A COMPARATIVE STUDY OF THE TEMPERATURE DEPENDENCE OF LASING WAVELENGTH OF CONVENTIONAL EDGE EMITTING STRIPE LASER AND VERTICAL CAVITY SURFACE EMITTING LASER

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Abstract: Semiconductor lasers are the integral parts of optical communication systems. The temperature dependence of the lasing wavelength of a laser is an important issue because it is used in different environment with varying thermal conditions. In this paper, a comparative study of the temperature dependence of lasing wavelength of two types of laser diode has been presented. The comparison was made between an InGaAsP/InP stripe geometry edge-emitting laser and vertical cavity surface emitting laser (VCSEL) with GaAs in the active region. For both cases, the temperature dependence was observed for different heat sink temperatures ranging from 20ºC to 50ºC at an interval of 5ºC for an operating current of 0.763A and 1.88mA respectively. The lasing wavelength shifts for stripe laser and VCSEL have been found to be 0.3nm/K and 0.06nm/K respectively. VCSEL exhibits significantly greater thermal stability than stripe laser. The result has also been elucidated with a comprehensive theoretical excerpt.

1 INTRODUCTION

Modern optical communication systems for military or aerospace applications work in a wide range of temperature, typically from -30ºC to +50ºC (Jamieson, 1981). Therefore, the study of temperature dependence on laser operation is of prime importance as it is the most important part of the transmission end of optical communication system. Laser characteristics like lasing wavelength, threshold current density, conversion efficiency etc. are considerably affected by temperature. In this paper, we have studied the temperature dependence of the lasing wavelength of two types of laser, namely, the edge emitting stripe geometry gain guided laser and the Vertical Cavity Surface Emitting Laser (VCSEL). Figure 1 depicts the schematic diagram of a double-heterostructure InGaAsP stripe geometry edge emitting laser with gain guided structure that is considered in our study.

A simple sketch of a VCSEL is shown in Figure 2.

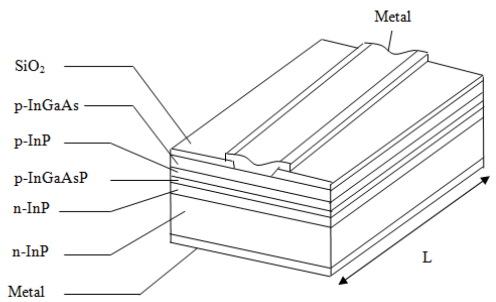

Figure 1: Schematic diagram of double-heterostructure InGaAsP stripe laser with gain guided structure.

For edge emitting stripe laser, the lasing wavelength is primarily determined by the peak-gain wavelength whereas for VCSEL lasing wavelength is fixed by the cavity wavelength (Kondow et al., 2000). However, this temperature dependence is predominantly influenced by two of the material properties: refractive index and the bandgap energy. Temperature dependence of refractive index and bandgap wavelength has been studied for GaAs and other materials in (Camassel et al., 1975- Tanguy, 1996).

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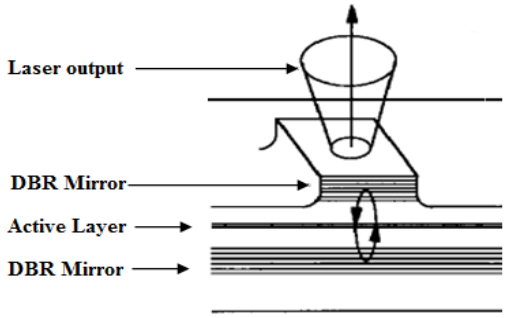

Figure 2: Schematic diagram of VCSEL (active layer contains GaAs and DBR mirrors contain $Al_{0.7}Ga_{0.3}As$ /GaAs quarter-wave Bragg stacks) (Jamieson, 1981) other materials in (Camassel et al., 1975- Tanguy, 1996).

The paper is organized as follows: in the subsequent section the temperature dependence of the lasing wavelength of laser has been explained elaborately and then the outcomes of our study has been presented with numerical findings.

2 EFFECT OF TEMPERATURE ON LASING WAVELENGTH

The lasing wavelength of a laser depends on several factors like chemical composition and doping of active region and external physical parameters, such as temperature, pressure, magnetic field etc. (Eliseev et al., 1994). In this paper, we have confined our study only to the temperature dependence of lasing wavelength. However, this temperature dependence of lasing wavelength varies for different types of laser diodes.

The well-known resonance condition for the cavity resonant wavelength, λ is given by (Keiser, 1991),

$$\lambda = \frac{2nL}{m} \tag{1}$$

where, 'n' is the spatially averaged refractive index, 'L' is the resonator length and 'm' is a positive integer.

