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Investigation of Effects of Attenuation and Dispersion Levels of Various Fibre Optics Lengths in the Telecommunication Industry

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Abstract

Optical communication systems have a greater advantage over conventional cable communication system. The most important advantage of Optical Communication system is the availability of enormous communication bandwidth which is a measure of information carrying capacity. But there are limitations to the distance over which the information can be conveyed without any distortion. This inevitable distortion is due to optical phenomenon called Attenuation and Dispersion. Attenuation is the reduction or degradation of signal strength while dispersion is the pulse spreading during transmission. Because of this reduction or degradation of signal and pulse spreading during transmission, optical amplifiers are needed for distances greater than 20km in order to regenerate the signal back to its original form, and this makes the transmission network very expensive to implement and maintain. The investigation discussed here is based on the use of an adaptive Dispersion-Compensation Technique on fibre in order to improve the optical link for up to a distance of 100Km. This technique involves the insertion of fibres with dispersion of negative slope and higher absolute value. Their lengths can be 17-20km. Lengths that are too high that nonlinear effects arise will cause a problem. They have wide bandwidth suitable for WDM applications (~20nm).

Keywords: Attenuation; Dispersion; Single Mode fibre (SMF); Multimode fibre (MMF); Dispersion Compensation fibre (DCF).

1.0 Introduction

It is not exaggeration today to say that fibre Optics have indeed revolutionized the Telecommunication industry. The uses of fibre Optics today are quite numerous. With the explosion of information traffic due to the Internet, electronic commerce, computer networks, multimedia, voice, data, and video, the need for a transmission medium with the bandwidth capabilities for handling such vast amounts of information is paramount. Fiber optics, with its comparatively infinite bandwidth, has proven to be the solution.

Today with new technologies such as dense wavelength-division multiplexing (DWDM) and erbium-doped fiber amplifiers (EDFA) have been used successfully to further increase data ratesto beyond a *terabit per second* (>1000 Gb/s). This is equivalent to transmitting 13 million simultaneous phone calls through a single hair-size glass fiber.

But the maximum transmission distance in optical fiber system is limited by attenuation and optical dispersion along the transmission link; this is the reduction or degradation and pulse spreading of signal strength during transmission.

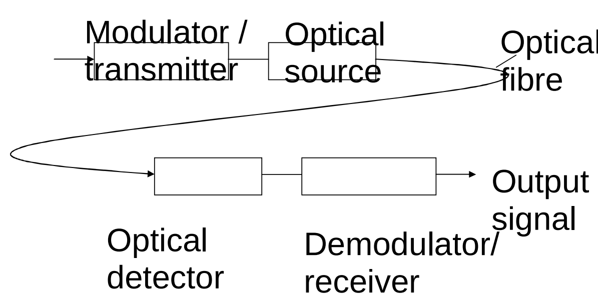

Fig 1: The Basic fibre Optics Transmission System

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1.1 Optical Fiber

In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding made of glass whose refractive index is slightly lower than that of the core's refractive index. The light or the optical signals are guided through the silica glass fibers by total internal reflection. The overall diameter of the fiber is about 125 to 200 μm. Cladding is necessary to provide proper light guidance i.e. to retain the light energy within the core as well as to provide high mechanical strength and safety to the core from scratches [1].

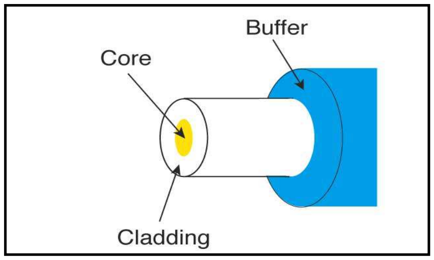

Fig 2: Structure of Optical Fiber

A fiber core is fairly thick relative to the wavelength of the light and allow the light to enter it at many different angles. There are a finite number of angles at which the ray reflect and propagate the length of the fiber. Each defines a path or a mode. Considerable insight in the guiding properties of optical fibers can be gained by using a ray picture based on geometrical optics[1]. The geometrical-optics description, although approximate, is valid when the core radius *a* is much larger than the light wavelength.

