CHAPTER 4

EFFECT OF TEMPERATURE ON THE DISPERSION PROPERTIES OF AN INSB-FILLED PCF

In this chapter, the effect of temperature on the dispersion properties of a hexagonal lattice photonic crystal fiber (PCF) is studied. The cladding holes of the PCF are filled with a semi-conductor material, InSb which has temperature dependence in the terahertz optical frequency. The effective index of PCF is calculated with the help of a semi-vectorial finite difference technique. Using the effective index values, computation of chromatic dispersion parameters is done, which are plotted against wavelength. Four temperatures have been considered in our work from 290 to 335 *K* in equal steps. The results show that as the temperature is increased the value of effective index of PCF decreases but dispersion increases.

4.1 GENERAL

A lot of research has been carried out on photonic crystal fibers (PCF) since they were first proposed prominently by P. Russell in the year 2003. The unique structure of PCF containing air hole arrangement in cladding distinguishes it from the conventional types of single mode and multi-mode optical fibers [127]. In long distance optical communications, PCFs can be employed as dispersion compensators to minimize the dispersion generated in single mode fibers [128]. They can also provide flattened dispersion over a particular range of wavelength. Along with the dispersion compensating application, PCFs have also the ability to show other characteristics like non-linearity control, high birefringence, large mode-area etc. The simulation of a PCF can be carried out by a number of methods such as finite element method (FEM), multi pole method (MPM), finite difference time domain (FDTD), plane wave expansion (PWE), and beam propagation method (BPM). Out of all these methods FDTD is the most advanced and simple to implement technique. It is also faster than FEM, which in turn is more widely used as it is more powerful to solve complex problems.

In this work, we have studied a unique aspect in context of PCF, which is the influence of surrounding temperature on its dispersion characteristics. Indium antimonide (InSb) has been filled into the cladding holes of PCF whose dielectric constant is a function of temperature [129]. The dielectric constant of core and that of cladding background material viz. Silica (Corning 7980) also has a shift with temperature [130]. D. B. Leviton and B. J. Frey in their work calculated refractive index of fused silica for the temperature range 30-300 Kelvin. Using the formula given in their work, it is feasible to calculate refractive index of silica at any temperature. Figure 4.1 shows plots of the refractive index of fused silica against wavelength at different temperatures. Due to high index of InSb and its refractive index contrast with Silica, there is a considerable shift in the output dispersion of PCF with small change in temperature. While going from low to high temperature, there takes place thermal expansion of InSb as well as Silica [131]. W. Souder and P. Hidnert [132] in their work took 17 samples of fused silica to measure their thermal expansion coefficients. A total of 48 expansion tests were performed on the 17 samples. Also, they compared their results with the results of similar work done, previously.

