Effects of Variation of Injection Current, Differential Gain and Injection Current Efficiency on the Modulation Performance of a GaInP Based 635nm MQW Red Laser

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***Abstract*—In this work, the effects of variation of Injection Current, Differential Gain and Current Injection Efficiency on the Modulation performance characteristics of a GaInP based 635nm Red laser have been obtained through proper simulation and computations. Here the analyzed red laser consists of 3 multiple quantum well (MQW) and separate confinement heterostructure (SCH). The total simulation process of the designed $Ga_{0.5}In_{0.5}P/(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ is completed by using MATLAB software. The injection current is proposed 90mA where the threshold current is maintained 6.7mA at the temperature of 300K. By sustaining the proposed injection current the peak intensity is found at exactly 635nm wavelength with the power of 105mW. A maximum resonance frequency is obtained 10 GHz with the modulation bandwidth of 16.25 GHz. By varying the value of different parameters the total analyses and the performance of the laser has been optimized.**

***Keywords*— Differential Gain, Injection Current, Injection Current Efficiency, Laser Diode and Modulation Response**

I. INTRODUCTION

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. Lasers differ from other sources of light because they emit light coherently. Its spatial coherence allows a laser to be focused to a tight spot, and this enables applications like laser cutting and laser lithography. Its spatial coherence also keeps a laser beam collimated over long distances, and this enables laser pointers to work. Laser also has high temporal coherence which allows them to have a very narrow spectrum, i.e., they only emit a single color of light [8]. Semiconductor laser diodes have applications in the field of data storage, printing, optical communications, spectroscopy etc. due to their small size, low power dissipation and high quantum efficiency. For the modern secured communication system as the sensor device the red laser is vastly practical. As the 635nm red laser is widely used for data transfer communication system as well as used to indicate any type of coding system sensing system (as signal controlling), (as bar code) and for other application so on this basis my research interest is to enhance the performance of this widely used red laser.

By maintaining the concentration of the basic designed red laser here the analysis has been completed. In this paper, the modulation performance analysis and optimization of a MQW Separate Confinement Heterostructure 635*nm* $Ga_{0.5}In_{0.5}P/(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ Red Laser are presented considering the effects of variation of injection current, differential gain and injection current efficiency.

II. THEORY

The basic concept is very important to analysis a laser. Maintaining all condition of proper lasing the following performance characteristics has been analyzed.

A. Gain Calculation

The optical gain has to be found for the active region material to design a practical laser. In the DH active region, the injection current provides a generation term and a radiation term. Thus the rate equation can be written as [1]:

$$\frac{dN}{dt} = G_{gen} - R_{rec} \tag{1}$$

Where, G_{gen} is the rate of injection electrons (generation term) and R_{rec} is the rate of recombining electrons per unit volume in the active region (radiation term). The gain expression is given as [2], [3].

$$g(E) = \left(\frac{q^2 \pi \hbar}{\varepsilon_o m_0^2 ncE}\right) |M_T|^2 \rho_r (f_2 - f_1) \tag{2}$$

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Where ε_0 is the free space permittivity, E is the transition energy, f_2 and f_1 are quasi-Fermi functions in the conduction and valence band respectively, q is the electronic charge, c is the speed of light, $|M_T|^2$ is the square of the transition momentum matrix element, ρ_r is the refractive index of the laser structure, ħ is the rationalized Planck's constant.

B. Calculation of Modulation response

The modulation response is conveniently described in terms of the following two-parameter modulation transfer function [1]:

$$H(\omega) = \frac{\omega R^2}{\Delta} \equiv \frac{\omega R^2}{\omega R^2 - \omega^2 + j\omega\gamma} \qquad (3)$$

Where, ω_R is the relaxation resonance frequency and γ is the damping factor.

This is very important to find out modulation response of laser. By using the following transfer function as equation (4) the modulation response can be found out. If the value $\omega = 2\pi f$ is replaced to equation (3) the new form that equation will be set as:

$$H(f) = \frac{f_R^2}{f_R^2 - f^2 + j\left(\frac{f}{2\pi}\gamma\right)} \qquad (4)$$

The damping parameter can be expressed as:

$$\gamma = \gamma_o + K f_R \qquad (5)$$

The threshold damping factor $\gamma o = 1/\tau\Delta N$, where $\tau\Delta N$ is the differential carrier lifetime. In the above equation the parameter constant K- factor has been defined as:

$$K = 4\Pi^2 \left(\tau_p + \frac{\varepsilon}{v_g\, a}\right) \qquad (6)$$

Where, ε is the gain compression parameter, and τ_p is the photon lifetime of a laser [1].

