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Design of Low Dispersion Flattened Optical Fiber

Dr. Alaa Hussein Ali*

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Abstract

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. When considering the major implementation of optical fiber transmission which involves some form of digital modulation, then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. This paper demonstrates that non-zero dispersion flatting optical fiber is achievable with dispersion extended over more than spectral range of 300nm. A total dispersion of (0.0398444 ps/nm.km) is obtained due to a design of an optical fiber with triple-clad at wavelength of 1551nm. Also the flatting optical fiber is tested using computer simulation at two distances at 50km and 100km.

Keywords: Flattened Optical Fiber, Dispersion.

تصميم ليف بصري متسطح واطى التشتت

الخلاصة

تشتت الاشارة الضوئية المرسلة يسبب تشويه لكل من الارسال التناظري والرقمي على طول الليف البصري.عند الاخذ بنظر الاعتبار التنفيذ الاكبر لعملية الارسال في الليف البصري والتي تقتضي على بعض الاشكال من التضمين الرقمي,عند ذاك فأن مكانيكية التشتت ضمن الليف تسبب توسع نبضات الضوء المرسلة على مدى وصولها ضمن القناة. أن هذا البحث يوضح الحصول على ليف بصري متسطح غير صفري مع تشتت ممتد على مدى طيفي لأكثر من (300) نانومتر. تم تحقيق تشتت كلي مقداره (0.0398444 ps/nm.km) نتيجة لتصميم ليف بصري ثلاثي الاغلفة عندالطول الموجي nm 1551. كذللك فأن هذا البحث يوضح فحص الليف البصري المتسطح عبر أستخدام محاكاة الحاسبة ولمسافتين (5 0) كم و (100)كم.

1. Introduction

The possibility of low dispersion over extended range of wavelength was presented by Kawakami and Nishida in 1974 [1], and studied extensively thereafter by [2, 3]. By manipulating the index profile of a fiber, total dispersion can be to go to zero at two or three different wavelengths, and remain close to zero in between. Dispersion flattening occurs by partial cancellation of waveguide dispersion by material dispersion in the wavelength range of operation. In some applications such as wavelength division multiplexing, where a number of signals with different wavelengths are carried by one fiber, it is desired to design the fiber optic system such that all optical signals experience relatively the same low distortion.

The information capacity of fiber-optic systems using dispersion flattened fiber and wavelength division multiplexing (WDM) schemes can be increased many

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* Laser Engineering and Optoelectronic Department, University of Technology/Baghdad

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

folds .Multiclad fibers , including double , triple, and quadruple-clad fibers can be used to design dispersion-flattened fibers[4]. In applications where two or more modes travel simultaneously though the fiber, intermodal as well as intramodal dispersion exist. Intermodal dispersion does not occur in single-mode fibers, but is a significant effect in multimode fibers. It occurs as a result of different modes having different group velocities at the same frequency.

Each type of dispersion mechanism leads to pulse spreading. As a pulse spreads, energy is overlapped, [5]. There are two types of intramodal dispersion. The first type is material dispersion and the second type is waveguide dispersion.

2. Material Dispersion

The same physical processes which introduce fiber attenuation also produce a refractive index which varies with wavelength. This intrinsic or material dispersion is primarily a property of the glass used in the core, although the dispersion of the cladding will influence the fiber in proportion to the fraction of guided energy which actually resides outside the core. Material dispersion is particularly important if sources of broad spectral width are used [6]. For example, the step index fiber has a transit time t_p for propagation constant $b = n_1$ (core refractive index) is given by $t_p = zn_1/c$. If n_1 varies with wavelength, the incremental time differential Δt is written as $\Delta t = z\Delta n_1/c$ where Δn_1 is given by

$$\Delta n_1 = n_1(l) - l\frac{dn_1}{dl} \text{...... (1)}$$

Δn_1 Is called the on axis group index n_a. The pulse width t_d assuming that $dl \le l$ leads to

$$t_d = \left|\frac{\partial t}{\partial l}\right| dl = \frac{zl}{c}\left|\frac{d^2 n_1}{dl^2}(l)\right| dl \text{ .... (2)}$$

The group index $n_g(r,l)$ for a general refractive index $n(r,l)$ is written as

$$n_g(r,l) = n(r,l) - l\frac{dn}{dl}(r,l) \text{... (3)}$$

In the description of dispersive fiber material, we limit our discussion to linear dispersion. In other words $n_g = a(l)n + b(l)$, where a and b are functions of l only [7]. Therefore, the dispersion material factor can be given by

$$D_M = -\frac{l}{c}\left(\frac{d^2 n(l)}{dl^2}\right) \qquad \text{..... (4)}$$

3. Waveguide dispersion

The energy distribution in single-mode fiber is a consequence of the boundary conditions at the core – cladding interface, and is therefore a function of optical frequency. The waveguide dispersion occurs because a 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.

