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STRANGE BEHAVIOR IN SEMICONDUCTOR LASER SUBJECTED TO OPTICAL FEEDBACK AT DIFFERENT TEMPERATURES

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ABSTRACT

In this paper we present significant study on the effect of temperature on the characteristics of a diode laser system subjected to external optical feedback. The presence of the feedback is seen to reduce the threshold current and slope efficiency which are important parameters for the solitary diode laser. In this sense the threshold reduction is a good indicator of the feedback level. At certain temperatures, the effect of optical feedback was actually seen to cause slight increase on the threshold current value. The results presented in this paper with regard to the temperature dependence and single optical feedback effect on the threshold and optical power output of diode laser systems will help in understanding the dynamical behavior of such systems.

Keywords: Diode Lasers, optical feedback, external cavity, temperature effect, light-current characteristics.

INTRODUCTION

Unlike light from standard sources such as light bulbs, laser light is highly coherent. The coherent light of a laser is achieved by coupling the active medium with a laser cavity. The cavity selects some of the photons emitted spontaneously to re-propagate through the medium. These photons 'stimulate' other photons to propagate in the same direction with the same phase or constant phase difference. In order to obtain laser output one of the reflective ends of the cavity is made semi-reflective, thus allowing some of the coherent light to escape. Since some of the laser's output will be reflected back into the cavity. It is important to choose a laser diode with highly reflective coating on the back face and a reduced reflectivity coating on the output face. While many low power diode lasers do not have such coatings, diode lasers that produce 30mW or more output power generally have these extra coatings (Al-Dwayyan *et al*., 2007). In this work a laser diode with an output power rating of < 5mW was used. The phenomena of optical feedback in semiconductor lasers is considered undesirable (Servagent *et al*., 1998) as it significantly affects the operating behavior of the laser. Conversely, optical feedback has also been found to be useful in purposes such as mode selectivity and line width reduction (Lang and Kobayashi, 1980; MacAdam *et al*., 1992). The use of feedback can be extended into many other applications including target displacements, range finding and velocity measurement (Bosch *et al*., 1998a; Bosch *et al.* 1998b; Amann *et al*., 2001), optical microscopy (Katagirl and Hara, 1998) and various medical applications (Mito *et al*., 1993). In addition, optical feedback of appropriate level has been found to increase the side mode suppression, narrow the line width, and provide enhanced tunability and frequency stability, relative to that of the solitary diode laser (Goldberg *et al*., 1982; Osmudsen *et al*., 1983). A source for coherent optical communication systems and spectroscopic applications is required to be single frequency, narrow linewidth, and continuously tunable over a wide range of wavelengths (Helms *et al*., 1992; Olsson and van der Ziel, 1987). There are many spectroscopic techniques for which diode lasers with feedback are ideal sources (Yabuzaki *et al*., 1991; Boshier *et al.*, 1991). The reflection of the light emitted by the laser, due to the presence of an external mirror, is capable of inducing chaotic dynamics at the output intensity (Takiguchi *et al*., 1998; Liu *et al*., 2001; Fujita and Ohtsubo, 2005; Buldu, 2003). The output power is one of the most important parameter to characterize a diode laser. Figure 1 shows the typical light-current (L-I) characteristics, which depicts output power of a typical continuous wave (cw) semiconductor diode laser as a function of injection current (L-I curve) (Derry *et al*., 1995).

When the forward bias current is below threshold, the laser diode operates like a light-emitting diode (LED) where the carrier density in the active layer is not high enough for population inversion, spontaneous emission dominates producing a small amount of incoherent light (see Fig. 1). As the bias increases, population inversion occurs, stimulated emission becomes dominant and cavity losses are compensated at a certain bias current, the current at this point is called *threshold current*. The injection current above the threshold induces the abrupt onset of lasing action and coherent light is emitted from the diode laser. The laser threshold current is evaluated by extrapolating the linear part of the characteristic to zero output power (Ye, 2004).

