Characteristics of a Designed 1550 nm AlGaInAs/InP MQW VCSEL

Raja Rashidul Hasan and Rinku Basak

***Abstract*– The vertical-cavity surface-emitting laser (VCSEL) is becoming a key device in high-speed optical local-area networks (LANs) and even wide-area networks (WANs). In this work, the design and characteristics of a 1550 nm Multi Quantum Well (MQW) VCSEL using AlGaInAs/InP Materials have been obtained through computation and simulation using MATLAB simulation Tool. The obtained characteristics have been analyzed for obtaining better performance. For achieving a superior performance, the concentrations of AlGaInAs QW material have been chosen using the results of another research works. The material gain of the $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ MQW VCSEL has been theoretically computed. Using the peak material gain obtained from this computation the performance characteristics of the designed VCSEL have been obtained. At 300K, the threshold current of the VCSEL has been obtained as 0.6075 mA. A maximum output power of 1.02 mW has been obtained for this designed VCSEL at 8.5 mA injection current. Corresponding to this the modulation bandwidth has been obtained as 14.2 GHz which indicates a high speed performance of the designed VCSEL for applications in optical fiber communication. Further by increasing the injection current up to 16.5 mA a maximum bandwidth is obtained as 19.5 GHz.**

***Keywords*– Bandwidth, MQW, VCSEL and Laser Diode**

I. INTRODUCTION

In recent years Vertical-Cavity Surface-Emitting Lasers (VCSELs) have been finding wide applications in optical telecommunication system, in optical information processing systems, and in optical interconnection switches [1-8]. Due to the availability of performance data of a number of new compositions of compound semiconductor materials it is now possible to make high performance VCSELs using these materials in the quantum wells [9-10]. During the last decade the design of mirrors, gain structures, fabrication techniques of a VCSEL have been progressing significantly with the aim of obtaining better electrical and optical confinement [11-12]. Compound semiconductor based VCSELs have mostly designed for wavelength of 980 nm and above which are suitable for long haul telecommunication.

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It is well known that the small active volume and high mirror reflectivity of a VCSEL contribute to its very low threshold current [12]. With this low threshold current VCSELs allow high-speed operation around 10 Gbps in data transmission over the optical fiber. It is also well known that compared to an Edge-Emitting Laser (EEL), shorter cavity length of a VCSEL cause it to operate inherently in a single longitudinal mode. Beside this, less divergent output beam of such a device makes it easier to couple the device to optical fiber. The surface emission and its small size make it possible to fabricate very dense two-dimensional arrays of VCSELs, suitable for multi-channel parallel transmission modules.

In this work, the performance characteristics of a designed 1550 nm MQW VCSEL using AlGaInAs/InP materials have been obtained. The obtained characteristics have been analyzed and presented in this work with the aim of obtaining better performance of the VCSEL.

II. STRUCTURE AND DESIGN OF A 1550 nm MQW VCSEL

The structure of a top emitting VCSEL, presented in Fig. 1, consists of an active region with three quantum wells which is separated by two cladding layers. The internal structure of the VCSEL cavity consists $Al_{0.09}Ga_{0.38}In_{0.53}As$ QWs with bandgap energy of 0.89 eV, refractive index (n_1) of 3.511. Each of the QWs has a thickness of 12.5nm and surrounding these there are two barriers of InP with bandgap of 1.351 eV, a refractive index (n_2) of 3.146, each having a thickness of 17nm as shown in Fig. 2.

