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Araştırma Makalesi / Research Article

Change of Dielectric Constant of Highly Doped-Silica Glass Used in Optical Fibers with Frequency and Temperature Under the Effect of Polarization

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Abstract

In this study, the variation of the dielectric constant, i.e. relative permittivity of highly doped-silica glass used in optical fibers with frequency and temperature under the effect of polarization has been investigated. In this context, simulations of the relationship between the dielectric constant and both frequency and temperature have been carried out in the Matlab environment. According to simulation and theoretical analysis, it has been concluded that the dielectric constant of highly doped-silica glass tends to increase with the increase of ambient temperature. On the other hand, as the frequency of the source increases linearly, the dielectric constant decreases. Hence, the variations of highly doped-silica glass with temperature and frequency have been found to be 2.884×10^{-5} $(°K)^{-1}$ and -7.50×10^{-15} $(Hz)^{-1}$, respectively. Moreover, in response to the change in frequency between 10^{11} Hz and 10^{12} Hz, the dielectric constant has taken values between 2.085 and 2.070. Additionally, for dielectric constant variations in 2.070 – 2.085 range, values of the relative change in polarization have been obtained in the range of 9.4695×10^{-12} F/m – 9.6023×10^{-12} F/m.

Keywords: Dielectric constant, Dielectric polarization, Frequency, Temperature, Highly doped-silica glass, Optical fiber.

Optik Fiberlerde Kullanılan Yüksek Katkılı Silika Camın Dielektrik Sabitinin Polarizasyon Etkisi Altında Frekans ve Sıcaklıkla Değişimi

Öz

Bu çalışmada, optik fiberlerde kullanılan yüksek katkılı silika camın dielektrik sabitinin yani bağıl geçirgenliğinin polarizasyon etkisi altında frekans ve sıcaklıkla değişimi incelenmiştir. Bu bağlamda dielektrik sabiti ile frekans ve sıcaklık arasındaki ilişkinin Matlab ortamında simülasyonları gerçekleştirilmiştir. Simülasyon ve teorik analizlere göre yüksek katkılı silika camın dielektrik sabitinin ortam sıcaklığının artmasıyla birlikte artma eğiliminde olduğu sonucuna varılmıştır. Diğer taraftan, kaynağın frekansı doğrusal olarak arttıkça dielektrik sabiti azalmaktadır. Dolayısıyla, yüksek katkılı silika camın sıcaklık ve frekansa göre değişimi, sırasıyla 2.884×10^{-5} $(°K)^{-1}$ ve -7.50×10^{-15} $(Hz)^{-1}$ olarak bulunmuştur. Ayrıca, frekansın 10^{11} Hz ile 10^{12} Hz arasındaki değişimine karşılık dielektrik sabiti, 2,085 ile 2,070 arasında değerler almıştır. Bunun yanı sıra, 2,070 ile 2,085 aralığındaki dielektrik sabiti değişimleri için bağıl polarizasyon değişimi değerleri, 9.4695×10^{-12} F/m – 9.6023×10^{-12} F/m aralığında elde edilmiştir.

Anahtar Kelimeler: Dielektrik sabiti, Dielektrik kutuplanma, Frekans, Sıcaklık, Yüksek katkılı silika cam, Optik fiber.

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1. Introduction

In some materials, it is not possible to excite electrons from the valance band to the conduction band using an applied electric field or thermal energy. These materials known as dielectric materials, in which valence electrons are tightly bonded to the nucleus, are exposed to different types of electric fields such as direct current (DC), alternating current (AC) and static in electronic systems. Thus, they may exhibit different behavior under the influence of different types of fields. In other words, they are subjected to different types of polarization mechanisms under the influence of an applied electric field on the dielectric material. These polarization mechanisms are influenced by the frequency of the source supplying the system and temperature variations of the ambient (Gupta, 2015).

