Published in AJSE, Vol:16, Issue: 02
Received on 20th November 2016
Revised on 27th March 2017
Accepted on 6th April 2017

AIUB JOURNAL OF SCIENCE AND ENGINEERING
ISSN: 1608 – 3679(print) 2520-4890(Online)

Optimized High Performance Characteristics of a designed 450 nm InGaN/AlGaN True Blue Laser Considering Different Injection Current

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***Abstract*—-- In this work, the effects on the performance characteristics of a $In_{0.1558}Ga_{0.8442}N$ / $Al_{0.0416}Ga_{0.9584}N$ 3QW separate confinement heterostrcture 450 nm true blue edge-emitting laser are presented by considering different injection current. At the temperature of 300 K, the threshold current of the laser is 11 mA. The peak material gain for the designed laser is obtained as 1106 cm^{-1} and further used for the analysis of the performance characteristics of the designed double-heterostructure laser for the variation of injection current. The injection current can be applied to the device is at around 12 to 15 times of the threshold current. At the value of injection current 152 mA, the maximum output power of the laser is 256.4 mW, the maximum resonance frequency is 14.5 GHz and the corresponding modulation bandwidth is 25.3 GHz at the temperature of 300 K.**

Keywords*— MQW, true blue laser, resonance frequency, modulation bandwidth, varying injection current;

I. INTRODUCTION

Near Ultra-Violet nitride based semiconductor laser diodes have suitable applications like document production, compact disk technology, optical communications etc. because of their shorter wavelength, higher quantum efficiency, longer lifetime and low power consumption. A true blue semiconductor laser diode having emission wavelength of 450 nm offers a brand new area of projection applications. True blue lasers are of great interest for full color laser projection. Especially directly modulated blue laser diodes are the light sources for scanning beam projectors. InGaN laser is the preferred blue light source, which is small size and has good modulation frequency. The main advantage of nitrides over other high bandgap semiconductors is the strong chemical bond which is responsible for making the material more stable [1-4].

GaN based laser diodes have many scientific applications like spectroscopy etc. Here they can easily compete with gas and solid-state lasers which are expensive and large spectroscopic sources. For improving the quality and resolution of the printed text, printers require the number of dots per inch to be high which is possible to achieve by using a true blue laser diode which has a shorter wavelength compared to the generally used an infra-red beams [5-7]. In this paper, the performance analysis and of a 450 nm $In_{0.1558}Ga_{0.8442}N$ / $Al_{0.0416}Ga_{0.9584}N$ MQW SCH edge emitting laser are presented considering the effects of variation of injection current.

II. DEVICE DESIGN

The Quantum Well (QW) material has been chosen as InGaN and AlGaN is considered for SCH layer and the barrier. The cladding material is also AlGaN. The transition energy E is equal to the summation of the bandgap energy of the QW region and confined state energies of Conduction Band (E_C) and Valence Band (E_V). It can be expressed as: $E = E_g\,(QW) + E_C + E_V$. E is found to be 2.7608 eV. The confined state energy for the conduction band and the valence band can be expressed as [8]:

$$E_C = \frac{h^2}{8m_C l_w^2} \quad \dots (1)$$

$$E_V = \frac{h^2}{8m_V l_w^2} \quad \dots (2)$$

Where, l_w is the thickness of the Quantum Well, m_c and m_v are the effective masses of electron in the conduction band and valence band respectively. Confined state energy for conduction band is calculated as 0.048257 eV and Confined state energy for valence band is calculated as0.030317 eV, considering the thickness of the Quantum Well as 6.5 nm, the effective masses of electron in the conduction band and valence band can be expressed as m_c=0.18443 m_0 and m_v=0.293568 m_0 respectively. The bandgap energies and the refractive indices for different layer materials can be found from the following equations [9, 10]

