

ZERO-DISPERSION SHIFTED OPTICAL FIBER DESIGN BASED ON GA AND CD OPTIMIZATION METHODS

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Abstract—In this paper, the RII depressed core triple clad based structure as Zero-dispersion Shifted optical fiber is optimized to obtain small pulse broadening factor (small dispersion and its slope) and low bending loss suitable for long haul communications. The proposed structures allow reducing the dispersion, its slope and the bending loss. The Genetic Algorithm (GA) and the Coordinate Descent (CD) technique are used for the optimization. The suggested design approach involves a special cost function which includes dispersion, its slope, and bending loss impacts. The proposed algorithm and structure have inherent potential to obtain large effective area and extend tolerance of bending loss simultaneously. Meanwhile, an analytical method is used to calculate the dispersion and its slope. In the meantime, the thermal stabilities of the designed structures are evaluated.

1. INTRODUCTION

For long distance transmission, small broadening factor (small dispersion and its slope), small nonlinearity (large effective area), and less bending loss are needed. Gathering all these properties in the proposed fibers is so hard and usually there is a trade off between nonlinearity and bending loss. Meanwhile, introducing a dispersion shifted fiber including small dispersion slope is difficult to realize. Owing to loss, the amplitude of the pulse is reduced so that the initial information can not be restored in noisy conditions. So in fiber design, one likes to shift the zero dispersion wavelength to the region that fiber

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has lowest level attenuation. The combination of natural attenuations of silicon based optical fiber has a global minimum around $1.55 \mu\text{m}$ and that is why most optical communication systems are operated at this wavelength.

We are going to review some interesting reported papers. As a first and interesting work, we will discuss the paper presented by Savadi et al. [1]. In that paper, the authors have introduced a design method to control the chromatic dispersion and its slope simultaneously. For the proposed MII fiber structures, the small dispersion and its slope have been obtained thanks to a design method based on genetic algorithm. But there is no any concentration on the bending loss characteristic at the design process. A class of low nonlinearity dispersion shifted fibers based on depressed core multi-step index profile was investigated in [2, 3]. A systematic approach for designing these fibers is presented in which a reference depressed inner clad called W-type fibers is used to initiate the design. Transmission properties, including effective area, mode field diameter, dispersion, dispersion slope, and cutoff wavelength were evaluated for several design examples. The effects of varying fiber dimensions and indices on effective area and mode field diameter were assessed. Also, the bending loss is investigated in this paper. Theoretical method to analyze three-layer large flattened mode fibers was presented in [4]. The modal fields, including the fundamental, higher order modes, and bending loss of the fiber are analyzed. Recently, in [5], the authors have stabilized the analytical approach to calculate the dispersion and dispersion slope. Due to analytically based relationships, this strategy accurately covers all the numerical method presented so far. For a case study, the given method has been used to analyze the M-type fiber structure. A bending loss formula for the optical fibers with an axially symmetric arbitrary-index profile was derived by approximating the refractive index profile with a staircase function [6]. The permissible bending radius R^* defined for a given value of bending loss was evaluated. That paper is a basic publication in the bend loss calculation domain. The refractive index thermal coefficient has been analyzed by Gosh [7], for three optical fiber based glasses in a physically meaningful model for the first time to compute refractive indexes at any operating temperature and wavelength. He believes that the energy gap corresponding to the peak position of the electronic absorption which lies in the vacuum ultraviolet (VUV) spectral region is the major contributor to the dispersion of thermo-optic coefficients of these glasses.

In this work, we present a novel design method to manage dispersion and dispersion slope curves and control bending loss property simultaneously. Our proposal is based on the Genetic

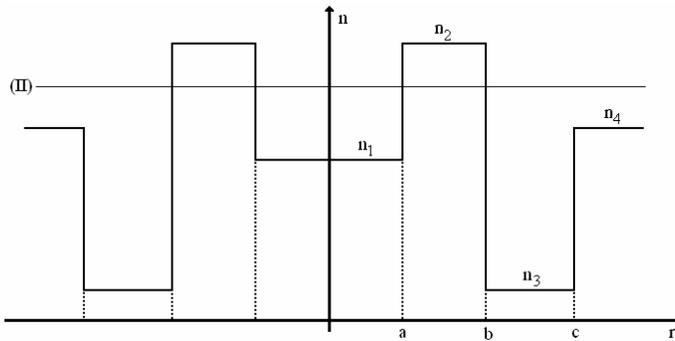


Figure 1. Index of refraction profile for RII structure.

