The Study of Bending Loss and Mode Field Diameter in Two Multi-clad Single Mode Optical Fibers

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Summary
In this paper, bending loss and mode field diameter (MFD) of two new multi-clad single mode optical fibers are investigated. Effects of optical and geometrical parameters in these fibers on bending loss and MFD are examined. The simulated results indicate that with increase of core radius (a), that is excellent in practice, bending loss and MFD coefficients are decreased. Thus, large core radius in these fibers for optimization of bending loss can be used. We show that type-II optical fiber is so sensitive to optical and geometrical parameters than type-I. Based on the presented simulations, it can be said that bending loss for a given MFD, strongly depends on profile of field distribution in the cladding region. On the other hand, field amplitude and rate of damping in the cladding region determine bending loss of the fiber.

Key Words:
Multi-clad Single Mode Optical Fiber, LP Approximation, Bending Loss, Mode Field Diameter

1. Introduction

Optical fiber communication is basic and good alternative for high speed communications today. Because of low loss and manageable dispersion, this method is so interesting. Recently since multi-channel optical signal propagation systems such as optical time division multiplexing (OTDM) and dense wavelength division multiplexing (DWDM) systems are required in industry. Since these applications are so interesting, then developing optical fibers covering these properties will be so important. Dispersion and loss properties of optical fibers in these applications should be considered. Also, it is so necessary to consider bending loss in optical integrated circuits (OIC) because of progress of optical integrated circuits on single chip and small bending radius. Fiber loss is one of the significant restrictions in optical fiber communication links. It limits the maximum distance that information can be sent without presence of repeaters. Also, owing to loss, the amplitude of the pulse is reduced so that the initial information can not be restored in noisy condition. The combination of natural attenuations has a global minimum around 1.55μm and that is why most optical communication systems are operated at this wavelength.

In [1], two multi-clad optical fibers named type-I and type-II were examined and the impacts of optical and geometrical parameters on dispersion and pulse broadening factor curves were investigated. Analytical deriving of dispersion and dispersion slope has been presented in [2] which cover all numerical approaches accurately. In [3] bending loss property of three-layered large flattened mode fibers was studied. In calculating the bending loss, they substituted the fiber core and inner cladding by an equivalent current radiating as an antenna in an infinite medium of index equal to the refractive index of the most external layer. A bending loss formula for optical fibers with an axially symmetric arbitrary-index profile was derived by approximating the refractive-index profile with a staircase function [4]. The permissible bending radius R^* defined for a given value of bending loss was derived. They showed that R^* is nearly proportional to wavelength when the normalized frequency and the refractive-index difference are fixed. This paper is a basic publication in this domain. Also, the loss formula for optical fibers with constant radius of curvature of their axes was derived by expressing the field outside of the fiber in terms of a superposition of cylindrical outgoing waves [5]. The expansion coefficients were determined by matching the superposition field to the field of the fiber along a cylindrical surface that is tangential to the outer perimeter of the curved fiber. This method is a direct extension of the curvature-loss formula for slab waveguides of the author. This paper is also good for developing of bending loss in multi-clad fibers. A mathematical solution of the wave equation for coaxial fibers having four different refractive index profiles was presented in [6]. The transcendental equations were obtained under LP approximation and calculated for comparison of HE_{mn}-mode dispersion characteristics. In this paper, there is not any discussion about loss profile.

In this paper, following the investigation derived in [1], two multi-clad single mode optical fibers named type-I

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and type-II are considered and studied from bending loss and mode field diameter points of view. For this task, LP approximation is used for obtaining field distribution in these fibers.

Organization of the paper is as follow.

Mathematical formulation is presented in section 2. In this part, LP approximation and background formulation of bending loss and mode field diameter are reviewed. Simulation results and discussion is presented in section 3. Finally the paper ends with a short conclusion.

2. Mathematical Formulation

In this section, mathematical formulations for extraction of fiber bending loss and mode field diameter coefficients are presented. We focus on the two multi-clad single mode optical fibers, which the refractive index profiles are illustrated in Fig. 1 and labeled type-I and type-II. Layers refractive index is defined as below:

$$n(r)=\begin{cases} n_1,\ 0<r<a \\ n_2,\ a<r<b \\ n_{3,}\ b<r<c \\ n_4,\ c<r<d \\ n_5, d<r \end{cases} \qquad (1)$$

where r is the radius position.

