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Dispersion compensation: impact of integration of soliton transmission and cascaded apodized FBGs

Fathy M. Mustafa[1] · Mohamed M. Abdelhalim[2] · Moustafa H. Aly[3]

Abstract

In this paper, we present a tanh apodized FBG as a dispersion compensator in optical fiber communication systems. This grating is integrated as a hybrid system of four cascaded apodized FBGs with soliton transmission technique. This enhances the linewidth of the light source to get the most out of transmission per-channel bit rate of 9.687 Tbps at a temperature of 20 °C, a relative refractive index difference of 0.002, a Germania doping ratio of 0.2, and a signal wavelength of 1.65 μm.

Keywords Dispersion compensation · Soliton · Optical fiber communication

1 Introduction

The growth of new technologies which became available to everyone, increased the appetite of customers who are already hungry for information. To meet the increasing demand for data traffic, high-speed optical communication systems are required to withstand all disturbances in the event of data transmission. This can be accomplished using solitons. Optical solitons are, in fact, "stable pulses" spread through controlled media on the basis of optical fibers without changing their shape by using mutual compensation of dispersion and nonlinear effects. They are considered one of the most important concepts in modern communications. Optical solitons are used to enhance the optical fiber performance which is deteriorated due to dispersion. Dispersion is mainly caused by propagation delays at different frequencies spread along the fiber. This expands the information signal pulse, leading to intersymbol interference and data loss. There is an urgent need to mitigate the dispersion effects. Some of the technologies used to compensate the dispersion effects are Dispersion Compensating Fibers (DCF), Fiber Bragg Gratings (FBG), use of digital filters and Optical Phase Conjugation (OPC) (Sinha 2017).Yue Zhou et al. introduced a 40 Gbps

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✉ Moustafa H. Aly
  mosaly@aast.edu

1   Electrical Engineering Department, Faculty of Engineering, Beni-Suef University, Beni-Suef, Egypt

2   Electrical Engineering Department, Faculty of Engineering, Fayoum University, Fayoum, Egypt

3   Electronics and Communication Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria 1029, Egypt

high-speed optical fiber transmission system with various low-pass filter optical duobinary (LPF-ODB) coding dispersion compensation plans and combinations of DCF, single mode fiber (SMF) and erbium-doped fiber amplifier (EDFA) simultaneously (Zhou 2016). M. Kaur et al. presented a dispersion compensation analysis with 10 Gbps DCFs for 250 km of SMF and 50 km of DCF providing three dispersion compensation schemes (pre-, post-, and symmetrical/mix-compensation) (Kaur 2015). From all the different compensation technologies, Modern optical communication systems have piqued the FBG's interest due to its small size, low cost, inclusion loss, and its compatibility with the systems (Dar 2016). N. M. Faiyaz et al. suggested improving the hyperbolic tangent profile for FBG as a dispersion compensator (Faiyaz 2014).

An appropriate profile for many FBG parameters could be determined using coupled mode theory equations, which can play a more important role in dispersion compensation. Many profile parameters have been changed, as well as parameters for apodization and data parameters. This analysis allowed choosing a suitable hyperboloid tangent (tanh) profile for the least possible dispersion. By varying the coupling profile, they achieved an optimized profile for FBG that can compensate for chromatic dispersion up to 2237 ps/nm at 1550 nm. Abd El–Naser A. Mohammed, and A. Rashed have chosen the soliton transmission technique to handle both data rate and bit rate length product in 200—600 channels range (Mohammed 2010).

In this paper, we will try to limit the impact of dispersion throughout the optical fiber the design concept is based on the utilization of four tanh apodized FBGs in a series form to reduce the source linewidth, which plays an important role in increasing transmission rate. We were able to attain a high transmission rate through the trial as we improved the soliton transmission technology by combining it with a tanh apodized FBG. We also studied the parameters that affect the rate of transmission of silica-doped fibers.

The remainder of this work is arranged in the following manner. The mathematical soliton transmission technique, the FBG and the proposed model are illustrated in Sect. 2. The simulation results are displayed and discussed in Sect. 3. Section 4 is dedicated with the main conclusion.

