Comparison Power of Semiconductor Lasers at wavelength 1480nm using InGaAs InGaAsP Materials for EDFA Pumping Scheme paper

by Mark Finne

Comparison Power of Semiconductor Lasers at wavelength 1480nm using InGaAs & InGaAsP Materials for EDFA Pumping Scheme

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***Abstract*— Long distance Optical Communications are affected by many problems; loss of signal is one of them. Erbium Doped Fiber Amplifier (EDFA) is the key to solve it. By using Semiconductor Laser as pumping source for EDFA, the signal can be brought back to it is normal condition. EDFA has a good wavelength operation at 1480nm. To achieve selected wavelength, we must construct the Semiconductor Laser that suitable in 1480nm. In that case, *InGaAs* and *InGaAsP* are the base materials to construct the Semiconductor Laser. At wavelength of 1480nm the materials that used are *InGaAs* and *InGaAsP*. The reason is it is suitable for wavelength selection. By using selected wavelength and materials, the Semiconductor Laser can be produced properly. Also, determining the parameter is the important thing to construct the Laser. By using Rate Equation, comparison of output power for *InGaAs* and *InGaAsP* at wavelength of 1480nm based on rate equation and can obtained four result. Those are injection current vs voltage, carrier density, photon density and output power vs injection current.**

Keywords-Semiconductor Laser, Fabry-Perot, EDFA, Materials InGaAs and InGaAsP

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I. INTRODUCTION

Light Amplification by Stimulated Emission of Radiation (LASER) has been used in many application such as telecommunication, medic of surgery, entertainment, and military and so on. The most applicable in Semiconductor Laser is Telecommunication, because Semiconductor Laser has a unique properties such as high monochromaticity, narrow spectral width and high temporal coherence. As a source of light, Semiconductor Laser can be used to Erbium Doped Fiber Amplifier (EDFA) as amplifier the signal to brought back into normal condition.

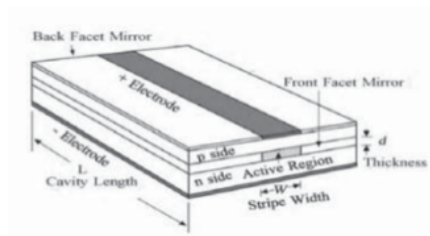

Figure 1 Semiconductor Laser Structure [5]

Due to the usage of EDFA, the applicable wavelengths is 1480nm. Since *InGaAs* has range of wavelength between 900nm – 1700nm, the semiconductor Laser wavelength of 1480nm is workable. In addition, for *InGaAsP* has range of wavelength between 1400nm-1600nm, in that case it's workable either. Basic structure of Semiconductor Laser for *InGaAs* and *InGaAsP* at 1480nm can be seen at Figure 1.

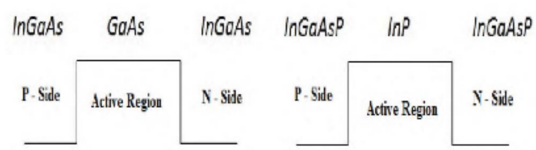

Figure 2 Structure for *InGaAs* and *InGaAsP* [1]

The length and width of Semiconductor Laser used are the same except the thickness of the active region. Calculation was based on assumption made that the Semiconductor Laser only works on the active region. Using the structure like in Figure 1, Figure 2 illustrated the differences among two materials at active region and cladding.

II. THEORY

In order to activate Semiconductor Laser it is important to formulate Rate Equation in order to obtain the output power. Rate Equation shows the correlation between carrier density and photon density where can be expressed as [2]:

$$\frac{dn}{dt} = \frac{I}{qV_{act}} - \frac{n}{\tau_n} - G(n)S \qquad (1)$$

$$\frac{dS}{dt} = G(n)S - \frac{S}{\tau_p} + \beta_{sp}\frac{n}{\tau_n} \quad (2)$$

where I is injection current, q is electron charge, V_{act} is volume of the active region, τ_n is carrier lifetime, τ_p is photon density, β_{sp} is spontaneous emission coupling factor and $G(n)$ is stimulated emission where can be defined as:

$$G(n) = \Gamma g_0(n - n_0) \quad (3)$$

The sign of Γ means optical confinement factor, g_0 gain slope constant, n_0 transparency carrier density. By using Rate Equation, the expression of threshold current can be derived from the Equation (1) and (2). In steady-state, the Rate of Carrier Density $\frac{dn}{dt}$ and the Rate of Photon Density $\frac{dS}{dt}$ are zero and can be simplified to

$$\frac{I_{th}}{qV_{act}} - \frac{n_{th}}{\tau_n} = 0 \quad (4)$$

Where I_{th} is the threshold current and n_{th} is threshold carrier density. The value of n will be equal to n_{th} where $I = I_{th}$, while Injection Current reach threshold the carrier density will reach the threshold either. Rearranging Equation (4) then can be obtained