There are basically two modes of transmission in a fiber. A multimode fiber has a number of path in which the light may travel. A single mode has a light ray in one direction only. Fibers are classified by the refractive index profile of their core. They can be either step index or graded index. Here are three main types of fibers: Multimode step index fiber, Multimode graded index fiber and Single mode fiber.

2.0 Theory

The mathematical analysis of wave propagation on non conducting medium without free charges, Maxwell's equations are known to be important factors particularly where calculations of propagation of waves in electromagnetic fields are involved.

2.1 Wave Propagation

Like all electromagnetic phenomena, propagation of optical fields in fibers is governed by *Maxwell's equations*. For a non conducting medium without free charges, these equations take the form

$$\nabla X\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (1)$$

$$\nabla X\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad (2)$$

$$\nabla . \vec{D} = \rho \qquad (3)$$

$$\nabla . \vec{B} = 0 \qquad (4)$$

Where $\vec{E}$and $\vec{H}$are the electric and magnetic field vectors, respectively, $\vec{D}$and $\vec{B}$are the corresponding flux densities. The flux densities are related to the field vectorsby the constitutive relations

$$D = \varepsilon_{\circ}E + P \qquad (5)$$

$$B = \mu_{\circ}H + \mathrm{M} \qquad (6)$$

Where $\varepsilon_{\circ}$ is the vacuum permittivity and $\mu_{\circ}$ is the vacuum permeability, Pand **M** are the induced electric and magnetic polarizations, respectively. For optical fibers **M** = 0 because of the nonmagnetic nature of silica glass[2]. Evaluation of the electric polarization **P** requires microscopic quantum-mechanical approach. Although such an approach is essential when the optical frequency is near a medium resonance, a phenomenological relation between **P** and **E** can be used far from medium resonances[2].

Hence, of all properties of the material, we retain only the ones which influence the polarization. Using these approximations, Maxwell's equations are reduced to:

$$\nabla X\vec{B} = \mu_{\circ}\frac{\partial \vec{D}}{\partial t} \qquad (7)$$

$$\nabla . \vec{D} = 0 \qquad (7b)$$

$$\nabla . \vec{B} = 0 \qquad (7c)$$

Taking the curl of eqn (1) yields,

$$\nabla X\nabla \ \mathrm{X} \ \vec{\mathrm{E}} = \nabla \ \mathrm{X} \ \left(-\frac{\partial \vec{\mathrm{B}}}{\partial \mathrm{t}}\right) \qquad (8)$$

$$\nabla(\nabla . \vec{E}) - \nabla^2\vec{E} = -\partial/_{\partial t} \ (\nabla X\vec{B}\,) \qquad (9)$$

Upon taking into account of eqn (7a) and (5) eqn (9) becomes

$$\nabla(\nabla.\vec{E}) - \nabla^2\vec{E} = -\partial/_{\partial t}\left(\mu_\circ \frac{\partial \vec{D}}{\partial t}\right)$$

$$= -\ \mu_\circ \frac{\partial^2}{\partial t^2}\vec{D}$$

$$= -\ \mu_\circ \varepsilon_\circ \frac{\partial^2}{\partial t^2}\vec{E} - \mu_\circ \frac{\partial^2}{\partial t^2}\vec{P}$$

Thus the wave equation becomes

$$-\nabla(\nabla.\vec{E}) + \nabla^2\vec{E} = \frac{1}{C^2}\frac{\partial^2}{\partial t^2}\vec{E} + \mu_\circ \frac{\partial^2}{\partial t^2}\vec{P} \quad (10)$$

2.2 Wave guiding by Total Internal Reflection

The key feature of light propagation in a fiber is that the fiber may bend around corners. Provided the bend radius is not too tight (2 cm is about the minimum for most multimode fibers) the light will follow the fiber and will propagate without loss due to the bends[2] . This phenomenon is called total internal reflection. A ray of light entering the fiber is guided along the fiber because it bounces off the interface between the core and the (lower refractive index) cladding. Light is said to be bound within the fiber.

