High Performance $In_{0.42}Ga_{0.58}As/In_{0.26}Ga_{0.74}As$ Vertical Cavity Surface Emitting Quantum Well Laser on $In_{0.31}Ga_{0.69}As$ Ternary Substrate

Md. M. Biswas, Md. M. Hossain, and Shaikh Nuruddin

Abstract**—**This paper reports on the theoretical performance analysis of the 1.3 µm $In_{0.42}Ga_{0.58}As$ /$In_{0.26}Ga_{0.74}As$ multiple quantum well (MQW) vertical cavity surface emitting laser (VCSEL) on the ternary $In_{0.31}Ga_{0.69}As$ substrate. The output power of 2.2 mW has been obtained at room temperature for 7.5 mA injection current. The material gain has been estimated to be ~3156 cm^{-1} at room temperature with the injection carrier concentration of 2×10^{17} cm^{-3}. The modulation bandwidth of this laser is measured to be 9.34 GHz at room temperature for the biasing current of 2 mA above the threshold value. The outcomes reveal that the proposed InGaAs-based MQW laser is the promising one for optical communication system.

Keywords**—**Quantum well, VCSEL, output power, material gain, modulation bandwidth.

I. Introduction

THE introduction of light into the world telecommunication network represents one of the most important revolutions in modern society and semiconductor lasers have played a vital role in its success [1]. The semiconductor laser is an active light source in optical fiber communication due to its high quantum efficiency, pure output spectrum and the narrower gain spectra, direct modulation capability, and high reliability. Different materials are used to reach 1.3 µm wavelengh. In recent years, the potential applications of compositionally homogeneous bulk $In_xGa_{1-x}As$ single crystals are found to be as substrate for InGaAs-based laser diode. This is because its lattice constant can be changed according to our desire [2]. Conventional 1.3 µm lasers are mainly based on the InGaAsP or, InGaAlAs quantum well active material system on an InP substrate. These 1.3 µm InP-based diode lasers exhibit poor lasing performances at high temperatures [3]. Again, desired performances are not found due to lattice mismatch between the substrate and the epilayer. Particularly, the gain characteristics and temperature characteristics of these lasers are poor [4]. The InGaAs ternary based laser has the characteristics temperature (T_0) of 150 K which is comparably higher than InP-based laser. The 1.3 µm QW lasers fabricated on $In_{0.31}Ga_{0.69}As$ ternary substrate have shown good temperature characteristics [5].

Generally two types of quantum well lasers are fabricated, such as VCSEL and edge emitting laser (EEL). The VCSELs have been intensively studied due to expected performance improvement over edge emitting lasers in terms of ease of processing, light emission in a single longitudinal mode, lower divergence, construction in the form of large & planar arrays, and suitability for parallel optical signal processing. The VCSEL also has relatively small cross-sectional area, which significantly reduces the operating current [1].

At room temperature, the single mode output power for the InGaAs QWLs was found to be 1.2 mW with a threshold of 3.5 mA [6]. Using 50 nm offset devices, the small signal 3-dB bandwidth has been estimated to be 8 GHz at room temperature [7]. It is still desirable to continually demonstrate devices having high output power, high material gain with less carrier injection, and large modulation bandwidth. In this work these performance parameters have been analysed with enhanced results for InGaAs based VCSEL.

II. Device Structure

The device structure of the proposed top emitting VCSEL structure is shown in Fig. 1. The active region contains 8 nm thick undoped $In_{0.42}Ga_{0.58}As$ QWs, separated by 11 nm thick $In_{0.26}Ga_{0.74}As$ barrier layers. The $In_{0.24}Ga_{0.76}As$ cladding layer is used to sandwich the active region. Intra-cavity contacts are made to these InGaAs active layer, allowing for the undoped DBRs. A p-InAlGaAs/n-InAlGaAs tunnel junction (TJ) is introduced for electrical and optical confinement. The band gap energies for active, barrier, and cladding layers are considered to be 0.870, 1.062, and 1.090 eV respectively.