Dielectric materials, i.e. dielectrics can exist in gaseous, liquid and solid states. Porcelain, bakelite, glass, mica, porcelain, fused silica, and plastic are some examples of solid dielectric materials while pure water and transformer oil are liquid dielectrics. The dry air, ozone and nitrogen can be gaseous dielectrics (Gupta, 2015). Characteristic properties used to define dielectric materials can be classified as dielectric strength, dielectric constant (or relative permittivity), and dielectric loss parameters. These parameters are influenced by temperature and frequency changes. A good dielectric has high dielectric strength and dielectric constant but low dielectric loss factor.

The core of the optical fiber is generally produced using dielectric materials such as highly doped- silica glass, plastic and silicate glasses. These dielectric materials undergo ionic and electronic polarizations in the infrared/ultraviolet and optical frequency region, due to the applied electric field. These polarization formations are affected by the frequency of the source supplying the system, and changes in the ambient temperature.

In the literature, there are numerous studies on the dielectric strength, dielectric constant and dielectric loss factor of the fused silica used for the production of optical fiber core (Lie and at al., 2014; Fontanella and et al., 1979; Molla, 2004). In these studies, temperature and frequency dependencies of these parameters have been investigated. Moreover, there are several research papers and academic studies related to the polarization effect occurred in dielectric materials and the behavior of dielectric parameters under polarization have been reported in the literature (Travasso and et al., 2009; Tan and Arndt, 1994). On the other hand, there is no direct study in the literature that examines the effects of frequency and temperature formations on highly doped-silica glass under the polarization mechanisms and presents findings in this context.

Since, the highly doped-silica glass is used for the production of core of the optical fiber, behavior of its dielectric constant depending on both the frequency and the temperature formations under polarization effect occurring in the dielectric is vitally important for optical fiber sensor

applications and fiber communications systems. Therefore, in this study, the variation of the dielectric constant of highly-doped silica glass used in optical fibers with temperature and frequency under polarization has been examined, and the frequency and temperature dependencies of the dielectric constant have also been analyzed. Furthermore, simulations regarding the relative change in polarization with the electric field have also been performed and theoretical analyses have been obtained, accordingly.

2. Theory

In dielectric materials, a shift occurs in the charge centers at the atomic scale depending on the applied electric field. In other words, when an electric field is applied to a dielectric material, negative charges are displaced towards the positive end of the field and positive charges are displaced towards the negative end of the electric field, accordingly.

This situation causes the formation of atomic structures called dipoles which are produced in the dielectric due to this displacement. These dipoles retain their moments under polarization effect. Polarization is defined as the sum of the total dipole moments of these dipoles produced within the volume of the dielectric when an electric field is applied (Gupta, 2015). The dipoles formed in the dielectric return to their previous states, called relaxation, when the field effect is removed. The duration of the relaxation process is called relaxation time and polarization types are classified depending on the relaxation time.

In this study, dielectric medium is assumed as the simple. Therefore, the expression of the electric flux density (D) in the simple medium for any dielectric material can be written by

$$D = \varepsilon E = \varepsilon_0 \varepsilon_r E \tag{1}$$

where E is the electric field effect applied on a dielectric material and ε_0 and ε_r are the dielectric constants of vacuum and material, respectively.

The dielectric constant is considered a measure of polarization in dielectric materials and is defined as the ratio of absolute permittivity to the permittivity of vacuum. Thus, dielectric constant ε_r is given as

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{2}$$

where ε and ε_0 are absolute permittivity and the permittivity of vacuum, respectively.

In (2) ε_r is dimensionless. The value of ε_r = 1 for vacuum. Dielectric constant for teflon is 2.1, for mica is 8, for silicon is about 12, and for pure water is 81 (Gupta, 2015).

By subtracting and adding $\varepsilon_0 E$ in equation (1) and reorganizing (1), the electric flux density (D) depending on the parameters of polarization (P) and electric field effect (E) and dielectric constant of the vacuum (ε_0) can be stated as following.

$$D = \varepsilon_0 E + P \tag{3}$$

where D is the electric flux density and P is the polarization occurring in dielectric. The unit of P is Farad/meter.