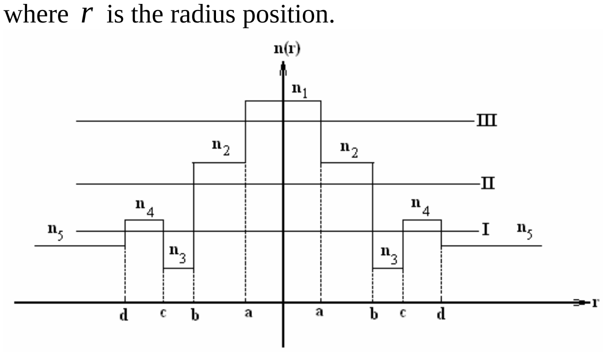

Fig. 1-a

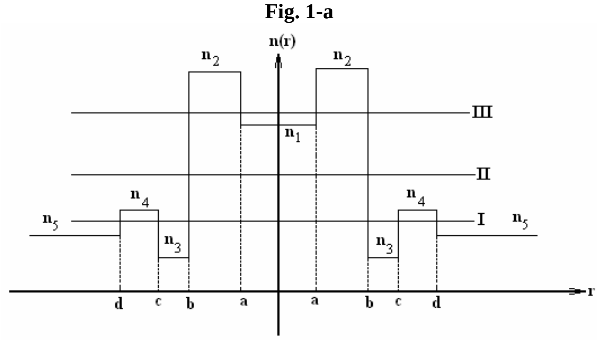

Fig. 1-b

Fig. 1 The Index of Refractive Profiles of Two Fibers, (1-a) type-I, (1-b) type-II.

According to LP approximation [6-7] for calculation of propagation wave vectors and by applying boundary conditions, the electric field distribution can be calculated. The effective refractive index is given by:

$$n_e = \frac{\beta_g}{k_0} \qquad (2)$$

where β_g is the longitudinal propagation constant of the guided mode and k_0 is the wave number in vacuum.

We defined the geometrical parameters of introduced optical fiber structures as:

$$P=\frac{b}{c},\ Q=\frac{a}{c},\ L=\frac{c}{d} \qquad (3)$$

and the optical parameters as:

type-I:

$$R_1=\frac{n_1-n_2}{n_1-n_3},\ R_2=\frac{n_1-n_4}{n_1-n_5},\ R_3=\frac{n_2-n_3}{n_2-n_4}, \qquad (4)$$

$$\Delta=\frac{n_1{}^2-n_5{}^2}{2n_5{}^2}\approx\frac{n_1-n_5}{n_5}$$

type-II:

$$R_1=\frac{n_2-n_1}{n_2-n_3},\ R_2=\frac{n_2-n_4}{n_2-n_5},\ R_3=\frac{n_1-n_3}{n_1-n_4}, \qquad (5)$$

$$\Delta=\frac{n_2{}^2-n_5{}^2}{2n_5{}^2}\approx\frac{n_2-n_5}{n_5}$$

By solving Maxwell's equations, the electric field in these two multi-clad single mode optical fibers are calculated and given in table1. The $e^{j\beta_g Z}$ term is abbreviated for brevity.

A_i , B_i $(i=1,2,3,4,5)$ are constant and computed by applying electric and magnetic field continuities at boundaries. $\mathrm{J}_\upsilon, \mathrm{Y}_\upsilon, \mathrm{I}_\upsilon$ and K_υ are Bessel and modified Bessel functions of order υ respectively. It should be kept in mind that B_5 is set to zero due to I_υ divergence when r tends to infinity. The γ_i, κ_i transversal propagating constants are defined as follows:

$$\gamma_i=\left(\beta_g{}^2-n_i{}^2k_0^2\right)^{\frac{1}{2}},\quad \kappa_i=\left(n_i^2k_0^2-\beta_g^2\right)^{\frac{1}{2}} \qquad (6)$$

One desired quantity in this investigation, which has strong relation with fiber bending loss characteristic, is mode field diameter (d_0), which is defined as bellow:

$$d_0^2=8\frac{\int_0^\infty|\psi(r)|^2 rdr}{\int_0^\infty\left|\frac{d\psi(r)}{dr}\right|^2 rdr} \qquad (7)$$

where $\psi(r)$ is modal field distribution.