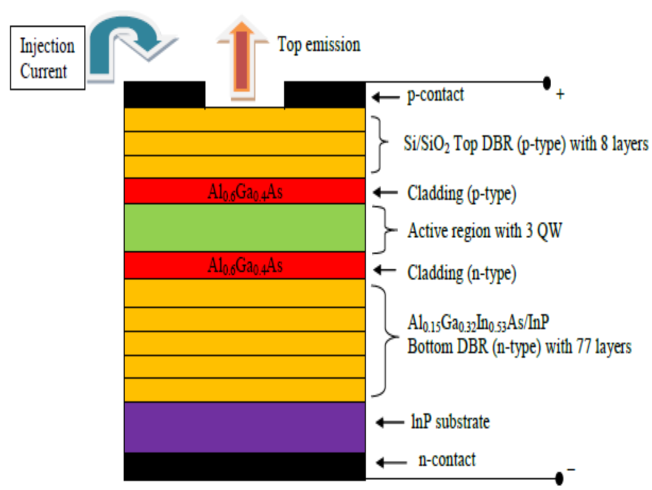

Fig. 1. The structure of a top emitting VCSEL consisting upper and bottom DBR stacks

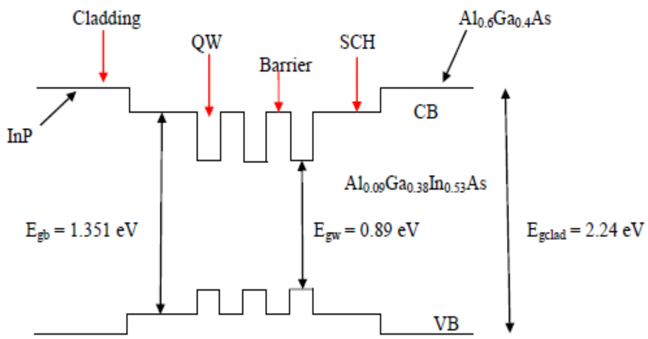

Fig. 2. The cavity of a VCSEL consisting 3 quantum wells active region

The active layer is sandwiched by two Separate Confinement Hetero-structure (SCH) layers of InP where the photons are confined. The SCH layers are sandwiched by two cladding layers of $Al_{0.6}Ga_{0.4}As$. The top cladding layer is p-doped while the bottom layer is n-doped. The cladding layers of 2.24 eV each are used for optical confinement in the cavity and have a refractive index (n_3) of 3.131.

The laser resonator consists of two distributed Bragg reflector (i.e., top DBR and bottom DBR) mirrors parallel to the wafer surface with an active region. 8 layers of Si/SiO_2 materials in the upper DBR stack and 77 layers of $Al_{0.15}Ga_{0.32}In_{0.53}As/InP$ materials in the bottom DBR stack of the designed VCSEL are considered for achieving a high reflectivity of 99.9% which is required for the emission due to short cavity length of the VCSEL. Current is injected through the upper p-type contact of the device and the lower n-type contact is connected with InP substrate as shown in fig. 1.

Theoretically, for designing a VCSEL an optimum choice of material gain and transparency carrier density of InP and $Al_{0.6}$ $Ga_{0.4}As$ materials has to be made. The transparency carrier density of a material is related to the effective masses of carriers in the conduction band (CB) and valence band (VB) as [6]

$$N_{tr} = 2\left(\frac{kT}{2\pi\hbar^2}\right)^{3/2}(m_c m_v)^{3/4} \qquad (1)$$

where, ķ is the Boltzmann const, T is the temperature in k, ħ is the Planck's constant divided by 2π , m_c and m_v are the effective masses of carriers in the CB and VB respectively.

The above equation is used to compute the transparency carrier density of QW and barrier materials. The transparency carrier densities of $Al_{0.09}Ga_{0.38}In_{0.53}As$ and InP materials are calculated using equation (1) and the calculated results are $1.378e^{18}$ cm^{-3} and $2.5301e^{18}$ cm^{-3} respectively. These two materials are lattice matched because of same lattice constant of $5.869A^0$ [13]. For lower transparency carrier density of $Al_{0.09}$ $Ga_{0.38}In_{0.53}As$ it is suitable to use as a QW material and InP is chosen as a barrier material.

The material gain of a VCSEL is expressed as [2], [6], [14-16].

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

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, f_2 and f_1 are the electron quasi-Fermi functions in the CB and VB respectively.

