

Optimized High Performance Characteristics of a Designed 420nm InGaN/AlGaN MQW Blue Violet Laser

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Abstract: In this work, the performance characteristics of a designed 420nm multi quantum well (MQW) Blue Violet Laser using InGaN/AlGaN materials are presented. A high performance of the designed laser is obtained with the optimized values of injection current and differential gain. A maximum optical output power of 214.45mW is obtained for 87mA injection current and $1 \times 10^{-16} \text{ cm}^2$ differential gain, where, the threshold current is 8.7mA. The modal gain of 74.155 cm^{-1} and the differential quantum efficiency of 67.02% are obtained. A maximum resonance frequency of 7.9675GHz and the corresponding modulation bandwidth of 10.75 GHz are obtained for the same values of injection current and differential gain. The performance of the laser is also analyzed by varying injection current and differential gain. A maximum output power of 214.45mW is obtained for 117mA injection current and $4 \times 10^{-16} \text{ cm}^2$ differential gain. For this, a maximum resonance frequency of 18.742 GHz and the corresponding modulation bandwidth of 25 GHz are obtained which enhances the dynamic performance of the designed laser for applications in data storage, optical discs and displays.

Keywords: Output Power, Resonance Frequency, Modulation Bandwidth, MQW, Blue Violet Laser

1. INTRODUCTION

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. The laser diodes can be designed for different emission wavelengths based on applications. High resolution laser color printers and low cost full color projection systems could be designed by moving towards shorter wavelength laser diodes. The density and at the same time resolution can be improved by a reduction in emission wavelength of the laser diode. Infra-red laser diodes which are being affordable prices are being widely used.

Nitride materials are stable at high temperatures and also chemically stable. GaN material has been chosen for the emission in shorter wavelength because this material has a wide band gap and sufficient to emit light in the ultraviolet region (Lee *et al.* 2010), (Kuchibhatla 2005), (Kehl Sink 2000). The band gap of this material could be varied by forming alloys with other materials. It has higher quantum efficiency and longer life time although it has a high defect density. GaN material can be alloyed with other materials like InN and AlN to obtain a range of emission wavelengths which is possible with the variation of the Indium and Aluminium concentrations. Analysis of InGaN material characteristics is required for deep UV laser diodes which have applications in biosensing such as detecting chemical agents.

The active layer of the Nichia devices was formed by InGaN quantum wells. This new invention enabled the development of small, convenient and low-priced blue violet laser and

opened the way for applications such as high-density HD DVD data storage, Blue-ray discs, Micro projectors and displays (Brüninghoff *et al.* 2009), (Skierbiszewski *et al.* 2011), (Holc *et al.* 2012), (Strau *et al.* 2008), (Lonsdale *et al.* 2002).

In this work, the optimization of a designed 420nm InGaN/AlGaN based MQW Blue Violet Laser is presented with the aim of obtaining high performance characteristics.

2. DEVICE STRUCTURE

The active region of a Blue Violet semiconductor laser, presented in fig. 1, consisting 3 QWs of $\text{In}_{0.12}\text{Ga}_{0.88}\text{N}$ (bandgap energy, $E_g=2.9566\text{eV}$; refractive index, $n=2.6147$; effective mass of electron in the conduction band, $m_c=0.18443m_0$; effective mass of hole in the valence band, $m_v=0.293568m_0$; where, m_0 is the mass of electron) of 5nm each and 2 barriers of $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ ($E_g=3.683\text{eV}$, $n=2.44$) of 7 nm each. The concentrations of the materials are selected for achieving the operating wavelength of the device of nearly 420nm (Adachi 2005), (Vurgaftman *et al.* 2001). The volume of the active region V is calculated as $4.35 \times 10^{-11} \text{ cm}^3$, where, the total thickness (d) of the active region in x-y plane is 29nm considering 3 QWs and 2 barriers, the width (w) is $2\mu\text{m}$ and the length (L) in the z-direction is $750\mu\text{m}$.

