Indonesian Journal of Electrical Engineering and Computer Science
Vol. 21, No. 1, January 2021, pp. 287~295
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v21.i1.pp287-295

Conventional doped silica/fluoride glass fibers for low loss and minimum dispersion effects

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Article Info

Article history:

Received Mar 30, 2020
Revised Jun 29, 2020
Accepted Jul 19, 2020

Keywords:

Aluminum fluoride fibers
Doped silica fibers
Low loss
Minimum dispersion

ABSTRACT

This paper has clarified the conventional silica doped (SiGeO2) and aluminum fluoride (AlF3) fibers for low loss and minimum dispersion effects for upgrading fiber-optic communication systems. The total dispersion with the total losses are modeled for both fibers. Fiber bandwidth and the power received are estimated based on different dopant ratios. The spectral and thermal effects are applied on both fibers. The study assured the negative effects of increasing ambient temperatures and the positive effects of increasing dopant ratios on the performance of the fibers.

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1. INTRODUCTION

The power of the transmitted signal is considered due to the disturbances that accompany the transmission and reception of the signal (electronic noise, interference, etc.). Receivers may not detect and demodulate input signals with a power lower than a minimum level [1-9] called the sensitivity of the receiver. Further specifications, which affect the quality of service, are given in terms of signal-to-noise rate and bit error rate [10-14]. All these impose a lower limit to the minimum power that can be received [15-19]. Once the characteristics of attenuation on physical media and the sensitivity of the receiver are known, the limitation on the received power results in a limitation on the maximum distance that the link is capable of supporting (assigned the maximum power that the transmitter can provide). One way of summarizing the two issues just mentioned, the spectral efficiency and energy of a given transmission system, is to introduce a measure of overall efficiency given by the product between the maximum transmission rate obtained over a half with a given technique modulation and the maximum distance [20-25].

2. MODEL DESCRIPTION AND RESEARCH METHOD

The total fiber dispersion factor can be modeled by the following equation [1-4, 26]:

$$D_T = -\frac{\lambda}{c}\frac{d^2 n_{core}}{d\lambda^2} - \frac{\Delta n\, n_{core}}{c\,\lambda}\left(\frac{n_{eff}}{n_{core}}\right)^2 M(V) \tag{1}$$

The relative refractive index difference and the normalized frequency can be estimated by [2, 3, 5-8, 27]:

$$\Delta n = \left(\frac{n_{core} - n_{clad}}{n_{core}}\right) \tag{2}$$

$$V = 2\pi\, a\sqrt{n_{core}{}^2 - n_{clad}^2} \tag{3}$$

$$M(V) = 0.8 + 0.549(2.834 - V)^2 \text{ for silica doped fiber} \tag{4}$$

$$M(V) = 1.34 + 0.056\,(9.543 - 0.5V)^2 \text{ for Fluoride fiber} \tag{5}$$

where a is fiber core radius, n_{core} is core refractive index, n_{clad} is the clad refractive index [9-12, 26, 27].

$$n_{core}{}^2 = 1 + \frac{S_1\lambda^2}{\lambda^2 - B_1^2} + \frac{S_2\lambda^2}{\lambda^2 - B_2^2} + \frac{S_3\lambda^2}{\lambda^2 - B_3^2} \tag{6}$$

With S_1=0.6961+0.1107 x, S_2=0.4079+0.3102 x, S_3=0.8974-0.0433 x (7)

B_1=0.068+0.0005 x, B_2=0.116+0.0377 x, B_3=9.896+1.94577 x (8)

the first and second differentiation with respect to wavelength can be estimated by the following equations:

$$\frac{dn_{core}}{d\lambda} = \frac{-\lambda}{n_{core}}\left(\frac{S_1B_1^2}{(\lambda^2 - B_1^2)^2} + \frac{S_2B_2^2}{(\lambda^2 - B_2^2)^2} + \frac{S_3B_3^2}{(\lambda^2 - B_3^2)^2}\right), \tag{9}$$

