Influence of Magnetic Field on the Threshold Current, Temperature Characteristics, and on the Output Power in AlGaInP Multiple Quantum Well Laser

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Abstract

In this paper we report the effects of relatively weak magnetic fields (up to 2T) on the threshold current, temperature characteristics and output power of AlGaInP MQW laser. The threshold current and temperature characteristics increased while the output power decreased by applying the magnetic field at different directions with respect to the quantum well plane. This paper presents a new insight into the mechanism that influence changes in the properties of MQW laser on application of magnetic fields based on the dynamics of electron-hole recombination.

Keywords: MQW laser, Magnetic field

1. Introduction

In comparison with Double Heterojuntion (DH) injection lasers, Quantum Well Lasers (QWL) exhibit a higher efficiency as a result of the quasi-two dimensional character of the carriers and their step-like density of states function. In addition, their threshold current is less sensitive to the temperature changes. This makes them very useful for application in optoelectronic devices (Berendschot *et al.*, 1989). The oscillation output power, threshold current and wavelength of laser diodes depend on the injection current, laser temperature and composition. However, it is also known to depend on magnetic field and pressure (Sato, 1994). To control the oscillating wavelength by injection current or laser temperature alone, it is difficult because of mode jump characteristics of the oscillating wavelength of semiconductor laser (Acsente, 2007). Accordingly, researchers have been interested in the study of changes in laser characteristics influenced by magnetic field. Semiconductor lasers exposed to magnetic fields (both low and high) have been studied and changes in oscillating wavelength (Sato *et al.*, 1986; Smesters *et al.*, 1986; Berendschot *et al.*, 1989; Sato *et al.*, 1998), optical output power (Sato *et al.*, 1998), threshold current (Sato *et al.*, 1986; Smesters *et al.*, 1986; Sugwara, 1995; Sato *et al.*, 1998), and modulation bandwidth (Sugwara, 1995) observed. Earlier studies were performed at very low temperatures (T<100K) and very high magnetic fields (4T – 20T) taking advantage of the fact that only semiconductor lasers can operate at very low temperatures. Later studies were carried out at room temperature (Sato *et al.*, 1986; Sato *et al.*, 1989; Sato *et al.*, 1993; Sato *et al.*, 1994; Sugwara, 1995; Sato *et al.*, 1998; Matsuda *et al.*, 1998; Sato *et al.*, 2000; Seto *et al.*, 2005; Miyamoto *et al.*, 2006) and low magnetic fields (Sato *et al.*, 1986; Sato *et al.*, 1989; Sato *et al.*, 1993; Sato *et al.*, 1994; Sato *et al.*, 1998; Matsuda *et al.*, 1998; Sato *et al.*, 2000; Seto *et al.*, 2005; Miyamoto *et al.*, 2006). Berendschot et al. (1989) investigated the effect of very high magnetic fields up to 20T on a high power GaAs/AlGaAs graded index separate-confinement heterostructure MQW laser. At 120K they found a wavelength shift of less than 0.1nm (blue-shift) operating around 805nm. They also observed a shift of 60K in the charateristic temperature T_0 when the magnetic field is increased from 0T to 20T. In the experiment carried out by Smesters et al. (1986) on a GaAs/AlGaAs DH laser, threshold current shift of around 7% was observed at 25T magnetic field at very low temperatures (~25-46K) with the field lines parallel to the direction of injection current. In another work, Sugwara (1995) studied the threshold currents of InGaAsP/InP strained QW lasers operating around 1.3-1.6 μm, exposed to a field of 13T. At a temperature of 318K he found a threshold current shift of ~2mA. He also observed that the threshold current shift increases with increasing temperature. The works by Sato et al. (1986, 1998) were carried out at room temperature and relatively low magnetic fields up to 1.4T. In an experiment (Sato *et al.*, 1986) performed with AlGaAs diode laser, they observed a frequency shift of 500MHz (red-shift) at 1.4T and a quadratic dependence of the shift with the flux density when the field direction is normal to the active region. In a later work (Sato *et al.*, 1998), they observed a frequency shift of 1GHz (red-shift) with a high power MQW laser oscillating at 780nm. In more recent works (Seto *et al.*, 2005; Miyamoto *et al.*, 2006) at room temperature and up to 1.4T magnetic fields, researchers have observed red-shift in the oscillating wavelength, decrease in the optical output power and increase in the terminal voltage of a number of MQW laser diodes oscillating at 780nm.