M. M. Biswas is with the Department of Electrical and Electronic Engineering (EEE), Bangladesh University of Engineering and Technology, Dhaka-1200, Bangladesh (e-mail: multan_eee@stamforduniversity.edu.bd).
M. M. Hossain is with the Stamford University Bangladesh as a lecturer of EEE, Dhaka-1217, Bangladesh (e-mail: mottaleb77@ieee.org).
S. Nuruddin was with the Department of EEE, Khulna University of Engineering and Technology, Bangladesh (email: engr_nuru@yahoo.com).

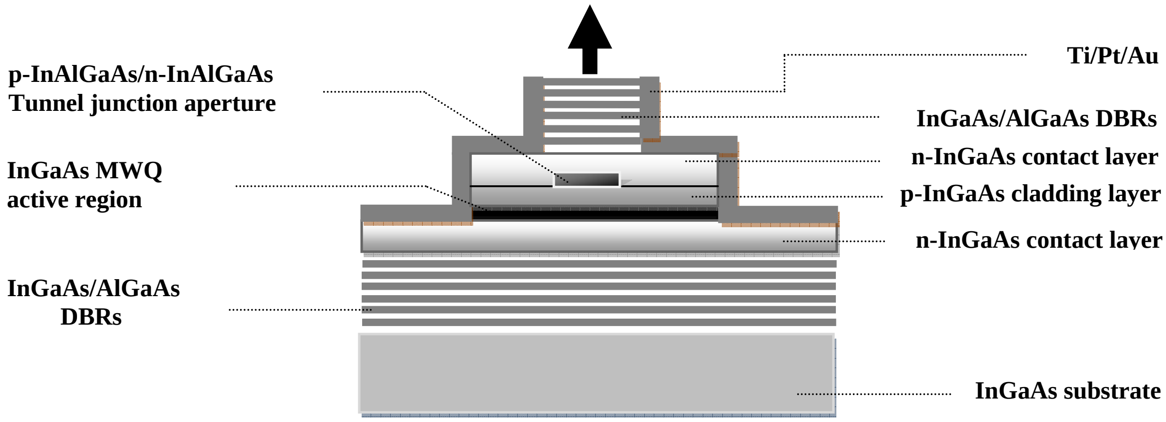

Fig. 1 Basic device structure of the proposed top emitting VCSEL.

III. Computation Methodology

Theoretical analysis for the proposed QWL structure is focused mainly on light current characteristics, modulation response, and gain characteristics. The output power of the laser is an important performance parameter and is expressed as [8],

$$P_0 = (I - I_{th})(\frac{\eta h \upsilon}{q})\frac{\frac{1}{2l}\ln(\frac{1}{R_1 R_2})}{\left[\gamma + \frac{1}{2l}\ln(\frac{1}{R_1 R_2})\right]} \quad (1)$$

where hv is the energy per photon, η depends on two factors: (i) the injection efficiency accounting for the fraction of injected carriers contributing to the emission process and (ii) the optical efficiency accounting for the fraction of generated photons that are transmitted out of the cavity [9], γ is the losses within the cavity, I_{th} is the threshold current, I is the injection current, l is the active layer length, and R_1 & R_2 be the reflectivities.

The material gain available from a quantum well is expressed as [10],

$$g(E) \cong 5.7\times 10^4 \frac{\sqrt{(E-E_g)}}{E}\left[f^e(E^e) + f^h(E^h) - 1\right] \quad (2)$$

where E and E_g be the photon energy and bandgap energy of the material concerned, $f^e(E^e)$ and $f^h(E^h)$ denote the electron and hole occupation probability, respectively. From (2), it is clear that the value of $f^e(E^e) + f^h(E^h)$ must be greater than one in order to obtain positive gain. The material gain available from a quantum well can be affected by a number of factors that need to be taken into account. It is well known that the QWs have to be designed with a low density of states and a closely matched density of states in the valence and conduction bands [11]–[13]. However, a low density of states will cause rapid rising of Fermi level with increased temperature. This means more carriers may escape from the QW at elevated temperatures. Therefore, a large conduction band offset is required to secure the carrier confinement [14].

