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SEGMENTED-CORE SINGLE MODE OPTICAL FIBER WITH ULTRA-LARGE-EFFECTIVE-AREA, LOW DISPERSION SLOPE AND FLATTENED DISPERSION FOR DWDM OPTICAL COMMUNICATION SYSTEMS

Babita Hooda* **and Vipul Rastogi**

Department of Physics, Indian Institute of Technology Roorkee, Roorkee-247667, India

Abstract—In this paper we present designs of fibers having non-zero positive, non-zero negative and near-zero ultra-flattened dispersion with small dispersion slope and ultra-large effective area over a wide spectral range. The designs consist of a concentric multilayer segmented core followed by a trench assisted cladding and a thin secondary core. The central segmented core helps in maintaining desired dispersion over a wide range of wavelength. The second core of the fiber helps in achieving ultra-large effective area and trench assisted cladding reduces the bending loss. The designs of the fiber have been analyzed by using the transfer matrix method. For positive non-zero dispersion flattened fiber we have optimized dispersion near +4.5 ps/km/nm in the wavelength range 1.46–1.65 μm. Maximum value of dispersion slope of the fiber in above mentioned wavelength range is 0.026 ps/km/nm^2. In the design of negative non-zero dispersion flattened fiber, dispersion has been achieved near −6 ps/km/nm in the spectral range of 1.33–1.56 μm and maximum value of dispersion slope is 0.048 ps/km/nm^2. Dispersion and dispersion slope of near zero dispersion flattened fiber lie in the range [0.0039–0.520] ps/km/nm and [(0.0004)–(0.0365)] ps/km/nm^2 respectively in the spectral range of 1.460–1.625 μm. The near zero dispersion flattened fiber has an ultra-high effective area ranging from 114 μm^2 to 325.95 μm^2 in the aforementioned wavelength range, which covers the entire S+C+L-band. These values of mode area are noticeably higher than those reported in literature for flattened dispersion fibers with large mode area. Designed fiber shows very small bending loss. We report breakthrough in the mode area of the single mode optical fiber with ultra flattened dispersion and low dispersion slope.

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* Corresponding author: Babita Hooda (babitaphy@gmail.com).

1. INTRODUCTION

The communication system based on the dense wavelength division multiplexing (DWDM) has come into existence after the successful development of broadband erbium doped fiber amplifiers (EDFAs) [1, 2]. Optical fiber is a medium to realize the task of DWDM and has two basic problems which must be considered for data transmission. These drawbacks are basically related to dispersion and nonlinear effects. In a conventional silica optical fiber value of dispersion increases with wavelength therefore different channels suffer from different broadening. Dispersion compensators can be the alternative for reshaping the signal after a suitable length of the fiber [3–10]. But in optical network the placement of dispersion compensating module increases the cost of the system, loss added by dispersion compensating module increases effective noise figure of the system and different optical channels in a fiber see different amount of accumulated dispersion. To overcome this difficulty fibers with small finite dispersion and dispersion slope have been proposed [11–14].

Another drawback of the conventional optical fibers is the small effective area which leads to nonlinear effects like self phase modulation (SPM) and cross-phase modulation (XPM) [15]. XPM limits the number of different wavelength signals that can be transmitted through the fiber. Therefore, there is need of proper transmission medium for high bit rate information transmission. Fiber having small positive dispersion is suitable for short distances because of modulation instability in positive dispersion in long distance transmission and fiber with small negative dispersion is suitable for long distance transmission [16]. The maximum distance a signal can travel depends on the choice of optical transmitter and its characteristics. Different types of optical transmitters like directly modulated distributed feedback lasers (DMLs), electro-absorption modulated distributed feedback lasers (EA-DFBs) or externally modulated lasers using Mach-Zehnder $LiNbO_3$ modulators (MZ) are considered depending on per wavelength bit rate. Recently, low-cost DMLs have attained much attention [17]. Negative dispersion fibers can balance the positive chirp characteristic of directly modulated laser (DML) transmitters and can enhance transmission distance. To achieve this, suitable refractive index profiles of the fibers which lead to small dispersion, dispersion slope and large effective area have been developed [18–21]. Recently, we proposed a segmented core design for large-mode-area near-zero dispersion flattened fiber [22]. Here we review some of these designs and propose a novel segmented-core fiber structure which can be tailored to have small positive dispersion, small negative dispersion and near zero dispersion with ultra-large mode effective area and flattened dispersion over the entire S+C+L band.