Theory based on the formation of Landau levels was used to successfully explain the behavior of laser diodes at very low temperatures and in strong magnetic fields (Galeenev *et al.*, 1965; Calawa *et al.*, 1969; Arakawa *et al.*, 1983). The magnetic field confines the movement of charged particles into a plane perpendicular to it. This results in the quantization of the cyclotron orbits of charged particles. The necessary condition for the formation of Landau levels is $KT \ll \hbar\omega_c$ where ω_c is the angular frequency of the cyclotron orbit. This condition is only achieved at very low temperatures ($T < 100K$) and strong magnetic fields. Around the room temperature, the thermal agitation is high enough to wash out Landau splitting. Also, contrary to the observed higher frequency side shifts of the oscillating wavelength of semiconductor lasers at low temperatures and high magnetic fields, at room temperature and relatively low magnetic fields (upto 1.4T), researchers have obtained shifts in the oscillating wavelength towards the lower frequency side (Sato *et al.*, 1986; Sato *et al.*, 1989; Sato *et al.*, 1993; Sato *et al.*, 1994; Sato *et al.*, 1998; Matsuda *et al.*, 1998; Sato *et al.*, 2000; Seto *et al.*, 2005; Miyamoto *et al.*, 2006) indicating device heating effects. In order to explain the observed effects at room temperature and low magnetic fields, researchers have propounded theory based on the heating of the active region of the device as the magnetic field is switched on and longitudinal magneto-resistance effects. This theory lacks consistency and cannot explain the simultaneous changes in optical output power and oscillating wavelength. Further, in one of the works, Sato and his co-workers (1986) talked about a delay of 70ms in the observed spectral changes and magnetic field switching. They attributed this delay to the time taken for heating of the active region. They failed to mention the time scale that the magnetic field takes to stabilize once it is switched on.

In the present study we examine the output power, threshold current, temperature characteristics of AlGaInP MQW laser at different temperatures (10-40ºC) in relatively weak magnetic field (up to 2T). The range of temperature is important as maximum diode laser based applications are performed in this range including telecommunication applications. We have observed changes in the optical output power, threshold current and temperature characteristics influenced by the magnetic field. We have attempted to explain these changes in low magnetic fields based on the dynamics of charge carrier recombination together with the carrier confinement effect. The paper is organized as follows: in Section 2 we describe the experimental setup while in Section 3 the details of the results obtained is discussed. Finally, in Section 4 we conclude the paper.

2. Experimental Setup and Methods

Figure (1) shows the experimental setup where the semiconductor laser is AlGaInP Index Guided Multiple Quantum well active laser (Model: DL3149-056) with the peak lasing wavelength around 668 nm at 25°C. A standard laser diode comes with a protective covering, which consists of a ferromagnetic material with a glass window, to protect the laser diode itself. The stability of the experiment might be affected without this protective package. The thickness of the covering was small enough to ignore its effect over the experiment as reported earlier (Sato *et al.*, 2000). The laser diode is placed between the poles of an electromagnet on L-shape copper block. The poles of the electromagnet tapers down to a diameter of 1.5cm and the gap between the poles is about 7.5mm. The copper block is mounted upon Peltier's element (Thermoelectric module TOM-8-127-4-6.0M) driven by DC current works as a thermal pump. The heat pump is squeezed between the copper plate and the heat sink. Laser mount, photodiode and lens are fixed on high precision XYZ micropositioning mounts. Current controlling circuitry was designed in our laboratory to effectively stabilize injection current to the laser diode between 0-60 mA with an accuracy of 0.01 mA (Zaker *et al.*, 2011). The temperature controller was designed both to set the laser operating temperature and to stabilize it within ± 0.05°C. The output of the laser beam is fed directly into the photodetector through collimating lens. We used a Hamamatsu (S2281) Si photodiode that has large active area making it well suited for optical power meters. The output power of laser diode was measured by using highly sensitive programmable multimeter (CADDO 62) through 1.5 kΩ terminal resistance. Error in this measurement was of the order of 0.2 μW and temperature variation less than 0.02 ºC observing the photodetector's output and terminal voltage of laser diode in an experiment lasting a few minutes. The fluctuation in power output, laser diode injection current, laser diode temperature and electromagnet current are recorded together by a digital video camera, and the time resolution of this measurement is determined by frame of the video camera system which is about 1/60 sec. Based on the information gained from earlier works we found that the relation between the magnetic field and the laser diode direction is also important. Therefore, the experiment was performed in the following ways. First the magnetic flux density vector **B** and the normal direction **n** of the layered surface of the laser diode are parallel to each other (**B//n**) as shown in Fig. (2a), and second they are perpendicular (**B⊥n**) as shown in Fig. (2b).