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$$E_g(Al_xGa_{1-x}N) = 6.28x + 3.42(1-x) - 0.98(1-x) \quad \ldots (3)$$

$$E_g(In_xGa_{1-x}N) = 1.89x + 3.42(1-x) - 3.8(1-x) \quad \ldots (4)$$

$$n(Al_xGa_{1-x}N) = 2.5067 - 0.43x \quad \ldots (5)$$

$$n(In_xGa_{1-x}N) = 2.5067 + 0.91x \quad \ldots (6)$$

For the quantum well material, the bandgap energy E_g (InGaN) was found to be 2.682 eV and refractive index (n1) was found to be 2.6485. For the SCH material, the bandgap energy E_g (AlGaN) was found to be 3.5 eV and refractive index (n_2) was found to be 2.4888. For the Cladding layer material, the bandgap energy was found to be 3.542 eV and refractive index (n_3) was found to be 2.47. Figure 1 shows the bnadgap energy of the cavity along with the SCH and the cladding layer of the designed laser.

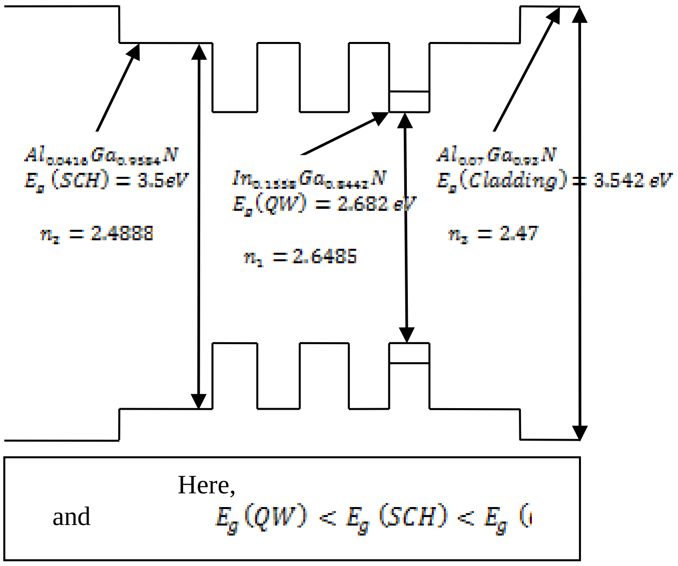

Fig. 1. The active region of a True Blue EEL consisting of 3 Quantum Wells and 2 Barriers

The structure of the designed laser is presented in figure 2. Active layer consists of 3 Quantum Wells, where the material InGaN has the concentration of $In_{0.1558}Ga_{0.8442}N$. SCH and the barrier material AlGaN have the concentration of Al0.0416Ga0.9584N. Cladding layer material AlGaN for both p and n contact has the concentration of $Al_{0.07}Ga_{0.93}N$. The concentrations of the materials have been chosen for obtaining high performance [11, 12].

The thickness of the active region is calculated in x-y plane. The thickness of the each QW is 6.5 nm and each barrier is 7.5 nm. So, Total active layer thickness (*d*) is 34.5 *nm*. Width (*w*) is considered as 2 μm and length (*L*) in the z-direction is considered as 800 μm. Active layer is sandwiched between two SCH layer of each 63 *nm* and the two cladding layers having thickness of each 1.2 μm. So, total cavity thickness is: thickness of 2 SCH layer + thickness of Active layer = 160.5 *nm*. Active volume (Va) is 5.520×10^{-11} cm^3. The thickness of the SCH region is added to the active layer thickness for computing total cavity volume. Cavity volume is found to be 2.5680×10^{-11} cm^3. The Confinement factor has been calculated from $\Gamma = Va / Vp = 0.2163$.

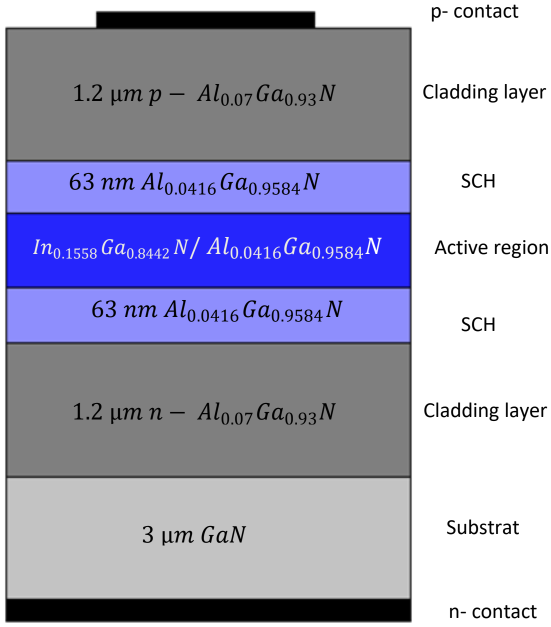

Fig. 2. The structure of a designed True Blue EEL consisting of 3 Quantum Wells and 2 Barriers..