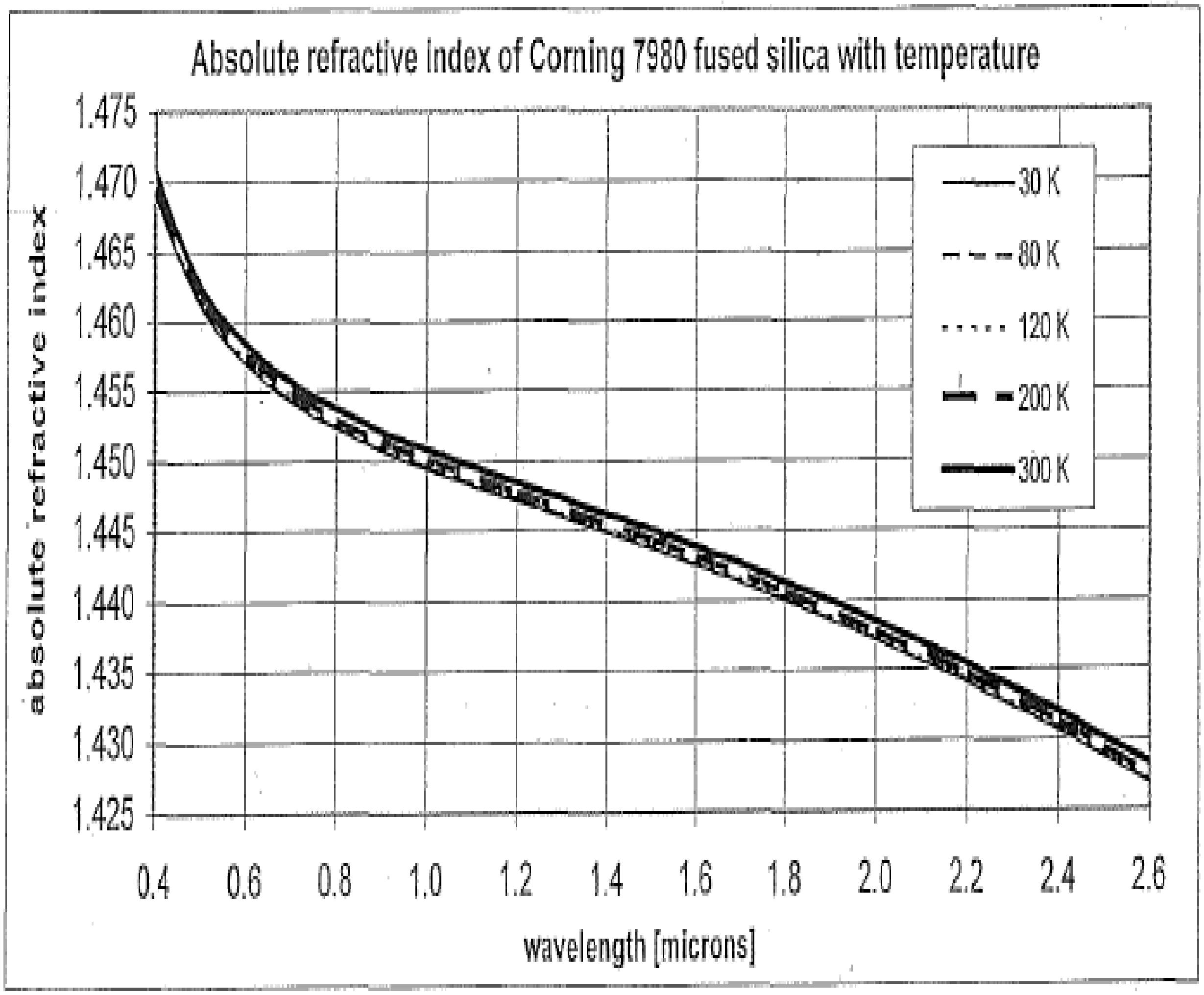


Figure 4.1 Measured absolute refractive index, n, of Corning 7980 fused silica at selected wavelengths and temperatures.

Figure 4.2 shows equipment used by them in the investigations related to thermal expansion.

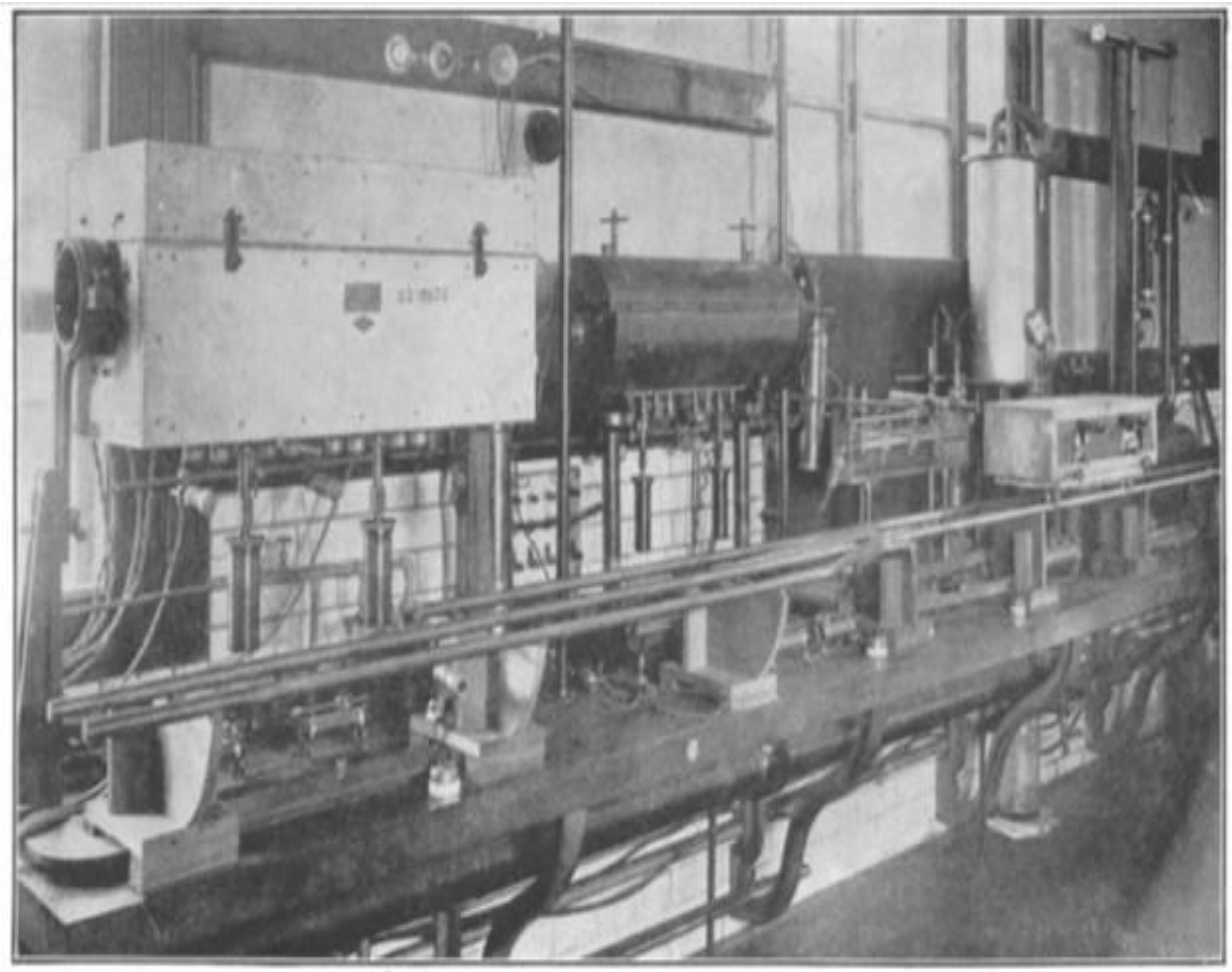


Figure 4.2 Expansivity furnaces, standard bar and comparator.