3. Results and Discussions

Figures (3) and (4) show the plots for the optical output power with the injection current for a wide range of temperature (5 – 45 ºC) with and without magnetic field (**B**=2Tesla) for **B//n** and **B⊥n** respectively. From the plots one can see the onset of lasing action beyond the threshold and that the threshold current increases with the increase in the temperature. Alternatively, for fixed injection current, the laser's output increases rapidly as the temperature is lowered. As the temperature was raised from 5 to 45 ºC in steps of 5 degrees, the threshold current changed from 17.65 mA to 25 mA. By applying the magnetic field parallel to the quantum well planes, the curves shifted to the high threshold current side as shown in Fig.(3). The effect was small when we applied the magnetic field perpendicular to the quantum well planes as shown in the Fig.(4). We have determined the values of the characteristic temperature T_0 which is commonly used to characterize the temperature sensitivity of the laser diode from the following expression (Berendschot *et al.*, 1989)

$$\frac{I_{th}(T_2)}{I_{th}(T_1)} = exp\left[\frac{T_2 - T_1}{T_0}\right] \tag{1}$$

where $I_{th}(T)$ denotes the value of the threshold current at temperature T. The values obtained for T_0 at **B** = 0T and at **B** = 2T were 117K and 127K, respectively, when **B//n**. To investigate the changes in the threshold current with magnetic field, the current versus light output characteristics of the MQW laser were measured. Figure (5) shows the result obtained for (**B//n**), it can be seen from this figure that the threshold current increases with corresponding increase in the magnetic field. We also measured the dependence of I_{th} as a function of magnetic field for **B//n** at 35 ºC as shown in Fig. (6). As the magnetic field was increased from 0 to 2T, the threshold current increased from 22.86 mA. to 23.23 mA. In the case of **B⊥n** the effect of magnetic field was very small as shown in Fig. (7). Figure (8) shows the optical output-power shift versus magnetic flux density at T = 35 ºC and injection current I = 1.05 I_{th} condition for **B//n** and **B⊥n**. The optical output power decreases when the MQW laser, subjected to a magnetic field that was swept from 0 to 2T. In the case **B//n**, the output power drops from 574.2 to 481.4 μW, while it drops from 574.2 to 555 μW in the case of **B⊥n**.

The above results of the threshold current variation of AlGaInP Index Guided MQW laser diode with temperature (with and without magnetic field) are summarized in Table 1. Light versus current curves show an increase in threshold current with increasing temperature giving a characteristics temperature T_0 a value of 117K for **B**=0 and 127K for **B** = 2Tesla when **B//n**. Threshold current and the optical output power are related to the internal quantum efficiency and the electron concentration necessary for band-to-band absorption, and these were found to be less sensitive to temperature changes. This low sensitivity to temperature variation results in high value of T_0. The threshold current increases and the optical output power reduce, when a magnetic field was applied especially for **B//n**. The variation of threshold current is mainly determined by the variation of the carrier density in the active region which is required to reach threshold condition for laser operation (Bluyssen and Van Ruyven, 1981). The magnetic field affects currents within and/or around the active layer and the current flow is altered by the Lorentz force (Miyamoto *et al.*, 2006). Hence, the magnetic field affected change in the current path causes a change in the current density in the active layer leading to a change in carrier distribution and in turn the oscillation threshold current and output power shift. In particular, the current **I** and magnetic field **B** are parallel (**B//I**) for **B//n**, suppressing the current diffusion leading to a higher current density than the case when **B⊥n**, as a result the threshold current is shifted towards higher side and the output power drops.