2.3 Snell's Law

In order to fully understand the ray propagation in fiber, consider Figure 3

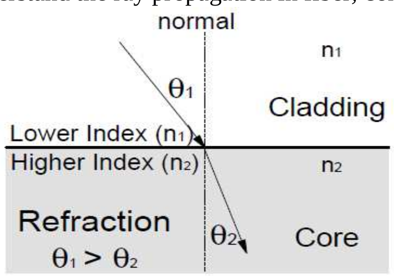

Fig 3: Refraction of light

If n_1 and n_2 denotes the refraction of medium 1 and medium 2 respectively, then *Snell's* law states that

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (11)$$

Fig 3. Shows that:

(a) The angle $\theta_1$is the angle between incident ray and an imaginary line normal to the plane of the Core-cladding boundary.

(b) When light passes from material of higher refractive index to a material of lower index the (refracted) angle $\theta_2$gets larger.

(c) When light passes from material of lower refractive index to a material of higher index the (refracted) angle θ_2 becomes smaller.

3.0 Practical and Computational Aspects

3.1 Dispersion Compensation

Dispersion compensation essentially means cancelling the chromatic dispersion of some optical element(s).Let's look at a pulse (with spectral width of $\Delta\lambda_0$) which is propagating through a fibre characterized by the propagation constant β. The spectral width $\Delta\lambda_0$ could be due to either the finite spectral width of the laser source itself or the finite duration of a Fourier transform-limited pulse[3]. We consider the propagation of such a pulse with the group velocity $v_g$given by:

$$\frac{1}{v_g} = \frac{d\beta}{d\omega} \quad (12)$$

For a conventional single mode fibre with zero dispersion around 1300nm, a typical variation of v_g with wavelength is shown by the solid curve in Figure 4.

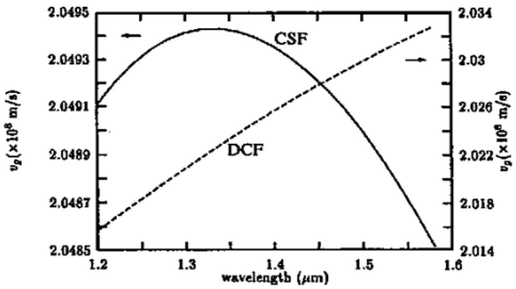

Fig4: Graph of Pulse through Dispersion Compensation Fiber and Conventional Single Mode Fiber

As can be seen from Fig 4. $v_g$has a maximum value at the zero dispersion wavelength and on either side it monotonically decreases with wavelength. So, if the central wavelength of the pulse is around 1.55 μm, then the longer wavelengths will travel slower than the smaller wavelengths of the pulse [3]. Because of this (chromatic dispersion) the pulse will get broadened. The leading edge of the output pulse is blue shifted and the trailing edge is red shifted. Now, after propagating through such a fibre for a certain length L_1, we allow the pulse to propagate through another fibre where the group velocity varies, as shown by the dashed curve inFigure 4. The longer wavelengths will now travel faster than the shorter wavelengths and the pulse will tend to reshape itself into its original form. This is the basic principle behind dispersion compensation. Now the total dispersion of a single mode fibre is given by:

$$D_1 = D_m + D_w = -\frac{2\pi c}{\lambda_0^2}\frac{d^2}{d\,w^2}\,\beta \qquad (13)$$

Thus, $d^2\beta/d\omega^2 < 0$ implies operation at $\lambda_0 > \lambda_z$ (λ_z is the zero dispersion wavelength) and conversely. Let $(D_t)_1$ and $(D_t)_2$ be the dispersion coefficient of the first and second fibre, respectively. Thus, if the lengths of the two fibres (L_1 and L_2) are such that

$$(D_t)_1 L_1 + (D_t)_2 L_2 = 0 \qquad (14)$$

then the pulse emanating from the second fibre will be identical to the pulse entering the first fibre. In order to fully understand this, let's look at the Figure5.