2 Analytical models

2.1 Transmission soliton technique

Single mode fiber is the most common type (SSMF) consists of both GeO_2-SiO_2 materials. The refractive index, n, as a function of the operating wavelength is given by Sellmeier equation (Fleming 1984)

$$n = \sqrt{1 + \frac{C_1\lambda^2}{\lambda^2 - C_2^2} + \frac{C_3\lambda^2}{\lambda^2 - C_4^2} + \frac{C_5\lambda^2}{\lambda^2 - C_6^2}} \tag{1}$$

The Sellmeier equation coefficients as functions of ambient temperature, T(°C) are (Mohamed 2011)

$$C_1 = (0.6961663 + 0.06542X), \tag{2}$$

$$C_2 = \left(0.03684043\left(\frac{T}{T_0}\right)^2\right), \tag{3}$$

$$C_3 = (0.4079426 + 0.00122X), \tag{4}$$

$$C_4 = \left(0.0116241\left(\frac{T}{T_0}\right)^2\right), \tag{5}$$

$$C_5 = (0.8974749 + 10.543X), \tag{6}$$

$$\text{and } C_6 = \left(84.76543\left(\frac{T}{T_0}\right)^2\right). \tag{7}$$

where T_0 is the room temperature and X is the germania doping ratio.

Consequently, the total chromatic dispersion D_{total} in SSMF fibers, that reduces the transmission bitrates of the communication system, can be calculated as (Rashed 2011)

$$D_{total} = \frac{\Delta\tau}{\Delta\lambda.L} = -\left(D_m + D_w\right) \tag{8}$$

where $\Delta\tau$ is the total pulse broadening, $\Delta\lambda$ is the spectral linewidth of, L is the distance of transmission, D_m and D_w are the material dispersion coefficient and the waveguide dispersion coefficient, respectively. They are given by

$$D_m = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2} - \frac{\Delta\lambda}{2c}\left(\lambda\frac{d^3n}{d\lambda^3} + \frac{d^2n}{d\lambda^2}\right) \tag{9}$$

$$D_w = -n_{cladding}\left(\frac{\Delta}{\lambda.c}\right)M(V) \tag{10}$$

where $n_{cladding}$ is the cladding material refractive index, Δ is the relative refractive-index difference, c is the free space light velocity, $\Delta\lambda$ is the spectral linewidth of light source and the operating wavelength is λ.

According to the research in (Mohamed 2010), $M(V)$ is a function of the normalized frequency, V, as

$$M(V) = 1.38V - 6.98V^2 + 13.45V^3 - 4.84V^4 - 1.48V^5 \quad 0 \le V \le 1.15 \tag{11}$$

Moreover, we are taking into account V-number as $V = 1$ to emphasize single mode fiber type.

In a lossless medium, the soliton would have moreover the same amplitude while the signal propagates. The equilibrium between the nonlinearity impacts from one side and the dispersion impacts from the other side makes a solitary wave. Within the nonappearance of non-linearity, the dispersion of a medium causes the various frequency components to spread at diverse velocities; while in the absence of dispersion the nonlinearity makes the pulse energy being constantly injected, so we can say, the dispersion results

in extending the pulse shape while the nonlinearity tends to sharpen it. Based on the analysis of (Mohammed 2009), the peak power is given by:

$$P_{peak} = \frac{\Delta\lambda^3 D_{total} A_{eff}}{4\pi^2 c n_{nl} t_o^2} \tag{12}$$

where $\Delta\lambda$ is the spectral linewidth of the optical source, D_{total} is the total chromatic dispersion coefficient, A_{eff} is the effective area, and n_{nl} is the nonlinear Kerr coefficient. Then, the pulse intensity width in is given by:

$$t_o^2 = \frac{\Delta\lambda^3 D_{total} A_{eff}}{4\pi^2 c n_{nl} P_{peak}} \tag{13}$$

Then, the soliton transmission bit rate per optical network channel is given as (Mohamed 2011)

$$B_{Soliton/channel} = \frac{0.1}{t_o} \tag{14}$$

2.2 Uniform FBG theory

As appears in Fig. 1, when light with an incident spectrum passes through a grating, part of the light is reflected while the greater part passes.

