A Novel Multiclad Single Mode Optical Fibers for Broadband Optical Networks

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1. Introduction

The demand for data communication is growing rapidly due to the increasing popularity of the Internet and other factors [1]. The unprecedented success of information technology in recent years ushers an explosive growth in demand for the Internet access in the 21st century. Ultra-wideband transmission media are needed in order to provide high-speed communications for a much larger number of users. A promising solution to the capacity crunch can come from wavelength-division-multiplexed optical fiber communication systems that are shown to provide enormous capacities on the order of terabit per second over long distances. These systems utilize single-mode fibers, in conjunction with erbium-doped fiber amplifiers, as the transmission medium [2]. The optical silica fiber might be the only proper choice to realize this task. Optical fiber based communication is the excellent alternative for these purposes which needs low dispersion as well as dispersion slope and large bandwidth supported by optical physical medium[3]. Optical transmission began to be used in trunk cables about 1990; the capacity of those systems was several hundred Mbit/s per fiber. The capacity jumped to 2.5 (5.0) Gbit/s per fiber with the introduction of optical repeaters using erbium-doped fiber amplifiers in 1995. It jumped again in 1998, to 10 (20) Gbit/s per fiber, with the introduction of wavelength division multiplexing (WDM) [5]. Overall transmission capacity now exceeds 100 Gbit/s per fiber due to improvements in WDM techniques [6]. Usually, those techniques are called dense WDM (DWDM). In recent years, the increasing demands for transmission capacity have led to intense research activities on high capacity DWDM communication system [7].

Nowadays, applications such as optical time division multiplexing (OTDM) and dense wavelength division multiplexing (DWDM) are usual tasks in industry [1]. Therefore by considering these applications, providing a large bandwidth and high-speed communication possibility using optical fibers is highly interesting [3].

In the following, we review requirements for DWDM, Dispersion properties, optical nonlinearity, loss properties, and design of optical fiber for DWDM.

2. Requirements for DWDM

The number of wavelengths (channels) in the fibers of DWDM systems is increasing. As discussed earlier, a WDM signal typically occupies a bandwidth of 30 nm or more, although

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it is bunched in spectral packets of bandwidth ~ 0.1 nm (depending on the bit rate of individual channels) [1]. To use such new optical transmission systems, the DWDM fiber should overcome three transmission related limitations: dispersion, optical fiber nonlinearity and loss properties. For 10-Gb/s channels, the third-order dispersion does not play an important role as relatively wide (> 10 ps) optical pulses are used for individual channels. However, because of the wavelength dependence of β_2, or the dispersion parameter D, the accumulated dispersion will be different for each channel [4]. Wavelength division multiplexing (WDM) systems have been widely introduced for large capacity transmission. In order to further increase the transmission capacity, several techniques have been investigated, such as higher bit-rate transmission [8], enhancement of the spectral efficiency [9], and use of new transmission bands [10, 11]. In those systems, optical fibers are required more strongly to reduce the nonlinearity and the dispersion slope [5].

3. Dispersion properties

Silica fibers suffer from some disadvantages especially dispersion and dispersion slope. Meanwhile, these two factors cause severe restrictions for high-speed pulse propagation [1]. The dispersion value becomes larger by the wavelength increasing in the conventional optical fibers. So owing to the dissimilar broadening for different channels, the multi-channel application realization would be hard. A suitable optical fiber should meet the small dispersion as well as the small dispersion slope in the predefined wavelength interval. The dispersion properties are the dispersion itself and the dispersion slope of the optical fiber. The dispersion value cannot be in the zero-value region because FWM causes interaction between signals (optical channels) in DWDM systems when there is phase matching between the optical channels due to zero dispersion. Therefore, the dispersion value in the signal wavelength region must have the proper non-zero value. The sign of the dispersion value should be positive for short-distance transmission and negative for ultra-long-distance transmission [12] because of modulation instability in the positive dispersion in a long link. When the signal wavelength band becomes wider, the difference in the dispersion values at the edges of the wavelength band becomes larger. Dispersion compensation thus becomes difficult for long distance DWDM transmission. To achieve both long distance and high speed transmission with easy dispersion compensation for a wide wavelength band, the dispersion slope should be reduced. For single wavelength communication, dispersion shifted fiber is enough. But for applications such as DWDM this method cannot provide high speed possibility. In these applications, the physical media should provide the flat, minimum, and uniform dispersion as well as dispersion slope ideally. An important limitation induced by chromatic dispersion and its slope is broadening factor which restricts the bit rate parameter.

To minimize pulse broadening in an optical fiber, the chromatic dispersion should be low over the wavelength range used. A fiber in which the chromatic dispersion is low over a broad wavelength range is called a dispersion-flattened fiber.