III. STRUCTURE AND DESIGN OF 635NM RED LASER

In this work, the concentration of Ga, In and P is chosen from the resultant value after proper computation using Vegard's law for attaining the maximum performance from the laser. For the construction of active layer GaInP is selected for red laser. Using Vegard's law at 300K all parameters can be calculated. For example, in $Al_{1-x}Ga_xIn_yP_{1-y}$, we obtain [1].

For utilizing the designed laser in this research work the higher peak material gain has to be obtained near the emission wavelength of 635nm with the lower transparency carrier density.

$$a(x,y) = xya_{GaIn} + x(l-y)a_{GaP} + (1-x)ya_{AlIn} + (1-x)(1-y)a_{AlP}. \qquad (7)$$

Each quantum well of the active region is having a thickness of 80Å which are separated by the barriers $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ of thickness 100Å.

From the Fig. 1 it is shown that the active region is sandwiched by a SCH layer maintaining the concentration of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ and which having a thickness of 900Å each and also are enclosed within a cladding layer of $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ which has been doped properly.

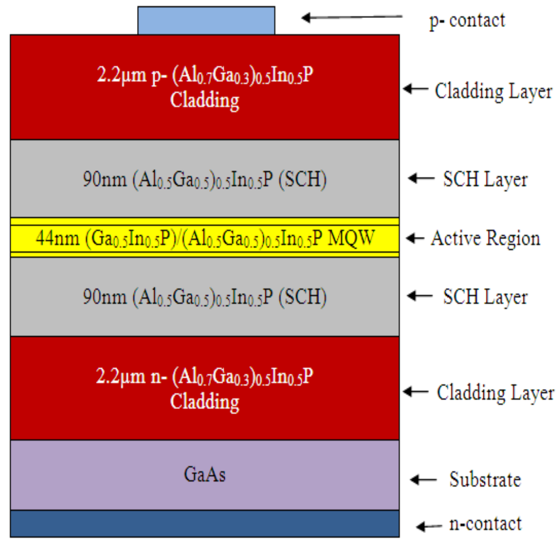


Fig. 1. Structure of designed 635nm MQW Red Laser

The ends of the device are cleaved to form flat planes which is called 'facets'. This facets act as partially reflective mirror. Here the mirror reflectivity is achieved 33.5%. According the structure current is injected through the upper p-type contact and the n-type contact is attached with the GaAs substrate. Using the concept of equation 1 and maintain the proposed injection current 90mA at 300K the peak material gain for the $Ga_{0.5}In_{0.5}P/(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ MQW SCH EEL is obtained $770cm^{-1}$ at around the wave length of 625nm which is shown in the following figure. This result is much better than the previous research work.

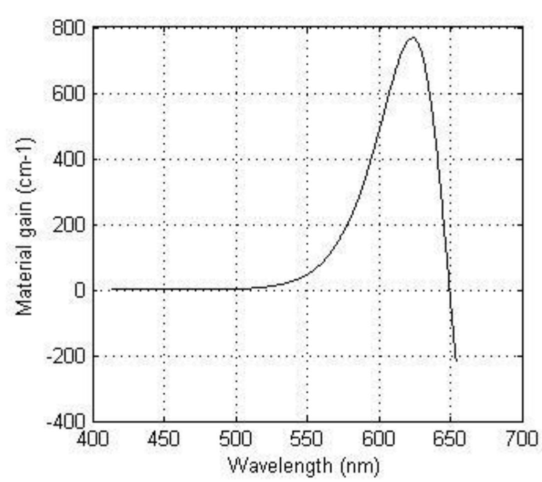


Fig. 2. Plot of material gain vs. wave length with the maximum gain $770cm^{-1}$ at around 625nm wave length

Besides it is very much important to find the value of transparency carrier density.

By using the effective masses of CB and VB the N_{tr} can be obtained with the following equations [1].

$$N_{tr} = 2(kT/2\pi\hbar^2)^{3/2} (m_c m_v)^{3/4} \qquad (8)$$

Where, T is the temperature in Kelvin, k is the Boltzmann constant, ħ is the rationalized Planck's constant. At 300K, the N_{tr} is calculated of $Ga_{0.5}In_{0.5}P$ is 1.1513×10^{18} cm^{-3} which is lower than that barrier material.

