Characterization of Standard Single-Mode Fiber Link for a NRZ Modulated Optical Signal at 40 Gbps

by

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Submitted to the Department of Electrical Engineering and Computer Science and the Faculty of the Graduate School of the University of Kansas in partial fulfillment of the requirements for the degree of Master of Science.

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Committee members

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Date project accepted

Abstract

Chromatic dispersion and polarization mode dispersion (PMD) are major impairments of long distance transport at higher bit-rates. To overcome the limitations posed by dispersion, compensation techniques have to be adopted.

Firstly, we updated the 10 Gbps bit error rate tester (BERT) to a 40 Gbps pattern generator with a 1:4 splitter and 4:1 multiplexer. We performed experiments in the laboratory at 40 Gbps and observed that we can go just 4 km after which we need to employ dispersion compensating fiber (DCF) modules to nullify the effects of chromatic dispersion. The adaptive PMD compensation system developed in the laboratory was tested initially at 10 Gbps. We tested the compensation system at 40 Gbps and satisfactory results were observed. As the PMD compensation algorithm uses degree of polarization (DOP) to monitor the PMD of the link, we noticed a considerable rise in DOP value when we compensated for the PMD in the fiber link. From experiments, it was determined that a signal-to-noise ratio (SNR) of at least 25 dB has to be maintained to get a DOP of 90 % or higher. Finally, we conducted a field trial on an underground fiber-optic link spanning about 95 km, provided by Sprint and a bit-error rate (BER) of 6.1×10^{-2} was obtained.

Acknowledgements

I would like to express my sincere gratitude to Dr. Chris Allen for giving me the opportunity to work in the lightwave communication systems laboratory and for his invaluable guidance, support and encouragement throughout my course of study at the University of Kansas.

I am greatly indebted to Dr. Ron Hui for helping me with the 40 Gbps system and for his continuous support. I would like to thank Dr. Ron Hui and Dr. Victor Frost for serving on my committee.

I would like to thank my former colleagues Arun Prasad Chimata for familiarizing me with the adaptive PMD compensation system and Pradeep Kondamuri for helping me with the measurement of PMD on the real link.

I would like to thank my parents for encouraging me in every aspect of my life and believing in me. Special thanks to my friend, Nandish Chalishazar, for giving me moral support and standing by me in all times. I would also like to thank the ITTC staff for their support and cooperation.

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1 Introduction

Phenomenal growth of the Internet has led to an ever-increasing demand for bandwidth. In today’s networks, the traffic is dominated by IP-based data traffic rather than traditional telephone-based traffic. To support a number of high-capacity network applications, we can either increase the number of wavelengths at 10 Gbps (OC-192) or increase the bit rate to 40 Gbps (OC-768). We can achieve a spectral efficiency of 0.4 b/s/Hz by deploying 10 Gbps channels on 25 GHz channel spacing or 40 Gbps channels on 100 GHz spacing. The latter seems attractive in the optical telecommunications industry for a number of reasons.

Nonlinear effects such as four-wave mixing and cross-phase modulation become a major concern when we decrease the channel spacing. At 40 Gbps, the channel spacing can be increased to 100 GHz and hence degradation of the system performance due to nonlinearities can be minimized. By increasing the per channel rate, we can achieve the same capacity with fewer components. Fewer components and fewer channels result in increased system reliability, survivability, and reduced operational expenses. There is less equipment to be monitored and less number of wavelengths need to be restored. There is a significant reduction in cost because the investment on equipment goes down, power and housing requirements go down and manpower is also reduced.

For the reasons stated above, 40 Gbps technologies are very attractive and it is not going to be long when all the major backbone networks will be operating at a channel rate of 40 Gbps.

The project aims at characterizing a link at 40 Gbps by addressing chromatic dispersion, polarization mode dispersion and signal-to-noise ratio issues. Chapter 2 talks in brief about the limitations at 40 Gbps and how to tackle them. Signal degradation due to chromatic dispersion and PMD and improvement in performance after compensation are presented in Chapter 3. It also has a description of the measurement set-up to send data at 40 Gbps through 95 km of buried standard SMF provided by Sprint with the results and analysis. Finally, the conclusions drawn and scope of future work are listed. The appendix discusses the measurement set-up for chromatic dispersion along with the results obtained and detailed analysis.

2 Challenges at 40 Gbps

A number of factors degrade the performance of fiber optic communication systems operating at 40 Gbps per channel. Optical signal-to-noise ratio (OSNR), chromatic dispersion and polarization mode dispersion (PMD) are serious limitations in 40 Gbps systems.