4. Optical nonlinearity

The response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. Even though silica is intrinsically not a highly nonlinear material, the waveguide geometry that confines light to a small cross section over long fiber lengths makes nonlinear effects quite important in the design of modern light wave systems [1]. The much higher power level due to simultaneous transmission of multiplexed channels and propagation over much longer distances made possible with the utilization of fiber amplifiers, cause the otherwise weak and negligible fiber nonlinearities to affect the signal transmission significantly [2]. When the number of signal wavelengths carried in an optical fiber increases, the average transmission power density becomes larger than that in conventional systems. Consequently, optical-fiber nonlinearities have emerged as a main issue. This nonlinearity seriously limits transmission capacity with various nonlinear interactions, which are generally categorized as scattering effects and optical signal interactive modulation. Because the signal power density is stronger due to the greater number of channels in DWDM systems, optical fiber nonlinearity limits the number/spacing of the channels and the length/speed of the transmission. In general, the refractive index of optical fiber has a weak dependence on optical intensity (equal to signal power (p) per effective area (A_{eff}) in the fiber. Optical fiber nonlinearity arises from modulation of the refractive index caused by changes in the optical intensity of the signal. This cause four wave mixing (FWM), self-phase modulation (SPM) and cross phase modulation (XPM) can be observed in the fiber. The XPM and SPM distort the signals. Therefore, optical fiber nonlinearity must be reduced. The most practical way to do this is to enlarge A_{eff} [13]. The relationship between A_{eff} and mode field diameter (MFD) is direct and proportional. As a result, enlarging MFD is a practical solution for low nonlinearity. The choice of dispersion shifted fibers (DSFs) along with erbium-doped fiber amplifiers (EDFAs), for operation at 1550nm window, would be an ideal one to achieve greater transmission distance and utilize full capacity of transmission system [5,7,15]. However, when the system is operated at the zero dispersion wavelengths, the nonlinear interaction between the channels and noise components is increased. The system working slightly away from the zero dispersion wavelengths can reduce these unwanted interactions. The WDM system reduces the nonlinear effects and enables multi-wavelength transmission through non-zero dispersion shifted fibers having very small dispersion in duration 1530-1610 nm. In order to increase the information carrying capacity, latest high speed communication system is based on the dense wavelength division multiplexing/demultiplexing (DWDM) [16, 17]. In such systems, nonlinear effects like four wave mixing (FWM), which arise due to simultaneous transmission at many closely spaced wavelengths and high optical gain from EDFA, imposes serious limitations on the use of a DSF with zero dispersion wavelength at 1550 nm [18,19]. To overcome this difficulty, the nonzero dispersion shifted fibers having small dispersion in the range ~ 2−4 ps/km/nm over the entire gain window of EDFA have been proposed [20, 21]. In such fibers, the phase matching condition is not satisfied and hence the effect of FWM becomes negligible due to small dispersion [15].

5. Loss properties

Progress in optical fiber fabrication technologies has resulted in a routine production of low loss single mode fibers. This enables us to apply the single mode fibers promisingly in high bit rate and long haul optical transmission systems. Structural optimization must be established so as to provide desirable transmission characteristics for given operating conditions. A basic design consideration has been made by taking into account transmission characteristics such as fiber intrinsic loss, bending loss, splice loss, and launching efficiency [22, 23]. Use of commercially available erbium doped fiber amplifiers (EDFA), which forces optical communication systems to be operated in the 1550 nm window, has significantly reduced the link length limitation imposed by attenuation in the optical fiber [15]. The fiber loss is one of the significant restrictions in the optical fiber communication links. It is one of some reasons limit the maximum distance that information can be sent without presence of the repeaters. Meanwhile, due to the loss, the pulse amplitude reduces so that the initial information cannot be restored in the noisy conditions. Seeing that, in the fiber design one likes to shift the zero dispersion wavelength to the region that the fiber has the lowest level attenuation. The combination of natural attenuations has a global minimum around 1.55 μm and that is why most optical communication systems are operated at this wavelength [4, 18]. A kind of loss which must be taken into account in fiber design is the bending loss. Every time an optical fiber is bent, radiation occurs. When a bent occurs, a portion of the power propagating in the cladding is lost through radiation.

6. Design of DWDM fiber

There are three methods to increase the capacity of a DWDM transmission system, using a broad wavelength range, narrowing channel spacing and increasing a bit rate per channel. However, one of disadvantages for the last two methods is the degradation of the transmission performance due to optical nonlinear effects. In this area, there are three categories which cover all designs. There are based on using zero dispersion shifted fibers (ZDSFs), non-zero dispersion shifted fiber (NZDSFs) and dispersion flattened fibers (DFFs).

7. Zero Dispersion Shifted Fibers (ZDSFs)

Use of commercially available erbium doped fiber amplifiers (EDFA), which forces optical communication systems to be operated in the 1550 nm window, has significantly reduced the link length limitation imposed by attenuation in the optical fiber. However, high bit rate (~10 Gb/s) data transmission can be limited by the large inherent dispersion of the fiber. Dispersion shifted fibers (DSF), which has zero dispersion around 1550 nm, have been proposed and developed to overcome this problem. Dispersion shifted fiber for single wavelength optical communication is a proper choice. The much higher power level due to simultaneous transmission of multiplexed channels and propagation over much longer distances made possible with the utilization of fiber amplifiers, cause the otherwise weak and negligible fiber nonlinearities to affect the signal transmission significantly. The effects of fiber nonlinearities on pulse propagation and on the capacity of fiber optic communication systems have been studied extensively by many researchers. To mitigate the nonlinear effects in long fiber optic communication systems by zero dispersion shifted fiber, a new generation of optical fibers, referred to as large effective area fibers, has been introduced. As said earlier, in order to reduce nonlinear effects, it is preferred to increase effective area. Gathering zero dispersion and large effective area together will be an appropriate solution in this task. The large effective area fibers allow a much smaller light intensity inside the guiding region, thus resulting in less refractive index nonlinearity than the conventional single mode fibers. In addition to reduced nonlinearities, large effective area fibers must also provide low attenuation, low bending and micro-bending losses, low chromatic dispersion, and low polarization mode dispersion. In recent years, a variety of large effective area fiber designs have been reported in the literature. These designs may be broadly classified into two groups based on their refractive index profiles; R-type and M-type. Each of two types is divided to two other categories too named type I and II. A small pulse broadening factor (small dispersion and dispersion slope), as well as small nonlinearity (large effective area) and low bending loss (small mode field diameter) are required as the design parameters in Zero dispersion shifted fibers [24]. The performance of a design may be assessed in terms of the quality factor. This dimensionless factor determines the trade-off between mode field diameter, which is an indicator of bending loss and effective area, which provides a measure of signal distortion owing to nonlinearity [25]. It is also difficult to realize a dispersion shifted fiber while achieving small dispersion slope. Here, we attempted to present an optimized MII triple-clad optical fiber to obtain exciting performance in terms of dispersion and its slope [24]. The index refraction profile of the MII fiber structure is shown in Fig. 1. According to the LP approximation [26] to calculate the electrical field distribution, there are two regions of operation and the guided modes and propagating wave vectors can be obtained by using two determinants which are constructed by boundary conditions [27].