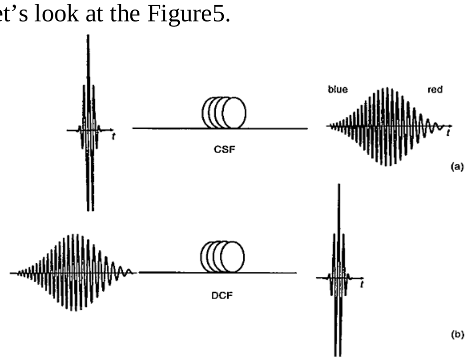

Fig 5:(a) Unchirpped Pulse (b) Compressed Chirped Pulse

In Figure 5 (a), we can see the broadening of an unchirped pulse as it propagates through a fibre characterized by $(D_t)_1 > 0$ ($\lambda_0 > \lambda_z$). Thus, the pulse gets broadened and chirps, the front end of the pulse gets blue shifted, and the trailing edge of the pulse gets red shifted. The pulse is said to be negatively chirped[4]. If such a negatively chirped pulse is now propagated through another fibre of length L_2 characterized by $(D_t)_2 < 0$, then the chirped pulse will get compressed Figure5 (b), and, if the length satisfies equation (14), then the pulse dispersion will be exactly compensated.

3.2 Dispersion Compensating Fibre

Conventional single mode fibres are characterized by large (~ 5-6 μm) core radii and zero dispersion occurs around 1300 nm. Operation around λ0 at 1300nm thus leads to very low pulse broadening, but the attenuation is higher than at 1550 nm. Thus, to exploit the low-loss window around 1550nm, new fibre designs were developed that had zero dispersion around 1550nm wavelength region. These fibres are called Dispersion Shifted Fibres (DSF) and have typically a triangular refractive index profiled core. Using DSFs operating at 1550nm, one can achieve zero dispersion as well as minimum loss in silica-based fibres[4].

One could increase the transmission capacity of conventional single mode fibres (CSFs) by operating at 1550nm and using WDM techniques and optical amplifiers. But, then there will be significant residual (positive) dispersion. Compensation of dispersion at a wavelength around 1550nm in a 1310nm optimized single mode fibre can be achieved by specially designed fibres whose dispersion coefficient (D) is negative and large at 1550nm. These types of fibres are known as Dispersion Compensating Fibres (DCFs). Since the DCF has to be added to an existing fibre optic limit, it would increase the total loss of the system and, hence, would pose problems in detection at the end. The length of the DCF required for compensation can be reduced by having fibres with very large negative dispersion coefficients[5].

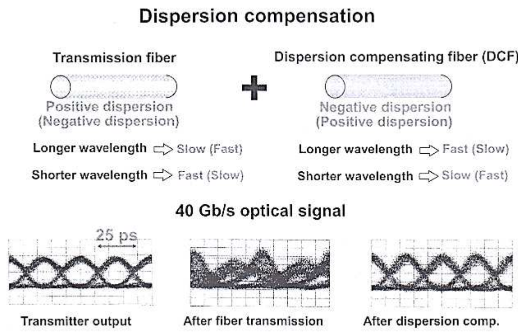

Fig 6: Dispersion through fibers of 50Km length at 40 Gb/s Bandwidth

The higher the dispersion coefficient of the compensating fibre, the smaller will be required length of the compensating fibre. Fig 6 shows the waveforms at the input to a 50km conventional single mode fibre, the output without the dispersion compensator, and the output with a DCF with D = -548 ps/km*nm and of length 1.44 km. Note that without the compensating fibre, no information can be retrieved while the DCF fully restores the pulses[6].

