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Fiber Optic Sensors (FOSs) for Thermal Sensing Applications

Ahmed Nabih Zaki Rashed
Electronics and Electrical Communications Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT
E-mail: ahmed_733@yahoo.com
Tel.:+20483660716, Fax.:+20483660716

***Abstract*— Fiber optic sensors were first developed few decades ago for markets where no other sensing solutions existed, such as applications where high electromagnetic interferences (EMI) could be present. Typical applications were for instance temperature measurements in microwave ovens or in high power transformers, strain measurements in electrical welding jaws, pressure measurements for medical applications. If insensitivity to EMI is probably the most interesting advantage of such sensors, other interesting advantages are now being considered: since optical technologies proved to be reliable and accessible, new applications are emerging where reduced size or geometry of such sensors could be the most interesting features. This paper has presented the important transmission characteristics of thermal sensors over wide range of the affecting parameters. The free spectral range (FSR), sensor accuracy, sensor resistance and capacitance, thermal sensing signal quality, sensor thermal sensitivity and response time are the major interesting design parameters in our current research under low and high temperature effects.**

Index Terms*— *Intrinsic sensor, fiber optic sensors, Thermal sensors, Free spectrum range, Response time and Signal quality.

I. INTRODUCTION

The world of fiber optic sensors lies at the intersection of fiber optic communication and optoelectronics. Fiber optic sensors offer many advantages over conventional electrical or electromechanical sensors [1]. First, optical fiber is a dielectric, so it is not subject to interference from electromagnetic waves that might be present in the sensing environment. Secondly fiber optic sensors can function under harsh environment, such as high temperature, toxic or corrosive atmospheres where metals or other materials can be corroded. In addition, semiconductor based photodectctors and laser diode sources are usually small and light, so fiber-optic sensors are useful as sensing devices for wider range of physical and chemical phenomena that include temperature, pressure, acoustic field, position, rotation, electrical current [2], liquid level, biochemical composition, and chemical concentration. Indeed, fiber-optic sensors can perform the functions of virtually any conventional sensor and even faster and with greater sensitivity. Particularly, they can perform measurement tasks that would be impracticable with conventional sensors. For instance, they can be embedded in critical structures, such as airplanes and bridges, reporting continuously on structural integrity, and possibly averting a catastrophic failure [3]. The numerous advantages of fiber optic sensors will ensure that they continue to attract research funding for their further development. Even more noteworthy is the fact that commercially available fiber optic sensors are increasing. It is a promising field with clear advantages over conventional sensors in certain applications [4].

Fiber optic sensors have many advantages such as ease of embedding, flexible sensor size, wide temperature range, high sensitivity and etc [5]. Thus, fiber optic sensors have been introduced into many composite structures. Especially, FBG (Fiber Bragg Grating) strain sensors have noticeable attractions due to multiplexing capability, linear response and absolute measurement [6]. However, the use of FBG sensors is limited by their simultaneous dependence on strain and temperature, directional sensitivity variation, weakened sensor head due to fabrication process, etc [7]. In case of detecting high frequency signals, multiplexing capability is worse and conversely, most multiplexed FBG systems have low frequency ranges. And the sensitivity fadeout problem in the intensity demodulation method is another issue for FBG vibration sensor system. To overcome sensitivity fadeout problems, some passively controlled systems for a single head FBG sensors system were suggested but do not guarantee uniform sensitivity [8]. And to measure internal and external strains of the composite pressure vessels in real time, the mechanical failure of FBG sensors or optical fiber and the spectral distortion in reflected signals have to be overcome [9]. Thus, in order to implement FBG sensors to real structures, much attention has been paid to overcome these limitations.

In the present study, fiber optic sensor technology has been and is being increasingly exploited by the research community because of its relatively simple design, low power consumption, low cost, relatively low maintenance cost, and the flexibility it offers for both commercial and military applications. In particular, fiber optic thermal sensors have been recognized as promising technologies for numerous applications, which include intruder detection and perimeter multiplexing systems for commercial applications.

II. INTRINSIC FIBER OPTIC SENSORS

Fiber optic sensors have advantages over other sensors. They have a further range, lower cost, and generally smaller in size. These sensors can be intrinsic or extrinsic [10]. Figure 1 represents a basic intrinsic sensor with length L_s, sensor diameter (D_s=D_{clad}) is equal to fiber cladding diameter and its length, L_f, sensor refractive index (n_s=n_2) is equal to cladding refractive index and based on polymer fiber cladding as a guidance of temperature sensing technology. This sensor uses the optical fiber that is carrying the light, and detects an environmental effect which forces information on the light inside the fiber.

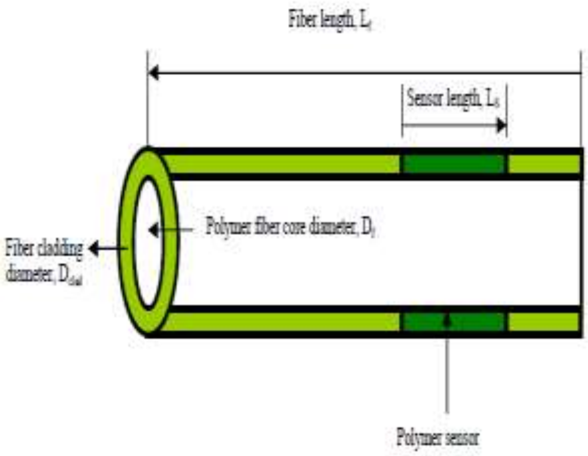

Fig. 1. Schematic diagram of the core based fiber optic sensor.

Optical fibers can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fiber so that the quantity to be measured modulates the intensity, phase, polarization, wavelength or transit time of light in the fiber. Sensors that vary the intensity of light are the simplest, since only a simple source and detector are required. A particularly useful feature of intrinsic fiber optic sensors is that they can, if required, provide distributed sensing over very large distances [11].

III. THEORETICAL MODEL ANALYSIS

The investigation of both the thermal and spectral variations of the refractive index require empirical equation. The set of parameters required to completely characterize the temperature dependence of the refractive index of both fiber core and sensor are given below, Sellmeier equation is under the form [12]:

$$n_c = \sqrt{\frac{A_1\lambda^2}{\lambda^2 - A_2^2} + \frac{A_3\lambda^2}{\lambda^2 - A_4^2} + \frac{A_5\lambda^2}{\lambda^2 - A_6^2}}\ , \qquad (1)$$

$$n_s = \sqrt{\frac{B_1\lambda^2}{\lambda^2 - B_2^2} + \frac{B_3\lambda^2}{\lambda^2 - B_4^2} + \frac{B_5\lambda^2}{\lambda^2 - B_6^2}}\ , \qquad (2)$$

The thermo-optic effect and spectral variations are present in all transparent materials and describes the dependence of the material index of both fiber core and sensor can be expressed as the following [13]:

$$\frac{dn_c}{dT} = \left(-\frac{\lambda^2}{n_c}\right)\left[\frac{A_1A_2\frac{\partial A_2}{\partial T}}{\left(\lambda^2 - A_2^2\right)^2} + \frac{A_3A_4\frac{\partial A_4}{\partial T}}{\left(\lambda^2 - A_4^2\right)^2} + \frac{A_5A_6\frac{\partial A_6}{\partial T}}{\left(\lambda^2 - A_6^2\right)^2}\right] \qquad (3)$$

$$\frac{dn_s}{dT} = \left(-\frac{\lambda^2}{n_s}\right)\left[\frac{B_1B_2\frac{\partial B_2}{\partial T}}{\left(\lambda^2 - B_2^2\right)^2} + \frac{B_3B_4\frac{\partial B_4}{\partial T}}{\left(\lambda^2 - B_4^2\right)^2} + \frac{B_5B_6\frac{\partial B_6}{\partial T}}{\left(\lambda^2 - B_6^2\right)^2}\right] \qquad (4)$$

$$\frac{dn_c}{d\lambda} = -\frac{\lambda}{n_c}\left[\frac{A_1A_2^2}{\left(\lambda^2 - A_2^2\right)^2} + \frac{A_3A_4^2}{\left(\lambda^2 - A_4^2\right)^2} + \frac{A_5A_6^2}{\left(\lambda^2 - A_6^2\right)^2}\right] \qquad (5)$$

$$\frac{dn_s}{d\lambda} = -\frac{\lambda}{n_s}\left[\frac{B_1B_2^2}{\left(\lambda^2 - B_2^2\right)^2} + \frac{B_3B_4^2}{\left(\lambda^2 - B_4^2\right)^2} + \frac{B_5B_6^2}{\left(\lambda^2 - B_6^2\right)^2}\right] \qquad (6)$$

Where the set of the parameters of empirical equation coefficients for different polymeric materials based both sensor and fiber core as a function of ambient temperature T, and room temperature T_0 are listed in Table 1.

Table 1: Sellemier coefficients for polymeric materials based both fiber core and sensor [12, 17, 19].