III. Computatuion of Parameters

A. *Calculations of material gain (g(E))*

The material gain of the designed true blue laser is calculated using the following equation [13]

$$g(E) = \left(\frac{q^2\pi\hbar}{\varepsilon_0 m_0^2 ncE}\right)|M|^2 \rho_r(f_1 - f_2) \quad \ldots (7)$$

Where, q is the electron charge, ε_0 is the free-space permittivity, c is the vacuum speed of light, n is the refractive index of the laser structure, E is the transition energy, m_0 is the mass of electron, $|M_T|^2$ is the transition momentum matrix element. ρ_r is the reduced density of state, h is the Plank's constant divided by 2π, f_2 and f_1 are the electron quasi Fermi functions in the conduction and valance band respectively.

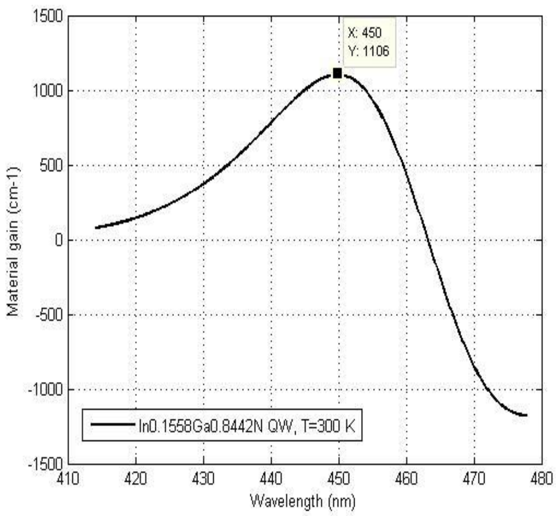

Fig. 3. Plot of material gain vs. wavelength of the designed 450 nm True Blue Laser.

Using equation (7), at 300K, the material gain for a 450 nm multi quantum well edge-emitting true blue laser using $In_{0.1558}Ga_{0.8442}N$ / $Al_{0.0416}Ga_{0.9584}N$ materials is calculated using MATLAB by varying wavelength. The obtained result is plotted as shown in figure 3.

The structure of the designed laser is presented in figure 2. Active layer consists of 3 Quantum Wells, where the material InGaN has the concentration of In0.1558Ga0.8442N. SCH and the barrier material AlGaN have the concentration of Al0.0416Ga0.9584N. Cladding layer material AlGaN for both p and n contact has the concentration of Al0.07Ga0.93N. The concentrations of the materials have been chosen for obtaining high performance [11, 12].

Developing the codes in MATLAB, It is observed that, starting material gain is rising to higher value with the increase of the wavelength. A maximum material gain is obtained as 1106 cm^{-1} at 450 nm wavelength at the value of photon energy of 2.762 eV. After this region, material gain is decreased in accordance with the increasing of wavelength.

B. *Calculations of transparency carrier density (N_{tr}), threshold carrier density (N_{th}), photon life time (τ_p) and threshold current (I_{th}) of the designed laser*

The transparency carrier density (Ntr) of a material is related to the effective masses of electron in the conduction band and valence band as [13]

$$N_{tr} = 2\left(\frac{kT}{2\pi\hbar^2}\right)^{3/2}\left(m_c m_v\right)^{3/4} \quad \dots (8)$$