The Landau based theory explains well the changes in the characteristics of semiconductor laser at low temperature (<100K) and high magnetic fields (4T – 20T). The range of temperature for our experiments was 278K to 308K.while the magnetic fields were less than 2T. Therefore, the Landau based theory cannot explain the changes that occur in the output characteristics of MQW laser in our experiments. The theory propounded by Sato and his co-workers, in which the influence of low magnetic field at room temperature heats up the active region and gives rise to the longitudinal magnetoresistivity, does not wholly explains the changes observed in semiconductor laser output characteristics.

To begin with, we analyze the force fields that charge carriers experience in a MQW structure. In the absence of external electric field (injection current), magnetic field and electromagnetic radiation inside the structure, electrons in the conduction band possess thermal energy and experiences periodic potential and an additional potential due to quantum confinement. The thermal energy gives rise to ‘diffusive’ motion, while the periodic potential results in the formation of electronic energy bands and sub-bands of allowed and disallowed energies to propagate through the structure. The quantum confinement results in the quantization of electronic energies.

When external bias (electric field) is applied, charge carriers are injected into the structure perpendicular to the QW planes. The charge carriers then 'drift' into the wells where the recombination rate is high due to low energy gap and quantum confinement. The presence of optical fields inside the active region gives rise to an additional interaction of the charge carriers with optical fields. Physically, this interaction leads to 'stimulated' absorption and emission processes. In a semiconductor structure, the band to band optical transition obeys the 'k-selection' rule (Yariv and Zhao, 1999). This indicates that electron-hole recombination process obeys momentum conservation or in other words, electrons and holes possessing identical wave-vectors can recombine to produce a photon.

Application of magnetic field in general exerts Lorentz force on the charge carriers. When static magnetic field is applied along the direction of the injection current i.e. perpendicular to the QW planes (**B//n**), charge carriers travelling along the direction of the injection current remains unaffected. The carriers that 'diffuse' out of the injection current due to thermal agitation having component of momentum in the direction normal to the magnetic field direction (parallel to the QW planes), experiences magnetic confinement. Even at low magnetic field values, contrary to the belief, the magnetic field actually suppresses the recombination rate of the 'diffusing' charge carriers as the cyclotron frequencies ($\omega_c = Bq / m^*$) for electrons and holes that otherwise had same momentum will be different due to the differences in the effective masses (m^*) and charges (q). As a consequence, the output optical power decreases while the threshold current increases with increasing magnetic field. Around room temperature and low magnetic field values, the quasi-Fermi distributions (Yariv and Zhao, 1999) of the charge carriers modifies in such a way that the gain function for the MQW laser is shifted towards the lower frequency side (red-shift) as observed by certain researchers (Sato *et al.*, 1989; Sato *et al.*, 1993; Sato *et al.*, 1994; Matsuda *et al.*, 1998; Sato *et al.*, 2000; Seto *et al.*, 2005; Miyamoto *et al.*, 2006). In physical terms, it means that the magnetic field sweeps away some of the 'diffusing' charge carriers from recombining in the quantum wells even though they are confined magnetically as well as quantum mechanically. This leads to a decrease in the 'band filling' or 'state filling' of the lasing state of the QW laser. Hence, there is a change in the oscillating wavelength of the MQW laser towards lower frequency side.

When the magnetic field is applied parallel to the QW planes (B⊥**n**), the field has little effect on the charge carriers confined to the wells except that it may push small number of charge carriers out of the well depending on the strength of the quantum confinement and strength of the Lorentz force. We, therefore, observed only a small change in the output characteristics of the MQW laser for B⊥**n**. A detailed analytical theory will be published elsewhere (Hafiz and Zaker, 2011).

4. Conclusion

In conclusion, we have experimentally analyzed the effects of low magnetic fields (up to 2T) on the characteristics of AlGaInP Index Guided MQW laser diode within a temperature range of interest. The threshold current is seen to increase while the optical output power is seen to decrease on application of the magnetic field. These changes become more pronounced as the temperature of the diode laser is increased. The direction of the magnetic field with respect to the QW planes plays a crucial in the changes observed in the output characteristics. Existing theories based on the heating of the active region on application of magnetic fields and longitudinal magnetoresistivity, do not completely explain the observed changes at low magnetic fields and at room temperature. Similarly, the Landau based theory is also not applicable in the present scenario. We have therefore attempted to qualitatively explain the observed changes in the output characteristics of index guided AlGaInP MQW laser in relatively low magnetic fields based on the carrier dynamics and changes in the recombination rate of charge carriers. Further studies on the spectral characteristics at different temperatures will be helpful to assert our hypothesis.

