COMPARISON OF DIFFERENT GLASS COMPOUNDS FOR INTRINSIC FIBER OPTIC TEMPERATURE SENSORS

H. Golnabi*

Institute of Water and Energy, Sharif University of Technology, Tehran, Islamic Republic of Iran

Abstract

Different glasses suitable for temperature sensing in the fiber optic sensors were studied in this article. The phase changes for eight different glass materials were calculated and results were compared. Our results showed that extra dense flint glass is the most sensitive one, while pure silica results in the lowest phase change. In another study the effect of wavelength on the phase variation was also investigated and the results were presented. Finally, the effect of glass formation in phase change was considered for different glasses, which were prepared using different techniques. The result showed that the Corning glass #7940 offers the highest sensitivity in comparison with the other three glasses for temperature sensing. Our studies for different silica glasses indicated that glass formation is important in preparing the glass materials required for the fiber sensors.

Introduction

During past decades, scientists have been studying various properties of glass-forming metals and glasses. Because of the application of such materials in different fields, a rapid increase in the variety of glass-forming substances has been noted in recent years. In general, a kind glass is specified by different physical, mechanical and chemical properties. Crystallization, glass transition temperature, and glass formation are important points in the glass preparation. Diffusion, permeation and solubility of gases are the other parameters involved in glass formation and its applications.

Density, thermal expansion, specific heat, thermal conductivity, viscosity, and optical properties are the other crucial physical parameters. Electrical and magnetic properties of the glass are features to be considered in glass analysis. Elastic and internal frictions, strength, surface tension, and microhardness describe the major mechanical properties of the glass materials. Finally, chemical durability is another point, which is important in this respect.

There have been many attempts in order to study the microstructure of glasses. Analytical techniques such as Raman spectroscopy and electron microscopy [1] have been developed to explain different properties of glass formation and crystallization of glasses and glass alloys. An important technique is the electron microscopy that has been proved as a valuable tool in extending our understanding of the microstructure of glasses.

The goal of this paper is to study the glass material involved in the fiber optic sensors in order to improve the performance of such sensors. The reported results can lead to fabrication of sensors with higher sensitivities and precision. For this purpose we first describe the principle of the temperature sensing based on the phase change in the interferometric

Keywords: Fiber optic; Sensor; Temperature; Silica glass; Composition

* *E-mail: golnabi@sina.s.sharif.ac.ir*

arrangements. In this respect, we calculate and report the phase change for different silica and silica compound glasses, then a comparison is given between these glasses and the optimum material for the fabrication of a sensitive temperature sensor is suggested.

Principle of Operation

Optical fiber sensors have found many applications in recent years. Various physical effects have been used to develop a variety of sensors for monitoring displacement [2], pressure and temperature [3], and other parameters [4-9]. Patrick *et al*. [10] reported the development of a sensor employing a graded index lens for displacement measurements. We reported an optical fiber sensor design for measuring the thermal expansion of metals [11].

A Mach-Zehnder type interferometer [8] can be used to detect the phase change as a result of an external perturbation. Figure 1 shows a typical block diagram of such an interferometer device that can be used as a temperature sensor [8]. Such a sensor system requires a stable, single-longitudinal-mode laser light source with low phase noise, a beam splitter producing two separate light beams, two single-mode optical fibers forming the two arms, a beam combining means, and a detector for monitoring the intensity of the interfering beams.

In this geometry, one of the fiber arms is considered as a reference while the other one serves as a probe coil in the sensing region. The optical path lengths of the two arms are nearly equal and define the resulting phase shift in the interference pattern. The lights from these fibers interfere and result in bright or dark fringes depending on the phase shift between these two light path lengths. Using an appropriate detecting system one can monitor the intensity of such interference pattern.

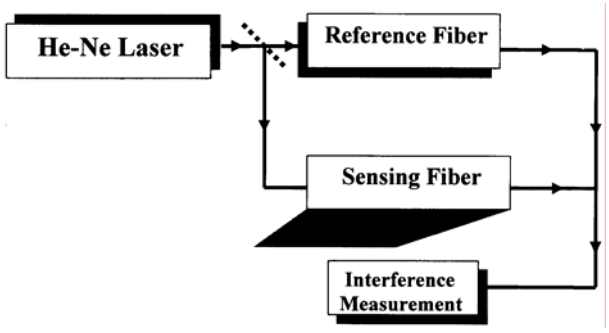

Figure 1. The block diagram of a Mach-Zehnder interferometer that can be used for temperature sensing.