2.1 Optical signal-to-noise ratio

OSNR indicates the degree of degradation when an optical signal is carried in an optical transmission system. OSNR is the ratio of optical signal power to noise power in the channel.

$$OSNR\,(dB) = 10\log\left(\frac{S}{N}\right) \qquad \textbf{(1)}$$

where S is the optical signal power and N is the optical noise power.

Typically, a signal is affected by attenuation and dispersion. In a system with optical amplifiers to boost the signal, additional impairments such as amplified spontaneous emission (ASE) noise come into the picture. As a result, the OSNR degrades along the link. A good OSNR has to be maintained to enable the receiver to detect the signal accurately. In systems operating at 40 Gbps per channel, we need an OSNR of 6 dB higher than that required for 10 Gbps systems to achieve the same BER.

Increasing the gain of the amplifier will not serve the purpose because of addition of ASE noise and increasing the optical power will cause nonlinear effects, therefore we need to boost the signal periodically and balance the gain against the ASE noise, which the amplifier introduces.

2.2 Chromatic dispersion

Chromatic dispersion is a critical impairment in high-speed optical networks. Different spectral components travel with different velocities along the length of the fiber. This difference in propagation velocities arises from the variation of the refractive index of the core as a function of wavelength. This results in broadening of the pulse.

Pulse spreading will cause the pulse to overlap with neighboring pulses and if there is a considerable overlap, the adjacent pulses cannot be recovered completely at the receiver and this will cause errors. At a bit-rate of 10 Gbps, the bit period is 100 ps and at 40 Gbps, the bit period is reduced to 25 ps; hence, probability of detecting incorrectly is high in the latter.

The dispersion 'D' that can be tolerated is inversely proportional to the square of the bit rate 'R'. It is given by [3]

$$D\left({}^{ps}\!\!/\!_{nm}\right) = \frac{10^5}{R^2} \qquad \textbf{(2)}$$

At 10 Gbps, we can tolerate dispersion of 1000 ps/nm and at a data rate of 40 Gbps, we can tolerate a dispersion of 62.5 ps/nm. Therefore, we see that a channel operating at 40 Gbps is 16 times more sensitive to dispersion.

Hence, dispersion compensation has to be employed to send information at high bit rates. Standard single mode fiber (SSMF) has a positive chromatic dispersion of about 17 ps/nm-km at 1.55 μm and dispersion compensating fiber (DCF) has negative chromatic dispersion at 1.55 μm. Therefore DCF is used to compensate this positive dispersion with its negative dispersion.

2.3 Polarization mode dispersion

PMD is not an issue at low bit-rates. It is a serious limitation of long distance transport in 40 Gbps systems. Even in single mode fibers, there are actually two modes of propagation. An optical wave is represented as linear superposition of two orthogonal polarization modes. In ideal fibers, where the core has circular symmetry, the two modes are indistinguishable. In real fibers, loss of circular symmetry of the core leads to birefringence where the two polarization components travel with different propagation velocities. As a result, light pulse input into the fiber splits along the two modes and the pulses arrive at the end of the fiber with different velocities. The time difference between the pulses is called the differential group delay (DGD). Pulse broadening due to this is given the name polarization mode dispersion (PMD). Figure 2.1 illustrates the effect of PMD when a pulse is input into a short fiber.

PSP concept: Single mode fiber has a set of two orthogonal principal states of polarization (PSPs), which have the following properties. If the state of polarization (SOP) of light is aligned with one of the PSPs at the input of the fiber, the pulse emerges at the end of the fiber unchanged in shape and polarized along the output PSP of the fiber. If the input SOP of light is aligned somewhere in between the PSPs, the pulse is split into two orthogonal components along the PSPs and the pulses arrive at the end of the fiber, delayed in time.

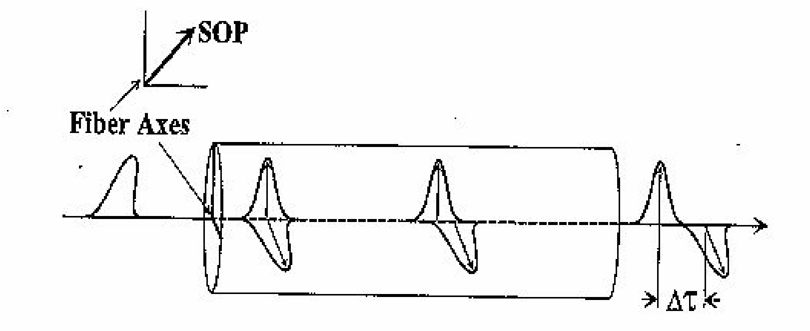

Figure 2.1 Time-domain effect of polarization mode dispersion in a short fiber

where $\Delta\tau$ is the differential group delay (DGD).

