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PRESSURE DEPENDENCIES OF RELATIVE CHANGE IN ELECTRICAL RESISTANCE, GAGE FACTOR AND POISSON'S RATIO IN BARE OPTICAL FIBERS

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ABSTRACT: In this paper, a distributed sensing method relying on the principle of pressure dependencies of relative change in electrical resistance, gage factor and Poisson's ratio of the bare optical fiber core has been proposed. Using this method, besides the pressure information, relations between pressure and relative change in electrical resistance, gage factor and Poisson's ratio of the bare optical fiber core have been examined and then the temperature dependencies of these parameters have been mathematically analyzed and matching simulations have also been carried out in Matlab R2021b and Simulink environments. Moreover, first-order equations expressing the relations between these parameters and their temperature dependencies have been derived benefiting from the curve-fitting method. For pressure variations in the range of 2.2×10^7 Pa – 12×10^7 Pa, relative changes in electrical resistance of the fiber core have been obtained in the range of $0.41 \times 10^{-3} - 2.13 \times 10^{-3}$. In other words, the pressure dependence of relative change in electrical resistance of the fiber core can be expressed as 1.841×10^{-2} R_{rc}(GPa)$^{-1}$, i.e. 1 GPa pressure variation occurring along the fiber core causes about 0.01841 unit of R_{rc} variation. Furthermore, pressure dependencies of the gage factor and Poisson's ratio have been acquired as 2.924×10^{-2} GF(GPa)$^{-1}$ and 1.462×10^{-2} σ(GPa)$^{-1}$, respectively.

***Keywords**: Distributed pressure sensing, Bare optical fiber, Relative change in electrical resistance of optical fiber core, Pressure, Gage factor, Poisson's ratio, Temperature*

Kılıfsız Optik Fiberlerde Bağıl Direnç Değişimi, Gage Faktörü ve Poisson Oranı'nın Basınç Bağımlılıkları

ÖZ: Bu makalede, kılıfsız optik fiber çekirdeğine ait bağıl direnç değişimi, gage faktörü ve Poisson oranının basınç bağımlılıkları prensibine dayalı bir dağınık algılama metodu önerilmiştir. Bu metot kullanılarak, basınç bilgilerinin yanı sıra, basınç ile kılıfsız optik fiber çekirdeğinin bağıl direnç değişimi, gage faktörü ve Poisson oranı arasındaki ilişki incelenmiş ve ardından bu parametrelerin sıcaklık bağımlılıkları matematiksel olarak analiz edilmiş ve ayrıca ilgili benzetimler Matlab R2021b ve Simulink ortamında gerçekleştirilmiştir. Buna ek olarak, bu parametreler ve bu parametrelerin sıcaklık bağımlılıkları arasındaki ilişkileri ifade eden birinci dereceden denklemler, eğri uydurma metodundan yararlanılarak türetilmiştir. Basıncın 2.2×10^7 Pa – 12×10^7 Pa aralığındaki değişimi için fiber çekirdeğine ait bağıl direnç değişimleri $0.41 \times 10^{-3} - 2.13 \times 10^{-3}$ aralığında elde edilmiştir. Diğer bir ifadeyle, fiber çekirdeğinin bağıl direnç değişiminin basınç bağımlılığı 1.841×10^{-2} R_{rc}(GPa)$^{-1}$ olarak ifade edilebilmektedir, yani fiber çekirdeği boyunca meydana gelen 1 GPa değerinde basınç değişimi, R_{rc} değerinde yaklaşık olarak 0.01841 birimlik değişime neden olmaktadır. Ayrıca, gage faktörünün ve

Poisson oranının basınç bağımlılıkları, sırasıyla 2.924 × 10^{-2} GF(GPa)$^{-1}$ ve 1.462 × 10^{-2} σ(GPa)$^{-1}$ olarak elde edilmiştir.