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A semiconductor laser is subjected to both internal and external losses. For lasing to begin, i.e. to reach threshold, the gain must be equal to these optical losses. The threshold gain per unit length is given by:

$$g_{th} = \alpha_i + \frac{1}{2L} ln\left(\frac{1}{R_F R_R}\right) \quad (1)$$

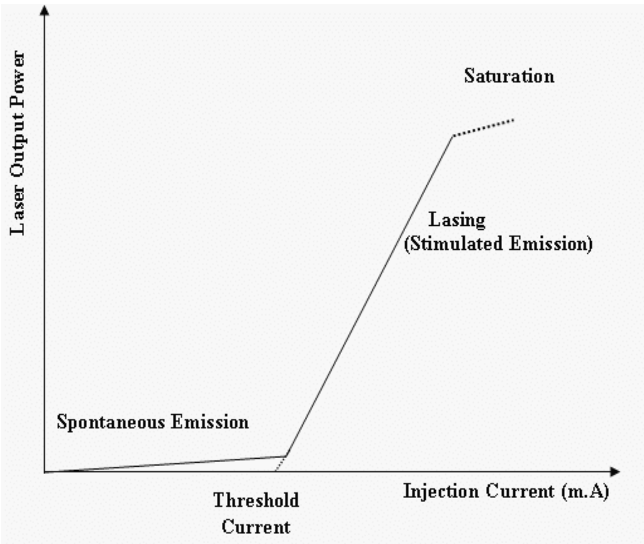


Fig.1. Schematic light output versus current curve.

Where α_i is the internal loss per unit length, L is the laser cavity length, and R_F and R_R are the front and rear facet reflectivity. The internal loss is a material parameter determined by the quality of the semiconductor layers (Ye, 2004). On the operation side, typical threshold current is few milliamperes and varies from device to device (Osmudsen *et al.*, 1983). Incident spontaneous emission light propagating to the reflection mirror is amplified by stimulated emission and comes back to initial position after a round trip inside the laser cavity as well as external cavity (Ye, 2004). Thus, the percentage of the light re-injected into the laser diode is complicated for estimation. In direct estimation is possible by studying the characteristics of the diode laser subjected to external optical feedback.

The aim of this paper is to study experimentally the characteristics of semiconductor lasers with optical feedback under the influence of certain range of temperatures (10 – 30˚C). This range of temperature is of particular interest as maximum diode laser applications are performed on this range. Even in telecommunication applications, the range of temperature is often centered between 25 and 30˚C (Alter, 2003). The study is of special interest not only from the point of view of nonlinear dynamics, but also for its application to optical communication. The motivation for the current work is therefore to understand the dynamics of how increasing the temperature of the semiconductor laser affects its output (stability and power) for this kind of systems. The output can, hence, be adjusted for a given application that can be achieved with a specific temperature range. In the following sections we describe the experimental setup and the results obtained followed by the conclusion.

MATERIALS AND METHODS

The system mainly consists of two controlling units (for temperature and current) and the laser diode which is made up of AlGaInP with the operating wavelength around 660nm. There was no particular choice for the laser diode chip as the effects discussed in this paper will not differ much for other types of diode lasers. As shown in figure 2, the external cavity consists of the uncoated facet of the laser diode (LD), an external high reflecting mirror (R _ 90%). A cubic beam splitter (25mm) is used to divide the light intensity equally (50%) between the cavity arm with the external mirror and the detector connected to the power meter. The length of the cavity arm is L=1.5m corresponding to round trip frequency of (f =c/2L = 100 MHz) and an external round trip time of (τ=1/f =10 ns).