In longitudinal multimode lasers like stripe laser, ridge-waveguide laser and buried heterostructure laser, the resonator is relatively long (typically, hundreds of times of λ which is in between few hundred micrometers and a few millimeters) and due to this long resonator length, lots of longitudinal modes satisfying the resonance condition overlap the active material gain bandwidth (Choquette and Hou, 1997, RP Photonics). Longitudinal mode spacing between two neighboring modes, $\Delta\lambda$ is given by (Keiser, 1991),

$$\Delta\lambda = \frac{\lambda^2}{2Ln_{gr}} \tag{2}$$

where, n_{gr} is the group refractive index. From Eq. 2, we observe that long resonator results in very smaller mode spacing between two consecutive resonant modes and hence very higher spectral density of the longitudinal modes. Now, differentiating Eq. 1 with respect to temperature, T and neglecting the thermal expansion of the resonator length, we obtain,

$$\frac{d\lambda}{dT} = \frac{\lambda}{n}.\frac{dn}{dT} \tag{3}$$

The temperature dependence of refractive index of the laser active medium $\left(\frac{dn}{dT}\right)$ can be approximated by (Numai, 2004),

$$\frac{dn}{dT} \approx (2 \sim 5)\times 10^{-4} \tag{4}$$

which implies that the refractive index has a positive gradient with respect to temperature. Consequently, we have from Eq. 3,

$$\frac{d\lambda}{dT} > 0 \tag{5}$$

Eq. 5 indicates that with the increase of temperature, the resonant modes shift to the right along the wavelength axis. Additionally, if we take the thermal expansion of the laser cavity into account, it also leads to the shift of resonant modes to longer wavelengths (Unger, 2000). On the other hand, temperature dependence of bandgap wavelength, $\lambda_g = \frac{hc}{W_g}$ (Precker, 2007) is given by,

$$\frac{d\lambda_g}{dT} = \frac{d}{dW_g}\left(\frac{hc}{W_g}\right) \tag{6}$$

where, h is the Planck's constant, c is the velocity of light and W_g is the bandgap-energy. Now, Eq. 6 can be written as,

$$\frac{d\lambda_g}{dT} = -\frac{hc}{W_g^{\,2}}.\frac{dW_g}{dT} \tag{7}$$

The increase in temperature yields in the shrinkage of the semiconductor material band gap which is given by Varshni's empirical equation (Varshni, 1967),

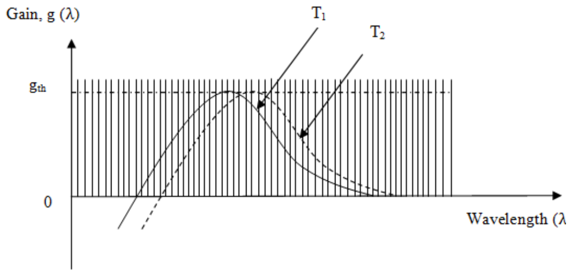

Figure 3: Schematic diagram of temperature dependence of material gain profile and resonant modes (g_{th} indicates threshold gain).

$$W_g(T) = W_g(0) - \frac{\alpha T^2}{T+\beta} \quad (8)$$

where, $W_g(0), \alpha, \beta$ are the fitting parameters. It is obvious from Eq. 8 that $\frac{dW_g}{dT} < 0$. This is equivalent to so called 'red-shift,' i.e. $\frac{d\lambda_g}{dT} > 0$ and this causes entire gain profile to shift to the right also. But the laser gain shift to larger wavelength $\left(\frac{d\lambda_g}{dT}\right)$ is faster (about a factor of 4 to 5) than the shift of the cavity resonant modes $\left(\frac{d\lambda}{dT}\right)$ (Choquette and Hou, 1997). So, for multimode lasers the temperature behavior of the lasing wavelength is mostly influenced by the temperature dependent drift of the gain spectrum of the active region (Blokhin et al., 2006). Due to this relative shift of modes and gain profile, larger wavelength modes move closer to peak-gain wavelength, as temperature increases. This temperature dependence of lasing wavelength for a multimode laser is illustrated in Figure 3. The figure shows the schematic diagram of temperature dependence of the material gain profile and the densely spaced resonant modes (vertical lines) of long Febry-Perot resonator. The solid gain profile is for temperature T_1 and the dashed gain profile is for temperature T_2, where $T_2>T_1$. As temperature increases from T_1 to T_2, higher wavelength (lower order) modes get closer to the peak-gain wavelength.

But for VCSEL, the resonator length is very small (only a few microns typically 1-3 µm). So from Eq. 2, the mode spacing between two consecutive resonant modes is large compared with that of long resonator multimode lasers. The mode spacing of VCSEL is approximately several orders of magnitude larger than that of a stripe laser.

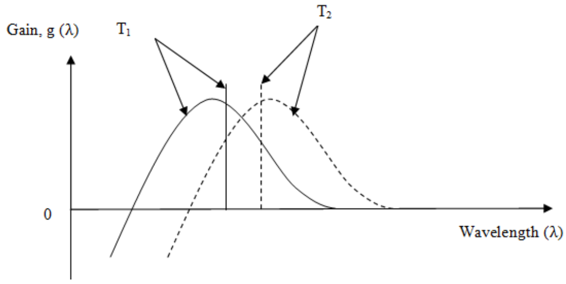

Figure 4: Schematic diagram of temperature dependence of material gain profile and resonant modes for a very short resonator.

