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An optimized design for non-zero dispersion shifted fiber with reduced nonlinear effects for future optical networks

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Accommodation of many channels in dense wavelength division multiplexing networks raises the average power density of the optical networks. This results in severe nonlinear effects in the optical networks. An optimized design of non-zero dispersion shifted fiber with an enormous effective area can overcome this nonlinear effect and also offer a minimum bending loss and splice loss for a dense wavelength division multiplexing system. In this paper, the alpha-peak profile is utilized for calculating electrical field distribution and designing the refractive index profile of the non-zero dispersion shifted fiber. This fiber has a high effective area of about 120 μm^2. Conjointly, the accomplished fiber has a very low bending loss of 1.40×10^{-14} dB/km and reduced splice loss of 4.46×10^{-3} dB. Due to this high effective area, the dense wavelength division multiplexing network performance is upgraded by diminishing nonlinear effects. In addition, the newly designed fiber has also a very low dispersion slope (0.057 ps/nm^{2}km). Thus, the proposed fiber is optimized to handle high bandwidth and multiple high bit-rate wavelength channels without nonlinear impairments in the 1.55 μm window long-haul dense wavelength division multiplexing systems.

Keywords: dense wavelength division multiplexing, non-zero dispersion shifted fiber, refractive index profile, effective area, dispersion slope.

1. Introduction

In order to satisfy the demand for a massive increase in capacity in a long-haul transmission system, dense wavelength division multiplexing (DWDM) fiber optical networks are implemented. Large bandwidth with increased information carrying capacity and ultra-high speed optical communication systems resulted due to this DWDM network. While incorporating a large number of signal wavelengths in DWDM systems, two types of limitations are experienced by the optical networks, namely nonlinear effects and dispersion.

As the number of signal wavelengths in DWDM network increases, the average transmission power density also increases. Subsequently, the refractive index gets modulated due to the rapid increase in the optical intensity of the signal [1]. As a result, nonlinear effects like four wave mixing (FWM), self phase modulation (SPM) and cross-phase modulation (XPM) come to the fore, which degrade the system performance of fiber optical networks. Large effective area fibers (LEAF) are used to overcome the signal distortion due to the nonlinear effects of a fiber [1, 2].

From the nonlinear fiber optics, it is clearly stated that the nonlinear parameter γ decreases when the effective area A_{eff} increases and the effective nonlinear refractive index n_2 decreases [3]. The mathematical expression for parameter γ is given by

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \tag{1}$$

Conventional single mode fiber (SMF) has zero dispersion wavelength λ_{ZDW} around 1.3 μm (1260–1360 nm, O-band). But fiber losses will be minimum at 1.55 μm (1530–1565 nm, C-band). To achieve minimum loss and very low dispersion, λ_{ZDW} is shifted to 1.55 μm. This fiber is known as zero dispersion shifted fiber (ZDSF) which is utilized to achieve large bandwidth for repeater fewer transmission networks.

Due to an increased number of signal wavelengths in DWDM systems, under phase matching conditions, FWM, will occur more intensively. This FWM in the ZDSF of the DWDM channels will induce inter-channel crosstalk, which in turn will degrade the system performance [4, 5]. In order to overcome this problem, non-zero dispersion shifted fibers (NZDSF) are fabricated in which the λ_{ZDW} is made to lie outside the C-band. This non-zero dispersion in C-band avoids the phase matching conditions and, consequently, reduces the FWM effect and simultaneously improves the DWDM system performance [1, 5]. NZDSF(+) (positive dispersion in transmission band) is used for terrestrial long-haul systems, but NZDSF(–) (negative dispersion in transmission band) is used for ultra-long distance submarine transmission systems [1, 6]. The advantage of positive dispersion is that it can be easily compensated when compared to negative dispersion. NZDSF(+) fiber is suitable for terrestrial long-haul high capacity WDM transmission systems, due to its optical pulse modulation stability in the positive dispersion region when compared to NZDSF(–) [6].

As the NZDSF has a lower dispersion in C-band, it is in need of a lower number of dispersion compensating fibers (DCF) which indeed depends on relative dispersion slope (RDS) [4, 7, 8], whereas, simple single mode fibers (SMF) consume more DCF. Moreover, a large effective area NZDSF is a cost optimized design for a reduced nonlinear effect in long-haul DWDM networks [9].

In order to reduce the nonlinear effects in DWDM networks, NZDSF fiber design based on Gaussian approximation method was used and large effective area, low bending loss and low splice losses were obtained [2]. Large effective area A_{eff} fibers will also have a very high mode field diameter (MFD). However, high MFD fibers will make the fiber more sensitive to bending [9]. Bending of the fiber not only induces both micro- and macro-bending losses but also induces birefringence, which results in polarization mode dispersion (PMD) [10]. Hence, bend insensitive fibers are developed using the trench index profile to reduce bending losses and splice losses [11]. Minimum dispersion slope fibers in turn are designed using flat field fibers. However, they too offer MFD and A_{eff} of the order of 8.3 μm and 56.1 μm^2, respectively [12].

These results are comparatively low for reducing the nonlinear effects. More recently, a large effective area NZDSF with an $A_{eff} = 95$ μm^2, dispersion slope of 0.1 ps/nm^{2}km and bending loss of 0. 005 dB with 30 mm bending radius and 100 turns have been reported in the literature [13].

