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A New Design of High Negative Dispersion Optical Fiber with -951ps/ (nm.km) at 1550nm

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Abstract

In this paper, a new design of high negative dispersion optical fiber is introduced. The generalized analysis of multiple-clad cylindrical dielectric structures with step index profiles is presented. The design is focused on quadrature-clad fibers. The optical fiber with step-index but certain profile is tested.

By using simulation program, the optical fiber with high negative dispersion was designed and tested. A very high negative dispersion (up to -951ps/nm/km) is obtained due to a design optical fiber with quadrature-clad at wavelength of 1550nm. Each of fiber profile and the relation between the dispersion and wavelength are plotted. The computer simulations show that an optimally designed negative dispersion fiber can reduce the dispersion of standard fiber when it is added with the existing standard fiber in a ratio of 50:1.

تصميم ليف بصري جديد ذات تشتت سلبي عالي بمقدار [-951ps/(nm. Km)] عند 1550nm

الخلاصة

في هذا البحث قد تم تصميم جديد لليف بصري ذات تشتت سلبي عالي وتقديم تحليل عام للتركيب عازل الاسطواني متعدد الكساء ذات معامل خطوي للمظهر جانبي وذلك من خلال فحص الليف البصري ذات معامل انكسار خطوي حيث ركز الفحص على ألياف رباعية الكساء.

تم الحصول على تشتت سلبي بمقدار [-951ps/(nm. km)] عند طول موجي مقداره 1550nm. كل من المظهر الجانبي لليف البصري و شكل العلاقة بين التشتت والطول ألموجي قد رسمت وفقا لمحاكاة الحاسبة والتي تبين بان تصميم المثالي لليف البصري ذا تشتت سلبي يستطيع أن يعوض تشتت الليف المعياري عندما يُضاف مع الليف المعياري الموجود بنسبة 50:1.

1. Introduction

The chromatic dispersion in single-mode transmission fibers represents one of the most important performance limitations in today's transmission systems, resulting in a reduced maximum transmission distance and a poor quality of transmitted signals. Another dispersion limitation is the dispersion slope which represents an issue in WDM systems with a large number of channels, resulting in different accumulated dispersion values per channel [1, 2].

in order to realize high data rates over long distances with already installed standard single mode fiber, techniques must be found to overcome the pulse spreading due to the positive chromatic dispersion of the transmission fiber. Several solutions to this problem have been suggested and can be classified as either an active compensation technique that involves time-dependent manipulation of some aspect of the light pulse, or as passive

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compensation techniques which relies on time independent properties of an optical element [3]. Unlike dispersion-shifted and dispersion-flattened fibers which are desired to have very small dispersion at $\lambda = 1.55\mu m$, dispersion compensating fibers are designed to provide negative dispersion at this wavelength.

This paper deal with a new design of dispersion compensating fibers with quadrature-clad fiber to obtain an very high negative dispersion. Section 2 explains the types of dispersion in optical fiber. In section 3, details of negative dispersion fiber design is explained. Section 4 deals with program results of dispersion compensating fibers. The summary of paper and present conclusion discuss in section 5.

2. Dispersion in optical fiber

Dispersion in optical fiber is an intremodel effect and it is result of group velocity dependence on wavelength. The spectral width of optical source usually is limited the amount of signal distortion. There are two distinct causes for wavelength dispersion in travel time in a single mode fiber; these are respectively the material dispersion (D_M) and waveguide dispersion (D_W), which is inherent in the waveguide geometry.

The total dispersion factor, D in the unit of ps/km.nm of a single optical fiber is given by:

$$D = D_M + D_W \qquad (1)$$

Material dispersion is caused by variations of refractive index of the fiber material with respect to wavelength. Variations of refractive index with respect to wavelength are described by the Sellmeier equation, which is expressed as follows [4]:

$$(n(l))^{1/2} = 1 + \sum_{i=1}^{3} \frac{a_i l^2}{l^2 - l_i^2} \qquad (2)$$

Where λ_i is the resonance wavelength and a_i is the oscillator strength. Here n(λ) represent refractive index depending on the dispersive properties of which layer is considered. These constants have been tabulated for several kinds of fibers in Table 1. The material dispersion factor, D_M is given by:

$$D_M = -\frac{l}{c}\left(\frac{d^2 n(l)}{dl^2}\right) \qquad (3)$$

The waveguide dispersion occurs because single-mode fiber only confines about 80 percent of the optical power to the core. Dispersion thus arises, since the 20 percent of the light propagating in the cladding travels faster than the light confined to the core. The amount of waveguide dispersion depends on the fiber design, since the modal propagation constant β is a function of the optical fiber dimension relative to the wavelength [4].