It is manifestly clear that optical fiber loses power by radiation if its axis is curved. Using the method introduced and discussed by Jun-ichi Sakai et al [4], the radiation loss, owing to uniform bending could be obtained. In this method, bending loss formula for optical fibers with arbitrary-index profile is derived by approximating the refractive index profile with a staircase function. Also it is supposed that the field near the inner layers in the curved fiber is almost similar to that in the straight one. It is useful to keep in mind that this approximation is moderately accurate for evaluation of radiation losses in single mode optical fibers. Then expansion coefficients of a field expansion are identified in the terms of cylindrical waves. These coefficients could be found by matching the field expansion with the mode field of straight one [5]. Bend loss formula is written as:

$$2\alpha = \frac{\sqrt{\pi}A_5^{\,2}}{2sP}\cdot\frac{d\exp\left(\frac{-4\Delta w^3}{3dV^2}R\right)}{w\left(\frac{wR}{d}+\frac{V^2}{2\Delta w}\right)^{\frac{1}{2}}} \qquad (8)$$

where d is denoted the radius of the fourth boundary, by referring to Fig. 1, R is the radius of curvature of the bent fiber, w is given by $\gamma_5 d$ and V is the normalized frequency which is defined by $k_0 d\sqrt{n_1^2-n_5^2}$ for type-I and $k_0 d\sqrt{n_2^2-n_5^2}$ for type-II. With respect to the LP mode order, s is defined as:

$$s=\begin{cases}2 & \upsilon=0\\ 1 & \upsilon\neq 0\end{cases} \qquad (9)$$

Based on the relation between effective refractive index and layers refractive index, P is explained as $P=\sum P_i$.

(I) $n_i k_0 > \beta_g$ (10)

$$P_i=\left[\frac{A_i^2 r^2}{2}\left(J_\upsilon^2-J_{\upsilon-1}J_{\upsilon+1}\right)+\frac{B_i^2 r^2}{2}\left(Y_\upsilon^2-Y_{\upsilon-1}Y_{\upsilon+1}\right)+A_iB_ir^2\left(J_\upsilon Y_\upsilon-J_{\upsilon-1}Y_{\upsilon+1}\right)\right]_{a_i}^{a_{i+1}}$$

The arguments $\kappa_i r$ of the Bessel functions are left out for brevity. a_i indicates the radius of the i th boundary.

(II) $n_i k_0 < \beta_g$ (11)

$$P_i=\left[\frac{A_i^2 r^2}{2}\left(K_\upsilon^2-K_{\upsilon-1}K_{\upsilon+1}\right)+\frac{B_i^2 r^2}{2}\left(I_\upsilon^2-I_{\upsilon-1}I_{\upsilon+1}\right)+A_iB_ir^2\left(K_\upsilon I_\upsilon-K_{\upsilon-1}I_{\upsilon+1}\right)\right]_{a_i}^{a_{i+1}}$$

The arguments $\gamma_i r$ of the modified Bessel functions are left out again.

3. Simulation Results and Discussion

Based on the method mentioned in the previous section, simulation results are illustrated to present effects of optical and geometrical parameters variation on mode field diameter and bending loss coefficients of considered type-I and type-II single mode optical fibers. These simulations have been done according to $a=1\mu m, Q=0.3, P=0.7, L=0.6$ geometrical and $\Delta=5e-3,\ R_1=0.2,\ R_2=0.6,\ R_3=7$ optical parameters. Each parameter is varied one at a time to investigate the effect of this parameter on bending loss at $\lambda=1.55\mu m$ and MFD curves and other parameters are like above and kept still. Fig. 2 and Fig. 3 show the influences of a and Δ variations on MFD respectively. With reduction of a, all layers width are decreased. Also, Δ presents the difference between higher refractive index of core and latest layer of clad. It is observed that with increase of a and Δ parameters, MFD is decreased.

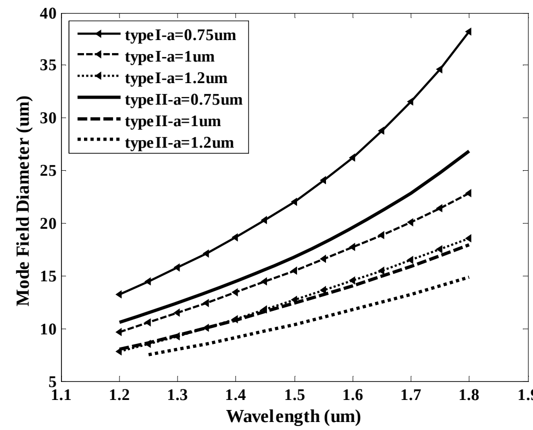

Fig. 2 MFD (μm) Vs. Wavelength (μm) for a as parameter.