The transition momentum matrix element $|M_T|^2$ of a laser with quantum well region can be calculated as [2], [14]

$$|M_T|^2 = \frac{m_0{}^2 E_{gw}(E_{gw} + \Delta)}{4m_c(E_{gw} + (2\Delta/3))} \qquad (3)$$

where, Δ is the split-off (SO) band potential and E_{gw} is the bandgap energy of QW material.

The reduced density for a quantum well laser (ρ_r) can be calculated as [6], [17].

$$\rho_r = \frac{m_r}{\pi\hbar^2 l_w}$$

(4)

where, m_r is the reduced effective mass of carriers and l_w is the thickness of each QW.

At 300K the material gain for a 1550 nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ $125A^0$ QW VCSEL is calculated by varying wavelength. The obtained results are plotted as shown in fig. 3.

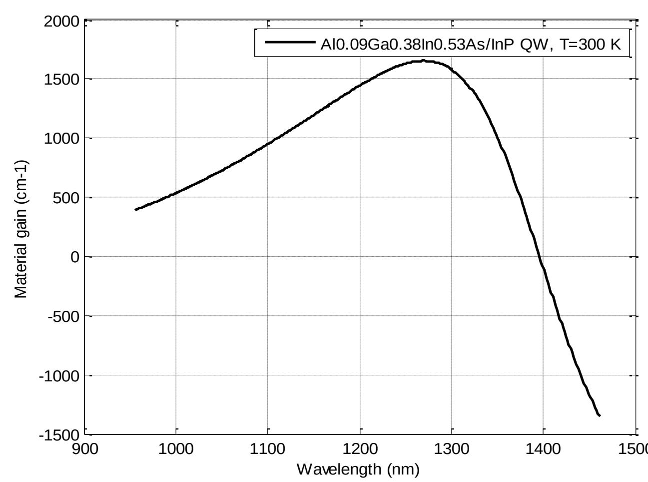

Fig. 3. Plots of material gain for $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125Å QW VCSEL by varying wavelength at 300K. A maximum gain of the material of 1652.3 cm^{-1} is obtained at 1270.3 nm

It is observed that at 0.89eV the material gain goes to positive level and a maximum gain is obtained as 1652.3cm^{-1} at 1270.3 nm wavelength. It is observed that the peak gain of the materials in the QW shifts to lower wavelength value from 1550 nm.

III. PERFORMANCE ANALYSIS OF THE DESIGNED 1550 nm VCSEL

Performance analysis of the designed 1550nm VCSEL is presented in this work. The rate equations of the VCSEL are solved for obtaining the optical output power. The rate of change of carrier density of a laser can be expressed as [2]:

$$\frac{dN}{dt} = \frac{\eta_i I}{qV_a} - \frac{N}{\tau_c} - \frac{v_g a(N - N_{tr})S}{1 + \varepsilon S} \quad (5)$$

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 carrier density at threshold point (N_{th}) is written as [2]

$$N_{th} = N_{tr} \times e^{\frac{(\alpha_i + \alpha_m)}{\Gamma \times g_0}} \quad (6)$$

The rate of change of photon density of a Laser can be expressed as [2]

$$\frac{dS}{dt} = \frac{\Gamma v_g a(N - N_{tr})S}{1 + \varepsilon S} + \Gamma \beta_{sp} \frac{\eta_i I_{th}}{q} - \frac{S}{\tau_p} \quad (7)$$

where, β_{sp} is the spontaneous emission coefficient, Γ is the confinement factor, τ_p is the photon lifetime and I_{th} is the threshold current of a Laser.

Using equation (5) the rate of change of carrier density of a VCSEL is plotted and presented in fig. 4.

