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# Performance Analysis of the Designed 1330nm VCSEL Using InGaAsP/InP

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**Abstract**

This research addresses the design and performance analysis of a 1330nm InGaAsP/InP VCSEL based on a model that accurately describes a multiple quantum well separate confinement heterostructure VCSEL. MATLAB is used as the simulation tool. ‘Material gain vs. photon energy’, ‘Material gain vs. Wavelength’ and ‘Power vs. wavelength’ characteristics are obtained from simulations. Threshold current and output power of the laser is calculated using different parameters. Obtained results correspond to a maximum resonance frequency of 12.312 GHz at 28 mA injection current, -162.3 dB/Hz RIN and a value of 104 dB of the VCSEL at 7 mA injection current.

***Keywords:*** VCSEL; Material gain; Carrier density; Photon density; Relative response; Relative intensity; Injection current.

## 1. Introduction

VCSEL, or Vertical Cavity Surface Emitting Laser, is semiconductor micro laser diode that emits light in a cylindrical beam vertically from the surface of a fabricated wafer, and offers significant advantages when compared to the edge-emitting lasers currently used in the majority of fiber optic communications devices. The vertical-cavity types typically consist of a circular dot geometry with lateral dimensions of a few microns [1].

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The Vertical Cavity Surface Emitting Laser (VCSEL) is emerging as the light source of choice for modern high speed, short wavelength communication systems. It produces a very good beam quality. The VCSEL has several advantages over edge-emitting diodes. They are- the inherent low cost of manufacture, enhanced reliability, no astigmatic and circularly symmetric optical output. The VCSEL requires less electrical current to produce a given coherent energy output. VECSELs can also be modulated with high frequencies for optical fiber communications. This paper deals with the Performance Analysis of a VCSEL using MATLAB. Here all the calculations, performance characteristics graphs and MATLAB files are presented.

### *1.1. Research Methodology*

The objective of this work is to design and analyze the performance characteristics of a Vertical Cavity Surface Emitting LASER (VCSEL) using MATLAB. More specifically the objectives are

- to solve the rate equation of this semiconductor LASER [5].
- to calculate the material, gain and modal gain for different values of photon energy and wavelength [5].
- to calculate the output power of the designed Laser [13] [5].
- to analyze the modulation response of the designed VCSEL.
- to obtain other static and dynamic plots of the designed LASER.

### *1.2. VCSEL Simple Construction and Fabrication*

What makes the VCSEL structure special is that it emits light perpendicular to the surface of the semiconductor [10] [14]. This makes more features available on VCSEL as compared to other conventional lasers. Therefore, the structure of a VCSEL is significantly different from other laser structures have been seen so far, such as stripe lasers or edge-emitting lasers. The construction of a VCSEL is particularly different from other lasers. VCSEL consists of a vertical cavity formed by epitaxial layers and employs a DBR above and below the active region [10].

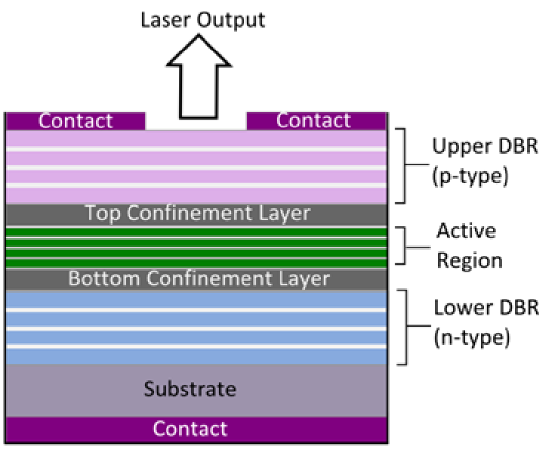


**Figure 1:** The cross sectional view of a general VCSEL [6]

To engineer a particular wavelength in VCSEL, one method used is the thickness-gradient placed in the DBR under the active region [4]. This creates a different cavity thickness across the structure with thickness-graded layers becoming thicker from left to right [10]. The DBR mirrors are highly reflective mirrors, with a reflectivity of greater than 99.9% [2]. The mirrors can be either epitaxial growth or dielectric multilayered. The two DBRs in the VCSEL are oppositely doped (n-DBR and p-DBR). Placed between the upper and lower DBRs is an active region emitting light, usually containing several quantum wells [3]. The active region receives current through a current-guiding structure by either proton-injected surroundings or through an oxide aperture [7].