Coefficients	Material based fiber core Polystyrene (PS)	Coefficients	Material based sensor Polymethylmethacrylate (PMMA)
A_1	0.08432	B_1	0.4963
A_2	12.07654 (T/T_0)	B_2	0.6965 (T/T_0)
A_3	2.06543	B_3	0.3223
A_4	0.976542 (T/T_0)	B_4	0.718 (T/T_0)
A_5	0.007431	B_5	0.1174
A_6	47.20652 (T/T_0)	B_6	9.237 (T/T_0)

The index of refraction for the polymer fiber from which the optical fibers are made is temperature dependent, causing the center wavelength of the sensor to be temperature dependent as well. The effective refractive index of the fiber core and sensor materials is given by [14]:

$$n_{eff} = \sqrt{\left(n_c^2 - n_s^2\right)b + n_s^2}\ , \qquad (7)$$

Where b is the normalized propagation constant and is given by [15]:

$$b(V) = \left(1.1428 - \frac{0.9660}{V}\right)^2, \qquad (8)$$

Where V is the normalized frequency. For single mode step index optical fiber waveguide, the cut-off normalized is approximately $V = V_c = 2.405$, and by substituting in Eq. (8), we can get the normalized propagation constant b at the cut-off normalized frequency approximately $b \approx 0.5$, and then by substituting in Eq. (7), then the deuced expression:

$$n_{eff} = \sqrt{0.5\left(n_c^2 + n_s^2\right)}\ , \qquad (9)$$

The effective refractive index n_{eff} is dependent on the refractive indices of the fiber and sensor materials, then by selecting proper materials of the sensor and fiber core to satisfy Eq. (9), an a thermal sensor can be designed. Differentiation of Eq. (7) with respect to both optical signal wavelength λ and ambient temperature T, which yields:

$$\frac{dn_{eff}}{d\lambda} = \left(\frac{0.5}{n_{eff}}\right)\left[n_c\frac{dn_c}{d\lambda} + n_s\frac{dn_s}{d\lambda}\right]\ , \qquad (10)$$

$$\frac{dn_{eff}}{dT} = \left(\frac{0.5}{n_{eff}}\right)\left[n_c\frac{dn_c}{dT} + n_s\frac{dn_s}{dT}\right]\ , \qquad (11)$$

By solving the coupled mode equations, the transmission property of light propagating along the fiber can be obtained.

The free spectrum range (FSR) of fiber optic sensor can be given as follow [16]:

$$FSR = \frac{\lambda^2}{\pi\, n_{eff}\, L_s}, \qquad (12)$$

Where L_s is the sensor length in mm, n_{eff} is the effective index of the mode propagating in the fiber and λ is the optical signal wavelength in μm. The thermal sensing quality factor (Q_s) of the sensor can be calculated as [17]:

$$Q_s = \frac{\lambda}{FWHM}, \qquad (13)$$

Where FWHM is the full width at half maximum which is applied to such phenomena as the duration of pulse waveforms and the spectral width of sources used for optical communications and the resolution of spectrometers and can be estimated as the following formula [18]:

$$FWHM = 0.635482\ BW_{sig.} \qquad (14)$$

Where $BW_{sig.}$ is the transmitted signal bandwidth for single mode fiber, which is given by [19]:

$$BW_{sig.} = \frac{0.44}{\tau} \qquad (15)$$

Where τ is the total pulse broadening through fiber core and is given by:

$$\tau = L_f\, D_t\, \Delta\lambda_s \qquad (16)$$

Where L_f is the fiber length, $\Delta\lambda_s$ is the spectral linewidth of the optical source in nm, and D_t is the total dispersion coefficient based standard multi mode fiber (MMF) which is given by [20]:

$$D_t = D_{mat.} + D_P\ , \qquad (17)$$

Where $D_{mat.}$ and D_P are the material and profile dispersion respectively, which they can be estimated as [21]:

$$D_{mat.} = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}, \qquad (18)$$

$$D_P = \left(\left(\frac{N_1 \Delta n}{c\lambda}\right)^2 \left(\frac{g-2-\varepsilon}{g+2}\right)^2 \times \frac{2g}{3g+2}\right)^{0.5} \qquad (19)$$

Where N_1 is the group index for the mode which is given by:

$$N_1 = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}\ , \qquad (20)$$

Where C_1 is a constant related to index exponent and profile dispersion and is given by:

$$C_1 = \frac{g-2-\varepsilon}{g+2}\ , \qquad (21)$$

Where g is the index exponent, and ε is the profile dispersion parameter and is given by:

$$\varepsilon = -\frac{2 n_{eff}}{N_1}\frac{\lambda}{\Delta n}\ , \qquad (22)$$

Δn is the relative refractive index difference and is given:

$$\Delta n = \frac{n_c - n_s}{n_c}\ , \qquad (23)$$

When the temperature is changed, the length and index of the fiber will be varied, which shifts the wavelength correspondingly. In order to obtain the wavelength in a dynamic temperature field, we make a derivation calculus to Eq. (12) on temperature, thus the relationship can be evaluated as below [22]:

$$\Delta\lambda_{shift} = \left(\alpha_{ps} + \beta_{ps}\right)\lambda\,\Delta T \qquad (24)$$

Where ΔT is the temperature variations above room temperature ($T-T_0$), α_{ps} is the coefficient of thermal expansion of the polystyrene fiber, $\beta_{ps}=1/n_c\ (dn_c/dT)$ is the thermal optical coefficient of the polystyrene fiber. Generally, the wavelength shift Δλ is small compared with wavelength λ. The response time in heating and cooling processes of these sensors can be described by the lumped system equation [23]. For these cylindrical polymers fiber with radius r_f and sensor with radius r_s, the thermal sensing response time equation can be described as:

$$T_R = \frac{c_p\, \rho \left(r_f + r_s\right)}{2h}\ , \qquad (25)$$

Where ρ is the density of the fiber material, c_p is its the specific heat, and h is the convection coefficient. it is indicated that the higher thermal sensing response time, the lower thermal sensing process. The intensity transmission coefficient T_s, representing the ratio of the transmission intensity to the input intensity, can be obtained according to general principle of fiber optic sensor [16, 23] and has the expression:

$$T_s = \frac{\exp\left(-\alpha_{ps} L_s\right) + (\sin(K)^2}{1 + \exp\left(-\alpha_{ps} L_s\right)\left(\sin(K)\right)^2}\exp\left(-c_p / h\right) \qquad (26)$$

Where K=0.5(2m+1)π is the coupling parameter, and m is an integer. Following the sensing mechanism the sensitivity can be defined as the following formula [24]:

$$SS = \frac{T}{n_{eff}}\left(\frac{dn_{eff}}{dT}\right), \qquad (27)$$

The fiber optic sensor thermal resistance R_s, for both low and high temperatures can be expressed as [25]:

$$R_s = R_{Ref.}\exp\left(\gamma\left(\frac{1}{T} - \frac{1}{T_{Ref.}}\right)\right), \qquad (28)$$

Where $R_{Ref.}$ is the reference resistance and is equal to 50 Ω and 20 Ω at low and high temperature respectively, γ is a coefficient and is equal to 0.81365×10^3/°C, and $T_{Ref.}$ is the reference temperature and is equal to 75 °C and 825 °C at low and high temperatures respectively. As well as the fiber optical sensor capacitance C_s can be given by [26]:

$$C_s = \frac{2\pi\, \varepsilon_0\, \varepsilon_r\, L_s}{\ln\left(r_s / r_c\right)}, \qquad (29)$$

Where ε_0 is the permittivity of free space, ε_r is the relative permittivity and is equal to 2.453 for PMMA material based fiber optic sensor. Therefore the fiber optic sensor operating frequency f_{os}, is given by:

$$f_{os} = \frac{0.263}{R_s\, C_s}, \qquad (30)$$

The total temperature error (TTE) and is related to the sensor accuracy (S_A) percentage at both low and high temperatures respectively can be given by [27, 28]:

$$S_{AL}(\%) = \frac{1}{TTE_L} = \frac{1}{h_1(75\,°C - T)(T - 25\,°C) - h_2(T - 25\,°C) + TE_{25\,°C}} \qquad (31)$$

$$S_{AH}(\%) = \frac{1}{TTE_H} = \frac{1}{h_3(125\,°C - T)(T - 125\,°C) + h_4(T - 825\,°C) + TE_{125\,°C}} \qquad (32)$$

Where $h_1=150 \times 10^{-6}$/°C, $h_2=7 \times 10^{-3}$, $TE_{25\,°C}=0.5$ °C, $h_3=-200 \times 10^{-6}$/°C, $h_4=-1 \times 10^{-3}$, and $TE_{125\,°C}=0.6$ °C.

IV. Simulation Results and Performance Analysis

We have investigated the core based intrinsic fiber optic absorption sensor over wide range of the affecting operating parameters as shown in Table 2. The Fiber optic sensors have developed fir thermal sensing over wide temperature range variations to be tested its high thermal sensitivity and sensor accuracy.