$$I_{th} = \frac{qV_{act}}{\tau_n}n_{th} \quad (5)$$

By neglecting spontaneous emission coupling factor β_{sp} in Equation (2) the photon density can be simplified to

$$(\Gamma g_0(n - n_{0)} - \frac{1}{\tau_p})S = 0 \quad (6)$$

Equation (6) can be arranging into Equation (7) as threshold carrier density

$$n_{th} = n_0 + \frac{1}{\Gamma \tau_p g_0} \quad (7)$$

then substitute Equation (7) into Equation (5), the threshold current can be derived into

$$I_{th} = \frac{qV_{act}}{\tau_n}(n_0 + \frac{1}{\tau_p g_0}) \quad (8)$$

Injection current needs to activate Semiconductor Laser, in that case, must be obtained using Equation (1) and (2). Rearranging Equation (1) and (2) the equation would be

$$S = -\beta_{sp}\frac{n}{\tau_n}\frac{1}{G(n) - \tau_p^{-1}} \quad (9)$$

$$I = qV_{act}\left[G(n)S + \frac{n}{\tau_n}\right] \quad (10)$$

the carrier density can be defined as

$$n = n_i \exp\left(\frac{qV}{2k_BT}\right) \quad (11)$$

where the intrinsic carrier concentration n_i can be defined as

$$n_i = 2\left(\frac{2\pi k_BT}{h^2}\right)^{3/2}(m_e m_h)^{3/4}\exp\left(-\frac{E_g}{2k_BT}\right) \quad (12)$$

By substituting Equation (11) into Equation (10) the injection current can be expressed as

$$I = qV_{act}\left[-\beta_{sp}\frac{n_i e^{qV/2k_BT}}{\tau_n}\frac{g_0(n_i e^{qV/2k_BT})}{g_0(n_i e^{qV/2k_BT}) - \tau_p^{-1}} + \frac{n_i e^{qV/2k_BT}}{\tau_n}\right] \quad (13)$$

Rearranging Equation (1) and (2) will be obtained

$$\frac{I}{qV_{act}} = G(n)S + \frac{n}{\tau_n} \quad (14)$$

$$\frac{S}{\tau_p} = G(n)S + \beta_{sp}\frac{n}{\tau_n} \quad (15)$$

then substitute Equation (3) into Equation (14) and (15) can be formulated

$$\frac{I}{qV_{act}} = \Gamma g_0(n - n_0)S + \frac{n}{\tau_n} \quad (16)$$

$$\frac{S}{\tau_p} = \Gamma g_0(n - n_0)S + \beta_{sp}\frac{n}{\tau_n} \quad (17)$$

therefore, the carrier density and photon density are given by

$$n = \frac{n_{th}}{2(1 - \beta_{sp})}X - \sqrt{X^2 - Y} \quad (18)$$

$$S = \frac{\beta_{sp}}{\Gamma g_0 \tau_n}\frac{X - \sqrt{X^2 - Y}}{2(1 - \beta_{sp}) - (X - \sqrt{X^2 - Y})} \quad (19)$$

where the value of X and Y can be defined as[1]

$$X = 1 + \frac{I}{I_{th}} - \beta_{sp}\frac{n_0}{n_{th}} \quad (20)$$

$$Y = 4(1 - \beta_{sp})\frac{I}{I_{th}} \quad (21)$$

By substituting Equation (20) and (21) into Equation (18) and (19) we will have the final equation for carrier density and photon density as

$$n = -\frac{n_{th}\left(\frac{I}{I_{th}} - \sqrt{\left(\frac{I}{I_{th}} - \frac{n_0\beta_{sp}}{n_{th}} + 1\right)^2 + \frac{I}{I_{th}}(4\beta_{sp} - 4)} - \frac{n_0\beta_{sp}}{n_{th}} + 1\right)}{2\beta_{sp} - 2} \quad (22)$$

$$S = \frac{\beta_{sp}\left(\frac{I}{I_{th}} - \sqrt{\left(\frac{I}{I_{th}} - \frac{n_0\beta_{sp}}{n_{th}} + 1\right)^2 + \frac{I}{I_{th}}(4\beta_{sp} - 4)} - \frac{n_0\beta_{sp}}{n_{th}} + 1\right)}{\Gamma g_0 \tau_n \left(\sqrt{\left(\frac{I}{I_{th}} - \frac{n_0\beta_{sp}}{n_{th}} + 1\right)^2 + \frac{I(4\beta_{sp} - 4)}{I_{th}}} - \frac{I}{I_{th}} - 2\beta_{sp} + \frac{n_0\beta_{sp}}{n_{th}} + 1\right)} \quad (23)$$

The Carrier Density and Photon Density have a correlation where the value of Threshold Current was same.