### *1.3. Experimental setup of Designing of a 1330nm VCSEL using InGaAsP/InP*

A. Design of a 1330nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}$/InP MQW VCSEL (T=300K)

QW material $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}$

Energy bandgap, $E_g$ = 0.936 eV

Refractive index, n = 3.56

Differential gain, a = 5.869Ao

Transparency carrier density, $N_{tr} = 1.5061*10^{18}$cm-3

Barrier material InP

Energy bandgap, $E_g$ = 1.351 eV

Refractive index, n = 3.188

Differential gain, a = 5.869Ao

Transparency carrier density, $N_{tr} = 2.530*10^{18}$ cm-3

Cladding material $Ga_{0.05}In_{0.95}P$ for Effective mass of electron at the conduction band, $m_e$ = 0.0805mo,

Effective mass of hole at the valence band, $m_{hh}$ = 0.6095 mo

Energy bandgap, $E_g$ = 1.395 eV

Refractive index, n = 3.182

Differential gain, a = 5.848Ao

The transparency carrier density, $N_{tr} = 2.6143*10^{18}$ cm-3

Average refractive index in the cavity region,

navg = ((3*3.65) + (4*3.188) + (2*3.182)) / 9

= 3.34

Length of the cavity,

$$Lcavity = \lambda / navg \qquad (1)$$

$= (1330*10^{-9} / 3.34)$

$= 3.982*10^{-7}$cm

Length of the cladding layers,

$$Lcladding = 2\lambda / 4navg \qquad (2)$$

$= 2*(1330*10^{-9} / (4* 3.34))$

$= 1.99*10^{-7}$cm

Length of the active layers, barriers and SCH regions,

$$L = \lambda /2\, navg \qquad (3)$$

$= 1330*10^{-9} / (2*3.34)$

$= 1.99*10^{-7}$cm

Length of the active region, Lactive = 3 * 100Ao ($30 * 10^{-7}$ cm)

Length of the barrier region Lbarrier = 2 * 120 Ao ($24 * 10^{-7}$cm)

Length of the SCH region LSCH = 2 * 725.5 Ao ($145.1 * 10^{-7}$cm)

The energy of the confined state in the conduction band (CB) well of thickness lw is calculated as

$= (((6.623 * 10^{-34})^2) / (8 * (5.1013 * 10^{-30})*((10^{-9})^2))) / 1.6*10^{-19}$

= 0.0672 eV

where, h is the Plank's constant and $m_e^*$ is the effective mass of electron in the conduction band.

The energy of the confined state in the valance band (VB) well of the thickness $l_w$ is calculated as [29]

$$E_{1'} = \frac{h^2}{8\, m^*_{hh}\, l_w^2} \qquad (4)$$

B. Performance Analysis of the Designed 1330nm VCSEL

Calculation of Threshold Current of a Laser

Threshold current [1] [19] [8],

$$I_{th} = \frac{q v_a N_{th}}{\eta_i \tau_c} \qquad (5)$$

Here,

Electron charge, q = 1.6* $10^{-19}$

Efficiency, $\eta_i$ = 0.8

Carrier lifetime, $n_c$ = 2.63* $10^{-9}$ sec

Active Region Volume, $V_a = L_{active} * area$ (6)

