Chapter 7

Design Aspects: High Power SLM Pulsed Dye Laser Development

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7.1 Introduction

Single longitudinal mode (SLM) dye laser, as the name suggests is a kind of laser in which oscillation of optical energy takes place at only one longitudinal (axial) mode of the laser cavity. SLM dye lasers are used to generate very narrow emission linewidth (typically $<$ 500 MHz). SLM dye laser are used in a variety of applications such as high resolution spectroscopy [96, 97], coherence spectroscopy [98], LIDAR [99], laser isotope separation (LIS) [96] etc. LIS is one of the important applications of narrow linewidth pulsed dye lasers. This application requires high average power with high pulse repetition rate (PRR) for efficient photo-ionization of the target isotope in the atomic vapor. Efficient SLM operation of dye lasers could be achieved because of high optical to optical conversion efficiency and homogeneously broadened gain bandwidth of the dye solution. There are several SLM dye laser cavity designs reported in the literature. Depending upon length of the laser cavity all the cavity designs can be broadly divided into two classes:

(i) Short cavity and

(ii) Long cavity [100].

If length of the cavity is < 10 cm, it is called a short cavity or else a long cavity. In the short cavity design, free spectral range (FSR) of the cavity is significantly larger than the gain bandwidth due to dispersive component grating. On the other hand, for long cavity design, cavity FSR is smaller than gain bandwidth due to grating but SLM operation is achieved by inserting highly dispersive etalon in the cavity which restricts laser oscillation only at single longitudinal mode. Short length cavity has advantage that it is simple to design and wavelength tuning is easy in comparison to long cavity but is has poor efficiency, higher sensitivity for wavelength fluctuations. Also, it is very difficult to achieve laser linewdith $\leq$ 300 MHz in short cavity design while it can be easily obtained with long cavity design. First step towards development of a SLM pulsed dye laser is to know the required specifications of dye laser such as- wavelength range, laser linewidth, pulse repetition rate (PRR), acceptable wavelength fluctuation, pulse duration etc. Present chapter briefly outlines some design considerations for a transversely pumped long cavity SLM dye laser (Fig. 7.1) with the help of examples from the lasers cavity developed at the laser facility in BTDG.

7.2 Description of SLM Dye Laser Oscillator

Here, a transversely pumped long cavity design has been chosen to discuss which is schematically shown in the Fig. 7.1. This oscillator is pumped with an optical fiber delivered green beam from copper vapor laser (CVL) master oscillator power amplifier (MOPA) chain operating at 6.25 kHz PRR. Fiber delivered CVL beam is first collimated using a custom designed lens assembly and then focused by a 50 mm focal length cylindrical lens to achieve the required pump beam size in the dye cell. The dye laser oscillator is consists of an output coupler (OC) with reflectivity ∼4%, a dye cell (cross-sectional area for flow channel: 10 mm x 0.3 mm), a dual prism beam expander (expansion factor: 40X), etalon (free spectral range

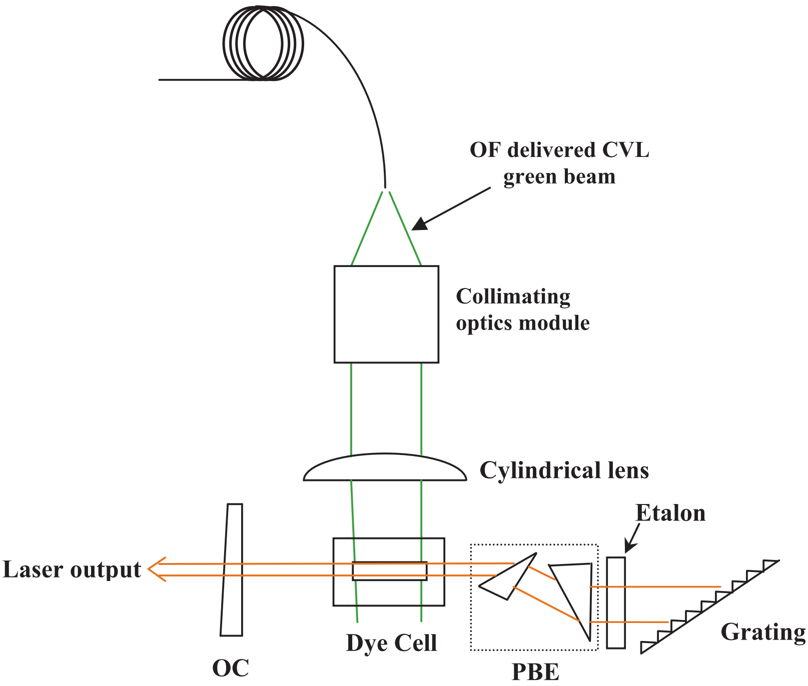

Figure 7.1: Schematic diagram of the developed SLM pulsed dye laser oscillator.