For diode lasers, the peak wavelength of emitted light is dependent on the temperature of the laser diode chip. Increase in temperature not only increases the lattice vibrations in the semiconducting material thereby changing the length of the internal cavity but also suppresses the radiative recombination of the charge carriers by increasing the scattering losses. The peak wavelength drifts typically by about 0.1nm per degree change in temperature with the drift being towards the red-shift for rise in temperature. Thus with the change in temperature, phenomena of mode hopping is also observed. A Precise control of the temperature of the laser mount is, therefore, essential for the long term reliable operation of the laser at a particular wavelength. The temperature of laser mount is controlled within an accuracy of ± 0.05˚C, using a thermistor, thermoelectric cooler and thermocouple (the remaining circuitry is contained in an external unit). This mount is designed to allow both for effective stabilization as well as good thermal contact with an Aluminum plate (base) situated below the mount. Figure 3 illustrates the basic construction of the mount and the schematic diagram of the whole system. There are two parts of the laser mount structure: 1) the aluminum base holder fixed on the anti-vibration optical table, and 2) the base that contained the major components. The laser holder is a small piece of Aluminum plate into which the laser diode (LD) and the thermistor are inserted. It rests on the thermoelectric cooler (TEC), making good thermal contact using a thermally conductive compound. This block is held to the heatsink by nylon screws to minimize direct heat transfer. The heat sink rests on a small fan for effective dissipation of heat to the surrounding. The laser diode is inserted into

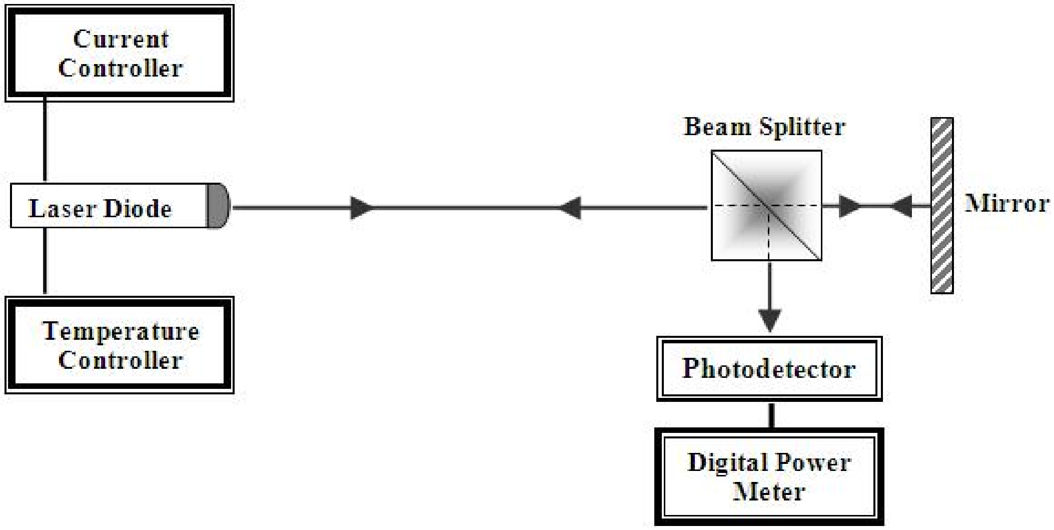


Fig. 2. Experimental Setup of Semiconductor Laser with External Cavity.