$$b_1 = n_2 k\left(b\frac{n_1 - n_2}{2} + 1\right) \qquad (4)$$

Where $k = 2p / l$ is the free space wave number and b is the normalized propagation constant, which is given by[5]:

$$b = \frac{2pb}{l}$$

The modal propagation constant β is generally given in term of the normalized frequency (V), therefore;

$$V = kr\sqrt{n_1^2 - n_2^2} \cong krn_1\sqrt{2D} \qquad (5)$$

The contribution of D_W to the total dispersion parameter D, is given by (5) depends on the V parameter of the fiber and is given by [6]:

$$Dw = -\left(\frac{n_1 - n_2}{l_c}\right)V\frac{d^2(Vb)}{dV^2} \qquad (6)$$

where V is the normalized frequency. The factor d(Vb)/dV can be expressed as[7]:

$$\frac{d(Vb)}{dV} = b\left[1 - \frac{2J_v(ur)}{J_{v+1}(ur)J_{v-1}(ur)}\right] \qquad (7)$$

and,

$$u = r\cdot\sqrt{k^2n^2 - b^2} \qquad (8)$$

Where J_v , are the Bessel functions of the first kinds, while K_v is the modified Bessel functions. In the central layer, i.e. in the core region, K(ur) must be discarded, because these function is undefined at $r = 0$. In the outer cladding layer, $r \geq r_4$, the field of guided modes must decay exponentially in the radial direction. The K(ur) function maintains this behavior only.

The choice of Bessel or modified Bessel functions in all but the outer layer region is determined by the sign of $(u/r)^2$. The sign of $(u/r)^2$ is determined by realizing that for guided modes $kn_5 < \beta < kn_{max}$, where n_{max} is the highest index in the profile. For example, for the profile in Fig.(2) with $n_{3,5} < n_1 < n_{2,4}$, fields in the core ($0 \leq r \leq r1$) involve only the $J_v(ur)$ function, while fields in the first inner cladding ($r_1 \leq r \leq r_2$) involve J_v function. However, in the second cladding region ($r_2 \leq r \leq r_3$) fields involve K_v function.

Hence, the proposed DCF fiber may be used for single-mode transmission, and the single-mode condition is determined by the value of V at which the TE01 and TM01 modes reach cutoff , therefore it must be put v=0 [5].

3. Negative dispersion fiber design

The large negative dispersion values can be achieved by variation of the fiber profile by doping the fiber cladding, introducing an increase in the refractive index difference between the core and cladding in other words the negative dispersion can obtained by change the value of waveguide dispersion.

The geometry considered here is limited to a five layers cylindrical dielectric structure, consisting of a core and four claddings as shown in Fig.(1). A unified formulation is developed which is applicable to all possible quadrature-clad fibers with step-index profiles.

To calculate the total dispersion (D), it must be calculate both the material dispersion and waveguide dispersion. The material dispersion depends mainly on the refractive index (see equation 3). By using Sellmeier equation, the refractive index of each layer can be calculated.

The *V*-dependent parameter representing the waveguide dispersion parameters D_W can be determined. Fig. (2) Represent the general quadrature-clad fiber profile DCF fiber. Therefore; nine fiber parameters namely core radius (r_1), first cladding radius (r_2), second cladding radius (r_3), third cladding radius (r_4), core index (n_1), first cladding index (n_2), second cladding index (n_3), third cladding (n_4) and outer cladding index (n_5), that optimized in designing very high negative dispersion fiber. Thereby, it is expected to obtain four waveguide dispersion factors for the four cladding regions, namely D_{W1}, D_{W2}, D_{W3} and D_{W4}. With aid equation (7), the waveguide dispersion factors can express by:

$$D_{W1}=-\left(\frac{n_1-n_2}{l_c}\right)V_1\frac{d^2(V_1b)}{dV_1^2} \qquad (9)$$

$$D_{W2}=-\left(\frac{n_2-n_3}{l_c}\right)V_2\frac{d^2(V_2b)}{dV_2^2} \qquad (10)$$

$$D_{W3}=-\left(\frac{n_3-n_4}{l_c}\right)V_3\frac{d^2(V_3b)}{dV_3^2} \qquad (11)$$

$$D_{W4}=-\left(\frac{n_4-n_5}{l_c}\right)V_4\frac{d^2(V_4b)}{dV_4^2} \qquad (12)$$

