

Strain and Curvature Stability Enhanced SMF Introduction

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Abstract

In this paper, the strain insensitive single-mode optical fiber with low nonlinear effects and ultra low bending loss (BL), appropriate for small curvature radius installation, is presented. The suggested design method is based on electrical field distribution Gaussian assumption in the core region which evaluates the refractive index profile considering proper mode field diameter (MFD) value. Then, so as to attain the enhanced bending loss and strain stability response for the optical fiber, the optimization tool of the evolutionary genetic algorithm (GA) is employed to determine the optical and geometrical parameters of the structure. In the first designed fiber, the calculations for BL, MFD, effective area (A_{eff}), and effective refractive index sensitivity to strain ($dn_{\text{eff}}/d\epsilon$) in the well-known wavelength of 1.55 μm are 0.0018 dB per each turn of 5 mm curvature radius, 8.53 μm , 58 μm^2 , and $-4.5 \times 10^{-8} \mu\epsilon^{-1}$, respectively. Furthermore, the effect of placing raised outer cladding in the fiber structure is investigated which exhibits the MFD of 8.63 μm , the bending loss of 0.0093 dB for single turn of 5 mm radius, and the A_{eff} of 87 μm^2 at 1.55 μm . In this case the strain sensitivity of n_{eff} is reached to $-6.7 \times 10^{-8} \mu\epsilon^{-1}$. The mentioned effective area is magnificently large in the domain of bend insensitive fibers. In the meantime, the designed structures are insensitive to strain which is a crucial feature in applications with small curvature radius.

1. Introduction

Current strong demands on computer communication services like internet access services require economical solutions to provide broadband capability to access networks. The broadest broadband is optical fiber; the only medium capable of moving data at multi-gigabit-per-second speeds. These demands lead the optical fiber the suitable choice for home applications [1, 2]. In order to rival conventional non-zero dispersion shifted fiber based system, the designed optical fiber must be efficient, commercially. However, apart from the economical option, several design considerations arise in the home applications [3]. The first challenge is to reduce the bending loss to meet the requirements of harsh end copper cable-like handling conditions. Bending loss in optical fibers has been studied, extensively, chiefly because of its adverse effect on power budget in telecommunications. The optical fiber is

compelled to be bent at various corners of walls and the bends can be as small as 5 mm, and hence a severe power penalty is caused. Bending loss of less than 0.1 dB/turn will ensure robust network performance under practical bending conditions such as tight ninety degree corners, fixation by stapling and excess cable storage in tightly confined spaces. Design of bend insensitive fibers for home application includes important technical challenges. The second challenge is the undesirable induced strain due to holders and staples in the small radius installations. The transmission characteristics of the designed bend insensitive optical fiber must be resistant to the refractive index profile variations made by the external applied strain [4, 5]. The next challenge is compatibility with the standard single-mode fibers (SMFs) installed in the telecommunication industry. This compatibility could be achieved by reducing splicing loss during splicing of bend insensitive fiber structures with the conventional SMF [6]. This is attained through adjustment of the MFD of the designed fiber to that of the standard conventional fiber.

There are several methods to reduce the bending loss. The simplest way to reduce the bending loss of a fiber is to increase the refractive index difference between the core and cladding in the step index profile [7]. This way results in MFD reduction. Furthermore, higher order modes would be appeared in it. Other bend minimizing techniques include depressed cladding, adding a low index trench, and photonic crystal fiber employment [8-10]. Photonic crystal fibers (PCFs) have shown superior transmission performance but their fabrication process is much more complicated than conventional fiber manufacture process. In contrast to conventional optical fibers, in PCFs, not only in higher wavelengths the BL surpasses the critical value but also in lower wavelengths they hold a short-wavelength bend loss edge due to bend-induced coupling from the fundamental to the higher-order modes [11].

Considering the three mentioned challenges, it is endeavored to introduce a design procedure so as to overcome these problems and present an optical fiber, holding superior characteristics in case of BL and nonlinear effects, without any reduction in MFD. Note that this structure is capable of use in small curvature applications, since the fiber response to any induced external strain is perfectly optimized.