The reflected light has a wavelength named the Bragg wavelength,λ_B, which is given by

$$\lambda_B = 2n_{eff}\Lambda \tag{15}$$

where n_{eff} is the effective refractive index and Λ is the grating period of the FBG structure.

2.3 Apodized FBG (AFBG)

AFBG brings a considerable improvement in suppression of the sidelobes, while maintaining reflectivity and narrow bandwidth. Ref. (H. M. El-Gammal 2015) represents the refractive index profile of apodized FBG, n(z)
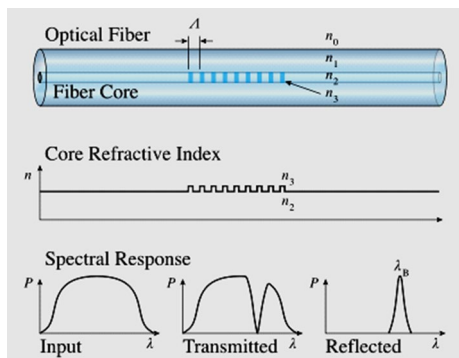
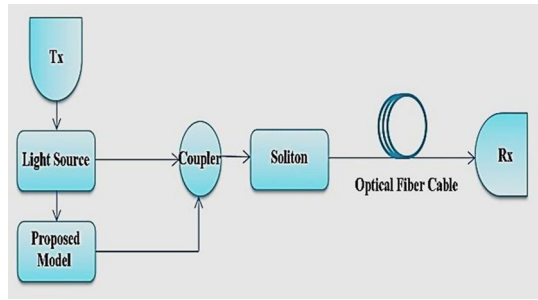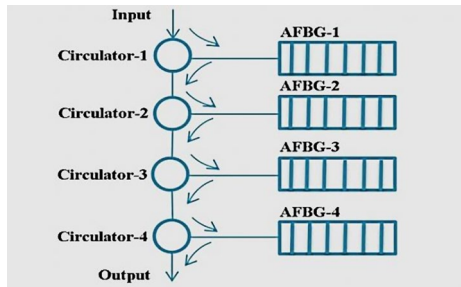**Fig. 1** Structure of uniform FBG

Fig. 2 The proposed system

Fig. 3 Proposed AFBG module

$$n(z) = n_{c0} + \Delta n_0 F(z) n_d(z) \tag{16}$$

where Δn_0 is the maximum index variation, $n_d(z)$ is the function of index variation and F(z) is the apodization function which is taken in our research as a tanh function and a raised cosine function, expressed by (ElZahaby 2017)

$$F(z) = tanh\left(\frac{8z}{L}\right) tanh\left(\frac{8(1-z)}{L}\right) \tag{17}$$

$$F(z) = \left(cos\left(\frac{2z}{L} - 1\right)\right)^8 \tag{18}$$

where $0 \leq z \leq L$ and L is the FBG length.

2.4 The suggested model

The suggested system is designed to compensate the chromatic dispersion, maximize reflectivity and narrowing bandwidth with suppressing sidelobes using apodized FBGs in a cascade.The reflection of each unit is produced relative to the first unit, where the signal reflected from each unit is considered the input to the new one.

As shown in Fig. 2, in the complete proposed system, we used the proposed model, shown in Fig. 3 after the light source directly to obtain minimum sidelobes and consequently minimum linewidth with acceptable reflectivity.

The concept of the dispersion compensation using AFBG is explained in (Fathy M. Mustafa 2021 and Toba 2019) by dividing the AFBG length L into m segments and

considering the reflected signal from the first AFBG as an incident signal to the second AFBG, and so on.

Through simulation, we found that the best design is using four stages AFBGs to obtain minimum sidelobes and acceptable signal reflectivity. This is because after five AFBG stages, we did not get significant enhancement and more cost and complexity drawbacks.

3   Results and discussion

In this part, we discuss the simulation results obtained for the proposed model and compare with the basic model results. This is done to validate in order to determine the success of the proposed model in increasing the transmission length as well as the rate of data transmission. The purpose of simulations is to design a fiber cable that will be robust against propagation problems.