The phase of the light leaving a sensing fiber can be changed when it is exposed to environment, by dimensional and/or index refraction changes. Thus, if the probe fiber is subject to a temperature different from the reference fiber, this difference appears as a displacement of the fringes that can be measured experimentally.

Let us consider a probe fiber with the length L and the effective index of refraction n. If we consider the phase change of the light traveling through such a fiber to be Φ, then we can write:

$$\Phi=\beta L, \tag{1}$$

where, β is the propagation constant in the fiber. For variation of Φ with temperature one can write:

$$\frac{d\Phi}{dT} = \beta\frac{dL}{dT} + L\frac{d\beta}{dT}, \tag{2}$$

and for β=2 πn/λ, the second term in Equation (2) is equal to:

$$\frac{d\beta}{dT} = \left(\frac{2\pi}{\lambda}\right)\frac{dn}{dT}. \tag{3}$$

After substitution of this term and some simplification the phase change per unit length for the unit temperature is obtained.

$$\frac{d\Phi}{(L)dT} = \left(\frac{2\pi}{\lambda}\right)\left[n(\lambda)\alpha(T) + \frac{dn(\lambda)}{dT}\right], \tag{4}$$

where, λ is the light wavelength in free space, α is the thermal coefficient of the glass material, and dn/dT shows the temperature variation of the index of refraction. The term in the left-hand side of Equation (4) indicates the phase change per unit length for one-degree temperature change. We consider this quantity throughout this article and calculate it for different cases. As can be seen from Equation (4) the phase shift can be due two effects: first, the change in the fiber length due to thermal expansion or contraction, and second the temperature-induced change in the index of the refraction of the probe fiber.

It must be pointed out that n, α and dn/dT are themselves function of temperature. Hence, the temperature dependence of these parameters is different for each glass type. For example, as indicated by Waxler and Cleek [12], the mean value of n for Corning glass #7940 at λ =587.6 nm for temperature range of –200°C to 650°C is given by:

$$n = 1.45846 + 8.16\times10^{-6}\,T$$

$$+ 1.04\times10^{-8}\, T^2 - 5.6\times10^{12}\, T^3. \quad (5)$$

The derivative of Equation (5) with respect to T results in dn/dT that can be evaluated at different temperatures. However, Equation (5) can only give the precise results for that particular glass. For other glasses we used data reported in [13] for T=20 and T= 100°C.

The variation of the fiber length L with temperature or change of α can be different for various glass materials with different components and impurities. As expressed by Hetherington [14] for a special silica glass (0.12% OH), the expanded length is given by

$$L = L_o[1 + (0.568\, T + 0.000524\, T^2)\, 10^{-6}], \quad (6)$$

where, L_o is the fiber length at zero temperature. From Equation (6) one can calculate $\Delta L/L$ and as a result α at different temperatures.

Computation and Result

For this study we considered the following glasses. Crown glass (C-1), borosilicate crown (BSC-2), light barium crown glass (LBC-2), dense barium crown (DBC-1), crown flint (CF-1), barium flint (BF-1), extra dense flint (EDF-3), and pure silica glass (SI). Composition, optical properties and thermal expansions for these glasses are given in Table 1 [13]. From now on we use the conventional abbreviations for these glasses as shown in Table 1.

Considering the given data, EDF with a 62% PbO has the highest specific gravity (4.51 g/cm^3) and also the index of refraction (1.689). On the other hand, pure silica has a specific gravity of 2.202 g/cm^3 and index of refraction of about 1.45846. Next to EDF glass, DF has a PbO percentage of 19.5% with specific gravity of 3.64 g/cm^3. This glass has index of refraction of 1.621. After this glass CF has an index of refraction of 1.5286.