And

$$V_1=kr_1\sqrt{n_1^2-n_2^2} \qquad (13)$$

$$V_2=kr_2\sqrt{n_2^2-n_3^2} \qquad (14)$$

$$V_3=kr_3\sqrt{n_3^2-n_4^2} \qquad (15)$$

$$V_4=kr_4\sqrt{n_4^2-n_5^2} \qquad (16)$$

Then,

$$u_1=r_1\cdot\sqrt{k^2n_1^2-b_1^2} \qquad (17)$$

$$u_2=r_2\cdot\sqrt{k^2n_2^2-b_2^2} \qquad (18)$$

$$u_3=r_3\cdot\sqrt{k^2n_3^2-b_3^2} \qquad (19)$$

$$u_4=r_4\cdot\sqrt{k^2n_4^2-b_4^2} \qquad (20)$$

It can calculate the total waveguide dispersion by:

$$D_W=D_{W1}+D_{W2}+D_{W3}+D_{W4} \qquad (21)$$

4. Simulation and Results

The proposed quadrature-clad fiber profile illustrates in Fig.(3) is tested by using Matlab® program. First, the Sellmeier coefficients of the materials are stored in the program and are used for specified materials to calculate the refractive indices. For best results, four different material types are selected from Table (1)[8]. These material (M4, M12, M10, M12, M10) that represent the core, first clad, second clad, third clad, forth clad respectively are used in the design. Also the refractive indices are calculated using Sellmeier equation with wavelength of 1.55µm. Then the martial dispersion also calculated using equation (3).

Fig.(3) shows the relationship between the refractive index(n) and radii of various layers. It can note that, core radius is 10µm with n_1=1.4461, first-clad radius is 0.65µm with n_2=1.5077, second-clad radius is 7µm with n_3=1.4385, third-clad radius is 0.72µm with n_4=1.5077, and forth-clad radius is 2µm with n_5=1.4385.

The values of the chromatic dispersion *D* versus the wavelength are demonstrated in Fig. (4). A high negative dispersion value *D* = –951 ps/nm.km can be achieved at 1.55 nm.

When the thickness of first clad increased, the phase-matching wavelength moves toward smaller wavelength with a highly increasing dispersion value. Until the certain value, the dispersion value will highly decrease. Therefore the selected width of this clad is very important and the value of its index is also very important. It can be consider these values as important design parameter. The increase width of third clad is effect on the dispersion curve and moves it toward larger wavelength. Also it cause decrease in the waveguide dispersion.

The experiment setup shown in Fig.(5) describe the optical communication system with using proposed dispersion compensation fiber (DCF). This system consists of optical transmitter with output power of 5dBm at wavelength of 1550nm. Optical transmitter produces the optical digital signal at bit rate of 20Gbit/s with return-to-zero (RZ) code. This signal travels over the standard single mode optical fiber. At end of fiber, the signal is divided by beam splitter into two rays to make comparison between the signals with using proposed DCF and without use it.

Fig.(6-a) shows (first test) the eye diagram of the received signal without using proposed DCF (i.e. single mode fiber only) with fiber length of 50km. The signal quality of the received signal is 3 and the eye diagram is very bad. While the eye diagram of received signal with using proposed DCF with length of 1km is shown in Fig.(6-b). It is very good with signal quality of 58.

5. Conclusions

This paper studied and optimized dispersion compensating fiber structure with five layers.

The dispersion values achieved in this paper are extremely high as compared to the previous studies. The proposed negative dispersion optical fiber is designed with waveguide dispersion of -960 ps/nm.km and total dispersion of -951 ps/nm/km measured at wavelength of 1550nm.

The proposed very high negative dispersion fiber can reduce the dispersion of standard fiber when it is added with the existing standard fiber in a ratio of 50:1.

The very important point it's, the proposed DCF has core radius of 10µm, therefore the coupling with single mode fiber or other standard optical communication components become easy.

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Table(1): Sellmeier's coefficients for material compositions of silica-based glasses [8].