Algorithm (GA) and Coordinate Descent (CD) with introducing appropriate cost function for demanded targets. We use this strategy to design a Zero Dispersion Shifted Fiber (ZDSF) based on the R type depressed core triple clad single mode fiber. The results prove efficiency of this method which could obtain small dispersion slope and bending loss simultaneously. Meanwhile, the optical transmission characteristics as a function of temperature are investigated.

2. MATHEMATICAL FORMULATION

The mathematical background to extract the properties of the suggested structure is introduced in this section. The index refraction profile of the RII fiber structure is shown in Figure 1. According to the LP approximation to calculate the electrical field distribution, there is a region of operation and the guided modes and propagating wave vectors can be computed by using a determinant which is constructed by boundary conditions [8]. It is well-known that in this approximation, the modes are assumed to be nearly transverse and can have an arbitrary state of polarization.

To calculate the dispersion, its slope and bending loss characteristics of the structure, the geometrical and optical parameters are defined as follows.

$$p = \frac{b}{c}, \quad q = \frac{a}{c} \tag{1}$$

$$R_1 = \frac{n_2 - n_3}{n_2 - n_1}, \quad R_2 = \frac{n_1 - n_4}{n_2 - n_1}, \quad \Delta = \frac{n_2^2 - n_4^2}{2n_4^2} \approx \frac{n_2 - n_4}{n_4}. \tag{2}$$

Furthermore, the transversal propagating constants are defined as

follows.

$$\gamma_i = (\beta_g^2 - n_i^2 k_0^2)^{\frac{1}{2}}, \quad \kappa_i = (n_i^2 k_0^2 - \beta_g^2)^{\frac{1}{2}} \quad (i = 1, 2, 3, 4), \quad (3)$$

where β_g is the longitudinal propagation wave vector of the guided modes and k_0 the wave number in vacuum. In the following, in order to calculate the dispersion and its slope in the proposed structure, the total dispersion (D) and the dispersion slope (S) are given.

$$D = -\frac{\lambda}{c} \frac{d^2 n_4}{d\lambda^2} \left[1 + \Delta \frac{d(VB)}{dV} \right] - \frac{N_4}{c} \frac{\Delta}{\lambda} V \frac{d^2(VB)}{dV^2}, \quad (4)$$

$$S = -\frac{\lambda}{c} \frac{d^3 n_4}{d\lambda^3} \left[1 + \Delta \frac{d(VB)}{dV} \right] - \frac{1}{c} \frac{d^2 n_4}{d\lambda^2} \left[1 + \Delta \frac{d(VB)}{dV} \right] + \frac{N_4}{c} \left(\frac{\Delta}{\lambda^2} \right) V^2 \frac{d^3(VB)}{dV^3} + 2 \frac{N_4}{c} \frac{\Delta}{\lambda^2} V \frac{d^2(VB)}{dV^2} + 2 \frac{\Delta}{c} \frac{d^2 n_4}{d\lambda^2} V \frac{d^2(VB)}{dV^2}, \quad (5)$$

where $N_4 = n_4 - \lambda(dn_4/d\lambda)$ is the group index of the outer cladding layer, $andV$ and B are the normalized frequency and normalized propagation constant defined by:

$$V = k_0 a \sqrt{n_2^2 - n_4^2}, \quad B = \frac{\beta_g/k_0 - n_4}{n_2 - n_4}. \quad (6)$$

The Sellmeier formula is used to calculate the material dispersion. It should be mentioned that the first, second and third order derivatives of VB is computed analytically and used the approach which has been outlined by Rostami et al. in [5].

The bending loss is one of the most important factors to evaluate the overall fiber losses. It is manifestly clear that the optical fiber loses the power by radiation if its axis is curved. Using the method introduced and discussed by Sakai and Kimura [6], the radiation loss, owing to the uniform bending, can be obtained. In this method, it is supposed that the field near the inner layers in the curved fiber is similar to that in the straight one. This approximation is greatly accurate to evaluate the radiation losses in single mode optical fiber. Then expansion coefficients of a field expansion are identified in the terms of cylindrical waves. These coefficients can be gained by matching the field expansion with the mode field of straight one. The bending loss coefficient is written as:

$$2\alpha = \frac{\sqrt{\pi} A_4^2}{2sP} \cdot \frac{c \exp\left(\frac{-4\Delta w^3}{3cV^2} R\right)}{w \left(\frac{wR}{c} + \frac{V^2}{2\Delta w}\right)^{\frac{1}{2}}}, \quad (7)$$

where c denotes the radius of the third boundary, by referring to Figure 1. R is the radius of curvature of the bending, and w is given by

