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Cavity Length Effects on Performances of InGnAsP/InP Multiple Quantum Well Laser Diode

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Abstract: Software has been developed using the MATLAB language to analyze laser diode having the architecture InGaAsP/InP .The cavity length of active region of multi quantum well semiconductor laser effect on threshold current, quantum efficiency and optical output power of InGaAsP/InP and separate confinement heterostructure (SCH) is investigated. High-speed communication systems, especially those that use optical fiber communication for high-speed data transmission, use lasers with a wavelength of 1.55 µm. here, the performance of changing the cavity length values of active region between 250 to 500 µm at room temperature is study in this work. The characteristics power–current (P– I) and related features, threshold current and slope efficiency have been investigated. The threshold current decreases with increase of cavity lengths because the carrier density in the quantum well is very high. This effect is particularly pronounced in the shortest cavity measured (250µm), we extractI_{th}=6.25ma,α_i=30mA and η_d=63%. These modifications show that our proposed structure is better compared to the GaInP/GaAs 5QW laser structure (Ith=360mA and ηd=51%).

Keywords:*Downsizing, multi-quantum well laser, rate equations, telecommunication wavelength*

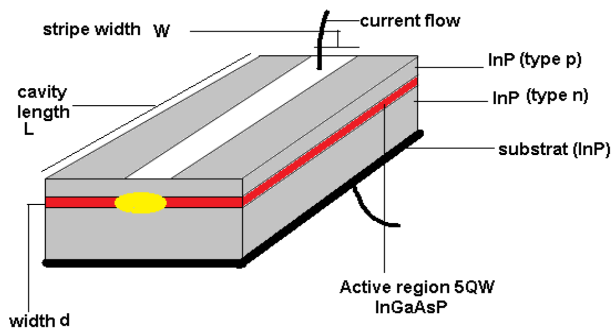
1. Introduction

Lasers are being progressively miniaturized with their dimensions approaching the scale of the wavelength [13]. They now play an essential role in numerous domains of human efforts, including industry, healthcare, defense, and telecommunications [1-3].the dynamic of semiconductor laser behaviour and operation are significantly influenced by its cavity length. Furthermore, for some applications, the quantum well (QW) laser device must be smaller. Studying laser operation at micro-scale dimensions at different cavity lengths is important. [4]. Then, the width of the quantum well in semiconductor laser diodes plays a critical role in determining both the material gain and the lasing wavelength of the device. Material gain refers to the amplification of light within the active region of the laser diode, while the lasing wavelength corresponds to the specific wavelength of light emitted by the device when it lases [5]. In addition, various methodologies are explored for examining both the dynamic and static aspects of radiation from semiconductor lasers and optical amplifiers, along with the intricate interplay of physical phenomena within the active region that influence their radiation characteristics. Additionally, this discussion encompasses certain device configurations and highlights aspects of their computational implementation [6].

The proposed structure allows increasing the efficiency and minimizing the mirror losses and improving the emission power. We are interested in improving the efficiency, reducing the threshold current and minimizing the losses on the laser cavity.

2. Derivation of an Analytical Model of Power and Quantum Efficiency of InGaAsP/InP MQW

Fig.1 show the laser structure used in this investigation. According to quantum physics, the active region of the MQW InGaAsP laser is so small that quantum confinement takes place. The width of the quantum well



[7], or the material band gap at which the device is realized determines the wavelength of light emitted by laser diode [8, 17].

Fig. 1. Sample structure

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The structure consists of multiple quantum wells (5QWs) sandwiched between barrier layers, with cladding layers on top and bottom. It is assumed that all structure grows on an InPsubstrate. The active region is made from InGaAsP, with a thickness of 100 nm. The active region consists in a way that makes its band gap less than the barriers and its refractive index greater than the barriers.