Therefore, the expression of the polarization effect caused by the electric field applied on a dielectric is given with

$$P = D - \varepsilon_0 E = (\varepsilon_r - 1)\varepsilon_0 E = \varepsilon_0 \varkappa E \tag{4}$$

where $\varkappa$ is the electric susceptibility of dielectric material.

Using (4), the relative change in polarization P_R depending on the electric field can be obtained as stated in (5).

$$P_R = P/E = \varepsilon_0(\varepsilon_r - 1) \tag{5}$$

Polarization mechanisms are mostly affected by the frequency of the voltage or electric field supplied to the systems and the temperature formations occurring in the medium.

Figure 1 shows the variation of the dielectric constant with frequency and the polarization mechanisms occurring in the entire frequency spectrum (Gupta, 2015). The frequency-dependent change of the dielectric constant can be linearized using the values at points a, b, c, d and e shown in Figure 1. These points correspond to transition zones in the polarization process and can be considered as the ending point of one polarization process and the starting point of the other.

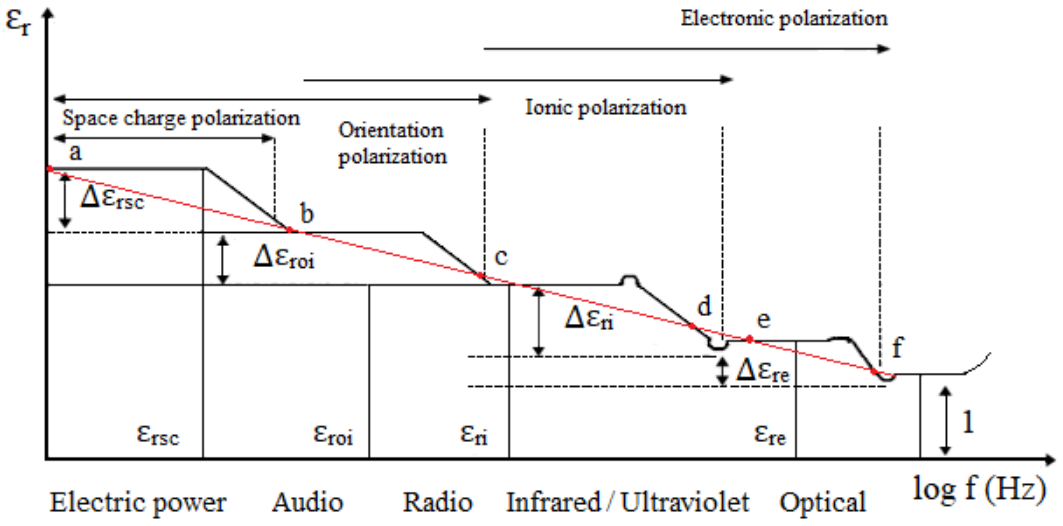

Figure 1. Frequency dependence of dielectric constant and polarization mechanisms

As obviously seen from Figure 1, the dielectric constant decreases depending on the logarithmic increase in frequency of the electric field applied on the dielectric. Moreover, the polarization effect occurs at all frequencies, from the electrical power frequency region to the optical frequency region. As can be seen from the Figure 1, four different polarization mechanisms occur in dielectric materials: space charge, orientation, ionic and electronic. Orientation polarization occurs between 10^6 and 10^8 Hz while the space charge polarization occurs at frequencies below ~ 100 Hz.

Orientation and ionic polarizations occur between audio and infrared frequency regions in the spectrum. Dipole and orientation polarizations are considered slow polarization. In slow polarizations, when the electric field effect is removed, the dipoles try to return to their initial positions. Depending on the type and temperature of the material, the rotation of the dipoles may not be complete.

Ionic polarization which is influenced by the electric field effect is a temporary polarization caused by external effect, just like electron polarization. Since the masses of ions are much larger than electrons, it is more difficult for them to be displaced (Gupta, 2015). Therefore, it only occurs in radiation waves with frequencies below ~ 10^{13} Hz.