The paper organization is as follows.

The design procedure and mathematical relations are presented in section 2. Then, in section 3, simulation results

are discussed for validating our suggested process. The multilayer cladding impact is exhibited in section 4. Finally, the paper ends up with a brief conclusion.

2. Mathematical formulation and design procedure

The purpose of this paper is introduction of a design method to evaluate the profile for refractive index of the optical fiber with suitable resistance against small radius curvature and induced external strain by controlling the mode field diameter, straightly. The procedure is based on the reverse engineering. Firstly, a relevant function for the modal field distribution is assumed. Through some logical considerations, the suitable refractive index profile holding the desired MFD is extracted. In the weakly guiding approximation, the transverse component of the electric field satisfies the scalar wave equation [6]:

$$r^2 \frac{d^2 \Psi(r)}{dr^2} + r \frac{d \Psi(r)}{dr} + \{k_0^2 [n^2(r) - n_{eff}^2] r^2 - l^2\} \Psi(r) = 0 \quad (1)$$

where, $\Psi(r)$ is the electric field along radius r , k_0 is the wave number in the free space, $n(r)$ is the refractive index profile of fiber, l is the azimuthal mode number and n_{eff} is the effective refractive index of the structure.

The Gaussian approximation of the fundamental mode in conventional optical fibers gives this idea to choose exact Gaussian function as an answer of wave equation in the core layer [12]. In this case the relationship between n_{eff} and MFD is available at exclusive operational wavelength (λ_{op}). However, similar to all kinds of optical fibers, the refractive index of least cladding layer must be constant, so the assumption of normalized electrical field distribution is extended to the following model:

$$\Psi(r)|_{\lambda_{op}} = \begin{cases} e^{-\frac{r^2}{\omega^2}} & r < r_e \\ A_e K_l(\gamma_e r) & r > r_e \end{cases} \quad (2)$$

where ω = MFD/2, r_e and K_l are core radius and modified Bessel function of the l order. A_e and γ_e are defined as follows:

$$A_e = \frac{\exp(-\frac{r_e^2}{\omega^2})}{K_l(\gamma_e r_e)}, \gamma_e = k_0 \sqrt{n_{eff}^2 - n_e^2} \quad (3)$$

where n_e is the clad refractive index. This electrical field distribution must satisfy the Eq. 1 at λ_{op} wavelength. To avoid any sharp difference in the refractive indexes of the core and the clad, the refractive index of the clad layer (n_e) must be equal with the core refractive index at the core and clad boundary (r_e). This subject is not mentioned in [13, 14]. Straightaway, the profile of the refractive index is extracted. By substituting Eq. 2 in Eq. 1:

$$n(r) = \begin{cases} \sqrt{n_{eff}^2 + \frac{4}{k_0^2 \omega^2} \left(1 - \frac{r^2}{\omega^2}\right)}, & r \leq r_e \\ \sqrt{n_{eff}^2 + \frac{4}{k_0^2 \omega^2} \left(1 - \frac{r_e^2}{\omega^2}\right)}, & r > r_e \end{cases} \quad (4)$$

Based on the mentioned equation, the refractive index profile directly depends on the values of the MFD, core radius, and effective refractive index. In the meantime, the type of the core refractive index is graded and peaks in the core center. By substituting the special definition of the n_e in Eq. 3, the γ_e is defined as follows:

$$\gamma_e = \frac{2}{\omega} \sqrt{\left(\frac{r_e^2}{\omega^2} - 1\right)} \quad (5)$$

In order to guarantee the single-mode operation, the modal analyses of estimated graded index optical fiber is done by piecewise constant representation of the graded index profile that resembles a staircase. In this approach, the refractive index of optical fibers with an arbitrary but axially symmetric profile is approximately expressed by a staircase function. According to the linear polarization approximation (LP), the guided modes and propagating wave vectors can be obtained by using transfer matrix method (TMM) [15].

