TELKOMNIKA, Vol.17, No.5, October 2019, pp.2675~2683
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i5.11745

Comparison of semiconductor lasers at wavelength 980 nm and 1480 nm using InGaAs for EDFA pumping scheme

Satyo Pradana*[1], Ary Syahriar[2], Sasono Rahardjo[3], Ahmad H Lubis[4]
[1,2,4]Electrical Engineering Department University of Al Azhar Indonesia Jakarta, Indonesia
[3]The Agency for the Assessment and the Application of Technology, BPPT, Serpong, Indonesia
*Corresponding author, e-mail: satyo_pradana@yahoo.com

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 brought back the performed of EDFA into normal condition. EDFA has a good wavelength operation at 980 nm and 1480 nm in that case semiconductor laser using InGaAs at 980 nm and 1480 nm is suitable for them. By using selected wavelength and materials, the semiconductor laser can be produced properly. Also, determining the parameter is the important things to construct the Laser. By using rate equation, the performed of semiconductor laser can obtained several result. Those are injection current as a function of voltage, carrier density, photon density and output power as a function of injection current.

Keywords: *EDFA, fabry-perot, InGaAs and InGaAsP, materials, semiconductor laser*

1. Introduction

In last recent years, light amplification by stimulated emission of radiation (LASER) has been used in many industries, from small scale like surgery in medical world until the large scale like military weapon [1]. LASER also can be used in material processing, cutting material and entertainment like laser lighting and compact disk (CD), however the widest application of semiconductor laser are Telecommunication. LASER is an active device, it's a bunch of photon produced from electron that flow from high energy to lower energy by pump using injection current. Laser can be meant as processes or a device, and that means are same true. Semiconductor laser has a unique properties such as high monochromaticity, narrow spectral width and high temporal coherent. As a source of light, semiconductor laser can be used to erbium doped fiber amplifier (EDFA) as amplifier the signal to brought back the performance of EDFA into normal condition. The process of pumping laser as a part of EDFA pumping scheme can be seen at Figure 1.

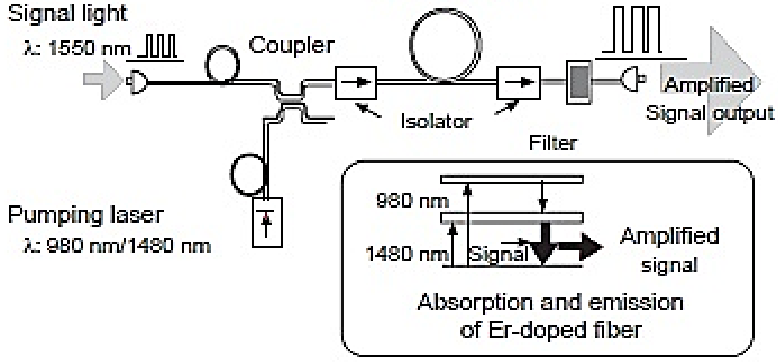

Figure 1. EDFA pumping scheme [2-4]

Received October 5, 2018; Revised March 28, 2019; Accepted April 12, 2019

Semiconductor laser play an important key role in EDFA, the applicable wavelengths for EDFA is around 980 nm and 1480 nm like Figure 1 [5]. Since InGaAs has wavelength range between 900 nm – 1700 nm, therefore the semiconductor lasers for those wavelengths are workable. As an active device, semiconductor laser have a waveguide structure. The basic structure of semiconductor laser used in this paper can be shown in Figure 2, where semiconductor laser have different structure depends on function and type of semiconductor laser. In this paper, the structure that be used is the basic structure in Figure 2, where the other works are using different structure like in Figure 3. The structure that be used in this paper is to perform the basic semiconductor laser, make it simple with different method.

