Progress In Electromagnetics Research C, Vol. 12, 79–92, 2010

MODIFIED W-TYPE SINGLE-MODE OPTICAL FIBER DESIGN WITH ULTRA-LOW, FLATTENED CHROMATIC DISPERSION AND ULTRA-HIGH EFFECTIVE AREA FOR HIGH BIT RATE LONG HAUL COMMUNICATIONS

A. Rostami and S. Makouei

Photonics and Nanocrystals Research Laboratory
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz 51664, Iran

Abstract—A proposal for the new modified W type optical fiber structure with ultra high effective area and small dispersion as well as dispersion slope is presented. For the proposed structure, all these features are achieved due to placing extra depressed cladding layers, which is the key to achieve higher effective area and flat dispersion curve compared with the conventional W structures. Meanwhile, the suggested design method is based on the Genetic Algorithm optimization technique to choose optimal value for the structural parameters. Also, our calculation for extracting optical properties of the proposed structure is evaluated analytically. The designed dispersion flattened single mode fiber has dispersion and its slope respectively within [0.1741–0.9282] ps/km/nm and [(−0.011)–(0.0035)] ps/km/nm^2 in the spectral range of [1.46–1.625] μm (S+C+L bands) which are noticeably smaller than the reported value for ultra-low dispersion slope fibers [5]. The designed fiber has ultrahigh effective area from 103.56 to 232.26 μm^2 in the above wavelength interval. Meanwhile, we show that there is a breakthrough in the quality factor of the ultra-low, ultra-flattened chromatic dispersion single mode optical fiber.

1. INTRODUCTION

In order to increase the information carrying capacity, the communication system based on the dense wavelength division

---

Corresponding author: A. Rostami (rostami@tabrizu.ac.ir).

multiplexing (DWDM) comes to existence. To realize this task, a proper media is essential. Silica fibers suffer from some disadvantages especially dispersion and its slope. The dispersion value of the conventional optical fibers grows by increasing the wavelength. So, different broadenings appear in sequence channels. Consequently, suitable optical fibers should meet the small dispersion as well as dispersion slope in the employed communication bands.

Nonlinear effect problems like cross phase modulation (XPM), which limits the number of different wavelength signals, can be solved by increasing effective area of the fiber. Thus, very high bit rate information transmission for long distances can be achieved using DWDM systems with fibers having high effective area as well as small dispersion and dispersion slope [1, 2].

To introduce optical fibers for high speed long haul communications, some fiber structures have been scrutinized, which fall in the categories of depressed index inner clad (W) and depressed index core (R) fiber structures [3–11]. It is noticeable that these optical fibers could have flat dispersion curve with sophisticated adjustments of the structural parameters. Excess investigation of the previous works show that the dispersion value, as well as the dispersion slope, of the W-based flattened fiber is small compared to the R-type ones [6, 8]. However, W structures have a high nonlinear coefficient due to the small effective area and cannot be employed for long distance and high optical power transmission. To overcome the drawback of the W structure, R fibers have been developed, with the expense of larger dispersion value. The effective area of these structures is higher than that of W cases. Through a suitable geometrical and optical parameters design in the R-based fibers, electrical field distribution is moved towards cladding region. Therefore, the high effective area can be achieved. As a consequence, it can be said that there is a trade-off between ultra-low dispersion as well as its slope and high effective area in the dispersion flattened optical fibers.

There are some interesting papers, which we are going to review and present their limitations for the proposed purposes.

An exhaustive and simple method for dispersion flattening in double-clad single mode W fiber is presented by Lundin [6]. The root mean square chromatic dispersion over the [1.25–1.60] μm wavelength range is minimized by one-dimensional minimization followed by direct inspection. It was found, as well known, that the W fiber is capable of dispersion flatting. The designed structure introduces 198 nm bandwidth in the [1.348–1.546] μm duration which just covers the S band completely. The maximum value of the dispersion met in above interval is 0.7779 ps/km/nm which is properly small. The effective area from 11.67 to 13.31 μm^2 in the spectral range of [1.46–1.625] μm is realized. It is obvious that the introduced designed structure is not proper for high speed long haul communication owing to almost small effective area.