[FSR]: 17 GHz and finesse: 17) and a holographic plane grating in littrow configuration (groove density: 3000 gr/mm). There is a provision of course and fine tuning in grating and etalon. Coarse tuning is achieved by stepper motors while fine tuning is achieved by piezo-electric transducers (PZT). In this oscillator output coupler has been mounted on a linear micro-meter drive to control laser cavity length. In addition, a PZT has been also attached to the output coupler mount for fine tuning of the laser cavity length. The PZT along with the electronic servo control is used to stabilize the wavelength of the output laser beam. All these components have been mounted on a type 304 stainless steel base plate.

7.3 Principle of SLM Operation

Any resonator can support laser oscillation only at certain discrete frequencies depending upon its effective length. These discrete frequencies are called longitudinal (axial) modes. When there is a dispersive element in the laser cavity it restricts the number of longitudinal modes on which laser oscillations can take place. The number of longitudinal modes in laser oscillation depends upon the dispersive power of the dispersive element and gain in the active medium. In the present oscillator design a combination of grating and etalon have been used to achieve SLM operation. Dispersive power of the grating is chosen such that laser linewidth due grating is < FSR of the intra-cavity etalon. This condition suppresses laser oscillation for multiple orders of the etalon. Bandpass of the intra-cavity etalon is chosen such that it allows lasers oscillation corresponding to single longitudinal mode of the laser cavity. Schematic representation of the cavity modes, laser linewidth due to grating (3000 gr/mm) in littrow configuration and etalon passband are shown in Fig. 7.2 for illustration purpose.

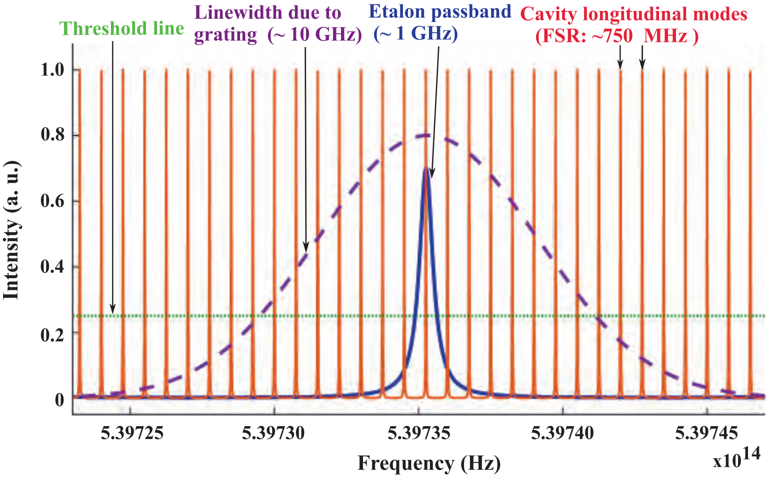

Figure 7.2: Schematic representation of the cavity modes, laser linewidth due to grating (3000 gr/mm in littrow configuration and etalon passband [Effective cavity length ~20 cm].

7.4 Design Aspects

7.4.1 Dye solution and its flow related

Optimization of dye concentration

In a dye laser with organic dye solution as active medium, concentration of dye molecules (C) in the dye solution greatly affects performance of the dye laser oscillator. At any given pump power, efficiency of dye laser increases with increasing dye concentration but one cannot increase dye concentration arbitrarily. Increase in dye concentration leads to increase in probability of dimer formation and decrease in penetration depth of the pump beam. The decrease in pump penetration depth results in poor beam quality (high beam divergence, larger laser linewidth & poor spatial homogeneity) and increased probability of dye cell damage. On the other hand lowering of dye concentration results in poor dye laser efficiency and higher amplified spontaneous emission (ASE) content in the laser beam due to increased in laser build-up time. Therefore, optimization of dye concentration is needed to trade-off between laser efficiency and size of the laser beam along pump beam propagation direction. Typical variations of the pump photon flux with depth in the dye solution for different concentrations of Rh6G molecules in dye solution taking into account saturation effect are shown in Fig. 7.3.