Electronic polarization occurs in all dielectric materials. The frequency of standing wave movements of electrons is about 10^{16} Hz. Light waves with frequencies of about 10^{14} Hz can easily affect electrons and create this kind of polarization effect, accordingly. Although it occurs in all materials, electron polarization has little effect on the dielectric constant. Electron polarization is largely observed at frequencies above approximately 10^{14} Hz. Ionic and electronic polarizations are fast polarization mechanisms. In other words, relaxation times ($\tau < 10^{-13}$ s) are smaller in fast polarizations that those of slow polarization mechanisms (Gupta, 2015).

The dielectric constants and the dielectric loss factors of some dielectric materials are given in Table 1 (Gupta, 2015).

Table 1. Dielectric properties of some dielectric materials

Dielectric material	Dielectric constant values		Dielectric loss factor
	60 Hz	10^6 Hz	(tan δ)
Elastomer	4.0	2.7	0.003
Bakelite	4.4	4.4	0.028
Fused silica	4.0	3.8	0.0001
Nylon 6.6	4.0	3.5	0.020
P.V.C.	7.0	3.4	0.050
Transformer oil	5.0	2.5	0.0001
Polyethylene	2.3	2.3	0.0004

As seen in Table 1 the dielectric constant generally tends to increase as the frequency of the source increases. In other words, it decreases as the frequency increases logarithmically. On the other hand, dielectric loss factors are not affected by frequency change. Dielectrics with the lowest loss factor are fused silica and transformer oil. Their value is 0.0001. One of the conditions for a material to be a good dielectric material is that its loss factor is very low.

3. Results and Discussion

In this study, simulations related to the temperature and frequency dependencies of the dielectric constant of highly doped-silica glass and the relative change in the polarization effect depending on the dielectric constant have been carried out.

In dielectric materials, there is a relationship between the dielectric constant and the refractive index as given in equation (6) (Zhi-Yong and et al., 2014).

$$n = \sqrt{\varepsilon_r} \tag{6}$$

The refractive index of highly doped-silica glass can be expressed as a function of the temperature as

$$n(T) = 1.4389 + 1x10^{-5}T \tag{7}$$

where T is temperature in Kelvin (Bansal and Doremus, 1986; De Souza, 1999; Günday, 2018).
As can be seen from (6) and (7), the dielectric constant, i.e. relative permittivity of highly doped-silica glass varies with temperature.

Using (6) and (7), the dielectric constant of highly doped-silica glass was obtained for changes in temperature between 0 and 500 K and is shown in Figure 2.