The first study considers the change of refraction index with temperature relative to 0°C. Temperature data for different glasses is taken from [13]. This change is presented in Figure 2 for LBC and EDF glasses. In Figure 2 the value of n variation is plotted from –100 to 100 °C for three different wavelengths (480, 589, and 644 nm). As can be seen in Figure 2, EDF glass shows the higher variation in the index of refraction while LBC has a little change for this temperature range. Another point is that as described for the pure silica glass, this variation can be positive or negative as indicated in this study. A careful study of Figure 2 shows that the index of refraction change is higher for the shorter wavelength (in this case 480 nm).

It seems that a single mode laser light source, at 480 nm (Argon ion laser), with an appropriate detector would be the best choice for such a temperature sensing application. However, a specific choice of source wavelength for the proposed temperature sensor depends on the type of the photo detector to be used in the construction of the sensor system.

Figure 3 shows the result of the second study for the phase change for two different temperatures. Since exact data given in [13] is for 578 nm, therefore, we consider this wavelength for such analysis. The results given in this study are for λ=578 nm and typical temperatures are the room temperature of around 20 and 100°C. As can be seen in Figure 3, at the room temperature EDF has the highest phase value (200.573 radian/°C-m), while pure silica shows the lowest sensitivity (114.669 radian/°C-m) in this study.

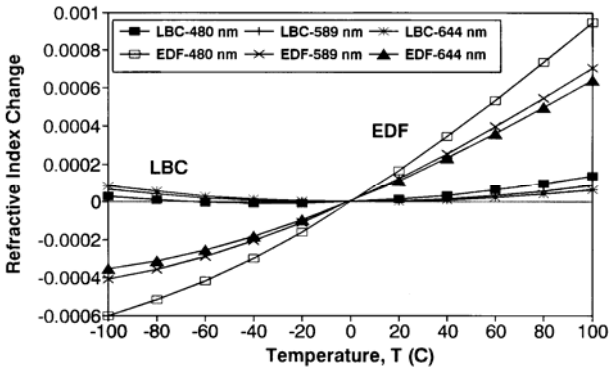

Figure 2. Variation of the index of refraction with respect to temperature for different wavelengths.

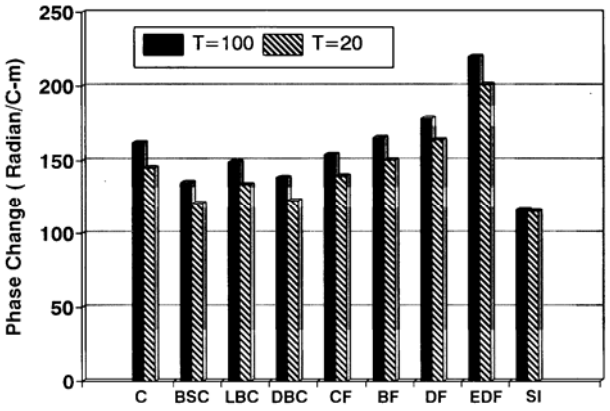

Figure 3. The phase changes for different optical glasses for two temperatures.

Table 1. Thermal expansion and composition of different optical glasses [13]

Glass type			Composition (%)							
Name	α_{20}	α_{90}	SiO_2	B_2O_3	Na_2O	K_2O	BaO	PbO	Al_2O_3	ZnO
C	8.0	8.7	73	1		15	-	-	-	-
BSC	6.5	7.0	68.6	11.4	3.9	10	1.8	-	-	2
LBC	7.8	8.3	48.1	4.5	1	7.5	28.3	-	-	10.1
DBC	6.4	7.0	34.6	11	-	-	46.9	-	5	1.1
CF	7.3	7.7	81	-		11	-	3	-	3.5
BF	8.0	8.4	49.8	-	1.2	8.2	13.4	18.7	-	8
DF	7.3	7.6	73.5	-		6.5		19.5		0.5
EDF	7.5	8.0	33.7	-	-	4	-	62	-	-
SI	0.5	0.505	100	-	-	-	-	-	-	-

Thermal expansion coefficient, α multiplied by 10^6.
Components constituting less than 0.5% are not listed.