After the extraction of the refractive index profile with the desired mode field diameter, the bending loss and strain response of the fiber is taken into account. In single-mode fibers, the radiation loss from the fundamental mode to leaky core modes arises whenever there is a change in curvature of the fiber axis. Using the method introduced and discussed by Jun-ichi Sakai et al. [16], 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 almost similar to that in the straight one. This approximation is greatly accurate to evaluate the radiation losses in single-mode optical fiber [17]. The radiation loss 2α , due to uniform bending, is defined by the following equation:

$$2\alpha = \frac{\sqrt{\pi} A_e^2}{4P} \times \frac{r_e \exp\left(\frac{-4\Delta w^3}{3r_e v^2 R_b}\right)}{w \left(\frac{w R_b}{r_e} + \frac{v^2}{2\Delta w}\right)^{0.5}}$$

$$P = \int_0^\infty \Psi(r)^2 r dr, \quad (6)$$

which in r_e denotes the core and least cladding boundary position, referring to Eq. 2, A_e is the constant component of the electrical field of the outer layer, R_b is the radius of curvature of the bend, w is given by $(r_e \gamma_e)$ and Δ is the refractive index difference between n_{max} and n_e . v is the normalized frequency which is defined by:

$$v = k_0 r_e \sqrt{n_{max}^2 - n_e^2}. \quad (7)$$

The n_{max} is happened at the core center which is defined as follow:

$$n_{max} = \sqrt{n_{eff}^2 + \frac{4}{k_0^2 \omega^2}}. \quad (8)$$

The optical fiber response to strain occurs due to changes in the refractive index and physical dimensions of the layer, both of which manage the n_{eff} variation [18]. Physical change in core height and width is related to the Poisson ratio (ν). The term relating the refractive index changing to strain is dominated by photoelastic effect. Getting exposed to strain, the bandgap shift of silica causes the change in the absorption coefficient of it. The variation in the absorption coefficient affects the refractive index of silica. Therefore, the strain-induced bandgap change is related to the changes of the refractive index [4]. Generally, the change in refractive index is deduced to be [5]

$$\Delta n_i = \sum_{j=1}^6 \frac{\partial n_i}{\partial \varepsilon_j} \varepsilon_j + \frac{\partial n_i}{\partial T} \Delta T = -\frac{n_i^3}{2} \sum_{j=1}^6 p_{ij} \varepsilon_j + \frac{\partial n_i}{\partial T} \Delta T \quad (9)$$

Where p_{ij} are the photoelastic coefficients, n_i is the refractive index of the i th layer, ε_j is the strain tensor element and ΔT is the temperature variation. Assuming

the homogeneity and isotropic behavior of silica and also the application of force perpendicular to the fiber cross section, Eq. 9 can be simplified to

$$\Delta n_i = -\frac{n_i^3}{2}(p_{12} - \nu(p_{11} + p_{12}))\varepsilon + \frac{\partial n_i}{\partial T}\Delta T \quad (10)$$

Where, for the pure silica at 1550 nm, $p_{11}=0.113$, $p_{12}=0.252$, $\nu=0.17$.

Accomplishing the presentation of the prerequisite relevant relations, the optimization of the bending loss and strain behaviors of the structure is regarded. In order to design the bend insensitive optical fiber with a satisfactory resistance to external induced strain, the GA is employed [19]. In this process, the optical and geometrical parameters of the fiber are set by minimization of the appropriate cost function at operational wavelength which is defined as follows:

$$\text{cost function}|_{\lambda_{op}} = \alpha BL|_{\lambda_{op}} + \gamma S_\varepsilon|_{\lambda_{op}},$$

$$S_\varepsilon = \frac{\Delta n_{eff}}{\Delta \varepsilon} \quad (11)$$

Where ε is the unavoidable induced strain in installation processes with small curvature radius and α and γ are the weight coefficients which prohibit the dissipation of the low value term in the cost function confronting the high value term. Since n_{eff} stands for the most fundamental feature of the optical fiber, its variation as a result of strain induction switches the fiber characteristics. So, the less sensitivity of n_{eff} to strain assures the more stability of structure response.