Hatayama et al. have reported dispersion flattened fiber with effective area more than $50\,\mu\text{m}^2$ [21]. However, the bandwidth that could be achieved is small for DWDM applications [20]. Lundin has presented a design of single mode W fiber which shows flattened dispersion over the wavelength range 1.25–1.60 μm [14]. The root mean square value of the chromatic dispersion over the aforementioned wavelength range in this design is less than 1 ps/km/nm. The small core radius of the fiber results in small effective area and restricts its application in DWDM long-haul optical communication system [14]. Varshney et al. have proposed design of a flat field fiber with positive dispersion and small dispersion slope over the wavelength range of 1.53–1.61μm [13]. In this fiber they have reported effective area of $56.1\,\mu\text{m}^2$ at 1.55 μm wavelength. They have shown dispersion of the proposed fiber as 2.7–3.4 ps/km/nm within the wavelength range of 1.53–1.61 μm. The dispersion slope of the designed fiber at 1.55 μm wavelength is $0.01\,\text{ps/km/nm}^2$ [13]. However, the mentioned wavelength range of the fiber does not cover the entire S+C+L band. Tian and Zhang have proposed ring index profiles named RI and RII triple-clad optical fibers with effective area ranging from 95–$118\,\mu\text{m}^2$ in the spectral range of 1.54–1.62 μm [19]. The reported total dispersion and dispersion slope within the aforementioned wavelength range are 4.5 ps/km/nm and $0.006\,\text{ps/km/nm}^2$ respectively [18]. The wavelength range reported by them also does not cover the entire S+C+L band. Okuno et al. have reported a fiber having negative dispersion of about -8 ps/km/nm over the entire telecommunication band [17]. However, the reported mode area is small. Recently Rostami and Makouei have proposed a modified W-type single mode optical fiber with ultra low dispersion, dispersion slope and ultra high effective area [20]. They show very small dispersion varying from 0.1741–0.9282 ps/km/nm within the spectral range of 1.460–1.625 μm. Dispersion slope and mode area reported by them in the aforementioned wavelength range are $[(-0.011)\text{–}(0.0035)]\,\text{ps/km/nm}^2$ and $[103.56\text{–}232.26]\,\mu\text{m}^2$ respectively. In their structure they have achieved all these features by introducing extra depressed cladding layers in W-type fiber [19].

In this paper we present a segmented core dispersion flattened fiber which is capable to be designed as (i) small positive-non-zero dispersion flattened fiber, (ii) small negative-non-zero dispersion flattened fiber, and (iii) near-zero dispersion flattened fiber. The designed fibers show ultra low dispersion slope, ultra large mode effective area and small bending sensitivity over the S+C+L band.

We have organized the paper as follows:

Method of analysis of the fiber design is presented in Section 2. The designs of the proposed fiber, fabrication feasibility and performances of the fiber through our simulation results are discussed in Section 3. Compatibility of the designed fiber with other optical fiber based components has been discussed in Section 4. Sensitivity analysis of the structural disorders on the performance of the fiber has been discussed in Section 5. Concluding remarks are presented in Section 6.

2. THEORY

We have used transfer matrix method (TMM) for modal analysis of the designed fiber [23]. The mode field of the fiber can be obtained by solving the following wave equation in different regions and applying appropriate boundary conditions.

$$\frac{d^2\psi}{dr^2} + \frac{1}{r}\frac{d\psi}{dr} + k_0^2\left(n^2(r) - n_{\mathit{eff}}^2\right)\psi = 0 \tag{1}$$

where k_0 is a free space wave number. n_{eff} is the effective index of the fundamental mode of the fiber. $n(r)$ is the refractive index profile of the fiber and ψ is the modal field. Light transmission through the single mode fiber undergoes material and waveguide dispersion. Total induced dispersion (D) in ps/km/nm is defined as:

$$D = -\frac{\lambda}{c}\frac{d^2 n_{\mathit{eff}}}{d\lambda^2} \tag{2}$$

where c is the velocity of light in free space and λ the free space wavelength. Another optical property of the fiber which describes the power density within the fiber is mode effective area (A_{eff}). Nonlinear effects in the fiber strongly depend on A_{eff}. We have calculated A_{eff} of the fiber by using the following relation [24].

$$A_{\mathit{eff}} = \frac{2\pi\left[\int\limits_0^\infty |\psi(r)|^2\, r dr\right]^2}{\int\limits_0^\infty |\psi(r)|^4\, r dr} \tag{3}$$

The mode field diameter (MFD) of the fiber has been calculated using the Peterman II method using MFD $= 2w_1$ [25] where

$$w_1^2 = \frac{2\left[\int\limits_0^\infty |\psi(r)|^2\, r dr\right]}{\int\limits_0^\infty \left[\frac{d\psi(r)}{dr}\right]^2 r dr} \tag{4}$$