The results obtained compared with the previous works have been plotted in Figure 4.3.

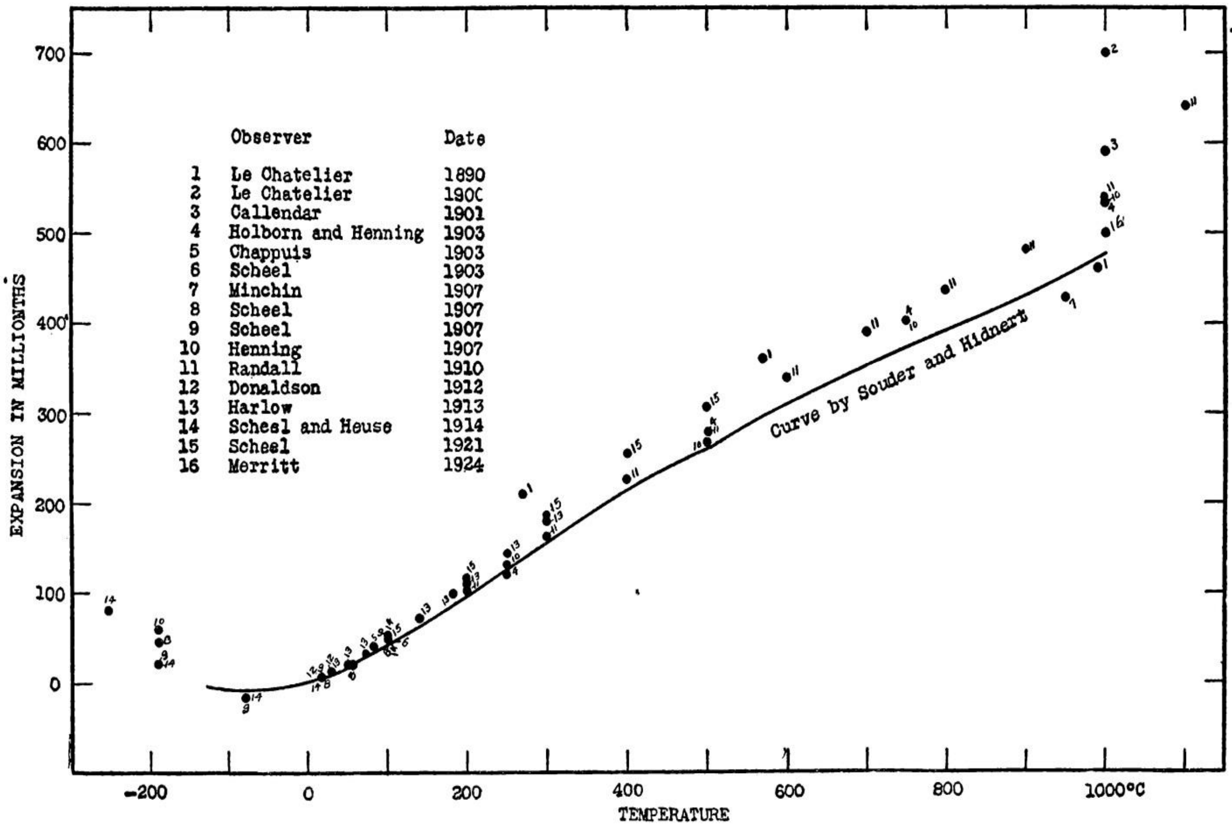


Figure 4.3 Comparison of the average expansion curve obtained in the present investigation on fused silica, with data from previous observers.

We have taken into account the refractive index change due to temperature and wavelength both of InSb and Silica in our calculations. In addition to, the physical expansion of both the core and cladding materials (InSb plus Silica) has also been considered to find out the output dispersion charactersitics of PCF.

In the areas where temperature is not constant and it varies from one point to another, this type of PCF can be applied to compensate multiple values of dispersion. It can be employed with different optical communication links according to the value of dispersion compensation required. Also, this type of PCF when utilized in harsh environments can provide flattened dispersion at the abnormal surrounding temperature without the use of any special equipment. Calculation of dispersion is done for four temperatures ranging from 290-335 *K* in equal steps, in our work. Two values of diameter to pitch ratio (d/Λ) viz. 0.4 and 0.8 have been considered of the PCF for computation of the dispersion values. In this work, normalized frequency (V_{eff}) also has been calculated of the PCF at different temperatures. V_{eff} is a measure of the number of modes that can travel through a PCF at a given point of time. We have found out that there is absolutely no change in the mode carrying capacity of the PCF with respect to temperature.