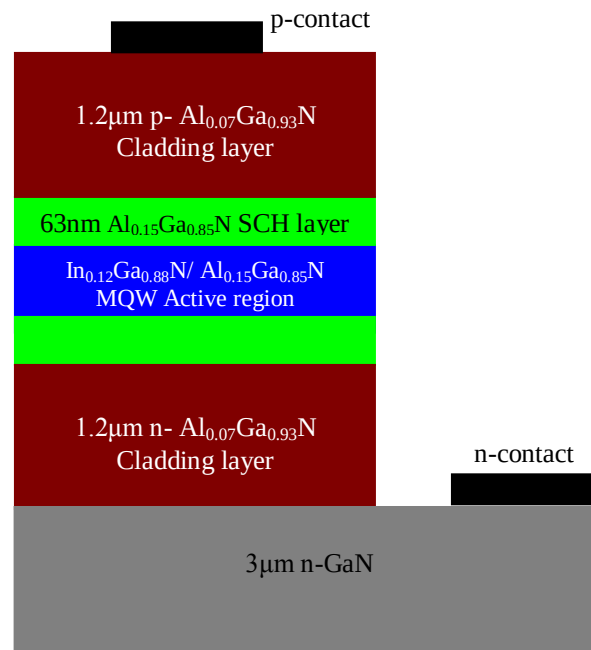


Fig. 1. The structure of a designed InGaN/AlGaN based 420 nm Blue Violet Laser.

The active region of the laser is sandwiched by two Separate Confinement Heterostructure (SCH) layers of $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ ($E_g=3.683\text{eV}$, $n=2.44$) of 55nm each. The total thickness of the cavity including SCH is calculated as 139nm. The cavity length is same as the active length and for the same width the cavity volume V is calculated as $2.085 \times 10^{-10} \text{ cm}^3$. The confinement factor is calculated as $\Gamma = \Gamma_{xy}\Gamma_z = 0.2086 \times 1 = 0.2086$. The p -type and n -type cladding layers of $\text{Al}_{0.07}\text{Ga}_{0.93}\text{N}$ ($E_g=3.535\text{eV}$, $n=2.47$) of $1.2\mu\text{m}$ each. The n -GaN substrate of $3\mu\text{m}$ is connected with the lower n -contact and the upper p -contact is connected with the p -cladding layer as shown in fig. 1.

3. SIMULATION RESULTS AND DISCUSSIONS

The transparency carrier density of the QW $\text{In}_{0.12}\text{Ga}_{0.88}\text{N}$ material is calculated as (Sale 2005)

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

where, k is the Boltzmann const, T is the temperature in K, $\hbar$ is the Planck's constant divided by 2π .

and the obtained result is $2.8147 \times 10^{18} \text{ cm}^{-3}$. For a low transparency carrier density and low bandgap energy $\text{In}_{0.12}\text{Ga}_{0.88}\text{N}$ is selected as a QW material of the designed 420nm blue violet laser. Considering this calculation of material gain, solution of rate equations, calculations of output power and modal gain, and the analysis of modulation response using MATLAB simulator are presented as follows.

(a) Calculation of material gain

The material gain g of the designed true blue laser is calculated for obtaining the optical output power as (Sale 2005), (Chang *et al.* 2006), (Selmic *et al.* 2001), (Coldren *et al.* 1995)

$$g(E) = \left(\frac{q^2 \pi \hbar}{\epsilon_0 m_0^2 n c E} \right) |M_T|^2 \rho_r (f_2 - f_1) \quad (2)$$

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, $|M_T|^2$ 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 is calculated as (Chang *et al.* 2006), (Coldren *et al.* 1995)

$$|M_T|^2 = \frac{m_0^2 E_g (E_g + \Delta)}{4m_c (E_g + (2\Delta/3))} \quad (3)$$

where, E_g is the bandgap energy in the QW region and Δ is the split-off (SO) band potential.

At 300K the material gain of the $\text{In}_{0.12}\text{Ga}_{0.88}\text{N}/\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ QW 420nm blue violet laser is calculated using equations (2) and (3); and the results are plotted as shown in fig. 2. It is observed that the material gain of the laser varies with the variation of photon energy and wavelength. At 2.9566eV the material gain goes to positive level and a maximum gain is obtained as 1109.7 cm^{-1} at nearly 409.21nm wavelength.