Table 2: Proposed operating parameters for electro-absorption modulators [2, 5, 7, 12, 15].

Parameter	Definition	Value and unit
T_{low}	Low ambient temperature	25 °C— 75 °C
T_{high}	High ambient temperature	125 °C— 825 °C
α_{ps}	Thermal expansion coefficient	$-1x10^{-5}$/°C
L_s	Sensor length	5 mm—10 mm
T_0	Room temperature	25 °C
ΔT_{low}	Low temperature variations	0 °C— 50 °C
ΔT_{high}	High temperature variations	100 °C— 800 °C
λ	Optical signal wavelength	1.3 μm— 1.65 μm
r_s=0.5 D_s	Sensor radius	210—250 μm
r_f=0.5 D_f	Fiber core radius	200 μm
$\Delta\lambda_s$	Spectral linewidth of optical source	0.1 nm
β_{ps}	Thermal optical coefficient	$5x10^{-5}$/°C
ρ	Fiber material density	1.102 g/cm^3
c_p	Specific heat	0.00874 J/g/T, T in °C
h	Convection coefficient	0.04 $Watt/cm^2$.T, T in °C
L_f	Fiber length	50 mm
g	Index exponent	2
m	Integer	1
ε_0	Permittivity of free space	$8.854x10^{-14}$ f/cm

Based on the model equations analysis, assumed set of the operating parameters, and the set of the series of the Figs. (2-22), the following facts are assured:

i) Figs. (2, 3) have indicated that FSR increases with increasing both ambient temperatures with its low and high values and operating optical signal wavelength. It is indicated that FSR has presented its higher values under high temperatures effects compared to lower values under low temperatures effects.

ii) As shown in Figs. (4, 5) have assured that FSR decreases with increasing sensor length under low and high temperature effects. While FSR has presented its higher values under high temperatures effects compared to lower values under low temperatures effects.

iii) Figs. (6, 7) have demonstrated that as both operating optical signal wavelength and ambient temperatures with its low and high values increase, this leads to increase in thermal sensing quality factor. It is observed that thermal sensing quality factor has shown its higher values under high temperatures effects compared to lower values under low temperatures effects.

iv) As shown in Figs. (8, 9) have assured that wavelength shift increases with increasing both ambient temperatures and operating optical signal wavelength under low and high temperature effects. While wavelength shift has shown its higher values under high temperatures effects compared to lower values under low temperatures effects.

v) Figs. (10, 11) have demonstrated that as both sensor radius and ambient temperatures with its low and high values increase, this results in increasing thermal sensing response time. It is observed that thermal sensing response time has shown its higher values under high temperatures effects compared to lower values under low temperatures effects.

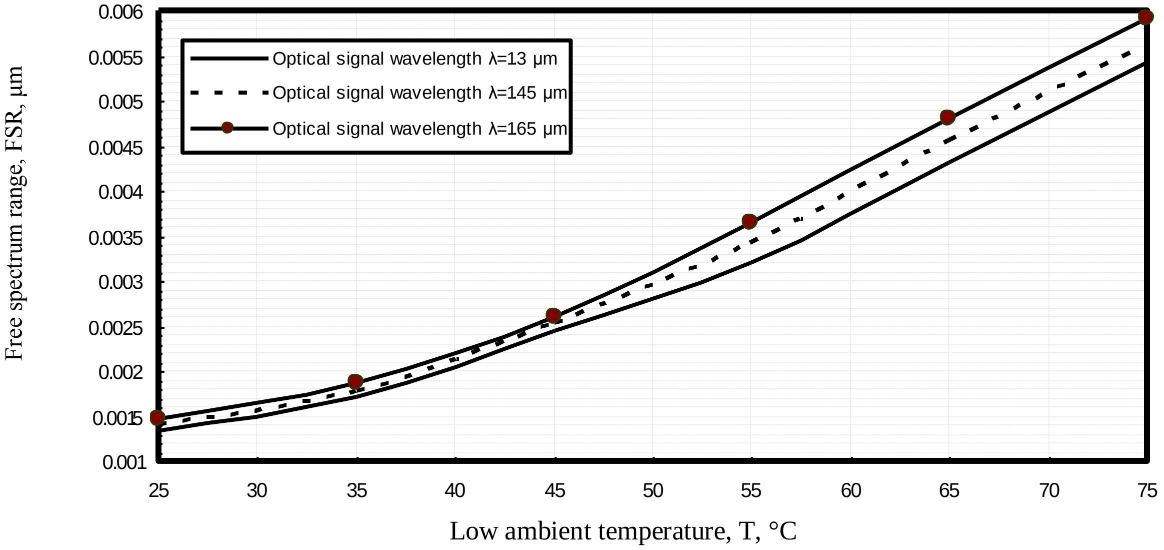

Fig. 2. free spectrum range of fiber optic sensor in relation to low ambient temperatures and operating optical signal wavelength at the assumed set of the operating parameters.

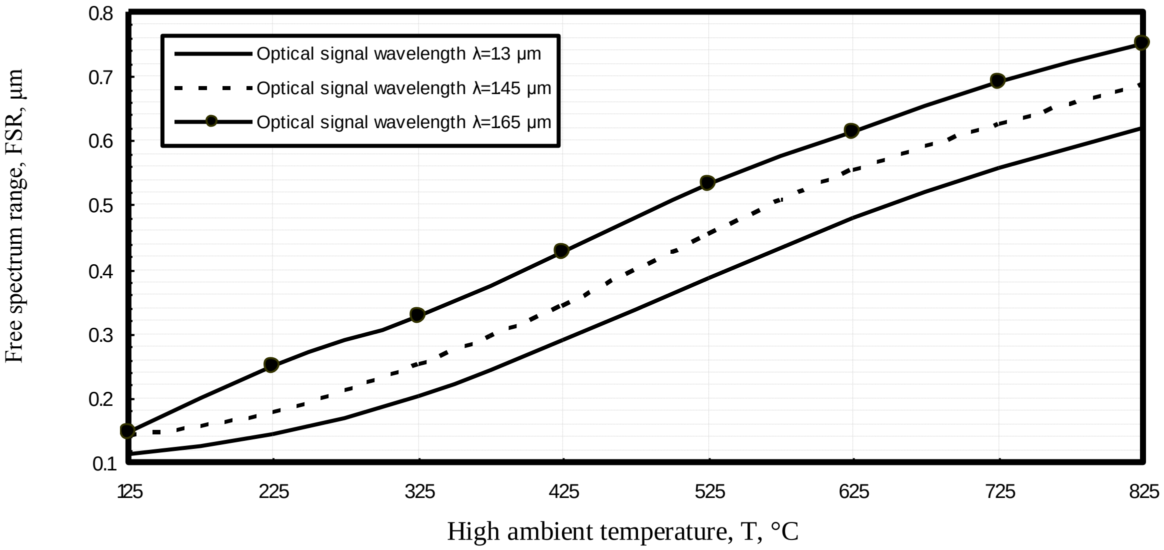

Fig. 3. free spectrum range of fiber optic sensor in relation to high ambient temperatures and operating optical signal wavelength at the assumed set of the operating parameters.

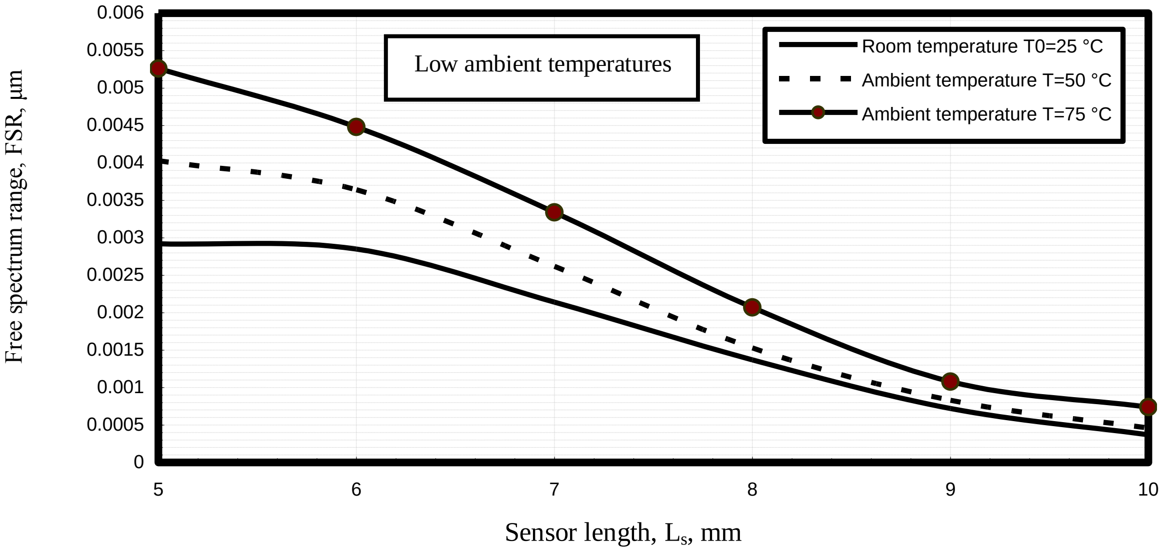

Fig. 4. free spectrum range of fiber optic sensor in relation to sensor length and low ambient temperatures and at the assumed set of the operating parameters.