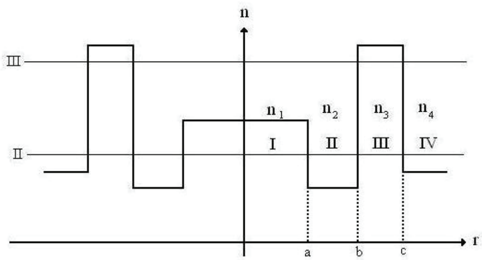

Fig. 1. Refractive index Profile for MII Structure.

For calculation of dispersion and dispersion slope the following parameters are used.

$$P = \frac{b}{c}, \tag{1}$$

$$Q = \frac{a}{c}, \tag{2}$$

where P and Q are geometrical parameters. Also, the optical parameters for the structure are defined as follows.

$$R_1 = \frac{n_3 - n_1}{n_3 - n_2}, \tag{3}$$

$$R_2 = \frac{n_2 - n_4}{n_3 - n_2}. \tag{4}$$

For evaluating of the index of refraction difference between core and cladding the following definition is done.

$$\Delta = \frac{n_3^2 - n_4^2}{2n_4^2} \approx \frac{n_3 - n_4}{n_4} \tag{5}$$

Here, we propose a novel methodology to make design procedure systematic. It is done by the aim of optimization technique and based on the Genetic Algorithm. A GA belongs to a class of evolutionary computation techniques [28] based on models of biological evolution. This method has been proved useful in the domains that are not understood well; search spaces that are too large to be searched efficiently through standard methods. Here, we concentrate on dispersion and dispersion slope simultaneously to achieve to the small dispersion and its slope in the predefined wavelength duration. Our goal is to propose a special fitness function that optimizes the pulse broadening factor. To achieve this, we have defined a weighted fitness function. In fact, the weighting function is necessary to describe the relative importance of each subset in the fitness function [24]; in other words, we let the pulse broadening factor have different coefficient in each wavelength. To weight the mentioned factor in the predefined wavelength interval, we have used the Gaussian weighting function. The central wavelength (λ_0) and the Gaussian parameter (σ) are used for the manipulation of the proposed fitness function and their effects on system dispersion and dispersion slope. To express the fiber optic structure, we considered three optical and geometrical parameters. According to the GA technique, the problem will have six genes, which explain those parameters. It should be mentioned that the initial range of parameters are chosen after some conceptual examinations. The initial population has 50 chromosomes, which cover the search space approximately. By using the initial population, the dispersion (β_2) and dispersion slope (β_3), which are the important parameters in the proposed fitness function, can be calculated. Consequently elites are selected to survive in the next generation. Gradually the fitness function leads to the minimum point of the search zone with an appropriate dispersion and slope. Equation (6) shows our proposal for the weighted fitness function of the pulse broadening factor.

$$F = \sum_{\lambda} e^{-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}} \sum_{Z} [1 + (\frac{\beta_2(\lambda)Z}{t_i^2})^2 + (\frac{\beta_3(\lambda)Z}{2t_i^3})^2]^{\frac{1}{2}}, \quad (6)$$

where $\lambda_0, \sigma, t_i, Z, \beta_2$ and β_3 are central wavelength, Gaussian parameter, full width at half maximum, distance, second and third order derivatives of the wave vector respectively. In the defined fitness function in Eq. (6), internal summation is proposed to include optimum broadening factor for each length up to 200 km. By applying the fitness function and running the GA, the fitness function is minimized. So, the small dispersion and its slope are achieved. This condition corresponds to the maximum value for the dispersion length and higher-order dispersion length as well. By using this proposal, the zero dispersion wavelengths can be shifted to the central wavelength (λ_0). Since, the weight of the pulse broadening factor at λ_0 is greater than others in the weighted fitness function; it is more likely to find the zero dispersion wavelength at λ_0 compared to the other wavelengths. In the meantime, the flattening of the dispersion curve is controlled by Gaussian parameter (σ). To put it other ways, the weighting Gaussian function becomes broader in the predefined wavelength interval by increasing the Gaussian parameter (σ). As a result, the effect of the pulse broadening factor with greater value is regarded in different wavelengths, which causes a considerable decrease in the dispersion slope in the interval. Consequently, the zero dispersion wavelength and dispersion slope can be tuned by λ_0 and σ respectively. The advantage of this method is introducing two parameters (λ_0 and σ) instead of multi-designing parameters (optical and geometrical), which makes system design easy.

The flowchart given in Fig. 2 explains the foregoing design strategy clearly.

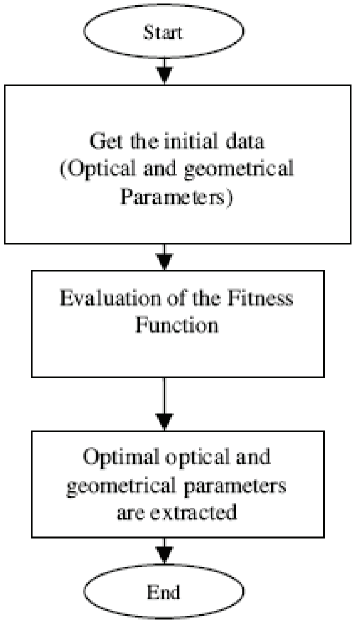

Fig. 2. The scheme of the design procedure

To illustrate capability of the suggested technique and weighted fitness function, the MII triple-clad optical fiber is studied, and the simulated results are demonstrated below. In the presented figures, we consider four simulation categories including dispersion related quantities, nonlinear behavior of the proposed fibers, electrical field distribution in the structures, and fiber losses.

For all the simulations, we consider λ0=1500, 1550 nm and σ = 0, 0.027869 and 0.036935 μm as design constants. To apply the GA for optimization, we consider the search space illustrated in Table 1 for each parameter as a gene. The choice of these intervals is done according to two items. The designed structure must be practical in terms of manufacturing and have high probability of supporting only one propagating mode [24].

Parameter	a (μm)	p	Q	R_1	R_2	Δ
duration	[2-2.6]	[0.4-0.9]	[0.1-0.7]	[0.05-0.99]	[(-0.99)- (-0.05)]	[2×10^{-3} - 1×10^{-2}]

Table 1. Optimization Search Space of Optical and Geometrical Parameters

The wavelength and distance durations for optimization are selected as follows. For λ_0=1550nm: 1500 nm<λ< 1600 nm, for λ_0=1500 nm: 1450 nm <λ< 1550 nm, and 0 < Z < 200 km. In this design method Z is variable. In the simulations an un-chirped initial pulse with 5 ps as full width at half maximum is used. Considering the information in Table 1 and GA method, optimal parameters are extracted and demonstrated in Table 2.