Table 1 displays the values and the parameters that were employed in the investigation were in the following ranges.

The system is simulated for conditions:

(1)   The transmission bit rate analysis versus different parameters using soliton transmission technique without FBG.
(2)   The transmission bit rate analysis versus different parameters using hybrid system of soliton transmission technique with four cascaded apodized FBGs.

3.1 3.1 Case one: Bit rate per channel transmitted versus Δ

Depending on T and X, we investigate the bit rate per channel versus the relative refractive index difference Δ.

3.1.1 Impact of ambient temperature

The relationship between transmitted bit rate and Δ is depicted in Fig. 4. This is depicted at various ambient temperature levels.

The comparison in Fig. 4a, b indicates that the transmitted bit rate per channel drops as Δ increases. In Fig. 4a, the maximum bit rate equals 31.0115 Gbps and is accomplished at

Table 1 Simulation parameters and their value ranges

Parameter	Value
λs	$1.65\ \mu m \geq \lambda s \geq 1.35$
Δλ	$0.1\ nm \geq \Delta\lambda$
Δn	$0.008 \geq \Delta n \geq 0.002$
T	$50\ °C \geq T \geq 20$
Percentage of GeO_2 doping (X)	$0.2 \geq X \geq 0.0$
Effective area (Aeff)	$85\ \mu m^2$
Peak power (Ppeak)	600 m Watt
Nonlinear Kerr coefficient (nnl)	$2.6 \times 10\text{–}20\ m^2/Watt$

Fig. 4 a Bit rate per channel transmitted using soliton with variations in Δ at various values of T **b** Bit rate per channel transmitted using soliton-tanh AFBG with the variations in Δ at various values of T
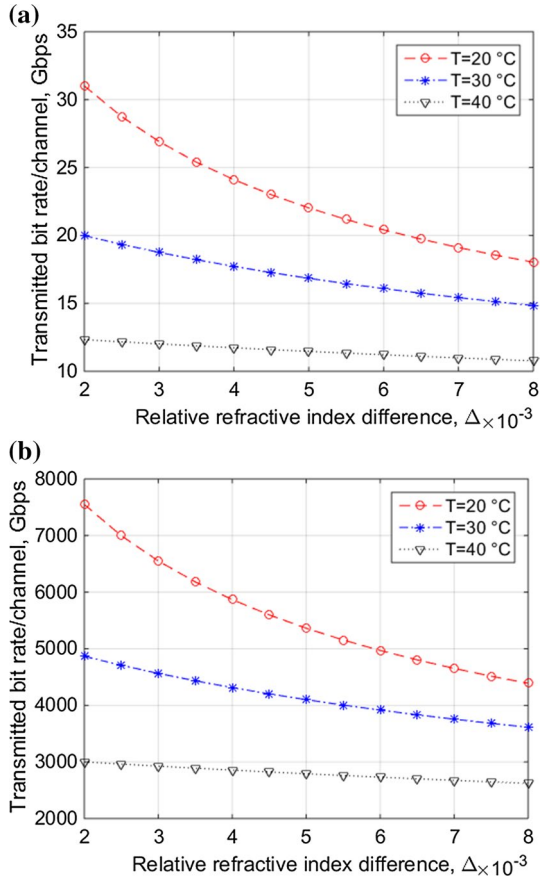
$T=20$ °C and $\Delta=0.002$, while Fig. 4b the maximum bit rate equals 7549.6 Gbps after utilising model that has been proposed, at the same time altering parameters.

3.1.2 The effect of the X ratio

A Germania dopant of ratio X is doped into the silica-doped fiber. Figure 5a, b depicts the influence on the transmitted bit rate per channel.

From Fig. 5b $B_{Soliton}=9459.4$ Gbps, thus it's evident that as X ratio rises, the transmitted bit rate rises as well.

Table 2 illustrates that when the proposed model is utilized, the best results are obtained. In Table 2, the finest outcomes produced in the event in case one and the proposed (soliton with 4 cascaded tanh AFBGs) is compared to the fundamental model (soliton).