3. Simulation results and discussion

Based on the procedure explained in the previous section, the proposal of the bend and strain insensitive single-mode optical fiber is presented. All the results exhibited in this section are attained at $\lambda_{op}=1.55 \mu\text{m}$, bend radius of 5 mm and the desired MFD of $8.5 \mu\text{m}$. Moreover, the induced strain is considered to be in $\pm 10000 \mu\text{e}$ interval. During the simulations the room temperature is preserved. The distinct pairs of n_{eff} and r_e form the forty chromosome initial population in GA.

The outputs of the optimization tool are listed in Table 1. It is obvious that the core radius of the designed structure is large which is good from fabrication point of view.

Table 1: GA results for optimal parameters value.

Parameter	n_{eff}	$r_e(\mu\text{m})$
Value	1.4501	4.802

The refractive index profile for the designed bend and strain insensitive single-mode optical fiber is illustrated in Figure 1. This profile is calculated by adjustment of the mode field diameter value to $8.5 \mu\text{m}$ at $1.55 \mu\text{m}$ operational wavelength. The conventional approach for bending loss reduction in the optical fibers is the shrinkage of the MFD by the means of augmentation of the difference in the refractive indices of the core and the cladding which may lead to high inequality in viscosity properties of the layers. As a result, extra mechanical and thermal stresses are

produced in the fiber [20, 21]. The graded nature of the refractive index profile in the core region would reduce the outline stresses.

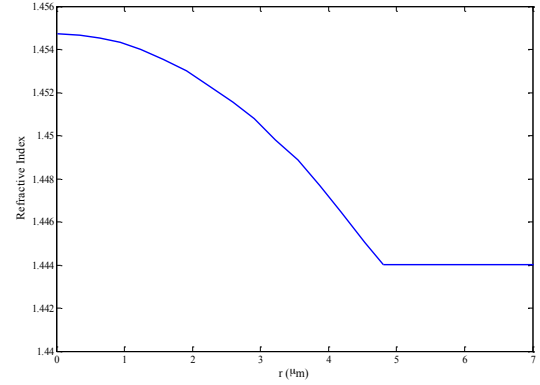


Figure 1: Refractive index profile of the designed structure.

The bending loss value of the structure at $1.55 \mu\text{m}$ with 5 mm radius of curvature is 0.0018 dB/turn. The negligible BL is achieved owing to the introduced cost function. The bending loss behavior of the structure is illustrated in Figure 2. According to ITU-T G652.B recommendation, the bending loss value of the bend insensitive fiber at $1.55 \mu\text{m}$ must be less than 0.1 dB/turn for 5mm bending radius. The designed structure not only satisfies the desired condition at $1.55 \mu\text{m}$, but also in the S+C+L communication bands. In the well-known communication bands of S, C and L, the bending loss is calculated to be in $[3.6\text{e-}4 : 1.6\text{e-}3]$, $[1.6\text{e-}3 : 3.8\text{e-}3]$ and $[3.8\text{e-}3 : 1.1\text{e-}2]$ dB/turn intervals, respectively.

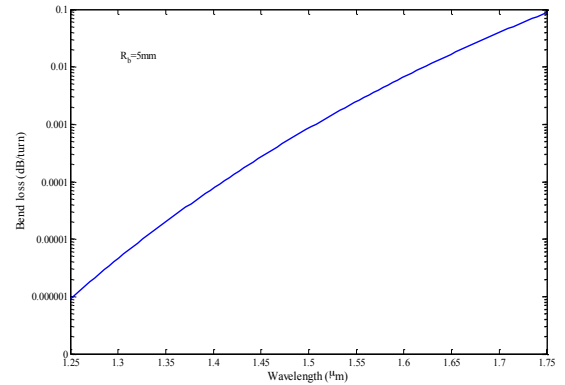


Figure 2: Bending loss (dB/turn) vs. wavelength (μm) for 5mm curvature radius.