$\gamma_4 c$. A_4 and γ_4 are respectively the constant component of the electrical field of the outer layer and its transversal propagating constant, and V is normalized frequency. Regarding to the LP mode order, s is defined as:

$$s = \begin{cases} 2 & v = 0 \\ 1 & v \neq 0 \end{cases} \quad (8)$$

According to the relation between the effective refractive index and the layers refractive index, P is explained as $P = \Sigma P_i$.

(I) $n_i k_0 > \beta_g$,

$$P_i = \left[\frac{A_i^2 r^2}{2} (J_v^2 - J_{v-1} J_{v+1}) + \frac{B_i^2 r^2}{2} (Y_v^2 - Y_{v-1} Y_{v+1}) + A_i B_i r^2 (J_v Y_v - J_{v-1} Y_{v+1}) \right]_{a_i}^{a_i+1}, \quad (9)$$

(II) $n_i k_0 < \beta_g$

$$P_i = \left[\frac{A_i^2 r^2}{2} (K_v^2 - K_{v-1} K_{v+1}) + \frac{B_i^2 r^2}{2} (I_v^2 - I_{v-1} I_{v+1}) + A_i B_i r^2 (K_v I_v - K_{v-1} I_{v+1}) \right]_{a_i}^{a_i+1}. \quad (10)$$

J_v , Y_v , I_v , and K_v are the Bessel and modified Bessel functions of order v , respectively. The related arguments of the Bessel and modified Bessel functions are left out for brevity. a_i indicates the radius of the i th boundary. A_i and B_i ($i = 1, 2, 3, 4$) are constant and computed by applying the electric and magnetic field continuities at boundaries.

It is apparent that the transmission performances are manipulated and optimized by controlling the optical and geometrical parameters in the fiber structures. As a result, any undesired alteration in the fiber structure parameters, can distract the transference performances. The refractive index variation as a function of temperature (dn/dT) is the critical feature in the optical fibers. The method used in this paper has been introduced by Ghosh [7]. In this model, the Thermo-optic coefficient dn/dT contains the contribution of electrons and optical phonons. Consequently, it can be described in the optical transmission range in terms of linear expansion coefficient α and the temperature variation of energy gap (dE_g/dT) by the relation [9]

$$2n(dn/dT) = \chi_e \left[-3\alpha - \frac{2}{E_g} \cdot \frac{dE_g}{dT} \cdot \frac{E_g^2}{(E_g^2 - E^2)} \right] \quad (11)$$

where χ_e , E , and E_g are the electronic susceptibility, photon energy, and the suitable energy gap lying in the vacuum ultraviolet regio,

Table 1. Interpolated coefficient in the relation $2n \cdot dn/dT = GR + HR^2$.

G ($10^{-6}/^\circ$)	H ($10^{-6}/^\circ$)	λ_g (μm)	α ($10^{-6}/^\circ$)
-1.6548	31.7794	0.109	0.45

respectively. The above equation can be rewritten in terms of a normalized wavelength $R = \lambda^2/(\lambda^2 - \lambda_g^2)$ as

$$2n \left(\frac{dn}{dT} \right) = GR + HR^2 \quad (12)$$

where the constants G and H are related respectively to the thermal expansion coefficient (α) and the energy gap temperature coefficient (dE_g/dT) according to the relations presented in [7] and their values are given in Table 1 for silica glasses.

3. DESIGN ALGORITHM

As said earlier, we attempted to present an optimized RII triple-clad optical fiber to obtain the wondering performance from dispersion, its slope, and bending loss points of view. The design method is based on the combination of the GA and CD approaches. It is well known that the GA is the scatter-shot and the CD is the single-shot searching technique. The single-shot search is very quick compared to the scatter-shot type, but depends critically on the guessed initial parameter values [10]. This description indicates that for the CD search, there is a considerable emphasis on the initial search position. On the other hand, the GA is useful in the domains that are not understood well. In this method, it is possible to define a cost function and evaluate every individuals of the population with it. So we have combined the CD and GA methods to improve the initial point selection with the help of generation elite and inherit the quick convergence of coordinate descent. In other words, we cover and evaluate the answer zone by initial population and deriving few generations and use the elite of the latest generation as an initial search position in the CD (Figure 2).