3.2 Case two: Bit rate per channel transmitted in comparison to the ambient temperature

We plot the bit rate per channel against T at various levels of Δ and X, respectively.

Fig. 5 **a** Soliton transmitted bit rate per channel with variations in Δ at various Germania dopant values. **b** Transmitted bit rate per channel employing soliton-tanh AFBG with varying values of Germania dopant and variations in Δ
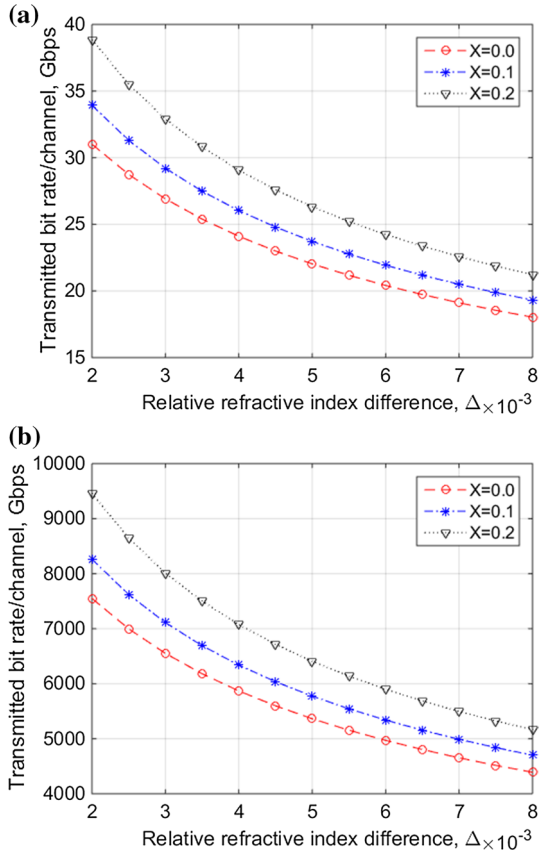

(a)

(b)

**Table 2** Case one yielded the best outcomes, at Δ = 0.002

Parameters	$B_{soliton}$ of a fundamental model (Gbps)	$B_{soliton}$ of proposed model (Gbps)
T = 20 °C	31.0115	7549.6
X = 0.2	43.5719	9459.4

3.2.1 The effect of a variation in Δ

Figure 6a, b, show the results obtained from simulation model design.

It is clear that as long as we have a small relative refractive index, we get large transmitted bit rate but the disadvantages of the high ambient temperature impact must be taken into account. Furthermore, if the proposed approach is implemented, the transmitted data rate at Δ = 0.003 and T = 20 °C is 6551.4 Gbps, whereas the basic model equals 26.9111 Gbps under the same conditions.

Fig. 6 **a** The relation between transmitted bit rate per channel using soliton with the variations of T at different values of Δ. **b** The relation between transmitted bit rate per channel using soliton-tanh AFBG with the variations of T at different values of Δ
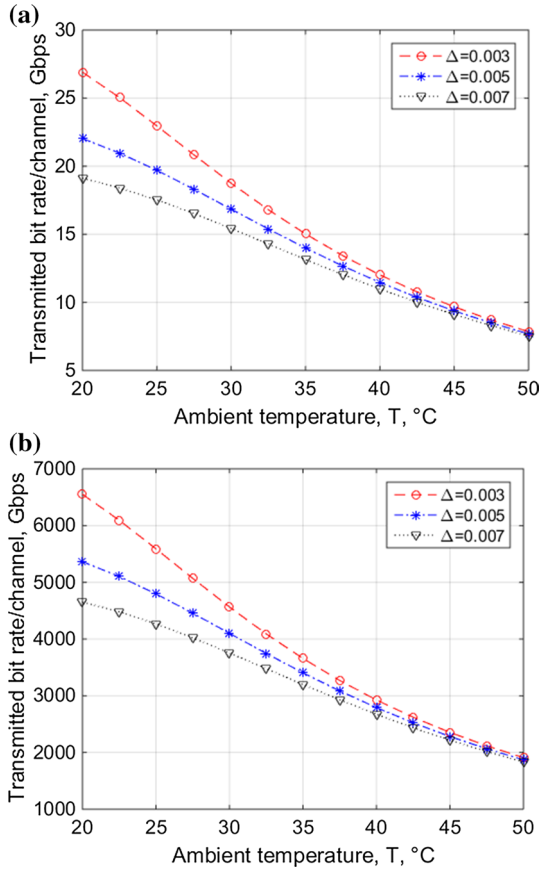
3.2.2 The effect of X