4.2 THEORETICAL METHOD

We have employed a finite difference based semi-vectorial technique to solve a hexagonal PCF for effective index values. To start with, a semi-vectorial wave equation is taken of the form, as given below:

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_r}\frac{\partial \varepsilon_r}{\partial x} E_x\right) + \frac{\partial^2 E_x}{\partial y^2} + (k_0^2\varepsilon_r - \beta^2)E_x = 0 \qquad (4.1)$$

Here, k_0 and β represent wave number and propagation constant respectively for the input wave whereas ε_r is the relative permittivity of the material inserted into the cladding holes of PCF. This equation is for a quasi TE mode where the E_y component of the electric field is supposed to be zero. The area of the cross-section of PCF is transformed into a hypothetical mesh containing a large number of small divisions connected by nodes. An Eigen-value matrix equation is generated by solving the TE-mode expression for each node using finite difference technique, as shown below:

$$[A_{i,j}]\{\emptyset\} = \beta^2\{\emptyset\} \qquad (4.2)$$

In the above equation, $A_{i,j}$ represents a Hermitian operator and the values of β provide the values of n_{eff} using the relation $n_{eff} = \beta / k_0$. The permittivity of InSb at different wavelengths is calculated with the help of a Drude model [133]. The damping constant present in the Drude model has been neglected by us to simplify calculations and emphasize the effect of change in temperature on the permittivity of InSb. Temperature (T) ranging from 290-335 *K*, in equal steps of 15 *K* is put in the below relation obtained from [135], one by one to find intrinsic carrier density N:

$$N=5.76 \times 10^{14}\, T^{3/2} \exp(-0.13/k_b T) \tag{4.3}$$

The values of N are then substituted into the plasma frequency parameter (ω_p) of the Drude model to evaluate permittivity (ε) of InSb for specific values of temperature. Thus the refractive index (n_s) of InSb can be calculated by taking square root of its permittivity. The refractive index values of InSb and Silica, computed at various temperatures and wavelengths are then utilized to find effective index values of PCF using Equations 4.1 and 4.2. To include the thermal expansion of InSb and Silica, pitch (Λ) and diameter (d) of air holes both, of the PCF have been adjusted accordingly for each computation. Finally, the dispersion parameter (D) of PCF is calculated with the help of following identity:

$$D= - \frac{\lambda}{c} \frac{\partial^2 (\mathrm{Re}[n_{eff}])}{\partial \lambda^2} \tag{4.4}$$

Here, D stands for the chromatic dispersion, a sum of material and waveguide dispersion.

The parameter c is the speed of light in vacuum, λ is the wavelength of the field transmitting in the fiber and $Re(n_{eff})$, the real component of effective index values.

Another important parameter related to PCF that has been calculated in this paper is the normalized frequency (V_{eff}). Through the values of V_{eff}, number of modes that propagate inside a fiber can be determined. The relation for finding out the values of V_{eff} is as given below:

$$V_{eff} = \frac{2\pi}{\lambda}\Lambda\,(n_{co}^2 - n_{eff}^2)^{1/2} \tag{4.5}$$

In the above equation, n_{co} designates the core refractive index of PCF while pitch (Λ) is a measure of the distance between the centers of two consecutive air holes present in the cladding region.

4.3 NUMERICAL ANALYSIS AND RESULTS

We have designed a hexagonal PCF containing 5 rings of air holes in the cladding region, as shown in the Figure 4.4. The diameter of each air hole in the cladding is taken to be 0.9 µm whereas the distance between centers of two consecutive air holes, known as pitch (Λ) is 2.25 µm. The background material is taken to be Silica whose refractive index is computed for the temperature range 290-335 *K* at each of the wavelengths in the 1.0-2.0 µm span. Similarly for the material filled into cladding holes viz. InSb, refractive index values have been evaluated in the said temperature and wavelength range. The combination of InSb and Silica into the making of PCF provides a significant refractive index contrast to the fiber structure, which in turn makes the PCF suitable for dispersion applications. The major shift in dispersion w.r.t. temperature has been provided by InSb as it has higher refractive index, causing the effective index or thus dispersion of PCF to vary substantially. The PCF is subjected to four temperatures i.e. 290, 305, 320 and 335 *K*, effective index computation is done at these temperatures for the wavelength range 1.0-2.0 µm. Figure 4.5 (a) and (b) show the plots of effective index of hexagonal PCF against wavelength at the four temperatures, for d/Λ= 0.4 and 0.8 respectively. It can be seen that the value of effective index of PCF rises with decrease in temperature for each value of d/Λ. The value of n_{eff} for d/Λ=0.4, λ=2.0 µm and temperature =335 *K* is 3.52 and the value of n_{eff} for d/Λ=0.8 at the same parameters is 3.74.