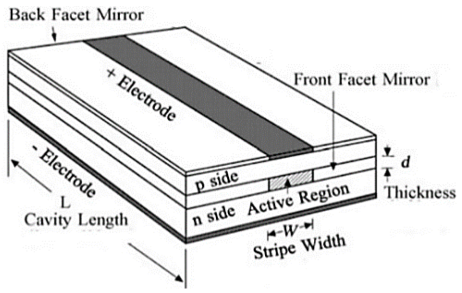

Figure 2. Semiconductor laser structure [6, 7]

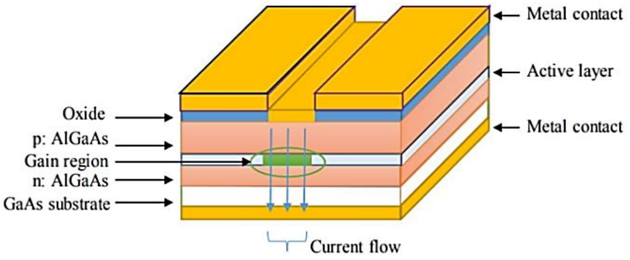

Figure 3. The structure of gain-guided edge emitting semiconductor laser [8]

The difference of semiconductor laser in this paper compared the other works are the type of materials and the structure of semiconductor laser, using the same structure like in Figure 2. Figure 4 illustrated the materials at active region and cladding, where the active region is the place where the light are comes out. The length and width of semiconductor laser are the same, but thicknesses are different in the active region. The calculation was based on assumption made that the semiconductor laser only works on the active region.

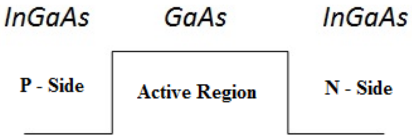

Figure 4. Structure for *InGaAs* [9]

2. Research Method

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 [9-13]:

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

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

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 [14-19]:

$$G(n) = \Gamma g_0(n - n_0) \tag{3}$$

The sign of Γ means optical confinement factor, n_0 gain slope constant, n_0 transparency carrier density [20-25]. By using rate equation, the expression of threshold current can be derived from (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:

$$\frac{I_{th}}{qV_{act}} - \frac{n_{th}}{\tau_n} = 0 \tag{4}$$

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 (4), it can be obtained:

$$I_{th} = \frac{qV_{act}}{\tau_n} n_{th} \tag{5}$$

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

$$\left(\Gamma g_0(n - n_0) - \frac{1}{\tau_p}\right) S = 0 \tag{6}$$

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

$$n_{th} = n_0 + \frac{1}{\Gamma \tau_p g_0} \tag{7}$$

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

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

Injection current needs to activate semiconductor laser, in that case, must be obtained using (1) and (2). Rearranging (1) and (2), the equation would be:

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

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

the carrier density can be defined as:

$$n = n_i \exp\left(\frac{qV}{2k_B T}\right) \tag{11}$$

where the intrinsic carrier concentration n_i can be defined as:

$$n_i = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2} (m_e m_h)^{3/4} \exp\left(-\frac{E}{2\pi k_B T}\right) \tag{12}$$

by substituting (11) into (10) the injection current can be expressed as:

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

rearranging (1) and (2) will be obtained:

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

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

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

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

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

therefore, the carrier density and photon density are given by:

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

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

where the value of X and Y can be defined as [4]:

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

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

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

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

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

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 obtain equation of power against injection current by using photon density in the active layer. The output power can be expressed by:

$$P=h\omega v_g AS \tag{24}$$

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.

3. Results and Analysis

Based on simulation, the semiconductor laser used in this paper are InGaAs materials, the specification is listed in the Table 1. 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. According to literature study, each parameter has different value depends on wavelength and materials. Meanwhile this paper has same type of materials, so only wavelength has an impact to the parameter. Therefore, the parameters are divided into two tables. Table 2 is the parameter for InGaAs at 980 nm and Table 3 is the parameter for InGaAs at 1480 nm. Table 2 shows the specification of InGaAs at 980 nm indicating that the most influential variables that can affect the output are volume of active region and frequency.

Table 3 shows the specification of InGaAs at 1480 nm 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 as a function of voltage for both semiconductor lasers by using (13). After achieved the parameter for simulation, the result will be display in the next section. The first result will be display injection current against voltage for both wavelength and can be seen at Figure 5.