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Table 1. Values of threshold current (I_{th}) for temperature variation from (5-45 ºC) with and without magnetic field .

T ˚C	5	15	25	35	45
I_{th}(in mA) B=0	17.65	18.82	20.75	22.86	25
I_{th}(in mA) B=2T B//n	17.98	19	21	23	25.07

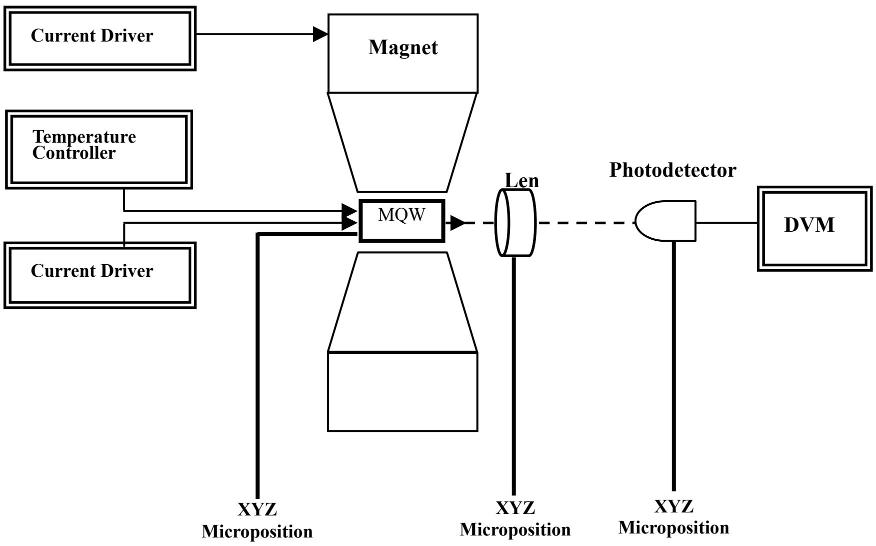

Figure 1. Experimental setup