=3*$10^{-7}$* $\pi$ *(5.65*$10^{-4}$) $^2$

=3.086*$10^{-12}$$cm^3$

Here,

Area= $\pi$ *(5.65*$10^{-4}$) $^2$

=1.0029*$10^{-6}$ $cm^2$

$L_{active}$ = Nqw*dqw (7)

= 3*$10^{-7}$cm

Threshold carrier density [5], $N_{th} = N_{tr} \exp^{(\langle\alpha_i\rangle+\alpha_m)/\Gamma g_0}$ (8)

=3.3154*$10^{18}$

Here,

Mirror loss, $\alpha_m = (1/ L_{eff}) * \log (1/R)$ [13] *(9)*

=26.9043

Here,

Reflectivity of both mirrors, R =0.995

Intrinsic absorption loss, $\alpha_i = 20$

Threshold Current, $I_{th} = 0.75mA$

C. Calculation of Output Power of a Laser [13]

Output power, Pout = αm * vg * hυ * svp *(10)*

Here,

Plank's Constant, h = $6.676*10^{-34}$

Current injection efficiency, ηi = 0.8

Threshold Current, Ith=0.758mA

Injection Current, I=$5.37*10^{-4}$

=0.537mA

Electron's Charge, q=$1.6*10^{-19}$

gamma= 2*(Lactive/Lefft)*0.9

=0.0290

gain(j)=2.8842

υ=c/λb

=$2.2556*10^{16}$ Hz

Here,

Velocity of light, c= $3*10^{10}$ cms-1

Lasing wavelength, λb=1330*$10^{-7}$ cm

Mirror loss, αm = (1/ Leff) * log (1/R) [13] *(11)*

= 26.7721

Here,

Effective length, Leff = Lcavity + Lefft+ Leffb *(12)*

= 1.8723*$10^{-4}$

Reflectivity of both mirrors, R= 0.995

Output power, Pout= 53.068 dBW

### *1.4. Experimental Results and characteristic curves*

The various characteristics [17] of 1330nm VCSEL is shown below using Matlab simulation.

#### *1.4.1. Carrier density vs. time characteristic*

At 300K the steady state carrier density for 1330nm In0.7Ga0.3As0.644P0.356 /InP MQW VCSEL is calculated for value of time, the results are plotted as shown in Figure using the equation below:

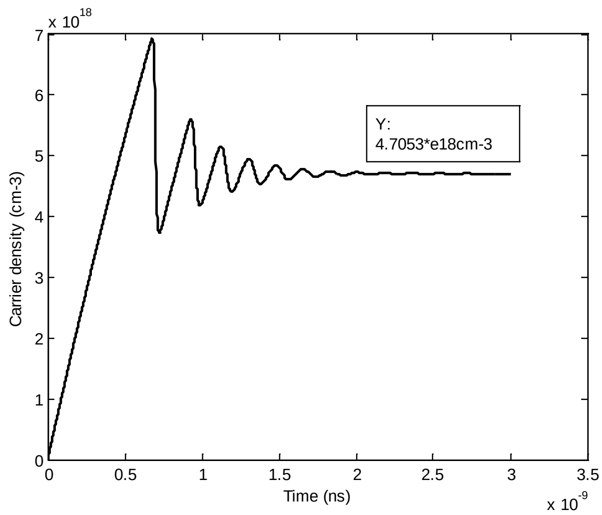


**Figure 2:** Plots of carrier density vs. time of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356} / InP$ 100A° QW VCSEL at 300K, where the injection current is 7mA. A steady state carrier density of 4.7053*$10^{18}$ $cm^{-3}$ was achieved.