Because of the fact that, the resonant modes are far away from each other, one single cavity resonant mode spectrally overlaps the gain medium bandwidth (Choquette and Hou,1997) allowing the VCSEL to be single mode laser. The spectral alignment between the resonant single optical mode and the gain profile mainly influence the temperature dependence of VCSEL lasing wavelength. Figure 4 shows the temperature dependence of lasing wavelength of VCSEL. As temperature increases from T_1 to T_2, both the gain profile and the resonant mode shift to a new position of longer wavelength as in the case for stripe laser. But still there is one mode in optical cavity because the other non overlapping resonant modes locate far away from the gain bandwidth and the new position of the resonant mode is now the lasing wavelength. Therefore, except for a detuned laser (where the overlap between the single resonant mode and the gain bandwidth is very weak), the wavelength shift of the lasing wavelength for VCSEL is determined mainly by the wavelength shift of the resonant single mode but not by the material gain profile as in the conventional edge emitting laser (Michalzik and Ebeling).

3 RESULTS AND DISCUSSION

This section presents the observed results of our study. As mentioned before, we have studied the temperature dependence of the lasing wavelength of stripe laser and VCSEL for an operating current of 0.763 A and 1.88 mA respectively. The outcomes of our study are visualized in Figure 5 and Figure 6. The figures show the observed lasing wavelength shift for different heat sink temperature for the stripe laser and VCSEL respectively. From Figure 5, we can calculate the lasing wavelength shift for the stripe laser by calculating the slope as,

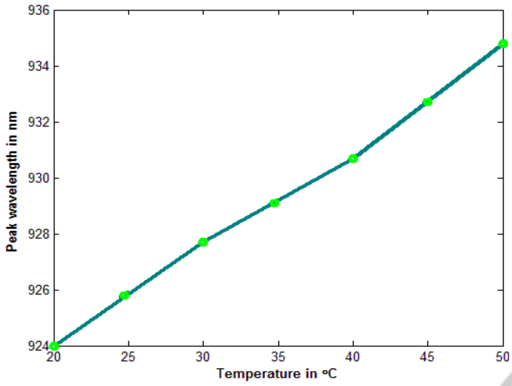

Figure 5: Temperature dependence of peak wavelength for the stripe laser at an operating current of 0.763 A.

$$\frac{d\lambda_p}{dT} = \frac{930.7nm - 927.7nm}{40^0C - 30^0C} = 0.3nm/^0C = 0.3nm/^0K$$

Similarly, the lasing wavelength shift for VCSEL is given by,

$$\frac{d\lambda_p}{dT} = \frac{856.0nm - 855.4nm}{40^0C - 30^0C} = 0.06nm/^0C = 0.06nm/^0K$$

Therefore, the lasing wavelength shift of stripe laser is significantly greater than that of the VCSEL. The smaller wavelength shift of VCSEL can be attributed to the fact that for VCSEL, the temperature dependence of lasing wavelength is primarily determined by the temperature dependence of refractive index of the laser active medium, whereas for stripe geometry edge-emitting multimode laser, the temperature dependence of lasing wavelength is dominated by the temperature dependent drift of the gain profile, which is the result of temperature dependence of bandgap wavelength.

4 CONCLUSIONS

As VCSEL is selective to one wavelength, the lasing wavelength is mainly influenced by the temperature dependence of only refractive index, but for longitudinal multimode lasers like stripe lasers, the lasing wavelength is dependent mostly on temperature dependence of gain profile. So, lasing wavelength is more prone to change for stripe lasers than for VCSEL. In this paper, we obtained the temperature dependent wavelength shift as 0.3 *nm /ºK* for InGaAsP/InP stripe laser and 0.06 *nm/ºK* for GaAs based VCSEL respectively. This temperature stable behavior of VCSEL spectrum has gone a long way to add another plus point to its other versatile advantages.

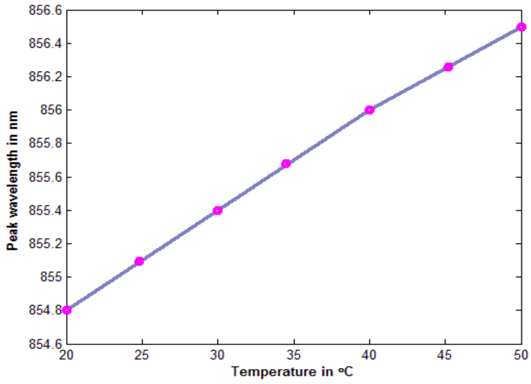

Figure 6: Temperature dependence of peak wavelength for VCSEL at an operating current of 1.88 mA.

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