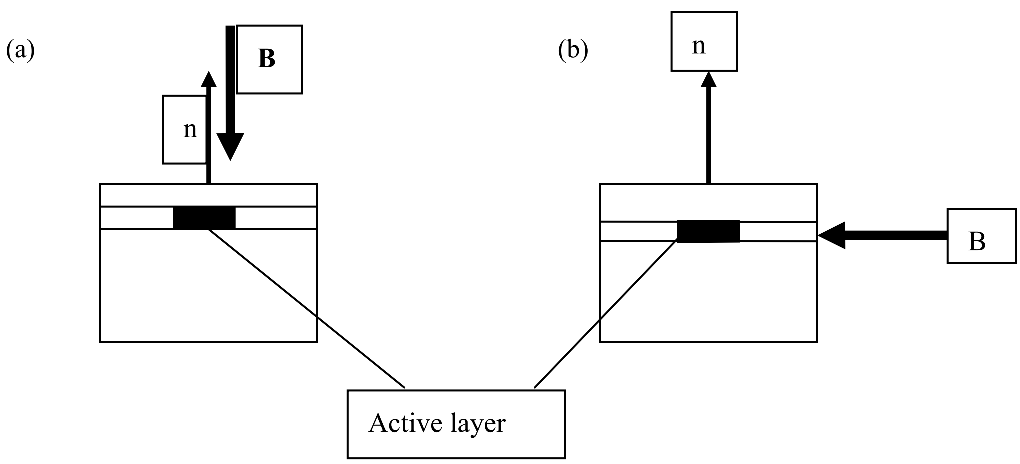

Figure 2. Orientation of the magnetic field

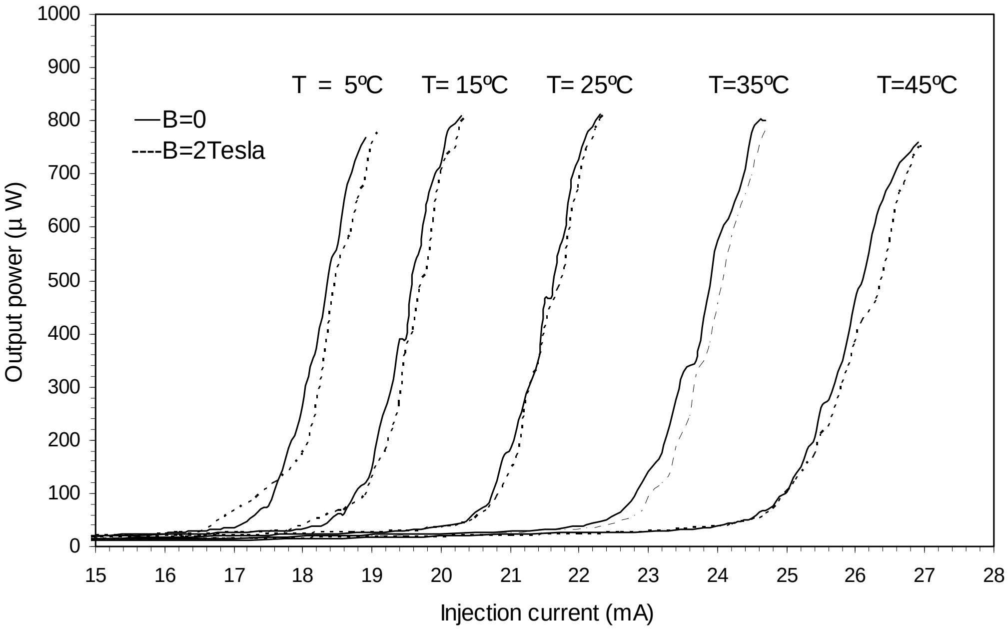

Figure 3. Light versus current characteristics as a function of temperature for B=0 and B=2 Tesla when B//n

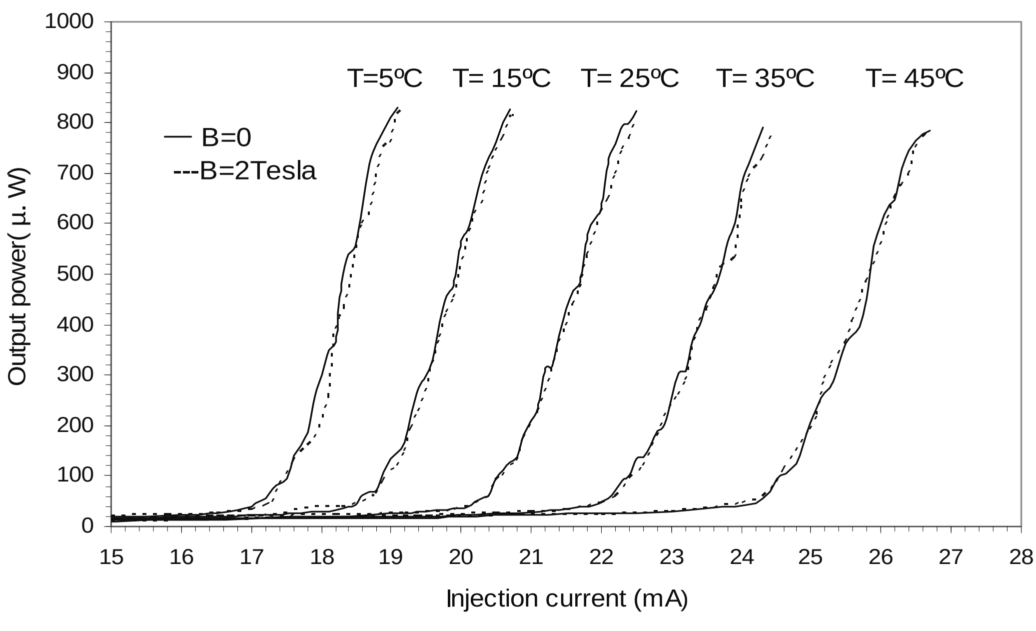

Figure 4. Light versus current characteristics as a function of temperature for B=0 and B=2 Tesla when B⊥n