In this paper, an optimized design for penta-clad-type NZDSF without nonlinear effects of future optical networks is presented. The alpha-peak profile is used for calculating electrical field distribution of the designed refractive index profile. From the calculated results, an optimized fiber with high effective area is designed. In addition, the resulted fiber design has a very low dispersion slope, extremely low bending loss and reduced splice loss. The simulated results show that our newly designed fiber is optimized to handle high bandwidth and multiple high bit-rate wavelength channels without nonlinear impairments in the 1.55 μm window over long-haul DWDM networks.

2. Design of optimized NZDSF

We have considered a fiber consisting of a graded index core with five cladding regions (penta-clad-type fiber) for the design of NZDSF. The refractive index profile of the proposed fiber is shown in Fig. 1 and is given by,

$$n(r) = \begin{cases} n_0(x) & |r| \le R_0 \\ n_1 & R_0 < |r| \le R_1 \\ n_2 & R_1 < |r| \le R_2 \\ n_3 & R_2 < |r| \le R_3 \\ n_4 & R_3 < |r| \le R_4 \\ n_5 & R_4 < |r| \le R_5 \end{cases} \tag{2}$$

where $n(r)$ is the refractive index profile of the designed fiber and $n_0(x)$ is the highest refractive index of the core described by the alpha-peak profile; n_1, n_2, n_3, n_4 and n_5

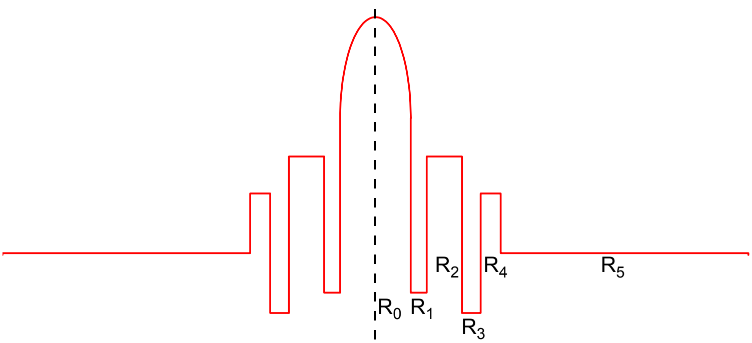


Fig. 1. Refractive index profile of the proposed optimized NZDSF.

are the refractive indices of various cladding regions and R_0, R_1, R_2, R_3, R_4 and R_5 are respective radius parameters.

Here the alpha-peak profile is used to design a graded index core fiber. The alpha--peak profile is described by the following equation

$$n(x) = n_{max}\sqrt{1 - 2\Delta\left(\frac{x}{w}\right)^{\alpha}} \qquad (3)$$

where n_{max} is the maximum refractive index value when $r = 0$, x is the region's local coordinate, w is the width of the region, α is the profile parameter and Δ is the normalized refractive index difference and is given by,

$$\Delta = \frac{n_{max}^2 - n_{min}^2}{2n_{max}^2} \qquad (4)$$

Effective mode area A_{eff} is given by [3, 9]

$$A_{eff} = \frac{\left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E(x, y)|^2 \mathrm{d}x\,\mathrm{d}y\right]^2}{\int_{-\infty}^{\infty}|E(x, y)|^4 \mathrm{d}x\,\mathrm{d}y} \qquad (5)$$

where $E(x, y)$ is the optical mode field distribution.

Mode field diameter (MFD) is given by [9]:

$$d_{eff} = \frac{2\sqrt{2}\int E_i^2 r\mathrm{d}r}{\sqrt{E_i^4 r\mathrm{d}r}} \qquad (6)$$

or simply,

$$d_{eff} = \frac{2}{\sqrt{\pi}}\sqrt{A_{eff}} \qquad (7)$$

where $E_i(r)$ is the optical mode field distribution of the near-field of the fundamental mode at radius r from the axis of the fiber.

The newly designed NZDSF fiber has the optimum performance for the following conditions:

- $a = 62.5$ μm (fiber radius),
- $R_0 = 1.1$ μm $\Rightarrow a_0 = 1.1$ μm,
- $R_1 = 0.4$ μm $\Rightarrow a_1 = 1.5$ μm,
- $R_2 = 1.149$ μm $\Rightarrow a_2 = 2.649$ μm,
- $R_3 = 0.7$ μm $\Rightarrow a_3 = 3.349$ μm,
- $R_4 = 0.6$ μm $\Rightarrow a_4 = 3.949$ μm,
- $R_5 = 58.551$ μm $\Rightarrow a_5 = 62.5$ μm;

For alpha-peak profile (Eq. (3)):
- n_1 = 1.44492,
- n_2 = 1.4519,
- n_3 = 1.4439,
- n_4 = 1.44992,
- n_5 = 1.44692,

where
- n_{max} = 1.459,
- Δ = 0.41,
- α = 2.

Due do the symmetry nature of the fiber, we have discussed the refractive index profile for half of the fiber in terms of its radii; a_0, a_1, a_2, a_3 and a_4 represent the cumulative radius of the regions of width R_0, R_1, R_2, R_3 and R_4, respectively, and a denotes the overall fiber radius.

3. Design route of the proposed optimized NZDSF

NZDSF (G.655) must have a low but non-zero dispersion at 1.55 μm, in addition with the high effective area in order to reduce the nonlinear crosstalk between the DWDM channels. Furthermore, the FWM effect can be reduced due to the high phase mismatch in order to increase the performance of the DWDM networks [5, 9]. Keeping this in mind, initially the design of proposed NZDSF started with the highest refractive index core R_0 and dual cladding (innermost cladding R_1 and outermost cladding R_5). However, the fundamental mode could not be numerically calculated for wavelengths above 1.2940 μm.