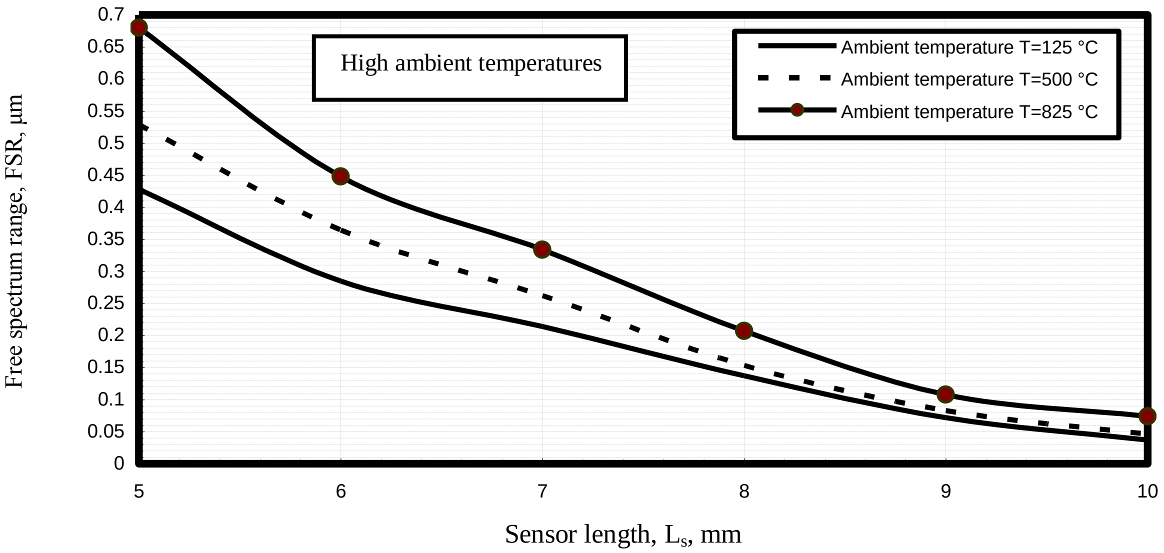

Fig. 5. free spectrum range of fiber optic sensor in relation to sensor length and high ambient temperatures and at the assumed set of the operating parameters.

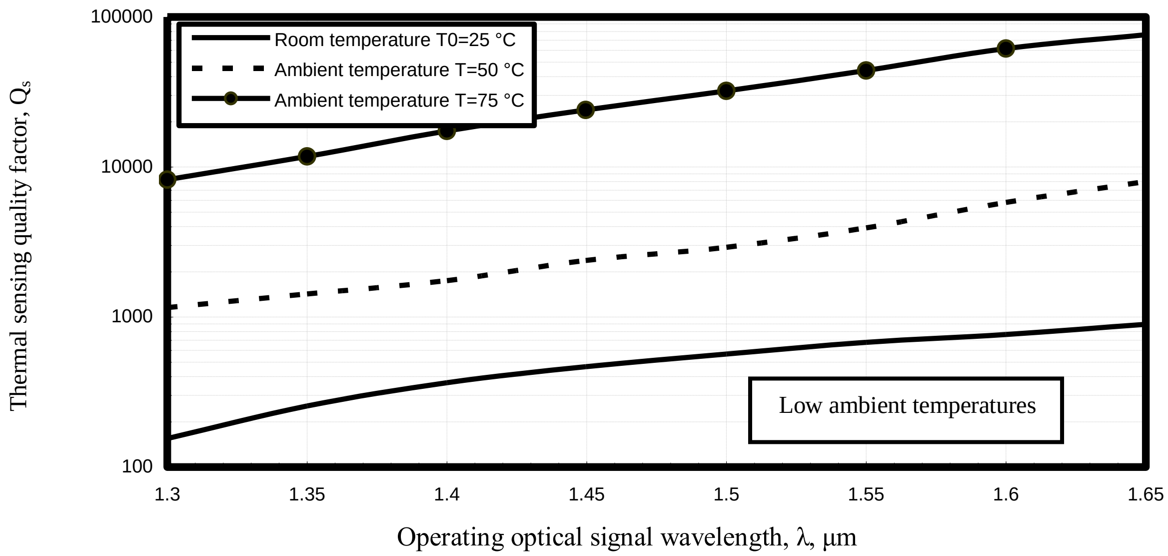

Fig. 6. Thermal sensing quality factor of fiber optic sensor in relation to operating optical signal wavelength and ambient temperature at the assumed set of the operating parameters.

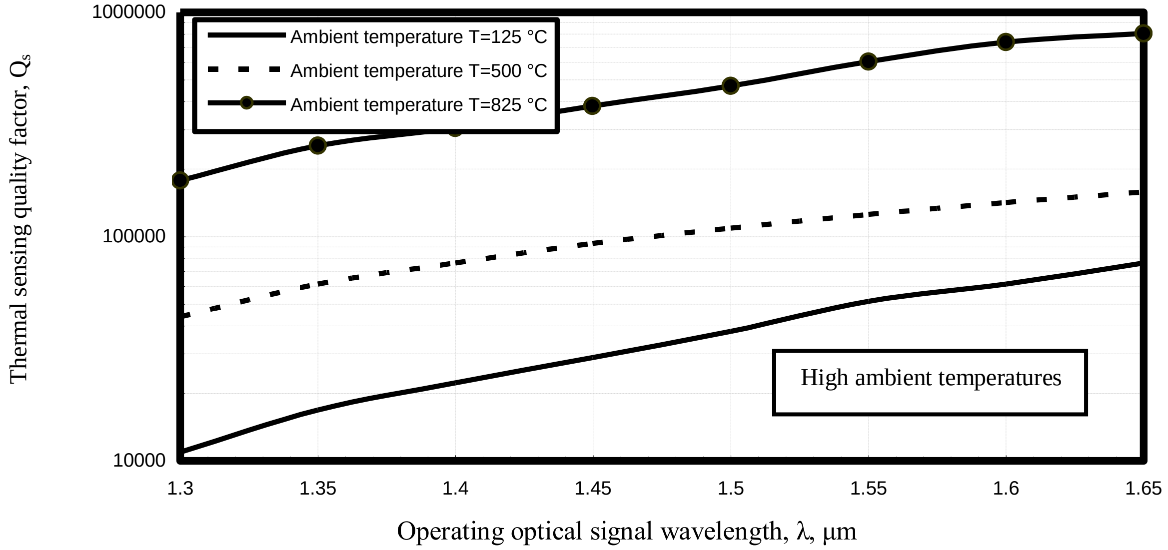

Fig. 7. Thermal sensing quality factor of fiber optic sensor in relation to operating optical signal wavelength and ambient temperature at the assumed set of the operating parameters.

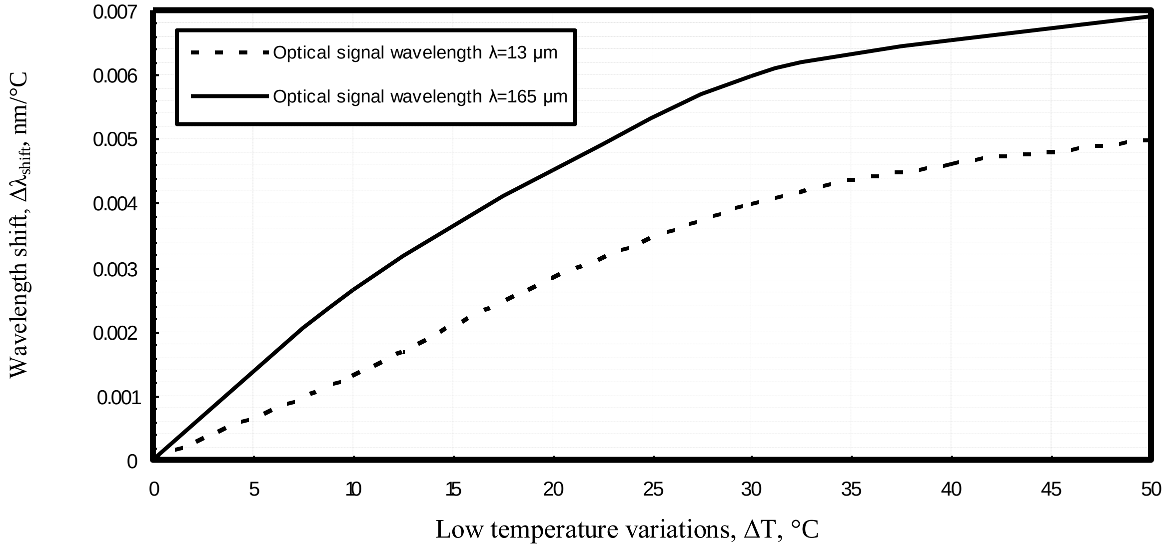

Fig. 8. Wavelength shift in relation to low temperature variations and operating optical signal wavelength at the assumed set of the operating parameters.