In the following section performance characteristics of the designed 635*nm* SCH edge emitting Red laser have been presented using the resultant value of peak material gain.

IV. ANALYSIS AND OPTIMIZE THE PERFORMANCE OF 635NM RED LASER

To analysis the performance some important parameters are needed to establish a simulation process which is done by using MATLAb software.

A. Important Parameters of the designed laser

The following table is containing the important parameters of the designed laser. Some of the parameters are also included in this list from practically implemented lasers from the following sources [4], [5]. Considering all these parameters the total analysis is completed. But in this research work among these parameters to enhance the performance of the 635nm red laser three parameters are proposed and the effect of varying those parameters will be shown in the resultant graphs. The effects are represented by corresponding computation of modulation response.

Here the simulation work and the resultant graphs have been done using MATLAB software.

TABLE I
PARAMETER VALUES OF THE 635NM RED LASER

Symbols	Type of Parameters	Value
V	Active region volume	7.92×10^{-11} cm^3
V_p	Cavity Volume	4.032×10^{-10} cm^3
m_e	Electron effective mass	$0.092m_0$
m_h	Hole effective mass	$0.179m_0$
K	Temperature in Kelvin	300K
α_i	Intrinsic absorption loss	5 cm^{-1}
ε	Gain compression factor	1.5×10^{-17} cm^3
β_{sp}	Spontaneous emission factor	0.869×10^{-4}
R_{sp}	Spontaneous emission rate	1×10^3
Γ	Confinement factor	0.1964
R	Reflectivity	0.335
η_i	Injection current efficiency *	0.9
a	Differential gain *	5.1×10^{-16} cm^2
I	Injection current *	90mA

* proposed value of the parameter.

B. Computation of the Performance Characteristics and obtained results

Maintaining equation (10) the threshold carrier density N_{th} has been found $1.2902\times10^{18}cm^{-3}$ at 300K and photon life time τ_p is obtained 6.637ps from the group velocity v_g of 8.7848×10^9 cms^{-1}. The following equation express output power where g is material gain, I is injection current, α_m is mirror loss coefficient, v is frequency of emitted photon and h is the Planck's constant [1].

$$P_{out} = \frac{\alpha_m h v \eta_i}{q g \Gamma}(I - I_{th}) \qquad (9)$$

For the calculation of I_{th} in equation (10) all these parameters are occupied with the injection current efficiency η_i and carrier life time τ_c [1].

$$I_{th} = \frac{q V_a N_{th}}{\eta_i \tau_c} \qquad (10)$$

At 300K the I_{th} is found 6.7mA with injection current efficiency 0.9. From equation (9) it is found that with the increase of injection current I, the output power will be increased.

Here the chosen (applicable) value of injection current is 90mA. For the calculation of output power vs. injection current graph equation (9) is needed to reformatting. Equation (11) expresses the analysis and the graph has been shown in following Fig. 4 [1].

$$P_{out} = \frac{\alpha_m h v \eta_i}{q(\alpha i + \alpha m)}(I - I_{th}) \qquad (11)$$

Sustaining the injection current at 90mA the output power will be varied according the change of wavelength which is shown in Fig. 3. By maintaining equation (9) at 300K the peak intensity for the designed red laser is obtained 635nm.

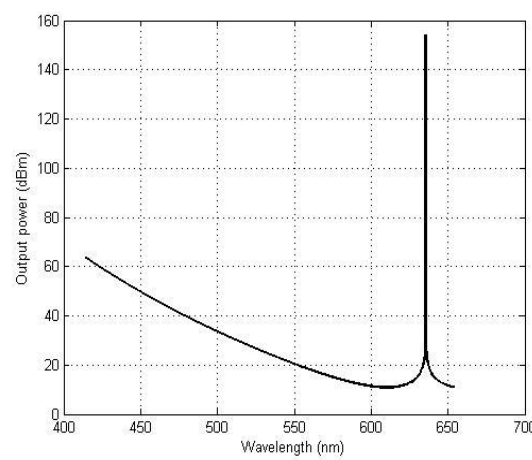


Fig. 3. Plot of power vs. wavelength of the designed red laser at 300K. A peak intensity of the power is obtained at 635nm wavelength