To redeem the refractive index profile, we included an intermediate cladding region R_2 between R_1 and R_5. The cutoff wavelength was defined as the wavelength where the higher-order modes experience bending losses high so that they can no longer be considered as being guided [4]. By adding a cladding region R_2 with increased

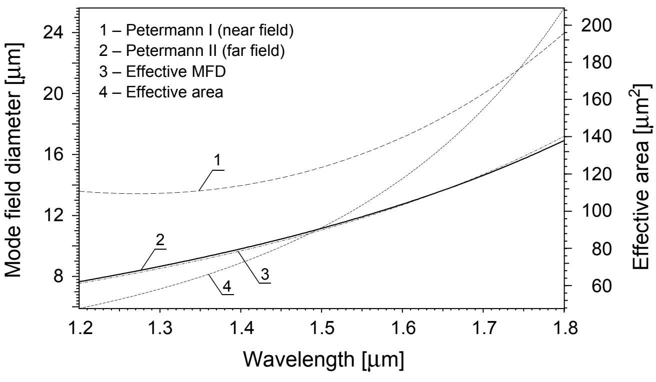


Fig. 2. Variations of effective area and MFD *vs*. wavelength due to the addition of region R_2 in refractive index profile.

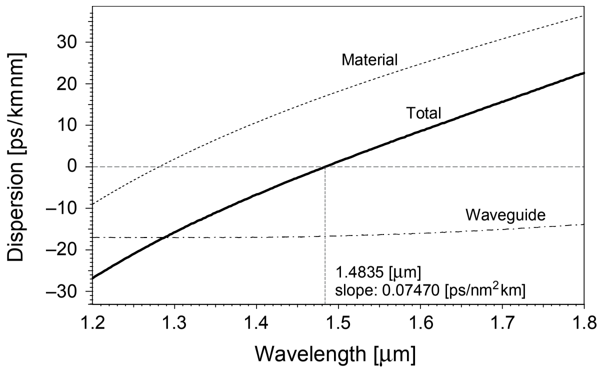


Fig. 3. Variations of dispersion *vs*. wavelength due to the addition of region R_2 in refractive index profile.

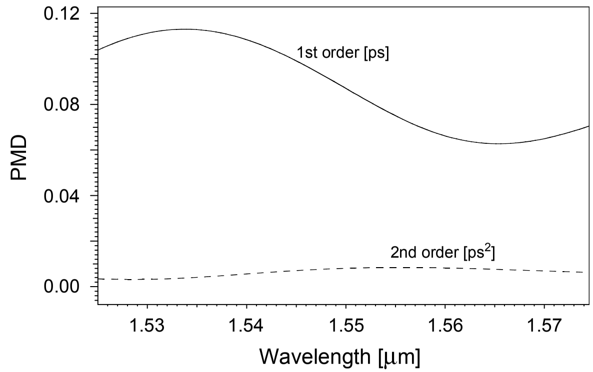


Fig. 4. Variations of PMD *vs*. wavelength due to the addition of region R_2 refractive index profile.

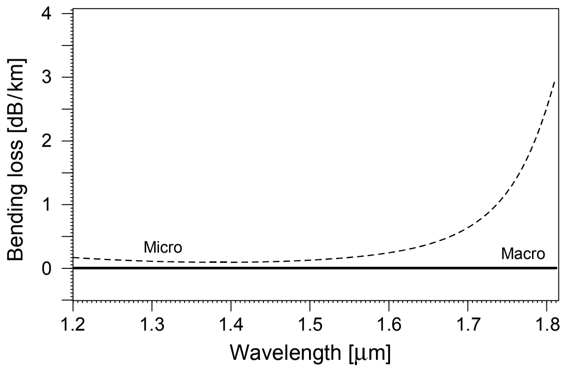


Fig. 5. Variations of bending loss *vs*. wavelength due to the addition of region R_2 in refractive index profile.

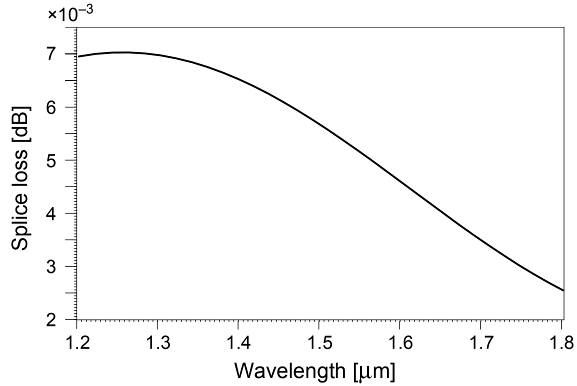


Fig. 6. Variations of splice loss *vs*. wavelength due to the addition of region R_2 in refractive index profile.

width and higher refractive index, a higher cutoff wavelength 1.45 μm for linearly polarized (LP) LP(0, 1) made was achieved. By adding this R_2 region, we could get the large effective area of 102 μm^2 and high MFD of about 11.3 μm at $\lambda = 1.55$ μm, as shown in Fig. 2.

Simultaneously, we observed the dispersion slope as 0.07 $ps/nm^2 km$. In addition, we found that the fiber had a low polarization mode dispersion of 0.09 ps. Figures 3 and 4 show the dispersion and PMD characteristics of the fiber, respectively.