Anahtar Kelimeler: *Dağınık basınç algılama, Kılıfsız optik fiber, Optik fiber çekirdeğinin bağıl direnç değişimi, Basınç, Gage faktörü, Poisson oranı, Sıcaklık*

1. INTRODUCTION

In the optical fiber-based distributed sensing and detection systems where the physical formations such as pressure, temperature, acoustic and strain formations are detected, in particular Brillouin, Raman and Rayleigh scattering schemes are exploited. In the last decade, applications of optical fiber-based distributed sensing systems have been increasing due to the growing need for enhanced sensing systems with accurate measurement capabilities. In this regard, scientific developments accomplished in the fields of optical fiber sensing and detection systems give opportunities to detect all kinds of measurands, simultaneously (Yu, 2006; Pehlivan, 2007; Chen *et al.*, 2015; He *et al.*, 2016; Ding *et al.*, 2018; Schenatoa *et al.*, 2020; Li *et al.*, 2020; Arslan and Bayrak, 2022). Nevertheless, with the aid of innovative improvements performed in the material science, utilization of the characteristic properties of optical fiber core has become useful and favorable for getting information simultaneously about the physical measurands such as temperature, pressure, vibration and acoustic formations occurring in the working medium (Gu *et al.*, 2012; Boydak and Yücel, 2017; Gökbulut *et al.*, 2017; Günday *et al.*, 2018; Bilsel and Navruz, 2020).

In this paper, relations between pressure formations along the bare optical fiber and relative change in electrical resistance of the fiber core have been theoretically analyzed and hereby a different alternative approach in terms of sensing principle to the pressure transducers like strain-gage, load cell and piezoresistive pressure detectors has been proposed. In other words, a novel sensing method for measurements of distributed pressure formations which in principle is based on the pressure dependence of relative change in electrical resistance has been put forward. The pressure induced by the force applied to a substance causes the longitudinal and lateral stresses and strain formations on the substance and leads to variations in its elasticity modulus, as well. For this reason, pressure effects arising along the optical fiber can cause to stretch the optical waveguide and hence induces the strain formations through the bare optical fiber and thus vary the relative change in electrical resistance, gage factor and Poisson's ratio of the fiber core. Therefore, pressure dependencies of relative change in electrical resistance, gage factor and Poisson's ratio of the bare fiber core have been investigated and the mathematical equations have been derived in Matlab 2021b and Simulink environments in this study.

2. MATERIAL AND METHOD

The pressure applied to a matter is defined as the ratio of the force applied on a matter and the surface area influenced by the force. In other words, pressure formations can be stated as a function of the elasticity modulus which is the ratio of stress, below the proportional limit, to the corresponding strain formations as given with (Sokkar, 2012; Günday *et al.*, 2014; İrsel, 2021)

$$P = \frac{F}{A} = E.\varepsilon \quad (1)$$

where P is the pressure formation, F is the external force acting on the object, A is the cross-sectional area of the object, E is the elasticity modulus and ε is the mechanical strain formation, respectively.

The mechanical strain is generally caused by external loads and constraints. In this context, the combined effect of thermal formation in the medium and the mechanical strain which is a geometrical measurement of deformation describing the relative displacement between particles in a matter causes a relative change in the electrical resistance of the matter. The relative change in electrical resistance ΔR/R (R_{rc}) is a characteristic parameter that can be formulated by (Tuttle and Brinson, 1984)

$$R_{rc} = \varepsilon . GF + \alpha . \Delta T \quad (2)$$

where GF denotes the gauge factor or strain factor of a strain gauge, α and ΔT denote the temperature coefficient and temperature difference, respectively. Temperature coefficient α of the bare optical fiber core used in the sensing model in this study has been taken as 5.5×10^{-7}/°K.

The gage factor shows a change depending on Poisson's ratio which is an important material characteristic utilized for determining the elasticity of the substance and the strain formation for the materials having strong resistive properties. When a substance is compressed in one direction, Poisson's ratio generally tends to enlarge in the other two directions perpendicular to the direction of compression. This event is called the Poisson's effect in the literature and Poisson's ratio (σ) is stated as a measure of the Poisson's effect (Wang, 2012; Carneiro and Puga, 2018).