Figure 4.6 (a) and (b) show dispersion plotted against wavelength at different temperatures, for d/Λ=0.4 and 0.8 respectively. As we can see from the figures, that the value of dispersion increases with increase in the temperature. The dispersion graph is more flattened at the lower temperature compared to higher one. With increase in the d/Λ ratio from 0.4 to 0.8 the dispersion graphs move down on the positive axis and the difference between them increases. There is a difference of 91 ps/nm-km dispersion between the points corresponding to temperature 290 and 335 K for d/Λ=0.4 at data communication wavelength 1.55 μm. This gives us the average increase in the value of dispersion per degree Kelvin rise in temperature as nearly 2 ps/nm-km. The average increase in dispersion in case of d/Λ=0.8 comes out to be 1.68 per degree rise in Kelvin, at λ=1.55 µm.

Finally, we have calculated and plotted the values of normalized frequency V_{eff} against wavelength. Figure 4.7 shows the graphs of V_{eff} for all the temperatures considered corresponding to d/Λ=0.4 and 0.8. It can be seen that there is no change in the values of V_{eff} with respect to temperature but when the ratio d/Λ of the PCF is increased from 0.4 to 0.8, the values of V_{eff} shift downwards.

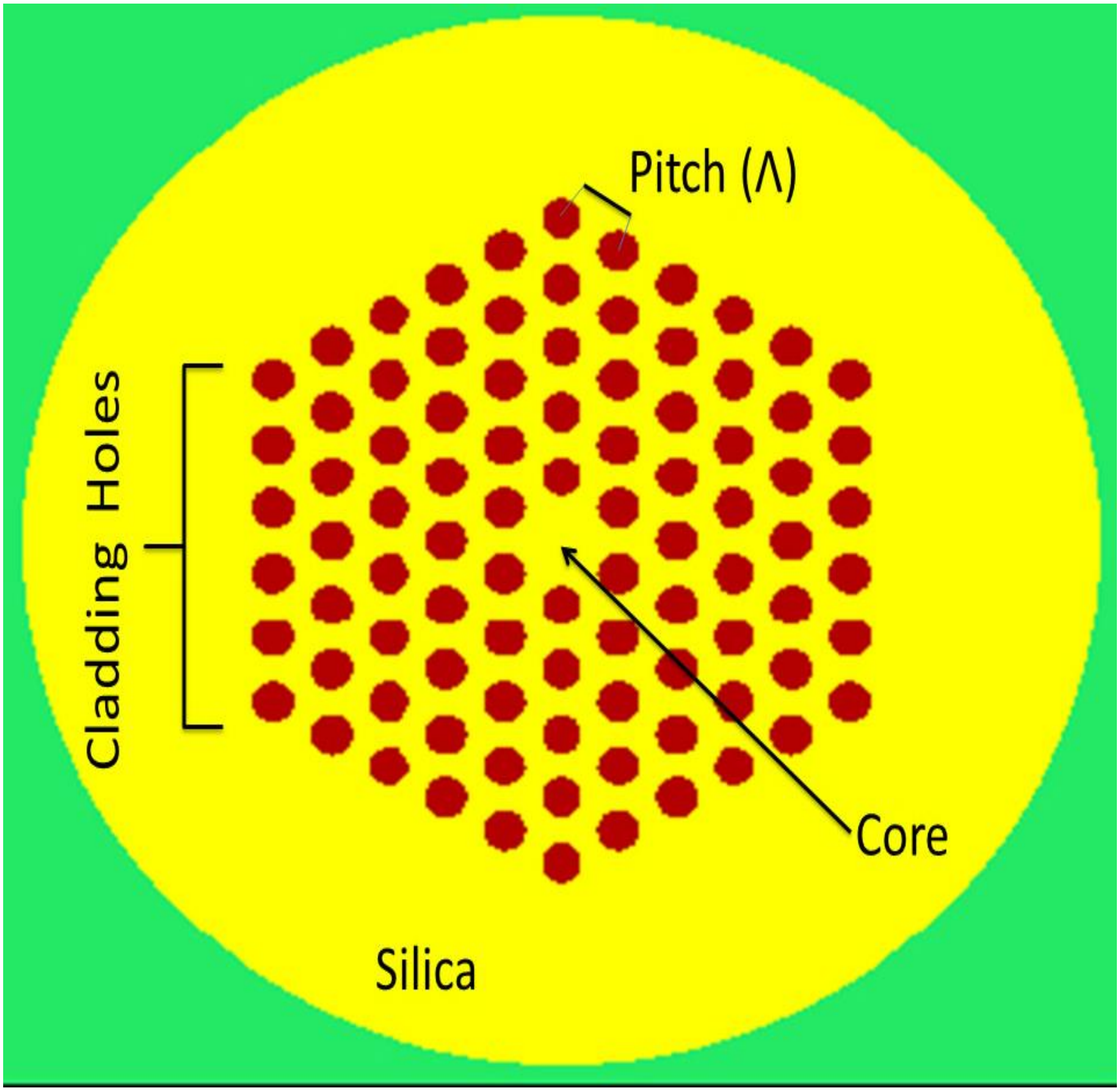


Figure 4.4 Cross-section of the Hexagonal photonic crystal fiber.