The effect of waveguide dispersion D_W on pulse spreading can be approximated in assuming that the refractive index of the material is independent of the wavelength, where [8]

$$D_W = -\left(\frac{n_1 - n_2}{l_c}\right) V \frac{d^2(Vb)}{dV^2} \quad \dots (5)$$

Where, V is the normalized frequency

$$V = ka(n_1^2 - n_2^2)^{\frac{1}{2}} \cong kan_2\sqrt{2\Delta} \quad ..(6)$$

The contribution of D_W to the total dispersion parameter D, is given by [9]

$$D = D_M + D_W \qquad \dots\dots. (7)$$

4. Dispersion flattened fiber design

Dispersion-flattened fibers are special fibers that provide small dispersion over an extended range of wavelengths. The fiber presented in this paper is four layer circular dielectric waveguides, consisting of a core and three claddings as shown in fig. (1) A unified formulation is developed which is applicable to all possible four layer fibers with step-index profiles. Furthermore, by reducing one or two layers to zero, triple-clad, and double-clad geometries are also covered by this formation.

The sensitivity of the total dispersion of fiber due to changes in the structural parameters $(r_0, r_1, r_2, n_0, n_1, n_2, n_3)$ are shown in fig. (1), twelve different fiber material types of silica base and different doping concentration of dopants are used as core and/or cladding. These materials and their Sellmeir's coefficients are tabulated in Table (1). To calculate the total dispersion (D), both the material dispersion and waveguide dispersion must be calculated. The material dispersion depends mainly on the refractive index. By using equation (8), the refractive index of each layer can be determined.

$$n^2(l) = 1 + \sum_{J=1}^{3} \frac{B_J l^2}{(l^2 - l^2{}_J)} \quad \dots.. (8)$$

Where, l_J is resonance wavelength and B_J is the oscillator strength. These constants have been tabulated for several kinds of fibers in table (1). The first and second derivatives of the Sellmeir's equation must be calculated, these derivatives of the refractive index as a function of wavelength can then be used to obtain the material dispersion factor D_M as [8].

$$\frac{dn(l)}{dl} = \frac{\sum_{J=1}^{3}\left\{\frac{2lB_J}{l^2 - l_J^2}(1 - \frac{l^2 B_J}{(l^2 - l_J^2)})\right\}}{2\sqrt{1 + \sum_{J=1}^{3}\frac{l^2 B_J}{(l^2 - l_J^2)}}} \quad \dots.(9)$$

$$\frac{d^2 n(l)}{dl} = \frac{\sum_{J=1}^{3}\frac{2B_J}{l^2 - l_J^2}\{1 - \frac{5l^2}{(l^2 - l_J^2)} + \frac{4l^4}{(l^2 - l_J^2)^2}\}}{2\sqrt{1 + \sum_{J=1}^{3}\frac{l^2 B_J}{(l^2 - l_J^2)}}} - \frac{\sum_{J=1}^{3}\frac{2lB_J}{l^2 - l_J^2}\{1 - \frac{l^2}{(l^2 - l_J^2)}\}}{4\{1 + \sum_{J=1}^{3}\frac{l^2 B_J}{(l^2 - l_J^2)}\}^{\frac{3}{2}}} \quad \dots (10)$$

The V- dependent parameter representing the waveguide dispersion parameter D_W can be determined. Eight fiber parameters namely core radius (r_0), first cladding layer radius (r_1), second cladding layer radius (r_2), third cladding layer radius (r_3), core index (n_0), first cladding layer index (n_1), second cladding layer index (n_2), outer cladding layer index (n_3), are optimized in designing this fiber. Thereby, it is expected to obtain three waveguide dispersion factors for the three cladding regions. The waveguide dispersion factors for triple-clad are the extension of equation (5) and are given by:

$$D_{W1} = -\left(\frac{n_0 - n_1}{l_c}\right) V_1 \frac{d^2(V_1 b)}{dV_1^2} \quad ..\ (11)$$

$$D_{W2} = -\left(\frac{n_1 - n_2}{l_c}\right) V_2 \frac{d^2(V_2 b)}{dV_2^2} \quad ...\ (12)$$

$$D_{W3} = -\left(\frac{n_2 - n_3}{l_c}\right) V_3 \frac{d^2(V_3 b)}{dV_3^2} \quad ..(13)$$