Where, k is the Boltzmann constant, T is the temperature in Kelvin, $\hbar$ is the rationalized Planck's constant, m_c and m_v are the effective masses of the carriers in the conduction band and valence band respectively. At the temperature of 300 K, the calculated value of transparency carrier density of $In_{0.1558}Ga_{0.8442}N$ QW material is 2.8×10^{18} cm^{-3}. At 300K, the carrier density at threshold point (N_{th}) of 3.0228×10^{18} cm^{-3} has been found using the following equation. [13]

$$N_{th} = N_{tr} \times e^{\frac{(\alpha_i+\alpha_m)}{\Gamma\times g_0}} \quad \dots (9)$$

Where, N_{tr} is the transparency carrier density, g_0 is the peak material gain coefficient, α_i is the intrinsic absorption loss and α_m is the mirror loss co-efficient.

Using group velocity v_g and mirror loss (α_m), it is possible to find out photon lifetime(τ_p) using the expression given below [13] where the group velocity is calculated as 1.1679×10^{10} cm/s.

$$\tau_p = \frac{1}{\left(v_a \times \left(\alpha_i + \alpha_m\right)\right)} \quad \dots (10)$$

The photon lifetime was found to be 4.5861×10^{-12} s. Finding the threshold carrier density, the threshold current (I_{th}) is calculated from [13]

$$I_{th} = \frac{q * V_a * N_{th}}{\eta\tau_c} \quad \dots (11)$$

It is found that at the temperature of 300K the threshold current is 11 mA with an injection current efficiency (η_i) of 0.9, carrier lifetime (τ_c) of 2.71×10^{-9} s.

C. *Computation of the output power (P_{out}) of the designed laser*

The optical output power of the designed laser can be calculated with the variation of the injection current as [13]

$$P_{out} = \frac{\alpha_m h v \eta_i}{qg\Gamma}\left(I - I_{th}\right) \quad \dots (12)$$

Where, α_m is the mirror loss coefficient, g is the material gain, h is the Planck's constant, υ is the lasing frequency, Γ is the confinement factor, I is the injection current and I_{th} is the threshold current.

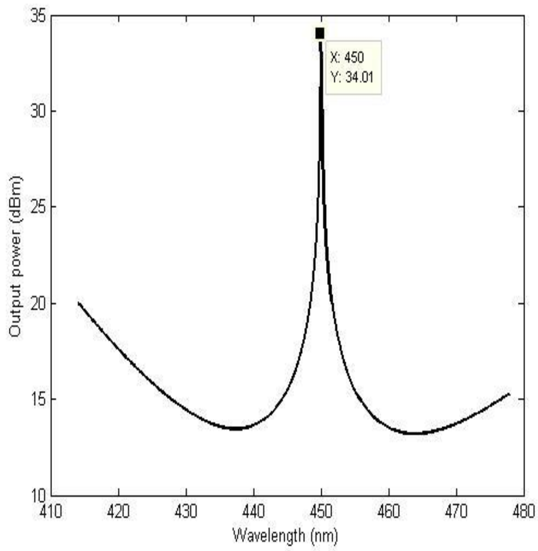

Fig. 4. Plot of output power vs. wavelength of the designed 450 nm True Blue Laser.

Developing the codes in MATLAB, using equation (12), at 300 K temperature, the true blue laser output power is calculated by varying wavelength. The obtained result is presented as shown in figure 4.

The output power of the designed laser is calculated by varying the wavelength considering a fixed injection current value of 132 mA. It is found that the material gain of the designed laser keeps varying with the variation of wavelength which results the further variation in the output power of the laser. It is observed that, a peak intensity of the output power is obtained exactly at 450 nm wavelength for the fixed value of injection current.The emission wavelength of the laser is related to the bandgap energy of the material and can be calculated from the following expression [8]

$$\lambda = \frac{hc}{E_g(QW) + E_c + E_v} \quad \dots (13)$$

Using equation (13), the total transition energy is calculated as 2.7606 eV and the corresponding emission wavelength of the designed Laser is found as 450.04 nm which is almost equal to the obtained result.