To derive the suggested design methodology, the following weighted cost function is introduced. In fact, the weighting function is necessary to describe the relative importance of each subset in the cost function; in other words, we let the pulse broadening factor have different coefficient in each wavelength. Meanwhile, we have normalized the pulse broadening factor in the manner to be comparable

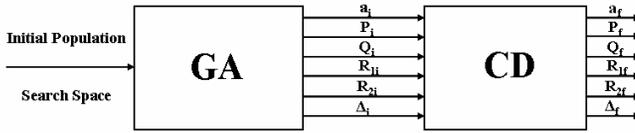


Figure 2. The block diagram of the proposed method.

with bending loss. This normalization is essential to optimize the pulse broadening factor and bending loss simultaneously. If not, the bending loss impact will be imperceptible and be lost in the broadening factor term.

$$\text{cost function} = \sum_{\lambda} e^{-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}} \left(\frac{1}{z} \sum_Z \left[\left(1 + \frac{\beta_2(\lambda)Z}{t_i^2} \right)^2 + \left(\frac{\beta_2(\lambda)Z}{t_i^2} \right)^2 + \left(\frac{\beta_3(\lambda)Z}{2t_i^3} \right)^2 \right]^{\frac{1}{2}} \right) + BL(\lambda), \quad (13)$$

where t_i , Z , λ , λ_0 , β_2 , β_3 , σ and BL are, respectively, initial full width at half maximum of input pulse, distance, wavelength, central wavelength, the second derivative of the guided wave vector, the third derivative of the guided wave vector, Gaussian parameter and bending loss quantity. The bending radius is set on 1 cm and kept still. The cost function includes dispersion (β_2), dispersion slope (β_3), and bending loss (BL) impacts. In the defined weighted cost function, internal summation is proposed to include optimum broadening factor for each length up to 200 km. One can adjust the zero-dispersion wavelength at λ_0 and dominate the dispersion slope by Gaussian parameter (σ). The advantage of this design method is introducing two parameters (λ_0 and σ) instead of multi-designing parameters (optical and geometrical), which makes system design easy.

4. SIMULATION RESULTS

Based on the developed cost function, the simulation results are presented in this section. All simulations are done at $\lambda_0 = 1.55 \mu\text{m}$ with σ as parameter. To carry out the simulations, the weighted cost function introduced in Section 3 is used. The wavelength and distance durations for optimization are $1.5 \mu\text{m} < \lambda < 1.6 \mu\text{m}$ and $0 < Z < 200 \text{ km}$. In the simulations an unchirped initial pulse with 5 ps as full width at half maximum is used.

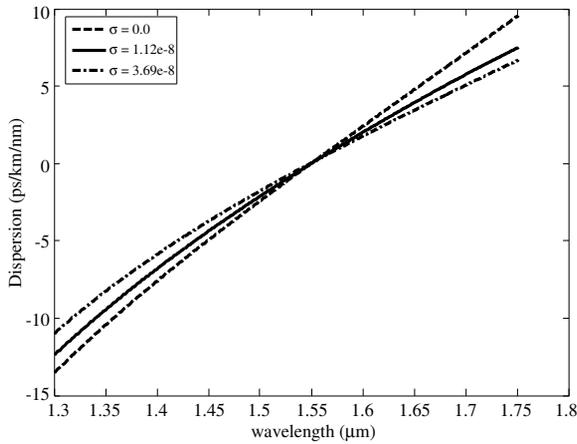


Figure 3. Dispersion vs. wavelength at $\lambda_0 = 1.55 \mu\text{m}$.

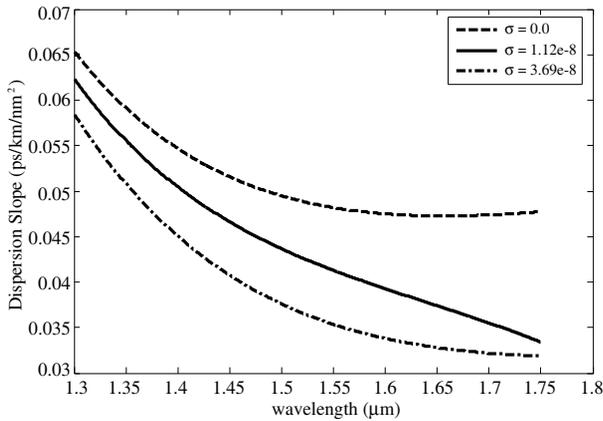


Figure 4. Dispersion slope vs. wavelength at $\lambda_0 = 1.55 \mu\text{m}$.