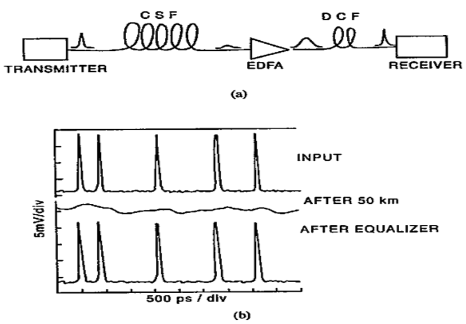

Fig 7:(a) Dispersion Compensation Techniques using EDFA Amplifier (b) Pulses after 50 Km

To achieve a very high negative value of D, the core of the compensating fibre has to be doped with relatively high GeO_2 compared with the conventional fibres. Unfortunately, the total fibre loss (α) increases because of this doping. Hence, for DCFs a measure of the dispersion compensation efficiency is given by the Figure of merit (FOM)., which is defined as the ratio of the dispersion coefficient to the total loss and has a unit of ps/(dB-nm)[6].

$$\text{FOM(ps/(dB*nm))} = |D|/\alpha \qquad (15)$$

For high data rates such as 40 Gbit/s or 160 Gbit/s, pulse broadening becomes much stronger than for 10 Gbit/s, for example. This is essentially because the spectral bandwidth of the signal becomes larger. It is then generally not sufficient to compensate the second-order dispersion only; one also needs to deal with higher-order dispersion. Problems can arise, for example, when dispersion-shifted fibbers with a substantial dispersion slope are used, and only dispersion of second order is compensated. Figure 8 show this effect for a single 2-ps pulse at 1550 nm after 10 km and 50 km of such a fibre. Mainly uncompensated third-order dispersion is responsible for the resultingdistortions[8].

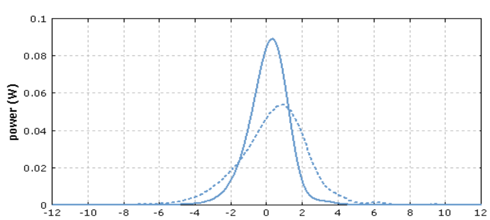

Fig 8: Distortion of a triple pulse after 10 km (solid curve) and 50 km (dashed curve) of a dispersion shifted fibre, when only second-order dispersion is compensated.

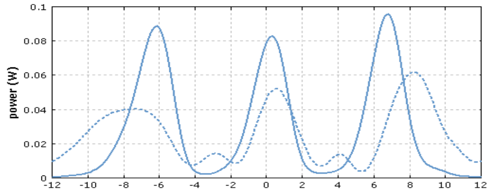

Fig 9: Pulse distortion after 10 km (solid curve) and 50 km (dashed curve) of a dispersion-shifted fibre, when only second-order dispersion is compensated.

Fig 9 shows Pulse distortion on 1335 transmission window which have modified waveguide dispersion so as to shift the zero dispersion wavelength into the 1.5-µm region. This is achieved by modifying the refractive index profile of the core. Common index profiles of dispersion-shifted fibers have a triangular, trapezoidal or Gaussian shape[9].

3.3 Adaptive Dispersion Compensation Technique

In order to Use the adaptive Dispersion Compensation to Improve Transmission Over 100km, thetotal dispersion from the transmitter to receiver for a fibre length of 100km is given by;

Dispersion = FL x FD x (Δλ) (16)

Where FL = fiber length

FD = fiber Dispersion coefficient

Δλ = source spectral width

Therefore, the source spectral width (in nm) is

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta f}{f}$$

Where Δf is the source spectral width determined by the modulator bandwidth (12GHz).