It is shown that Figure 5 shows the comparison of injection current as a function as voltage of InGaAs at 980 nm and 1480 nm. The injection current for InGaAs at 980 nm is greater than InGaAs at 1480 nm does. This is due to the InGaAs at 980 nm has greater volume of active region compared to InGaAs at 1480 nm. This consequently leads InGaAs at 1480 nm need more Injection Current compared to InGaAs at 980 nm. After obtained injection current, the result of carrier density can be obtained at Figure 6. It shows the comparison of carrier density as a function of injection current between InGaAs at 980 nm and 1480 nm. This result can be obtained by using (22). It is shown that InGaAs at 1480 nm have smaller threshold current along injection current compared to InGaAs at 980 nm. Even though InGaAs at 980 nm have smaller carrier density compared to InGaAs at 1480 nm. Both semiconductor lasers were conducted at 1 volt. The main cause is the differences in carrier density is due to threshold carrier density and spontaneous emission coupling factor.

Where the carrier density has the same corelation with photon density due to same time, the result of photon density can be seen at Figure 7. Figure 7 shows the comparison of photon density between InGaAs at 980 nm and 1480 nm. This result can be obtained by using (23). It is shown that InGaAs at 1480 nm has smaller threshold current than InGaAs at 980 nm does. This leads to the InGaAs at 980 nm has a larger output of photon but need more injection current to reach above the threshold for photon density to rise. For InGaAs at 1480 nm is more efficient than InGaAs at 980 nm, but has smaller value of photon density.

Table 1. Fixed Parameters Used for both Semiconductor Laser

Parameters	Values	Parameters	Values
Cavity Length L	300 (µm)	Temperature T	20 (ºC)
Emitter Width w	150 (µm)	Carrier Lifetime τ_c	10 (ps)
Voltage V	1 (V)	Intrinsic Carrier Concentration n_I *GaAs*	9x10^{6} (cm^{-3})
High Reflection R2	0.9		
Partial Reflection R1	0.1	Transparency Carrier Density n_0	4.7x10^{20} (m^{-3})

Table 2. Parameter of Semiconductor Laser for InGaAs at Wavelength 980 nm

Parameters	Values	Parameters	Values
Spontaneous Emission Factor β_{sp}	5.744x10^{-5}	Velocity Group V_g	7.22x10^{5} (cm/s)
Quantum well Thickness d	267 (Å)	Photon Lifetime τ_p	0.343 (ns)
Volume V_{act}	1.2x10^{-15} (m^3)	Optical Confinement Factor Γ	0.231
Area A	4x10^{-12} (m^2)	Frequency ω	1.92x10^{6} (GHz)

Table 3. Parameter of Semiconductor Laser for InGaAs at Wavelength 1480 nm

Parameters	Values	Parameters	Values
Spontaneous Emission Factor β_{sp}	$8.7x10^{-4}$	Velocity Group V_g	$8.42x10^{5}$ (cm/s)
Quantum well Thickness d	75.3 (Å)	Photon Lifetime τ_p	0.294 (ns)
Volume V_{act}	$3.38x10^{-16}$ (m^3)	Optical Confinement Factor Γ	0.204
Area A	$1.13x10^{-12}$ (m^2)	Frequency ω	$1.27x10^{6}$ (GHz)

Finally, the last result for this paper can be explained by looking graph at Figure 8. It shows comparison of output power as a function of injection current for InGaAs at 980 nm and 1480 nm. This result can be obtained by using (24). The output power against injection current can be analyzed and compared by looking InGaAs at 980 nm and 1480 nm. It is shown that InGaAs at 1480 nm has smaller threshold current than InGaAs at 980 nm does. However, the output power of InGaAs at 980 nm larger than InGaAs at 1480 nm. This can be analyzed that InGaAs at 980 nm has larger output power but not efficient compared to InGaAs at 1480 nm.