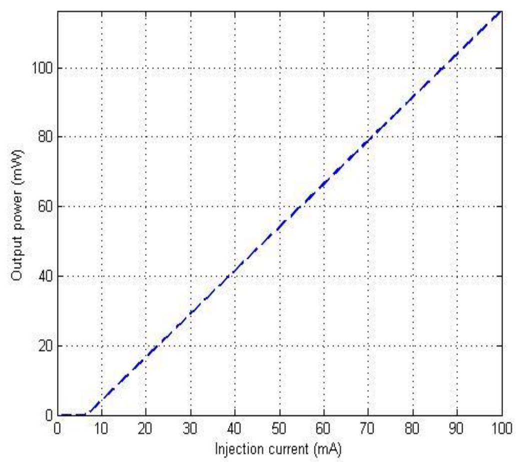


Fig. 4. Plot of Output power vs. Injection current of the designed red laser at 300K maintaining injection current 90mA

Using the output of the computation work above, a plot of carrier density vs. time is presented in Fig. 5 for the designed 635*nm* red laser.

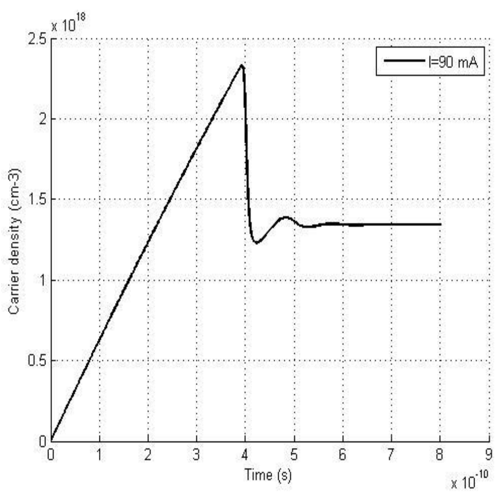


Fig. 5. Plot of Carrier density vs. Time. The steady state carrier density of 1.365×10^{18} cm^{-3} is found at 90mA

It is very much important for keeping the carrier density according the following concept [1]:

$$N > N_{th} > N_{tr}$$

Where N is the carrier density, N_{th} is the threshold carrier density, and N_{tr} is the transparency carrier density.

After computation these three types of carrier density the above theoretical concept has been satisfied.

A photon density vs. time plot is shown in Fig. 6 for the designed 635nm red laser.

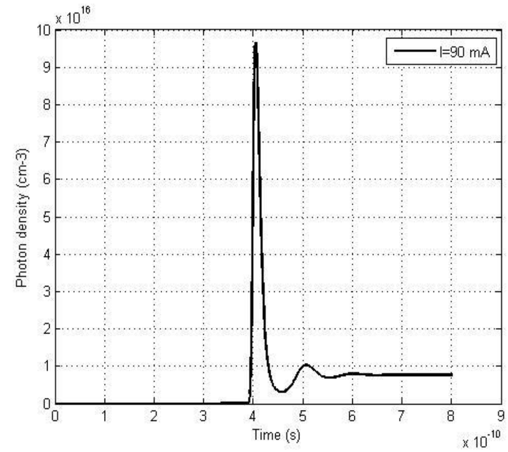


Fig. 6. Plot of Photon density vs. Time. The steady state photon density at 90 mA is found 8.763×10^{15} cm^{-3}

C. Modulation response of designed 635 nm red laser

Using the transfer function of relative response equation (4) the effect of modulation response has been shown in the following Fig. 7:

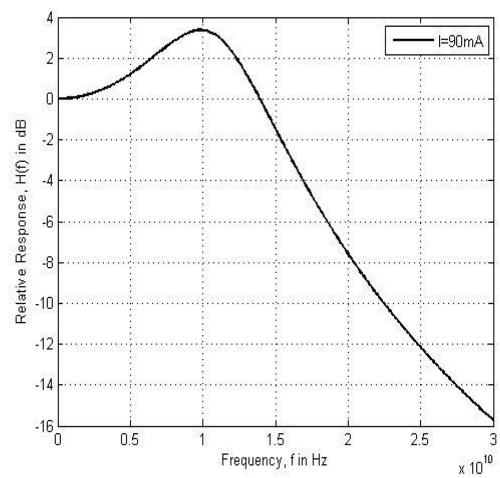


Fig. 7. Plot of relative response vs. Frequency of $Ga_{0.5}In_{0.5}P$/ $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ at 300K

From the above figure the resonance frequency is obtained 10 GHz and the modulation bandwidth 16.25 GHz maintaining injection current 90mA.