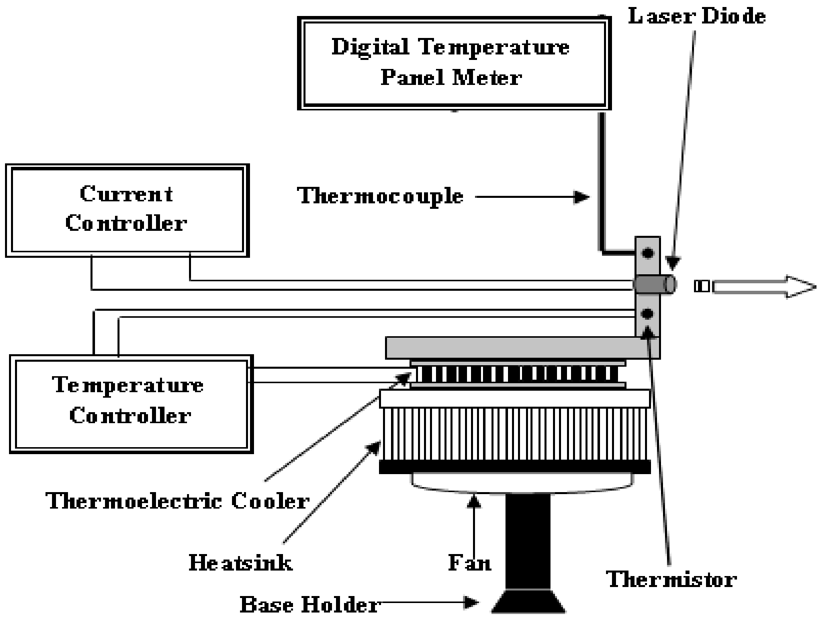


Fig.3. Schematic diagram of the Laser Mount connected to Current and Temperature Controllers.

the hole at the middle of the mount and very close to the thermistor, thermoelectric cooler and thermocouple.

The output of the diode laser strongly depends on the injection current. With the increase in the injection current above the threshold value, not only the optical power increases but the operating wavelength is blue-shifted. The current controller with an accuracy of ± 0.01 mA is therefore used for effective stabilization of the output. The optical power emitted by the laser without feedback is measured using an optical power meter placed in front of the laser diode. The injection current is scanned from zero to about 40mA in steps of 0.1mA and the corresponding optical power is measured each time. This process is repeated for different temperature values. The whole experiment is repeated by constructing an external optical cavity as shown in figure 2. The differential slope efficiency (dL/dI) is the slope of the L-I characteristic at a particular current value. Slope efficiency for a laser should be constant above and below the threshold region. Any variation in slope efficiency above the threshold along with the so called kinks in the laser characteristics may point to internal defects in the laser. Hence the slope efficiency is an important factor in determining the quality of a laser beyond threshold

RESULTS AND DISCUSSION

Figures 4 through 6 describe the behavior of the output characteristics of the diode laser with changes in temperature and optical feedback. The plots in figure 4 describe the variation of the threshold current with temperature in the absence [curve (a)] and presence [curve (b)] of optical feedback. The detail values are given in table 1. Clearly, it can be seen that the value for the threshold current increases in general with the increase in temperature. This results from the fact that, as the temperature increases, the lattice vibrations in the active region increases, thereby, increasing the losses as well as suppressing carrier recombination. The process of optical feedback is seen to reduce the threshold value up to a certain temperature (21˚C in our experiment). This is along the expected lines that optical re-injection 'stimulates' recombination process in the active region which results in the decrease of the threshold value. It is interesting to note that above that temperature (21˚C for our setup), there is an actual increase in the threshold current value due to optical feedback. Interestingly this temperature was also the temperature of the surroundings i.e. room temperature. Though the observed change in the threshold value as a result of optical feedback was small, the effect was regular.

Figure 5A shows the output optical power versus input current for the solitary laser diode, in the absence of optical feedback. The L-I curve was measured at different temperatures. The input current is varied from 0mA to 37mA. The L-I characteristics of the laser was then measured with optical feedback as shown in figure 5B. Small variations in the slope of the L-I characteristics (small kinks, or nonlinearity), can be observed around the threshold current, but these were most likely due to the onset of fluctuations in the output power due to the optical feedback, that influences the output power versus current characteristics (through the threshold injection current and slope efficiency dL/dI). The effect of optical feedback on the threshold and output power of the laser diode system has been explicitly shown in figure 6. For temperatures, below a certain temperature (which is 21˚C for our setup), optical feedback causes reduction in the value of the threshold current which can act as a good indicator of the feedback level. For higher temperatures optical feedback has the effect of increasing the threshold value and decreasing slightly the slope efficiency compared to that of the solitary diode laser.

