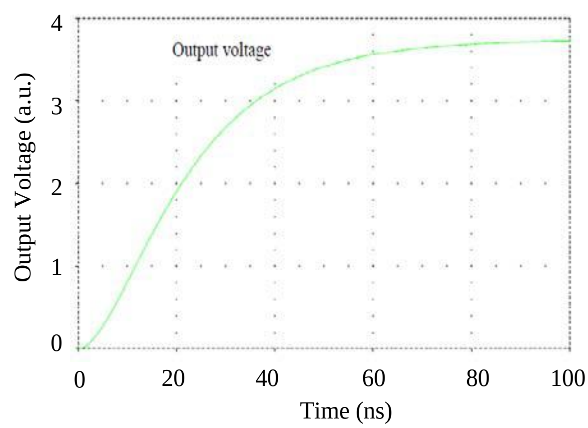

Fig.7: Output transient voltage of the laser.

Moreover, Fig.6 represents the output power with the variation of input current (L-I characteristics).The power output increases with the increase of input current. Threshold current of 6 mA and the slope efficiency of approximately 0.368 W/A are found from Fig.6.

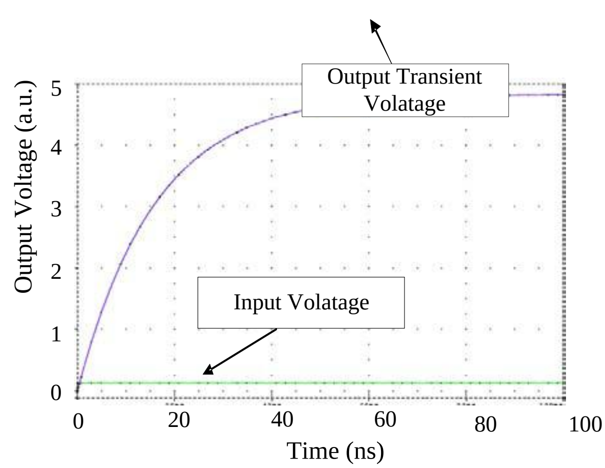

Fig.8: Turn on delay time of the quantum well laser.

The transient response of the laser is shown in Fig.7. The steady state values of output voltage are found after 60 ns. Turn on delay of 3 ns is calculated from Fig.8 for InGaN based laser. These results are in well consistent with the results obtained from the previous [16] discussions.

VI. Conclusion

A detailed electrical equivalent circuit model of 1.55 μm InGaN based laser has been studied numerically. The characteristics are realized through the development of the equivalent circuit modeling of the quantum well laser. The electrical circuit modeling of the laser is important to find out the electrical parameters. The PSPICE circuit simulation resulted in an increase in output power with the increase of input current. Threshold current of approximately 6 mA, bias voltage of 1.20 volts, slope efficiency of 0.368 W/A and turn on delay of 3 ns have been found from this circuit analysis. These electrical properties present the richness of InGaN based lasers, and are in agreement with the results of numerical simulations of the same model. Attention on ECM for the laser is important to understanding the electrical mechanism, and requires exhaustive investigation to be matched with electrical automatic power control, modulation scheme, level shifter and slow start circuits.

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