The change in resistivity ($\Delta\varrho$) for the materials such as optical fiber is assumed as zero, i.e. $\Delta\varrho = 0$, for this reason gage factor (GF) of a given material is expressed with

$$GF = 1 + 2\sigma \quad (3)$$

where σ is the Poisson's ratio of the substance (Wang 2012).

On the other hand, the gage factor or strain factor can be described as a ratio of the relative change in electrical resistance to the mechanical strain. For the temperature value of the optical fiber at 293 °K, Poisson's ratio (σ) is 0.165 and the change in resistivity ($\Delta\varrho$) is zero, thus GF is computed as 1.331, approximately (De Souza 1999; İrsel, 2021; Sanchez *et al.*, 2022).

Since the Poisson's ratio changes linearly due to the temperature variations (De Souza 1999), both the gage factor and the pressure formations occurring along the bare optical fiber core vary with ambient temperature, linearly. In other words, as the temperature varies in the medium, the gage factor and the pressure formations are influenced by thermal variations of the medium. If there are no temperature gradient ($\Delta T = 0$) and temperature effects in the medium or sensing system, the gage factor changes only with strain formations. However, if temperature variations occur in the sensing system, making use of (1) and (2) pressure formations $P(R_{rc})$ occurring along the entire length of the bare optical fiber core can be formulated as

$$P(R_{rc}) = \frac{1}{GF} . E . (R_{rc} - \alpha . \Delta T) \quad (4)$$

where P(Rrc) is the pressure formations along the bare optical fiber core and E is the elasticity modulus of the fiber core in terms of GPa.

In this paper, the relative change in electrical resistance of bare optical fiber core, gage factor, Poisson's ratio and temperature variations depending on the pressure effects have been analyzed and the simulations related to their dependencies have been performed utilizing the optical fiber-based distributed pressure sensing (DPS) model shown in Figure 1. In this DPS model exploiting the BOTDR principle which is based on the interaction of photons propagating inside the sensing fiber with acoustic waves, optical pulses launched into the sensing fiber are produced by distributed feedback laser (DFB-LD) with the output power of 2 mW and pulse duration of 10 ns. The sensing fiber used in the model constructed for getting pressure information is bare optical fiber, i.e. standard communication single-mode fiber (SMF) operating at 1550 nm.

The sensing fiber, i.e. bare optical fiber is exposed to pressure effects generated by the sensing equipment used in the model for producing pressure formations along the fiber. The optical signal pumped by the laser into the bare optical fiber is amplified via EDFA (Erbium-doped fiber amplifier) and then routed towards the AOM (Acousto-optic modulator) to suppress the ASE noise at the output end of EDFA and modulate the signal via acousto-optic effect. The directional coupler positioned in the sensing model has two arms that are connected to the AOM and photodetector. It is used for directing the optical signal towards the fiber under pressure (FUP), i.e. bare optical fiber with the length of 900 m and routed the backscattered optical signal to the photodetector to detect pressure formations occurring along the fiber. Finally, a photodetector is employed to convert incident light into the electrical signal and then the spectrum analyzer and the oscilloscope visualizer are exploited for getting frequency information and monitoring the output signal to accomplish the computational analysis, consecutively. Afterward, using the output electrical signal, corresponding simulations relevant to all the parameters are obtained in Matlab R2021b and Simulink environments.