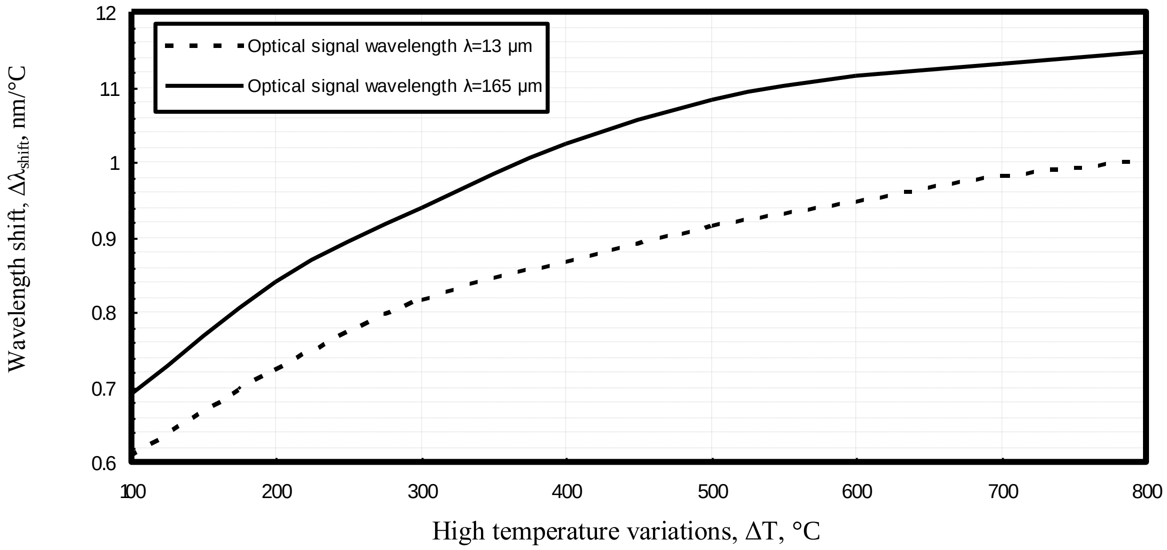

Fig. 9. Wavelength shift in relation to high temperature variations and operating optical signal wavelength at the assumed set of the operating parameters.

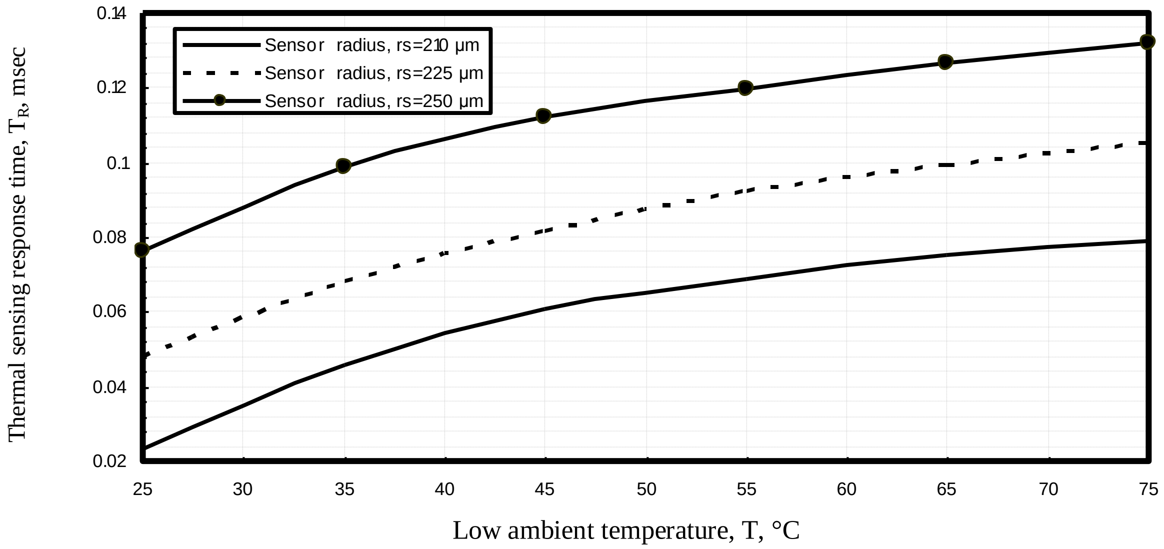

Fig. 10. Thermal sensing response time of fiber optic sensor in relation to low ambient temperatures and sensor radius at the assumed set of the operating parameters.

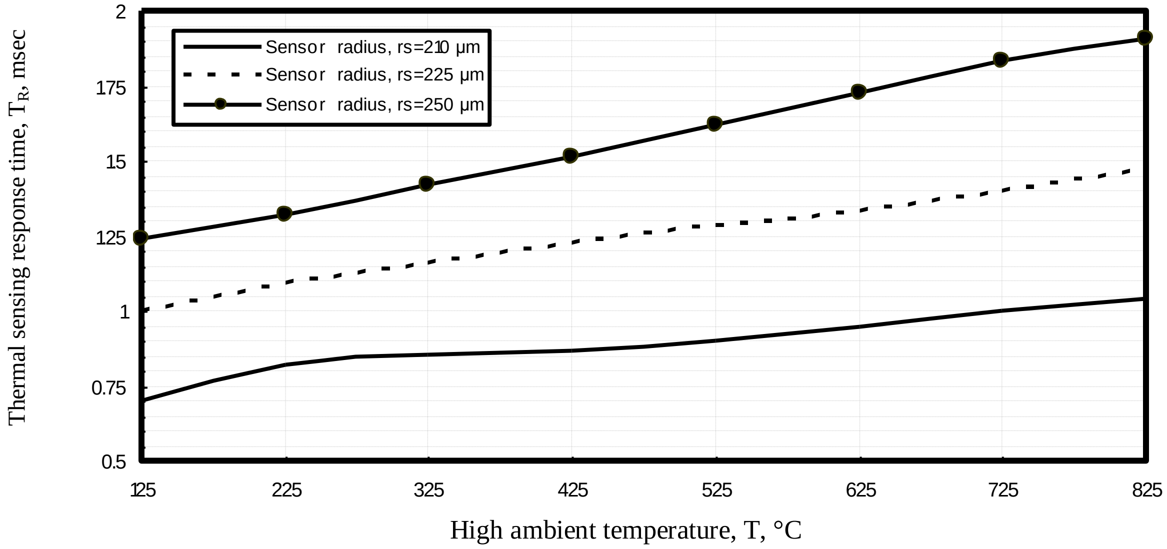

Fig. 11. Thermal sensing response time of fiber optic sensor in relation to high ambient temperatures and sensor radius at the assumed set of the operating parameters.

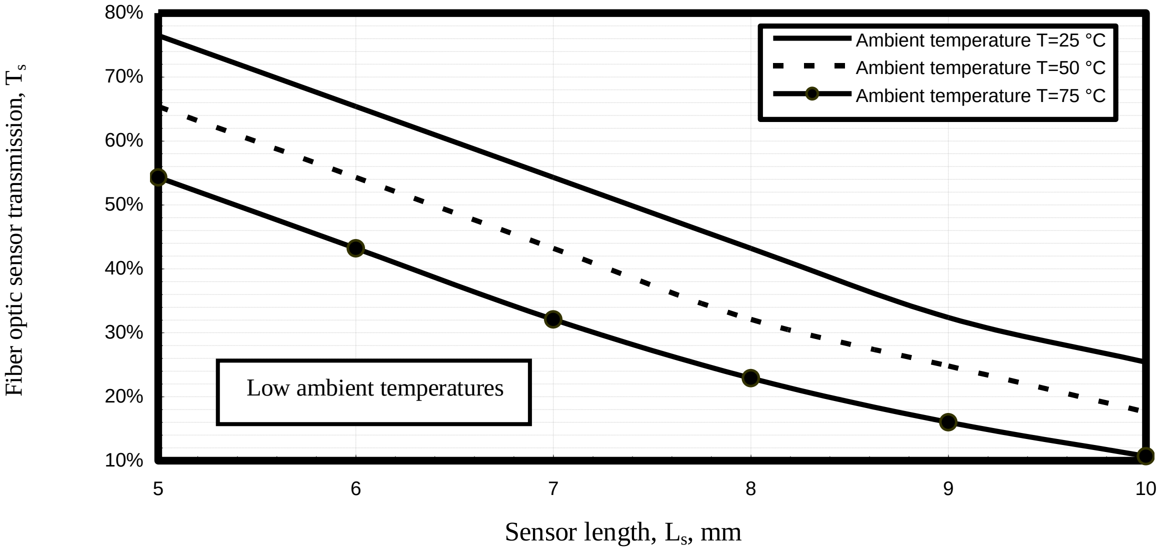

Fig. 12. Intensity transmission of fiber optic sensor in relation to sensor length and low ambient temperatures and at the assumed set of the operating parameters.