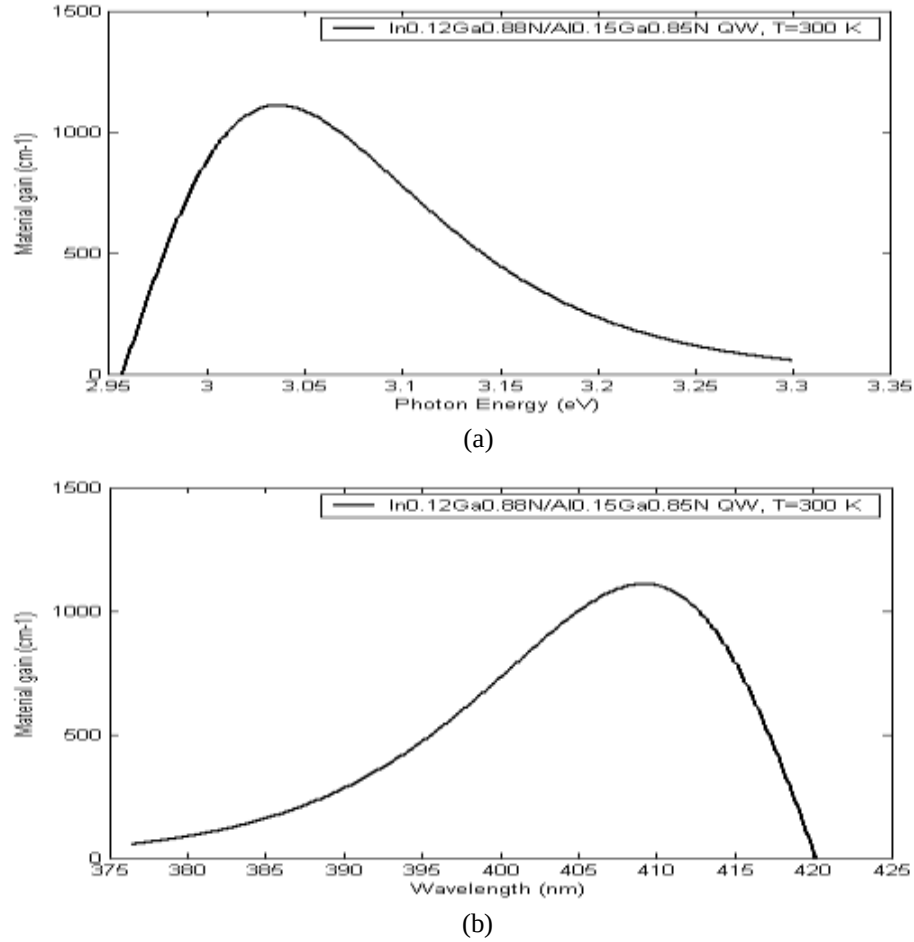


Fig. 2. Plots of (a) material gain vs. photon energy and (b) material gain vs. wavelength of a 420nm Blue Violet Laser. The maximum gain is obtained as 1109.7 cm⁻¹ at nearly 409.21nm wavelength, where the average refractive index is 2.52735.

(b) Calculations of carrier density, photon density and output power of the laser

The rate equations of a semiconductor laser are written as (Coldren *et al.* 1995)

$$\frac{dN}{dt} = \frac{\eta_i I}{qV_a} - \frac{N}{\tau_c} - \frac{v_g a(N - N_{tr})S}{(1 + \varepsilon S)} \quad (4)$$

$$\frac{dS}{dt} = \frac{\Gamma v_g a(N - N_{tr})S}{(1 + \varepsilon S)} + \Gamma \beta_{sp} R_{sp} - \frac{S}{\tau_p} \quad (5)$$