The radiative loss caused by bend when bending radius is much larger than the diameter of the fiber is defined by macrobending loss and has been computed using the following relation [26]:

$$\alpha_{macro} = \frac{10}{\log_e 10} \left(\frac{\pi V^8}{16 a R_b W^3}\right)^{1/2} \exp\left(-\frac{4 R_b W^3 \Delta_1}{3 a V^2}\right) \frac{\left[\int\limits_0^\infty (1-g)\psi r dr\right]^2}{\int\limits_0^\infty \psi^2 r dr} \quad (5)$$

where R_b is bending radius and a is core radius of the fiber. Other parameters appearing in Eq. (5) are given as:

$$V = k_0 a \sqrt{n_1^2 - n_2^2} \quad (6)$$

$$W = a \sqrt{\beta^2 - k_0^2 n_2^2} \quad (7)$$

$$g = \frac{n(r)^2 - n_{\min}^2}{n_{\max}^2 - n_{\min}^2} \quad (8)$$

$$\Delta = \frac{n_{\max}^2 - n_{\min}^2}{2 n_{\max}^2} \quad (9)$$

where $n_{\max}$ and $n_{\min}$ are the maximum and minimum values of refractive index respectively. β is the propagation constant of the mode. Splice loss (α) of the fiber has been calculated using the formula given below [27]:

$$\alpha\,(\mathrm{dB}) = -10 \log_{10} \left[\frac{2 w_1 w_2}{w_1^2 + w_2^2}\right]^2 + 4.343 \frac{2\delta^2}{w_1^2 + w_2^2} + 4.343 \left(\frac{2\pi n}{\lambda}\right)^2 \frac{(w_1 w_2)}{2\left(w_1^2 + w_2^2\right)} \sin^2(\theta) \quad (10)$$

where $2w_2$ is the MFD of conventional fiber. δ represents radial offset between the cores of the fiber and θ represents angular misalignment of the two fibers. n is the refractive index of the medium between the fiber ends. In Eq. (10) first term represents the splice loss from mode field mismatch, second term calculates the splice loss due to radial offset between the cores of the fibers and the last term constitutes the loss due to fiber angular misalignment.

3. FIBER DESIGN

We have considered the fiber profile as shown in Fig. 1. Refractive index of the proposed structure is defined as follows.

$$n(r) = \begin{cases} n_1, & 0 < r < a_1 \\ n_2, & a_1 < r < a_2 \\ n_3, & a_2 < r < a_3 \\ n_4, & a_3 < r < a_4 \\ n_5, & a_4 < r < a_5 \\ n_6, & a_5 < r < a_6 \\ n_7, & a_6 < r < a_7 \\ n_8, & a_7 < r < a_8 \\ n_9, & a_8 < r \end{cases} \tag{11}$$

$$\Delta_1 = \frac{n_1^2 - n_9^2}{2n_1^2}, \quad \Delta_2 = \frac{n_9^2 - n_7^2}{2n_9^2}, \quad \Delta_3 = \frac{n_8^2 - n_9^2}{2n_8^2} \tag{12}$$

where r is the radial position. Δ_1 and Δ_3 represent the relative index difference of n_1 and n_8 refractive-index up-doped layers respectively with respect to outermost silica layer (n_9). Δ_2 represents the level of down-doping of low index trench with respect to outer layer. Parameters of the fiber have been optimized in such a way as to achieve flattened dispersion with large effective area. The segmented core of the fiber is formed by six layers having monotonically decreasing refractive index. First five layers of the central core have equal widths while the width of the sixth layer is a bit larger. The cladding of the

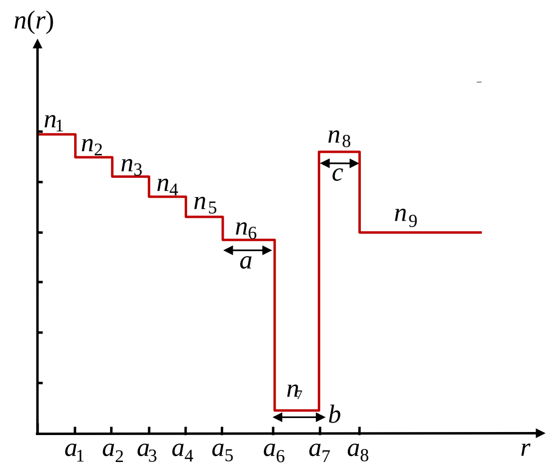

Figure 1. The refractive index profile of the proposed structure.

fiber is formed by a thin low-index trench which is followed by thin second core and a thick uniform outer cladding. Low-index trench in the cladding helps in reducing the bending loss of the fiber and segmented core helps in maintaining flattened dispersion. The second core of the fiber helps in achieving large A_{eff} as it taps some power from the central core. The fiber is a dual-core structure where resonance can lead to a high negative dispersion. We have optimized the parameters of the fiber in such a way that the resonance wavelength does not fall in the desired spectral range and the dispersion curve remains flat. By optimizing parameters of the fiber desired dispersion characteristics, large-effective-area and low bending loss can be obtained. Fiber can work as positive non-zero dispersion flattened fiber, negative non-zero dispersion flattened fiber and near-zero dispersion fiber in the wide band of wavelengths.