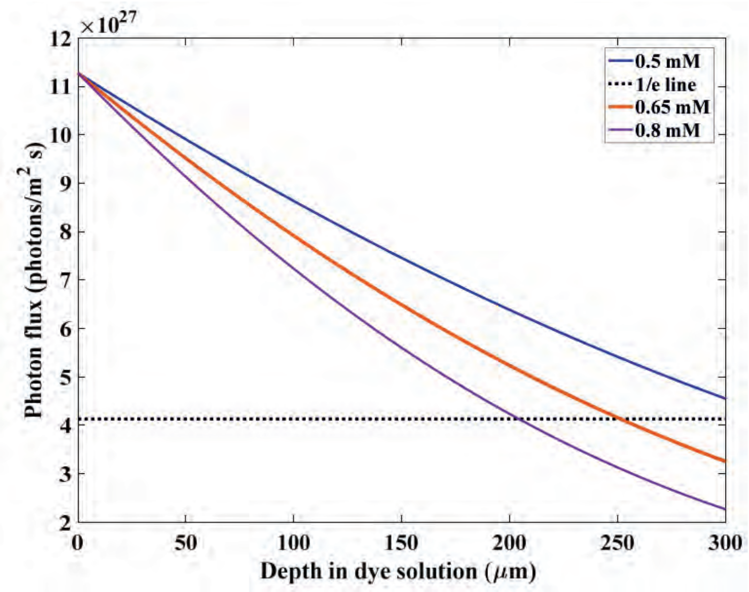

Figure 7.3: Variation of photon flux along depth direction in dye solution of different concentrations.

7.4.2 Choice of dye cell channel width and dye flow speed

Following two points are taken in to consideration for selecting dye cell channel width- Dye cell width should be kept slightly larger than the pump beam penetration depth so that pump beam does not get absorbed inside dye solution unnecessarily. Pump beam absorption beyond penetration depth just causes degradation of the dye molecules without taking part in lasing and increase in ASE (amplified spontaneous emission). Flow fluctuations of dye solution results in wavelength fluctuation of the output dye laser. Fluctuations in dye solution flow increases with Reynolds number (R_e) which is given by [101]:

$$R_e = \frac{v\ w}{\eta} \tag{7.1}$$

Here, v, w and η are flow velocity of the dye solution, hydraulic diameter of the dye cell channel and kinematic viscosity of the solution, respectively. Hydraulic diameter of a dye cell channel with length and width equal to l and d, respectively is given as [101]:

$$w = \frac{2\ l\ d}{(l + d)} \tag{7.2}$$

This indicates that R_e number depends upon flow velocity, channel cross-sectional area and kinematic viscosity of the dye solution. For a given dye laser system channel length is determined by optimum gain length, kinematic viscosity of the dye solution depends upon the solvent. Also, minimum flow velocity of the dye solution is limited by the pulse repetition rate and pump beam focusing height. Therefore, dye flow fluctuations can be reduced by reducing channel width. In addition to the dye cell channel width its shape also needs to optimized for minimizing flow fluctuations and required capacity of the circulating pump.

7.4.3 Suitable dye solvent

Solvent for dye solution needs to possess certain properties such as high solubility for laser dye, high photo-thermal stability of dye molecules in the solution, high thermal diffusivity (D) and low thermal coefficient for refractive index (dn/dT) etc. SLM operation of dye laser puts stringent demand for D and dn/dT because wavelength is very sensitive to thermal instability of dye solution. Water has excellent thermal and thermo-optic properties as solvent. Therefore, water is supposed to be an ideal solvent provided laser dye of use gets dissolved, retains sufficiently high photo-chemical stability and gain in the water. If dye does not dissolve purely in the water, binary solvent (water + some other organic solvent) maybe used to minimize effects of thermal instability.

7.4.4 Selection of output coupler (OC)

For any given configuration of dye laser oscillator, depending upon total losses and gain per round trip in cavity there is an optimum value of output coupler reflectivity (inner surface of OC). Since dye laser is a high gain laser system, apart from optimizing surface reflectivity of inner surface of OC care must be taken to avoid reflection from other surface of the OC to avoid formation of stray cavity. Also, reflectivity of the outer surface of OC should be as low as possible to minimize reflective losses of the laser beam from this surface.