Modulation bandwidth is the frequency at which the output power is reduced by 3 dB point with respect to input power [15]. The frequency response function is expressed as [9],

$$\left|\frac{s(\omega)}{j(\omega)}\right| \approx \frac{(\frac{\Gamma \tau_p}{qd})\omega_r^2}{\left[(\omega^2 - \omega_r^2)^2 + \omega^2(\frac{1}{\tau} + \tau_p \omega_r^2)^2\right]^{\frac{1}{2}}} \quad (3)$$

where τ is the carrier lifetime, Γ is the optical confinement factor, d is the thickness of the active region, τ_p is the photon lifetime, and ω_r is the relaxation resonance frequency. The relaxation resonance frequency can be expressed as [16],

$$\omega_r = \left[\frac{v_g a}{q V_p}\eta_i (I - I_{th})\right]^{\frac{1}{2}} \quad (4)$$

where $I-I_{th}$ is the relative drive current above threshold, η_i is the injection efficiency, V_p is the mode volume, a is the differential gain which depends upon the photon density, q is the electron charge, and v_g is the group velocity. Higher modulation bandwidth along with small operating current is very important for application in future high-speed optical communication systems. But the modulation response can either be RC limited or relaxation resonance frequency limited. Since these devices have a very small contact area, the estimated capacitance is low and the RC bandwidth is high. The more likely limitation in performance is the relaxation resonance response. Since bias effects introduce heating which thermally limits these devices, it is instructive to examine the resonance frequency in a form that depends upon drive current [17].

IV. Performance Evaluation

This section describes the performances of the proposed InGaAs-based 1.33 µm VCSEL. Optical output power variation with injection current is shown in Fig. 2. It is observed that the laser gives no light output in the region below threshold current which corresponds to spontaneous emission only within the structure. However, when the threshold current density is reached, the light output increases substantially for small increases in current through the device. This corresponds to the region of stimulated emission when the laser is acting as an amplifier of light. With the increase of well number, more injection current is required to obtain the

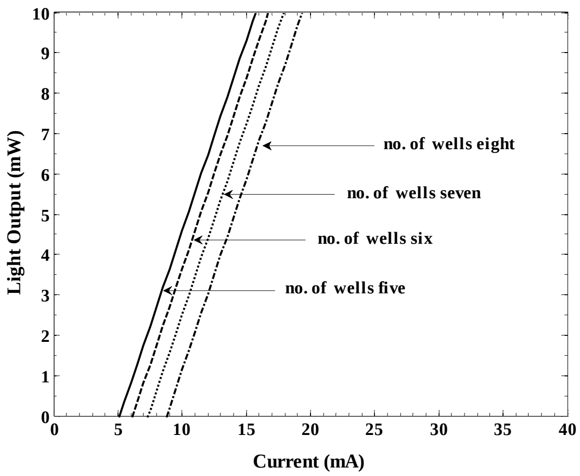

Fig. 2 The light current characteristics of QWL at different number of wells.

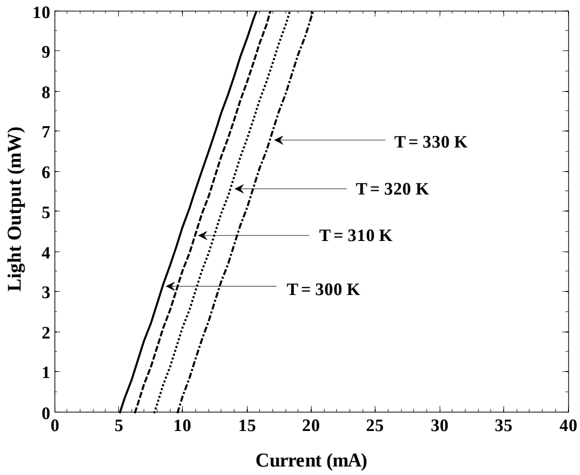

Fig. 3 The light current characteristics of QWL at different temperatures.

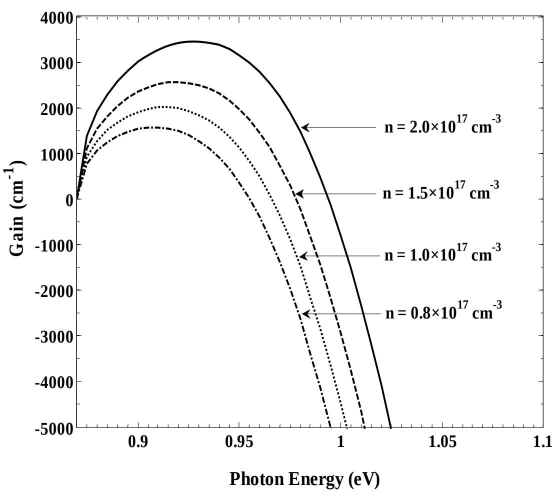

Fig. 4 Calculated gain spectra of InGaAs MQW active region as a function of photon energy at different injected carrier concentration.