IV. SIMULATION RESULTS AND DISCUSSIONS

This section is entirely dedicated to find the characteristics of the designed 450nm true blue laser for considering different injection current. The injection current is varied from a value of 112 mA to 152 mA with an interval of 10 mA. The rate of change of carrier density of a laser can be written as [13]

$$\frac{dN}{dt} = \eta_i \frac{I}{qV_a} - \frac{N}{\tau_c} - \frac{v_g a(N - N_{tr})S}{(1+\varepsilon S)} \quad \text{… (14)}$$

Where, N is the carrier density, S is the photon density, I is the injection current, q is the electron charge, V_a is the volume of the active region, η_i is the injection efficiency, τ_c is the carrier life time, v_g is the group velocity, a is the differential gain, N_{tr} is the transparency carrier density and ε is the gain saturation parameter of a laser.

The rate of change of photon density of a laser can be written as [13]

$$\frac{dS}{dt} = \frac{\Gamma v_g a(N - N_{tr})S}{(1+\varepsilon S)} + \Gamma\beta_{sp}\frac{\eta_i I_{th}}{q} - \frac{S}{\tau_p} \quad \text{… (15)}$$

Where, β_{sp} is the spontaneous emission coefficient, Γ is the coefficient factor, τ_p is the photon lifetime and I_{th} is the threshold current of a laser. The parameter values are taken as the photon lifetime of 4.5861 ps, the carrier lifetime of 2.71 ns, the reflectivity of 33.5% and the gain saturation of 1.5×10^{-17} cm^3.

The MATLAB is used for determining the characteristics of the designed laser. Different Codes are developed in MATLAB for obtaining optimized characteristics of the designed LASER. The first simulation is about the effects on rate equations for different injection currents are discussed below

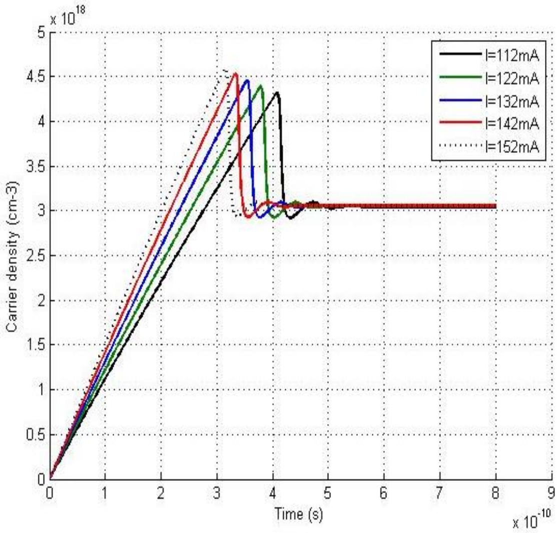

Fig. 5. Plot of carrier density versus time of the designed 450 nm True Blue Laser for different values of injection current.

The observation from the above figure is that, with the increase in injection current varying from 112 mA to 152 mA, the steady state carrier density is found to increase.

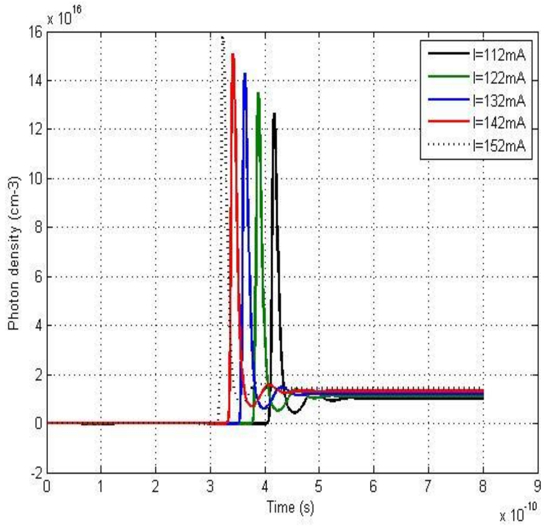

Fig. 6. Plot of photon density versus time of the designed 450 nm True Blue Laser for different values of injection current.

The observation from the figure is that, the steady state photon density increases in accordance with the increasing of injection current starting from 112 mA to 152 mA.