V. EFFECTS OF VARIATION OF DIFFERENT PARAMETERS ON THE MODULATION PERFORMANCE OF 635NM RED LASER

In this section, several effects of 635nm Red Laser will be discussed by varying injection current, differential gain and injection current efficiency. These characteristics scenario is very important for the proper establishment of a powerful laser.

A. Effects of Injection Current Variation

While the red laser is usually effectively used as sensor the power of the sensor must be sufficient for proper operation. From the performance analysis of red laser it is experimented that for obtaining more power, better modulation bandwidth with high resonant frequency and also proper peak intensity the injection current must be increased. Using the MATLAB simulation it is found that taking lower injection current than this designed laser the laser will give low power, low resonant frequency with small modulation bandwidth. That's why the variation of injection current has been analyzed and based on the analysis the injection current is set 90mA for the designed 635nm red laser. To prove the above analytical discussion plots of relative response vs. frequency are shown in Fig. 8 using the variation of the injection current at 300K. For this variation of the injection current the resonant frequency and the modulation bandwidth are also varied.

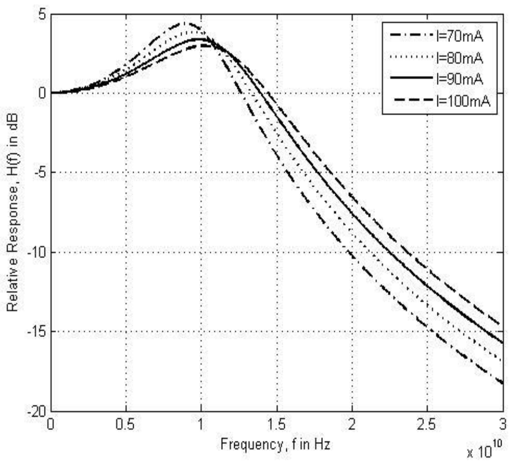
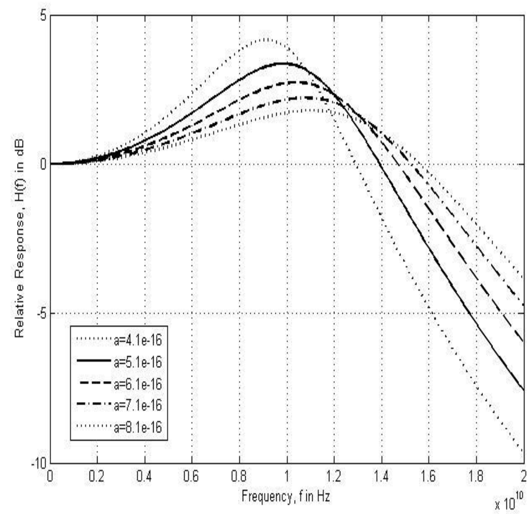


Fig. 8. Plots of relative response vs. frequency of $Ga_{0.5}In_{0.5}P$/ $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ at 300K with the variation of injection current

With the increase of injection current from 90mA to 100mA the resonant frequency are become increased and the modulation bandwidth are also increased. The temperature of the device will also be increased with the increase of injection current. Thermal condition must be considered for analyzing the performance of the laser based on this application. According this concept the maximum injection current of the laser is proposed to be 90mA which is approximately 13.5 times of the threshold current. Here four different values of injection current have been experimented for analyzing corresponding relative responses. At lower injection current (70mA) the resonant frequency is lower than the resonant frequency of highest injection current (100mA). As well as the modulation bandwidth is lower for the lowest injection current (70mA) than the modulation bandwidth of highest injection current (100mA).

B. Effects of Differential Gain Variation

Variation of differential gain is one of the important factors sustaining the injection current 90mA. It has the great impact on relative response of the laser. Here it is noticed that with the increase of the differential gain relative response will be zero at the highest frequency rate. According the following graph if the differential gain is taken as $8.1e^{-16}$ cm^2 at that time at frequency nearly 1.6×10^{10} Hz relative response will be zero so the resonant frequency is high. But at lower case of differential gain such as $4.1e^{-16}$ cm^2 relative response will be high and resonant frequency and modulation bandwidth is low at lower frequency (i.e., according graph frequency at 0.9×10^{10} Hz). All the possible variation has been shown in Fig. 9.