A second work reported by Tian et al. [11] discusses about the effective area increasing for RI and RII triple-clad optical fibers. A dispersion flattened fiber design with the total dispersion of about 4.5 ps/km/nm, dispersion slope of below 0.006 $ps/km/nm^2$ and effective areas from 95 to 118 μm^2 in the spectral range of [1540–1620] nm is presented. The proposed design has small bandwidth for DWDM applications, and the dispersion value is not so small for high speed data transmission.

In the paper published by Varshney et al. [8], a flat optical fiber is presented to minimize dispersion and its slope. In this design, the effective area is 56.1 μm^2 at 1.55 μm. According to their calculations, the dispersion duration is [2.7–3.4] ps/km/nm within [1.53–1.61] μm interval, and the dispersion slope is 0.01 $ps/km/nm^2$ at 1.55 μm wavelength. This paper introduces acceptable value for the effective area, but the dispersion value is very large to comply with DWDM operation.

Recently, Rostami et al. [12] have stabilized the analytical approach to calculate dispersion and its slope. Due to analytically based relationships, this approach accurately covers all the numerical method presented so far. For a case study, the given analytical method is used to analyze the M-type fiber structure.

In [13], for the proposed zero-dispersion shifted structure, small dispersion and dispersion slope are obtained due to a novel design method based on a weighted fitness function, which is applied to the genetic algorithm optimization technique. In the meantime, the foregoing structure introduces a special fiber whose mode field diameter is small and approximately insensitive to the effective area variation.

It is well known that a small pulse broadening factor (small dispersion and dispersion slope) and small nonlinearity are required for high speed long haul communications. But a thorough investigation of the previous works shows that gathering these features together is an open task. In this paper, we attempt to present a dispersion flattened optical fiber to obtain the wondering performance from dispersion, its slope, and nonlinearity points of view. In order to have a breakthrough in this field, the W type optical fiber structure is modified to express the low nonlinearity and small pulse broadening simultaneously. For improving the transmission quality of the optical fiber capable in the desired employment, we stabilize the new modified W-based fiber structure with extra depressed cladding layers, which is the key point to achieve higher effective area and flat dispersion curve compared with the conventional W-type structures. Our proposal of the modified W-based structure has inherited the conventional W-type dispersion flatness and R-type effective area largeness coincidentally. Meanwhile, we use a design method based on the Genetic Algorithm optimization technique to choose optimal value for the structural parameters [14]. The profile is analyzed using the weakly guiding approximation (LP). This approximation is justified by the fact that all materials used in the fiber fabrication have small refractive index difference [15–20]. Meanwhile, the dispersion and its slope are computed using the analytical approach presented in [12].

The paper is organized as follows.

The modal and dispersion analysis based on LP approximation method are presented in Section 2. Section 3 includes the structural and design principles. In this section, we introduce the optimization technique and give design guidelines for achieving the desired performance. Simulation results will be discussed for validating our suggested process in Section 4. Finally, the paper ends with a short conclusion.

2. MODAL AND DISPERSION ANALYSIS

The modal analysis based on the LP approximation is presented in this section for the proposed structure illustrated in Fig. 1. The philosophy of the suggested structure will be clarified in the next section. For this structure the refractive index is defined as follows.

$$n\left(r\right)=\begin{cases} n_1, & 0<r<a \\ n_2, & a<r<b \\ n_{3,} & b<r<c \\ n_4, & c<r<d \\ n_5, & d<r<e \\ n_6, & e<r \end{cases} \tag{1}$$

where r is the radius position.