But the increased effective area of NZDSF fiber made the fiber more sensitive to bending losses due to its high MFD [9]. In addition, MFD increased due to an increase in dispersion slope also [1]. As a result, bending loss got increased. The obtained values of macro-bending and micro-bending losses were 6.38×10^{-7} dB/km and 0.17 dB/km, respectively. Figure 5 shows the bending losses as a function of wavelengths. A splice is the dielectric interface between two optical fibers. Any index-of-refraction mismatch at any point in this interface will produce reflection and refraction of the light incident at that point. For splicing calculations, we assume that the mode field of single-mode guided fibers is nearly Gaussian. The coupling losses between two fibers can be calculated by evaluating the coupling between two misaligned Gaussian beams as described by Miller and Kaminow [14]. Due to the addition of this cladding region R_2, the splice loss obtained was 5.03×10^{-3} dB which is shown in Fig. 6. The effective nonlinear coefficients n_2 of optical fibers depend on the nonlinear indices of the bulk materials building the fiber and on its waveguiding properties such as shape of modes and degree of confinement. As a result, it can vary within broad limits. After adding R_2, the effective nonlinear coefficient n_2 is calculated by the method described by Marcuse [15]. As shown in Fig. 7, the obtained n_2 at 1.55 μm was 1.50×10^{-16} cm^2/W. Here the noisy structure shown in the shorter wavelength is due to the effect of frequency dependent electrostrictive contribution n_2e to the nonlinear refractive index [16].

Next, a new region R_3 (trench) was added to the refractive index profile. While adding the trench with a significantly lower refractive index and higher width, a tremendous increase in the effective area was achieved. The resulted A_{eff} value was above

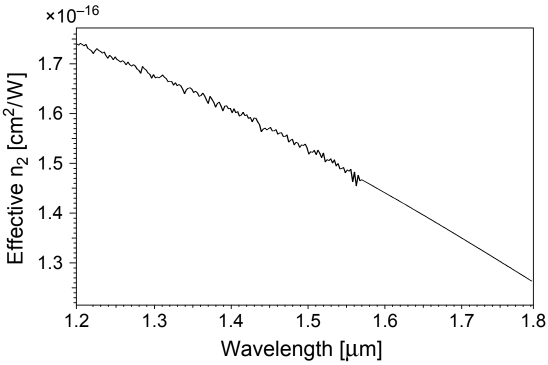


Fig. 7. Variations of n_2 *vs*. wavelength due to the addition of region R_2 in refractive index profile.

150 μm^2 and MFD value was around 13.3 μm. Now, an abrupt change in dispersion slope (0.11 ps/nm^{2}km) and dispersion (0.62 ps/kmnm) was noticed. Since the dispersion slope was very high, the usable bandwidth might decrease because the dispersion curve becomes narrower with rising RDS [4].

Now the RDS value was calculated as 0.182 nm^{-1} (RDS = S/D, where S and D were dispersion slope and dispersion, respectively) [4, 7, 8]. For RDS value above 0.01 nm^{-1}, it is very difficult to design dispersion compensating fibers that can be included as a dispersion compensating element along with NZDSF in an optical network [4]. As a result of increasing the width of the trench, the RDS value got increased, which in turn increased the bend sensitivity of the fiber [4]. The resulted macro- and micro-bend losses were 2.68×10^{-12} dB/km and 1.70 dB/km, respectively. The trench profile for the bend insensitive fibers [11] was applied to obtain good MFD compatibility in conventional single mode fibers. From this design, a minimal splice loss of 3.09×10^{-3} dB was obtained and n_2 was reduced further to 1.24×10^{-16} cm^2/w. As n_2 was decreasing, the nonlinear parameter γ also decreased much and finally nonlinear effects could be reduced [3].

Though the nonlinear effects were minimized to a great extent, the bending loss was not so. In order to also minimize this bending loss, a region R_4 with reduced width and very high refractive index was added and an optimized design of NZDSF was obtained. By using the finite difference method, it was calculated that fundamental mode LP(0, 1) cutoff wavelength was as high as 1.45 μm.

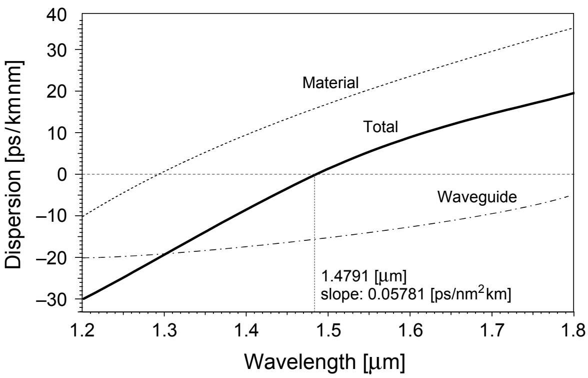


Fig. 8. Variations of dispersion *vs*. wavelength of our optimized fiber.

As shown in Fig. 8, a significantly lower dispersion slope of 0.057 ps/nm^{2}km and low dispersion of 5.76 ps/kmnm were achieved after incorporating R_4. Now the calculated RDS value is as low as 0.01 nm^{-1}, so that dispersion compensation could be done easily [4, 7, 8].

Ultra-low dispersion slope fibers in practice have an effective area up to 45 μm^2 [17]. But our proposed optimized NZDSF had an enormous effective area of about 120 μm^2, high MFD (12.08 μm) and reduced n_2 (1.41×10^{-16} cm^2/W) as shown in Figs. 9 and 10, respectively.