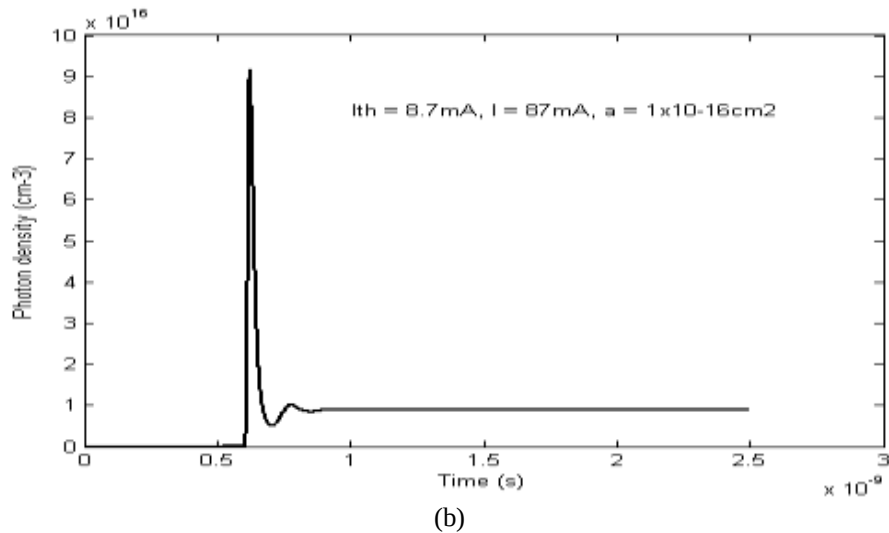
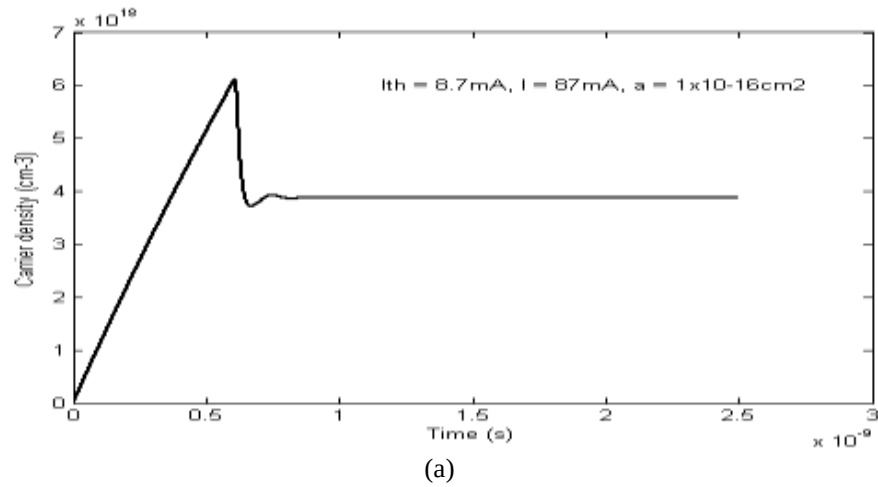
where, N is the carrier density, S is the photon density, I is the injection current, V_a is the volume of the active region, η_i is the injection efficiency, τ_c is the carrier lifetime, v_g is the group velocity, a is the differential gain, ε is the gain saturation parameter, β_{sp} is the spontaneous emission coefficient, R_{sp} is the spontaneous emission rate, τ_p is the photon lifetime.

The optical output power P_o of a semiconductor laser is related to the photon density as (Coldren *et al.* 1995)

$$p_o = v_g \alpha_m h \nu S V \quad (6)$$

where, α_m is the mirror loss coefficient, h is the Planck's constant, ν is the lasing frequency, and I_{th} is the threshold current of the laser.

The carrier density and photon density of the designed 420nm blue violet laser are calculated, by solving the rate equations (4) and (5), for a value of injection current of 87mA and the differential gain of $1 \times 10^{-16} \text{cm}^2$. The optical output power of the laser is also calculated, using equation (6), for the same values of injection current and differential gain. The parameter values are taken as the photon lifetime of 4.3022ps, the carrier lifetime of 2.71ns, the reflectivity of 33.5% and the gain saturation of $1.5 \times 10^{-17} \text{cm}^3$. The obtained results are presented as shown in fig. 3. The carrier density and photon density of the laser are obtained as $3.8774 \times 10^{18} \text{cm}^{-3}$ and $8.8136 \times 10^{15} \text{cm}^{-3}$ respectively. The maximum optical output power is obtained as 150.54mW, where, the threshold current is 8.7mA and the threshold carrier density is $3.0631 \times 10^{18} \text{cm}^{-3}$.