According to the LP approximation [15, 16] to calculate the electrical field distribution, there are three regions of operation, and the guided modes and propagating wave vectors can be obtained by using three determinants which are constructed by boundary conditions [17–20]. The three lines drawn in Fig. 1 demonstrate these operation regions. The effective refractive index is given by:

$$n_{\mathit{eff}}=\frac{\beta_g}{k_0}, \tag{2}$$

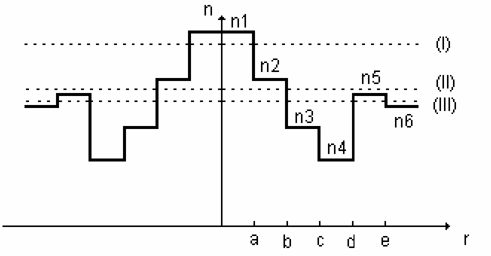

Figure 1. The refractive index profile of the proposed structure.

where β_g is the longitudinal propagation constant of the guided modes, and k_0 is the wave number in vacuum. Also, for easy handling of the problem and identifying the proposed fiber, following optical parameters are defined.

$$\begin{aligned}&\Delta_1=\frac{n_1^2-n_4^2}{2n_4^2}\approx\frac{n_1-n_4}{n_4},\quad \Delta_2=\frac{n_6^2-n_4^2}{2n_4^2}\approx\frac{n_6-n_4}{n_4},\\&n_2=n_5+\alpha\left(n_1-n_5\right),\quad n_5=n_6+\eta\left(n_2-n_6\right),\\&n_3=n_4+\mu\left(n_6-n_4\right)\end{aligned}\tag{3}$$

The Δ_1, Δ_2 are used to express the level of core and cladding-depressed layer refractive indexes respect to the outer one. If you hesitate, you will simply find that $\Delta_1>\Delta_2$. In order to explain other layers, the α, μ, η coefficients have been set between 0 and 1. It must be declared that the cladding layers thicknesses are equal to the core radius.

By solving Maxwell's equations, the electrical field in the suggested fiber is calculated and given in Table 1. $e^{j\beta_g z}$ is abbreviated for brevity.

The regions given in the table first row are the domains labeled (I), (II), and (III) in Fig. 1. A_i and B_i $(i=1,2,3,4,5,6)$ are constant and computed by applying the electric and magnetic field continuities to the boundaries. J_v, Y_v, I_v, and K_v are Bessel and modified Bessel functions of the order v respectively. It should be kept in mind that A_6 is set to zero due to I_v divergence when r tends to infinity. The γ_i and κ_i are the transversal propagating constants and defined as follows:

$$\gamma_i=\left(\beta_g^2-n_i^2k_0^2\right)^{\frac{1}{2}},\quad \kappa_i=\left(n_i^2k_0^2-\beta_g^2\right)^{\frac{1}{2}}\quad (i=1,2,3,4,5,6)\tag{4}$$

The propagation constant varies with wavelength, thus the group velocity depends on wavelength too and, consequently, different spectral components of the signal will travel with different group velocities. This phenomenon is called chromatic dispersion and given

Table 1. Waveguide solutions of the structure for the different regions with respect to the effective refractive index.

Region	(I) $n_2 < n_{eff} < n_1$	(II) $n_5 < n_{eff} < n_2$	(III) $n_6 < n_{eff} < n_5$
$0 < r < a$	$A_1 J_v(\kappa_1 r)$	$A_1 J_v(\kappa_1 r)$	$A_1 J_v(\kappa_1 r)$
$a < r < b$	$A_2 I_v(\gamma_2 r)$ $+ B_2 K_v(\gamma_2 r)$	$A_2 J_v(\kappa_2 r)$ $+ B_2 Y_v(\kappa_2 r)$	$A_2 J_v(\kappa_2 r)$ $+ B_2 Y_v(\kappa_2 r)$
$b < r < c$	$A_3 I_v(\gamma_3 r)$ $+B_3 K_v(\gamma_3 r)$	$A_3 I_v(\gamma_3 r)$ $+B_3 K_v(\gamma_3 r)$	$A_3 I_v(\gamma_3 r)$ $+B_3 K_v(\gamma_3 r)$
$c < r < d$	$A_4 I_v(\gamma_4 r)$ $+B_4 K_v(\gamma_4 r)$	$A_4 I_v(\gamma_4 r)$ $+B_4 K_v(\gamma_4 r)$	$A_4 I_v(\gamma_4 r)$ $+B_4 K_v(\gamma_4 r)$
$d < r < e$	$A_5 I_v(\gamma_5 r)$ $+B_5 K_v(\gamma_5 r)$	$A_5 I_v(\gamma_5 r)$ $+B_5 K_v(\gamma_5 r)$	$A_5 J_v(\kappa_5 r)$ $+B_5 Y_v(\kappa_5 r)$
$e < r$	$B_6 K_v(\gamma_6 r)$	$B_6 K_v(\gamma_6 r)$	$B_6 K_v(\gamma_6 r)$