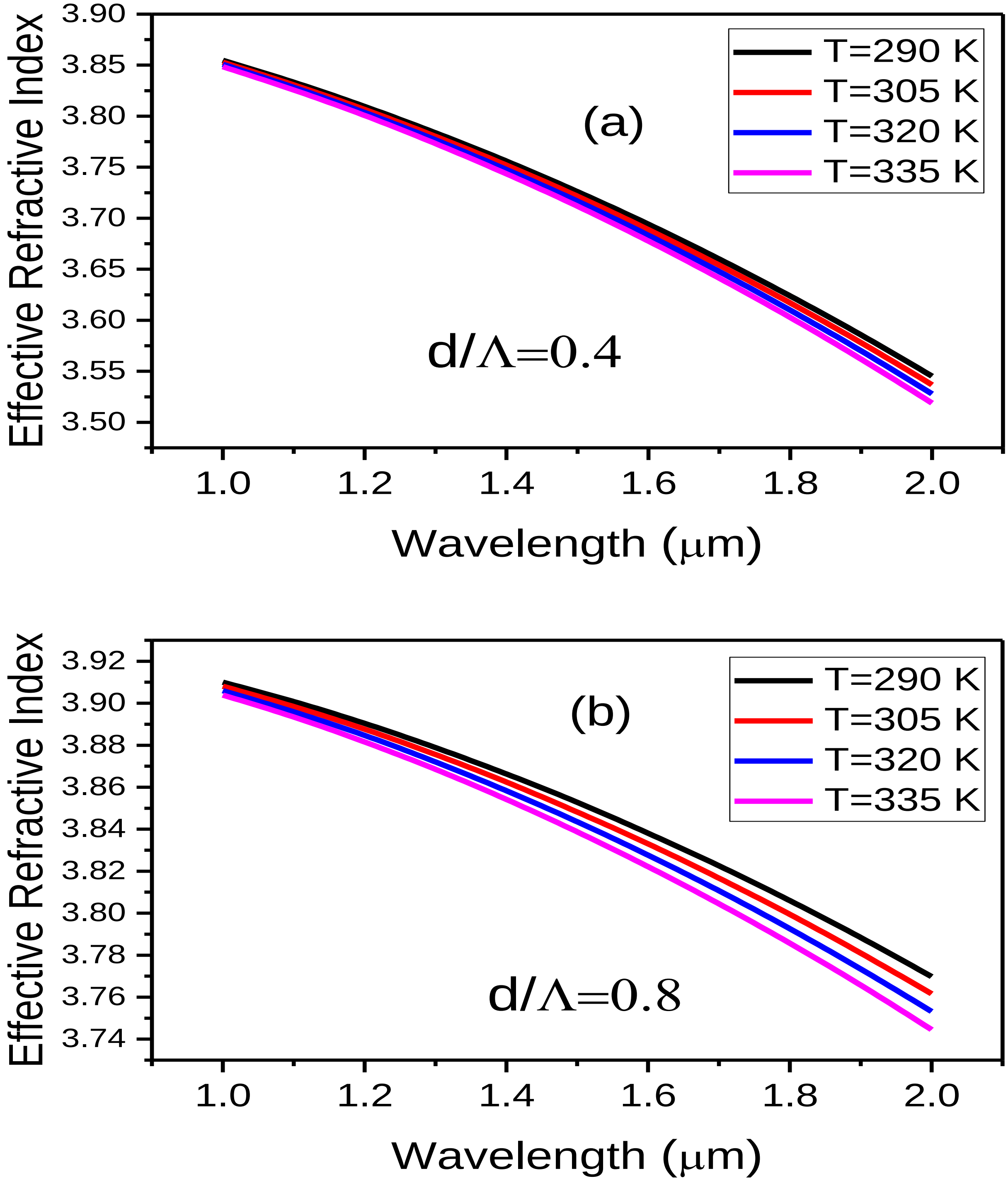
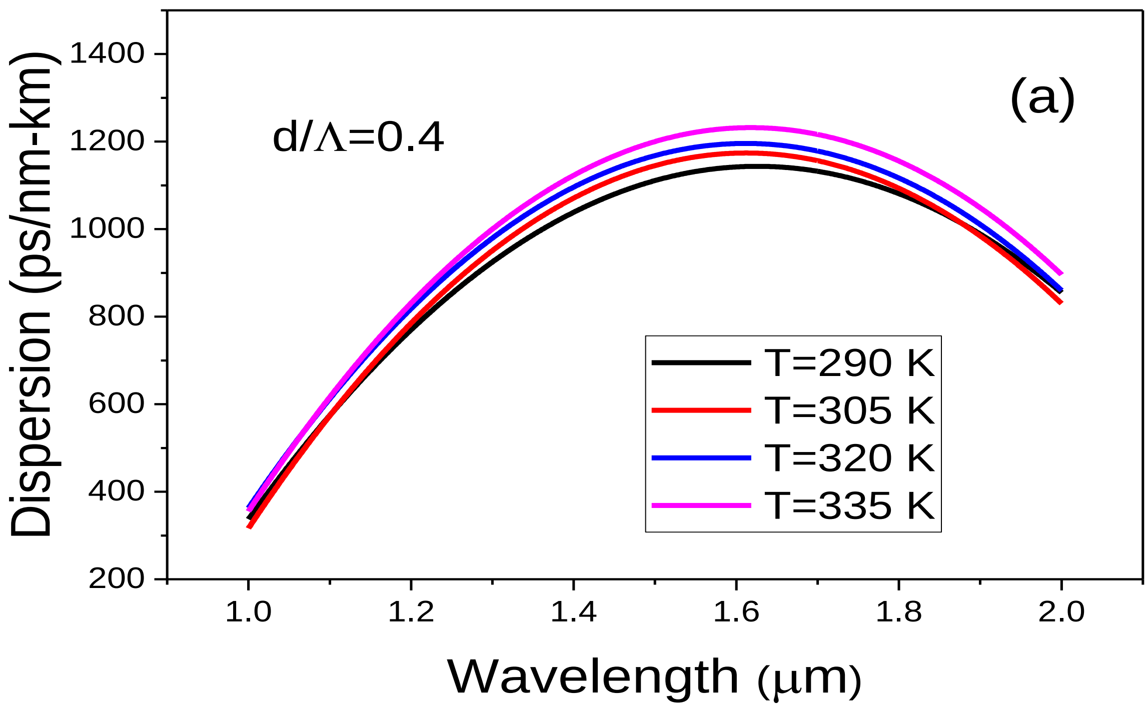