$$\frac{d^2 n_{core}}{d\lambda^2} = \frac{1}{n_{core}}\left(\frac{S_1B_1^2(3\lambda^2 + B_1^2)}{(\lambda^2 - B_1^2)^3} + \frac{S_2B_2^2(3\lambda^2 + B_2^2)}{(\lambda^2 - B_2^2)^3} + \frac{S_3B_3^2(3\lambda^2 - B_3^2)}{(\lambda^2 - B_3^2)^3} - \left(\frac{dn_{core}}{d\lambda}\right)^2\right), \tag{10}$$

where the effective refractive index of the fiber core is given by [7, 9, 12]:

$$n_{eff} = n_{core} - \lambda\frac{dn_{core}}{d\lambda} \tag{11}$$

For aluminum fluoride glass fibers, fiber core refractive index as a function of the wavelength is modeled by [7, 13, 14, 26, 27]:

$$n = \frac{A}{\lambda^4} + \frac{B}{\lambda^2} + C + D\lambda^2 + E\lambda^4 \tag{12}$$

A=9.37x10^{-5}, B=2.94x10^{-3}, C=1.49, D=-0.00125, and E=-4x10^{-6}, where the fiber losses for both silica doped and fluoride glass fibers are given by [1, 2, 5, 13-15, 26, 27]:

$$\alpha = A_m e^{b_m\lambda} + \frac{C_m}{\lambda^4} + D_m e^{-d_m\lambda} \tag{13}$$

A_m=0.0132 x/(1+733 x), b_m=4.8$\left(\frac{T_o}{T}\right)$, C_m=(0.74+66 Δn) $\left(\frac{T_o}{T}\right)$, D_m=4.9x10^{11}, d_m=48$\left(\frac{T_o}{T}\right)$

for silica doped (14)

$$A_m=0,\ b_m=0,\ C_m=0.6\ y\left(\frac{T_o}{T}\right),\ D_m=1.2167x10^{10},\ d_m=71.64\ y^2\left(\frac{T_o}{T}\right) \text{ for Fluoride fiber} \tag{15}$$

where T is temperature, T_0 is room temperature, and x is the germanium dopant ratio. The fiber bandwidth can be given by the mathematical relation [1-3, 5, 8, 10, 26, 27]:

$$BW_F=0.44/T_{min} \tag{16}$$

where the minimum pulse broadening due to the dispersion factor is given by [3, 5, 8, 12, 15, 26, 27]:

$$T_{min.}=D_T\ L\ \Delta\lambda \tag{17}$$

where L is the fiber length in km, Δλ is the spectral linewidth of the light source. In addition to the received power can be estimated by the following formula [2, 4, 9, 12, 15, 26]:

$$P_R = P_T \exp(-\alpha L) \tag{18}$$

The loss power percentage can be given by the mathematical relation:

$$P_{(Loss)}(\%) = \frac{P_T - P_R}{P_R} x100\ \% \tag{19}$$

3. PERFORMANCE ANALYSIS WITH DISCUSSIONS

The silica doped and aluminum fluoride fibers have been mathematically analyzed in detail. The total fiber losses and dispersion have been modeled to estimate the fiber bandwidth. The total pulse broadening due to dispersion is analyzed and estimated to evaluate the fiber bandwidth. The received power is evaluated based on the mathematical analysis of the total fiber losses. The performance key parameters are estimated based on the clarified variables in Table 1.

Figure 1 shows the fiber attenuation in relation to both signal wavelength and ambient temperature variations based on both silica doped/fluoride glass fibers at Ge/Al dopant ratio of 7%. With a temperature of 320K, the silica doped fiber attenuation at 1.3μm is 0.07 dB/km, while the fluoride glass fiber attenuation is 0.075 dB/km at the same wavelength. With a temperature of 450K, the silica doped fiber attenuation at 1.3 μm is 0.9 dB/km, while the fluoride glass fiber attenuation is 0.987 dB/km at the same wavelength. With a temperature of 320 K, the silica doped fiber attenuation at 1.55μm is 0.02 dB/km, while the fluoride glass fiber attenuation is 0.025 dB/km at the same wavelength. With a temperature of 450K, the silica doped fiber attenuation at 1.55μm is 0.2 dB/km, while the fluoride glass fiber attenuation is 0.265 dB/km at the same wavelength. The silica doped/fluoride glass fibers have better performance at a signal wavelength of 1.55μm than the other operating wavelengths.