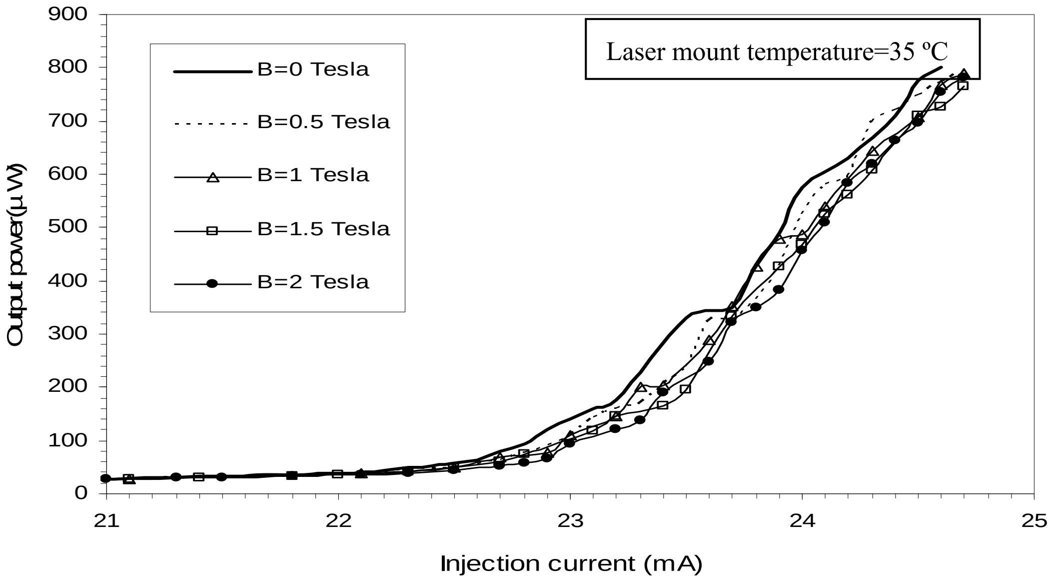

Figure 5. Light versus current characteristics as a function of magnetic field (B//n)