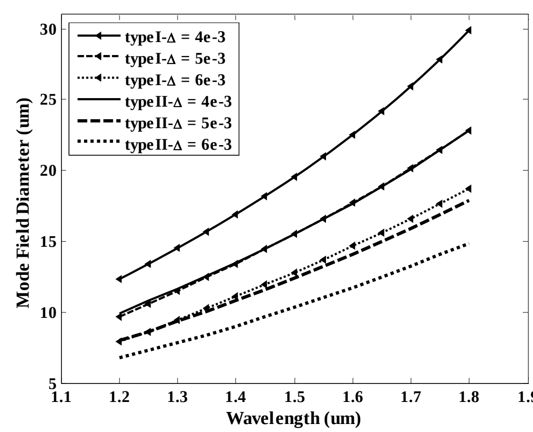

Fig. 3 MFD (μm) Vs. Wavelength (μm) for Δ as parameter

Fig. 4 and Fig. 5 illustrate the effects of Q and P . With increase of Q , in the except of central layer, other regions width are decreased. Also with variation of P , the widths of second and third layers are changed. It is found that with increase of Q geometrical parameter, MFD is raised, but the case is opposing about P . On the other hand, by attention on these four previous figures, it is clear that the considered parameters variations have strong impacts on the MFD value so by adjusting these parameters, MFD easily is matched with our desired value.

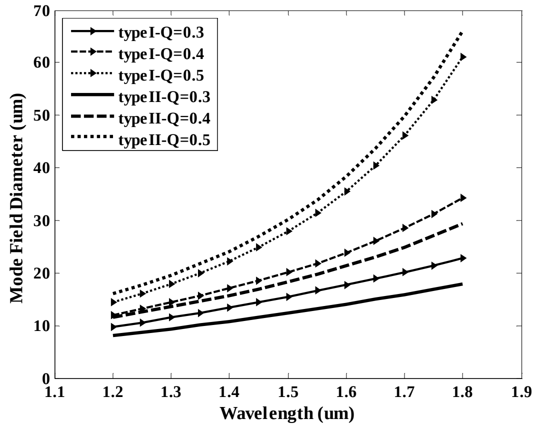

Fig. 4 MFD (μm) Vs. Wavelength (μm) for Q as parameter

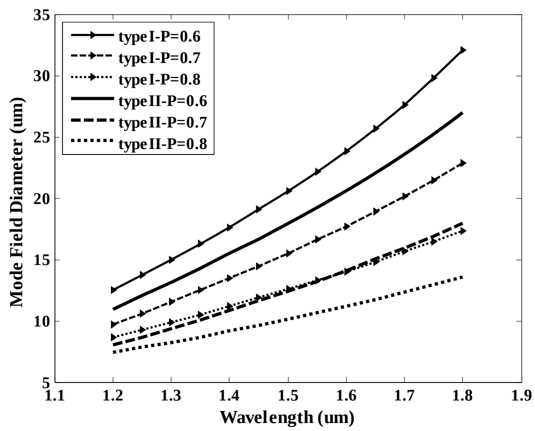

Fig. 5 MFD (μm) Vs. Wavelength (μm) for P as parameter

With increase of L, width of the fourth region is reduced and there is no impact on other layers. The influence of L variation is presented in Fig. 6. According to this figure, with increase of L, MFD is decreased in small wavelengths and raised in high wavelengths but the impact turning point is so higher in type-II. Furthermore, type-I is easily affected by L compared with type-II.

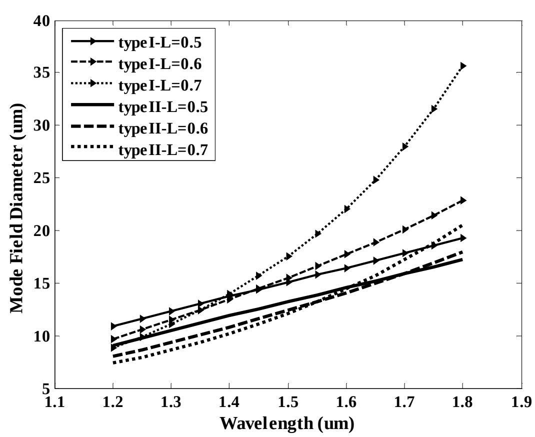

Fig. 6 MFD (μm) Vs. Wavelength (μm) for L as parameter

Fig. 7 is illustrated to demonstrate the effects of R_1. It is clear that with reduce of R_1, MFD is decreased in very small wavelengths and raised in high wavelengths. Also with increase of wavelength, both fiber types are easily affected by R_1.