The same parameter for the T=100°C is displayed in Figure 2 for a better comparison. It is noticed that in general, phase change for all of the glasses is increased at the higher temperature. This increase in response is about 8.6% for the EDF, which again shows the highest sensitivity (219.8 radian/°C -m) in this case. The noted increase is because of two effects. As can be seen in Equation (4), the value of n, and dn/dT are increased with T, and also α(T) shows increase with temperature at this range of 20-100 °C. However, it should be mentioned that dn/dT could also be negative at some temperature range. As indicated in [13] from –194°C to 0°C, dn/dT is negative for C-1 glass. In our calculation, however, for the given temperature range, dn/dT has positive value and as a result the second term in Equation (4) is increased with any increase in temperature.

With increasing temperature according to Equation (5), n increases. From Equation (6) it is noticed that whenever there is a temperature increase, α increases accordingly. Hence, in Equation (4) the first term is increased because of n and α. As described the second term is increased due to increase in the dn/dT. In comparing the results for the pure silica and other glasses it is noticed that the effect of the first term ($n\alpha$) is very smaller than the second term (dn/dT) for the silica while this is reverse for the composite glasses. The reason is the existence of the metal oxide in the composite of other glasses that show higher α value. As a result the first term in Equation(4) for pure silica is much less than the other composite glasses. For example, the ratio of the first term of EDF to that of silica (SI) is about 15. On the other hand, for the same glasses, the second term for EDF is about 6.1×10^{-6} in comparison to 10×10^{-6} /°C for the pure silica glass. This is again reasonable because of the some percentage of the metal oxides in the composition of EDF glass.

To see the role of the source wavelength in phase analysis, in this section we discuss this parameter. In Figure 4 we present the results of the phase change for the described glasses. These wavelengths are 480 nm, 589 nm, and 644 nm, all in the visible range. The values of n and dn/dT vary for each glass and as a result affect the phase change. As can be seen in [15], the value of n decreases as we increase the wavelength. The second term including dn/dT in Equation (4) behaves differently with wavelength as indicated for the silica glass in [15]. For 0.2-0.4 μm range it decreases sharply and from 0.4 to 0.7 μm decreases slowly. From 0.7 to 1.8 μm it increases and finally from 1.8 to 4 μm shows a slow decrease.

The conclusion of this part is that for a wavelength range of 0.4 to 1 μm that dn/dT does not vary considerably, the phase change for the visible region is decreased as we increase the wavelength. Another point is that $k= 2\pi/\lambda$ in Equation (4) decreases as the wavelength is increased, so this coefficient changes inversely with respect to the wavelength. Another point is that $n(\lambda)$ is decreased as we increase the wavelength. This has been shown in different studies.

For instance, for Corning glass #7940 at 0.23021 μm, n=1.52034, at 26 °C while for λ=0.578 μm n=1.45899, and at λ=1.01398 μm, n=1.45039, and finally at λ=3.37 μm n=1.4099. Hence there is a decrease because of three factors. First the propagation constant in free space is decreased with any wavelength increase. Second the $n(\lambda)$ is decreased as we increase the wavelength. The third factor is the dn/dT that shows a complex behavior, but for the visible wavelength range it is more or less constant.

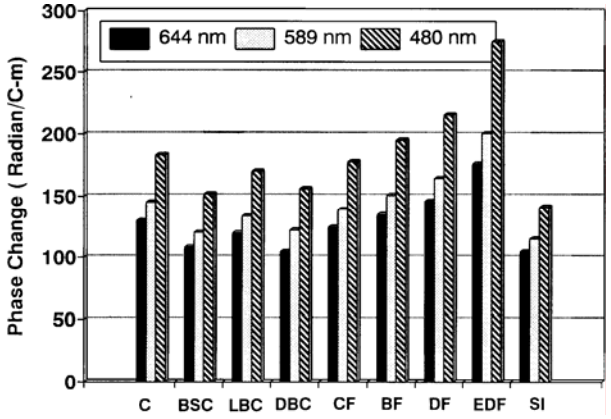

Figure 4. Shows the phase variation as function of source wavelength for different optical glasses.