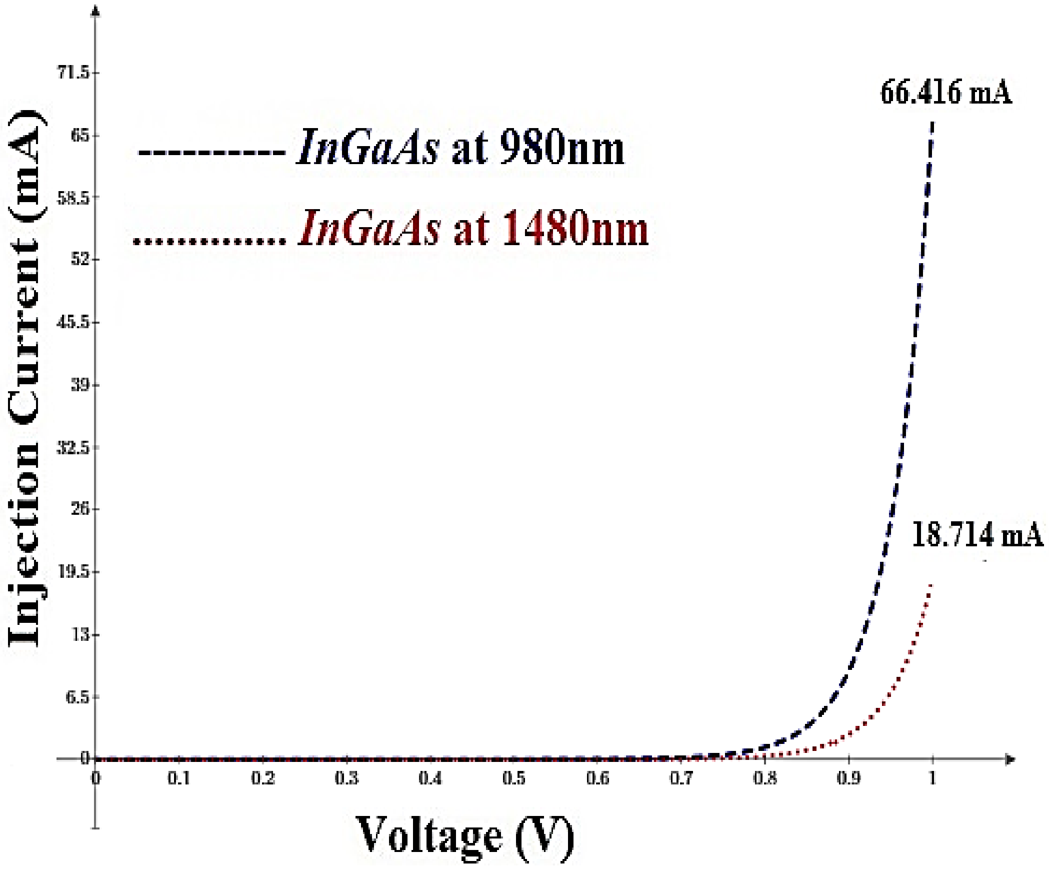

Figure 5. Comparison of injection current vs voltage for InGaAs at 980 nm and 1480 nm

By looking at Table 4, it can be concluded that the photon density for InGaAs at 980 nm are greater than InGaAs at 1480 nm, but the threshold current for InGaAs at 1480 nm is smaller than InGaAs at 980 nm. This leads InGaAs at 980 nm has a larger output power compared InGaAs at 1480 nm, but InGaAs at 1480 nm more efficient than InGaAs at 980 nm because it has low threshold current. InGaAs at 980 nm has larger slope efficiency compared InGaAs at 1480 nm.