First, the obtained dispersion behaviors of the structures are illustrated in Figure 3 which obviously demonstrates the λ_0 and σ parameters influences. It is clear that the zero-dispersion wavelength is successfully set on λ_0 and the dispersion curve is become flatter in the higher σ cases. In other words, by introducing two design parameters, the dispersion behavior of the structures can be managed.

The dispersion slope is strongly affected by the presence of σ in such a manner that its increase has a considerable influence on dispersion slope and drops it obviously. This fact is easily visible on Figure 4 which shows the dispersion slope versus wavelength with variance of σ as parameter.

Table 2. Dispersion, dispersion slope, bending loss, and affective area at $\lambda_0 = 1.55 \mu\text{m}$ and three given Gaussian parameters.

type	D ($\lambda = 1.55 \mu\text{m}$) (ps/km/nm)	S ($\lambda = 1.55 \mu\text{m}$) (ps/km/nm ²)	BL ($\lambda = 1.55 \mu\text{m}$) (dB/m)	A_{eff} ($\lambda = 1.55 \mu\text{m}$) (μm^2)
$\sigma = 0.00$	1.38e-4	0.048	1.90e-2	86
$\sigma = 1.12\text{e-}8$	-6.15e-4	0.041	1.67e-1	82
$\sigma = 3.69\text{e-}8$	4.50e-2	0.035	4.66e-2	86

Table 3. The optimal values of optical and geometrical parameters for three different designs.

type	a (μm)	p	q	R_1	R_2	Δ
$\sigma = 0.00$	2.2102	0.8934	0.3927	1.0602	-0.5743	8.791e-3
$\sigma = 1.12\text{e-}8$	2.5580	0.8328	0.4063	1.6255	-0.4491	8.993e-3
$\sigma = 3.69\text{e-}8$	2.4331	0.8513	0.3927	1.0962	-0.5743	8.949e-3

To show the capability of the proposed algorithm, Table 2 is presented to clarify the different characteristics of these three structures. Also the optimal geometrical and optical parameters of the designed fibers with different σ are listed in Table 3. By considering on Figures 3, 4 and Table 2, it is clear that there is a trade-off between the zero-dispersion wavelength tuning and the dispersion slope decreasing. In other words, it is found out that the zero value for the σ parameter can tune the zero-dispersion wavelength accurately (~ 100 times better than other cases).

The effective area or nonlinear behavior of the suggested structures is listed in Table 2. These values are high enough for the optical transmission applications. Owing to the special structure of the RII type fiber, the field distribution peak has fallen in the first cladding layer. As such most of the field distribution displaces to the cladding region. This is the origin of large effective area in the designed structures. The normalized field distribution of the RII based designed structures is illustrated in Figure 5.

Bending loss represents an important role in the single mode optical fiber design. The suggested structures bending loss behavior is illustrated in Figure 6. The bending losses on $1.55 \mu\text{m}$ with 1 cm radius of the curvature are less than 1 dB/m and given in Table 2. These results are outstanding compared to the bending loss response of the structure which is reported by Varshney et al. in [11]. In that paper, the bend loss reported value at $1.55 \mu\text{m}$ for 5 cm radius of curvature

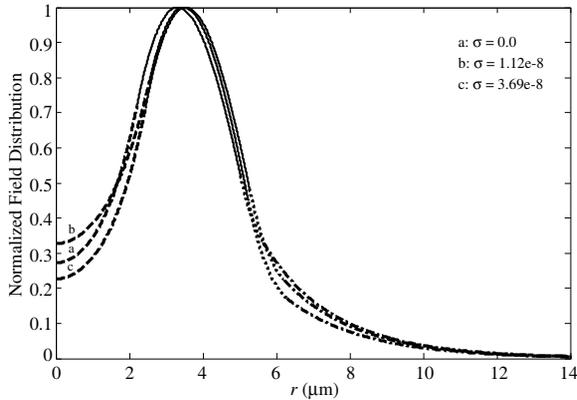


Figure 5. Normalized field distribution versus the radius of the fiber at $\lambda = 1.55 \mu\text{m}$ with σ as parameter (dashed, solid line, dotted, and dashed-dotted curve represent the core and three cladding layers, respectively).