by [2]:

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} + D_m \tag{5}$$

where c is the speed of light in a vacuum, and n_{eff} is the effective refractive index of the fundamental mode. D_m is the material dispersion and calculated from the Sellmeier relation [2]. It should be mentioned that the derivative of n_{eff} is computed analytically and uses the approach which has been outlined by Rostami et al. in [12].

The effective area is a property of optical fibers that appear when the nonlinear Schrodinger equation is derived [2]. Intuitively, the power divided by the effective area is a measure of power density inside the fiber. The larger is the effective area, the lower is the power density inside a fiber. Fiber nonlinearities strongly depend on the power density inside a fiber, thus an increase in the effective area results in a decrease in fiber nonlinearities and their effects on signal transmission. The effective area (A_{eff}) is defined as [2]:

$$A_{eff} = 2\pi \frac{\left[\int\limits_0^\infty |\psi(r)|^2 r dr\right]^2}{\int\limits_0^\infty |\psi(r)|^4 r dr}, \tag{6}$$

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

3. STRUCTURAL AND DESIGN PRINCIPLES

As said in the introduction, we attempt to present a dispersion flattened optical fiber to obtain the wondering performance from dispersion, its slope, and nonlinearity points of view. A small pulse broadening factor (small dispersion and dispersion slope) and small nonlinearity are required for high speed long haul communications. But gathering these features together was an open task. In order to have a breakthrough in this field, the W type optical fiber structure is modified to express the low nonlinearity and small pulse broadening simultaneously. For improving the transmission quality of the optical fiber capable in the desired employment, we stabilize the new modified W-fiber structure with extra depressed cladding layers, which is the key point to achieve larger effective area and flat dispersion curve compared with the conventional W structures. Due to pseudo Gaussian shape of the field distribution, acceptable value of the splice loss during splicing of the proposed fiber structure with the conventional single mode fiber (SMF) can be anticipated. The small dispersion, as well as its slope, and the large effective area are the main advantages of the putting forward structure, making it an ideal candidate for performing in high bit rate long haul communications.

The design method is based on the Genetic Algorithm to optimize the pulse broadening factor in the predefined wavelength duration. Eq. (7) shows our proposal for the fitness function of the pulse broadening factor.

$$\begin{aligned} F_{BF} = \sum_{\lambda}\sum_{Z}\Bigg[&\left(1+\frac{C\beta_2(\lambda)Z}{t_i^2}\right)^2 \\ &+\left(\frac{\beta_2(\lambda)Z}{t_i^2}\right)^2+\left(1+C^2\right)^2\left(\frac{\beta_3(\lambda)Z}{2t_i^3}\right)^2\Bigg]^{\frac{1}{2}}, \end{aligned} \tag{7}$$

where F_{BF}, C, β_2, t_i, λ, Z, and β_3 are broadening factor, chirp parameter, the second derivative of the guided wave vector, initial full width at half maximum of input pulse, wavelength, distance, and the third derivative of the guided wave vector respectively. According to GA technique, the problem would have some genes, which explain those parameters. It is remarkable that the initial range of parameters is chosen after some conceptual investigations. Initial population has fifty chromosomes, which cover search space approximately. By applying the proposed fitness function, the dispersion and dispersion slope are minimized simultaneously. The wavelength and distance durations for optimization are $1.45\,\mu\text{m} < \lambda < 1.65\,\mu\text{m}$ and $0 < Z < 200\,\text{km}$. In other words, the pulse broadening factor is minimized in wavelength range larger than the S+C+L communication bands. In the simulations, an unchirped initial pulse with 5 ps as full width at half maximum is used.