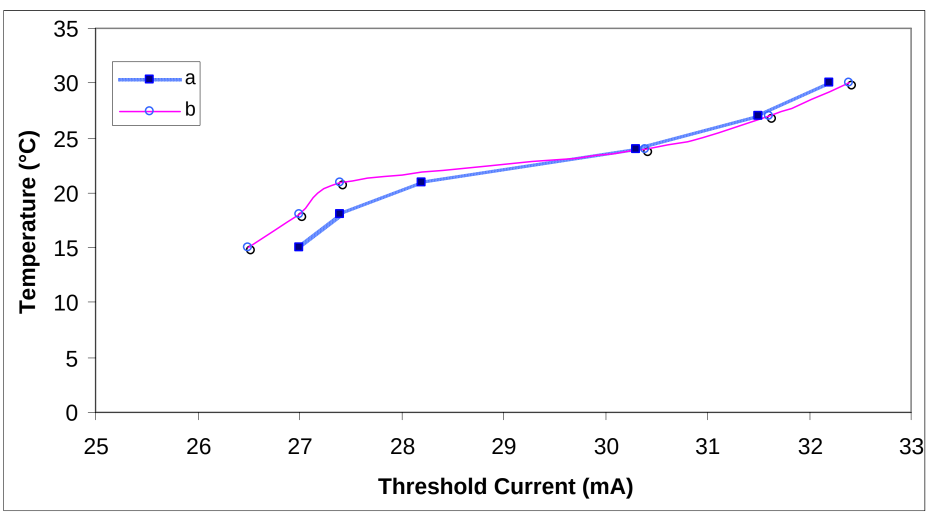
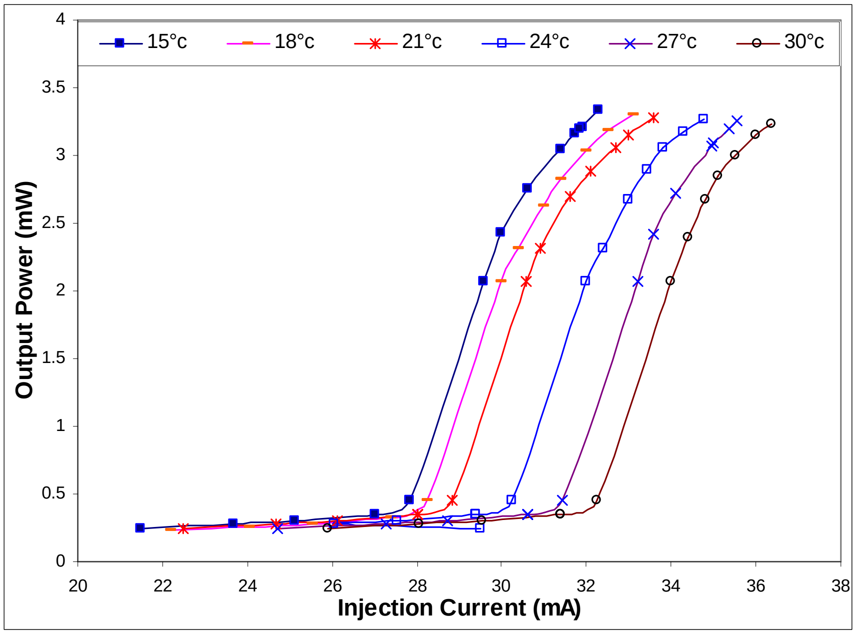


Fig. 4. Variation of threshold current of laser diode with temperature (a) without and (b) with optical feedback.

Table 1. Threshold Current for different temperature.