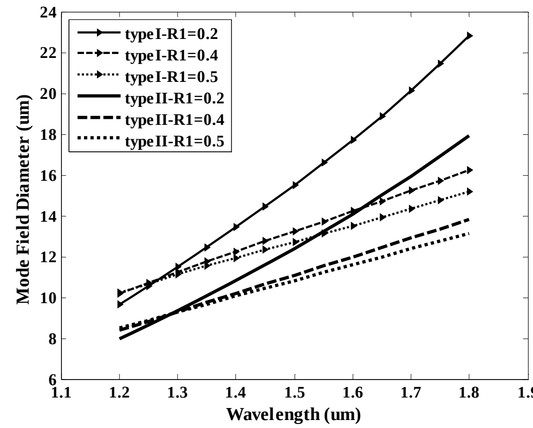

Fig. 7 MFD (μm) Vs. Wavelength (μm) for R_1 as parameter

From Fig. 8 and Fig. 9, it can be said that in both fiber types, with increase of R_2 and R_3, the amount of MFD is boosted. Also R_2 has imperceptible impact on small wavelengths in the case of type-II. As the other result, it is obvious that R_2 and R_3 variations have considerable effect on type-I compared with type-II. Eventually, these simulation results indicate that all optical and geometrical parameters of these two multi-clad fibers have strong influences on the MFD quantity so optimum design can be obtained by choosing sufficient values.

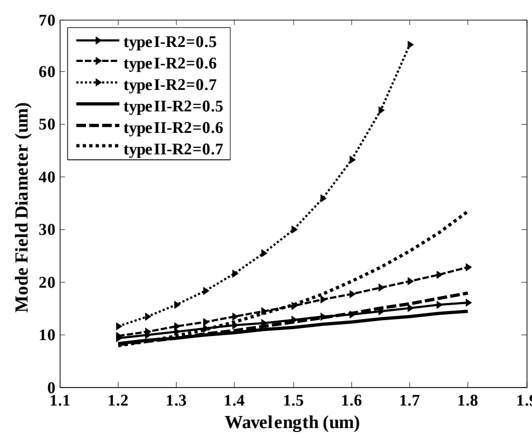

Fig. 8 MFD (μm) Vs. Wavelength (μm) for R_2 as parameter

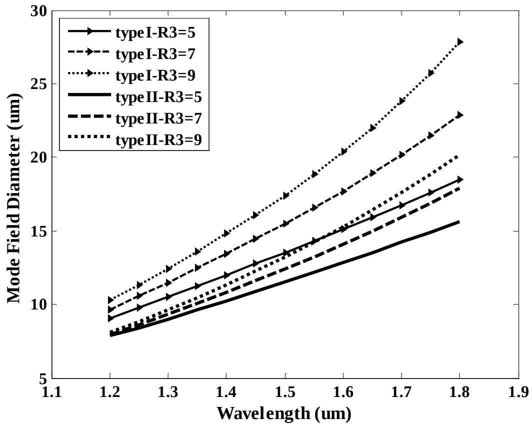

Fig. 9 MFD (μm) Vs. Wavelength (μm) for R_3 as parameter

A kind of loss which must be taken into account in optical fiber design is the bending loss. Every time the optical fiber is bent, radiation occurs. When the bend occurs, a portion of the power propagating in the cladding is lost through radiation, if not; the wave propagating in this portion should travel at speeds higher than the light speed to track down the field in the core. The common bending loss behaviors of type-I and type-II single mode optical fibers and the influence of optical and geometrical parameter variations are simulated and the results are illustrated here.

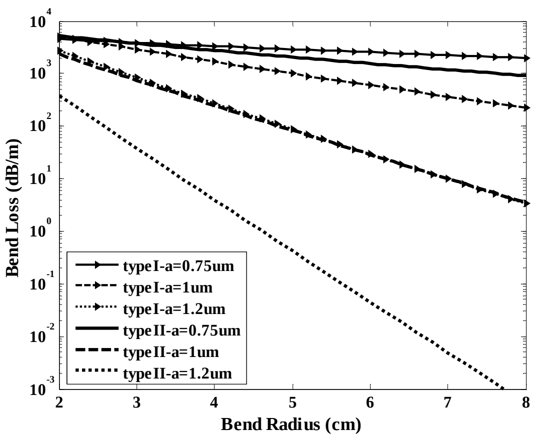

Fig. 10 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55 \mu m$ for core radius as parameter

Fig. 10 and Fig. 11 show the influences of core radius and Δ variations on bend loss value respectively. It is observed that with increase of a and Δ parameters, bending loss is decreased in both fiber types and type-II is more sensitive than type-I in both cases. This result is more beneficial from manufacturing point of view.

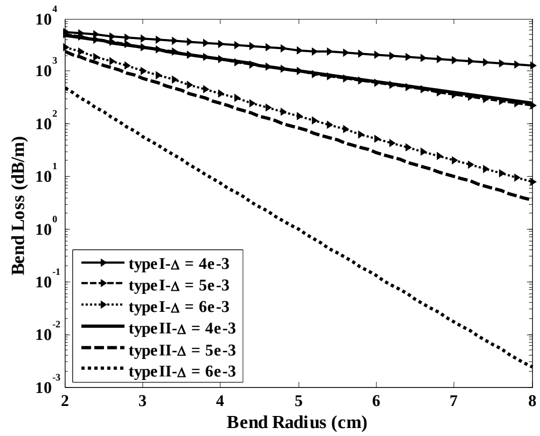

Fig. 11 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55 \mu m$ for Δ as parameter

Fig. 12 illustrates the influence of Q on bending loss value. It is clear that with increase of this parameter, the slope of bend loss curve respect to bend radius is decreased considerably. Also type-II is more sensitive than type-I.