3.1. Design of Near-zero Dispersion Flattened Fiber

To achieve successfully near-zero total chromatic dispersion, we need to design fiber in such a way that waveguide dispersion of the fiber is balanced by material dispersion. The optimized parameters of the designed fiber having near zero flattened dispersion are listed in Table 1 and refractive index profile is shown in Fig. 1. The effective refractive index of the fundamental mode and group delay are important parameters for obtaining dispersion. In order to achieve flattened dispersion we have first studied the spectral variations of the effective index and group delay of the fiber as shown in Fig. 2. We can see that group delay does not vary significantly over the wavelength range 1.460–1.625 µm. n_{eff} of the fundamental mode of the fiber varies linearly with wavelength which shows that there is no resonance point in the considered wavelength range. Spectral variation of the dispersion of the fiber has been calculated using Eq. (2) and results are shown in Fig. 3. One can observe from Fig. 3 that the dispersion is nearly flat and varies from 0.0039 ps/km/nm to 0.520 ps/km/nm within the spectral range 1.460–1.625 µm, which covers S+C+L band

Table 1. Proposed near-zero dispersion flattened fiber design parameters.

$n_1 - n_2 = n_2 - n_3 = n_3 - n_4 = n_4 - n_5 = n_5 - n_6 = 8 \times 10^{-4}$
$a_2 - a_1 = a_3 - a_2 = a_4 - a_3 = a_5 - a_4 = 1\,\mu\text{m}$
$a = 1.68\,\mu\text{m}$, $b = 1.2\,\mu\text{m}$, $c = 1.1\,\mu\text{m}$, $\lambda = 1.55\,\mu\text{m}$, $n_9 = 1.4444$
$\Delta_1 = 0.22\%$, $\Delta_2 = 0.49\%$, $\Delta_3 = 0.27\%$

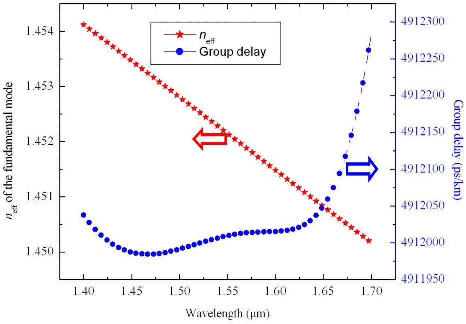

Figure 2. Spectral variations of effective refractive index and group velocity of near zero dispersion flattened fiber for the parameters given in Table 1.

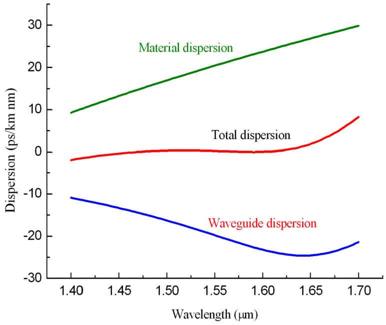

Figure 3. Spectral variations of material, waveguide and total dispersion of near zero dispersion flattened fiber for the parameters given in Table 1.

completely. Spectral variation of dispersion slope of the designed fiber is plotted in Fig. 4. We observe from Fig. 4 that the value of dispersion slope is very small in the aforementioned wavelength range. The maximum value of dispersion slope in the considered wavelength range is 0.0365 ps/km/nm^2. We have compared various characteristics of the designed fiber with the already existing design reported in [19]. Dispersion and dispersion slope of the proposed design and the design reported in [19] in various bands are shown in Table 2.

Table 2. Comparison of characteristics of proposed near-zero dispersion flattened fiber design with already existing design reported in Ref. [19].

Wavelength band →	S-band (1.460–1.530) μm		C-band (1.530–1.565) μm		L-band (1.565–1.625) μm	
	Proposed design	Ref. [19]	Proposed design	Ref. [19]	Proposed design	Ref. [19]
Average dispersion (ps/km/nm)	0.259	0.8179	0.269	0.3621	0.140	0.0832
Average dispersion slope (ps/km/nm^2)	0.0069	−0.0057	−0.0035	−0.0109	0.0059	0.0073

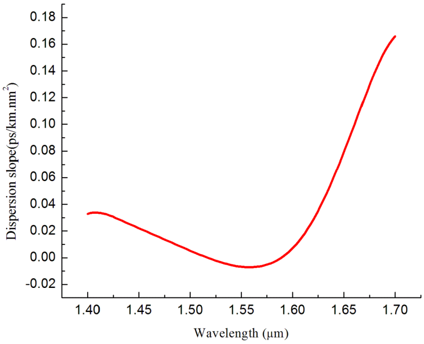

Figure 4. Spectral variation of dispersion slope of near zero dispersion flattened fiber for the parameters given in Table 1.

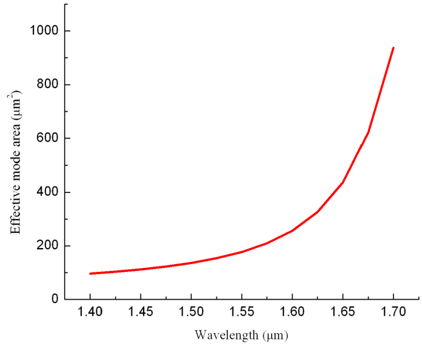

Figure 5. Spectral variation of effective mode area of fundamental mode of near zero dispersion flattened fiber for the parameters given in Table 1.