In Fig. 7a, b, the effect of the Germania dopant, X, on the transmitted bit rate is shown with the ambient temperature.

The transmitted bit rate is inversely related to the ambient temperature, T, as seen in Fig. 7. Because of the effect of FBGs, the highest bit rate after applying the suggested model is 9459.4 Gbps, but it is 38.8561 Gbps without the FBGs at the same settings.

In case two, the best results were obtained. at T = 20 °C, are summarized in Table 3. Table 3 demonstrates that the proposed model, which is a hybrid system consisting of a soliton and four cascaded tanh FBGs, produces the best results. The highest bit rate achieved was 9459.4 Gbps.

3.2.3 Case three: The transmitted bit rate per channel against input signal wavelength

In instance three, we investigate the bit rate per channel versus the wavelength of the optical signal, λs, at various values of Δ, T, and X.

Fig. 7 **a** The relation between transmitted bit rate per channel using soliton and variations of T at X. **b** The relation between transmitted bit rate per channel using soliton-tanh AFBG and T at different values of X
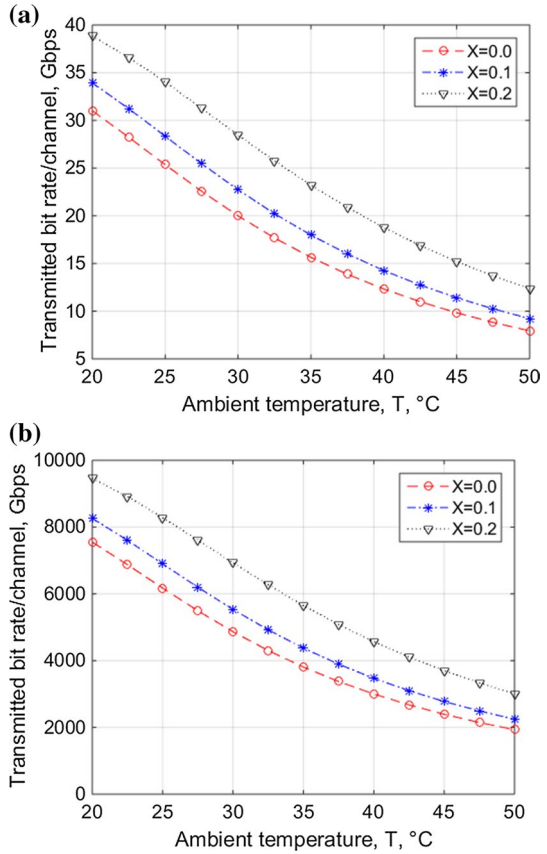

**Table 3** At T=20 °C, the best results were obtained similar to case two

Parameters	$B_{Soliton}$ of a fundamental model (Gbps)	$B_{Soliton}$ of proposed model (Gbps)
Δ=0.003	26.9111	6551.4
X=0.2	38.8561	9459.4

3.2.4 The effect of a variation in relative refractive index

At the assumed different values of Δ, Fig. 8a, b explains the relationship between transmitted bit rate and optical signal wavelength.

At λs = 1.65 μm and Δ=0.003, the highest value of transmitted bit rate $B_{Soliton}$ = 27.7136 Gbps is attained, as shown in Fig. 8a, however, as shown in Fig. 8b, utilizing the tanh apodized FBG model results in a higher value of transmitted bit rate of 6746.8 Gbps at the same affected parameters, indicating the benefits of adopting the tanh apodized FBG model.