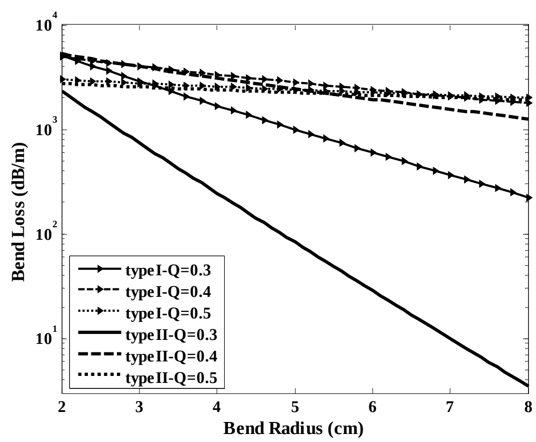

Fig. 12 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55 \mu m$ for Q as parameter

Fig. 13 and Fig. 14 present the effects of P and L respectively. It is found that with increase of P geometrical parameter, bending loss value is decreased, but the case is opposing about L. On the other hand, by attention on these two figures, it is obvious that P and L have comparably stronger impacts on type-II.

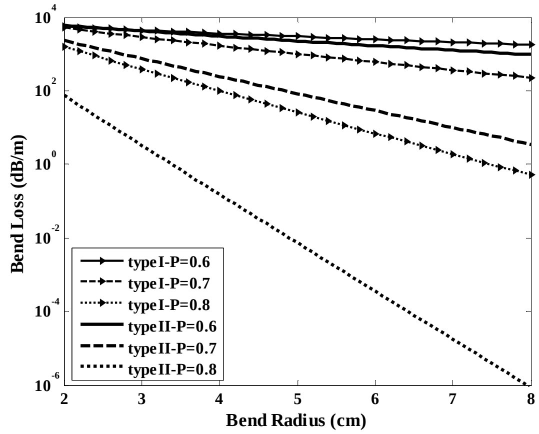

Fig. 13 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55\mu m$ for P as parameter

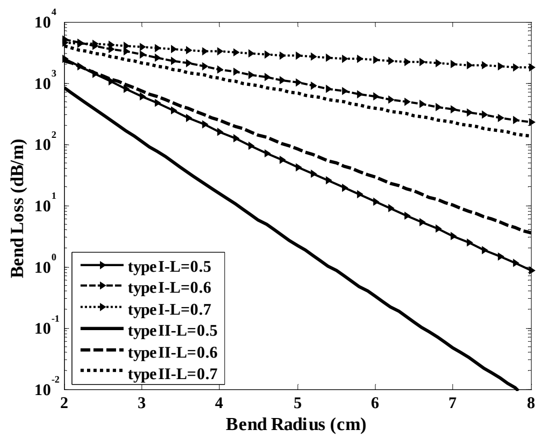

Fig. 14 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55\mu m$ for L as parameter

The influence of R_1 is investigated and simulation results are shown in Fig. 15. With increase of R_1, bend loss amount is reduced and the case is stronger for type-II.

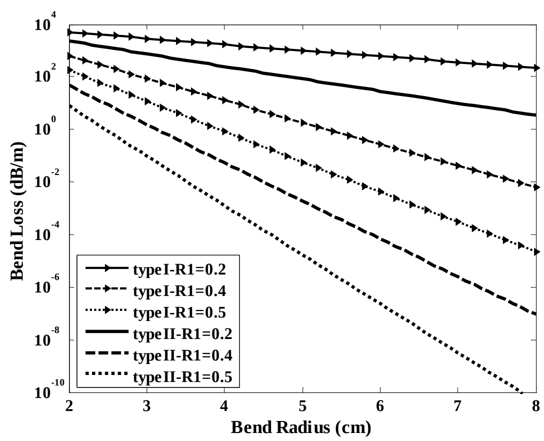

Fig. 15 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55\mu m$ for R_1 as parameter