Another important factor which limits the bit rate is nonlinear effects in single mode fiber. To overcome this difficulty one needs to design a fiber with large effective area while maintaining small dispersion and dispersion slope. We have calculated the effective area of the near zero dispersion flattened fiber using Eq. (3) and have plotted its spectral variation in Fig. 5. Minimum value of A_{eff} in the wavelength range 1.460–1.625 μm is 114 μm^2 and maximum value of mode area in the above mentioned wavelength range is 325.95 μm^2. The effective area of the fiber reported in [19] for ultra low dispersion fiber varies from 103.56 μm^2 to 232.26 μm^2 within the aforementioned wavelength range. Thus we show a significant improvement in the mode area of the proposed fiber.

3.2. Design of Positive Non-zero Dispersion Flattened Fiber

It is found that in a large effective area fiber (LEAF) positive dispersion of approximately +4 ps/km-nm at 1.55-μm wavelength is able to avoid four wave mixing (FWM) effect and enhance the performance of wavelength division multiplexed optical communication system. Therefore we have designed the fiber having dispersion around +4.5 ps/km/nm with large effective area, low dispersion slope and large bandwidth. The designed parameters of the positive non-zero dispersion flattened fiber are given in Table 3. To achieve the dispersion near +4.5 ps/km/nm we have increased the value of parameter a of near-zero dispersion flattened fiber to 2.5 μm and all other parameters

Table 3. Proposed positive-non-zero dispersion flattened fiber structure parameters.

$n_1 - n_2 = n_2 - n_3 = n_3 - n_4 = n_4 - n_5 = n_5 - n_6 = 8 \times 10^{-4}$
$a_2 - a_1 = a_3 - a_2 = a_4 - a_3 = a_5 - a_4 = 1\,\mu\text{m}$
$a = 2.5\,\mu\text{m}$, $b = 1.2\,\mu\text{m}$, $c = 1.1\,\mu\text{m}$, $n_9 = 1.4444$
$\Delta_1 = 0.22\%$, $\Delta_2 = 0.49\%$, $\Delta_3 = 0.27\%$

are kept same. Spectral variation of the dispersion and dispersion slope of the proposed fiber is shown in Fig. 6. Designed fiber has dispersion and absolute dispersion slope within $[4.5 \pm 0.5]$ ps/km/nm and [(0.00003)–(0.0303)] ps/km/nm^2 respectively in the spectral range of 1.460–1.650 µm. Table 4 shows characteristics of the designed fiber which are compared with the already existing fiber design reported in Ref. [13]. We see that the proposed design has nearly three times larger effective area at 1.55 µm. The absolute value of dispersion slope of the designed fiber is smaller over a larger bandwidth than that of fiber reported in Ref. [13]. Thus flattened dispersion with desired dispersion value and ultra-large effective area has been achieved with proposed design over a wide range of wavelength.

Table 4. Comparison of characteristics of proposed positive-non-zero dispersion flattened fiber with the existing fiber design reported in Ref. [13].

Fiber	Bandwidth (µm)	Dispersion (ps/km/nm)	Dispersion slope at 1.55 µm wavelength (ps/km/nm^2)	A_{eff} at 1.55 µm wavelength (µm^2)
Ref. [13]	1.53–1.61	3.05 ± 0.35	0.01	56.1
Proposed design	1.46–1.65	4.5 ± 0.5	−0.007	155.71

3.3. Design of Negative Non-zero Dispersion Flattened Fiber

Recently, a directly modulated laser (DML) has gained attention for metropolitan networks. However, in DML carrier induced change in the mode effective index leads to large chirp and small dispersion tolerance. This limits the transmission distance. Several techniques have been studied to improve the transmission distance. One of the techniques is to use negative dispersion fiber as transmission fiber. The

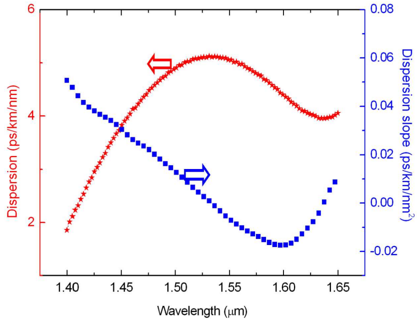

Figure 6. Spectral variation of dispersion and dispersion slope of small +ve dispersion flattened fiber for the parameters given in Table 3.