7.4.5 Prism beam expander (PBE)

It is known that expansion of a beam reduces its divergence. Therefore, using an intra-cavity PBE causes narrowing of laser linewidth due to grating. Use of PBE offers numerous advantages such low cost, compact size, easy alignment over telescopic beam expander. Particularly in the case of SLM dye lasers PBE is extremely useful to reduce cavity length which leads to increase in cavity FSR. Larger free spectral range for cavity longitudinal modes helps in SLM operation of a dye laser. In addition, use of PBE improves performance of intra-cavity etalon too. Magnification required in a dye laser cavity for achieving SLM operation depends upon initial size of the beam, groove density of the grating and FSR of the intra-cavity etalon. In designing a prism beam expander following considerations are involved –

- Required expansion factor;
- Prism material properties;
- Acceptable size of prism beam expander assembly along cavity length direction;
- Transmission loss of the expander.

Angle of incidence on second surface of the prism should be sufficient to avoid reflection from this surface to enter in the gain region. Otherwise, the reflected part of the beam may either form a stray cavity or extract gain which will be wasted. Schematic diagram illustrating magnification of beam due to prism is shown in Fig. 7.4. Magnification factor (M) and total transmission of PBE (p-polarized light) as a function of angle of incidence, angle inside prism with surface normal and exit angle are given as [80]:

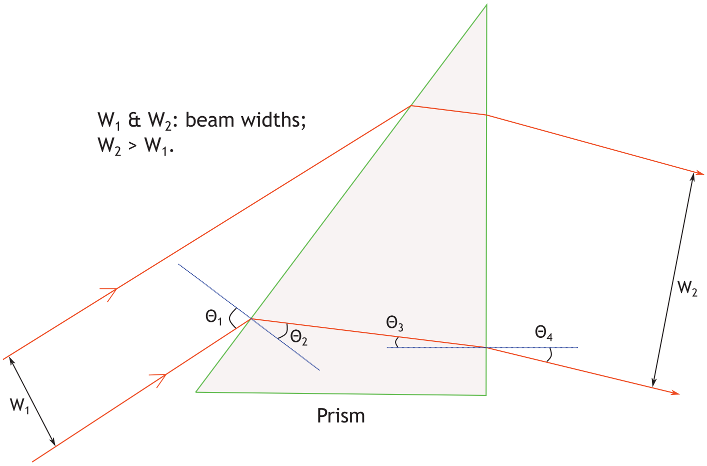

Figure 7.4: Schematic diagram illustrating laser beam expansion by a prism.

$$M = \frac{W_2}{W_1} = \frac{cos(\theta_2).cos(\theta_4)}{cos(\theta_1).cos(\theta_3)} \tag{7.3}$$

$$T = \left(1 - \frac{tan^2(\theta_1 - \theta_2)}{tan^2(\theta_1 + \theta_2)}\right) * \left(\frac{4n.cos(\theta_4).cos(\theta_3)}{[ncos(\theta_4) + cos(\theta_2)]^2}\right) \tag{7.4}$$

Here, n is refractive index of the prism material. Surrounding of prism is considered as air. Typical variations of the magnification factor and transmission from a single prism as a function of angle of incidence on first surface is plotted in Fig. 7.5. This figure clearly indicates that SF11 based PBE has higher transmittance for identical M.

7.4.6 Choosing an appropriate grating

For selecting a suitable grating to use in the SLM dye laser oscillator following points need to be considered: Wavelength range for use- it determines upper limit on the groove density. Decide mode of use (angle of incidence on grating) i.e. whether to use in Littrow or grazing incidence configuration. Grating should have sufficient angular dispersion so that laser linewidth without etalon to be much lower than the FSR of the intra-cavity etalon. Plane of polarization of the beam-grating efficiency significantly changes with plane of polarization of the incident beam. Hence, knowledge about plane of polarization of the beam incident on grating is important. Grating efficiency should be as high as possible in the working wavelength range. Grating length should be sufficient enough to handle expected beam size on