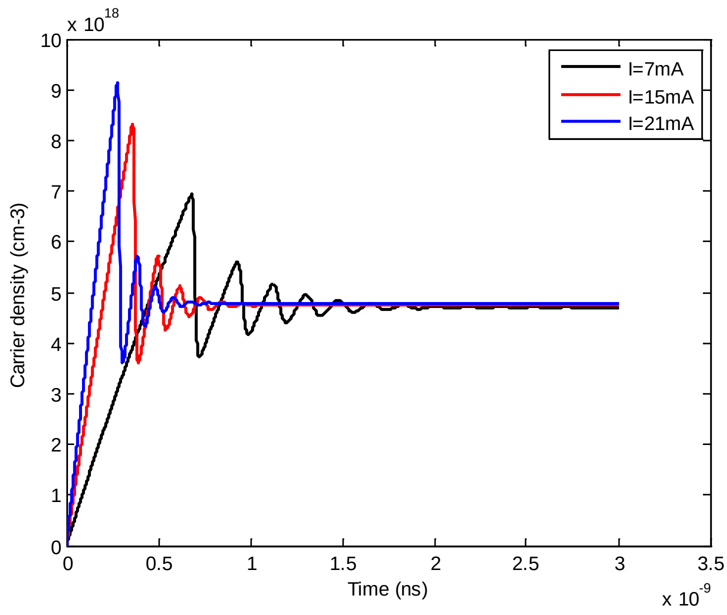


**Figure 3:** Plots of carrier density vs. time of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356} / InP$ 100A$^0$ QW VCSEL at 300K, where the injection current is 7mA. A steady state carrier density of 4.7053*10$^{18}$ cm$^{-3}$ was achieved.

### *1.4.2. Photon density vs. time characteristic*

At 300K the steady state photon density for 1330nm In0.7Ga0.3As0.644P0.356 /InP MQW VCSEL is calculated for value of time,

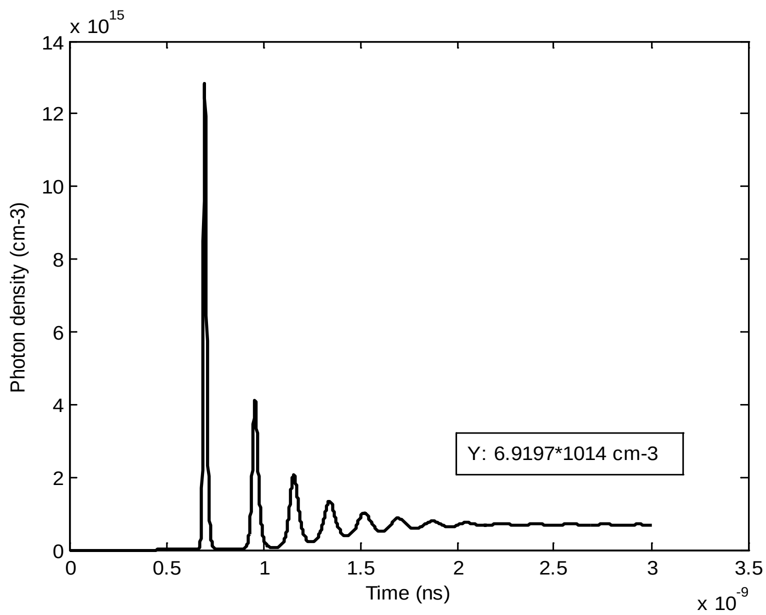


**Figure 4:** Plots of photon density vs. time of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356} / InP$ 100A$^{\circ}$ QW VCSEL at 300K, where the injection current is 7mA. A steady state carrier density of 6.9197*10$^{14}$ cm$^{-3}$ was achieved.