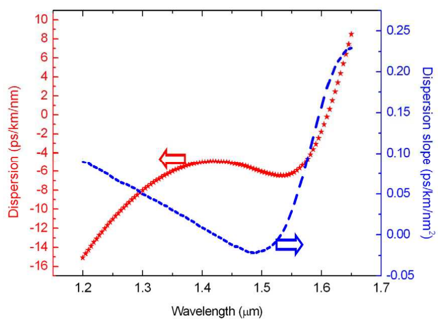

Figure 7. Spectral variation of dispersion and dispersion slope of small −ve dispersion flattened fiber for the parameters given in Table 5.

negative dispersion can compensate the positive chirp of the DML. Here we propose a design of negative dispersion fiber having negative dispersion around 6 ps/km/nm. Parameters of the designed fiber used for calculation are given in Table 5. To achieve negative dispersion we have decreased the value of parameter a of the near-zero dispersion flattened fiber to 1.1 μm. Difference between refractive index n_5 and n_6 of the near-zero dispersion flattened fiber has been increased to 1.3×10^{-3}. Dispersion and dispersion slope of the designed fiber are depicted in Fig. 7. We have compared characteristics of the proposed design with SMF-28 fiber and with the design reported in Ref. [16]. The comparison is shown in Table 6. We can observe from Table 6 that the proposed design shows smaller dispersion slope and ultra-large effective area while maintaining the required dispersion. A_{eff} of the SMF-28 is slightly more than double of the A_{eff} of that reported in Ref. [16]. However, A_{eff} of the proposed design is nearly three times of the A_{eff} of the SMF-28 and is remarkably larger.

Table 5. Parameters of negative non-zero dispersion flattened fiber.

$n_1 - n_2 = n_2 - n_3 = n_3 - n_4 = n_4 - n_5 = 8 \times 10^{-4}$; $n_5 - n_6 = 1.3 \times 10^{-3}$
$a_2 - a_1 = a_3 - a_2 = a_4 - a_3 = a_5 - a_4 = 1\,\mu\text{m}$
$a = 1.1\,\mu\text{m}$, $b = 1.2\,\mu\text{m}$, $c = 1.1\,\mu\text{m}$, $\lambda = 1.55\,\mu\text{m}$, $n_9 = 1.4444$
$\Delta_1 = 0.22\%$, $\Delta_2 = 0.49\%$, $\Delta_3 = 0.27\%$

Table 6. Comparison of characteristics of proposed negative non-zero dispersion flattened fiber with SMF-28 and the design reported in Ref. [16].

Fiber	Dispersion at 1.33 μm wavelength ((ps/km/nm)	Dispersion at 1.55 μm wavelength (ps/km/nm)	Dispersion slope at 1.55 μm wavelength (ps/km/nm^2)	A_{eff} at 1.55 μm wavelength (μm^2)
Ref. [16]	−6.9	−6.7	0.043	36.1
SMF-28	−0.08	16.4	0.056	80
Proposed design	−6.6	−6.24	0.026	219

3.4. Feasibility of Fabrication

In the proposed design the minimum width of the layer is typically 1 μm, and the minimum refractive index required is 8×10^{-4}. Such values are achievable by modified chemical vapor deposition (MCVD) technology. For example, recently Messerly et al. have fabricated a design containing wave-guiding rings using MCVD technology having tolerance of 0.01 μm on layer width and tolerance on refractive indices of the layer is of the order of 1×10^{-4} [28]. There are also reports on fabrication of triangular-core dispersion shifted fiber, which requires a precise control in layer by layer deposition of the core material to achieve a smooth profile [29] and fabrication of multi-step core fiber by MCVD [28, 30]. The present design essentially consists of a triangular core with finite number of layers and should be easier to achieve by deposition of Ge-doped silica layers using MCVD technology. Low-index trench of the structure can be achieved by depositing F-doped silica layers as demonstrated in Ref. [31].

4. COMPATIBILITY OF THE PROPOSED FIBER WITH CONVENTIONAL FIBER

It is very important to examine the bending sensitivity and the compatibility of the proposed design with conventional SM fiber and fiber based components. A fiber with a large effective area usually has high bending loss. Double or triple core fibers show large bending losses. In our design we have introduced a low index trench between the two cores of the fiber to reduce bending loss. To study bending sensitivity and compatibility of the proposed fiber, we have considered design of near-zero dispersion flattened fiber. We have calculated the bending loss of the fiber using Eq. (5) [21]. The macrobending loss of the fiber at 1.55 μm for bending radius 10 mm is 1.427×10^{-8} dB/km. We have used commercial fiber CAD software to calculate bending loss of the fiber. Effective MFD is an important parameter of the fiber while evaluating the performance of the fiber with regard to bending loss and splice loss. Long haul optical fiber communication link contains conventional single mode fiber (SMF) and fiber based components therefore the dispersion managed fiber is supposed to be spliced to the conventional SMF. To minimize splice loss MFD of the designed fiber should match with that of the conventional SMF. The effective MFD of the conventional single mode fiber at 1.55 μm is 10.4 ± 0.8 μm and that of the designed fiber is 14.0 μm, which matches quite well with that of the conventional single mode fiber. The splice loss of the fiber has been calculated by using Eq. (10) and has been found to be 0.059 dB at 1.55 μm by considering δ as 0.1 μm and θ as 0.2°. A parameter called quality factor has been introduced to check the overall performance of the fiber and has been defined as the ratio of A_{eff} to the square of MFD. This is a dimensional quantity and is used for assessing the overall performance of the fiber. Fiber having larger values of quality factor approaches towards the best design. Spectral variation of the quality factor of the designed fiber is shown in Fig. 8. The figure shows that the quality factor of the designed fiber varies from 0.8401 to 1.025 in the wavelength range 1.460–1.625 μm. The quality factor of the fiber reported in [16] varies from 0.8187–0.9957 in the same spectral range.