Where

$$V_1 = Ka_1\sqrt{n_0^2 - n_1^2} \quad ....\ (14)$$

$$V_2 = Ka_2\sqrt{n_1^2 - n_2^2} \quad ......\ (15)$$

$$V_3 = Ka_3\sqrt{n_2^2 - n_3^2} \quad ...\ (16)$$

Total dispersion can be calculated by :

$$D = D_M + D_{W1} + D_{W2} + D_{W3} \quad ...\ (17)$$

4. Simulation and Results

The triple-clad fiber profile illustrates in fig. (2) Is tested by using simulation software (optifiber software) include material compositions and radii of various layers of the waveguide, and the wavelength. A listing of silica based materials, commonly used in optical fiber fabrication, is provided in Table (1). The Sellmeir‘s coefficients of the materials are stored in the program and are used for specified materials to calculate the refractive indices. For best results, two materials are selected from the Table (1). These materials are (M_3, M_8, M_3, M_8) that represent the core index, first clad index, second clad index and third clad index respectively are used in the design and simulation of the dispersion flattening fiber.

Also the refractive indices are calculated using Sellmeir equation with wavelength 1.55mm . Fig. (3) Shows the relationship between the refractive index (n) and radii of various layers. It can note that, core radius is (1.44) mm with $n_1 = 1.50771$, first-clad radius is (5.44) mm with $n_2 = 1.43856$, second-clad radius is (6.54) mm with $n_3 = 1.50771$ and third-clad radius is (7.54) mm with $n_4 = 1.43856$. The values of the total dispersion (D) (material dispersion and waveguide dispersion) versus the wavelength are demonstrated in Fig. (4).By utilizing the optifiber software, the values of the total dispersion (D) equal to 0.0398444 ps/nm.km it can be achieved at 1.551nm with dispersion slope of 0.0525 ps/nm^2 .km.

The curve in fig. (4) Shows the dispersion of the DFF with triple clad. 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 then dispersion value will highly decrease. Therefore the selected width of this clad is very important and the value of this index is also very important. These values can be considered as important design parameters. The increase width of the third clad effects the dispersion curve and moves it toward larger wavelength. Also it causes decrease in the waveguide dispersion.

The experiment setup shown in fig. (5) Describes the optical communication system with using proposed dispersion flatting fiber (DFF). 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 40Gbit /s with none return-to-zero (NRZ) code as modulation type. This signal travels over the standard single mode optical fiber. Also, the proposed optical fiber (DFF) with length of 100km and total dispersion equal to 0.0398444 ps/nm.km is used. Fig. (6-a) shows the eye diagram of the received signal with using proposed DFF with length of 50 km, it is very good ,very clear and it has no disturbance .

While the eye diagram of received signal with proposed DFF with length of 100km is shown in Fig.(6-b).It is also very good, clear with a little disturbance. The international accepted value for bit error rate (BER) is 1×10^{-9} , when the BER for the designed fiber greater than the above value, therefore, the design is very bad. But in our case the BER for the proposed DFF with length of 100km is 7.11×10^{-10} and quality factor (Q) is 6.05.

5. Conclusions

The present paper concerned with a flatting dispersion optical fiber (DFF), and an optical transmission line incorporating it. The research studied and optimized this fiber geometry. The total dispersion (D) value achieved in this paper is very low with respect to the previous studies. The proposed DFF is designed with waveguide dispersion of (-13.1272 ps/nm.km), material dispersion of (13.0551 ps/nm.km), and the total dispersion of 0.0398444 ps/nm.km at 1551nm.The proposed DFF has a quality factor of (6.05) and BER of (7.11×10^{-10}) with length equal to 100km.

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Table (1) Sellmeier's coefficients for material compositions of silica-based glasses