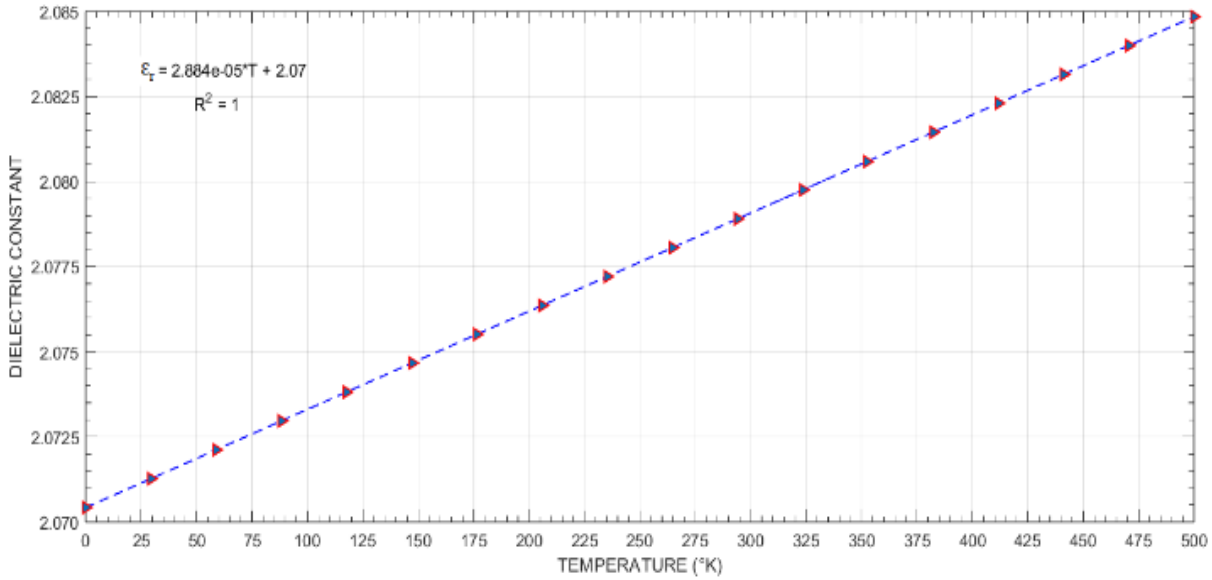

Figure 2. Dielectric constant versus temperature

As can be seen, the dielectric constant increases as the temperature increases. For temperature variations from 0 °K to 500 °K, dielectric constant changes in the range of 2.070 – 2.085. The fact that the change of dielectric constant with temperature occurs in a narrower range compared to its change with frequency is due to the smaller effect of temperature on the dielectric constant. This situation is also compatible with the results in practical applications.

(8.a) and (8.b) give the formulas representing the correlations between dielectric constant of the highly doped-silica glass and temperature in both linear and quadratic forms. They have been acquired by using regression method.

$$\varepsilon_r = 2.884 \times 10^{-5} T + 2.07 \quad (8.a)$$

$$\varepsilon_r = 1 \times 10^{-10} T^2 + 2.878 \times 10^{-5} T + 2.07 \quad (8.b)$$

The frequency region where it has its lowest value is around the infrared and optical regions of the spectrum. Ionic and electronic polarization mechanisms occur in this frequency region, as shown in Figure 1. Therefore, since highly doped-silica glass is used in the production of fiber optic cable cores, it can be affected by these polarization mechanisms. Thus, the dielectric constant changes due to both polarization effects.

Depending on ionic and electronic polarization effects, the dielectric constant, i.e. relative permittivity can be formulated with

$$\varepsilon_r = 1 + \Delta\varepsilon_{ri} + \Delta\varepsilon_{re} \quad (9)$$

where $\Delta\varepsilon_{ri}$ and $\Delta\varepsilon_{re}$ are the dielectric constant changes resulting from the ionic polarization and the electronic polarization, respectively.

However, since the effects of electronic polarization occurring at frequencies above 10^{14} Hz on the dielectric constant are small, they can be neglected compared to the effects of ionic polarization. Therefore, it can be considered that the determining effect on the change in dielectric constant is mostly due to ionic polarization. Hence, in this study, it is assumed that the frequency of the source varies in the frequency region of 10^{11} - 10^{12} Hz.

Moreover, in obtaining the simulation of the variations of the dielectric constant with frequency, dielectric constant data resulting from changes in temperature in the range of 0 - 500 °K have been utilized. In other words, the relevant simulation has been obtained using the dielectric constant changes caused by temperature changes.

Simulation concerning the relationship between frequency and dielectric constant of the highly doped-silica glass is shown in Figure 3.