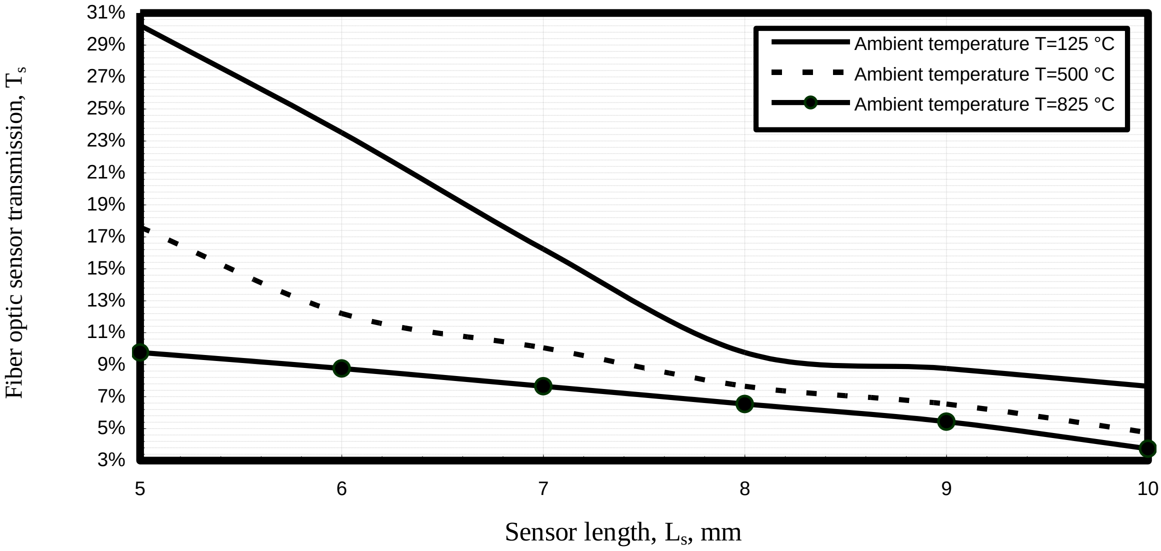

Fig. 13. Intensity transmission of fiber optic sensor in relation to sensor length and high ambient temperatures and at the assumed set of the operating parameters.

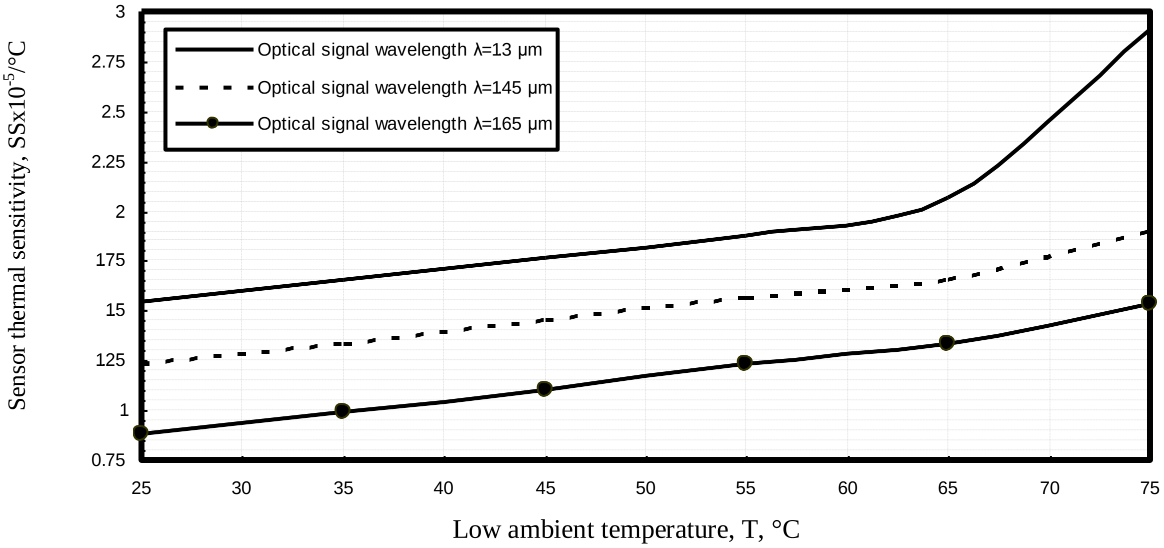

Fig. 14. Thermal sensitivity of fiber optic sensor in relation to low ambient temperatures and operating optical signal wavelength at the assumed set of the operating parameters.

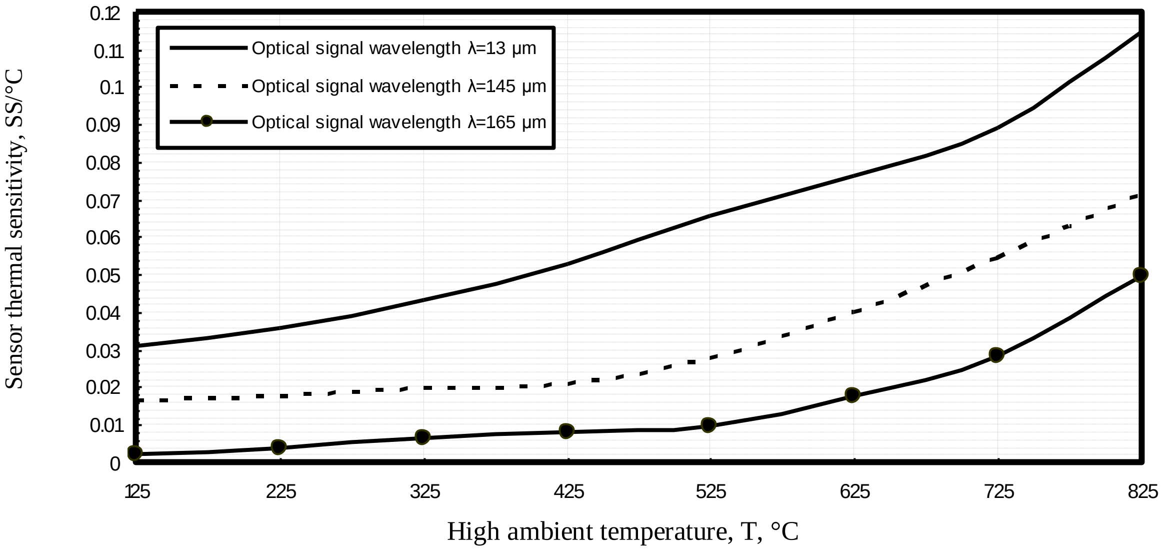

Fig. 15. Thermal sensitivity of fiber optic sensor in relation to high ambient temperatures and operating optical signal wavelength at the assumed set of the operating parameters.

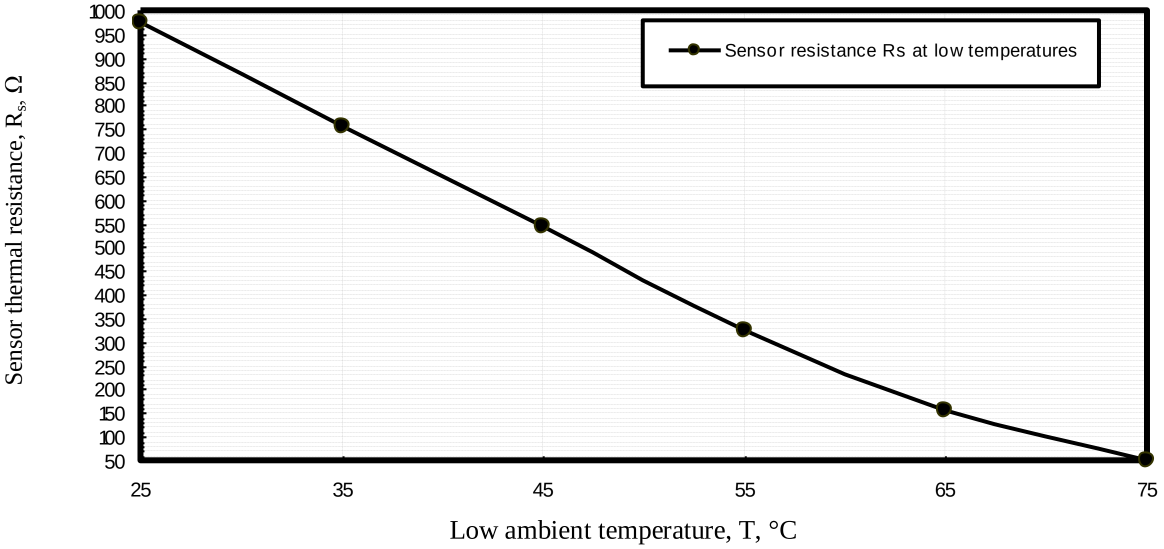

Fig. 16. Thermal resistance of fiber optic sensor in relation to low ambient temperatures at the assumed set of the operating parameters.