Temperature	15 ˚C	18 ˚C	21˚C	24 ˚C	27 ˚C	30 ˚C
Threshold Current of Solitary Laser Diode (mA)	27	27.4	28.2	30.3	31.5	32.2
Threshold Current with Optical Feedback (mA)	26.5	27	27.4	30.4	31.6	32.4

A



B

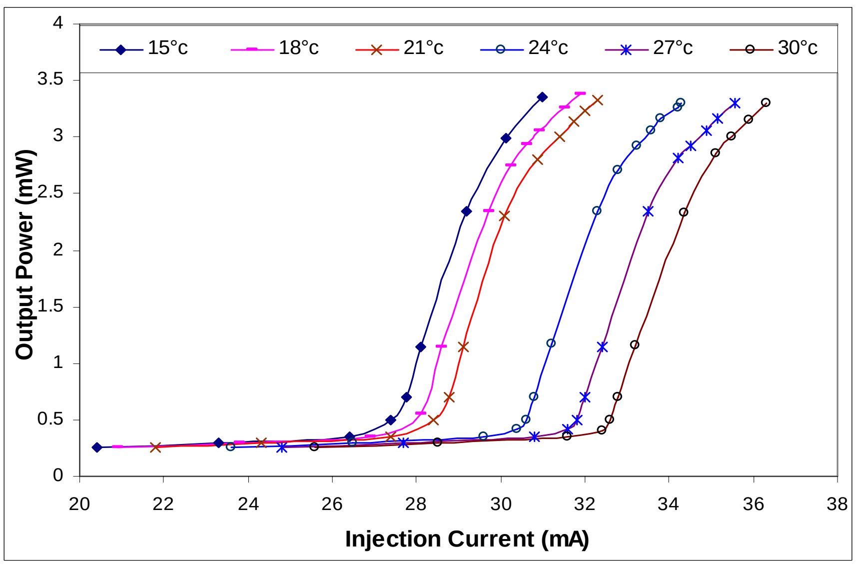


Fig. 5. Plots for injection current versus output power for diode laser (A) without and (B) with optical feedback at different temperatures.

The experiments were performed up to a maximum temperature of 30˚C keeping in mind the operating temperatures of optical communication systems. However, it will be interesting to carry out the experiments at much higher temperatures and with different types of semiconducting materials.

The observed increase in the threshold value and slope efficiency of the diode laser with the increase in temperature is well known resulting from the increase in optical losses. The effect of optical feeedback normally reduces the threshold value of the applied injection current to the diode laser due to the increase in optical density. Contrary to this we observed an actual increase in the value of the threshold at certain temperatures as a result of optical feedback. This ‘strange’ or anomalous behavior can be possibly explained as a combined effect of temperature and optical feedback. Increase in temperature results in red-shift of the oscillating frequency of the diode laser and hence mode-hopping. Not all modes respond in the same manner to optical feedback. Certain modes may destructively interact with the re-injected optical fields thereby suppressing the output optical power (amplitude decay). This will result in an increase in the threshold value.