To illustrate ability of the presented technique and suggested cost function, the foregoing optical fiber structure is investigated, and simulated results are demonstrated in the next section.

4. RESULTS AND DISCUSSION

Based to the presented formalism and structure in previous sections, in this part the simulation results are illustrated to evaluate the design methodology. In order to evaluate the efficiency of the designed structure, propagation characteristics are compared with the dispersion flattened optical fiber reported in [8]. Considering the parameter presented in Section 2 and GA method, optimal parameters are extracted and demonstrated in Table 2. It is found that small pulse broadening factor in the predefined wavelengths requires small values for the index of refraction differences (Δ_1, Δ_2). By concentrating on the results presented in Table 2, it is obvious that due to the small refractive index difference between materials used in the fiber fabrication, the LP approximation is sufficiently accurate for estimating modal indexes in the designed structure.

By applying the fitness function, the broadening factor is minimized in the [1.45–1.65] µm interval, and the bandwidth of dispersion curve is maximized. It is useful to note that the wavelengths duration between two zero dispersion wavelengths is labeled as a bandwidth in this paper. It is clear that the proper applicable bandwidth must have small dispersion and dispersion slope in the S+C+L interval. First we consider the dispersion and its slope behaviors of the designed modified W-based structure. From Fig. 2, it is clear that the suggestion of the modified W structure to achieve dispersion flattened profile in the communication bands is successful. By a brief glance, we can say that the dispersion curve of the designed structure is flatter, and its value is comparably lower than the structure reported by Varshney et al. [8]. Maximum value of the dispersion at the [1.39–1.64] µm duration is 0.928 ps/km/nm. It is useful to mention that the zero dispersion wavelengths have set at 1.395 µm and 1.595 µm.

Table 2. Design parameters and characteristics for the.

Core radius	Δ_1	Δ_2	α	η	μ
*2.1691 µm	4.430×10^{-3}	2.479×10^{-3}	0.8262	0.7198	0.5727

$*b = 2a,\ c = 3a,\ d = 4a,\ e = 5a$

In the meantime, the value of the dispersion is 0.3317 ps/km/nm at 1.55 μm which is properly small. According to the illustrated curves in Fig. 2, the bandwidth of the designed structure is 200 nm within the wavelength duration of [1.395–1.595] μm, whereas this quantity is 355 nm for [8] within [1.40–1.755] μm duration. Both structures cover the S+C+L bands completely, but in [8] case, the dispersion value is large for the efficient communication.

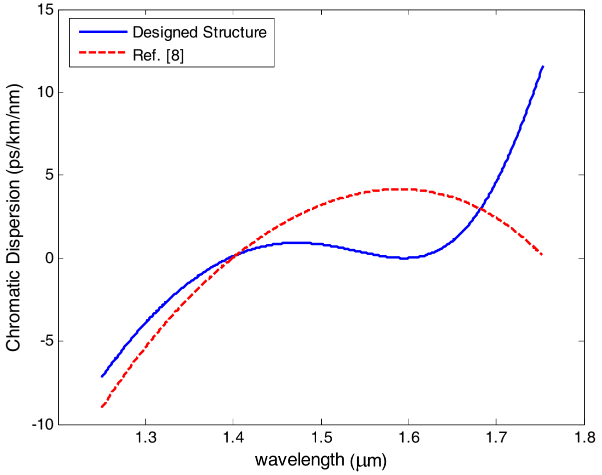

Figure 2. Chromatic dispersion (ps/km/nm) vs. wavelength (μm).