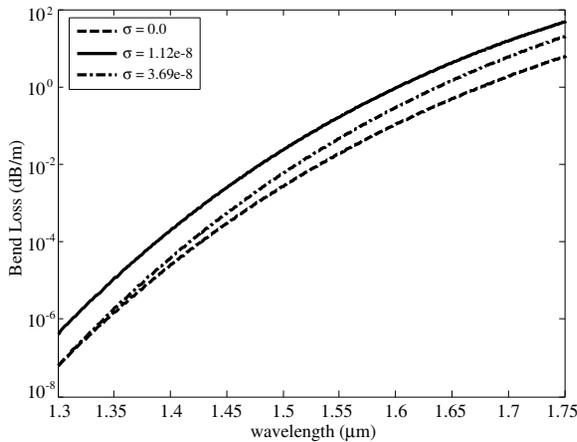


Figure 6. Bending loss (dB/m) Vs wavelength (μm) with 1 cm radius of the curvature.

is near 2.5 dB/m which is extremely larger than the results presented Table 2. The permissible bending radius R^* , where the loss value reaches 0.1 dB/km are 1.32 cm, 1.56 cm and 1.41 cm for $\sigma = 0.0$, $1.12\text{e-}8$, and $3.69\text{e-}8$ respectively.

Due to the refractive index thermo-optic coefficient and thermal expansion coefficient, the optical and geometrical parameters are altered. Consequently, the optical transmission characteristics of

Table 4. Dispersion, dispersion slope, and bending loss thermal coefficients at $\lambda_0 = 1.55 \mu\text{m}$ and three given Gaussian parameters.

Type	dD/dT (ps/km/nm/°C)	dS/dT (ps/km/nm ² /°C)	$d\lambda_0/dT$ (nm/°C)	dBL/dT (dB/m/°C)
$\sigma = 0.0$	-1.22×10^{-3}	$+2.83 \times 10^{-6}$	$+2.5 \times 10^{-2}$	$+3.97 \times 10^{-6}$
$\sigma = 1.12\text{e-}8$	-1.21×10^{-3}	$+2.93 \times 10^{-6}$	$+3.33 \times 10^{-2}$	$+2.70 \times 10^{-5}$
$\sigma = 3.69\text{e-}8$	-1.21×10^{-3}	$+2.93 \times 10^{-6}$	$+2.5 \times 10^{-2}$	$+8.79 \times 10^{-6}$

the optical fiber such as dispersion, its slope and bending loss are confronted to change. In order to evaluate the thermal stability of the designed structures, the following results are extracted and presented in Table 4. The dD/dT , dS/dT , $d\lambda_0/dT$, and dBL/dT expressions are respectively the chromatic dispersion, its slope, zero dispersion wavelength, and bending loss thermal coefficients at $1.55 \mu\text{m}$. It is found out that this environmental factor must be considered in the desired optical fiber design. For example, in the worst case, the zero dispersion wavelength can be shifted more than 3 nm with 100°C .

5. CONCLUSION

In this paper, we have focused on RII depressed core triple clad single mode optical fiber and presented a combined optimization approach to obtain desirable design goals. This design proposal is a mixture of Evolutionary Genetic Algorithm and Coordinate descent method. Furthermore, we have used the special cost function including dispersion, its slope and bending loss impacts simultaneously. With application of this cost function in the case of higher σ , we could obtain the dispersion and dispersion slope in $[1.5\text{--}1.6] \mu\text{m}$ interval to be $[(-1.77)\text{--}(+1.77)]$ ps/km/nm and $[(0.037)\text{--}(0.033)]$ ps/km/nm². Also the amount of bending loss at $1.55 \mu\text{m}$ with 1 cm radius of curvature and effective area are $4.66\text{e-}2$ dB/m and $86 \mu\text{m}^2$, respectively. The advantages of the proposed strategy are its capability to extend to all fiber structures and introducing a couple of parameters instead of multi-designing parameters. In the meantime, the thermal stabilities of the designed structures are evaluated. Also it is mentionable that the dispersion and its slope are calculated analytically.

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