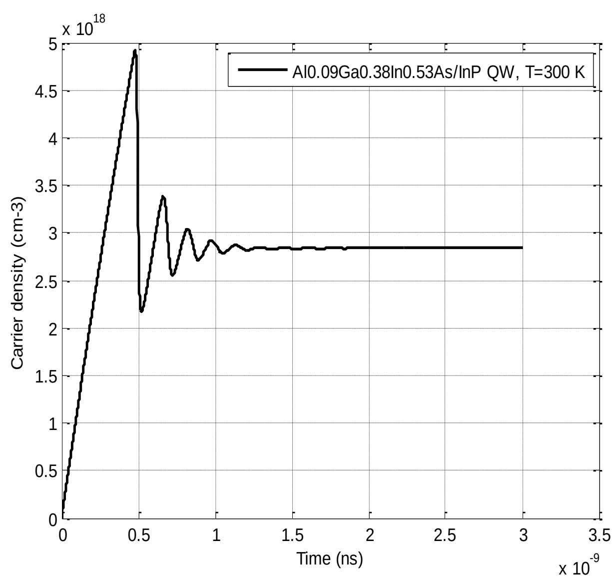

Fig. 4. Plot of carrier density vs. time of the 1550 nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125Å QW VCSEL at 300K,where ,the injection current is 8.5mA.A steady state carrier density of 2.837 × 10^{18} cm^{-3} is achieved

It is observed that at 300K, for a value of injection current of 8.5 mA the steady state carrier density of the VCSEL of 2.837 × $10^{18}$$cm^{-3}$ is achieved after a threshold value of 2.143 × 10^{18} cm^{-3}, where, the threshold current is 0.6075 mA and the transparency carrier density is 1.378 × 10^{18} cm^{-3}.

At the steady-state the photon density of a laser can be calculated as [2].

$$S = \eta_i \frac{(I - I_{th})}{q v_g g_{th} V_a} \quad (8)$$

Using equation (7) the rate of change of photon density of a VCSEL is plotted and presented in fig. 5.

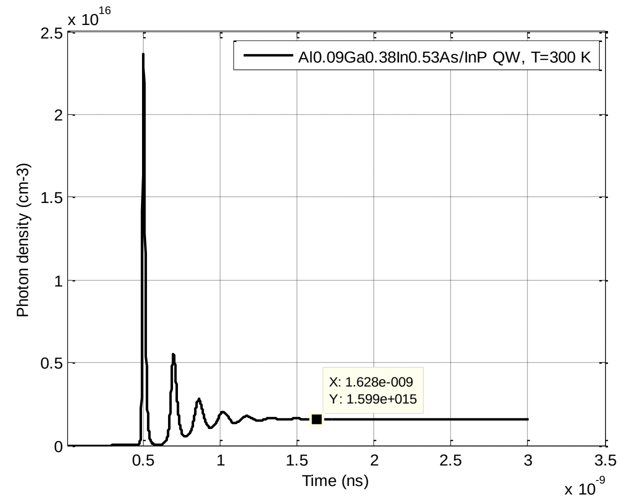

Fig. 5. Plot of photon density vs. time of the 1550 nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125Å QW VCSEL at 300K, where, the injection current is 8.5 mA. A steady state photon density of 1.59941 × 10^{15} cm^{-3} is achieved

It is observed that at 300K, for a value of injection current of 8.5mA the steady state photon density of the VCSEL is achieved as 1.59941x10^{15} cm^{-3}.

The output power (P_{out}) of a VCSEL can be expressed in terms of material gain g, mirror loss coefficient α_m, injection current I and threshold current I_{th} as [2]:

$$p_{out} = \frac{\alpha_m h\nu\eta_i}{qg\Gamma}(I - I_{th}) \quad (9)$$

where, *h* is the Planck's constant, *v* is the lasing frequency and *q* is the electron charge.

The mirror loss coefficient (α_m) is calculated as [2]

$$\alpha_m = \frac{1}{l} \times \ln\left(\frac{1}{R}\right) \quad (10)$$

where, l is the effective length of the VCSEL cavity and R is the reflectivity of DBR stacks.

At threshold condition, the material gain of a Laser is expressed as [2]

$$g = g_{th} = \frac{(< \alpha_i > + \alpha_m)}{\Gamma} \quad (11)$$

where, $< \alpha_i >$ is the internal loss coefficient.