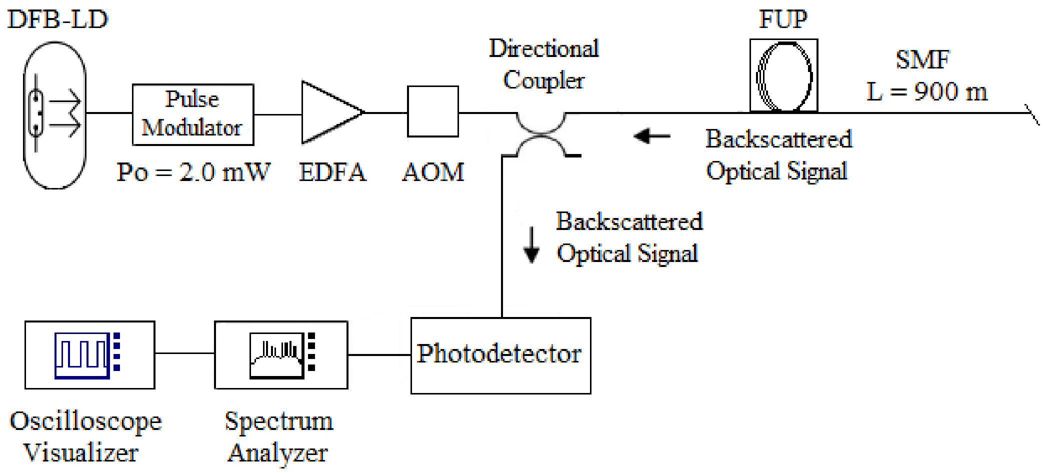

Figure 1. Optical fiber-based distributed pressure sensing (DPS) model

3. RESULTS AND DISCUSSIONS

Mathematical analysis and the simulations concerning the pressure variations, relative change in electrical resistance, gage factor, Poisson's ratio and ambient temperature have been performed via Matlab R2021b utilizing the sensing model shown in Figure 1. Parameters of the sensing fiber, i.e. bare optical fiber in the model for making analysis and getting simulations are given as the following: wavelength of the optical signal (λ) pumped by distributed feedback laser (DFB-LD) is 1550 nm, the core and the cladding refractive indices (n_1 and n_2) are 1.475 and 1.455, respectively. Rayleigh and Brillouin scattering coefficients (αR and αB) at 1550 nm are 3.5686×10^{-5} m^{-1} and 1.1071×10^{-6} m^{-1}, respectively. The spatial resolution (Δz) of the DPS model is 1.01625 m, the length of the bare optical fiber (L) is 900 m and the number of distributed measurement points ($R = L/\Delta z$) along the fiber length is 886.

Figure 2 shows the linear relation between pressure variation and relative change in electrical resistance of the bare optical fiber core. As is seen in Figure 2, as the pressure effect existing along the fiber increases, the relative change in electrical resistance of the fiber core shows tendency to increase linearly. This linearity between pressure effects and the relative changes in electrical resistance of the fiber core is caused by the dielectric property of the fiber core and so is important for designing the possible fiber-based pressure transducers in practical applications.

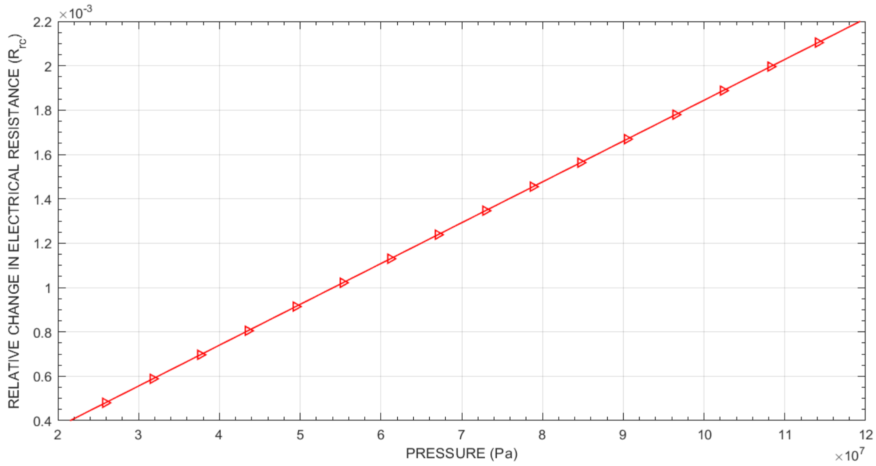

Figure 2. Relative change in electrical resistance versus pressure variation

Using (3), both the pressure dependence of relative change in electrical resistance ($R_{rc}(P)$) of the bare optical fiber core and the pressure variation as a function of relative change in electrical resistance ($P(R_{rc})$) can be formulated as given in (5) and (6)