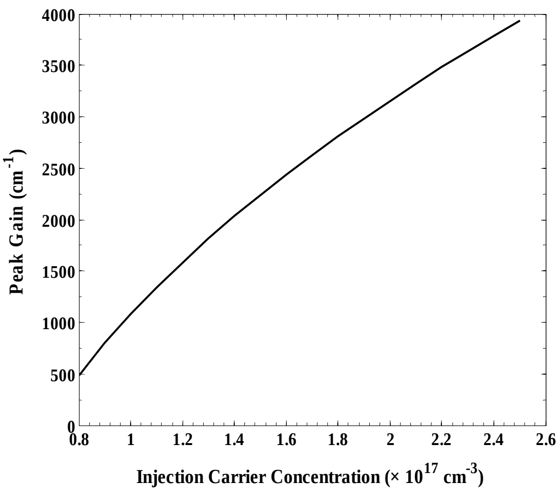

Fig. 5 Variation of peak gain with carrier concentration of InGaAs MQW active region.

light output. This is because threshold current increases with the increase of the number of wells.

The light-current characteristic of the quantum well laser for various temperatures is shown in Fig. 3. Higher injection current is required with increased temperature to attain the same light output. This is because the threshold current is increased with the increase in temperature. In our proposed device structure having five quantum wells in number, the output power has been estimated to be 2.2 mW at room temperature with a injection current of 7.5 mA.

Figure 4 shows the calculated gain spectra of the $In_{0.42}Ga_{0.58}As$ QWs with $In_{0.26}Ga_{0.74}As$ barrier at 300K as a function of emission photon energy at different injected carrier concentrations. At low injections, f^e and f^h are quite small and the gain is negative. As injection is increased, f^e also increases for electrons near the band edges and gain is positive. However, even at high injections, for $E >>E_g$, the gain is negative.

It is noted from Fig. 4 that the peak gain is different for various carrier concentrations. The peak gain is obtained when the sum of the occupation probabilities of electrons and holes is maximum. The combination of the occupation probabilities decreases as carrier concentration increase for any particular values of photon energy. Thus higher photon energy is required in order to obtain peak gain for higher concentrations. But carrier injection must be below the density of state for each material. Figure 5 shows the variation of peak gain with carrier concentration. In the proposed device structure material gain of ~3156 cm^{-1} has been obtained at photon emission of 0.95 eV and at injection carrier concentration of 2×10^{17} cm^{-3} respectively.

Variation of material gains with temperatures at different carrier concentrations is shown in Fig. 6. The gain is lower at lower temperature and higher at higher temperature. It can be concluded that the gain has a proportional relationship with carrier concentration and temperature. But the optimized value of carrier injection must be considered and temperature must not exceed 25^0C. This is because threshold current will also increase with the increase of temperature. The material gain has been estimated to be ~3156 cm^{-1} at room temperature with a carrier concentration of 2×10^{17} cm^{-3}.

The frequency response for the VCSEL is shown in Fig. 7 at the different values of biasing current above the threshold value. The figure shows the response of the laser at 2 mA, confirming the value of $f_{-3\ \mathrm{dB}}$ = 9.34 GHz. The resonance peak shifts outward with increasing bias, indicating a dependence on drive current. This reveals that it is relaxation resonance limited. Another contributing limitation, also related to heating, is the roll-off in the output power at higher currents, which ultimately reduces the photon density. After the peak power point (determined by heating), an increase in $I - I_{th}$

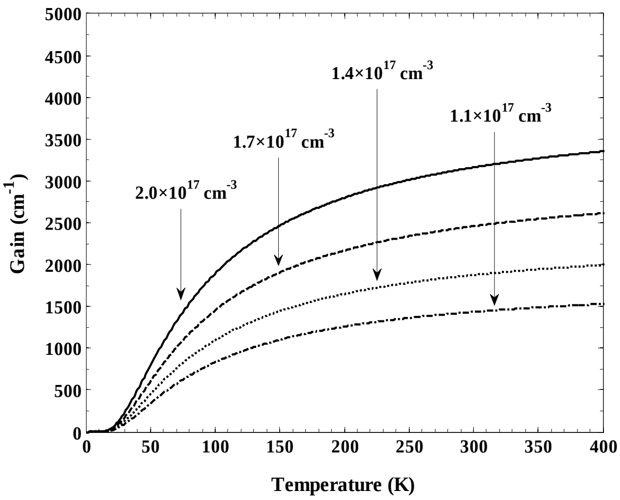

Fig. 6 Calculated gain spectra of InGaAs MQW active region as a function of temperature at different injected carrier concentration.