The threshold current, I_{th} is calculated as [2]

$$I_{th} = \frac{qV_a N_{th}}{\eta_i \tau_c} \quad (12)$$

For evaluating the performance of the designed 1550nm VCSEL the differential quantum efficiency (η_d) is calculated as [2], [8].

$$\eta_d = \eta_i \frac{\alpha_m}{\{(<\alpha_i>) + \alpha_m\}} \quad (13)$$

By considering the absorption and diffraction loss of 20 cm^{-1} in the materials of the cavity the calculated value of differential quantum efficiency of the designed 1550 nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125A^0 QW VCSEL is obtained as 16.708%.

For the designed VCSEL the output power is computed by using equation (9). Using the obtained results the plot of output power vs. wavelength is presented in Fig. 6. It is observed that for a value of injection current of 8.5 mA the peak intensity of output power of the VCSEL is obtained at 1322.98 nm wavelength.

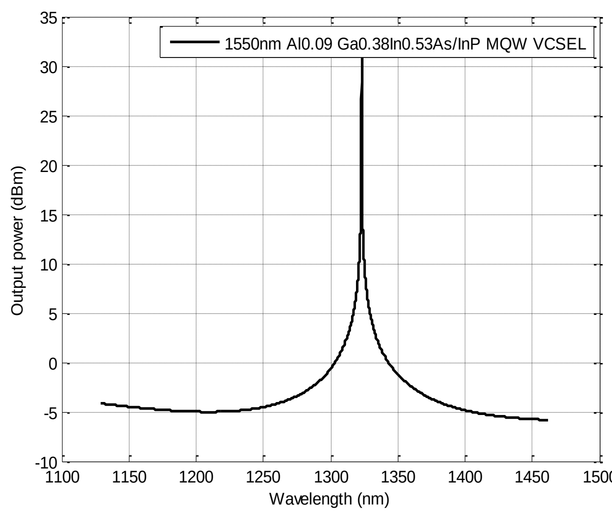

Fig. 6. Plot of output power vs. wavelength of the 1550nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125A^0 QW VCSEL at 300K, where, the injection current is 8.5 mA. A peak intensity of the power is obtained at 1322.98 nm wavelength

In this design, $Al_{0.09}Ga_{0.38}In_{0.53}As$ is selected as the quantum well (QW) material and the band gap energy is calculated for these material concentrations is 0.89 eV. But for designing a 1550 nm VCSEL, the required band gap energy is 0.8 eV. Due to this mismatch of band gap energy for the materials concentration and also the effects of the temperature the wavelength of the designed VCSEL is achieved 1322.98 nm. By adjusting the material concentrations and also considering the thermal effect it will be possible to achieve the wavelength close to 1550 nm.

The output power of the VCSEL is calculated as [2]

$$P_{out} = v_g \alpha_m h\nu S V_p \quad (14)$$

where, V_p is the volume of the cavity, υ is the lasing frequency.

The obtained results are plotted as output power vs. time characteristic and presented in fig. 7. It is observed that at 300K, for a value of injection current of 8.5 mA a steady state power of VCSEL is achieved 1.02 mW.

The transfer function of relative response of a VCSEL is related to the resonance frequency f_R and damping parameter γ ; and the expression is written as [2], [18].