$$R_{rc}(P) = 1.841x10^{-11}P + 3.815x10^{-6} \quad (5)$$
$$P(R_{rc}) = 5.433x10^{10}R_{rc} + 2.073x10^{5} \quad (6)$$

respectively, where P and R_{rc} denote the pressure variation and the relative change in electrical resistance of the fiber core, respectively.

From (4), it can be stated that the relative change in electrical resistance (R_{rc}) dependence of the pressure variation is 54.33 GPa$(R_{rc})^{-1}$. In other words, a change in the R_{rc} value of 1 unit, induces the variation in pressure value of 54.33 GPa, approximately. From another point of view, 1 GPa pressure effect occurring along the fiber core causes about 0.01841 unit in value of R_{rc}. For the relative change in electrical resistance of the bare optical fiber core in the range of 0.4×10^{-3} – 2.2×10^{-3}, pressure values show a change in the range of 20 MPa – 120 MPa. Pressure formation along the bare optical fiber core gets its average value of about 65 MPa for the relative change in electrical resistance (R_{rc}) value of 1.2×10^{-3}.

The pressure formations occurring along the bare optical fiber core with varying gage factor values are obtained using (4) as shown in Figure 3.

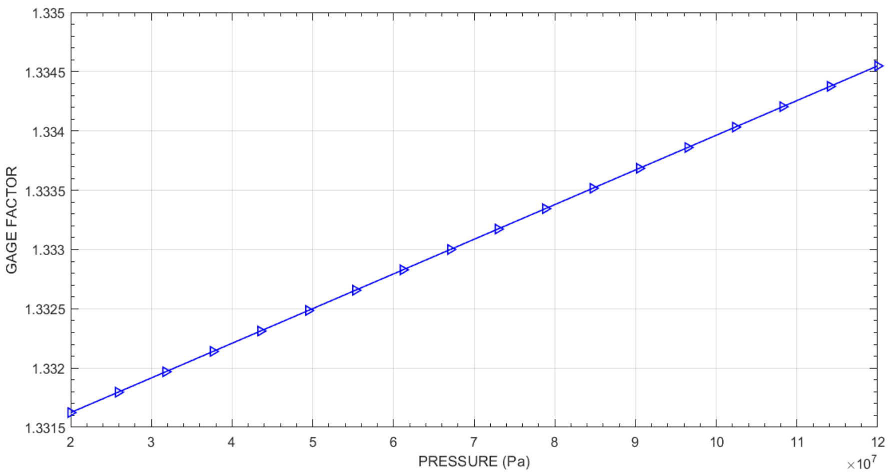

Figure 3. Gage factor changes versus pressure variations in the range of 1.3316 – 1.3345

There is a linear relation between pressure and gage factor variations as unambiguously seen in

Figure 3. The gage factor gets its minimum and maximum values of 1.3316 and 1.3345, respectively for pressure variations in the range of 2.2×10^7 Pa – 12×10^7 Pa.

Making use of the simulation represented in Figure 3 and the curve-fitting tool in Matlab R2021b, first-order equations describing the relations between pressure variations occurring along the bare optical fiber and change in the gage factor of the fiber core can be written by (7) and (8)

$$\mathrm{GF(P)} = 2.924\mathrm{x}10^{-11}\mathrm{P} + 1.331 \quad (7)$$
$$\mathrm{P(GF)} = 3.420\mathrm{x}10^{10}\mathrm{GF} - 4.552\mathrm{x}10^{10} \quad (8)$$

respectively, where GF(P) is the gage factor of the bare optical fiber and P(GF) is the pressure variation depending on the gage factor of the fiber core in terms of Pa.