Material	Composition	a_1	a_2	a_3	λ_1	λ_2	λ_3	n (1.55µm)
M1	Pure Silica	0.6961663	0.4079426	0.897479	0.0684043	0.1162414	9.896161	144402
M2	13.5 m/o*GeO2* 86.5 m/o *SiO2*	0.70724622	0.39412616	0.63301929	0.08047805	0.1092579	7.8908063	1.46598
M3	7.0 m/o *GeO2* 93.0 m/o *SiO2*	0.6869829	0.444795	0.7907351	0.0780876	0.1155184	10.436628	1.4554
M4	2.2 m/o *GeO2* 3.3 m/o *B2O3* 94.5 m/o *SiO2*	0.699339	0.4111269	0.9035275	0.0617482	0.1242404	9.896158	1.4462
M5	4.1 m/o *GeO2* 95.9 m/o *SiO2*	0.6867175	0.43481505	0.8965658	0.07267519	0.11514351	10.002398	1.45031
M6	9.1 m/o *GeO2* 7.7 m/o *B2O3* 83.2 m/o *SiO2*	0.7239388	0.4112954	0.79292034	0.085826532	0.1070526	9.3772959	1.45505
M7	4.03m/o*GeO2* 9.7m/o*B2O3* 86.27 m/o *SiO2*	0.7042042	0.4128941	0.95238253	0.06797497	0.12147738	9.6436219	1.44768
M8	0.1 m/o *GeO2* 5.4 m/o *B2O3* 94.5 m/o *SiO2*	0.69681388	0.4086517	0.89374039	0.07055551	0.07055551	9.8754801	1.44455
M9	9.1 m/o *P2O5* 90.9 m/o *SiO2*	0.69579	0.452497	0.712513	0.061568	0.119921	8.656641	1.45895
M10	13.3 m/o *B2O3* 86.7 m/o *SiO2*	0.690618	0.401996	0.898817	0.0619	0.123662	9.0986	1.43856

M11	1.0 m/o *F* 99.0 m/o *SiO2*	0.69325	0.3972	0.86008	0.06723987	0.11714009	9.776098 4	1.4394
M12	16.9 m/o *Na2O* 32.5 m/o *B2O3* 50.6 m/o *SiO2*	0.796468	0.497614	0.358924	0.094359	0.093386	5.999652	1.50771