Material	**Composition**	**B1**	**B2**	**B3**	l_1	l_2	l_3	n
M1	Pure Silica	0.6961663	0.4079426	0.897479	0.0684043	0.1162414	9.896161	1.44402
M2	0.1 m/o GeO_2 , 5.4 m/o B_2O_3 , 94.5 m/o SiO_2	0.69681388	0.4086517	0.89374039	0.07055551	0.07055551	9.8754801	1.44455
M3	16.9 m/o Na_2O , 32.5 m/o B_2O_3 , 50.6 m/o SiO_2	0.796468	0.497614	0.358924	0.094359	0.093386	5.999652	1.50771
M4	3.0 m/o B_2O_3 , 97.0 m/o SiO_2	0.6935408	0.4052977	0.9111432	0.0717021	0.1256396	9.896154	1.44218
M5	4.1 m/o GeO_2 , 95.9 m/o SiO_2	0.6867175	0.4348150	0.8965658	0.07267519	0.11514351	10.002398	1.45031
M6	9.1 m/o GeO_2 , 7.7 m/o B_2O_3 , 83.2 m/o SiO_2	0.7239388	0.4112954	0.79292034	0.085826532	0.1070526	9.3772959	1.45505
M7	3.5 m/o GeO_2, 96.5 m/o SiO_2	0.7042038	0.4160032	0.9074049	0.0514415	0.1291600	9.896156	1.44951
M8	13.3 m/o B_2O_3 , 86.7 m/o SiO_2	0.690618	0.401996	0.898817	0.0619	0.123662	9.0986	1.43856
M9	**9.1 m/o P_2O_5 , 90.9 m/o SiO_2**	**0.69579**	**0.452497**	**0.712513**	**0.061568**	**0.119921**	**8.656641**	**1.45895**
M10	**13.5 m/o GeO_2 + 86.5 m/o SiO_2**	**0.70724622**	**0.3941261**	**0.63301929**	**0.08047805**	**0.1092579**	**7.8908063**	**1.46598**

M11	**1.0 m/o F , 99.0 m/o $SiO2$**	**0.69325**	**0.3972**	**0.86008**	**0.06723987**	**0.11714009**	**9.7760984**	**1.4394**
M12	**3.0 m/o $GeO2$ +97.0 m/o $SiO2$**	**0.4052977**	**0.9111432**	**0.0717021**	**0.0780876**	**0.1256396**	**9.896154**	**1.44218**