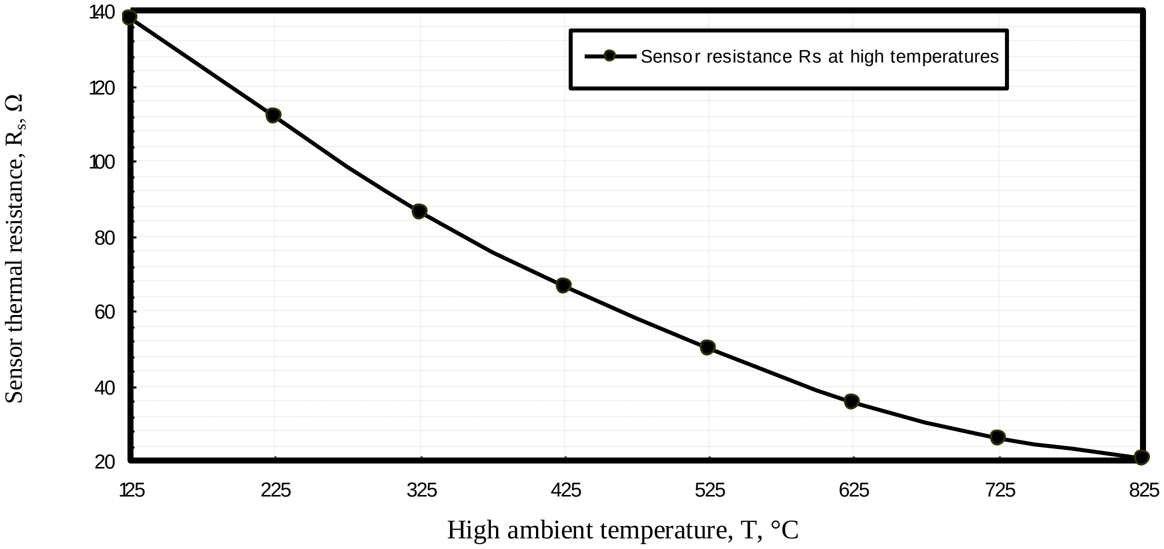

Fig. 17. Thermal resistance of fiber optic sensor in relation to high ambient temperatures at the assumed set of the operating parameters.

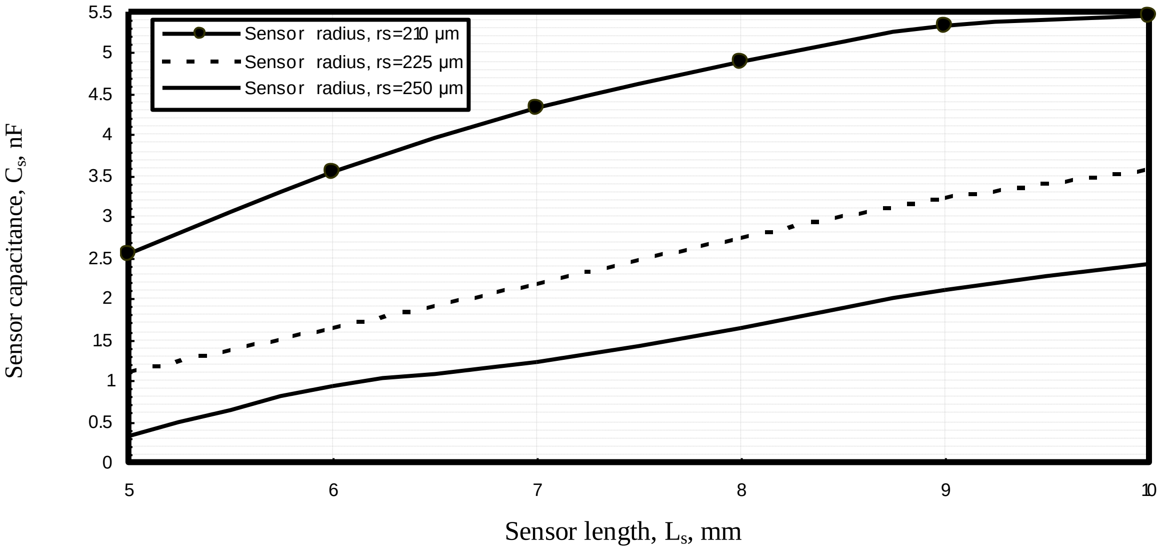

Fig. 18. Capacitance of fiber optic sensor in relation to both sensor length and radius and at the assumed set of the operating parameters.

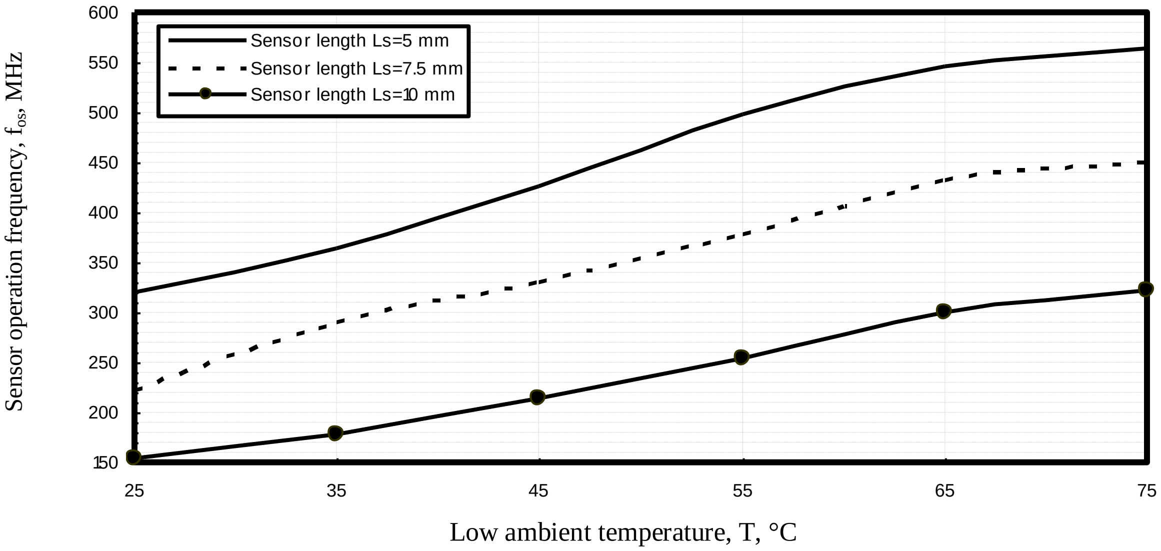

Fig. 19. Operation frequency of fiber optic sensor in relation to low ambient temperatures and sensor length at the assumed set of the operating parameters.

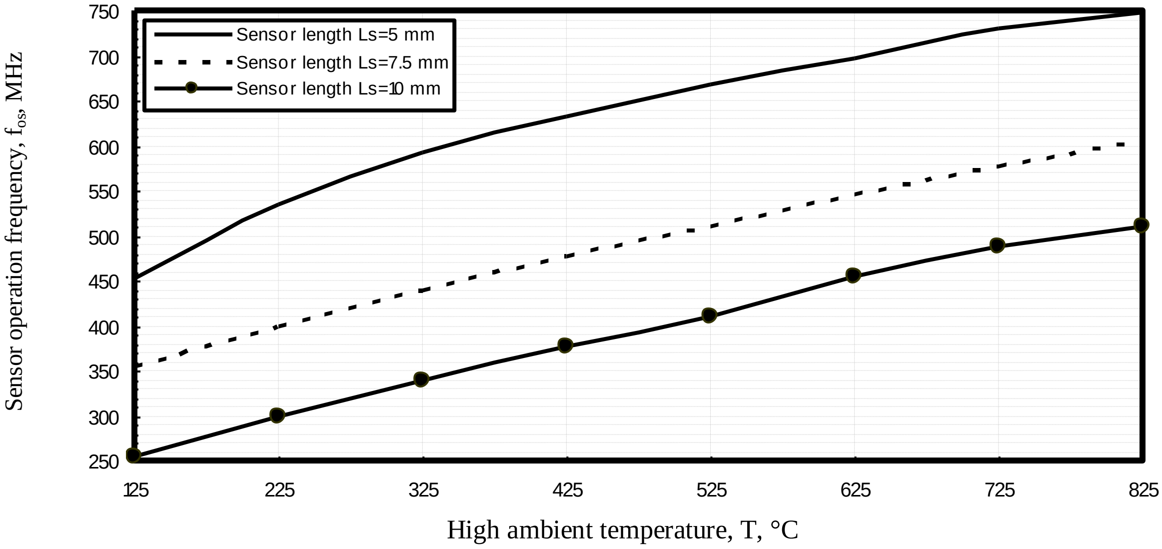

Fig. 20. Operation frequency of fiber optic sensor in relation to high ambient temperatures and sensor length at the assumed set of the operating parameters.