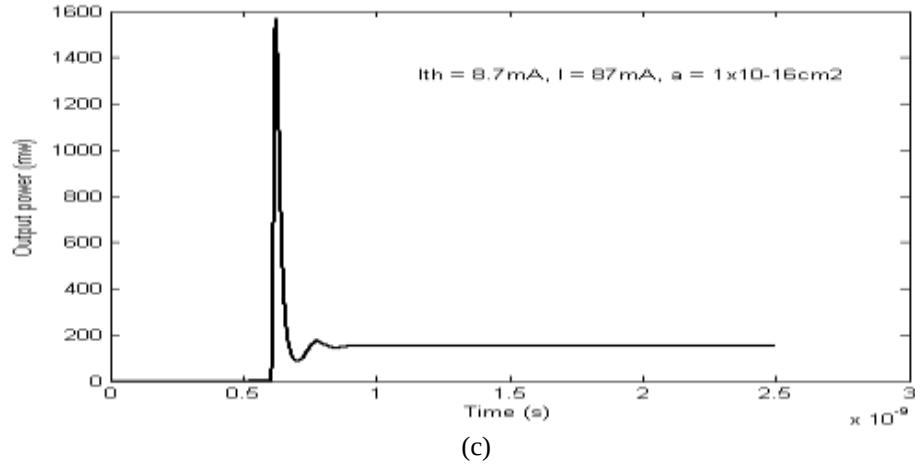


Fig. 3. Plots of (a) carrier density vs. time, (b) photon density vs. time and (c) output power vs. time of a 420nm Blue Violet Laser for a value of injection current of 87mA and the differential gain of $1 \times 10^{-16} \text{cm}^2$, where, the threshold current is 8.7mA.

The energy of the confined state in the CB well of thickness l_w is calculated as (Kasap 2001)

$$E_1 = \frac{h^2}{8m_c l_w^2} \quad (7)$$

The energy of the confined state in the VB well of thickness l_w is calculated as (Kasap 2001)

$$E_{1'} = \frac{h^2}{8m_v l_w^2} \quad (8)$$

The emission wavelength of the laser is calculated as (Kasap 2001)

$$\lambda = \frac{hc}{E_g + E_1 + E_{1'}} \quad (9)$$

Using equation (9), the total transition energy E is calculated as 3.0895eV and its corresponding emission wavelength is calculated as 401.95nm, where, the bandgap energy in the QW region (E_g) is 2.9566eV, the confined state energies in CB and VB are 0.0816eV and 0.0513eV respectively.

The optical output power P_o of a semiconductor laser is also calculated as (Coldren *et al.* 1995)

$$p_o = \frac{\alpha_m h \nu \eta_i}{qg\Gamma} (I - I_{th}) \quad (10)$$

where, α_m is the mirror loss coefficient, h is the Planck's constant, ν is the lasing frequency, and I_{th} is the threshold current of a laser.

Using equation (10), for the same value of injection current of 87mA the output power of the blue violet laser is calculated by varying wavelength and the results are presented as shown in fig. 4. At 300K the material gain varies with the variation of wavelength which

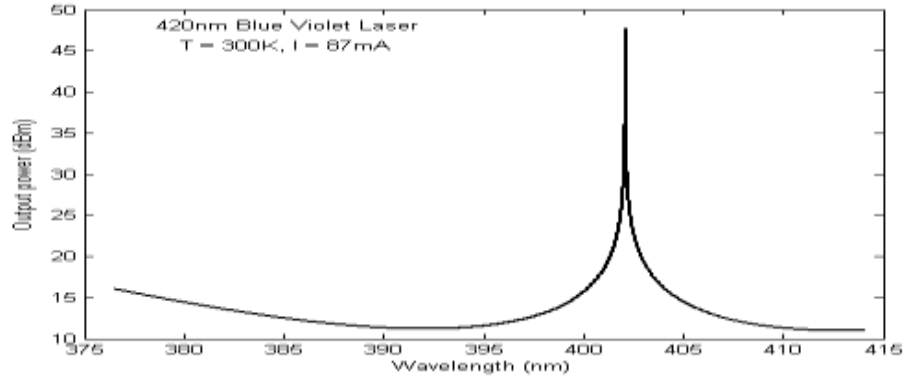


Fig. 4. Plot of output power vs. wavelength of a 420nm Blue Violet Laser for 87mA injection current. Here, the peak output power is obtained at 402.11nm wavelength.

further varies the optical output power of the laser and the peak output power is obtained at 402.11nm wavelength. The obtained result is very close to the calculated value.

(c) Calculation of modal gain

The confinement of material gain is called the modal gain and it is related to the carrier density as (Coldren *et al.* 1995)

$$\Gamma g = \Gamma g_0 \ln \left(\frac{N}{N_{tr}} \right) \quad (11)$$

where, Γ is the confinement factor, g_0 is the material gain constant, N is carrier density, and N_{tr} is the transparency carrier density of QW material.