The plot representing the changes in Poisson's ratio due to the pressure formations occurring along the optical fiber is indicated in Figure 4.

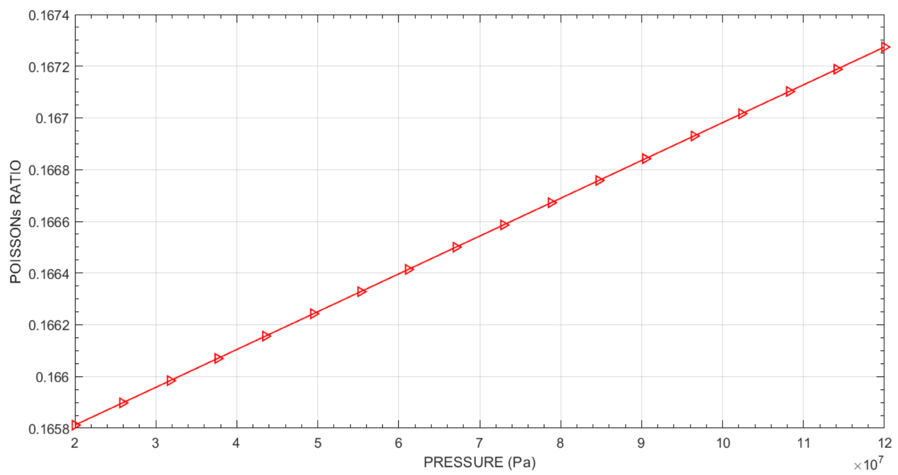

Figure 4. Poisson's ratio versus pressure variation

As is seen in this figure, there is a linear relationship between pressure variation and Poisson's ratio, similar to that of pressure variation with the relative change in electrical resistance and gage factor of the fiber core. In other words, an increase in the value of pressure causes the increase in the values of Poisson's ratio, gage factor and relative change in electrical resistance of the fiber core due to the material compositions both of the core and the cladding of the bare optical fiber.

First-order equations expressing both the Poisson's ratio as a function of pressure variation and the Poisson's ratio dependence of pressure variation can be written in (9) and (10)

$$\sigma(\mathrm{P}) = 1.462\mathrm{x}10^{-11}\mathrm{P} + 0.1655 \quad (9)$$
$$\mathrm{P}(\sigma) = 6.839\mathrm{x}10^{10}\sigma - 1.132\mathrm{x}10^{10} \quad (10)$$

respectively, where σ is the Poisson's ratio of bare optical fiber.

Using Figure 4 and (9) and (10), for Poisson's ratio variations in the range of 0.1658 – 0.1673, pressure values change in the range of 2.2×10^7 Pa – 12×10^7 Pa.

The pressure variations depending on the temperature formations occurring along the bare optical fiber are plotted as illustrated in Figure 5. It is obvious in Figure 5, thermal effects generated in the medium, i.e. temperature formations occurring along the bare optical fiber induce the pressure variations through the entire length of the fiber core.

The linear equation pointing out temperature dependence of pressure variation is derived from the simulation shown in Figure 5 as stated in (11).

$$P(T) = 1.974x10^6T - 5.827x10^8 \quad (11)$$

For temperature variations in the range of 300 °K – 500 °K, pressure formations change in the range of 0.095 × 10^8 Pa – 4.5 × 10^8 Pa, approximately.