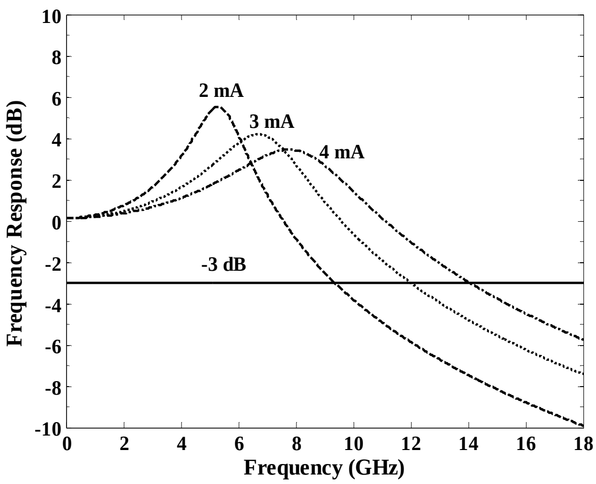

Fig. 7 Small signal frequency response of a VCSEL for different current above I_{th}.

only acts to compensate for the reduced photon density and injection efficiency. Since for the given mode volume, RC is not limited, hence the bandwidth is likely to be limited by device heating.

V. Conclusion

The InGaAs based 1.3 μm vertical cavity surface emitting laser has been theoretically designed and improved performances have been observed. The optical output power has been obtained to be 2.2 mW at room temperature. The modulation bandwidth has been evaluated to be 9.34 GHz. This wider bandwidth is very important for the application in future high-speed communication systems. The proposed structure has been successfully designed with acceptable enhanced results which will create a way to fabricate InGaAs based VCSEL.

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Md. Multan Biswas received the Bachelor of Science (B. Sc.) degree in Electrical & Electronic Engineering (EEE) from Khulna University of Engineering & Technology (KUET) in 2009. He is continuing his M. Sc. in Electrical Energy and Power Systems group in the department of EEE at Bangladesh University of Engineering & Technology (BUET), Bangladesh.

He is now with the Department of EEE at Stamford University Bangladesh as a Lecturer. He has some publications in peer reviewed international journals and conference. His present research interests are in the fields of Interconnected Power Systems, Power Electronics Converters, Renewable Energy, and Energy Storage Systems.

Mr. Biswas is a member of IACSIT, IAENG and an associate member of Institution of Engineers, Bangladesh (IEB).

Md. Mottaleb Hossain (SM’07–SM’08–GSM’10) received the Bachelor of Science (B. Sc.) degree in Electrical & Electronic Engineering (EEE) from Khulna University of Engineering & Technology (KUET), Bangladesh in 2009.

He is now with the Department of EEE at Stamford University Bangladesh as a lecturer. He is involved in research on Laser applications, Optics, Nanophotonics, and Quantum Electronics. He has several publications in peer reviewed journals and conferences in the relevant fields.

Mr. Hossain is a Graduate Student Member of IEEE. He is also a member of IEEE EDS, IEEE Photonics Society, IEEE Communication Society, SPIE, IACSIT, and IEB. He was a reviewer of IEEE ICCSIT, 2011.

Shaikh Nuruddin was born in Bangladesh. He received the Bachelor of Science (B. Sc.) degree in Electrical & Electronic Engineering (EEE) from Khulna University of Engineering & Technology (KUET) in 2009.

He is now with the SINHA Power Generation Company Limited, Bangladesh as a Junior Engineer (Electrical). His research interests are in the fields of Power Systems, Power Electronics, Renewable Energy, and Energy Storage Systems.

Md. Nuruddin is an associate member IEB.