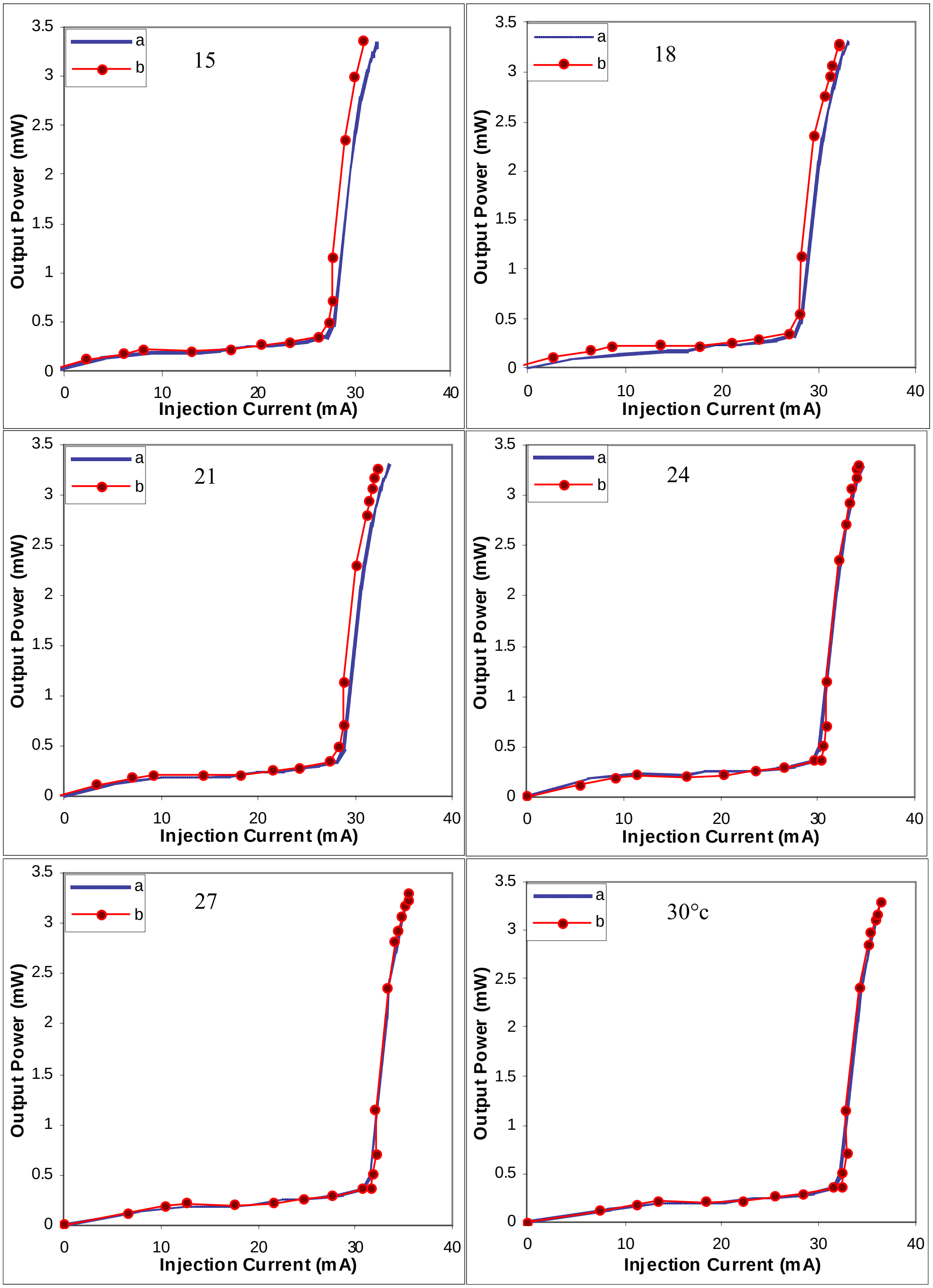


Fig. 6. Laser L-I characteristics (a) without and (b) with optical feedback at different temperatures.

CONCLUSION

In conclusion, we have experimentally analyzed the characteristics of the solitary diode laser and in presence of single optical feedback under the effect of temperature. The results obtained show dependence of the threshold current value on the temperature. With the increase in temperature the threshold is seen to increase while the output optical power gets reduced due to increase in the cavity losses. Below certain temperature (21˚C for our set up) the presence of the optical feedback is shown to reduce the threshold current and increase the slope efficiency relative to the solitary diode laser in this sense the threshold reduction is a good indicator of the feedback level. At higher temperatures, interestingly strange behavior is observed where the threshold current is seen to increase while the slope efficiency was only slightly affected by the optical feedback. This 'anomalous' behavior can be attributed to the combined effect of temperature and optical feedback on the oscillating mode resulting in its suppression due to destructive interference with the re-injection beam. With regard to temperature effect in this kind of systems these results are very helpful.

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