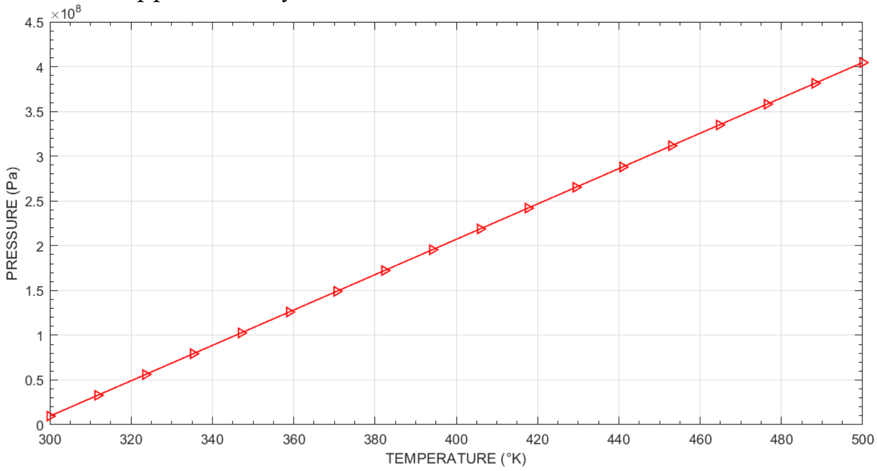

Figure 5. Pressure variations for temperature changes in the range of 300 °K – 500 °K

Using the simulation illustrated in Figure 5, the temperature dependence of pressure is computed as about 1.974 × 10^6 Pa/°K. In other words, a 1 °K variation in the temperature of the fiber core causes a 1.974 GPa variation in pressure formation occurring along the bare optical fiber.

The simulation result obtained for the correlation between relative change in electrical resistance and the temperature of the fiber core is shown in Figure 6.

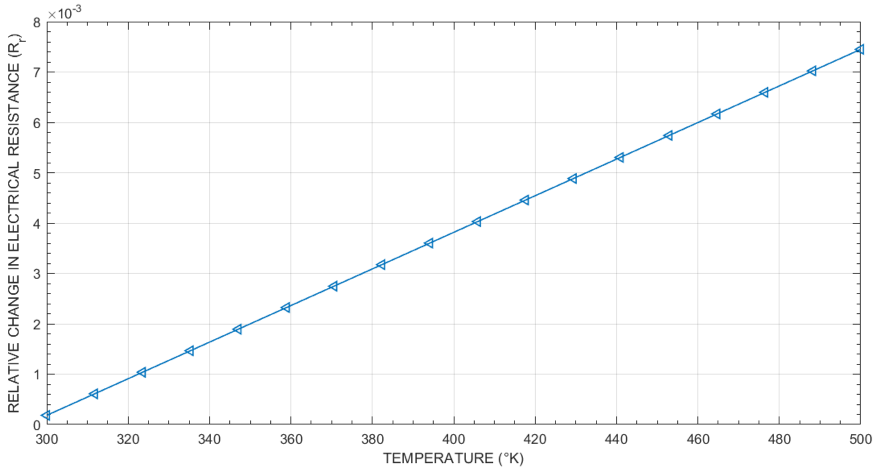

Figure 6. Relative change in electrical resistance of the fiber core with varying temperature

As obviously seen in the figure, relative change in electrical resistance of the bare optical fiber core changes linearly with temperature variation.

Using data of the parameters obtained from the simulation represented in Figure 6, a linear equation expressing temperature dependence of relative change in electrical resistance of the fiber core can be written as

$$R_{rc}(T) = 3.634x10^{-5}T - 0.01072 \quad (12)$$

where R_{rc} is the relative change in electrical resistance of the fiber core and T is the temperature of the fiber core, respectively.

For temperature variations in the range of 300 °K – 500 °K, changes of R_{rc} are obtained in the range of

$0.0109 \times 10^{-3} - 7.45 \times 10^{-3}$ along the bare optical fiber.

Figure 7 illustrates the gage factor variations in the range of 1.33132 – 1.34287 due to the temperature formations changing from 300 °K to 500 °K. In other words, for temperature values of 300 °K and 500 °K, the gage factor reaches to its minimum and maximum values with 1.33132 and 1.34287, respectively.