	λ_0 (μm)	a (μm)	Δ	R_1	R_2	p	Q
σ=0	1.55	2.0883	8.042e-3	0.5761	-0.4212	0.7116	0.3070
	1.5	2.1109	7.036e-3	0.6758	-0.2785	0.8356	0.2389
$\sigma = 2.7869 \times 10^{-8}$	1.55	2.0592	9.899e-3	0.7320	-0.2670	0.7552	0.2599
	1.5	2.5822	9.111e-3	0.5457	-0.4237	0.7425	0.2880
$\sigma = 3.6935 \times 10^{-8}$	1.55	2.2753	9.933e-3	0.5779	-0.4218	0.6666	0.3428
	1.5	2.5203	9.965e-3	0.4867	-0.3841	0.6819	0.3324

Table 2. Optimized Optical and Geometrical Parameters at λ_0=1500, 1550 nm and three given Gaussian parameters

It is found that optimization method for precise tuning of the zero dispersion wavelengths as well as the small dispersion slope requires large value for the index of refraction difference (Δ). That is to say that providing large index of refraction is excellent for the simultaneous optimization of zero dispersion wavelength and dispersion slope. First, we consider the dispersion behavior of the structures. To demonstrate the capability of the proposed algorithm for the assumed data, the obtained dispersion characteristics of the structures are illustrated in Fig. 3. It shows that the zero dispersion wavelengths can be controlled precisely by controlling the central wavelength. Meanwhile, the Gaussian parameters are used to manipulate the dispersion slope of the profile. Considering Fig. 3 and Table 3, it is found that the zero value for the Gaussian parameter can tune the zero dispersion wavelengths accurately (~100 times better than other cases).

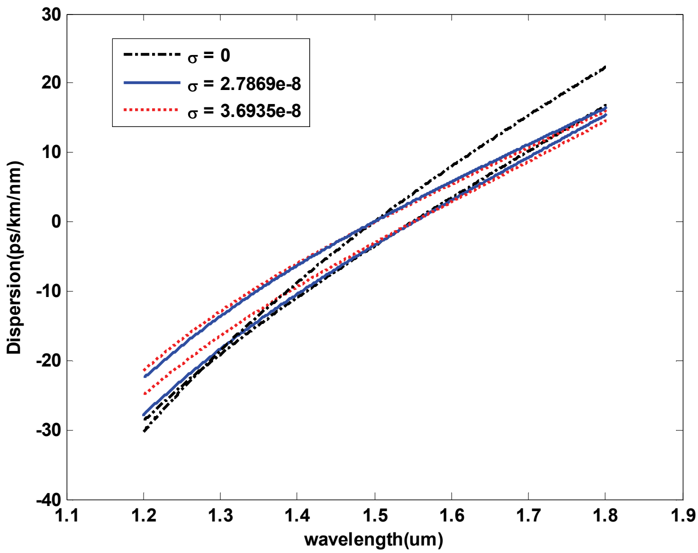

Fig. 3. Dispersion vs. Wavelength at λ0=1500nm, 1550nm with σ as parameter.

Second, the dispersion slope is examined. The presented curves say that by increasing the Gaussian parameter the dispersion slope becomes smaller, and it is going to be smooth in large wavelengths. Furthermore it is clear that there is a trade-off between tuning the zero dispersion wavelengths and decreasing the dispersion slope as shown in Figs. 3, 4, and Table 3.

type	$\lambda_0(\mu m)$	Dispersion $(ps/km/nm)$	Dispersion Slope $(ps/km/nm^2)$	Effective Area (μm^2)	Mode Field Diameter (μm)	Quality Factor
$\sigma = 0$	1.55	-2.57e-4	0.0695	191.92	7.95	3.04
	1.5	2.55e-5	0.0828	344.15	9.76	3.61
$\sigma = 2.7869 \times 10^{-8}$	1.55	-0.013	0.0647	194.79	7.12	3.85
	1.5	0.008	0.0597	209.95	6.70	4.68
$\sigma = 3.6935 \times 10^{-8}$	1.55	-0.085	0.0592	150.05	6.82	3.22
	1.5	-0.089	0.0564	164.21	6.55	3.82

Table 3. Dispersion, Dispersion Slope, Effective Area, Mode Field Diameter and Quality Factor at λ0=1500nm, 1550nm and three given Gaussian parameters

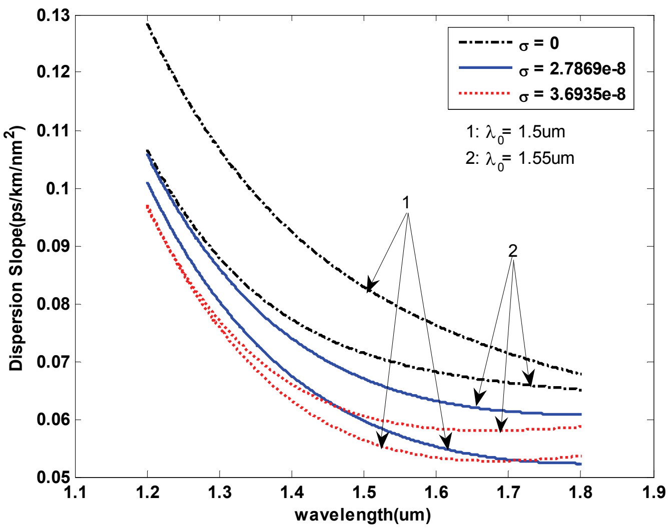

Fig. 4. Dispersion slope Vs. Wavelength at λ0=1500nm, 1550nm with σ as parameter.