The cost function of the optimization procedure has two significant terms. The first one is bending loss. The second term is responsible to reduce the sensitivity of the structure to applied external strain. Figure 3 shows the n_{eff} responses to strain in the designed fiber structure. Based on the curve presented in this figure, it is obvious that application of tensile strain leads to the reduction in n_{eff} value. In the meantime, this parameter increases with application of compressive strain. This response is expected regarding the results presented in [18], indeed. The strain sensitivity of the n_{eff} at $\lambda=1.55 \mu\text{m}$ is calculated to be $-4.5 \times 10^{-8} \mu\text{e}^{-1}$. According to Eq. 10 application of tensile and compressive

strains result respectively in reduction and increment in the refractive index and thus the effective refractive index experiences same trends, either. It is useful to mention that the n_{eff} sensitivity to strain is smaller than the results presented in [18, 22-24]. It is due to using of special cost function which enhanced the stability of the structure to strain.

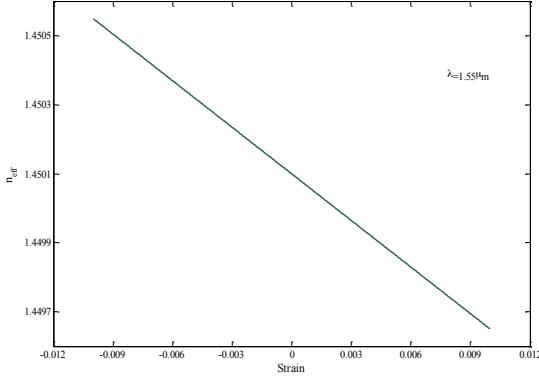


Figure 3: Effective refractive index vs. strain at $\lambda=1.55\mu\text{m}$.

The MFD is an important parameter to characterize an optical fiber and has been used extensively for conventional optical fibers. The MFD of the graded index based structure is successfully tuned to $8.53\mu\text{m}$ thanks to the design procedure. This parameter has a close relation with the electrical field distribution which is managed by effective refractive index of the structure. Any alteration in the n_{eff} of the structure due to applied strain could vary its MFD too. The strain impact on MFD of the considered optical fiber can be investigated, either. Figure 4 presents the variation of the MFD owing to strain at $1.55\mu\text{m}$. In this figure ΔMFD is:

$$\Delta\text{MFD} = \text{MFD}|_{\varepsilon=0} - \text{MFD}|_{\varepsilon \neq 0} \quad (12)$$

Generally, MFD enlarges gradually as the applied tensile increases. Through the physical point of view, based on Figure 3, due to the tensile strain induction the effective refractive index of the structure falls. Hence, the fiber capability to bind the light reduces and the electrical field spreads more in the cladding region. In other respects, the field distribution becomes smoother and consequently the mode field diameter enlarges. The same discussion would be valid for the effect of the compressive strain on MFD. It is considerable that the effective area (A_{eff}) of the fiber would vary due to these changes on the electrical field distribution. The strain sensitivities of the MFD and A_{eff} at $1.55\mu\text{m}$ are $1.8\text{ pm}\mu\text{e}^{-1}$ and $6.3 \times 10^{-6}\mu\text{m}^2\mu\text{e}^{-1}$ respectively. Noting the results reported in [18, 22-24] the transmission characteristics of the proposed structure exhibit high stability to external strain application.

The effective area of the designed optical fiber is about $58\mu\text{m}^2$ which is large for bend insensitive single-mode optical fibers. Another essential concept to consider is the higher order mode cut off wavelength (λ_c). According to ITU-T standard for bend insensitive optical fibers, the λ_c must be less than 1260 nm [25]. However, for the designed structure in this article, λ_c meets 1236 nm which totally conforms the mentioned standard.

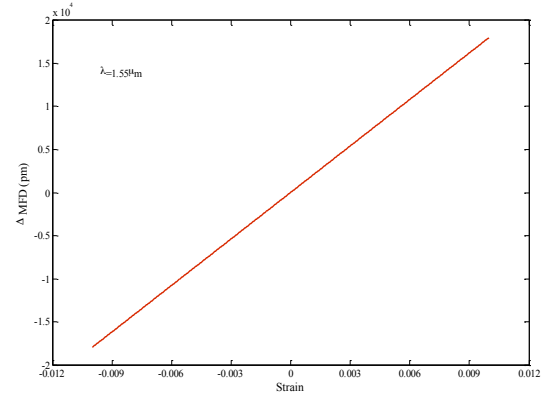


Figure 4: Mode field diameter variation (pm) vs. strain at $\lambda=1.55\mu\text{m}$.