This implies that the spectral width (in nm)

$$\Delta\lambda = \frac{\Delta f \lambda}{f} \quad (17)$$

Using the following data

Δf = 12GHz,

f (center frequency) = 193.1THz

λ (center emission wave length) = 1552.52438115nm,

and substituting these data into eqn (17) gives

$$\frac{12\text{x}10^9\text{Hz} \ \text{x} \ 1552.52438115\text{nm}}{193.1\text{x}10^{12}\text{Hz}}$$

= 0.0965 $\approx 0.1nm$

Then the dispersion = LD_{ch} Δλ,

Where L is 100Km length of the single mode fiber, D_{ch} is 16ps/km nm the chromatic dispersion coefficient and Δλ is the spectral width, Therefore, from eqn (16)

Dispersion = 100 x 16 x 0. 0965 = 154.4ps

$$\text{The ratio} = \frac{\text{link dispersion}}{\text{bit period}} \quad (18)$$

Bit rate = 9.953Gbit/s, then the bit period (T) can be calculated as:

$$T = \frac{1}{\text{Bit rate}}$$

$$= \frac{1}{9.953\text{x}10^9} \approx 100\text{ps}, \quad \text{then}$$

$$\frac{\text{The ratio link dispersion}}{\text{bit period}} = 154.4/100$$

= 1.544

In order to compensate for the dispersion as calculated above, the Dispersion Compensating Fibre (DCF) has to be introduced:

The dispersion of this fibre was found to be -80ps/km. nm, and therefore the Length of the DCF can be found from

-80 ps/km. nm x 0.0965 x L + 154.4 = 0

7.72 x L = 154.4 or

$$L = \frac{154.4}{7.72}$$

L = 20Km

In order to compensate for the system dispersion we have to use a DCF of 20km

The attenuation caused by the DCF is 20 x 0.55 = 11dB

4.0 Results and Discussion

The experiment was carried out for the six different fibre lengths in order to determine the BER of each length of the fiber. (Bit Error Rate or Bit Error Ratio) is the number of received binary bits that have been altered due to Dispersion and interference. Therefore, using eqn (16) and eqn (17), to determine the dispersion and compensating fiber respectively, table 1 shows the length of the fibres and the corresponding BER obtained by simulation ofvarious fibre lengths. The process involves adjusting the attenuator values while keeping the received power constant, the transmitted power, received power and the BER was noted and recorded as shown in the table 1

Table 1 Table of various fibre Length, Attenuation, Power & BER.

Length of fibre	Attenuator (dB)	Transmitted power(dBm)	Received power(dBm)	BER
1km	23.8	-2.826	-26.962	8.4259x10^{-9}
10km	22	-3,032	-26.979	2.13848x10^{-9}
20km	20	-2.981	-26.998	3.44625x10^{-9}
30km	18	-3.009	-27.001	8.64955x10^{-8}
50km	14	-3.002	-27.007	4.7996x10^{-8}
70km	10	-2.998	-27.003	1.31112x10^{-7}
100km	4	-2.978	-26.997	0.000203634

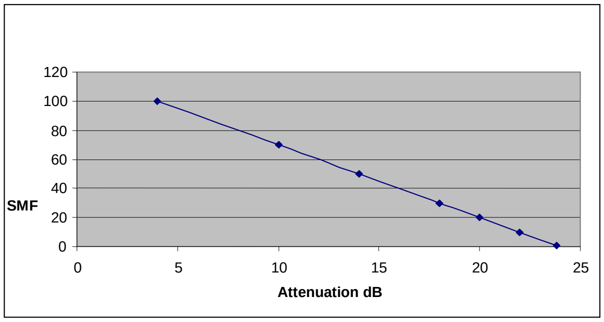

Fig 10: Graph of SMF against Attenuation

Fig 10 Shows attenuation on Single Mode fibers which is constant throughout the various lengths of the fibers

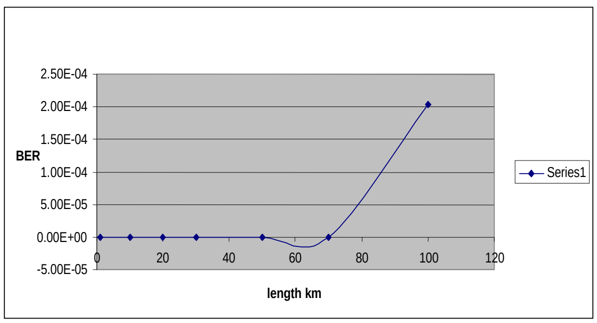

Fig11: Graph of SMF against BER

Fig 11 Shows Bit Error Rate on the Single Mode fibres which is very high between 50 to 100km