In MQW semiconductor lasers, the active region consists of several quantum wells, which can enhance performance by providing greater confinement and improved carrier recombination efficiency. The rate equations for MQW semiconductor lasers are similar to those for single QW lasers but include additional terms to account for the multiple wells and possible interactions between them. The rate equations of MQW semiconductor lasers are presented below:

$$\frac{dN_i}{dt} = \eta_i \frac{I}{qV_i} - R_{nr}(N_i) - R_{sp}(N_i) - R_{st}(N_i, S) - \frac{N_i - N_{i-1}}{\tau_{d,i}} \quad (1)$$

$$\frac{dS}{dt} = \Gamma\beta \sum_i R_{sp}(N_i) + \Gamma \sum_i R_{st}(N_i, S) - \frac{S}{\tau_p} \quad (2)$$

The laser power is modelled by (3):

$$P(t) = \frac{h\upsilon\eta_i V_a}{2\Gamma\tau_p} S(t) \quad (3)$$

Where, $R_{st}(N, S)$ represents the stimulated recombination rate in the cavity, $R_{nr}(N)$ is non-radiative recombination rate represents losses,$R_{sp}(N)$ is spontaneous emission leads to the creation of photons but is generally less efficient for stimulated emission,N_i is the carrier's density in the i^{th} quantum well, V_i and N_i are the volume and density of carrier of the i^{th}quantum well respectively, τd,i is the time constant for carrier transfer between adjacent wells. The term $(N_i - N_{i-1})/\tau_{d,i}$ represents the carrier exchange between the$i^{th}$and$(i-1)^{th}$wells, S is the total density of photons in the laser cavity, considering contributions from all quantum wells.Γ is the confinement within the active region, assumed to be similar across all wells,β and τ_p are spontaneous emission factor and the photon lifetime, respectively,V_a is the volume of active region (cm^{-3}),q is the carrier charge (C).

Equation (4) used to determine the transparency carrier density N_{th}, by using the effective masses $m_c, m_v$of conduction and valence band respectively [10].

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

Where, ħ is the rationalized Planck’s constant, k is Boltzmann's constant, T is the temperature in Kelvin.

Calculating (dP/dI) above the threshold current of the curve of optical output power laser facet versus injection current I, obtains the differential efficiencyη_d.

$$\eta_d = \frac{2q}{h\upsilon}\frac{dP}{dI} \quad (5)$$

Where, h is the Plank's constant.

Equation (6) relates η_d to internal efficiencyη_i, facet reflectivity R and laser cavity length L_{cav} [12]:

$$\frac{1}{\eta_d} = \frac{1}{\eta_i}\left(\frac{\alpha_i L_{cav}}{ln\left(\frac{1}{R}\right)} + 1\right) \quad (6)$$

Where,α_i is the internalabsorption loss.

3. Validation of Proposed Model

By changing the injection current we plot the output power for two cavity lengths values 200 and 500 µm, results from theoretical model using parameters given in Table1 are compared with experimental data from [4]. in Fig. 2 and 3.concerning the performance of (5QW) laser based *GaInP/GaAs* with different cavity lengths. Our theoretical model has been confirmed by the good agreement between it and the results of the experiment in [4].

Table 1. Parameter values of the 640 nm laser used in this work [10].

Symbol	Type of Parameters	Value
m_e	Electron effective mass	$0.7 m_0$
m_h	Hole effective mass	$0.12 m_0$
T	Temperature in Kelvin	300k
α_i	Intrinsic absorption loss	$17m^{-1}$
ε	Gain compression factor	1.5×10^{-17} cm^3
β_{sp}	Spontaneous emission factor	4×10^{-4}
B	Spontaneous emission rate	1.2×10^{-10}