After finding Carrier Density and Photon Density, we will find equation of Power against Injection Current by using Photon Density in the active layer. The output power can be expressed by:

$$P = h\omega v_g AS \quad (24)$$

where h is Planck`s constant, ω is angular frequency, v_g is velocity group and A is area of the active region. The Output Power is the final result for this Final Project, where we can compare the output by looking at the wavelength and material.

III. SIMULATION

Based on simulation, the Semiconductor Laser used in this paper are *InGaAs* and *InGaAsP* materials, the specification are listed in the tables below.

TABLE I. FIXED PARAMETERS USED FOR BOTH SEMICONDUCTOR LASER

Cavity Length L Emitter Width w	300 µm 150 µm	Temperature T Carrier Lifetime τ_c	20 °C 10 ps
Voltage V	1 V	Intrinsic Carrier Concentration n_i *GaAs*	9 x 10[6] cm[-3]
High Reflection R2	0.9	Intrinsic Carrier Concentration n_i *InP*	1.3 x 10[7] cm[-3]
Partial Reflection R1	0.1	Transparency Carrier Density n_0	4.7 x 10[20] m[-3]

Table 1 describes the fixed parameters used for the simulation. The voltage and intrinsic carrier concentration are considered to be the important parameter. Where in this paper the voltage can be assumed to be 1 Volt for all simulation of Semiconductor Laser.

TABLE II. PARAMETER OF SEMICONDUCTOR LASER FOR *INGAAS* AT WAVELENGTH 1480NM

Spontaneous Emission Factor β_{sp}	8.7 x 10^{-4}	Velocity Group v_g	8.421 x 10^5 cm/s
Quantum well Thickness d	75.3 Å	Photon Lifetime τ_p	0.294 ns
Volume V_{act}	3.3 x 10^{-16} m^3	Optical Confinement Factor Γ	0.204
Area A	1.13 x 10^{-12} m^2	Frequency ω	1.273 x 10^6 GHz

Table 2 shows the specification of *InGaAs* at 1480nm indicating that the most influential variables that can affect the output are volume of active region and frequency.

TABLE III. PARAMETER OF SEMICONDUCTOR LASER FOR *INGAASP* AT WAVELENGTH 1480NM

Spontaneous Emission Factor β_{sp}	6 x 10^{-4}	Velocity Group v_g	8.89 x 10^5 cm/s
Quantum well Thickness d	140 Å	Photon Lifetime τ_p	0.279 ns
Volume V_{act}	6.3 x 10^{-16} m^3	Optical Confinement Factor Γ	0.224
Area A	2.1 x 10^{-12} m^2	Frequency ω	1.273 x 10^6 GHz

Table 3 shows the specification of *InGaAsP* at 1480nm indicating that the most influential variables that can affect the output are volume of active region and frequency.

The first simulation is compared injection current against voltage for both Semiconductor Laser

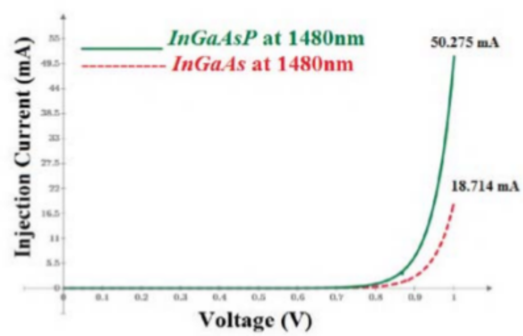

Figure 1 Comparison of Injection Current vs Voltage for *InGaAs* at 1480nm and *InGaAsP* at 1480nm

It is shown that Figure 1 shows the comparison of injection current against voltage of *InGaAs* at 1480nm and *InGaAsP* at 1480nm. The injection current for *InGaAsP* at 1480nm is greater than *InGaAs* at 1480nm does. This is due to the *InGaAsP* at 1480nm has greater volume of active region compared to *InGaAs* at 1480nm. This consequently leads *InGaAs* at 1480nm need more Injection Current than *InGaAsP* at 1480nm does.