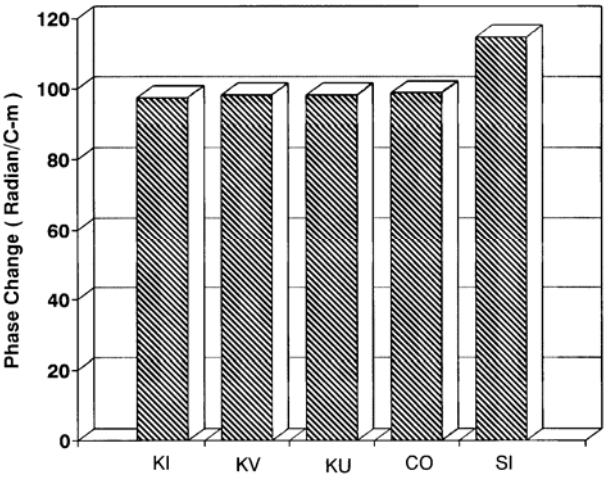

Figure 5. Shows the phase change for silica glasses prepared by different techniques.

Considering the results shown in Figure 4, we notice that the phase change at 480 nm has the highest value while at 589 nm it has the intermediate value. A light source at 644 nm produces the lowest phase change. For example the corresponding numbers for these three wavelengths are 274.749, 200.573, and 176.347 radian/°C-m, respectively. Comparing these numbers it is noticed that wavelength has a considerable effect on the phase variation. This point can be effectively used in choosing the proper light source for the sensor design.

In another study the phase change is considered for four different silica glasses prepared by different methods, Corning #7940, KI, KU, and KV as denoted in [15]. Thermal expansion for these glasses at 50°C is given by Amatuni *et al*. [16]. The glass denoted by KI is a silica glass that melted by electrothermal method (total impurity 1×10^{-2} wt%, and $<5\times10^{-4}$ wt% OH) with a density of 2.2077 g/cm^3. The KV glass is a silica glass melted by gas-flame method (total impurity $<1\times10^{-2}$ wt% and $(1.5\text{-}4)\times10^{-2}$ wt% OH) and density of 2.2047. The KU is a silica glass made by synthesis in vapor phase of $SiCl_4$ in a hydrogen-oxygen flame (total impurity$<0.2\times10^{-4}$ wt%, 0.1 wt% OH, and 1×10^{-2} wt% Cl). The density of this glass is about 2.2059 and the density of the Corning #7940 at 20 °C is 2.202 g/cm^3.

If we assume a nearly equal n=1.458462 for all the glasses and dn/dT as given in [15], then the amount of phase changes per unit length of probe fiber for 1°C temperature change can be calculated. For the Corning silica glass we assume that $\alpha= 0.5\times10^{-6}$ /°C and compare the results with pure silica in Figure 5. As can be seen, the KI has the lowest phase change while Corning glass produces the highest phase variation. It is also noted that among all these glasses the pure silica glass provides the higher phase change.

This study shows that the method of glass forming and its impurity are effective in the fabrication of fiber optic sensors. Hence, OH and other impurities affect the phase variation in such sensing devices. As a result optical property of a glass may change with temperature, pressure, and annealing of the glass during the glass preparation. This fact must be considered in the preparation of glass material for the fabrication of optical fiber temperature sensors.

Optical fiber fabrication is accomplished by using techniques such as vapor phase axial deposition (VAD), lateral deposition, or modified chemical vapor deposition (MCVD) process. Compound fibers are generally fabricated by using the double crucible method. In practice, one can take advantage of such method to fabricate fibers from glass materials proposed in this study. The result of this study suggests that the mentioned compositions can be used to draw fibers, which are more efficient for temperature sensor designs. However, in the fiber preparation process care must be taken to avoid the unwanted changes in the glass property. For example, any impurity such as OH can affect the phase variation of such fiber when used as a temperature sensor. Such parameters must be, therefore, controlled in order to be able to match the predicted theoretical results reported here. However, there are always some practical problems that limit the ultimate sensitivity of the designed sensor and can cause the experimental results to be less satisfactory than those of theoretical ones are.