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

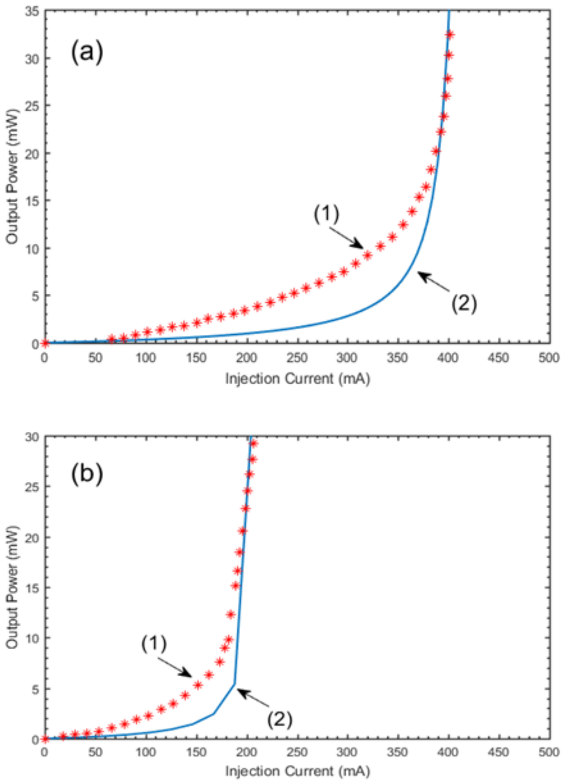

Fig. 2. Power output versus injection current for (a) 200 µm and (b) 500 µm. (1) the experimental data from Ref [4] and (2) Numerical data from this study

4. Results and Discussion

Table 2represents the comparison between the experimental and theoretical threshold current and the change in the output power over the change in current$\Delta P/\Delta I$ denoted by Slope for 200µm and 500µm cavity length values.

The differential quantum efficiency η_d values are parameters that are dependent on the cavity length of the laser diode defined in (5); these values are obtained by calculating the slope of the output power as a function of injection current curve,$\frac{\Delta P}{\Delta I}$, above threshold current. The best agreement between theoretical and experimental values from Table 2.

Table 2. Example of full page table

	Cavity length µ***m***			
	$\boldsymbol{L = 200}$µ$\boldsymbol{m}$		$\boldsymbol{L = 500}$µ$\boldsymbol{m}$	
	theoretical	***Experimental [4]***	***theoretical***	***Experimental [4]***
Threshold current (mA)	360	360	175	170
Slope efficiency mW/mA	0.53	0.503	0.36	0.34
differential quantum efficiency (%)	53	51	37	37

Results show the dependence of the downsizing of quantum well laser on the threshold current (Ith), differential efficiency and gain threshold. The threshold current valueI_{th}that allows the best superposition between our theoretical model and experimental curves is around $360mA$ for $L = 200$µm and $175mA$ for $L = 500um$ [4]. We clearly observe a good agreement between experimental data and theoretical results when the current injection above threshold current and very close when the current injection under threshold current.

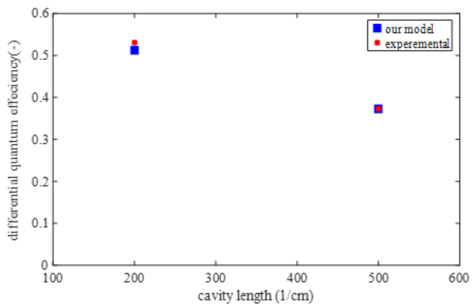

Fig. 3. Differential quantum efficiency, theoretical and experimental [4], as a function of cavity length (200µm and 500µm)

5. Cavity Length Effects on *InGaAsP/InP* MQW Laser Diode

After validation of our theoretical model, we analyzed cavity length dependence on threshold current, slope efficiency and optical characteristics of 1.55µm InGaAsP/InP MQW separate confinement heterostructure (SCH) semiconductor laser. At this wavelength, Semiconductor diode lasers used in telecommunications must have high power and low threshold currents. Fiber optic technologies enable the high-speed data transfer at this wavelength [14].

5.1. Output Power

The output power is firstly calculated by changing the injection current for different values of cavity lengths (250,300,400, and 500µm) as shown in fig.4. By taking the tangent of the output power linear curve and intercepting it with the x axis, we can determine the value of the threshold current shift towards the longer cavity length. For cavity length laser 250µm, we find that I_{th}=6.25mA, while for the 500µm cavity length laser, I_{th}=5.7mA. The decrease in mirror losses explained this outcome [13].