Fig. 8 **a** The transmitted bit rate per channel using soliton and input signal wavelength at different values Δ. **b** The transmitted bit rate per channel using soliton-tanh AFBG and of input signal wavelength at different values Δ
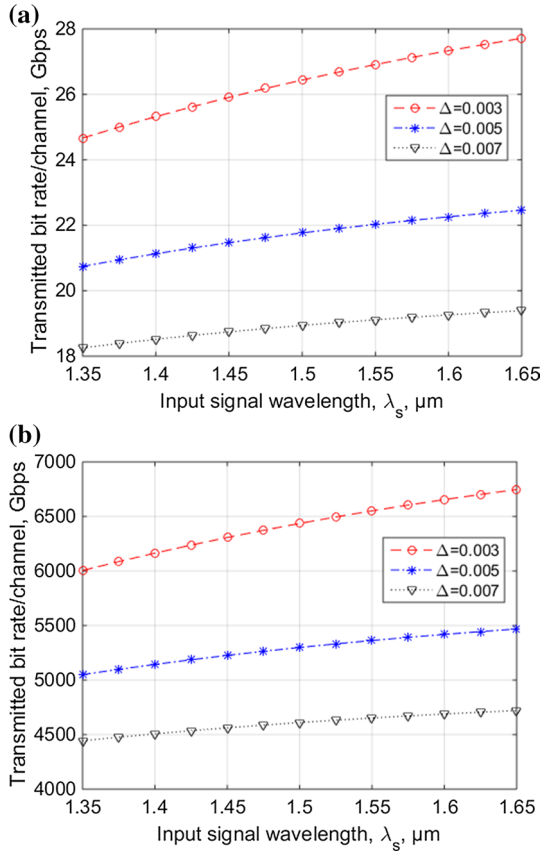
3.2.5 The effect of the ambient temperature

The relationship between bit rate/channel and input signal wavelength is seen in Fig. 9a, b at various ambient temperatures.

The data rate maximum value is 32.2580 Gbps at $T = 20$ °C and $\lambda s = 1.65$ μm, as shown in Fig. 9a. Using model that has been proposed, the bit rate maximum value equals 7853.1 Gbps at the same conditions, as shown in Fig. 9b.

3.2.6 The effect of the X

At constant quantities of germanium dopant X, Figs. 10(a, b) show the relationship between bit rate/channel and the input signal wavelength.

It is clear from the above figures that $X = 0.2$ achieves higher transmitted bit rate than $X = 0.0$.

In general, at the same conditions, the proposed model produces better results than the fundamental model.

Table 4 summarizes the best results found in case three, at $\lambda_s = 1.65$ μm.

Fig. 9 **a** The transmitted bit rate per channel using soliton and input signal wavelength at different values of T. **b** The transmitted bit rate per channel using soliton-tanh AFBG and input signal wavelength at different values of T
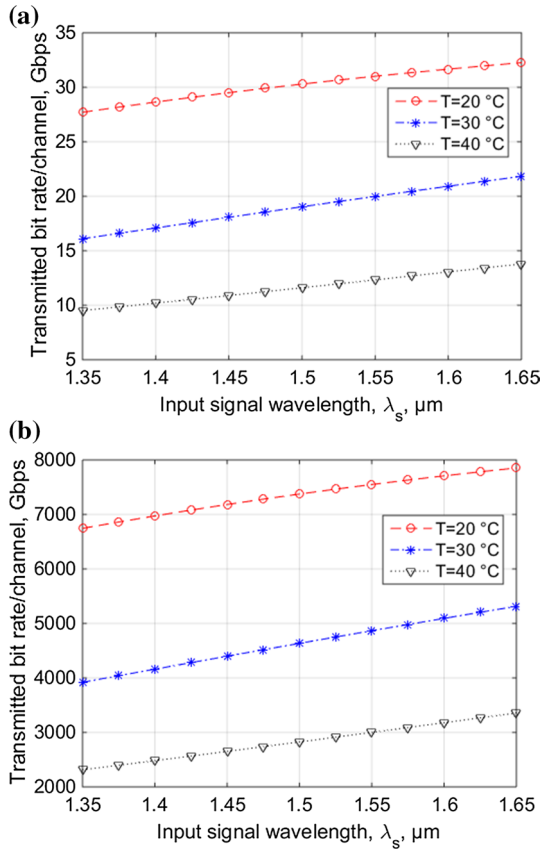

Table 4 demonstrates that when the suggested model is employed with the same parameters and a maximum bit rate of 9687 Gbps, the best results are obtained.