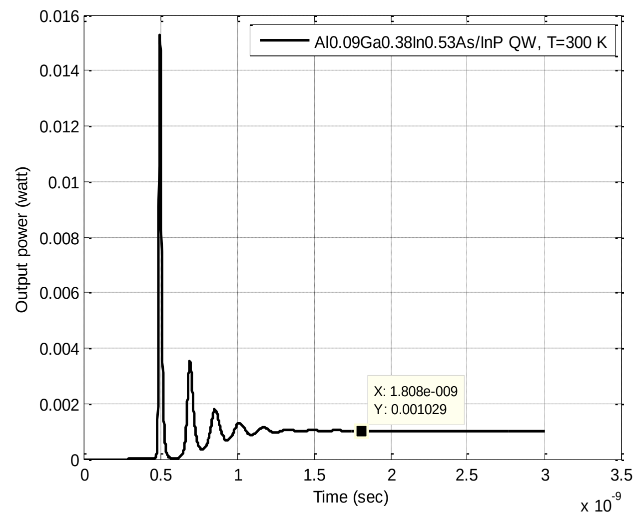

Fig. 7. Plot of output power vs. time of the 1550 nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125A^0 QW VCSEL at 300K, where, the injection current is 8.5 mA. A steady state power of 1.02 mW is achieved

$$H(f) = \frac{f_R^2}{f_R^2 - f^2 + j\frac{f}{2\pi}\gamma} \quad (15)$$

Using equation (15) the relative response of the VCSEL is calculated by varying frequency for different values of injection current. The obtained results are plotted as shown in fig. 8. From the plots it is observed that the resonance frequency of the VCSEL increases with increasing the injection current. At 8.5mA injection current the resonance frequency of 9 GHz is obtained and a maximum resonance frequency of 12.4 GHz of the VCSEL is obtained at 16.5 mA injection current. For the value of injection current of 8.5 mA the modulation bandwidth (-3dB cutoff frequency) is 14.2 GHz and at 16.5 mA injection current the maximum modulation bandwidth of 19.5 GHz of the VCSEL is obtained.

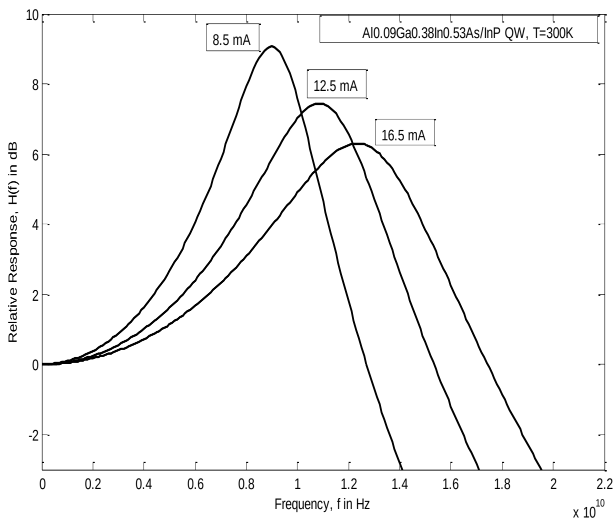

Fig. 8. Plots of relative response vs. frequency for different values of injection current of the 1550nm $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ 125A^0 QW VCSEL at 300K. A resonance frequency of 9 GHz of the VCSEL is obtained at 8.5 mA injection current and a maximum resonance frequency of 12.4 GHz of the VCSEL is obtained at 16.5 mA injection current

It has seen that with the increase in injection current, the maximum resonance frequency and maximum-3dB cutoff frequency (bandwidth) increases. The high modulation bandwidth obtained in this work, makes the VCSEL suitable for transmitting data at high speed through optical fiber [19].

IV. CONCLUSION

The characteristics of a designed 1550 nm AlGaInAs/InP MQW VCSEL has been presented in this work. A maximum output power of 1.02 mW is obtained at 8.5 mA injection current, where, the threshold current is 0.6075mA. A maximum resonance frequency of 9 GHz and the corresponding bandwidth is 14.2 GHz are obtained for the same value of injection current. A high modulation bandwidth and a moderate value of differential quantum efficiency of 16.708% indicate the superior performance of the designed 1550 nm $Al_{0.09}$ $Ga_{0.38}In_{0.53}As/InP$ MQW VCSEL and it makes the VCSEL capable for high-speed data transmission through optical fiber. Further by increasing the injection current from 8.5 mA to 16.5 mA a maximum modulation bandwidth is obtained as 19.5 GHz.

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