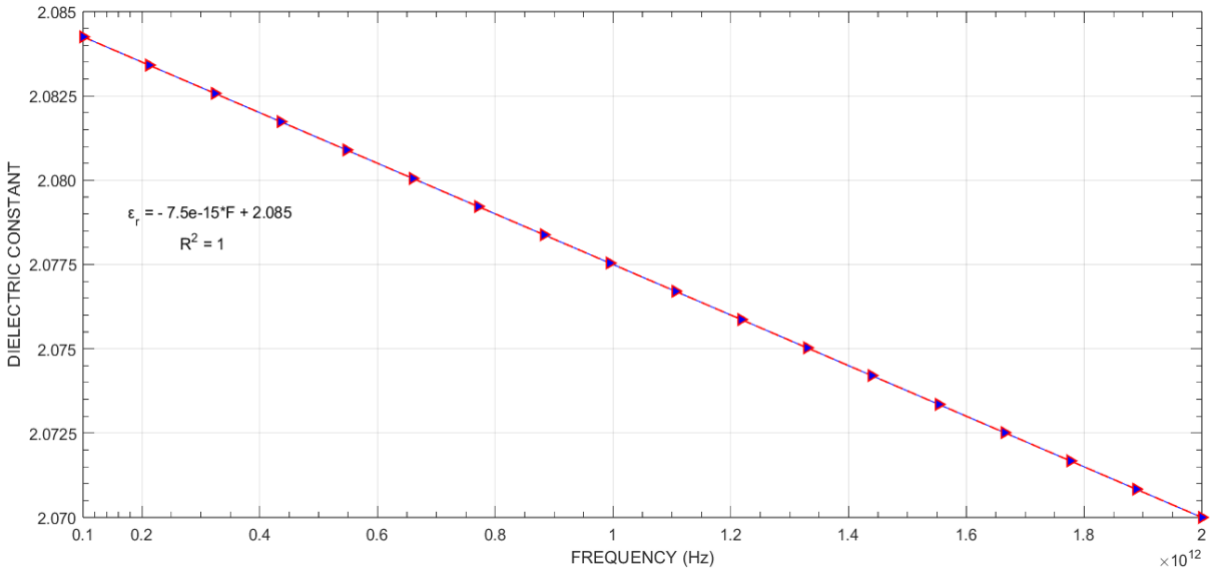

Figure 3. Dielectric constant versus frequency

As is seen from Figure 3, as the frequency increases in the range of 10^{11} – 10^{12} Hz, the polarization effect produced in the dielectric material and thus dielectric constant decreases, as well.

Using the simulation data in Figure 3 and the regression method, the dielectric constant can be written as a function of the frequency by

$$\varepsilon_r = -7.5 \times 10^{-15} F + 2.085 \quad (10)$$

where ε_r and F denote the dielectric constant of highly doped-silica and the frequency, respectively.

The regression coefficient for this formula has been computed as $R^2 = 1$. As obviously seen from the Figure 3, the dielectric constant of highly doped-silica glass reaches its maximum value of 2.085

approximately at the lowest frequency value and tends to decrease as the frequency value increases. The dielectric constant takes its lowest value as 2.070 for maximum frequency value of 10^{12} Hz.