Finally we study effects of R_2 and R_3, which are illustrated in Fig. 16 and Fig. 17 respectively. It is clear that with rising of R_2 and R_3, bending loss value is increased in both fiber types. By referring to last eight figures, it can be said that R_1 optical parameter variations has great and remarkable effect compared to other parameters. So with control of this parameter, bending loss value could be optimized. By notice on presented results, it is easily observed that there is a firm and close relation between the amount of bending loss and the mode field diameter of the fiber. From bending loss point of view, we can say that for obtaining acceptable loss value, the small amount of mode field diameter is necessary but not enough. The value of the MFD, nearly demonstrates the field distribution situation. On the other hand, it is well known that the small quantity of the electric field far from the core center and its quick falling, which has no

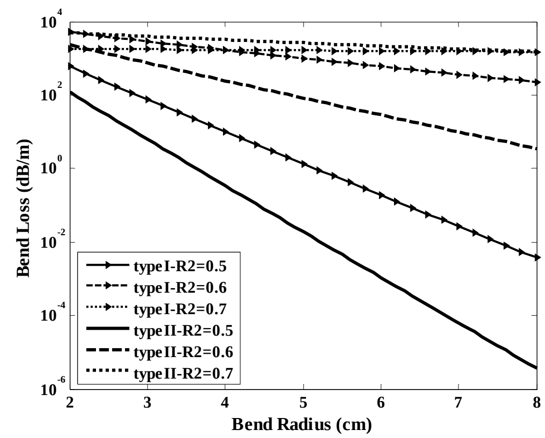

Fig. 16 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55\mu m$ for R_2 as parameter

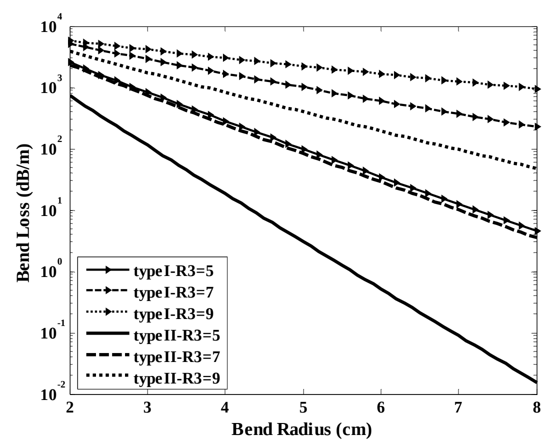

Fig. 17 Bend Loss (dB/m) Vs. Bend Radius (cm) at $\lambda = 1.55\mu m$ for R_3 as parameter

noticeable impacts on the MFD value, yields to looser bending loss tolerance. This fact is clearly observable by attention on Fig. 6 and Fig. 14, which illustrate influence of L variation on MFD and bending loss values respectively. In these simulations, on the case of type-II, the structures with smaller MFD are related to larger bending loss values.

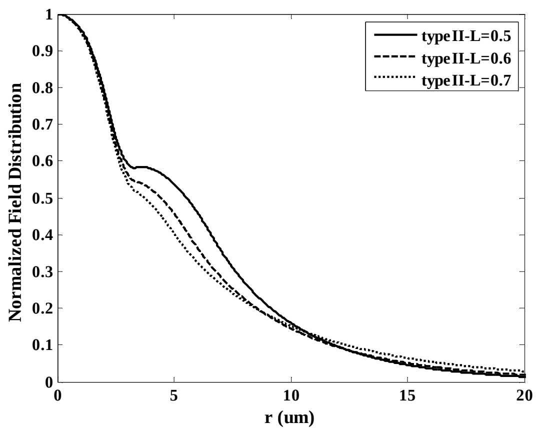

Fig. 18 Normalized Field Distribution of type-II Vs. Radius (μm) for L as parameter

These results are explainable with notice on Fig. 18, which shows the normalized field distribution of these simulated structures. As said before, with increase of L, the fourth region width is decreased so the local peak of field distribution which is located in this region is disappeared and consequently the amount of MFD is reduced. On the other hand, with rising of L, field distribution falling rate in the latest clad layer is decreased and causes larger bending loss value.

3. Conclusion

The mode field diameter and bending loss coefficients of two kinds of multi-clad single mode optical fibers named type-I and type-II were studied in this paper. The simulated results indicate that with increase of a, bending loss and MFD coefficients are decreased and this result is more beneficial from manufacturing point of view. We found that bending loss is very sensitive on variation of parameters in type-II compared with type-I. So type-II is more suitable than type-I from designing and controlling point of view. Finally, it can be said that the small amount of the electric field and its quick falling in the region far from the core center yields to greater tolerance of bending loss.

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Table1-a: Waveguide Solutions of type-I Structure for the Different Regions with Respect to Effective Refractive Index.