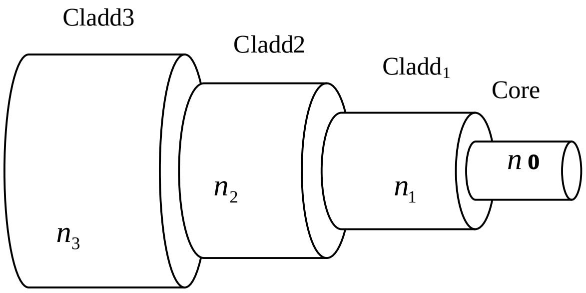

Figure (1) Four-layer cylindrical dielectric structure

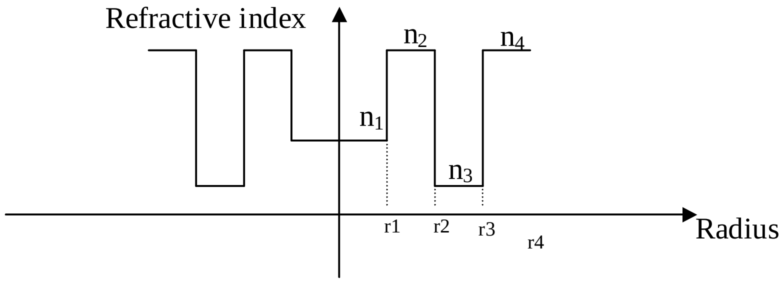

Figure (2) Index profiles four layer fiber structures

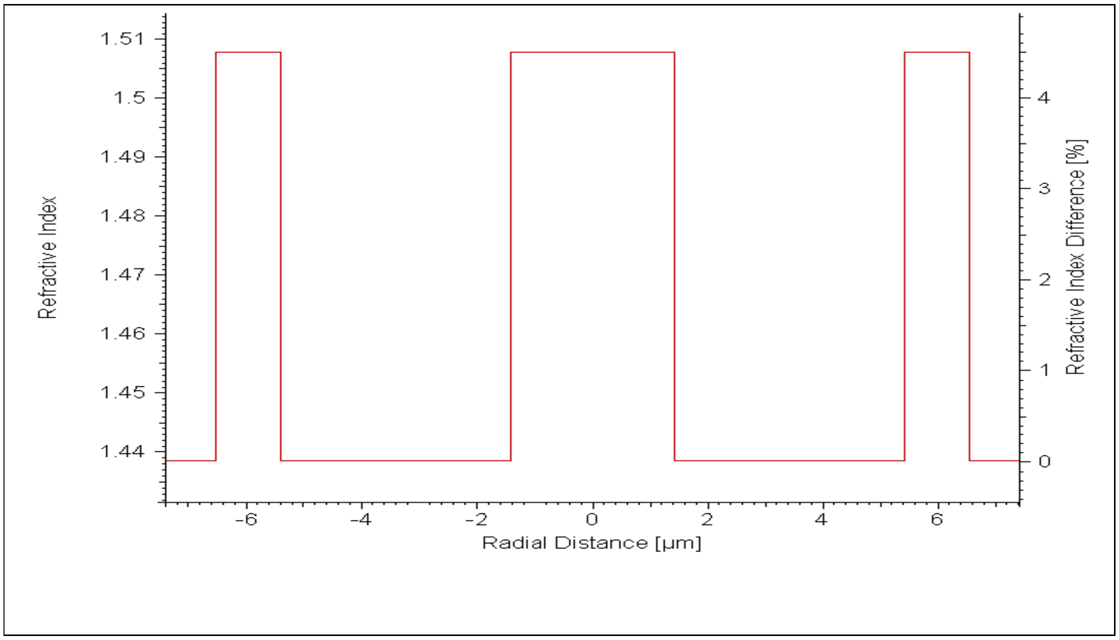

Figure (3) Index profiles of proposed four layer fiber structure

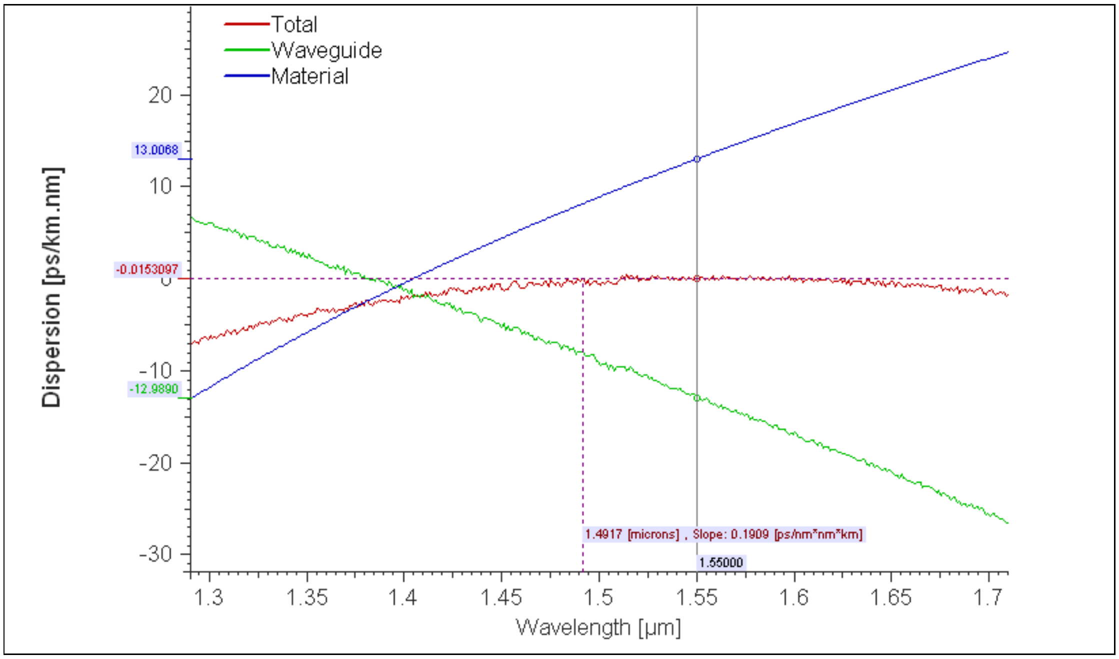

Figure (4) The relation between the total dispersion versus wavelength.

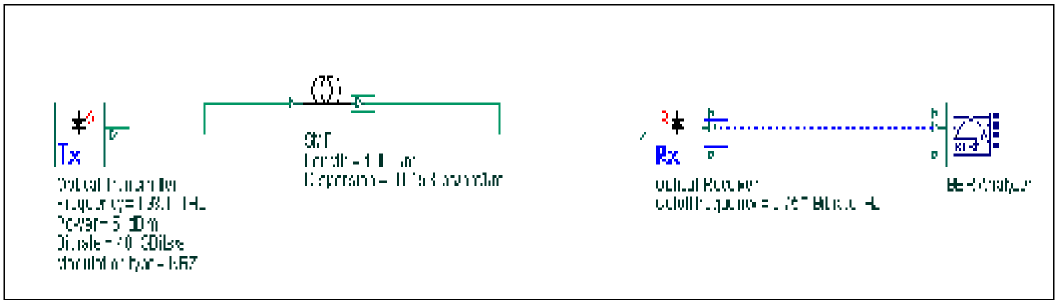

Figure (5) The experiment setup of optical fiber communication system with using DFF