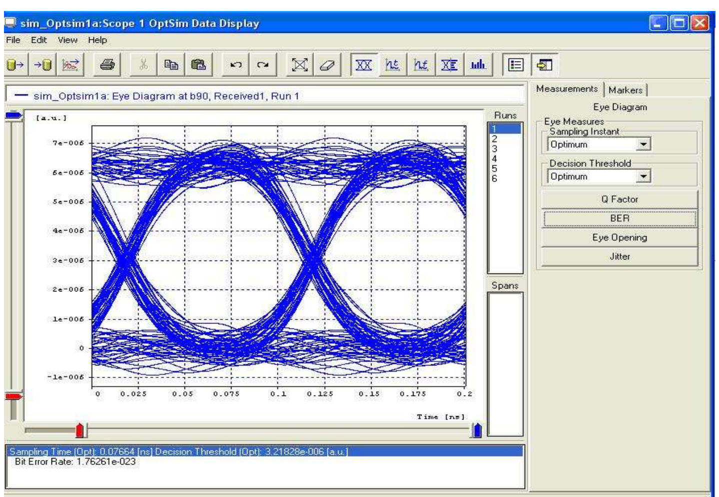

Fig 12: Screenshot of eye diagram for 1st run

Figure 12 illustrates the schematic for simulating the single mode(SM) fiber transmission; this design is a simplified representation of SM of optical fiber. In the transmitter section, a transmitter generates a 1552.52438115nm at 9.953Gbits/s NRZ signal. Optical receiver Sensitivity of -27dBm and error probability of 1x10^{-9} For 100 km fiber link a BER of 1.31112x10^{-7} was recorded. An eye chart gives an idea of the BER as the bigger the eye the lower the error rate.

5.0 Conclusion

We are able to demonstrate that by using adaptive dispersion-compensation technique on dispersion compensation fibre, the dispersion compensation fibre has significant impact on dispersion because it decreases the BER (Bit Error Ratio) as low as possible. This however increases the optical link for up to 100km without Optical amplifier(s).

Finally the effect of dispersion compensation fibre on dispersion was analysed and it was found that there was a significant impact of DCF which improve transmission over 100km and decrease the BER to $8.4259x10^{-10}$

References

[1] G. P. Agrawal, ***Nonlinear Fiber Optics***, 4th ed., Elsevier Academic Press, Amsterdam (2007)

[2] Fedor Mitschke, ***Fiber Optics Physics and Technology***, Springer-Verlag Berlin Heidelberg (2009)

[3] Harry.J.R.Dutton,1st ed. ***Understanding Optical Communications***, IBM Corporation, International Technical Support Organization.http://www.redbooks.ibm.com (2010)

[4] www.fiberoptics4sale.com/mechants2/graphics/00000001/what-are-the-compensenting -fibers_8603

[5] M. Born, E. Wolf,***Principles of Optics***, 7th ed., Cambridge University Press, Cambridge (1999)

[6] L. G. Cohen, Ch. Lin, ***A Universal Fiber-Optic (UFO) Measurement System Based on aNear-IR Fiber Raman Laser,*** IEEE Journal Quantum Electronics **QE-14**, 855–859 (1978)

[7] www.rp-photonics.com/dispersion_shifted_fibers.html

[8] Schott AG, Mainz (Germany): ***Optical Glass Catalog***. Available for download atwww.schott.com/advanced_optics/english/download/catalogs.html

[9] K. Nagayama, M. Kakui, M. Matsui, T. Saitoh, Y. Chigusa, ***Ultra Low Loss*** *(0.1484 dB/km)* ***Pure Silica Core Fiber and Extension of Transmission Distance***, Electronics Letters **38**,1168–1169 (2002)