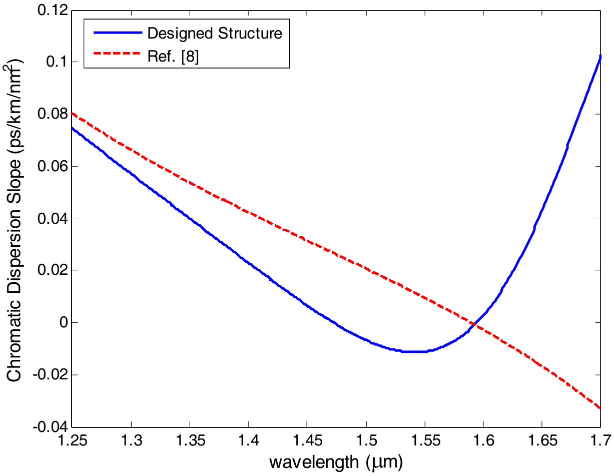

Figure 3. Chromatic dispersion slope (ps/km/nm^2) vs. wavelength (μm).

The dispersion slope of the designed structure is demonstrated in Fig. 3. It is evident that absolute of the dispersion slope value is smaller compared to the [8] structure, in almost all S+C+L communication bands. This figure clearly proves ultra flatness behavior of the modified W structure. It is well known that the small pulse broadening factor realizes with the small dispersion as well as dispersion slope simultaneously.

With precise investigation, extra information about the dispersion and its slope behavior can be extracted. The approximate average amount of the dispersion and its slope in S+C+L bands are listed in Table 3.

It is evident that not only the dispersion values are small, but also its variations are negligible In other words, the dispersion curve of the designed W-based fiber structure is properly smooth, flat, and almost zero in the communication bands.

For more illumination, these characteristics of the dispersion flattened fiber reported in [8] are listed in Table 4. It must be taken into account that [8] is the R-based structure.

Table 3. Average amount of dispersion and its slope of the designed structure in S, C and L bands.

Band	S [1.46–1.53] µm	C [1.53–1.565] µm	L [1.565–1.625] µm
Average dispersion (ps/km/nm)	0.8179	0.3621	0.0832
Average slope (ps/km/nm^2)	−0.0057	−0.0109	0.0073

Table 4. Average amount of dispersion and its slope of the Ref. [8] structure in S, C and L bands.

Band	S [1.46–1.53] µm	C [1.53–1.565] µm	L [1.565–1.625] µm
Average dispersion (ps/km/nm)	3.0464	3.9255	4.1133
Average slope (ps/km/nm^2)	0.0217	0.0106	0.0041

The nonlinear effects in a single mode fiber are the ultimate restricting factors for bit rate and distance in long haul optical fiber communication system. Therefore, the large effective area single mode fibers have been the subject of considerable studies recently [13, 21]. The effective area or nonlinear behavior of the suggested structure is illustrated in Fig. 4 and compared with [8]. From this figure, it is observed that there is a perceptible improvement in the dispersion flattened optical fiber domain. In other words, the ultra small dispersion, as well as dispersion slope, and ultra large effective area are achieved simultaneously, and our proposal about new fiber structure profile works truly. We can say that our proposal of the modified W-based structure has inherited the conventional W-type dispersion flatness and R-type effective area largeness coincidentally. According to the simulation outcomes, the effective area at 1.55 μm is 146.89 μm^2 which is remarkable in the dispersion flattened fiber situations. We would like to mention that the obtained effective area is nearly three times larger than the recently reported value (56.1 μm^2) for the ultra-low dispersion fibers [8]. The effective area from 103.56 to 232.26 μm^2 in the spectral range of [1.46–1.625] μm is realized.

Larger effective areas, however, are generally associated with larger mode field diameters which, in turn, imply higher bending losses. This loss, however, is not serious if the bending radius is sufficiently larger than a critical radius. It is now clear that a satisfactory design should maintain a balance between the effective area and the mode field diameter. A quality factor, defined as the ratio of effective area over