3.3 Comparison between a fundamental model and proposed model with raised cosine and tanh apodization function

For the raised cosine apodization function, the procedure is repeated. The obtained results are compared to the tanh apodization function results in Table 5. Using the tanh apodized FBG unit produces greater bit rate values in all cases, as seen in this table.

Fig. 10 a The transmitted bit rate per channel using soliton and input signal wavelength at different X. **b** The transmitted bit rate per channel using soliton-tanh AFBG and input signal wavelength at different X
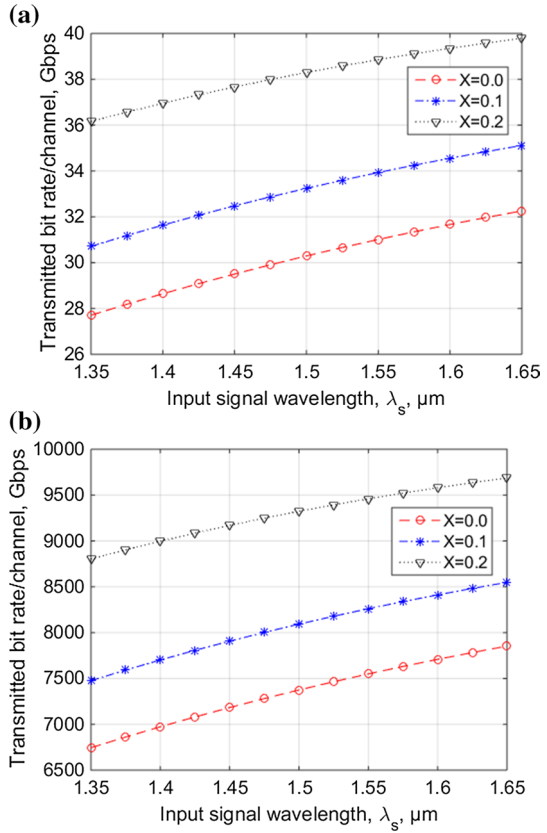
(a)

(b)

Table 4 Case three yielded the best outcomes, at $\lambda_s = 1.65$ μm

Parameters	$B_{Soliton}$ of a fundamental model (Gbps)	$B_{Soliton}$ of proposed model (Gbps)
$\Delta = 0.003$	27.7136	6746.8
$T = 20$ °C	32.2580	7853.1
$X = 0.2$	39.7909	9687.0

4 Conclusion

The properties of silica-doped fibers have been studied under different parameters. Soliton transfer method with a four stages of tanh AFBGs is used to reduce dispersion in optical systems within the corresponding controlling parameters. The obtained results show that the increase in ambient temperature and relative refractive index difference degrades the soliton transmission bit rate. It is also obvious that our proposed model boosts silica-doped materials transmission bit rates per channel. At $\Delta = 0.002$, $T = 20$ °C, and $X = 0.2$, a high transmission bit rate of 9.687 Tbps is attained.

Table 5 Best results for each case

Parameters of operation	$B_{soliton}$ (Gbps) Fundamental model	$B_{soliton}$ with raised cosine (Gbps) Proposed model	$B_{soliton}$ with tanh (Gbps) Proposed model
Case 1: at Δ = 0.002			
T = 20 °C	31.0115	1343.3	7549.6
X = 0.2	38.8561	1683.1	9495.4
Case 2: at T = 20 °C			
Δ = 0.003	26.9111	1165.7	6551.4
X = 0.2	38.8561	1683.1	9459.4
Case 3: at λ_s = 1.65 μm			
Δ = 0.003	27.7136	1200.4	6746.8
T = 20 °C	32.2580	1379.3	7853.1
X = 0.2	39.7909	1723.6	9687.0

Availability of data and materials The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not Applicable.

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