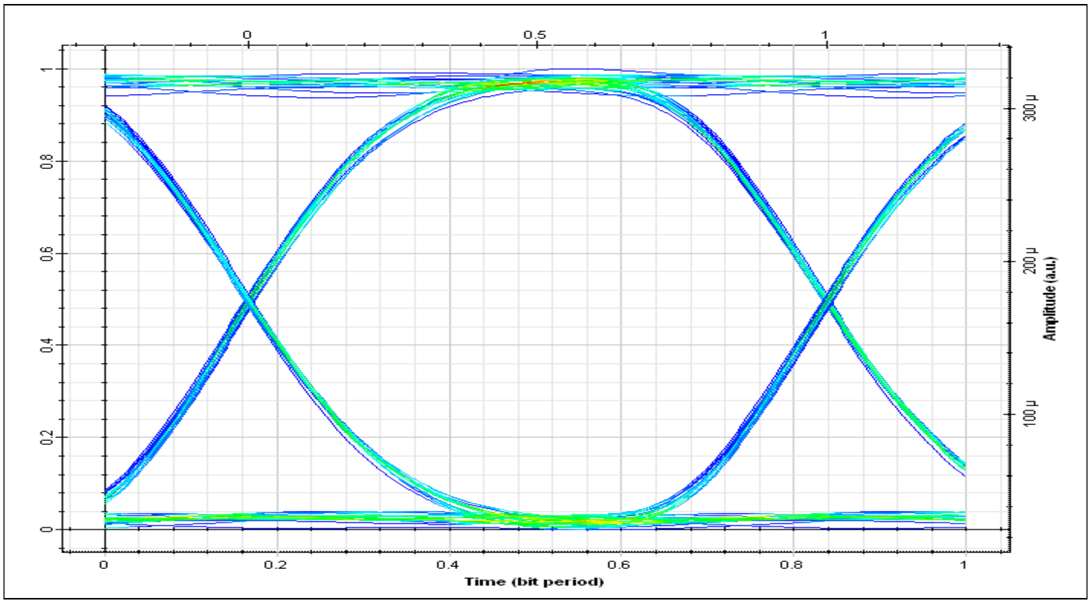

Figure (6-a) Illustrate the eye diagram of NRZ formats transmit over optical transmission system with using DFF of length 50km.

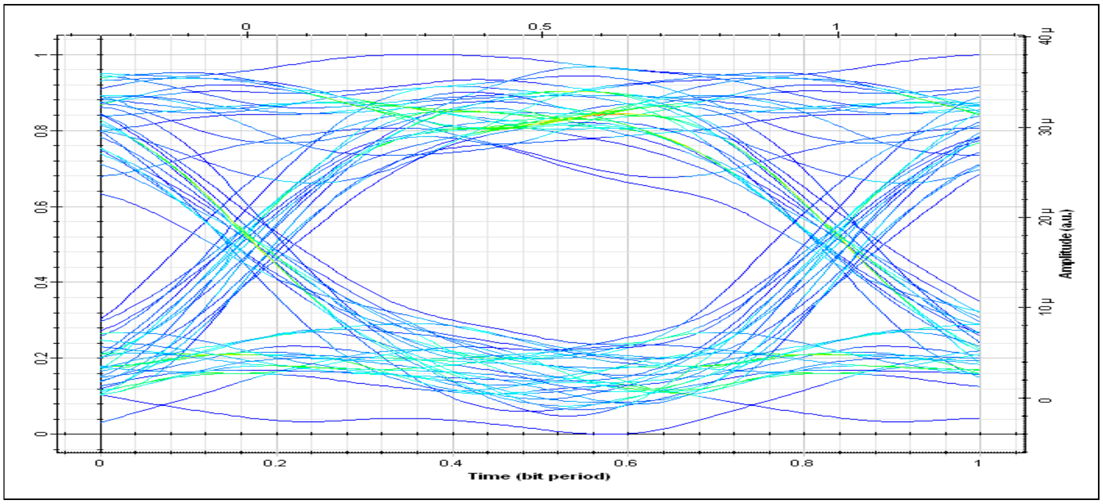

Figure (6-b) Illustrate the eye diagram of NRZ formats transmit over optical transmission system with using DFF of length 100km.