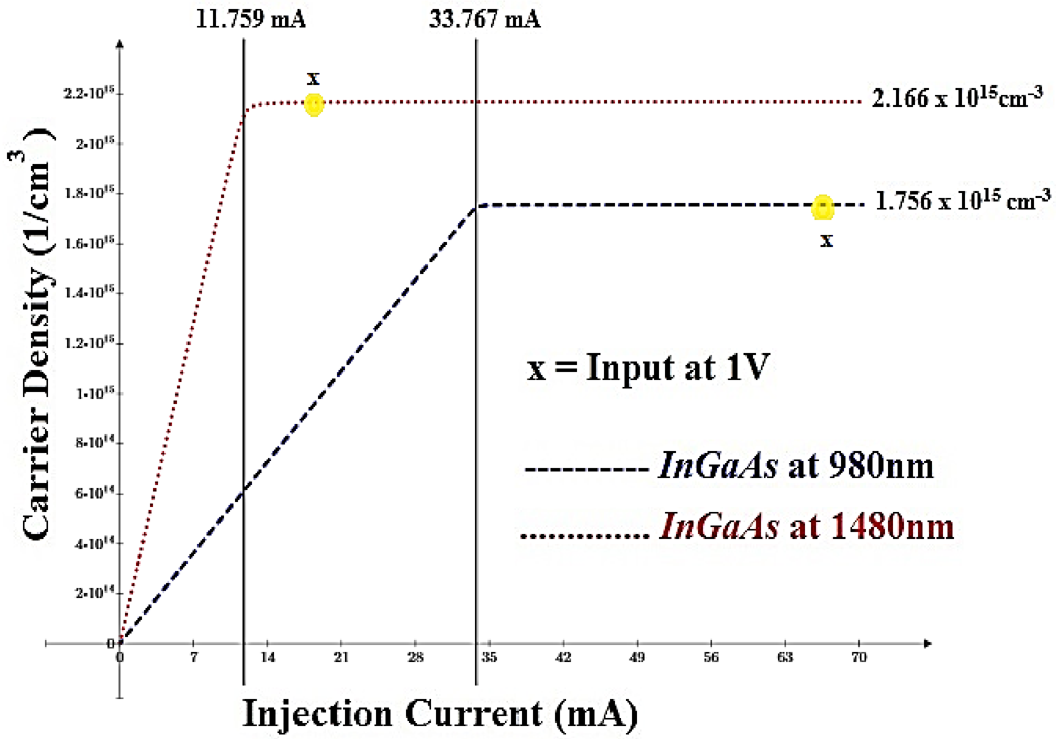

Figure 6. Comparison carrier density for InGaAs at 980 nm and 1480 nm

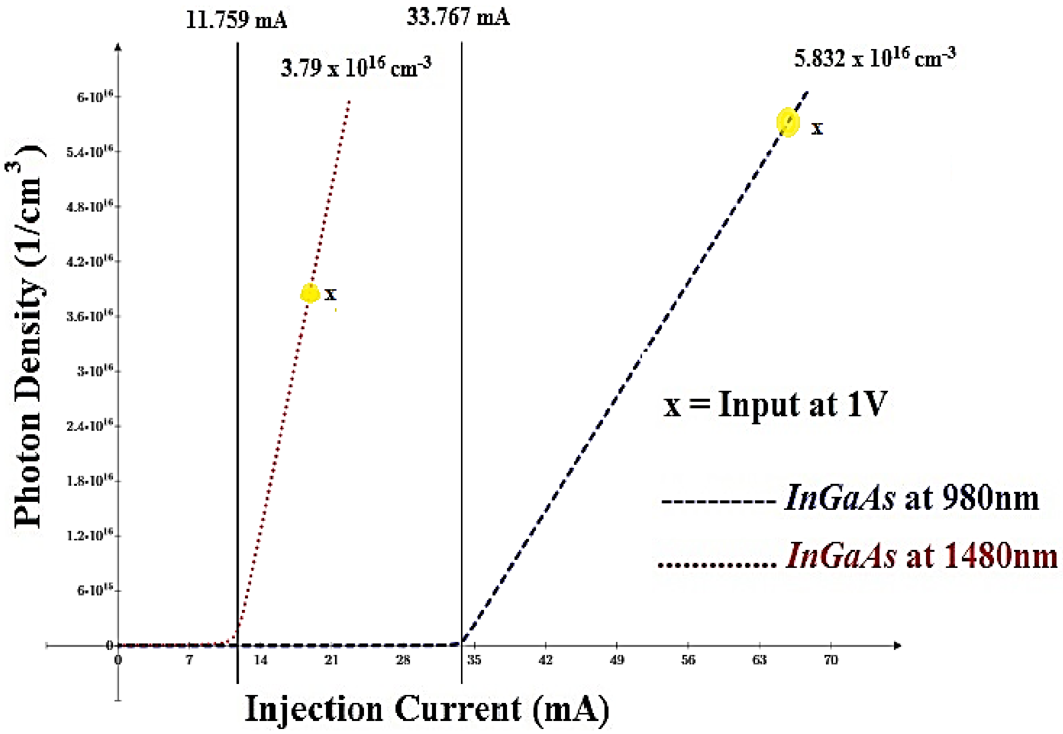

Figure 7. Comparison photon density for InGaAs at 980 nm and 1480 nm

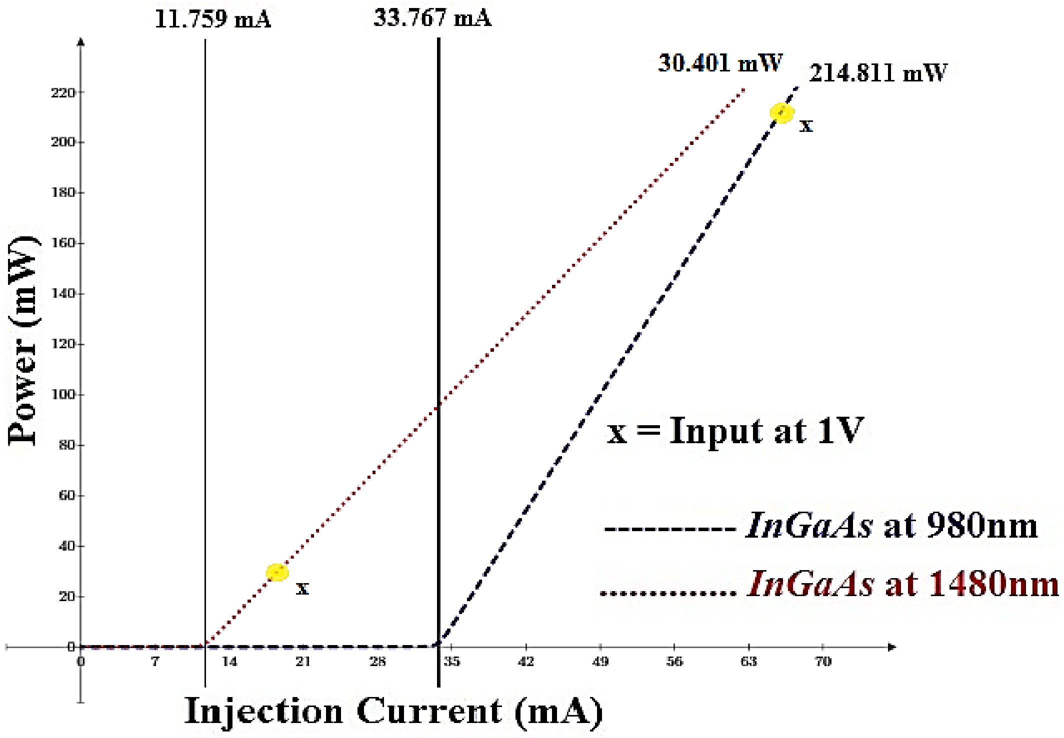

Figure 8. Comparison of power vs injection current for InGaAs at 980 nm and 1480 nm

Table 4. InGaAs at 980 nm and InGaAs at 1480 nm Result

Parameters	Values	Values
	InGaAs at 1480 (nm)	*InGaAs* at 980 (nm)
Injection Current	18.714 (mA)	66.416 (mA)
Threshold Current	11.759 (mA)	33.767 (mA)
Carrier Density	$2.166.10^{15}$ (cm^{-3})	$1.756.10^{15}$ (cm^{-3})
Photon Density	$3.79.10^{16}$ (cm^{-3})	$5.832.10^{16}$ (cm^{-3})
Output Power	30.401 (mW)	214.811 (mW)
Slope Efficiency	4.371 (mW/mA)	6.579 (mW/mA)

4. Conclusion

From the simulation result in this paper, it can be concluded that InGaAs at 980 nm has a larger injection current at 1 volt compared InGaAs at 1480 nm due to InGaAs at 980 nm has a larger volume than InGaAs at 1480 nm. Meanwhile InGaAs at 1480 nm has a larger carrier density compared to InGaAs at 980 nm at 1 volt due to InGaAs at 1480 nm has a larger threshold carrier density and spontaneous emission coupling factor. Then for InGaAs at 980 nm has a larger photon density compared InGaAs at 1480 nm due to InGaAs at 980 nm has a larger spontaneous emission coupling factor. Last, for InGaAs at 980 nm has a larger output power compared InGaAs at 1480 nm, the output power can be obtained by using photon density where the output power was influenced by area of the active region and frequency of materials. These cases are depending on parameters of semiconductor laser, by changing the value of fixed Parameter the new result can be obtained.