Figure 4.5 Effective index values of PCF plotted against wavelength for (a) d/Λ=0.4 and (b) d/Λ=0.8 at different temperatures.



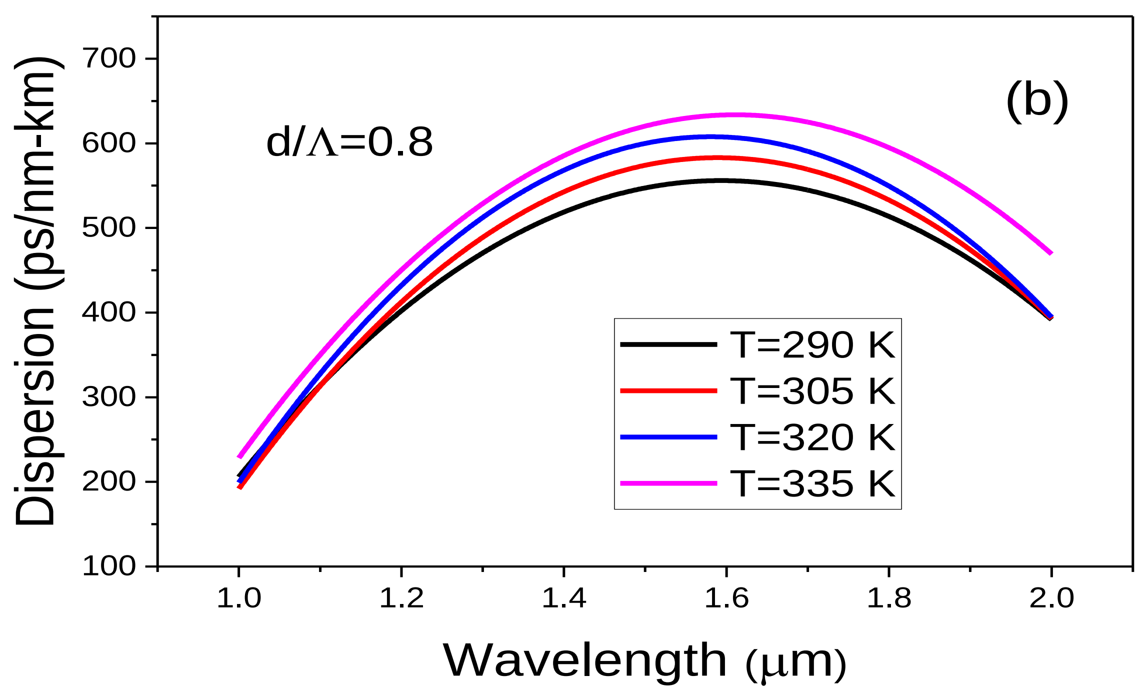


Figure 4.6 Dispersion properties of the PCF as a function of wavelength for (a) d/Λ =0.4 and (b) d/Λ = 0.8 at different temperatures.