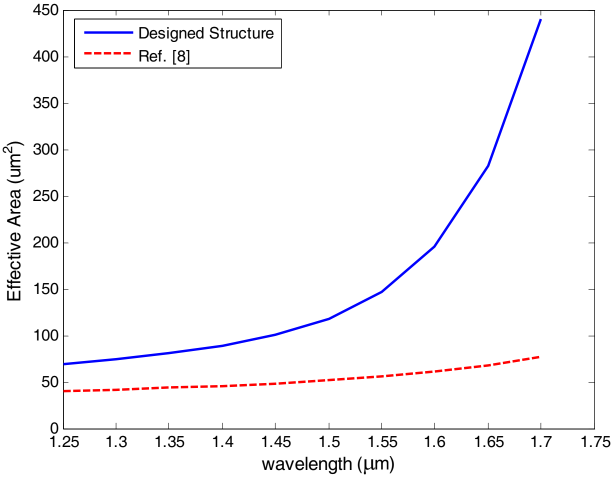

Figure 4. Effective area (μm^2) vs. wavelength (μm).

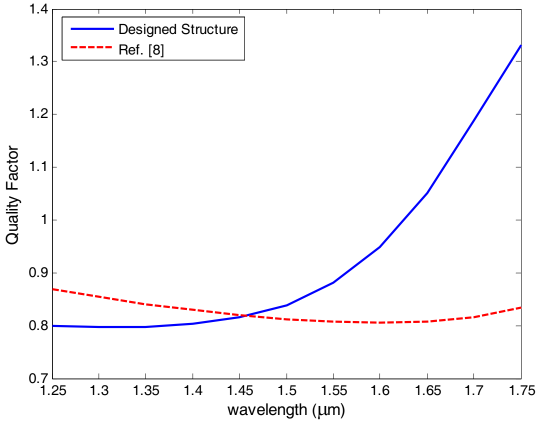

Figure 5. Quality factor vs. wavelength (μm).

the square of mode field diameter, is introduced as a means of assessing and comparing the overall performance of different large effective area fibers [2]. This factor is a dimensionless quantity that can be used to determine the trade-off between mode field diameter and effective area. So, the fiber that provides the largest quality factor is the best design. The quality factor of the designed fiber is illustrated in Fig. 5. The calculations show that the quality factor of the designed structure is larger than the [8] profile in S+C+L bands. It is mentionable that the quality factor is smaller than unity in the inner depressed clad fibers (W) and around unity in the depressed core fibers (R). In other words, the W structures has smaller quality factor than R ones. But from Fig. 5, it is clear that there is a progress in modified W structure in the manner that its quality factor is larger than the R-based designed structure reported so far. The modified W-based designed fiber has suitable quality factor within [0.8187–0.9957] range in the [1.46–1.625] μm wavelength interval.

In this paper, with sophisticated modification on W-type optical fiber and introduction of a new fiber structure, the fiber design with ultra-low dispersion and its slope and ultra-high effective area is presented. These features make it an ideal candidate for high bit rate long haul and high power transmission applications.

5. CONCLUSION

A proposal for the new modified W type optical fiber structure with ultrahigh effective area and small dispersion as well as dispersion slope is presented. For the proposed structure, all these features are achieved by stabilizing the new modified W-based fiber structure with extra depressed cladding layers, which is the key point to achieve higher effective area and flat dispersion curve coincidentally compared with the conventional W structures. We can say that our proposal of the modified W-based structure has inherited the conventional W-type dispersion flatness and R-type effective area largeness simultaneously. In the meantime, the Genetic Algorithm optimization technique is used to extract the optimal value for structural parameters. Our calculation for extracting optical properties of the proposed structure is done analytically. The designed dispersion flattened single mode fiber has dispersion and its slope respectively within [0.1741–0.9282] ps/km/nm and [(−0.011)–(0.0035)] ps/km/nm^2 in the spectral range of [1.46–1.625] μm, which are smaller than the reported value for ultra low dispersion slope fibers [8]. The designed fiber has ultrahigh effective area within [103.56–232.26] μm^2 in the above wavelength interval. Also, the designed fiber has suitable quality factor from 0.8187 to 0.9957 within the S+C+L wavelength interval.