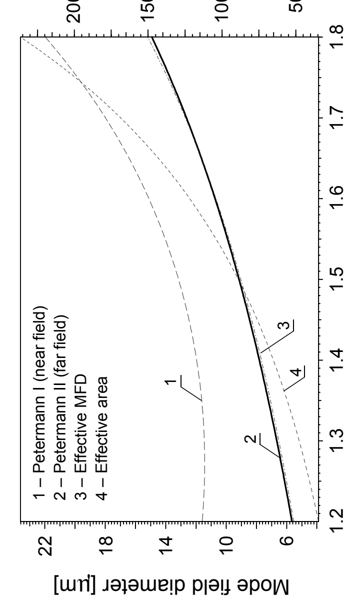


Fig. 9. Variations of effective area and MFD *vs.* wavelength of our optimized fiber.

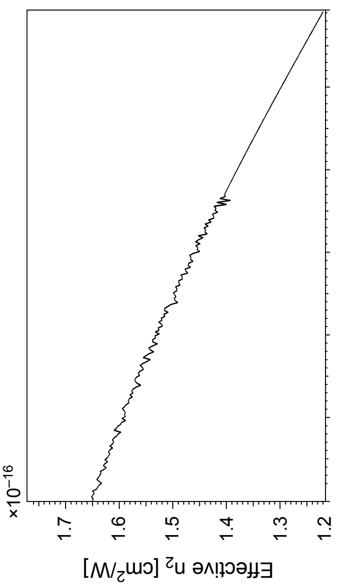


Fig. 10. Variations of n_2 *vs.* wavelength of our optimized fiber.

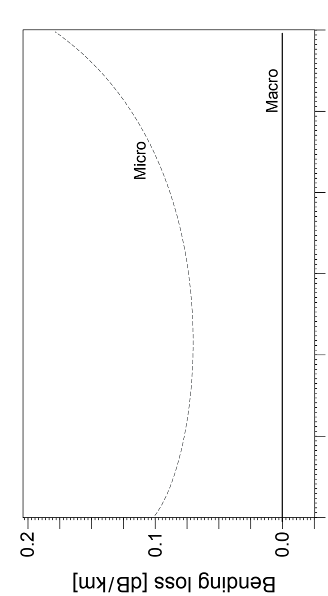


Fig. 11. Variations of bending loss via wavelength of our optimized fiber.

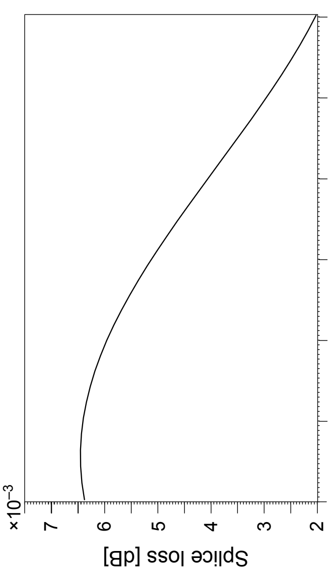


Fig. 12. Variations of splice loss via wavelength of our optimized fiber.

Due to a large effective area and reduced n_2, the nonlinear parameter γ decreased drastically and nonlinear effects also diminished further [3]. Figure 11 shows that our accomplished fiber has a low macro-bending loss of 1.40×10^{-14} dB/km (with 30 mm bending radius and 100 turns) and micro-bending loss of 0.07 dB/km. Furthermore, our proposed fiber has reduced splice loss (transversal) of 4.46×10^{-3} dB and reduced PMD of 8.77×10^{-3} dB. Figure 12 shows the splicing loss of this fiber as a function of wavelength.

4. Procedure for refractive index optimization

As an example, the procedure for optimizing the index profile for the region R_4 is discussed here since the same can be applied to other regions as well.

Figures 13, 14 and 15 show the variation of dispersion effective area and effective nonlinear coefficient n_2 with respect to wavelength with an index profile without region R_4. The dispersion slope is 0.098 ps/nm^{2}km, the effective area is 150 μm^2 and the zero dispersion wavelength is at 1.54 μm.

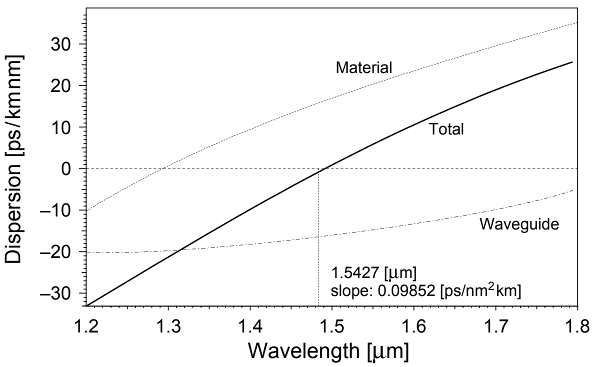


Fig. 13. Variations of dispersion *vs*. wavelength of fiber without region R_4.

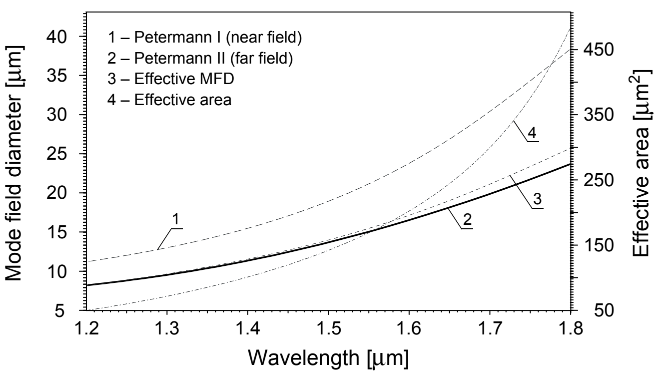


Fig. 14. Variations of effective area and MFD *vs*. wavelength of fiber without region R_4.