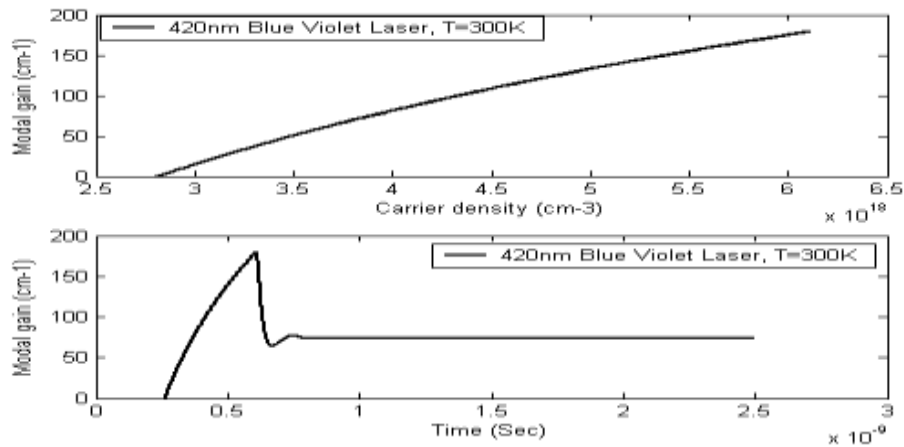


Fig. 5. Plots of modal gain vs. carrier density and modal gain vs. time of a 420nm Blue Violet Laser for a value of injection current of 87mA.

At 300K the modal gain of the laser is calculated, using equation (11), for a value of injection current of 87mA. The obtained results are presented as shown in fig. 5. It is observed that the modal gain goes to positive level at the transparency carrier density of $2.8147 \times 10^{18} \text{ cm}^{-3}$ and after that the modal gain of the laser increases with the increase of carrier density. The modal gain is also calculated with the variation of time and a steady value is obtained as 74.155 cm^{-1} .

(d) Calculation of differential quantum efficiency

The differential quantum efficiency of a laser is calculated as (Coldren *et al.* 1995), (Iga 2008)

$$\eta_d = \frac{\eta_i \alpha_m}{\alpha_a + \alpha_d + \alpha_m} \quad (12)$$

where, α_a is the absorption loss coefficient, α_d is the diffraction loss coefficient and α_m is the mirror loss coefficient of a laser.

The calculated value of differential quantum efficiency of the designed MQW 420nm blue violet semiconductor laser is obtained as 67.02%, where, the internal loss due to absorption and diffraction in the materials of the cavity is considered as 5 cm^{-1} , mirror loss coefficient is 14.5817 cm^{-1} and injection efficiency is 0.9. A high modulation bandwidth and a suitable efficiency improve the performance of the designed laser.

(e) Analysis of modulation response of the designed laser

A high output power contributes to the high modulation bandwidth which enhances the dynamic performance of the laser. The transfer function of modulation response (i.e. relative response) of a semiconductor laser is written as (Coldren *et al.* 1995), (Jungo *et al.* 2002)

$$H(f) = \frac{f_R^2}{f_R^2 - f^2 + j \frac{f}{2\pi} \gamma} \quad (13)$$

where, f_R is the resonance frequency and γ is the damping parameter of the laser.

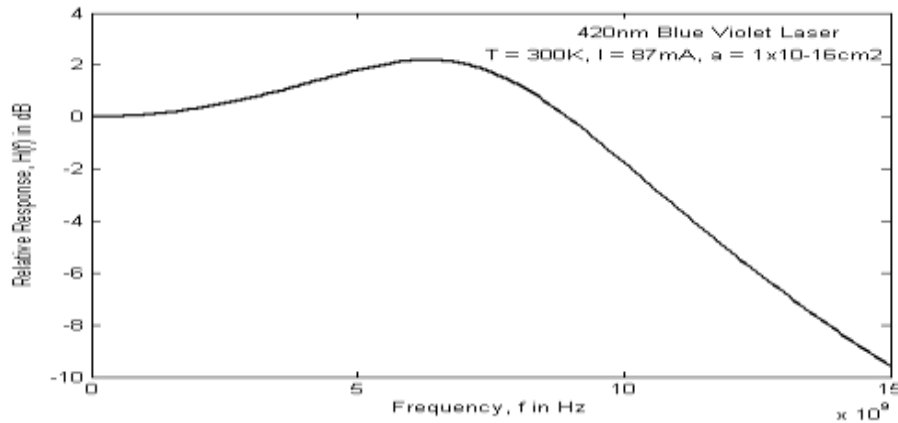


Fig. 6. Plot of relative response vs. frequency of a 420nm Blue Violet Laser, where, the injection current is 87mA and the differential gain is $1 \times 10^{-16} \text{ cm}^2$.