The normalized field distribution of the MII based designed structures is illustrated in Figs. 5 and 6. Because of the special structure, the field distribution peak has fallen in region III. As such most of the field distribution displaces to the cladding region. In addition it is observed that the field distribution peak is shifted toward the core, and its tail is depressed in the cladding region by increasing the Gaussian parameter (except σ=0). On the other hand the field distribution slope increases inside the cladding region by increasing of the Gaussian parameter.

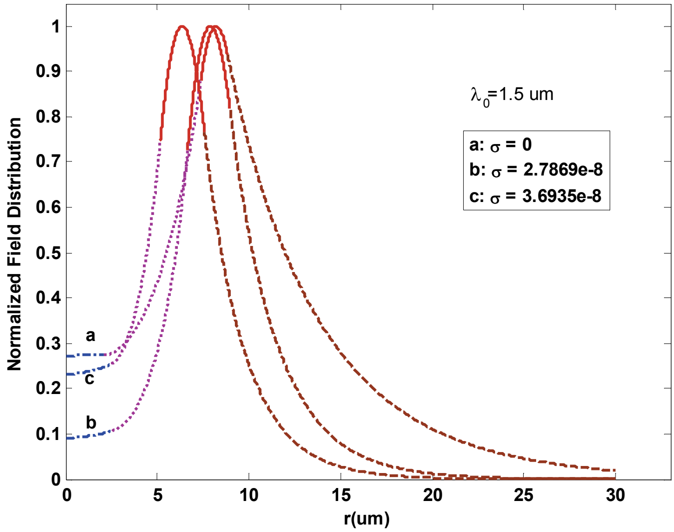

Fig. 5. Normalized Field distribution versus the radius of the fiber at λ_0=1500nm with σ as parameter (dashed-dotted, dotted, solid line, and dashed curves represent regions I, II, III and IV respectively).

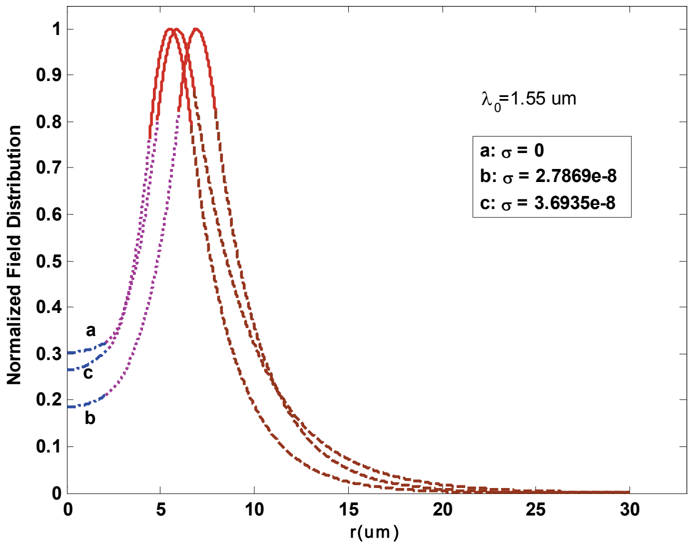

Fig. 6. Normalized Field distribution versus the radius of the fiber at λ_0=1550nm with σ as parameter (dashed-dotted, dotted, solid line, and dashed curves represent regions I, II, III and IV respectively).

The effective area or nonlinear behavior of the suggested structures is illustrated in Fig. 7. It is observed that the effective area becomes smaller by increasing the Gaussian parameter. Figs. 5–7, and Table 3 indicate a trade-off between the large effective area and the small dispersion slope. The results illustrated in Fig. 4 show that the dispersion slope reduces by increasing the Gaussian parameter. However the field distribution shifts toward the core, which concludes the small effective area in this case. Foregoing points show that there is an inherent trade-off between these two important quantities.

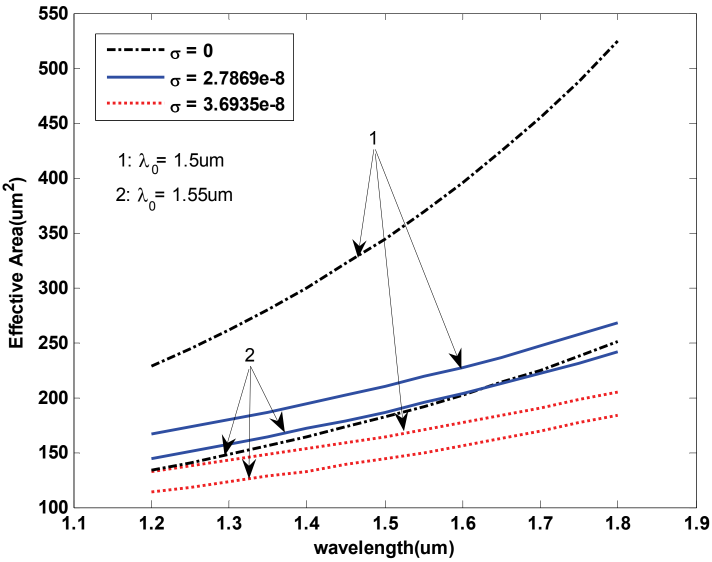

Fig. 7. Effective area versus wavelength at λ_0=1550nm, 1500nm with σ as the parameter.

The mode field diameter that corresponds to the bend loss is illustrated in Figs. 8 and 9 for both central wavelengths. It is clearly observed that the mode field diameter decreases by increasing the Gaussian parameter. In other words, the Gaussian parameter is suitable for the bend loss manipulation in these structures. Furthermore, Table 3 shows that the mode field diameter is ~7μm in the designed structure.

As another concept to consider, Table 3 says that the mode field diameter is not affected noticeably by increasing the effective area. This is the origin of raising the quality factor in these structures. This is a key point why the average amount of the quality factor in the proposed structures is increased in Fig. 9. The quality factor of the designed fibers is illustrated in Fig. 10. The calculations show that the quality factor is generally larger than 3. It is mentionable that the quality factor is smaller than unity in the inner depressed clad fibers (*W* structures) and around unity in the depressed core fibers (*R* structures). This feature shows the high quality of the putting forward methodology. It is observed that the quality factor decreases by increasing the Gaussian parameter. It is strongly related to the effective area reduction.