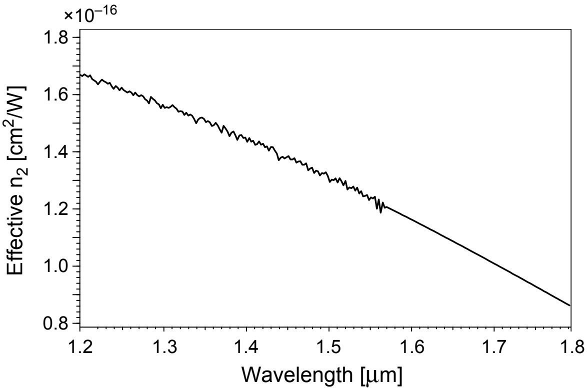


Fig. 15. Variations of n_2 *vs*. wavelength of our fiber without region R_4.

In order to attain the non-zero dispersion shifted fiber with a low dispersion slope along with all other controllable parameters, we include the region R_4 next to the region R_3. This region R_4 is varied from 0.4 to 0.9 μm with respect to different refractive indices from 1.442 to 1.452. Successive iterations are performed with the help of numerical analysis using optifiber simulation for different refractive indices and the optimum results are obtained at the refractive index of 1.4492. Figures 16–20 show the results for the width of the region R_4 for a fixed refractive index of 1.4492.

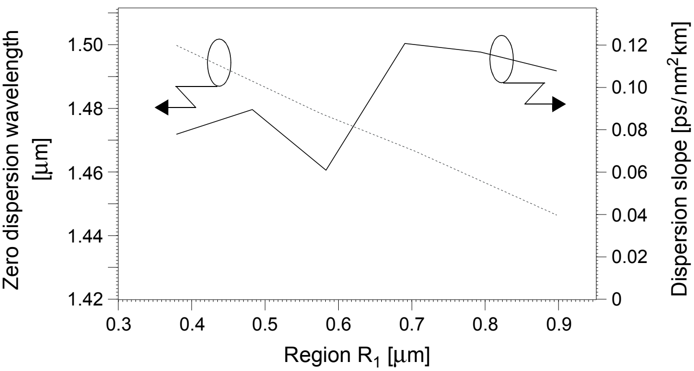


Fig. 16. Zero dispersion wavelength λ_{ZDW} and dispersion slope *vs*. region R_4 width.

The change in the width of region R_4 moves the dispersion towards shorter wavelength with the deterioration of the MFD and n_2 values. From these figures, we can identify that 0.6 μm produces the optimum result in terms of λ_{ZDW} of 1.4791 μm with a very low dispersion slope of 0.057 ps/nm^{2}km, but with a compromisation of MFD from 12.25 to12.08 μm and n_2 from 1.36×10^{-16} to 1.46×10^{-16}. However, beyond this 0.6 μm, the MFD, n_2 and the dispersion slope are further degraded. So it is considered that 0.6 μm is the optimum width for region R_4.

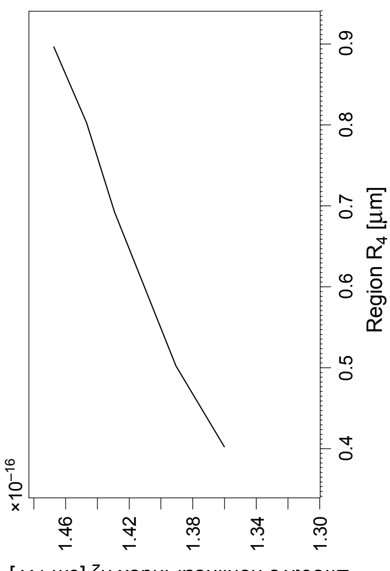


Fig. 17. Effective nonlinear index n_2 *vs.* region R_4 width.

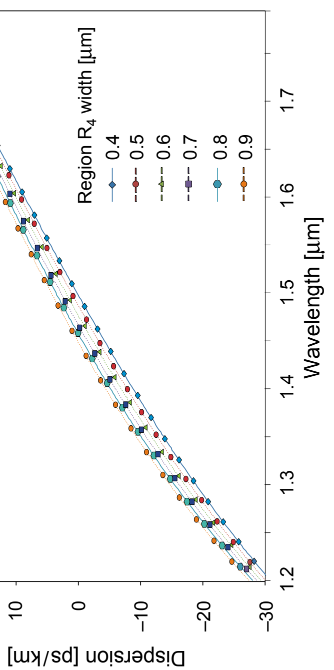


Fig. 18. Dispersion *vs.* wavelength variation.

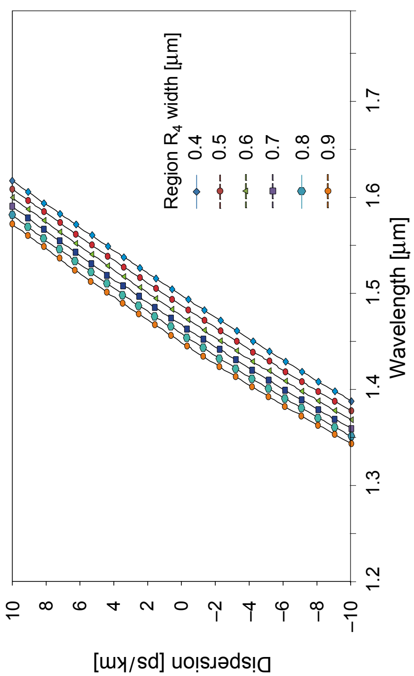


Fig. 19. Extracted image from Fig. 4 variation with respect to R_4 width.