Conclusion

The main results of this study can be classified as follows. Pure silica glass with no metal composition has the lowest phase change. EDF has the highest composition of metal oxide (62% PbO) that shows the highest phase variation to a temperature change. For the

pure silica the thermal expansion of fiber is negligible while the temperature change of the index of refraction is dominating. Inversely, in glass alloys with high metal oxides the thermal expansion is higher than the change of index of refraction with temperature, and in some cases they are comparable.

For applications that require the minimum phase change because of temperature, the special low expansion silica glass is suggested. For other applications such as sensing temperature, EDF offers the highest sensitivity. The overall result of this study is that with appropriate glass fiber one can devise a very sensitive phase based sensors. Glass impurities and metal components have to be controlled in fabrication of such sensing fibers.

Although some of the results given here are obtained for the bulk glasses, but there should not be much difference in those quantities when they are used in the fiber form. Therefore, the bulk glass results reported could be extrapolated to the fiber with a negligible error. It must be mentioned that drawing special fibers with the proposed compositions is costly, but high cost can be justified if this approach can provide a high degree of sensitivity in comparison with the other fiber sensors. On the other hand, the mass production of such fibers will lower the cost, which makes it more suitable for the real field applications. Finally, with the desired fibers in hand, one can use the described Mach-Zehnder type interferometer sensors to detect the phase change and as a result detect the temperature with a higher sensitivity.

Acknowledgements

This work was supported in part by the Sharif University of Technology research program. The author gratefully acknowledges the grant devoted to this research. He is also thankful to all the coworkers for the given technical assistance during this study.

References

1. Phillips, J. C., The physics of glass. *Physics Today*, February, 27-33 (1982).
2. Emmanuel, B., Sege, H. J. and Gilbert, B., Loss compensated fiber-optic displacement sensor including a lens. *Appl. Opt.*, **28**: 419-20 (1989).
3. Hocker, G. B., Fiber-optic sensing of pressure and temperature. *Appl. Optic.*, **18**: 1445-48 (1979).
4. Abdelrafik, M., Pierre, L., Jeanine, M., Christine, R. and Pierre, F., Optical fiber accelerometer based on a silicon micromachined cantilever, *Appl. Opt.*, **34**: 8014-17 (1995).
5. Goure, J. P., Optical sensors: fiber optic sensors. *International Chemical Engineering*, **32**: 706-17 (1992).
6. Giallorenzi, T. G., Bucaro, J. A., Dandrige, A., Sigel, G. H., Cole, J. H., Rashleigh, S. C. and Priest, R. G., Optical fiber sensor technology. *IEEE J. of Quantum Electron.*, **QE-18**: 626-64 (1982).
7. Kajanto, I. and Friberg, A. T., A silicon-based fiber optic temperature sensor. *J. Phys. E. Sci. Instrum.*, **22**: 652-56 (1988).
8. Allard, F. C., *Fiber Optics Handbook for Engineers and Scientists*. Mc Graw-Hill Pub. Comp., Chap. 8, (1990).
9. Dandrige, A., Cole, J. H., Burns, W. K., Giallorenzi, T. G. and Bucaro, J. A., *Optoelectronic Technology and Lightwave Communication System.* Van Nostrand Rienhold, New York, (1989).
10. Patrick, J. and Coursolle, T. P., Fiber optic displacement sensor employing a graded index lens. *Appl. Opt.*, **29**: 544-47 (1990).
11. Golnabi, H., Fiber-optic sensing of linear thermal expansion. *International Journal of Engineering*, IRI, **9**: 37-43 (1996).
12. Waxler, R. M. and Cleek, G. W., *J. Res. Nat. Bur. Stand.*, **98A**: 325-33 (1973).
13. Levy, L., *Applied Optics, A Guide to Optical System Design*. John Wiley & Sons, New York, Chap. 14, (1980).
14. Hetherington, G. and Jack, K. H., *Phys. Chem. Glasses*, **3**(4): 129-33 (1962 b).
15. Mazurin, O. V., Streltsina, M. V. and Shvaiko-Shvaikovskaya, T. P., *Physical Science Data 15, Handbook of Glass Data*. Part A, Elsevier, Amsterdam, (1983).
16. Amatuni, A. N., Shevchenco, E. B. and Mallyutina, T. I., *Tr. Metro. Inst. SSSR*, **131**(191): 116-25 (1972).