As another result the dispersion length is illustrated in Fig. 11 for the given Gaussian parameter and two central wavelengths. The narrow peaks at λ=1500nm and 1550nm imply the precise tuning of the zero dispersion wavelengths. The higher-order dispersion length of the designed fibers is demonstrated in Fig. 12. It is clear that the higher-order dispersion length increases by raising the Gaussian parameter.

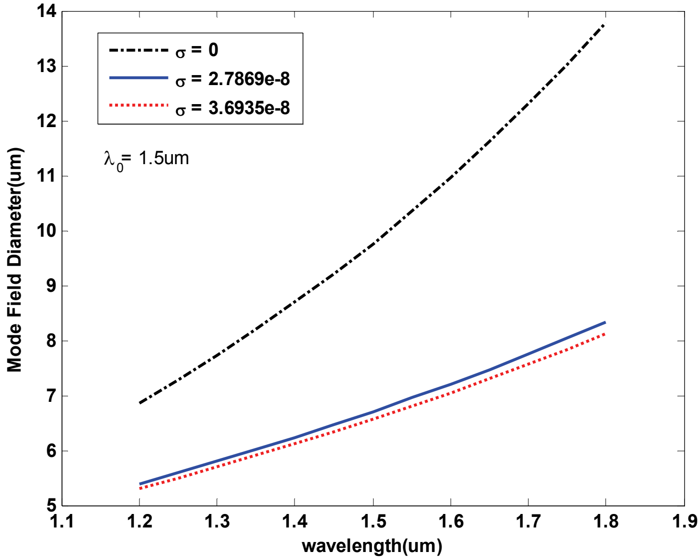

Fig. 8. Mode Field Diameter versus wavelength at λ_0=1500nm with σ as parameter.

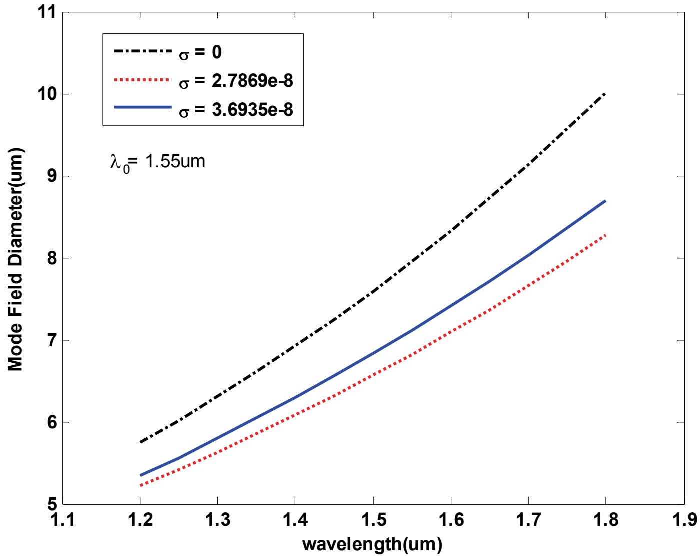

Fig. 9. Mode Field Diameter versus wavelength at λ_0=1550nm with σ as parameter.

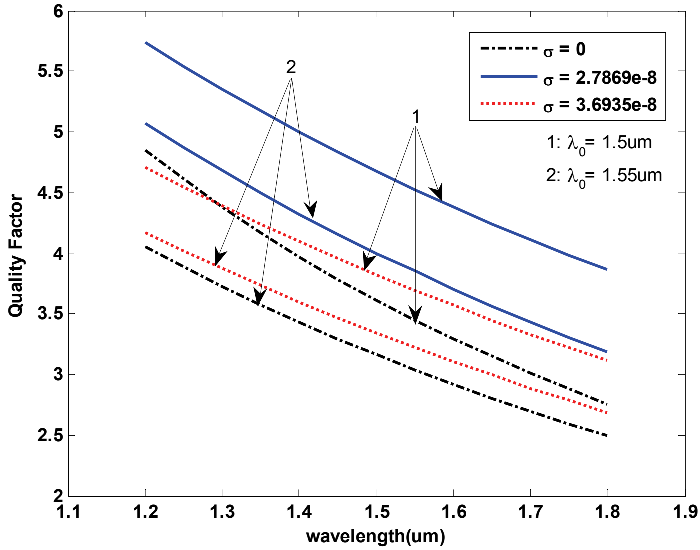

Fig. 10. Quality Factor versus wavelength at λ_0=1500nm, 1550nm with σ as parameter.

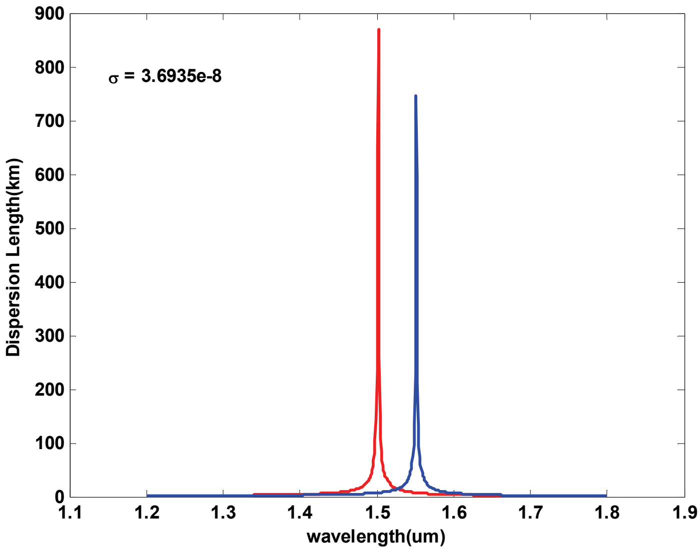

Fig. 11. Dispersion Length vs. Wavelength at $\lambda_0 = 1.5, 1.55\,\mu m$.

In the following, the nonlinear effect length for 1 mW input power is illustrated in Fig. 13. First, it can be extracted that the suggested structures have the high nonlinear effect length. For the general distances, these simulations show that the fiber input power can become some hundred times greater to have the nonlinear effect length comparable with the fiber dispersion length. Second, the nonlinear effect length decreases and increases, respectively, by raising the Gaussian parameter and wavelength.