Table 1. Numerical variables for this study [1, 3, 7, 13, 15].

Variables	Value/unit
Temperature (T)	320 K-450 K
Room temperature (T_0)	300 K
Refractive index difference (Δn)	0.001
Fiber cable length (L)	10 km
Source linewidth (Δλ)	0.1 nm
Transmitter power (P_T)	10 mW
Ge dopant ratio (x)	1%-7%
Aluminum dopant ratio (y)	1%-7% [20]
Fiber core radius	2.5 μm
Wavelength (λ)	1.3 μm-1.65 μm

Figure 2 indicates the fiber bandwidth variations against both Ge/Al dopant ratio and temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm. Fluoride glass fiber bandwidth has 0.5GHz at an Al dopant ratio of 1%, 4GHz at Al dopant ratio of 4%, and 32GHz at Al dopant ratio of 7% at a temperature of 320K.

Silica doped glass fiber bandwidth has 1GHz at a Ge dopant ratio of 1%, 8GHz at a Ge dopant ratio of 4%, and 64GHz at a Ge dopant ratio of 7% at a temperature of 320 K. Fluoride glass fiber bandwidth has 0.1GHz at an Al dopant ratio of 1%, 0.8GHz at an Al dopant ratio of 4%, and 6.4GHz at an Al dopant ratio of 7% at a temperature of 450K. Silica doped glass fiber bandwidth has 0.4GHz at a Ge dopant ratio of 1%, 3.2GHz at a Ge dopant ratio of 4%, and 26.5GHz at a Ge dopant ratio of 7% at a temperature of 450K.

Figure 3 clarifies the received power variations against both Ge/Al dopant ratio and temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm. Fluoride glass fibers received power has 7.765mW at an Al dopant ratio of 1%, 8.54Mw at an Al dopant ratio of 4%, and 9.56mW at an Al dopant ratio of 7% at a temperature of 320K. Silica doped glass fibers received power has 7.89mW at a Ge dopant ratio of 1%, 8.87mW at a Ge dopant ratio of 4%, and 9.765mW at a Ge dopant ratio of 7% at a temperature of 320K. Fluoride glass fibers received power has 6.65mW at an Al dopant ratio of 1%, 7.765mW at an Al dopant ratio of 4%, and 8.54mW at an Al dopant ratio of 7% at a temperature of 450K. Silica doped glass fibers received power has 6.98mW at a Ge dopant ratio of 1%, 3.27.89mW at a Ge dopant ratio of 4%, and 8.8765mW at a Ge dopant ratio of 7% at a temperature of 450K. The received power is upgraded with the increase of the dopant ratios of Ge/Al-based silica/fluoride glass fibers.