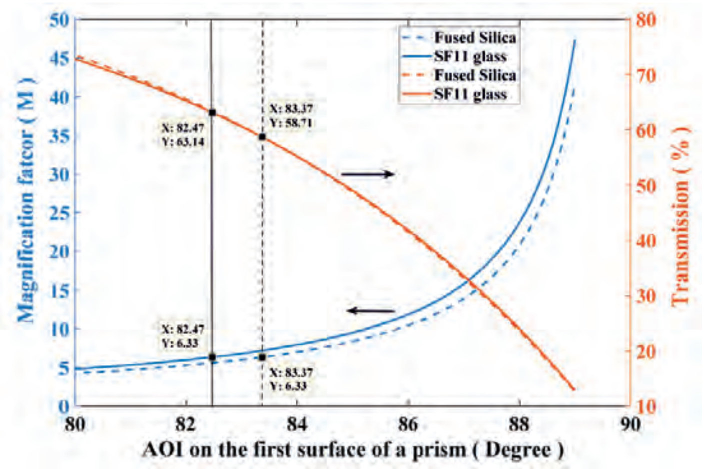

Figure 7.5: Variation of magnification factor and transmission with angle of incidence at prism first surface (p-polarized beam@ 581 nm). Exit angle at prism second surface ~5°.

it. As long as dye laser oscillator configuration is decided, mode of using the grating is also fixed. In this case grating is positioned in littrow configuration. The aim of this SLM laser development was to generate wavelength in the range 550-610 nm. This wavelength range puts a restriction on upper limit on grating groove density to be 3000 gr/mm. Lower limit on grating's groove density comes from required laser linewidth in the absence of etalon which is limited by FSR of intra-cavity etalon. In selecting grating it was considered that initial horizontal beam size in the dye size may vary in the range 200-300 μm depending upon dye concentration and intra-cavity etalon FSR will be in the range 15-17 GHz. Therefore, variations of lasers linewidth due to presence of only grating was calculated for different grating groove densities (Fig. 7.6) in the wavelength range of 550-610 nm for 250 μm initial beam size. Fig. 7.6 clearly reveals that for the initial beam size of 250 μm and etalon FSR (17 GHz), grating with 3000 gr/mm is the only choice for using in first order for SLM operation.

7.4.7 Etalon selection and tilt effects

For selecting etalon for SLM operation one has to consider following important considerations– FSR of the etalon should be reasonably higher than the achievable linewidth of laser due to grating to avoid laser oscillations at multiple etalon orders. Finesse of the intra-cavity etalon should be such that its bandpass is comparable to or smaller than dye laser cavity FSR. Choosing too small bandpass causes high transmission loss of the etalon resulting in reduced efficiency of the laser. Transmission should be as high as possible in the wavelength range of interest. Material of the etalon: etalon material to be judiciously chosen considering, expected size of the etalon, cost, misalignment issues and thermal effects. The FSR of an etalon depends upon refractive index of material and thickness of etalon. FSR of an etalon is given by the relation:

$$FSR = \frac{c}{2\ n\ l} \tag{7.5}$$

Here, c, n and l are speed of light, refractive index and thickness of etalon, respectively. One cannot choose arbitrarily high etalon FSR because increasing FSR leads to increase in passband width (PBW) for a given finesse of the etalon. Relation between passband width, FSR and finesse of the etalon is:

$$PBW = \frac{FSR}{F} \tag{7.6}$$

Also, finesse of the etalon cannot be chosen very high for reducing PBW because for attaining high finesse requires high surface reflectivity or high surface finish. Increasing surface reflectivity results in decrease in transmission through etalon and improving surface finish causes increase in cost of the etalon. Therefore, choices for finesse and FSR of the etalon have been made judiciously. For a given value of etalon FSR, minimum required finesse is decided by two factors namely- (i) frequency separation between longitudinal modes of the cavity (cavity FSR) (ii) Desired laser linewidth. Another important consideration is position of etalon in the cavity. Etalon should be positioned at the location where beam size is the maximum i.e. in expanded beam because for small size of the beam effective finesse is less due to higher divergence of the beam and beam walk-off problem is more pronounced. In addition, etalon should be kept as close to normal as possible after taking into account that its reflection does not coincide with gain volume because effective PBW of the etalon increases and transmittance decreases with increasing AOI of the laser beam on etalon surface [102]. Another important reason to keep etalon finesse as low as acceptable is that insertion of etalon in the laser cavity increases effective cavity length depending upon etalon thickness, refractive index and finesse.