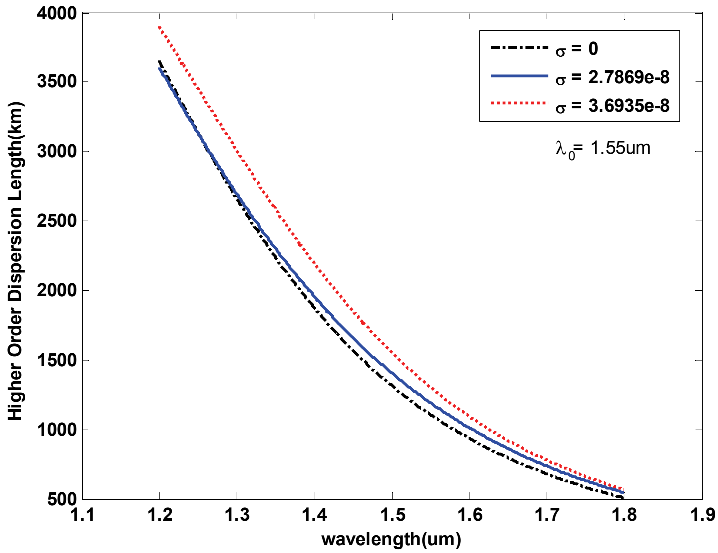

Fig. 12. Higher Order Dispersion Length vs. Wavelength at λ_0 =1.55 μm and Variance of the weight function as parameter.

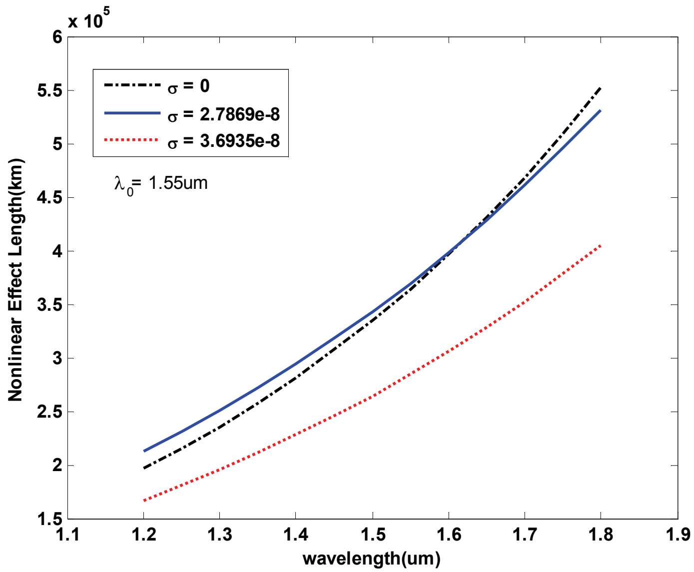

Fig. 13. Nonlinear Effective Length versus wavelength at λ_0=1550nm with σ as parameter.

The amount of the fiber bending loss strongly depends on the bend radius and the mode field diameter. Figures 14 and 15, respectively, illustrate the bending loss (dB/m) versus the bending radius (mm) at λ_0= 1550 nm and 1500nm with variance of the weighting function (σ) as a parameter. According to Figs. 8, 9, 14, and 15, it is clear that smaller mode field diameter yields to the greater tolerance to the bending loss.

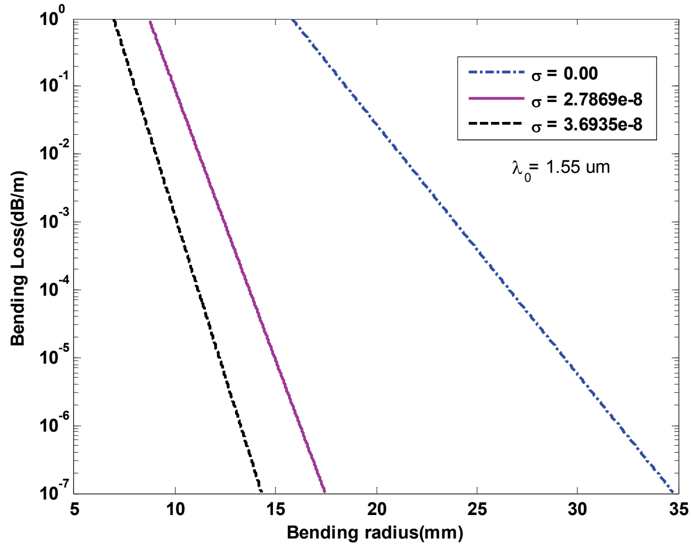

Fig. 14. Bending loss (dB/m) Vs. Bending radius at λ_0=1550nm with σ as parameter.

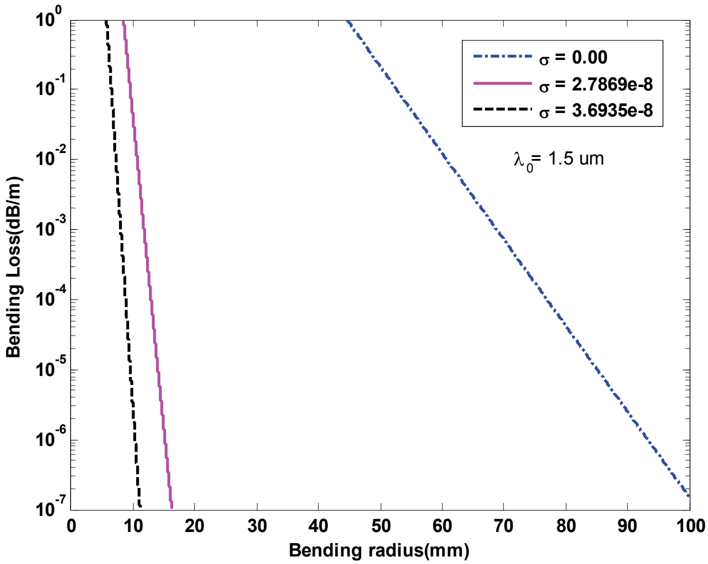

Fig. 15. Bending loss (dB/m) Vs. Bending radius at λ_0=1500nm with σ as parameter.