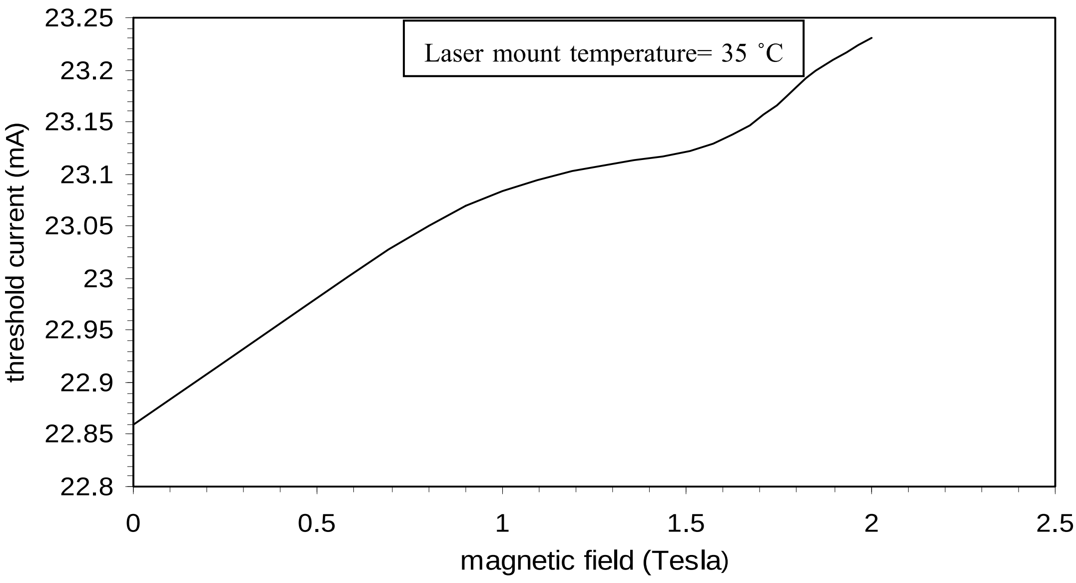

Figure 6. Threshold current as a function of magnetic field when B//n

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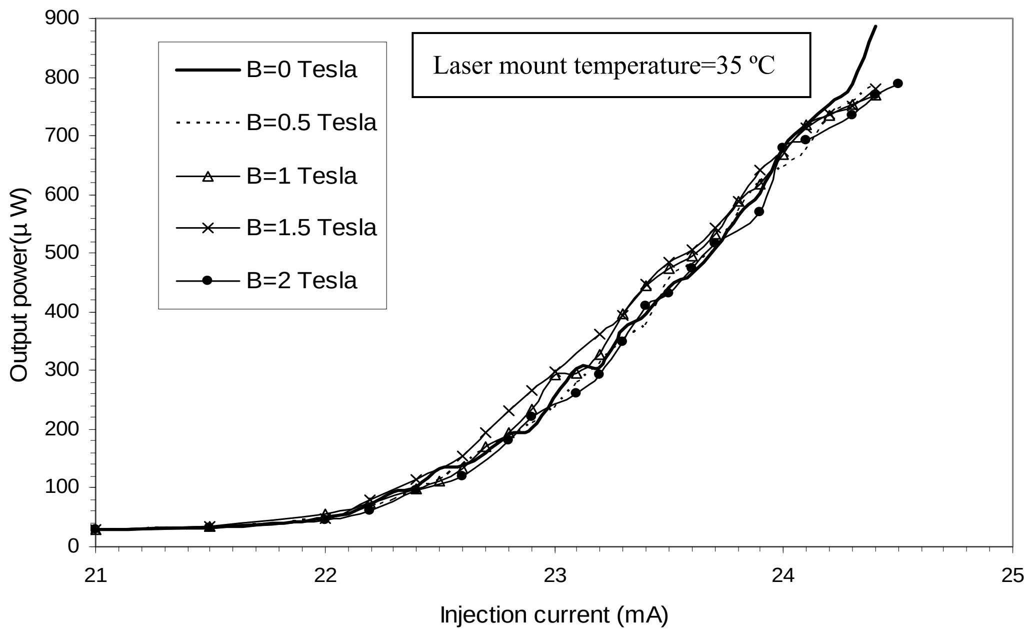

Figure 7. Light versus current characteristics with and without magnetic field for

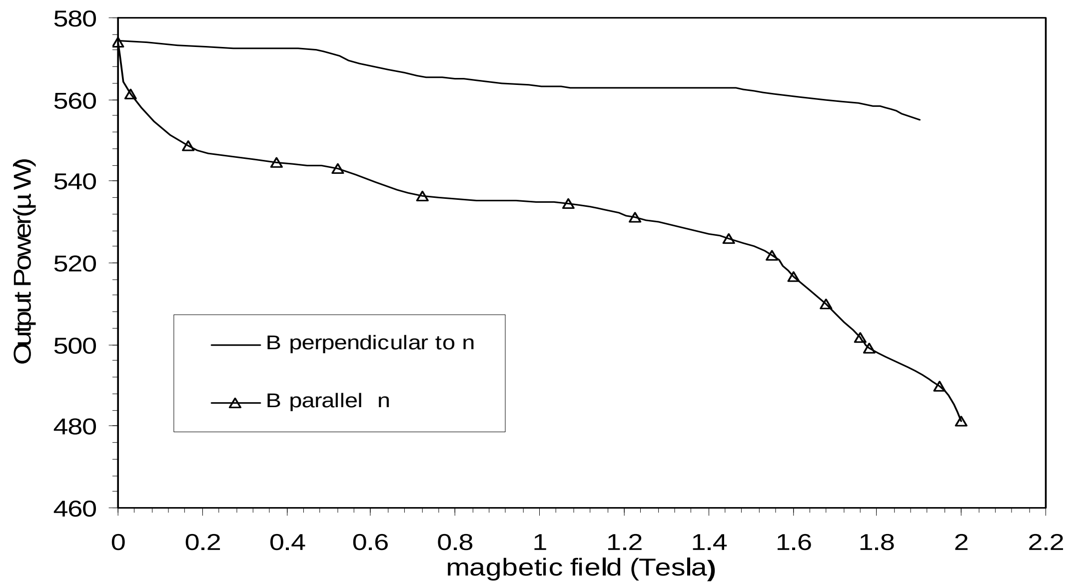

Figure 8. Optical output power vs magnetic field at T = 35 ºC and 1.05 I_{th} injection current condition for B//n and B⊥n