Region	$n_5 < n_e < n_4 (typeI)$	$n_4 < n_e < n_2 (typeI)$	$n_2 < n_e < n_1 (typeI)$
$0 < r < a$	$A_1 J_\upsilon(\kappa_1 r)\cdot\cos(\upsilon\theta)$	$A_1 J_\upsilon(\kappa_1 r)\cdot\cos(\upsilon\theta)$	$A_1 J_\upsilon(\kappa_1 r)\cdot\cos(\upsilon\theta)$
$a < r < b$	$[A_2 J_\upsilon(\kappa_2 r)+B_2 Y_\upsilon(\kappa_2 r)]\cdot\cos(\upsilon\theta)$	$[A_2 J_\upsilon(\kappa_2 r)+B_2 Y_\upsilon(\kappa_2 r)]\cdot\cos(\upsilon\theta)$	$[A_2 K_\upsilon(\gamma_2 r)+B_2 I_\upsilon(\gamma_2 r)]\cdot\cos(\upsilon\theta)$
$b < r < c$	$[A_3 K_\upsilon(\gamma_3 r)+B_3 I_\upsilon(\gamma_3 r)]\cdot\cos(\upsilon\theta)$	$[A_3 K_\upsilon(\gamma_3 r)+B_3 I_\upsilon(\gamma_3 r)]\cdot\cos(\upsilon\theta)$	$[A_3 K_\upsilon(\gamma_3 r)+B_3 I_\upsilon(\gamma_3 r)]\cdot\cos(\upsilon\theta)$
$c < r < d$	$[A_4 J_\upsilon(\kappa_4 r)+B_4 Y_\upsilon(\kappa_4 r)]\cdot\cos(\upsilon\theta)$	$[A_4 K_\upsilon(\gamma_4 r)+B_4 I_\upsilon(\gamma_4 r)]\cdot\cos(\upsilon\theta)$	$[A_4 K_\upsilon(\gamma_4 r)+B_4 I_\upsilon(\gamma_4 r)]\cdot\cos(\upsilon\theta)$
$d < r$	$A_5 K_\upsilon(\gamma_5 r)\cdot\cos(\upsilon\theta)$	$A_5 K_\upsilon(\gamma_5 r)\cdot\cos(\upsilon\theta)$	$A_5 K_\upsilon(\gamma_5 r)\cdot\cos(\upsilon\theta)$

Table1-b: Waveguide Solutions of type-II Structure for the Different Regions with Respect to Effective Refractive Index.

Region	$n_5 < n_e < n_4 (typeII)$	$n_4 < n_e < n_1 (typeII)$	$n_1 < n_e < n_2 (typeII)$
$0 < r < a$	$A_1 J_\upsilon(\kappa_1 r)\cdot\cos(\upsilon\theta)$	$A_1 J_\upsilon(\kappa_1 r)\cdot\cos(\upsilon\theta)$	$A_1 I_\upsilon(\gamma_1 r)\cdot\cos(\upsilon\theta)$
$a < r < b$	$[A_2 J_\upsilon(\kappa_2 r)+B_2 Y_\upsilon(\kappa_2 r)]\cdot\cos(\upsilon\theta)$	$[A_2 J_\upsilon(\kappa_2 r)+B_2 Y_\upsilon(\kappa_2 r)]\cdot\cos(\upsilon\theta)$	$[A_2 J_\upsilon(\kappa_2 r)+B_2 Y_\upsilon(\kappa_2 r)]\cdot\cos(\upsilon\theta)$
$b < r < c$	$[A_3 K_\upsilon(\gamma_3 r)+B_3 I_\upsilon(\gamma_3 r)]\cdot\cos(\upsilon\theta)$	$[A_3 K_\upsilon(\gamma_3 r)+B_3 I_\upsilon(\gamma_3 r)]\cdot\cos(\upsilon\theta)$	$[A_3 K_\upsilon(\gamma_3 r)+B_3 I_\upsilon(\gamma_3 r)]\cdot\cos(\upsilon\theta)$
$c < r < d$	$[A_4 J_\upsilon(\kappa_4 r)+B_4 Y_\upsilon(\kappa_4 r)]\cdot\cos(\upsilon\theta)$	$[A_4 K_\upsilon(\gamma_4 r)+B_4 I_\upsilon(\gamma_4 r)]\cdot\cos(\upsilon\theta)$	$[A_4 K_\upsilon(\gamma_4 r)+B_4 I_\upsilon(\gamma_4 r)]\cdot\cos(\upsilon\theta)$
$d < r$	$A_5 K_\upsilon(\gamma_5 r)\cdot\cos(\upsilon\theta)$	$A_5 K_\upsilon(\gamma_5 r)\cdot\cos(\upsilon\theta)$	$A_5 K_\upsilon(\gamma_5 r)\cdot\cos(\upsilon\theta)$