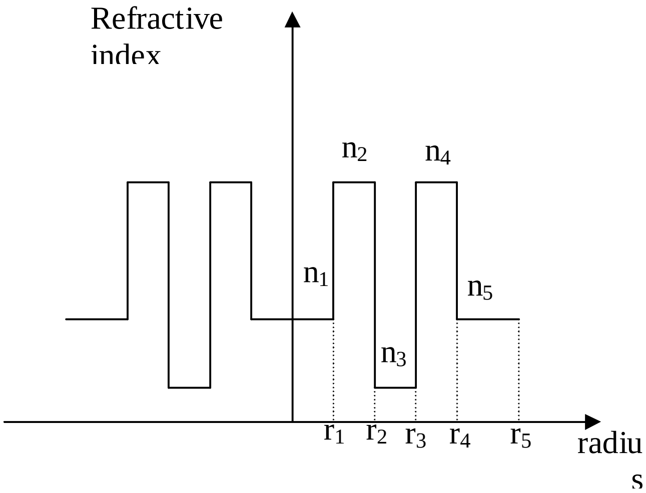


Figure (1): Index profiles Five-layer fiber structure

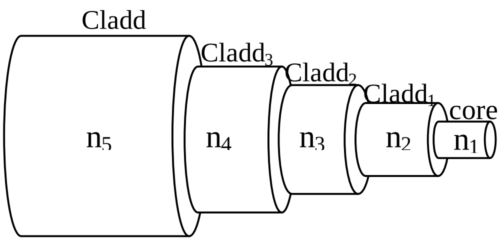
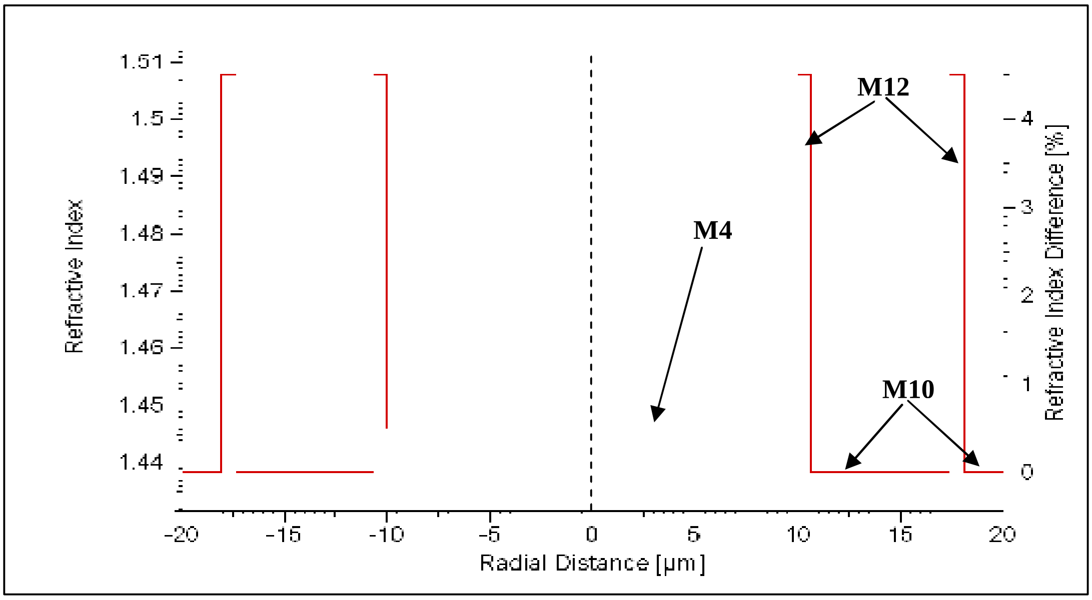
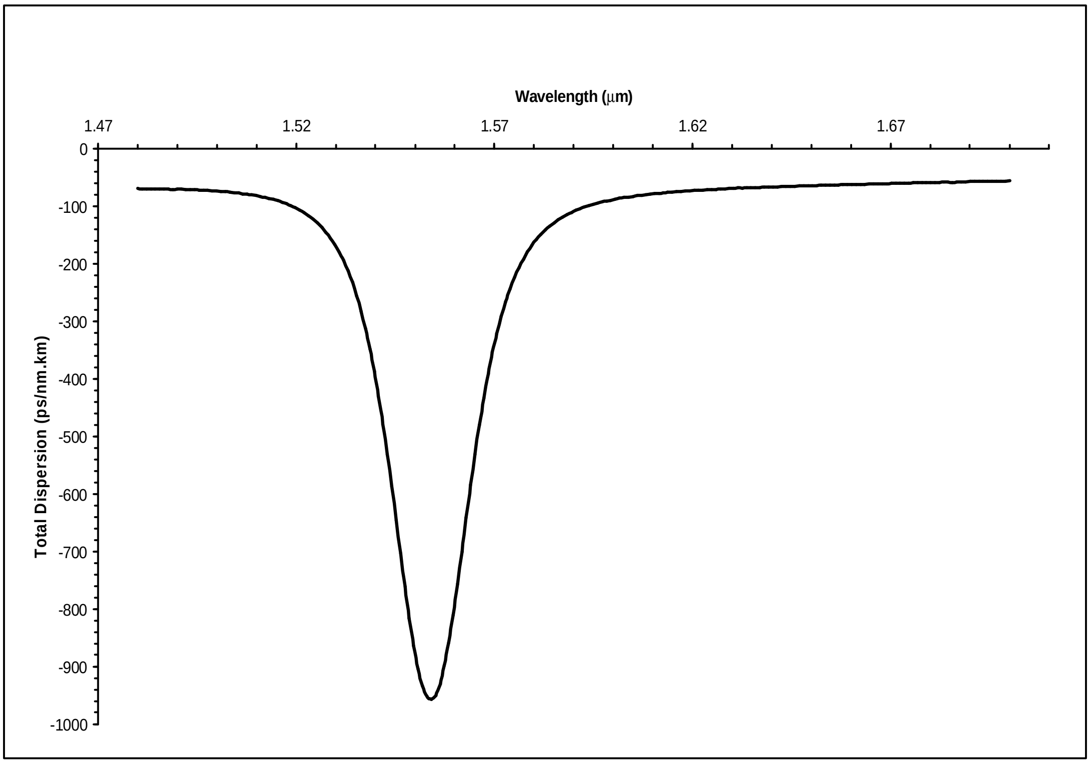