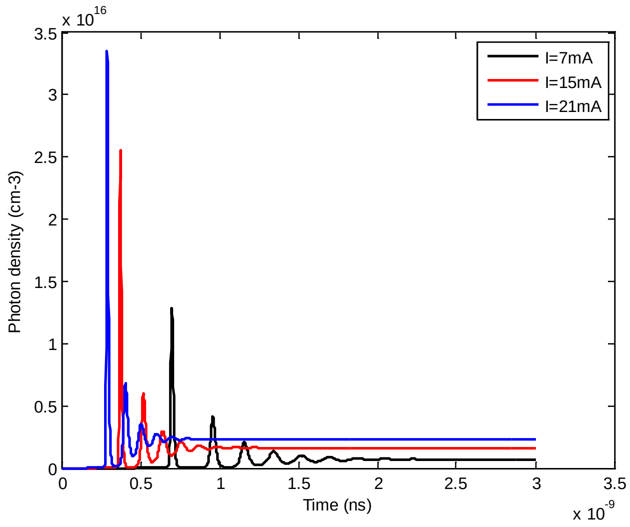


**Figure 5:** Plots of photon density vs. time of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A° QW VCSEL at 300K, where the injection current is 7mA. A steady state photon density of 4.7053*$10^{18}$ $cm^{-3}$ was achieved. . A maximum photon density of 3.51*$10^{16}cm^{-3}$ of the VCSEL is obtained at 21 mA injection current [11].

### *1.4.3. Output Power vs. Time characteristic*

The MATLAB simulation is shown below

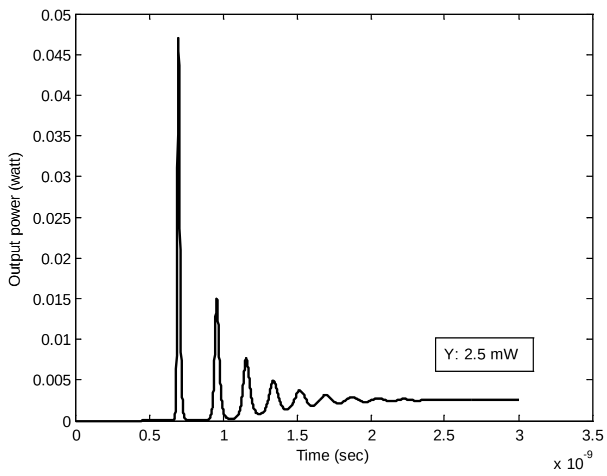


**Figure 6:** Plots of output power [18] vs. time of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A$^0$ QW VCSEL at 300K, where the injection current is 7mA. A steady state output power 2.5mW was achieved.

### *1.4.4. Modal gain vs. carrier density and modal gain vs. time characteristics*

At 300K the modal gain for 1330nm In0.7Ga0.3As0.644P0.356 /InP MQW VCSEL is calculated for value of carrier density and time, the results are plotted as shown in Figure 7 using the equation below:

$$\Gamma g = \Gamma g_0 \ln(\frac{N}{N_{tr}}) \qquad (13)$$

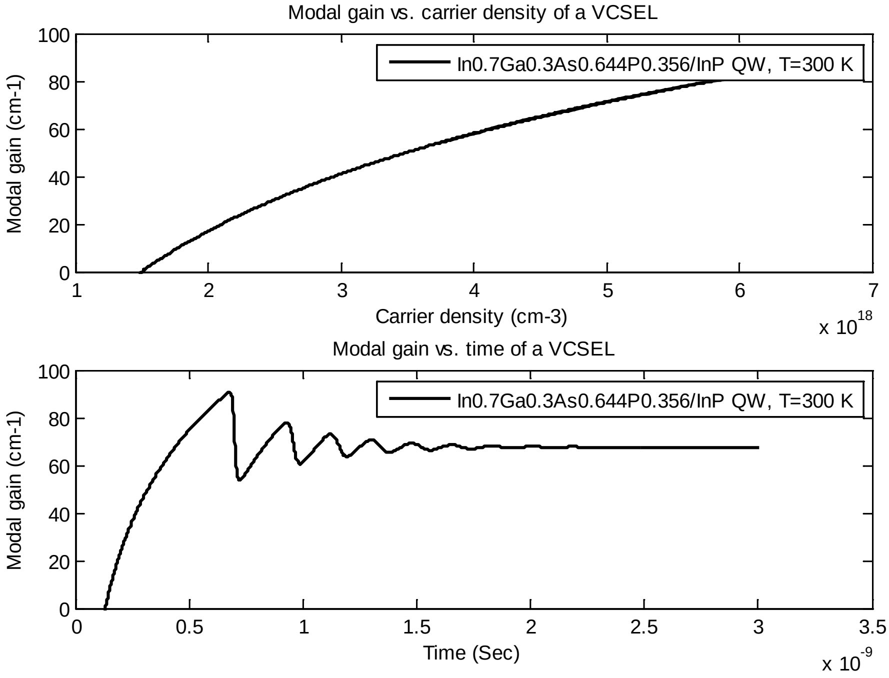


**Figure 7:** Plots of modal gain vs. carrier density and time of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A$^0$ QW VCSEL at 300K [9] [13].

### *1.4.5. Bias voltage vs. injection current and output power vs. injection current characteristics*

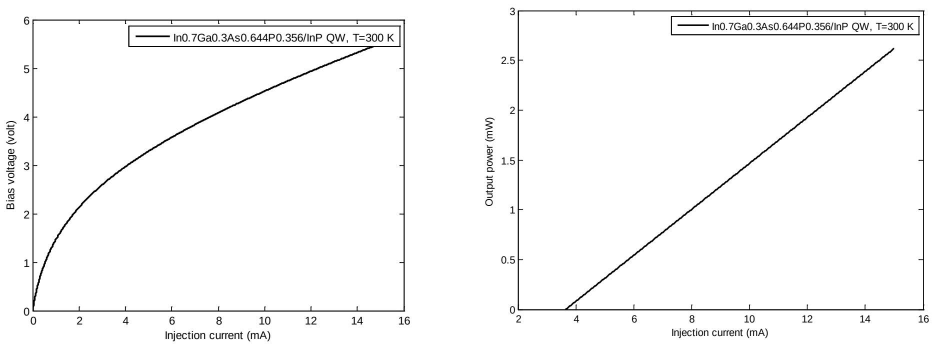


**Figure 8:** Plots of (a) bias voltage vs. injection current and (b) output power vs. injection current [12] of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A$^o$ QW VCSEL at 300K [11]. A bias voltage of 3.3V is required to achieve the threshold current of .785 mA and plot (b) is showing the linear characteristic between injection current and output power [9,16].

### *1.4.6. Relative Response vs. frequency characteristic*

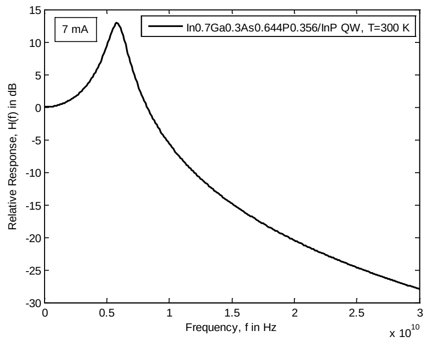


**Figure 9:** Plots of modulation response vs. frequency of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A° QW VCSEL at 300K. A resonance frequency of 5.91 GHz of the VCSEL is obtained at 7 mA injection current [16].

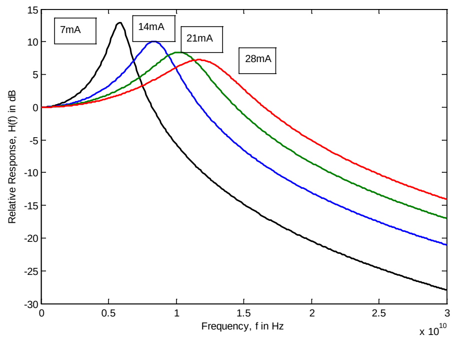


**Figure 10:** Plots of modulation response vs. frequency of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A$^0$ QW VCSEL at 300K. A maximum resonance frequency of 12.312 GHz of the VCSEL is obtained at 28 mA injection current.