REFERENCES

1. Hatayama, H., T. Kato, M. Onishi, E. Saasoka, and M. Nishimura, "Dispersion flattened fiber with effective core area more than 50 μm^2," *Proc. of OFC'98, ThK4*, 304, 1998.
2. Agrawal, G. P., *Nonlinear Fiber-optics*, 3rd edition, University of New York, Rochester, 2001.
3. Zhang, X. and X. Tian, "Analysis of waveguide dispersion characteristics of WI- and WII-type triple-clad single-mode fibers," *Optics & Laser Technology*, Vol. 35, 237–244, 2003.
4. Zhang, X. and X. Wang, "The study of chromatic dispersion and chromatic dispersion slope of WI- and WII-type triple-clad single-mode fibers," *Optics & Laser Technology*, Vol. 37, 167–172, 2005.
5. Zhang, X., L. Xie, X. Tian, and S. Hou, "Chirped Gaussian pulse broadening induced by chromatic dispersion in the triple-clad single-mode fiber with a depressed index inner cladding," *Optical Fiber Technology*, Vol. 10, 215–231, 2004.
6. Lundin, R., "Dispersion flattening in W fiber," *Applied Optics*, Vol. 33, 1011–1014, 1994.
7. Jie, L., Q. Qinan, and Y. Peida, "The relation between the dispersion characteristic of W-profile broad band dispersion compensation fiber and its structural parameters," *Optics Communication*, Vol. 21, 90–93, 2000.
8. Varshney, R. K., A. K. Ghatak, I. C. Goyal, and S. Antony C,

"Design of a flat field fiber with very small dispersion slope," *Optical Fiber Technology*, Vol. 9, 189–198, 2003.

9. Kumano, N., K. Mukasa, M. Sakano, H. Moridaira, T. Yagi, and K. Kokura, "Novel NZ-DSF with ultra low dispersion slope lower than 0.02 ps/km/nm^2," *Proceeding of ECOC. PDA*, 1–5, 2001.
10. Hussey, L., "Triple-clad single-mode fibers for dispersion flattening," *Optics Engineering*, Vol. 33, 3999–4005, 1994.
11. Tian, X. and X. Zhang, "Dispersion-flattened designs of the large effective area single-mode fibers with ring index profiles," *Optics Communication*, Vol. 230, 105–113, 2004.
12. Rostami, A. and M. Savadi, "Investigation of dispersion characteristic in MI- and MII-type single mode optical fibers," *Optics Communication*, Vol. 271, 413–420, 2007.
13. Oskoui, M. S., S. Makouei, A. Rostami, and Z. D. K. Kanani, "Proposal for optical fiber designs with ultrahigh effective area and small bending loss applicable to long haul communications," *Applied Optics*, Vol. 46, 6330–6339, 2007.
14. Spears, W. M., K. A. De Jong, T. Baeck, and P. Bradzil, "An overview of evolutionary computation," *Proceedings of European Conference on Machine Learning*, Vol. 667, 442–459, Springer-Verlag, Berlin, 1993.
15. Hautakorpi, M. and M. Kaivola, "Modal analysis of M-type-dielectric-profile optical fibers in the weakly guiding approximation, " *J. Opt. Soc. Am. A*, Vol. 22. 1163–1169, 2005.
16. Gloge, D., "Weakly guiding fibers," *Applied Optics*, Vol. 10, No. 10, 2252–2258, 1971.
17. Monerie, M., "Propagation in doubly clad single-mode fibers," *IEEE Journal of Quantum Electronics*, Vol. 18, No. 4, 535–542, 1982.
18. Nunes, F. D., C. A. D. S. Melo, and H. F. D. S. Filho, "Theoretical study of coaxial fibers," *Applied Optics*, Vol. 35, No. 3, 388–399, 1996.
19. Snyder, A. W. and J. D. Love, *Optical Waveguide Theory*, Chappman and Hall, 1983.
20. Kawano, K. and T. Kitoh, *Introduction to Optical Waveguide Analysis*, John Wiley & Sons, Inc., 2001.
21. Hattori, H. T. and A. Safaai-Jazi, "Fiber designs with significantly reduced nonlinearity for very long distance transmission," *Applied Optics*, Vol. 37, 3190–3197, 1998.