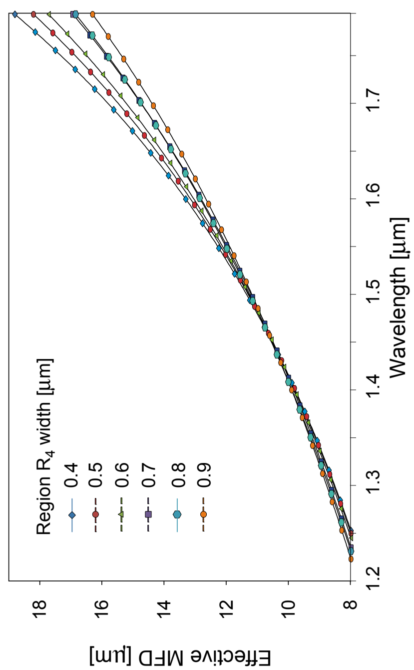


Fig. 20. Effective MFD *vs.* wavelength.

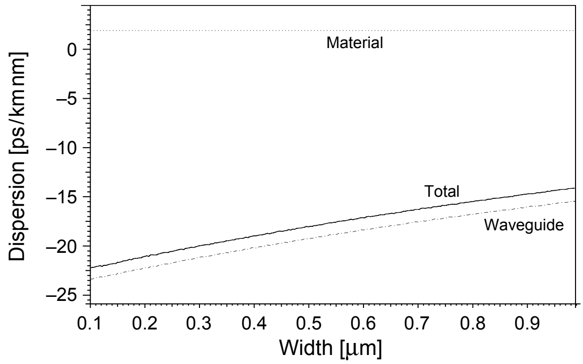


Fig. 21. Dispersion contribution *vs*. region R_4 width.

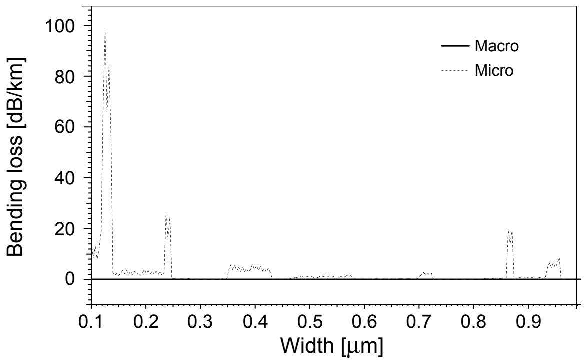


Fig. 22. Bending loss contribution *vs*. region R_4 width.

Figures 21 and 22 show the dispersion and bending loss in the fiber with respect to region width which is varied from 0.1 to 1.0 µm. Figures 23 and 24 show the dispersion and bending loss of this fiber with respect to the refractive index variation from 1.442 to 1.452. With the region R_4 width of 0.6 µm and refractive index of 1.4492, this

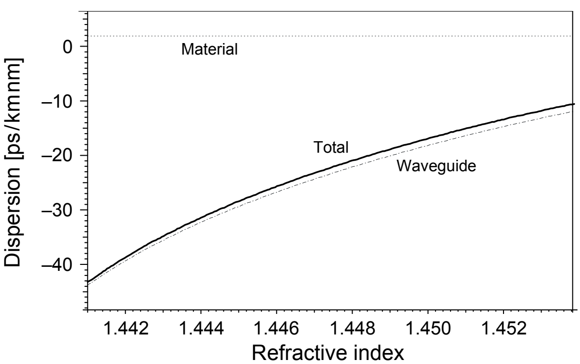


Fig. 23. Dispersion contribution *vs*. region R_4 refractive index.

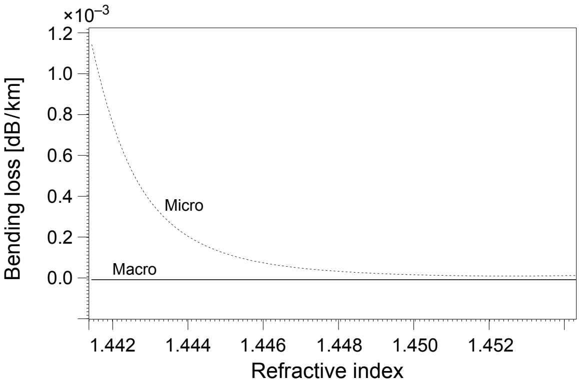


Fig. 24. Bending loss contribution *vs*. region R_4 refractive index.

fiber gives a good dispersion slope and bending loss characteristics. Similar procedures have been adopted to conclude the fiber parameters in the other regions as well.

5. Results at a glance

In order to analyze the optical performance of our optimized NZDSF, a comparison is done between two refractive index profiles namely fiber A and fiber B as shown in Tables 1 and 2. In order to analyze the optical performance of our optimized NZDSF,

Table 1. The optical performance of our optimally designed NZDSF with reduced nonlinear effects.