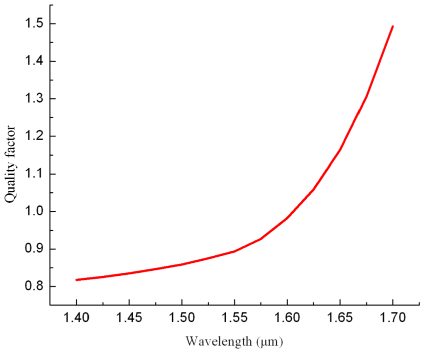

Figure 8. Spectral variation of quality factor for the parameters given in Table 1.

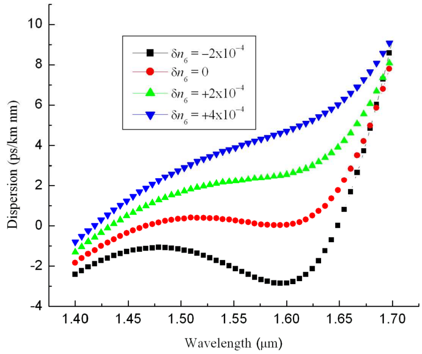

Figure 9. Spectral variations of total dispersion of near zero dispersion flattened fiber with variations in n_6 for the parameters given in Table 1.

5. SENSITIVITY ANALYSIS OF THE STRUCTURAL DISORDERS ON THE PERFORMANCE OF THE FIBER

In the previous sections, we numerically demonstrated that the proposed fiber has an exceptional chromatic dispersion flatness with low dispersion slope and large effective area in the S+C+L communication band. Now the question arises how the imperfections introduced during the fabrication process will affect the performance of the fiber? To evaluate the sensitivity of design parameters we have varied one of the parameters at a time while keeping all other parameters constant and calculated dispersion of near zero dispersion flattened fiber. Firstly, we varied n_6 by an amount δn_6 and the results are plotted in Fig. 9. One can observe that the maximum variation in dispersion value is at 1.6-µm wavelength. $\delta n_6 = -2 \times 10^{-4}$ results in 2.8 ps/km/nm deviation from the optimized dispersion at 1.6-µm wavelength. $\delta n_6 = +2 \times 10^{-4}$ results in 2.5 ps/km/nm deviation from the optimized value of dispersion. The analogous study has also been carried for variations in the values of parameter a and the results are plotted in Fig. 10. We see that positive deviation from the optimized value of $a = 1.68$ µm results in an increase in the value of dispersion where as negative deviation results in a decrease in value of dispersion while maintaining the flatness. Variation of ±11.9% in the optimized value of parameter a results in approximately 1 ps/km/nm variation in the value of dispersion at 1.55 µm wavelength. The sensitivity of the

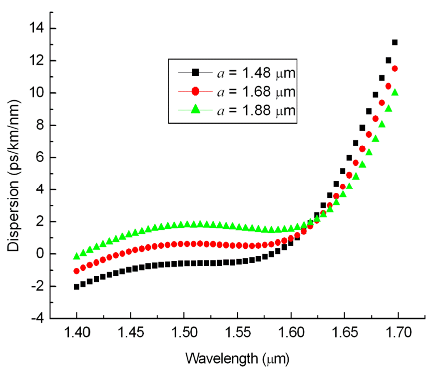

Figure 10. Spectral variations of total dispersion of near zero dispersion flattened fiber with variations in a for the parameters given in Table 1.

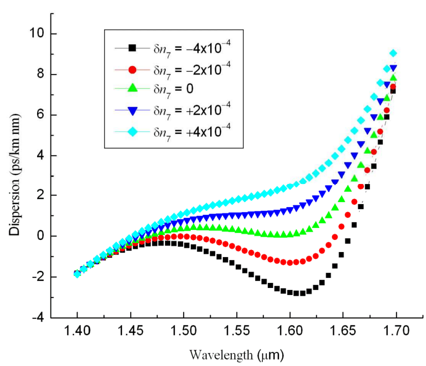

Figure 11. Spectral variations of total dispersion of near zero dispersion flattened fiber with variations in n_7 for the parameters given in Table 1.