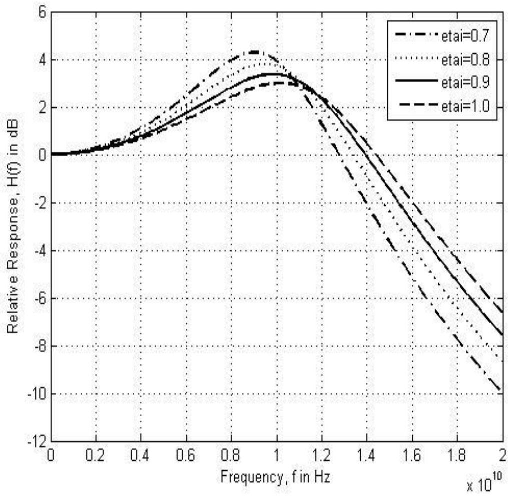
[Differential gain, a in cm^2]

Fig. 9. Plots of relative response vs. frequency of $Ga_{0.5}In_{0.5}P$/ $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ at 300K with the variation of differential gain at injection current 90mA

The resonant frequency is obtained lower for the lowest value of differential gain and modulation bandwidth is obtained higher for the highest value of differential gain.

C. Effects of Injection Current Efficiency Variation

By varying injection current efficiency (η_i) relative response of a laser will show the variation according the value of frequency. In the Fig. 10 it is seen that with the increase of injection current efficiency relative response become decrease and take higher range of frequency. So with the increase of the injection current efficiency resonant frequency and modulation bandwidth will be also increased. Within the limit of injection current efficiency 1 the analysis has been experimented, which has been shown in the Fig. 10.



[Injection current efficiency, etai (η_i)]

Fig. 10. Plots of relative response vs. frequency of $Ga_{0.5}In_{0.5}P/(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ at 300K with the variation of Injection current efficiency maintaining injection current 90mA

There is the additional analysis which can further affect on the performance of 635nm Red laser. On the basic analysis of modulation response the width of active region was set at 2×10^{-4} cm. But to get the effect of width variation on the performance of red laser for an example the width of active region may be set at four times of the initial one (i.e., 8×10^{-4} cm). The analysis is shown below in the Fig. 11 and corresponding results are shown in the following Table II.

TABLE II
COMPARISON BETWEEN THE RESULTS OF THE VARIATION OF WIDTH OF ACTIVE REGION

Width of Active Region, (w)	Area of observation	Obtained result (at 90mA & 300K)
2×10^{-4} cm	resonance frequency	10 GHz
	modulation bandwidth	16.25 GHz
8×10^{-4} cm	resonance frequency	8 GHz
	modulation bandwidth	14 GHz

Considering temperature 300K and by comparing with Fig. 7, it is seen that by increasing the width of active region the resonance frequency is obtained at lower frequency than the initial one. The modulation bandwidth becomes smaller than the original computation. Here the resonance frequency is obtained 8 GHz and the modulation bandwidth 14 GHz maintaining injection current 90mA.

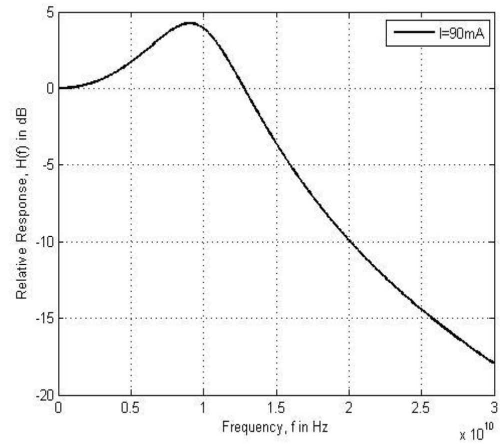


Fig. 11. Plot of relative response vs. Frequency of $Ga_{0.5}In_{0.5}P/(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ at 300K with the variation of width of active region (8×10^{-4} cm). The resonance frequency is obtained 8 GHz and the modulation bandwidth around 14 GHz at 90mA

VI. REVIEW OF PREEMINENT OBTAINED RESULTS AFTER THE SIMULATION

Maintaining the proposed Injection Current 90mA, Injection current efficiency 0.9 and material gain $5.1\text{X}10^{-16}\text{cm}^2$ at temperature 300K the review of obtained results are shown in the following Table III:

TABLE III
REVIEW OF OBTAINED RESULTS

Area of Observation	Results
peak material gain	770 cm^{-1} at around the wave length of 625nm
Resonance frequency	10 GHz
Modulation bandwidth	16.25 GHz
Peak intensity	at 635nm
Output power	105mW
steady state carrier density	1.365×10^{18} cm^{-3}
steady state photon density	8.763×10^{15} cm^{-3}

All the simulated results are taken according the proper analysis of the performance characteristics of the 635nm red laser. The maximum optimized performance of the laser has been obtained by the accurate computation of the characteristics of laser.