4. Study influence of raised outer cladding addition

In this section, the effect of raised outer cladding placement on transmission behavior of the suggested graded index optical fiber is studied. A well-known technique for the reduction of the nonlinear effects in conventional optical fibers is the addition of raised outer clad to the structure [26]. In this method, penetration of the electrical field in the cladding region boosts the A_{eff} which weakens the resistivity of the fiber to curvature. However, the BL could be restricted through augmentation of the field slope descent. The refractive index of the proposed multilayer structure is presented in Figure 5. According to the design procedure the profile of the core is extracted by the Gaussian assumption of the field distribution at the operational wavelength (λ_{op}). In order to evaluate characteristics of the structure, some optical and geometrical parameters are defined as follow:

$$\Delta = \frac{n_{max}^2 - n_4^2}{2n_4^2} \approx \frac{n_{max} - n_4}{n_4}$$

$$R = \frac{n_{max} - n_3}{n_3 - n_e}$$

$$Q = \frac{r_e}{b}, \quad P = \frac{r_e}{c}$$

where according to section 2, n_{max} and n_e are related to n_{eff} and r_e . Furthermore, the n_3 and n_4 values are relevant to n_{max} and n_e through Δ and R .

Based on the linear polarization approximation (LP), to calculate the electrical field distribution, the guided modes and propagating wave vectors are extracted using TMM. Employment of raised outer cladding leads to remarkable variation in the electrical field distribution manner in the cladding region. So, expectedly, the MFD management is partially failed. In other respects, the MFD value in the structure exhibited in Figure 5, depends on the field distribution not only in the core, but also in the cladding.

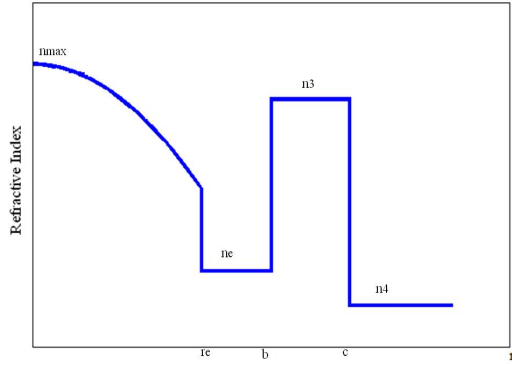


Figure 5: Refractive index profile of the suggested multi-clad structure.

Exploiting the cost function presented in Eq. 11, the optical fiber, holding the refractive index profile exhibited in Figure 5, is designed. In this case, the genes of the chromosomes in the initial population increase to six. Then by applying the defined cost function, the bending loss and strain sensitivity of the n_{eff} are minimized at $1.55\mu\text{m}$. The outputs attained from optimization process are listed in Table 2 and the refractive index profile of the optimized structure is illustrated in Figure 6. Both n_{eff} and r_e are smaller than the ones presented in Table 1. The n_{eff} decrement could raise the bending loss of the multilayer structure.

Table 2: GA results for optimal structural parameters of the multilayer fiber.

Parameter	n_{eff}	$re(\mu\text{m})$	\square	R	Q	P
Value	1.4487	3.9	$6.2\text{e-}3$	1.76	0.75	0.56

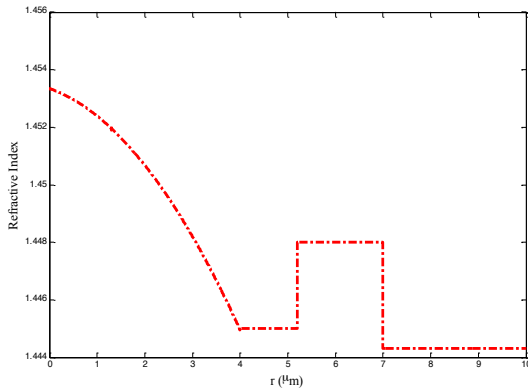


Figure 6: Refractive index profile of the designed multilayer structure.