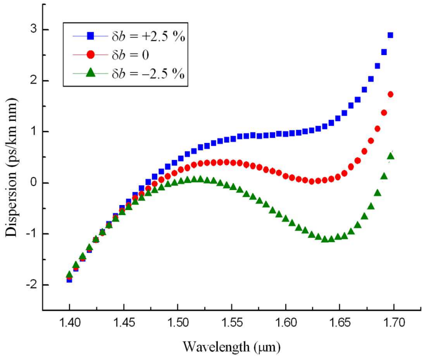

Figure 12. Spectral variations of total dispersion of near zero dispersion flattened fiber with variations in b for the parameters given in Table 1.

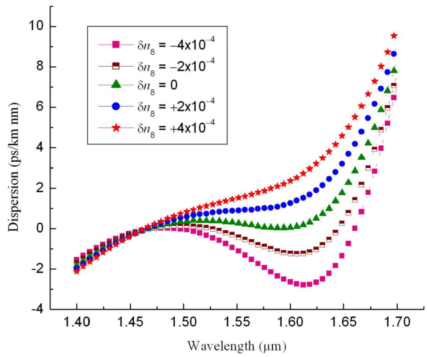

Figure 13. Spectral variations of total dispersion of near zero dispersion flattened fiber with variations in n_8 for the parameters given in Table 1.

design has also been examined against variations in value of n_7 and the results are plotted in Fig. 11. We observe that increase in value of n_7 results in an increase in value of dispersion however decrease in value of n_7 decreases the value of dispersion. Variations of $\delta n_7 = -2 \times 10^{-4}$ in values of n_7 result in nearly -1.48 ps/km/nm deviation in values of dispersion at 1.625 μm wavelength which is maximum deviation in considered spectral range. Variation of $\delta n_7 = +2 \times 10^{-4}$ results in maximum $+1.40$ ps/km/nm deviation from the optimized value at 1.633 μm wavelength. Sensitivity of the design has also been examined against $\pm 2.5\%$ variations (δb) in b and the results are shown in Fig. 12. One can see clearly from Fig. 12 that $\delta b = \pm 2.5\%$ results in maximum variation of ± 1.2 ps/km/nm in the values of optimized dispersion at 1.65-μm wavelength. Secondary core an important parameter of the design plays a significant role in the design of the fiber. Spectral variations of the dispersion against variations (δn_8) in the refractive index of secondary core n_8 are presented in Fig. 13. Variation of $\delta n_8 = \pm 2 \times 10^{-4}$ causes maximum ± 1.5 ps/km/nm deviations in the values of optimized dispersion at 1.633 μm wavelength. We have also examined the effect of width of secondary core (c) and results are shown in Fig. 14. We can see that $\delta c = \pm 5.4\%$ results in maximum ± 1.3 ps/km/nm variations in the value of dispersion at 1.633 μm wavelength.

As a general discussion of this section, we have estimated the impact of structural tolerances to important parameters of the designed

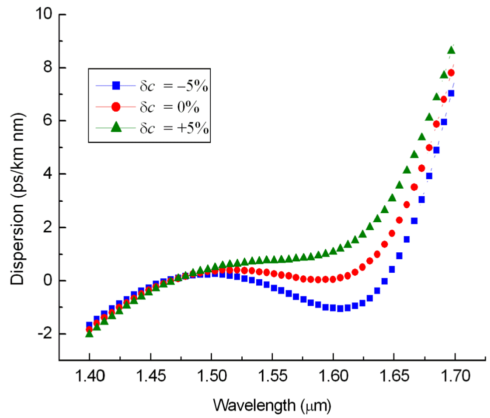

Figure 14. Spectral variations of total dispersion of near zero dispersion flattened fiber with variations in c for the parameters given in Table 1.

fiber. We showed that the dispersion of the fiber does not vary significantly with possible variations for the design parameters.

6. CONCLUSIONS

In this paper, we have presented a proposal for a segmented core fiber having near-zero, small positive non-zero, and small negative non-zero flattened dispersion with small dispersion slope and ultra-large effective area. The segmented core of the fiber helps in maintaining desired dispersion and dispersion slope. We have introduced a low index trench to reduce bending loss of the fiber. A secondary core of the fiber helps in achieving ultra large effective area. For positive non-zero dispersion flattened fiber optimized dispersion is near $+4.5$ ps/km/nm in the wavelength range 1.46–1.65 µm. For non-zero negative dispersion flattened fiber, dispersion has been achieved near -6 ps/km/nm in the spectral range 1.33–1.56 µm. In case of near zero dispersion flattened fiber effective area varies from 114–325.95 μm^2 within the wavelength range 1.460–1.625 µm which is the largest value reported for dispersion flattened fiber to the best of our knowledge. Dispersion and dispersion slope of the designed fiber are [0.0039–0.520] ps/km/nm and [0.0004–0.0365] ps/km/nm^2 respectively within the aforementioned wavelength range. The designed fiber has appropriate quality factor also which varies from 0.8401–1.025 over the entire S+C+L band. These characteristics of the fiber make it an attractive candidate for DWDM optical communication system.

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