7.4.8 Laser cavity length

Laser cavity should be kept as small as possible because decrease in cavity length results in increased cavity FSR, as per Eq. (7.5). Larger cavity FSR facilitates in achieving and maintaining single mode laser operation. A typical variation of cavity FSR with its length is shown in the Fig. 7.7.

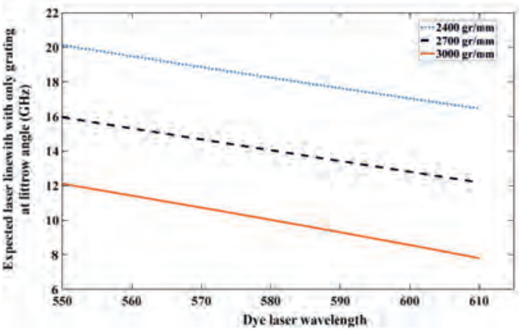

Figure 7.6: Variation of laser linewidth with laser wavelength due to gratings.

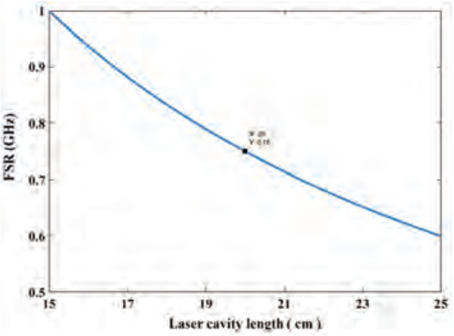

Figure 7.7: Variation of cavity FSR with length.

7.4.9 Effects of thermal and mechanical instabilities

Thermal and mechanical instability of different components of the laser cavity causes wavelength fluctuations due to variation in the effective cavity length. To minimize effects of mechanical instability on laser wavelength fluctuation, laser cavity is installed on a vibration isolated optical table and all the components are tightened properly. Effects of thermal instability is minimized by stabilizing temperature of the laser cavity components and using materials with low thermal expansion coefficient. Variation of laser wavelength with temperature is give as [103]:

$$\frac{d\lambda}{dT} = \frac{\lambda}{L}[(l_a \frac{dn_a}{dT}) + (l_d \frac{dn_d}{dT}) + (l_p \frac{dn_p}{dT}) + (l_e \frac{dn_e}{dT})] + (\frac{\lambda}{l} \frac{dl}{dT}) \tag{7.7}$$

In the above Eq. (7.7) 1st, 2nd, 3rd and 4th terms in the right hand side are contributions due to changes in refractive indices of air in the cavity, dye solution, prism beam expander (PBE) and etalon, respectively while 5th term is due to change in cavity length due expansion of base plate material. Here, $\lambda, L, l_a, l_d, l_p, l_e, \&\ l$ are wavelength of the laser, optical cavity length, thickness of air gap in cavity, dye gain length, thickness of PBE, thickness of etalon and physical cavity length, respectively; n stands for refractive index while subscripts *a, d, p* and *e* correspond to air, dye solution, PBE and etalon respectively.

7.4.10 Role of pump beam pointing instability

Pump beam pointing instability causes instability in the laser wavelength as well as laser power. Therefore, pump beam instability should be as small as possible. To improve beam pointing stability, the pump beam has been delivered by a fiber-optic cable.

7.4.11 Significance of pump pulse duration

It is known that increasing number of passes through the intra-cavity etalon causes reduction in laser linewidth. Number of passes of laser beam through etalon increases with increasing pulse duration, increasing gain and decreasing cavity length. Hence, laser linewidth can be decreased by stretching pump beam pulse duration.

7.4.12 Effect of air turbulence

Pressure fluctuations of the intra-cavity air causes fluctuations in refractive index of the air leading to fluctuations in the effective cavity length. Therefore, air turbulence near SLM cavity can lead to laser wavelength instability. Therefore, arrangement should be made mitigate effects of air turbulence (proper shielding or avoid direct air flow on the SLM cavity) to improve wavelength stability. Change in laser wavelength due to change in pressure is given by

$$\frac{d\lambda}{dP} = \frac{\lambda}{L}(l_a \frac{dn_a}{dP}) \tag{7.8}$$

Here, λ, L, l_a, n_a and P are wavelength of the laser, effective cavity length, length of the air gap in cavity, refractive index of air, and pressure respectively.