All of the presented outcomes show that the suggested idea has capability to introduce a fiber including higher performance. We have presented a novel method that includes the small dispersion, its slope, high effective area, and small mode field diameter simultaneously [24]. So all options required for the zero dispersion shifted communication system are achieved successfully. This advantage is obtained owing to the selection of the basic fiber structure as well as the method of optimization. Our selected fiber structure is the MII, and we use the weighted fitness function applied in the GA for optimization. By combining the suitable structure and the novel optimization method, all of the stated advantages can be gathered simultaneously. The features of the proposed method are capable of being extended to all of fiber structures, introduce two parameters instead of multi-designing parameters, and tune the zero dispersion wavelengths precisely.

The ring index profiles fibers have been closely paid attentions because it has the larger effective-areas that can minimize the harmful effects of fiber nonlinearity [29]. For the proposed MII fiber structures, the small dispersion and its slope have been obtained thanks to a design method based on genetic algorithm. But there is not any concentration on the bending loss characteristic at the design process. Here we want to enter bending loss effect on the fitness function directly and attempt to present an optimized RII triple-clad optical fiber to obtain the wondering performance from dispersion, its slope, and bending loss points of view. The index refraction profile of the RII fiber structure is shown in Fig. 16.

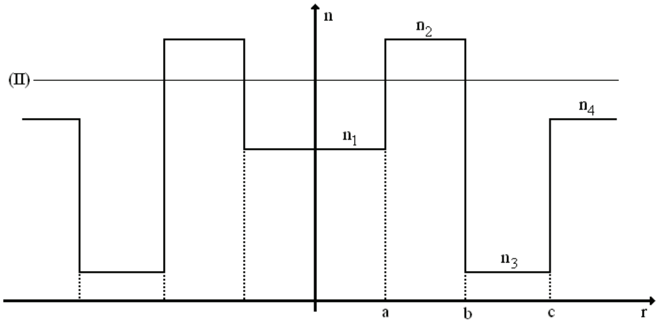

Fig. 16. Index of Refraction Profile for RII Structure

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

$$P = \frac{b}{c}\ ,\ Q = \frac{a}{c} \tag{7}$$

$$R_1 = \frac{n_2 - n_3}{n_2 - n_1},\quad R_2 = \frac{n_1 - n_4}{n_2 - n_1},\quad \Delta = \frac{n_2^2 - n_4^2}{2n_4^2} \approx \frac{n_2 - n_4}{n_4}. \tag{8}$$

The design method is based on the combination of the Genetic Algorithm (GA) and Coordinate Descent (CD) approaches. It is well known that the GA is the scatter-shot and the CD is the single-shot searching technique. The single-shot search is very quick compared to the scatter-shot type, but depends critically on the guessed initial parameter values. This description indicates that for the CD search, there is a considerable emphasis on the initial search position. In this method, it is possible to define a fitness function and evaluate every individuals of the population with it. So we have combined the CD and GA methods to improve the initial point selection with the help of generation elite and inherit the quick convergence of coordinate descent [30]. In other words, we cover and evaluate the answer zone by initial population and deriving few generations and use the elite of the latest generation as an initial search position in the CD (Fig. 17).

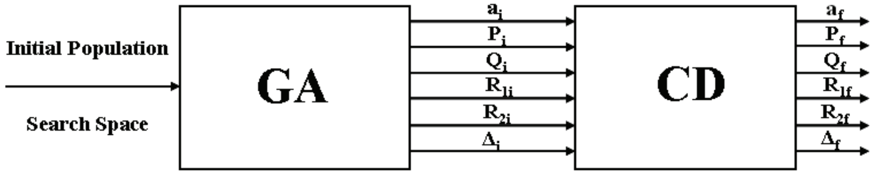

Fig. 17. The Block Diagram of The Proposed Method

To derive the suggested design methodology, the following weighted cost function is introduced. We have normalized the pulse broadening factor in the manner to be comparable with bending loss. This normalization is essential to optimize the pulse broadening factor and bending loss simultaneously. If not, the bending loss impact will be imperceptible and be lost in the broadening factor term.

$$F = \sum_{\lambda} e^{-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}} \left(\frac{1}{z} \sum_{Z} [(1+\frac{\beta_2(\lambda)Z}{t_i^2})^2 + (\frac{\beta_2(\lambda)Z}{t_i^2})^2 + (\frac{\beta_3(\lambda)Z}{2t_i^3})^2]^{\frac{1}{2}} \right) + BL(\lambda), \tag{9}$$

The bending radius is set on *1 cm* and kept still. The fitness function includes dispersion (β_2), dispersion slope (β_3), and bending loss (*BL*) impacts. In the defined weighted fitness function, internal summation is proposed to include optimum broadening factor for each length up to 200 km. as said at the beginning of this section, one can adjust the zero dispersion wavelength at λ_0 and dominate the dispersion slope by Gaussian parameter (σ). The obtained dispersion behaviors of the structures are illustrated in Fig. 18 which obviously demonstrates the λ_0 and σ parameters influences. It is clear that the zero-dispersion wavelength is successfully set on λ_0 and the dispersion curve is become flatter in the higher σ cases.

To show the capability of the proposed algorithm, Table 4 is presented to clarify the different characteristics of these three structures. By considering on Fig. 18 and Table 4, it is clear that there is a trade-off between the zero dispersion wavelength tuning and the dispersion slope decreasing. In other words, it is found out that the zero value for the σ parameter can tune the zero dispersion wavelength accurately (~100 times better than other cases).

The effective area or nonlinear behavior of the suggested structures is listed in Table 4. These values are high enough for the optical transmission applications. Owing to the special structure of the RII type fiber, the field distribution peak has fallen in the first cladding layer. As such most of the field distribution displaces to the cladding region. This is the origin of large effective area in the designed structures. The normalized field distribution of the RII based designed structures is illustrated in Fig. 19.