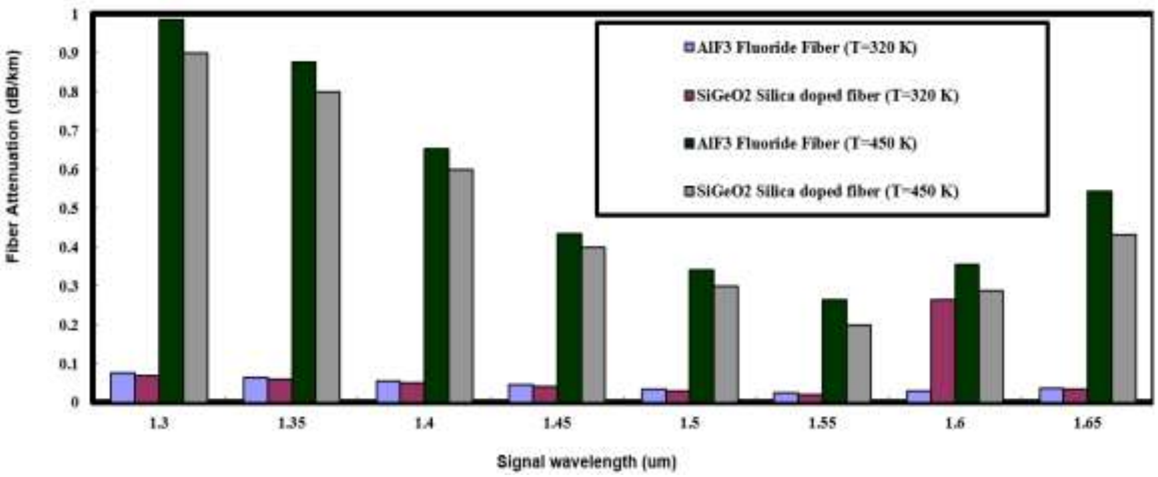

Figure 1. Fiber attenuation in relation to both signal wavelength and ambient temperature variations based on both silica doped/fluoride glass fibers at a Ge/Al dopant ratio of 7%

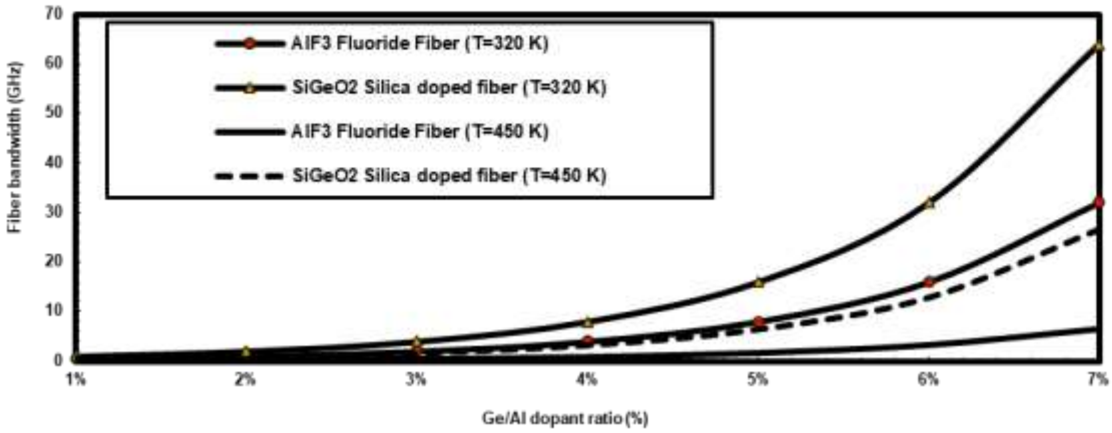

Figure 2. Fiber bandwidth variations against both Ge/Al dopant ratio and temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55m

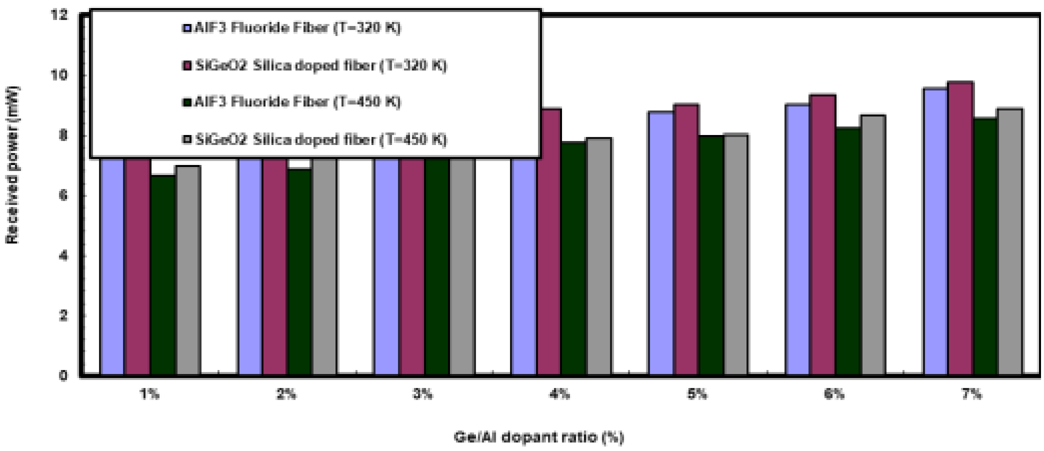

Figure 3. Received power variations against both Ge/Al dopant ratio and temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm

Figure 4 indicates the fiber bandwidth variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%. The fluoride glass fiber bandwidth is 32GHz at T=320K, while the silica doped glass fiber bandwidth is 64GHz at the same temperature, where the fluoride glass fiber bandwidth is 8 GHz at T=375K, while the silica doped glass fiber bandwidth is 16GHz at the same temperature. The fluoride glass fiber bandwidth is 0.5 GHz at T=450K, while the silica doped glass fiber bandwidth is 1GHz at the same temperature. The fiber bandwidth decreases with the increase of temperature.