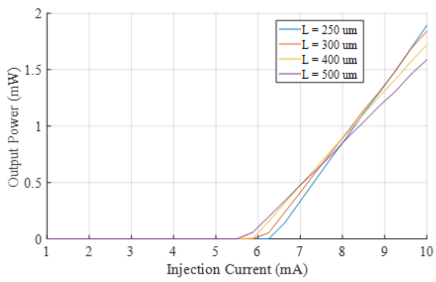

Fig. 4. *InGaAsP/InP* MQW optical power versus injection current for cavity length varying from 250 to 500 µm.

5.2. Threshold Current

To understand how the cavity length affected on threshold current I_{th}, we plotted the output power versus current injection. Fig.5 represents the threshold versus the inverse of cavity lengths of the 1.55µm MQW lasers. It can be observed that the I_{th} decreases with increasing the cavity length. As a result, the device with a 200µm cavity length exhibits faster carrier dynamics [15].

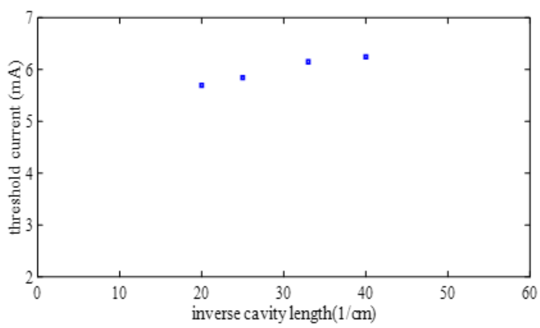

Fig. 5. Threshold current of InGaAsP/InP MQW lasers versus $(L_{cavity})^{-1}$

5.3. Differential Quantum Efficiency

One important parameter to measure laser diode performance is the differential quantum efficiency (η_d). The slope efficiency values above the threshold current (dP/dI) are used to determine differential efficiency(η_d) of the laser. Fig.6 represents the differential quantum efficiency of the devices as a function of cavity length, showing that as the cavity length increases, the efficiency decreases. We derive the best differential efficiency of around 63% and the internal efficiency α_i=30cm^{-1} from the shortest device length (250µm).

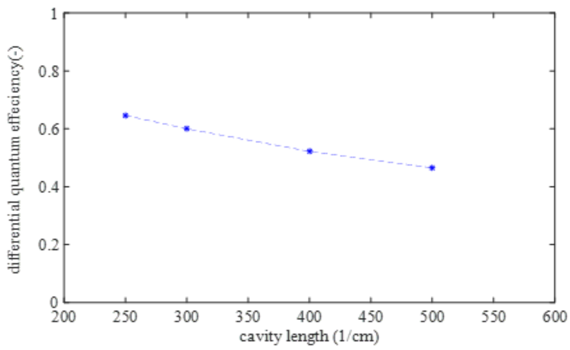

Fig. 6. Differential quantum efficiency with different cavity lengthof *InGaAsP/InP* MQW lasers.

6. Conclusion

In summary, this study presents an analytical approach based on using MATLAB solutions to solve rate equations, for calculate the optical power, threshold current and differential quantum efficiency of 1.55µm *InGaAsP/InP* MQW lasers used on telecommunication system, using data transmission through optical fiber communication with (5QW) at different cavity lengths (250,300,400 and 500µm) at T=300k. When the cavity length increases the I_{th} decreases, which is due to a reduction in mirror lossesα_m. Although the laser device with a short cavity length of 250 µm showed a relatively highI_{th}, it demonstrated the highest differential efficiency (η_d) of 63%, minimal current spreading, and the fastest carrier dynamics. This study demonstrated that we can decrease the threshold current of the laser and increasing the differential quantum efficiency, in the other word the output power and performance of MQW laser in speed communication system.

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