References

[1] Richard Scheps. Introduction to Laser Diode Pumped Solid State Lasers. SPIE Press. 2012.
[2] A Kasuakwa, T Mukaihara, T Yamaguchi, J Kikawa. State of the art high power lasers for EDFA. Furukawa Technical Journal. 2000; 105.
[3] H Ghafouri-Shiraz. The principles of semiconductor laser diodes and amplifiers analysis and transmission line laser modeling. London: Imperial College Press. 2004.

[4] Kaminow IP, Li T. Optical Fiber Telecommunications IV-A, Volume A, Fourth Edition Components (Optics and Photonics). Academic Press. 2002.
[5] ON Samijayani. Comparative Analysis of 980 nm and 1480 nm Pumping Scheme on C Band Erbium Doped Fiber Amplifier Using 1530nm Signal Wavelength. Jakarta: University of Al Azhar Indonesia. 2017.
[6] M Yamada. Theory of semiconductor lasers-From Basis of Quantum Electronics to Analyses of the Mode Competition Phenomena. Springer. 2014.
[7] Weng W Chow, Stephan W Koch. semiconductor laser Fundamentals: Physics of Gain Materials. Springer. 1999.
[8] T Numai. Fundamentals of semiconductor laser Second Edition. Springer. 2015.
[9] P Satyo. Comparison Power of semiconductor laser at wavelength 1480 nm Using InGaAs and InGaAsP Materials for EDFA Pumping Scheme. IEEE. 2018.
[10] D J Klotzkin. Introduction to semiconductor lasers for Optical Communications An Applied Approach. New York: Springer. 2014.
[11] T Hao. Calculation and Experimental Verification of Longitudinal Spatial Hole Burning in High Power semiconductor laser, Rose-Hulman Institute of Technology. 2014.
[12] Becker PM, Olsson AA, Simpson JR. (Optics and Photonics) Erbium-Doped Fiber Amplifiers Fundamentals and Technology. New York: Academic Press. 1999.
[13] Baranov, E Tournie. semiconductor lasers: Fundamentals and Applications. Woodhead Publishing. 2013.
[14] YF Wen. Extraction of semiconductor laser Rate Equation Parameters For Simulation of Fiber-Optical Communication System Purpose. Ontario: McMaster University. 2012.
[15] F Al Ayyubi. Characteristic of Cascaded Mach-Zehnder Interferometers with Different Arm Length. Jakarta: University of Al Azhar Indonesia. 2017.
[16] D Patil. semiconductor laser Diode Technology and Application. Intech. 2012.
[17] Haiyin Sun. A Practical Guide to Handling Laser Diode Beams. Springer Netherlands. 2015.
[18] Toshiaki Suhara. Semiconductor Laser Fundamentals. Marcel Dekker. 2004.
[19] Peter W Epperlein. Semiconductor Laser Engineering, Reliability and Diagnostics: A Practical Approach to High Power and Single Mode Devices. 2013.
[20] Dieter Meschede. Optics, Light and Lasers: The Practical Approach to Modern Aspects of Photonics and Laser Physics. Wiley-VCH. 2004.
[21] Bahaa EA Saleh, Malvin Carl Teich. Fundamentals of Photonics. Wiley. 1991.
[22] Philippe C, Becker N, Anders Olsson, Jay R, Simpson. Erbium Doped Fiber Amplifiers: Fundamentals and Technology. Academic Press.1999.
[23] Richard S, Quimby. Photonics and Laser: An Introduction. Wiley-Interscience. 2006.
[24] Katsunari Okamoto. Fundmentals of Optical Waveguides. Elsevier. 2006.
[25] Eli Kapon. Semiconductor lasers. Academic Press. 1999.