Figure 5 clarifies the received power variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%. The fluoride glass fiber received power is 9.56mW at T=320K, while the silica doped glass fibers received power is 9.765mW at the same temperature, where the fluoride glass fiber received power is 8.43mW at T=375K and the silica doped glass fibers received power is 8.945mW at the same temperature. The fluoride glass fiber received power is 6.744mW at T=450K, while the silica doped glass fibers received power is 7.69mW at the same temperature. The fiber received power decreases with the increase of temperature.

Figure 6 shows the fiber loss variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%. The fluoride glass fiber loss is 0.025 dB/km at T=320K, while the silica doped glass fibers loss is 0.02 dB/km at the same temperature, where the fluoride glass fiber loss is 0.035 dB/km at T=375K and the silica doped glass fiber loss is 0.03 dB/km at the same temperature. The fluoride glass fiber loss is 0.085 dB/km at T=450K, while the silica doped glass fiber loss is 0.08 dB/km at the same temperature. The fiber loss increases with the increase of temperature.

Figure 7 clarifies the fiber pulse broadening variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%. The fluoride glass fiber pulse broadening is 0.02ns at T=320K, while the silica doped glass fiber pulse broadening is 0.01ns at the same temperature, where the fluoride glass fiber pulse broadening is 0.08ns at T=375K and the silica doped glass fiber pulse broadening is 0.04ns at the same temperature. The fluoride glass fiber pulse broadening is 0.6545ns at T=450K, while the silica doped glass fiber pulse broadening is 0.32ns at the same temperature. The fiber pulse broadening increases with the increase of temperature.

Figure 8 indicates the power loss percentage variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%. The fluoride glass fiber power loss percentage is 0.25% at T=320K, while the silica doped glass fiber power loss percentage is 0.2% at the same temperature, where the fluoride glass fiber power loss percentage is 1.32% at T=375K, while the silica doped glass fiber power loss percentage is 0.876% at the same temperature. The fluoride glass fiber power loss percentage is 4.87% at T=450K, while the silica doped glass fiber power loss percentage is 3.765% at the same temperature. The fiber power loss percentage increases with the increase of temperature.

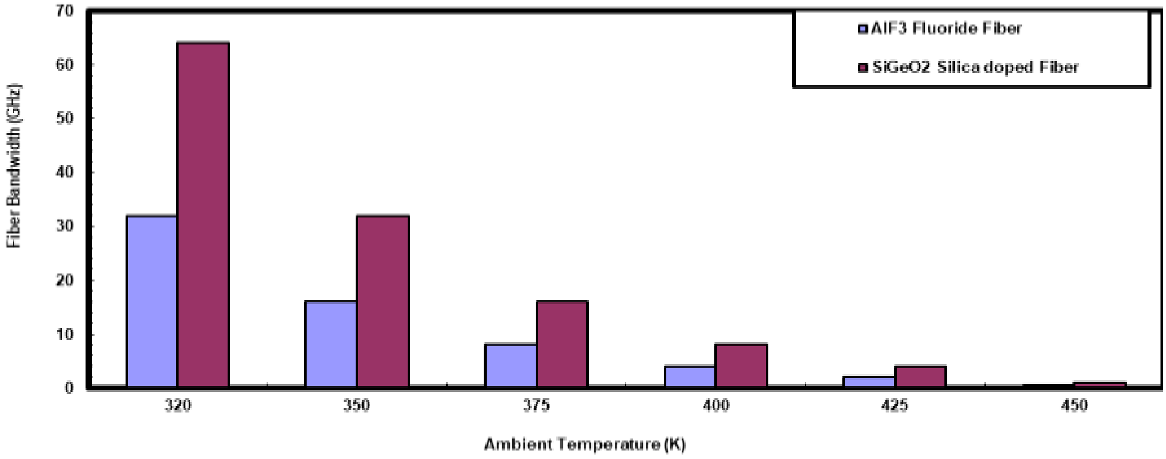

Figure 4. Fiber bandwidth variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%