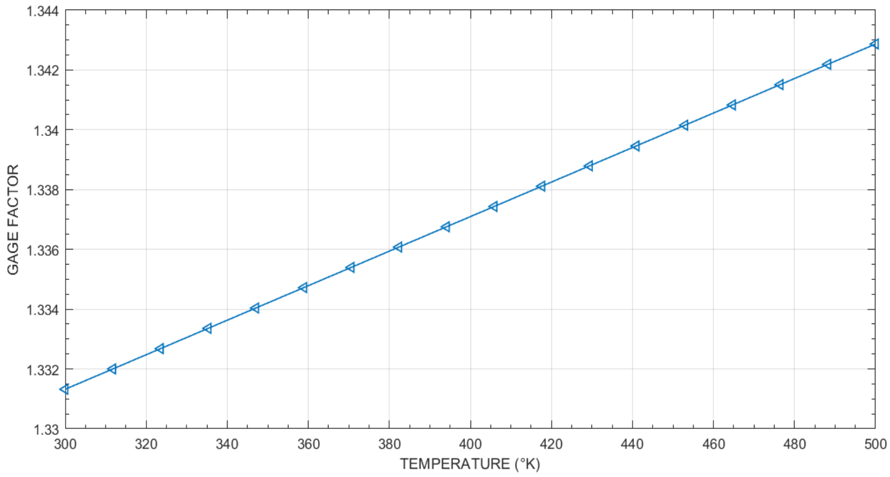

Figure 7. Gage factor versus temperature variation.

Using the mathematical method employing the curve-fitting tool in Matlab R2021b, the gage factor is expressed as

$$\mathrm{GF(T)} = 5.774\mathrm{x}10^{-5}\mathrm{T} + 1.314 \quad (13)$$

where GF is the gage factor and T is the temperature of the core in terms of Kelvin.

Taking the first-order derivative of (10), the temperature dependence of the gage factor is found as 5.774×10^{-5} GF(K^{-1}). It is useful for evaluating the sensing system performance depending on the gage factor or strain factor of the fiber core and well suited to the findings and the research studies accomplished in the literature.

4. CONCLUSION

This research paper presents a method for distributed measurements of pressure formations utilizing the relations between pressure and particularly the relative change in electrical resistance of the bare optical fiber core. To perform this method a model has been constructed and then both the pressure dependencies of relative change in electrical resistance, gage factor, Poisson's ratio of the fiber core and the relations between these parameters and temperature variations in the range of 300 °K – 500 °K have been mathematically analyzed and thus corresponding simulations have been performed in Matlab 2021b/Simulink environment. Within this scope, linear equations related to these parameters have also been derived by exploiting the curve-fitting method.

Benefiting from the equations and the simulation results obtained in this study, pressure dependence of relative change in electrical resistance of the fiber (R_{rc}) has been found as 1.841×10^{-11} $R_{rc}(Pa)^{-1}$ whilst R_{rc} dependence of pressure variation has been computed as 5.433×10^{10} $Pa(R_{rc})^{-1}$. On the other hand, pressure dependencies of the gage factor and Poisson's ratio have been acquired as 2.924×10^{-2} $GF(GPa)^{-1}$ and 1.462×10^{-2} $\sigma(GPa)^{-1}$, respectively. Furthermore, for temperature variations between 300 °K and 500 °K, pressure changes, gage factor and Poisson's ratio have been obtained as a function of temperature as 1.974×10^{6} Pa/°K, 3.634×10^{-5} R_{rc}/°K and 5.774×10^{-5} GF/°K, respectively.

Moreover, this research provides an innovative and different approach from the similar studies fulfilled in the literature in terms of the sensing method used for distributed measurements of the pressure variations and getting information about the relative change in electrical resistance, gage factor and

Poisson's ratio of the bare optical fiber. Consequently, it may form an important and valuable background for future investigations and empirical applications to be performed in the field and can be considered to be the best candidate to meet the requirements both in distributed sensing systems and strain gauge implementations in electronics so far.

5. DECLARATION OF INTERESTS

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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