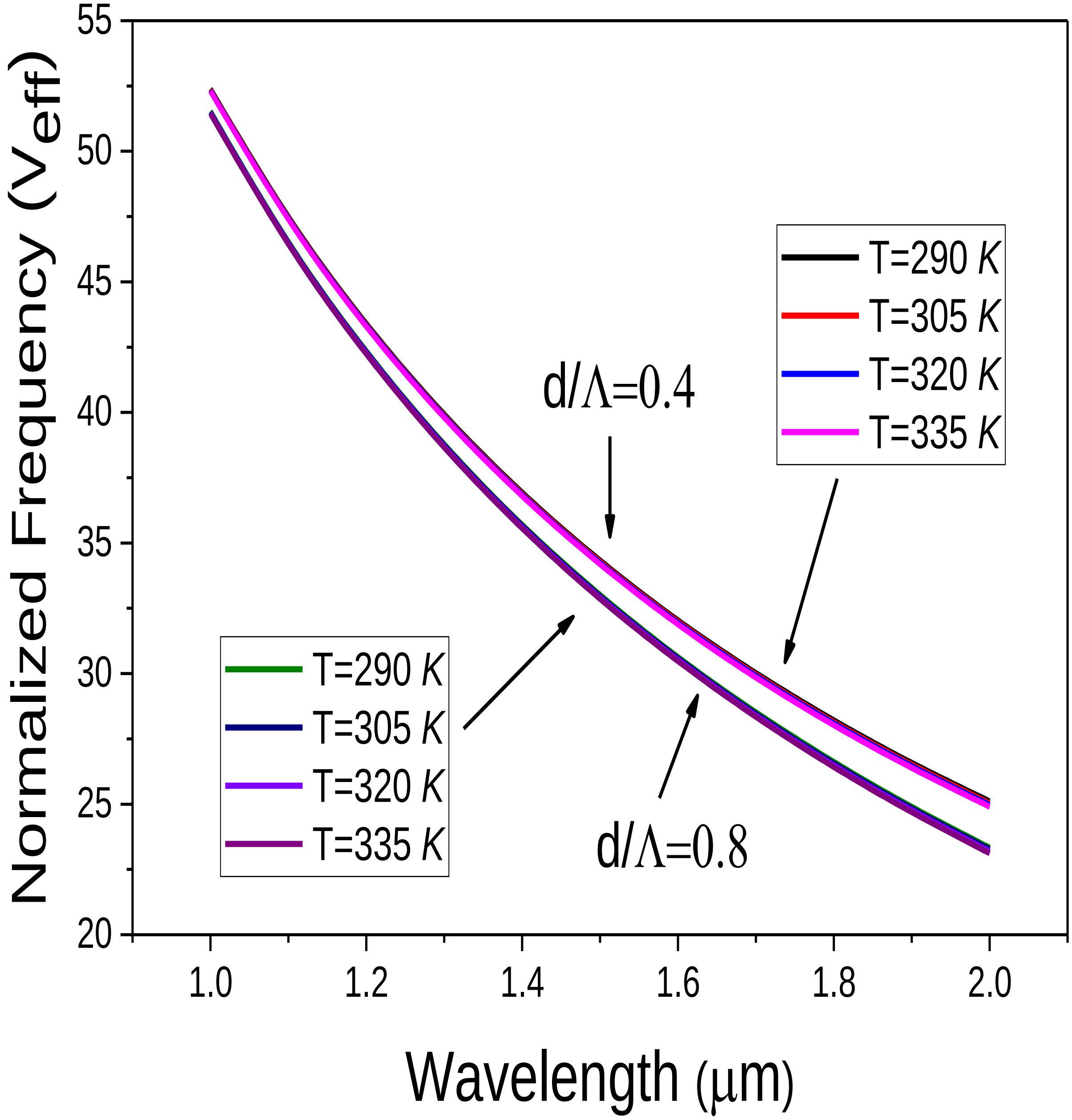


Figure 4.7 Wavelength dependence of V parameter value of PCF for d/pitch=0.4 and 0.8 at different temperatures.

4.4 CONCLUSION

A hexagonal photonic crystal fiber has been studied for its dispersion compensating applications with respect to temperature. InSb material has been filled into the cladding air-holes of PCF since its refractive index is a function of temperature and is responsible for a significant change in dispersion of PCF with small variation in temperature. Dispersion graphs of PCF have been plotted in the wavelength range 1.0-2.0 µm for four temperatures ranging from 290-335 K in equal steps of 15 K. It is seen that as the temperature is increased the value of dispersion also increases in the positive direction. The dispersion is more flattened for lower value of temperature as compared to the higher one. An average of 2 ps/nm-km climb in dispersion per degree Kelvin rise in temperature is observed for PCF with $d/\Lambda=0.4$ at communication wavelength 1.55 µm. A PCF whose dispersion can be shifted with the effect of temperature is proposed for the first time in our work. Places where temperature is not constant and keeps varying, this type of PCF can be installed for multiple optical channel dispersion compensating applications. Also in harsh environments where temperature increases or decreases substantially this PCF can show flattened dispersion at a particular temperature without the help of any special equipment.

In the last part of our work, the effect of temperature is observed on the normalized frequency characteristics of the PCF. It is seen that, with the change in temperature there is no shift in the values of V_{eff}. Thus we can say that the mode carrying capacity of the PCF remains the same irrespective of the surrounding temperature. This application is particularly useful when the number of modes or quantity of information needs to be preserved but dispersion of the PCF is to be varied with temperature.