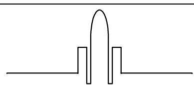
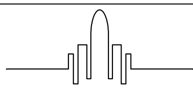
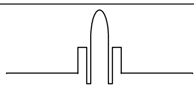
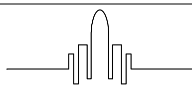
	Fiber A	Fiber B
Refractive index profile		
MFD [μm]	11.27	12.08
A_{eff} [μm^2]	102	120
Bending loss [dB/km]	6.38×10^{-7}	1.40×10^{-14}
Splice loss [dB]	5.03×10^{-3}	4.46×10^{-3}
n_2 [cm^2/W]	1.50×10^{-16}	1.41×10^{-16}

Table 2. The optical performance of our optimally designed NZDSF with reduced dispersion.

	Fiber A	Fiber B
Refractive index profile		
Zero dispersion wavelength λ_{ZDW} [μm]	1.48434	1.47952
Dispersion slope [ps/nm^{2}km]	0.07	0.057
Dispersion at 1.55 μm [ps/km nm]	4.93	5.78
PMD (1st order) [ps]	8.77×10^{-2}	8.77×10^{-2}

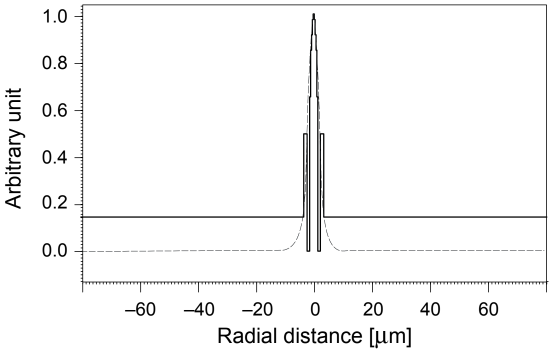


Fig. 25. Confinement in fiber A.

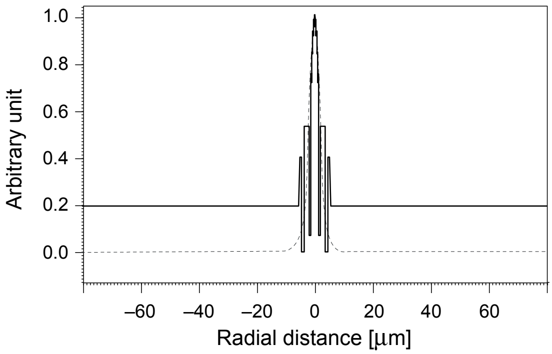


Fig. 26. Confinement in our optimized fiber B.

a comparison is done between two refractive index profiles namely fiber A and fiber B. Fiber A is NZDSF with only a triple-cladding-type profile and fiber B is our optimized refractive index profile (alpha-peak profile described a graded index core with a penta--cladding fiber).

Figures 25 and 26 show the confinement of optical power into the NZDSF fiber A and the confinement of optical power in our optimized NZDSF fiber B, respectively. Our optimized fiber B has better MFD and confinement of optical power that overcomes the nonlinearity of the fiber.

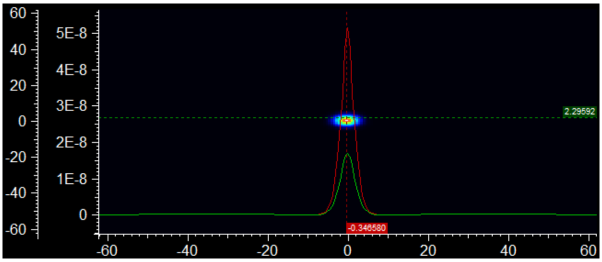


Fig. 27. Plot of the LP(0, 1) mode field *vs*. transverse dimensions of the fiber A.

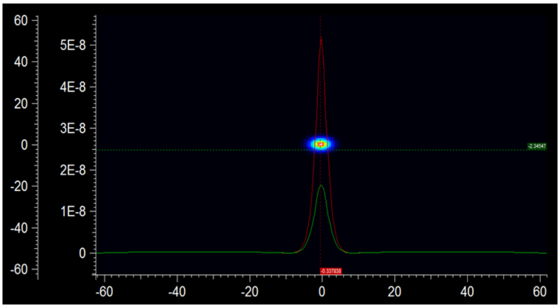


Fig. 28. Plot of the LP(0, 1) mode field *vs*. transverse dimensions of the fiber B.

Figures 27 and 28 show the plots of the LP(0, 1) mode field confinement *vs*. the transverse dimensions of the NZDSF fiber A and our optimized NZDSF fiber B, respectively. Convincingly, fiber B (alpha-peak profile described a graded index core with a penta-cladding fiber) was the optimized NZDSF.

6. Conclusion

Thus, we have designed an optimized NZDSF with reduced nonlinear effects for future optical networks. The calculated results show that this fiber has an enormous effective area of about 120 μm^2, high MFD (12.08 μm), good non-zero dispersion of about 5.75714 ps/kmnm and very low dispersion slope of about 0.057 $ps/nm^2 km$, while maintaining a very low bending loss of about 1.40×10^{-14} dB/km. Our proposed fiber has a low splice loss (4.46×10^{-3} dB) which is compatible to conventional fibers. Also due to our optimized NZDSF design, very low PMD of 8.77×10^{-2} dB and reduced n_2 of 1.41×10^{-16} cm^2/W were obtained. Thus by optimizing the radius parameters and refractive indices of our proposed non-zero dispersion shifted fiber, nonlinear effects are reduced very much and thereby DWDM network performance can be improved a lot.

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