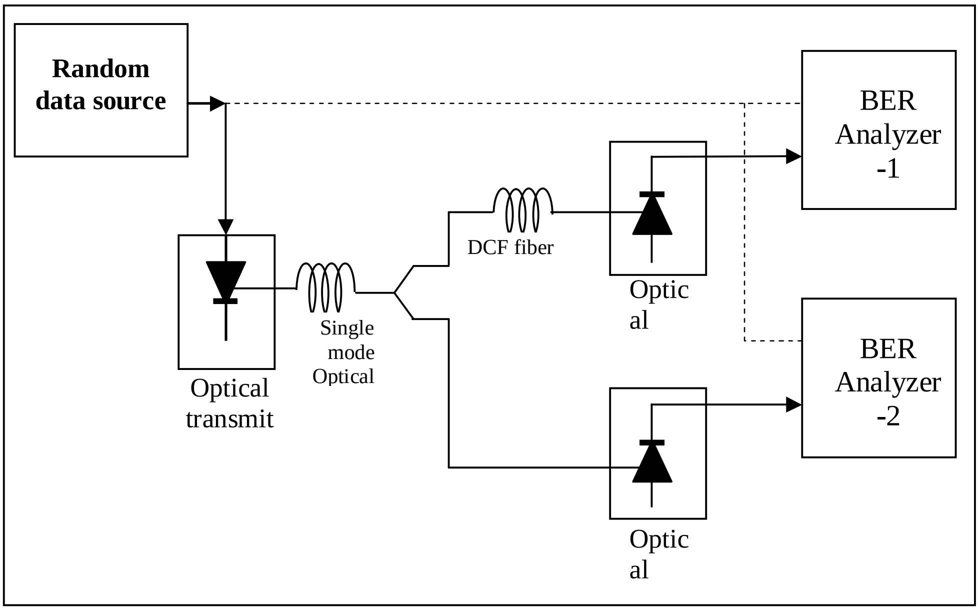
Figure (2): five layer cylindrical dielectric structure



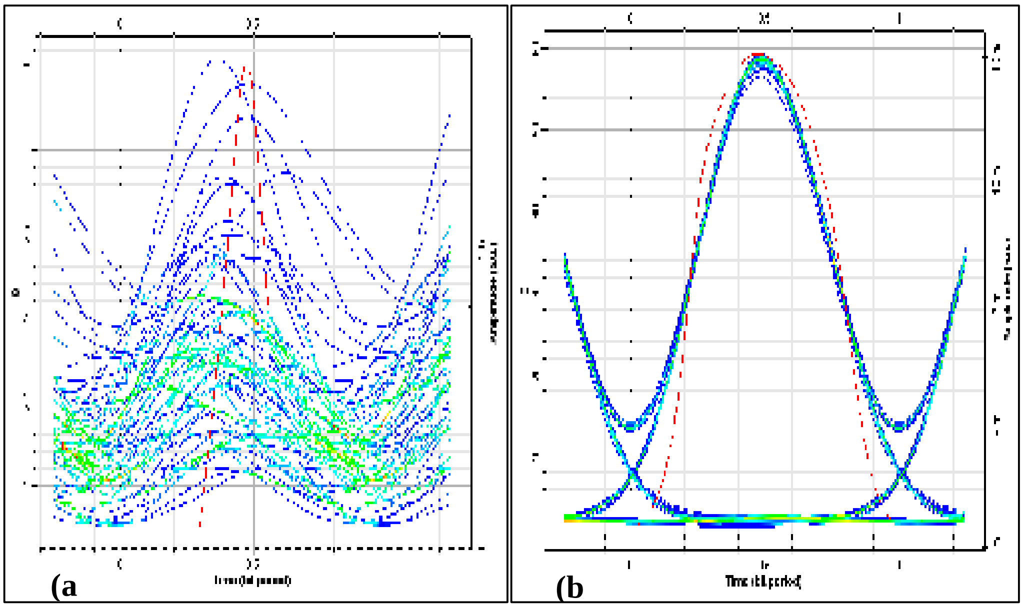
Figure(3): Index profiles of proposed five layers fiber structure



Figure(4): The relation between dispersion versus wavelength



Figure(5): The experiment setup of optical fiber communication system with using DCF.



Figure(6): Illustrate the eye diagram of RZ format transmit over optical transmission system with standard single mode fiber length of 50km .
a: without using DCF
b: with using proposed DCF at length of 1km.