VII. DISCUSSIONS

In this research work, the main concentration has been given to observe the effects of variation of modulation performance of the red laser with the change of different parameters. Enhancement the power and efficiency of the 635nm Red Laser is also a major field of this research work. Here the simulation work has been done using MATLAB software. Some concepts of simulation process have collected from some other research works on laser [6], [7]. But here the proposed injection current's value is set higher than the other research work, which is one of the vital decision and scenario for this total simulation. All the variation has been checked successfully on the graph. By analyzing the performance of the $Ga_{0.5}In_{0.5}P/\ (Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ multiple quantum well edge emitting laser the peak material gain is obtained at the proposed injection current 90mA.

The resulted peak material gain value is obtained around 770 cm^{-1}at around the wave length of 625nm. Sustaining threshold current of 6.7mA, a maximum resonance frequency of 10 GHz and the modulation bandwidth of 16.25 GHz have been obtained for the designed laser at 90mA injection current at 300K temperature. Maintaining the injection current 90mA, injection current efficiency 0.9 and material gain $5.1X10^{-16}cm^2$ and at 300K the peak intensity for the designed red laser is obtained exactly at 635nm and output power is attained nearly 105mW which is obtained around at 6×10^{-10} second. At 90mA the steady state carrier density of 1.365×10^{18} cm^{-3} is found. Besides, with the increase of the width of active region the resonance frequency is obtained and the modulation bandwidth is found at a lower value than the value of initial width at 90mA.

VIII. CONCLUSIONS

In this work, all the effects on the modulation performance of $Ga_{0.5}In_{0.5}P/(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ 635nm MQW red laser are carefully observed for getting the better optimized result to establish a powerful and efficient laser. During the analysis of the variation of different parameters all observation has been perfectly measured. All the analyses have been computed proposing the injection current at 90mA. But the main focus of this work to identify a perfect response from the designed laser. Besides it is observed that with the increase of injection current the designed red laser can supply more power.

For the future work based on this way of upgrading lots of work might be done on the base of Laser. The new material concentration of 635nm Red Laser can be adjusted which will be different from the material concentration used in this research work. The thermal effect can also be monitored more precisely and implement for the more upgrading of a laser. Besides, the different threshold values of different parameters of the laser can be varied; results will be observed and set.

REFERENCES

[1] L. A. Coldren and S.W. Corzine, Diode Lasers and Photonic Integrated Circuits, John Wiley & Sons, Inc, 1995, pp. 1-263.

[2] Conceptual physics, Paul Hewitt, 2002.

[3] J. V. Moloney et al., "Quantum design of semiconductor active materials: laser and amplifier applications", Laser & Photon. Rev. 1 (1), 24, 2007.

[4] I. Vurgaftman and J. R. Meyer, L. R. Ram-Mohan, "Band parameters for III–V compound semiconductors and their alloys", Journal of Applied Physics, vol. 89, no. 11;, 2001, pp. 5851-5862.

[5] Sadao Adachi, Properties of group-IV, III–V and II–VI Semiconductors, John Wiley & Sons, ISBN 0-470-09032-4; 2005, pp. 11-359.

[6] Tawsif Ibne Alam and Rinku Basak "Performance Analysis and Optimization of a Designed 635nm Ga0.5In0.5P/(Al0.7Ga0.3)0.5In0.5P MQW SCH Red Laser by Varying Differential Gain" American Academic & Scholarly Research Journal, Volume 5, Number 4; May 2013, pp. 44-53.

[7] Rinku Basak "High Modulation Performance of a Designed InGaN Based 405 nm Multi-Quantum Well Violet Laser" Trends in Opto-Electro & Optical Communications Published by STM Journals, Issue No: Vol. 3 No.2, August, 2013.

[8] http://fisica-microfisica.blogspot.com/2013/10/lazers-e-suas aplicacoes.html

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