The second simulation deals with the effect on output power for different injection currents. The output power versus time characteristic is shown below:

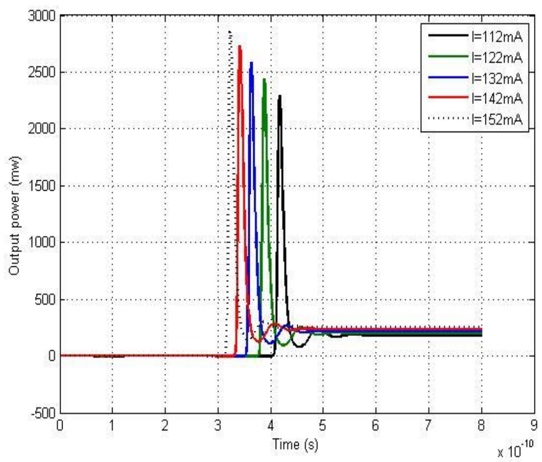

Fig. 7. Plot of output power versus time of the designed 450 nm True Blue Laser for different values of injection current.ss

From the above figure, it is seen that, with the increase in injection current the steady state output power is found to increase. It is found that the steady state output power of the laser is 256.4 mW

The last simulation is about the change in modulation response with the variation of injection current. The relative response versus frequency characteristic is given below:

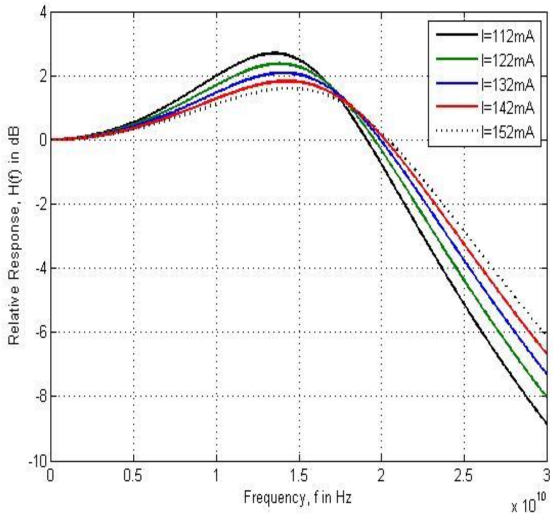

Fig. 8. Plot of relative response versus frequency of the designed 450 nm True Blue Laser for different values of injection current.

From figure 8, it is seen that, it is a plot of relative response versus frequency characteristic of a designed 450 nm True Blue Laser using $In_{0.1558}Ga_{0.8442}N$ / $Al_{0.0416}Ga_{0.9584}N$ materials, 65Å QW at 300K temperature by varying injection current. With the increase in injection current, maximum resonance frequency and cut off frequency increase. From injection current from 112 mA to 152 mA, a maximum resonance frequency is found to be 14.5 GHz. Maximum modulation bandwidth is found to be 25.3 GHz.

V. CONCLUSION

In this paper, variations in the characteristics of the designed 450 nm true blue laser using $In_{0.1558}Ga_{0.8442}N$ / $Al_{0.0416}Ga_{0.9584}N$ materials, 65Å QW at the temperature of 300K with the variation of injection current are presented. The dimensions of the designed laser along with the different parameter values are optimized for achieving a lot better performance characteristics. The emission wavelength of the designed laser is obtained exactly at 450 nm. The material gain for $In_{0.1558}Ga_{0.8442}N$ / $Al_{0.0416}Ga_{0.9584}N$ 3QW Separate Confinement Heterostrcture Edge-Emitting laser is obtained as 1106 cm^{-1}. At the temperature of 300K, the threshold current of the laser is found out to be 11 mA. From the performance analysis, it is found that the performance characteristics like steady state carrier density, steady state photon density, steady state output power, the maximum resonance frequency and the modulation bandwidth increase with the increase in injection current. It is found that the injection current can be applied to the device is at around 12 to 15 times of the threshold current. For the injection current of 152 mA, the steady state output power of the laser is 256.4 mW, the maximum resonance frequency is 14.5 GHz. The corresponding modulation bandwidth is 25.3 GHz which is the increase in the band width in a wide range thus enhances the performances of the laser.

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