The MFD, BL, and A_{eff} are $8.63\mu\text{m}$, 0.0093 dB/turn and $87.3\mu\text{m}^2$, respectively. Note that, although the BL is increased slightly due to further leading of electrical field distribution to the out of core region, the attained BL is still negligible. However, there is 50% modification in A_{eff} . Moreover, there is a boost in n_{eff} sensitivity to strain which is calculated to be $-6.7 \times 10^{-8}\mu\epsilon^{-1}$. This sensitivity is still of better stability compared to the results exhibited in [18, 22-24].

Despite the noticeable difference in the refractive index profiles of the two structures, the fibers designed according to Figure 1 and Figure 6, exhibit almost the equal MFDs. Yet, the effective areas of the two structures are entirely different. Physics behind this feature is explained regarding the integration of the electrical field distributions and also their deviations. The effective area depends only on the field distribution, but the MFD depends on both the field distribution and its first deviation. Figure 7 shows a relatively proportional growth in the integration of field distribution and its deviation in the raised outer-layer which remains the MFD unchanged. The noticeable point is that the raised outer-type structure holds large effective area and bend insensitive property.

As the final issue, the λ_c parameter in the multilayer structure is pointed. The value is reduced to 1228 nm as a result of fall in the core radius.

5. Conclusion

The proposal of the design method for bend insensitive single-mode optical fibers appropriate for indoor wiring is presented. The employed design procedure has assured the resistivity of the structure to external strain induction. Simulation results show bending loss of 0.0018 dB at $1.55\mu\text{m}$ for single turn of 5 mm curvature radius while the MFD and effective area are $8.53\mu\text{m}$ and $58\mu\text{m}^2$, respectively. The strain sensitivity of n_{eff} is calculated to be $-4.5 \times 10^{-8}\mu\epsilon^{-1}$. The impact of adding raised outer-clad has been investigated, either. Simulation outcomes admit that the designed graded index optical fiber with raised outer-clad structure is the ultra large effective area bend insensitive optical fiber. The values of bending loss for single turn of 5mm curvature radius, effective area, and MFD are, respectively, 0.0093 dB , $87\mu\text{m}^2$ and $8.63\mu\text{m}$ at $1.55\mu\text{m}$ operational wavelength. The changes in n_{eff} due to variation in applied strain is $-6.7 \times 10^{-8}\mu\epsilon^{-1}$ which is still of satisfactory stability.

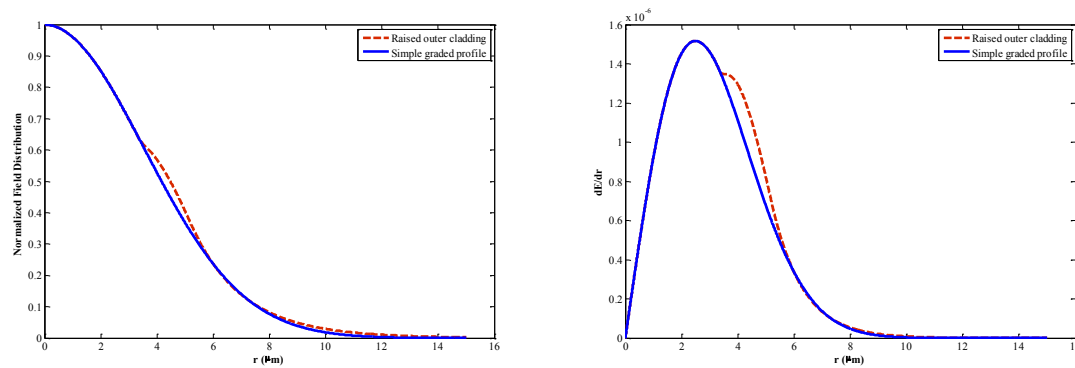


Figure 7: Normalized field distributions and their first deviation in simple graded index profile and raised outer-clad structures.

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