At 300K the relative response of the designed 420nm Blue Violet laser is calculated by varying frequency with the help of equation (13) and the obtained results are plotted as shown in fig. 6. Here, the injection current is taken as 87mA and the differential gain is $1 \times 10^{-16} \text{ cm}^2$.

From the plot of relative response vs. frequency a maximum resonance frequency of 7.9675GHz is obtained at 87mA injection current and for the same value of injection current a maximum bandwidth is obtained as 10.75 GHz. The dynamic performance of the designed Blue Violet laser is improved with the obtained high modulation bandwidth.

For achieving the high performance the modulation response of the designed 420nm Blue Violet laser is also analyzed by varying injection current at first and also by varying differential gain in the next.

(i) By varying injection current

At 300K for a fixed value of differential gain the relative response of the Blue Violet laser is calculated by varying injection current from 87mA to 117mA and the obtained results are plotted as shown in fig. 7. Here, the differential gain is taken as $1 \times 10^{-16} \text{ cm}^2$.

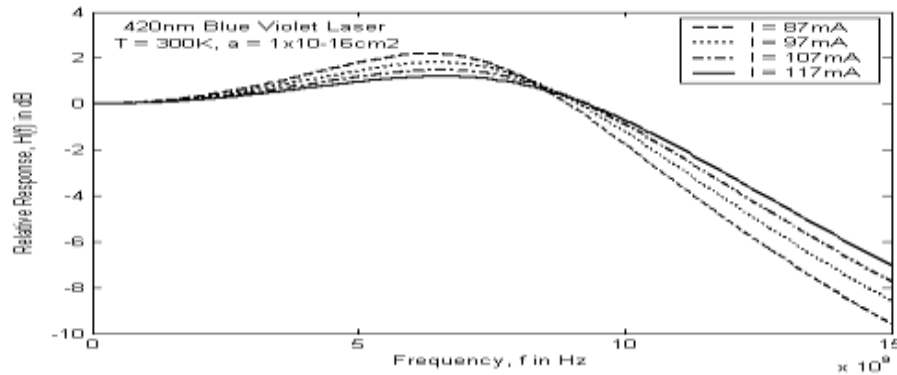


Fig. 7. Plots of relative response vs. frequency of a 420nm Blue Violet Laser for different values of injection current.

The carrier density, photon density and output power of the Blue Violet laser increases with the increase of injection current. The output power of the Blue Violet laser increases from 150.54mW to 209.748mW with the increase of injection current from 87mA to 117mA and for this a maximum resonance frequency is obtained as 9.3711 GHz. The carrier density of the Blue Violet laser increases from $3.8774 \times 10^{18} \text{ cm}^{-3}$ to $3.9261 \times 10^{18} \text{ cm}^{-3}$ and the photon density also increases from $8.8136 \times 10^{15} \text{ cm}^{-3}$ to $1.228 \times 10^{16} \text{ cm}^{-3}$. For a high value of injection current of 117mA a maximum modulation bandwidth is obtained as 12 GHz.

(ii) By varying differential gain

At 300K for a fixed value of injection current the relative response of the Blue Violet laser is calculated by varying differential gain from $1 \times 10^{-16} \text{ cm}^2$ to $4 \times 10^{-16} \text{ cm}^2$ and the obtained results are plotted as shown in fig. 8. Here, the injection current is taken as 87mA.

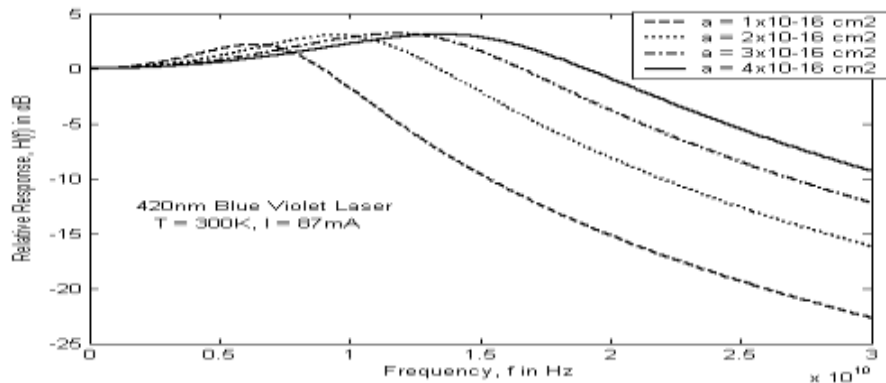


Fig. 8. Plots of relative response vs. frequency of a 420nm Blue Violet Laser for different value of differential gain.