### *1.4.7. Relative intensity noise (RIN) vs. frequency and Frequency Modulation (FM) Noise vs. frequency characteristics of the VCSEL*

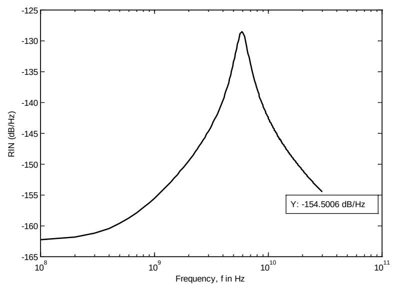


**Figure 11:** Plots of relative intensity noise vs. frequency of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356}/InP$ 100A$^0$ QW VCSEL at 300K. A value of -162.3 dB/Hz RIN of the VCSEL is obtained at 7 mA injection current.

### *1.4.8. Frequency modulation noise vs. Frequency*

The frequency modulation noise vs. frequency characteristic has been observed by using MATLAB simulation. The figure obtained is as shown in the following figure 4.11 below.

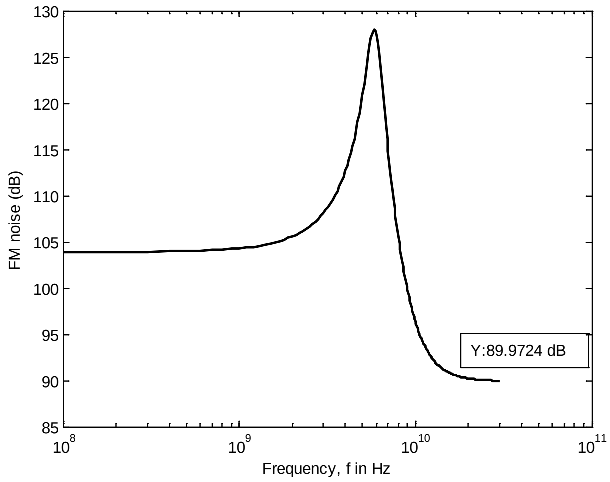


**Figure 12:** Plots of frequency modulation noise vs. frequency of 1330 nm $In_{0.7}Ga_{0.3}As_{0.644}P_{0.356} / InP$ 100A$^0$ QW VCSEL at 300K. A value of nearly 104 dB of the VCSEL is obtained at 7 mA injection current.

From the above plot it is observed that frequency modulation noise of the VCSEL varies with the frequency and a value of nearly 104 dB of the VCSEL is obtained at 7 mA injection current.

## 2. Conclusions

The necessary steps for designing a 1330nm MQW VCSEL using InGaAsP/InP materials and analyzing the performance characteristics have been illustrated here. To understand VCSEL concept, the basic construction and fabrication of it have been demonstrated. The simulations of performance characteristic analysis were done by using MATLAB software. Using VCSEL for wireless communication devices can open a new era in the field of optoelectronics. Detecting cancer cells use VCSELs has been tremendously successful [15]. VCSEL can also be used in core fiber optical transmission networks for smart grid communication services which requires high bit rate transmission, high spectral efficiency, multi-user supporting, and bidirectional communication. Moreover, the performance of VCSEL can be evaluated in long haul communication [20] and compared with Soliton or Gaussian Pulse [21,22]. The application of VCSEL can be evaluated in 4G-5G communication technology for feasibility testing [23], in Smart Grid communication [24], cyber physical power system communication [25] etc. This particular work is simulation based where we used several parameters and constraints. The experimental result is close to the real time based result, however if we had the chance to use parameters independently we could have achieved more precise result. Besides there may arise difficulties like temperature fluctuation and high power consumption due to use of longer wavelength devices. Such bottlenecks can be dealt with more research work along with latest technologies. To more efficiently remove the heat, we can either integrate the devices on a substrate with higher thermal conductivity [27], e.g., copper which has ~9 times of the thermal conductivity of GaAs, or provide additional heat sinking from the top surface and sidewalls using gold [28] or copper plating [29].

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