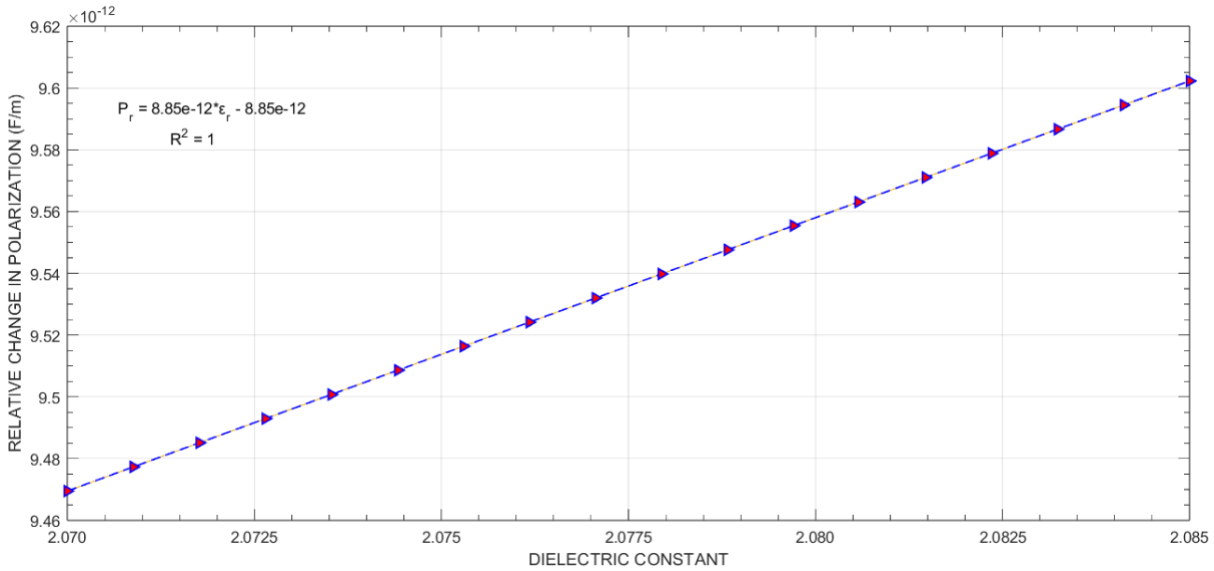

Figure 4. Relative change in polarization versus dielectric constant

Making use of (5), (6), and (7), the simulation related to the relative change in polarization depending on the dielectric constant of highly doped-silica glass is plotted as in Figure 4.

As represented in the Figure 4, the relative change in polarization varies linearly with dielectric constant. This is because the polarization varies linearly with the dielectric constant as given both in equations (4) and (5).

Linear and second-order equations representing the relationship between relative change in polarization and dielectric constant of highly doped-silica glass have been derived by using regression method as in (11.a) and (11.b).

$$P_R = 8.85 \times 10^{-12}\varepsilon_r - 8.85 \times 10^{-12} \quad (11.a)$$

$$P_R = 6.193 \times 10^{-21}{\varepsilon_r}^2 + 8.85 \times 10^{-12}\varepsilon_r - 8.85 \times 10^{-12} \quad (11.b)$$

The regression coefficient for these formulas is $R^2 = 1$, approximately. Equation (11.a) gives the linear change between relative change in polarization and dielectric constant and is the same as equation (5). However, equation (11.b) expresses the relationship between both parameters with a second-order equation. Therefore, this finding adds a different approach to the study.

Conclusion

In dielectric materials, the dielectric constant of the material changes due to the polarization effects. In other words, the dielectric constant of the dielectrics varies depending on the type of the polarization mechanisms occurring in the material. Since the core of optical fibers used for both communication and sensor purposes is doped silica, they are affected by electrical polarization mechanisms such as ionic and electronic. Both polarizations effectively occur in the optical operating frequency regions, i.e. infrared, ultraviolet, and optical regions, in the spectrum.

In this study, highly doped-silica glass which is used for the production of optical fibers has been investigated in terms of polarization mechanisms. In this context, the changes in the dielectric constant, which is the measure of polarization, with temperature and frequency have been analyzed. The findings and analyses obtained based on the simulations carried out in the study have shown that the dielectric constant of silica increased with increasing temperature. In contrast, the dielectric constant has decreased with the linear increase in frequency. For temperature variations in the range of $0 - 500$ °K, the dielectric constant has changed between 2.070 and 2.085 approximately. On the other hand, the change of dielectric constant in the given range has been obtained in response to the change in frequency between 10^{11} Hz and 10^{12} Hz.

According to the simulation and theoretical analysis results, the temperature and frequency dependencies of the dielectric constant of highly doped-silica glass have been computed as $-7.50 \times 10^{-15}\,(\text{Hz})^{-1}$ and $2.884 \times 10^{-5}\,(°\text{K})^{-1}$, respectively. Furthermore, for values of the dielectric constant varying between 2.070 and 2.085, values of the relative change in polarization have been obtained in the range of 9.4695×10^{-12} F/m – 9.6023×10^{-12} F/m. Therefore, it has been found that relative change in polarization varies linearly with the dielectric constant of highly doped-silica glass exploited for producing the optical fiber core.

As a result, this study will contribute to the literature by providing a numerical approach to the change of the dielectric constant of highly doped-silica glass used in the production of optical fiber with both frequency and temperature. The findings obtained will be beneficial in optical fiber communication systems and sensor applications.

Statement of Research and Publication Ethics

The author declares that all the rules required to be followed within the scope of "Higher Education Institutions Scientific Research and Publication Ethics Directive" have been complied with in all processes of the article, that The Black Sea Journal of Science and the editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than The Black Sea Journal of Science.

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