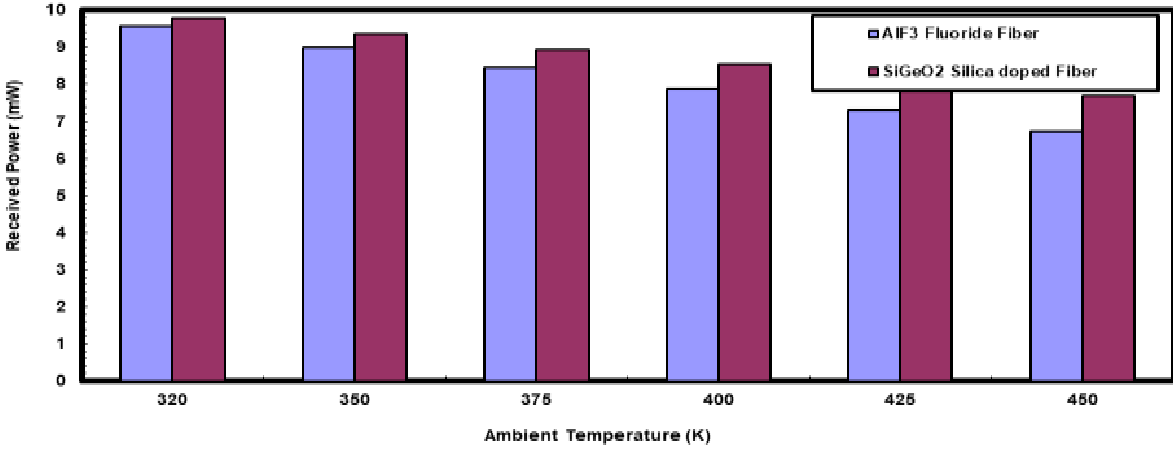

Figure 5. Received power variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%