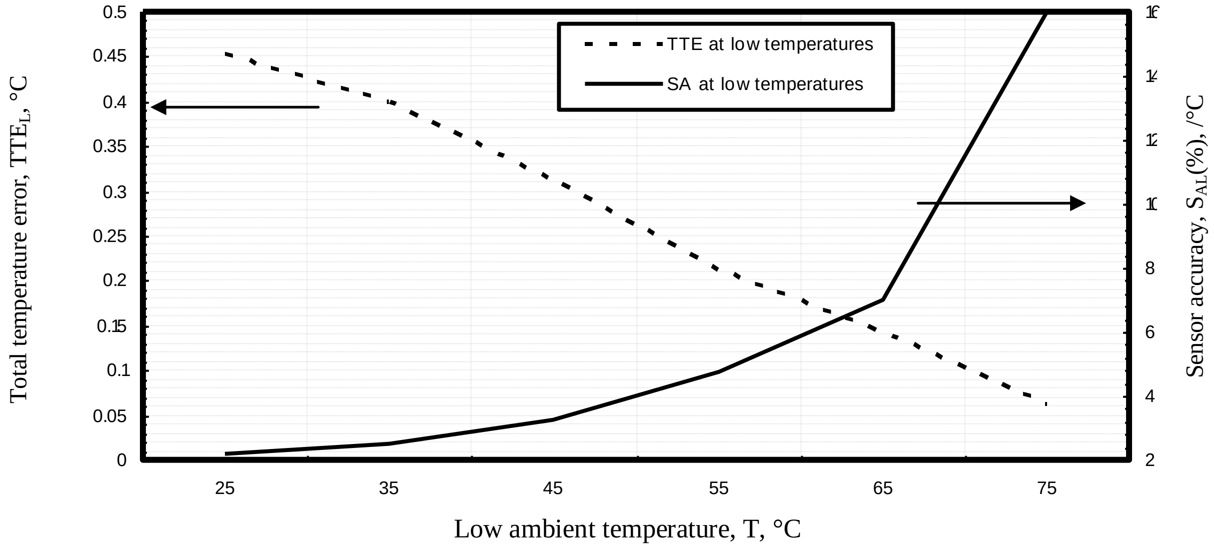

Fig. 21. Total temperature error and sensor accuracy in relation to low ambient temperatures at the assumed set of the operating parameters.

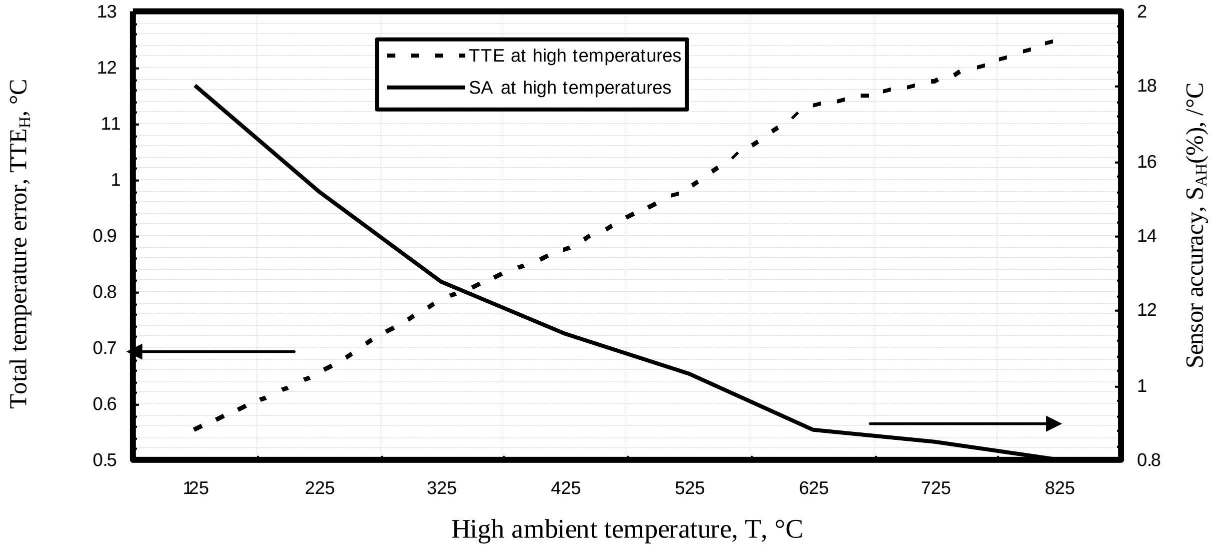

Fig. 22. Total temperature error and sensor accuracy in relation to high ambient temperatures at the assumed set of the operating parameters.

vi) As shown in Figs. (12, 13) have assured that fiber optic sensor transmission decreases with increasing sensor length under low and high temperature effects. Where fiber optic sensor transmission has presented its higher values under low temperatures effects compared to lower values under high temperatures effects.

vii) Figs. (14, 15) have demonstrated that as ambient temperatures with its low and high values increase, and operating optical signal wavelength decreases, this results in increasing sensor thermal sensitivity. It is observed that sensor thermal sensitivity has shown its higher values under high temperatures effects compared to lower values under low temperatures effects.

viii) As shown in Figs. (16, 17) have assured that fiber optic sensor resistance decreases with increasing temperature effects. Where fiber optic sensor resistance has presented its higher values under low temperatures effects compared to lower values under high temperatures effects.

ix) Fig. 18 has demonstrated that as sensor length increases and sensor radius decreases, this leads to increase in sensor capacitance.

x) Figs. (19, 20) have indicated that as sensor length decreases and ambient temperatures with its low and high values increase, this results in increasing sensor operation frequency. It is observed that sensor operation frequency has shown its higher values under high temperatures effects compared to lower values under low temperatures effects.

xi) Figs. (21, 22) have assured that total temperature error decreases and then sensor accuracy increases under low temperature effects. While total temperature error increases and then sensor accuracy decreases under high temperature effects.

V. CONCLUSIONS

In a summary, we have deeply presented the fiber optic sensor for thermal sensing under low and high temperatures over wide range of the affecting parameters. It is theoretically found that the increased low and high temperature effects, this result in increasing in free spectrum range, thermal sensing quality factor, sensor wavelength shift, thermal sensing response time, sensor thermal sensitivity, and sensor operation frequency, and decreasing in sensor resistance and fiber optic sensor transmission. As well as it is indicated that the increased operating optical signal wavelength, this lead to the increased FSR, sensor wavelength shift, and the decreased sensor thermal sensitivity. Moreover it is observed that the increased sensor length, this result in the increased sensor capacitance and the decreased FSR, sensor operation frequency and fiber optic sensor transmission. It is also found that the increased sensor radius, this lead to the increased thermal sensing response time, and the decreased sensor capacitance. Finally it is theoretically observed that at low temperatures effects, the total temperature error decreases, and therefore the sensor accuracy increases. While at low temperatures effects, the total temperature error increases, and therefore the sensor accuracy decreases.

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Author's Profile

Dr. Ahmed Nabih Zaki Rashed was born in Menouf city, Menoufia State, Egypt country in 23 July, 1976. Received the B.Sc., M.Sc., and Ph.D. scientific degrees in the Electronics and Electrical Communications Engineering Department from Faculty of Electronic Engineering, Menoufia University in 1999, 2005, and 2010 respectively. Currently, his job carrier is a scientific lecturer in Electronics and Electrical Communications Engineering Department, Faculty of Electronic Engineering, Menoufia university, Menouf. Postal Menouf city code: 32951, EGYPT. His scientific master science thesis has focused on polymer fibers in optical access communication systems. Moreover his scientific Ph. D. thesis has focused on recent applications in linear or nonlinear passive or active in optical networks. His interesting research mainly focuses on transmission capacity, a data rate product and long transmission distances of passive and active optical communication networks, wireless communication, radio over fiber communication systems, and optical network security and management. He has published many high scientific research papers in high quality and technical international journals in the field of advanced communication systems, optoelectronic devices, and passive optical access communication networks. His areas of interest and experience in optical communication systems, advanced optical communication networks, wireless optical access networks, analog communication systems, optical filters and Sensors. As well as he is editorial board member in high academic scientific International research Journals. Moreover he is a reviewer member in high impact scientific research international journals in the field of electronics, electrical communication systems, optoelectronics, information technology and advanced optical communication systems and networks. His personal electronic mail ID (E-mail:ahmed_733@yahoo.com). His published paper under the title **"High reliability optical interconnections for short range applications in high performance optical communication systems"** in Optics and Laser Technology, Elsevier Publisher has achieved most popular download articles in 2013.