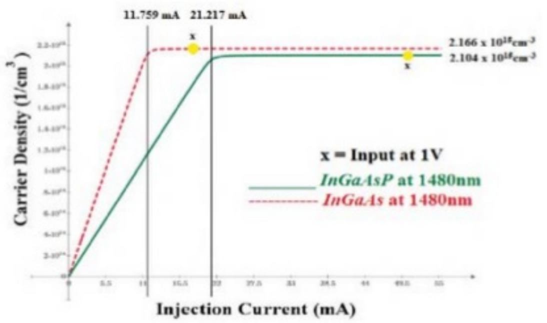

Figure 2 Comparison Carrier Density for *InGaAs* at 1480nm and *InGaAsP* at 1480nm

Figure 2 shows the comparison of carrier density against injection current between *InGaAs* at 1480nm and *InGaAsP* at 1480nm. It is shown that *InGaAs* at 1480nm have smaller threshold current value along injection current than *InGaAsP* at 1480nm does. Both were conducted at 1 volt. The main cause the differences in carrier density is due to threshold carrier density and spontaneous emission coupling factor.

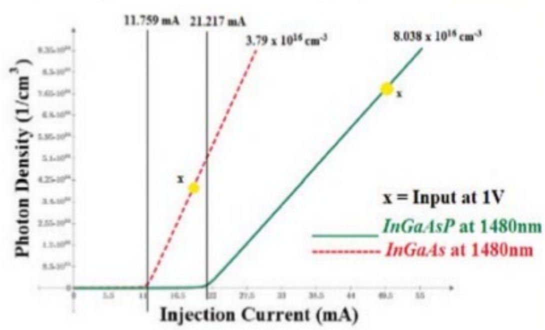

Figure 3 Comparison Photon Density for *InGaAs* at 1480nm and *InGaAsP* at 1480nm

Figure 3 shows the comparison of photon density between *InGaAs* at 1480nm and *InGaAsP* at 1480nm. It is shown that *InGaAs* at 1480nm has smaller threshold current than *InGaAsP* at 1480nm does. This leads to that the *InGaAsP* at 1480nm has a larger output of Photon but need more Injection Current to reach above the threshold for photon density to rise. For *InGaAs* at 1480nm is more efficient than *InGaAsP* at 1480nm, but have smaller value of photon density.

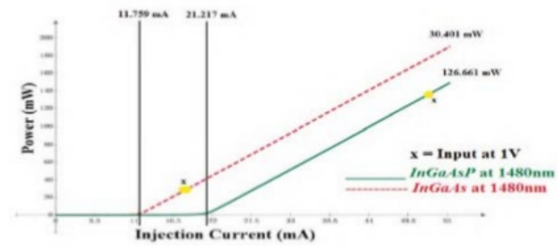

Figure 4 Comparison of Power vs Injection Current for *InGaAs* at 1480nm and *InGaAsP* at 1480nm

Figure 4 shows comparison of output power vs injection current for *InGaAs* at 1480nm and *InGaAsP* at 1480nm. The output power vs injection current can be analyzed and compared by looking *InGaAs* at 1480nm and *InGaAsP* at 1480nm. It is shown that *InGaAs* at 1480nm has smaller threshold current than *InGaAsP* at 1480nm does. However the output Power of *InGaAsP* at 1480nm larger than *InGaAs* at 1480nm. This can be analyzed that *InGaAsP* at 1480nm has larger output power but not efficient compared to *InGaAs* at 1480nm.

TABLE IV. *InGaAs* at 1480nm and *InGaAsP* at 1480nm Result

	InGaAs at 1480nm	*InGaAsP* at 1480nm
Injection Current	18.714 mA	50.275 mA
Threshold Current	11.759 mA	21.217 mA
Carrier Density	$2.166.10^{15}$ cm^{-3}	$2.104.10^{15}$ cm^{-3}
Photon Density	$3.79.10^{16}$ cm^{-3}	$8.5038.10^{16}$ cm^{-3}
Output Power	30.401 mW	126.661 mW
Slope Efficiency	4.371 mW/mA	4.359 mW/mA

Looking at Table 4 above, it can be concluded that the photon density for *InGaAsP* are greater than *InGaAs* at, but the Threshold Current for *InGaAs* is smaller than *InGaAsP*. This leads *InGaAsP* has a larger output power than *InGaAs*, but *InGaAs* more efficient than *InGaAsP* because have low Threshold Current. *InGaAs* has larger slope efficiency than *InGaAsP*.

IV. Conclusion

From the simulation done in this paper, it can be concluded that *InGaAsP* has a larger injection current at 1 volt compared *InGaAs* due to *InGaAsP* has a larger volume than *InGaAs*. Meanwhile *InGaAs* has a larger carrier density compared to *InGaAsP* at 1 volt due to *InGaAs* has a larger threshold carrier density and spontaneous emission coupling factor. Then for *InGaAsP* has a larger photon density compared *InGaAs* due to InGaAsP has a larger spontaneous emission coupling factor. Last, for InGaAsP has a larger output power compared InGaAs, the output power can be obtained by using photon density where the output power were influenced by area of the active region and frequency of materials. This cases are depends on parameters of Semiconductor Laser, by changing the value of fixed Parameter the new result can be obtained.

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