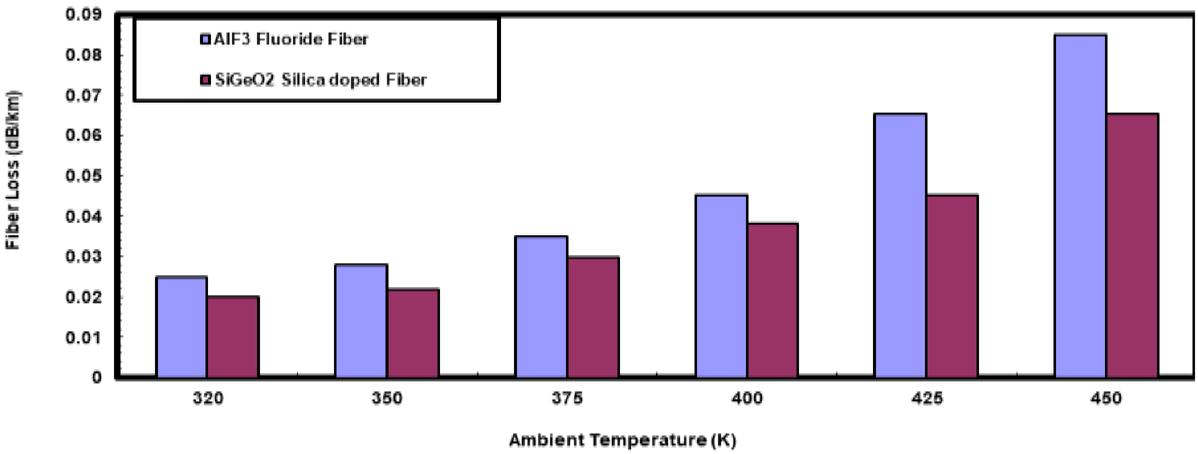

Figure 6. Fiber loss variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%

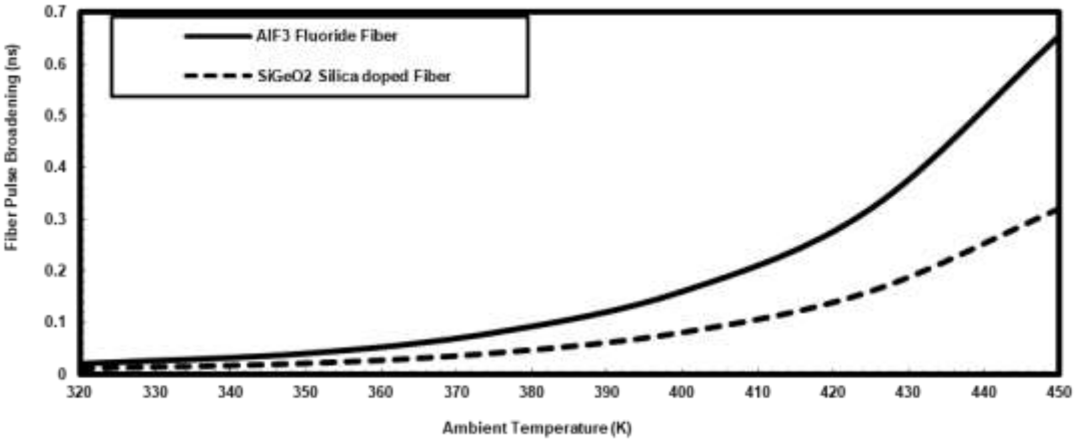

Figure 7. Fiber pulse broadening variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%

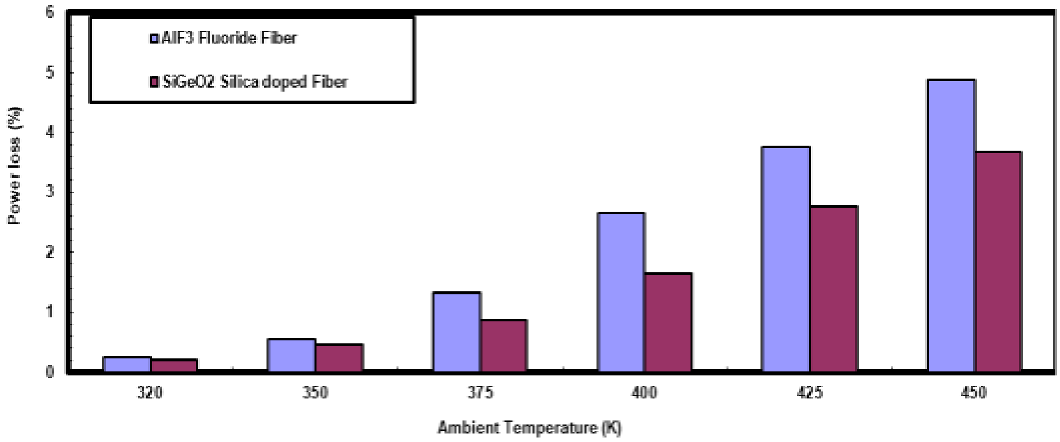

Figure 8. Power loss variations against temperature variations based on both silica doped/fluoride glass fibers at a signal wavelength of 1.55μm and a Ge/Al dopant ratio of 7%

4. CONCLUSION

This study has clarified the performance signature of silica doped/fluoride glass fibers in fiber-optic systems for propagation distances up to 10km. The study implies that the positive effects of adding dopants of Ge/Al to silica doped/fluoride glass fibers is to reduce the fiber loss, power loss, and dispersion effects. The increase of an ambient temperature has negative effects on the performance of both fibers. The power loss and fiber pulse broadening increase with the increase of temperature, which results in the decrease of fiber bandwidth and the signal power received. Silica doped fibers have presented better performance than fluoride fibers at the same dopant ratios and ambient temperature variations. The performances of both silica doped and fluoride fiber performance are upgraded with a dopant ratio of 7%, with room temperature at 300 K and signal wavelength employment at 1.55μm.

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