From the calculation it is found that the photon density and output power of the Blue Violet laser increases with the increase of differential gain; on the other hand the carrier density decreases. The output power of the laser increases from 150.54mW to 155.04mW with the

increase of differential gain from $1 \times 10^{-16} \text{ cm}^2$ to $4 \times 10^{-16} \text{ cm}^2$ and for this a maximum resonance frequency is obtained as 15.935 GHz. The photon density of the Blue Violet laser increases from $8.8136 \times 10^{15} \text{ cm}^{-3}$ to $9.0773 \times 10^{15} \text{ cm}^{-3}$, whereas, the carrier density decreases from $3.8774 \times 10^{18} \text{ cm}^{-3}$ to $3.0813 \times 10^{18} \text{ cm}^{-3}$. For a high value of differential gain of $4 \times 10^{-16} \text{ cm}^2$ a maximum modulation bandwidth is obtained as 22.5 GHz. Further by increasing the differential gain from $4 \times 10^{-16} \text{ cm}^2$ to $5 \times 10^{-16} \text{ cm}^2$ it is found that the carrier density decreases drastically below threshold and transparency as $3.028 \times 10^{16} \text{ cm}^{-3}$ although the photon density and output power slightly increases as $9.095 \times 10^{15} \text{ cm}^{-3}$ and 155.34mW respectively.

For achieving a better modulation performance at 300K the relative response of the Blue Violet laser is also calculated at 117mA injection current and a differential gain of $4 \times 10^{-16} \text{ cm}^2$; and the obtained results are plotted as shown in fig. 9.

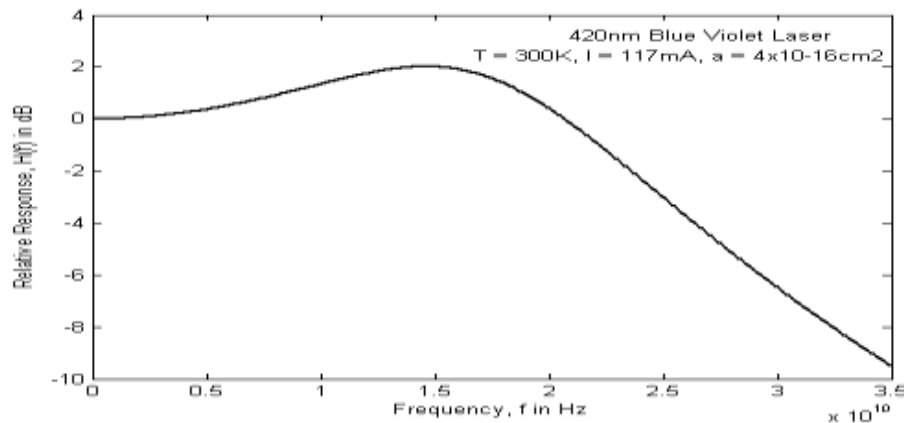


Fig. 9. Plot of relative response vs. frequency of a 420nm Blue Violet Laser, where, the injection current is 117mA and the differential gain is $4 \times 10^{-16} \text{ cm}^2$.

A maximum output power of 214.45mW of the Blue Violet laser is obtained. From the plot of relative response vs. frequency it is observed that a maximum resonance frequency of 18.742 GHz of the designed 420nm Blue Violet laser is obtained; and for the same values of injection current and differential gain the maximum modulation bandwidth is obtained as 25 GHz. This makes the device suitable for applications in data storage and projectors.

4. CONCLUSIONS

The optimized performance characteristics of a designed 420nm MQW Blue Violet semiconductor laser are presented in this work. The modal gain of 74.155 cm^{-1} and the differential quantum efficiency of 67.02% are obtained for 87mA injection current and $1 \times 10^{-16} \text{ cm}^2$ differential gain. By varying injection current and differential gain a maximum output power of 214.45mW and a maximum resonance frequency of 18.742 GHz are obtained with optimized values of injection current of 117mA and the differential gain of $4 \times 10^{-16} \text{ cm}^2$. A high dynamic performance of the laser is obtained by achieving a maximum modulation bandwidth of 25 GHz.

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