PMD is wavelength dependent and varies with movement of fiber and environmental changes such as temperature. Thus, PMD is a random process and to compensate for PMD, an adaptive PMD compensation system has been designed in the laboratory, here at KU.

2.3.1 Adaptive PMD compensation system

The block diagram of the adaptive first-order PMD compensation system is shown below in figure 2.2.

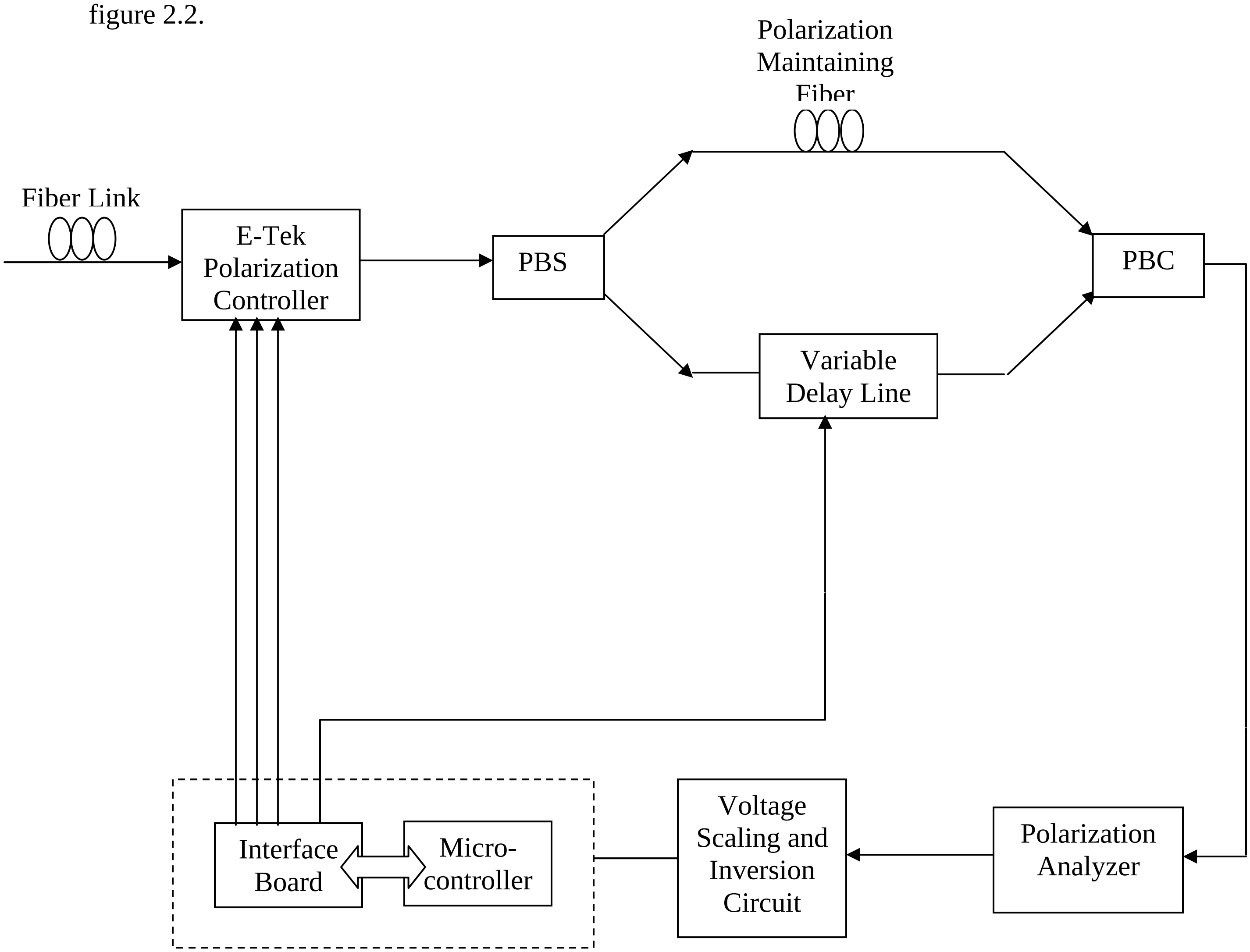

Figure 2.2 Functional Block Diagram of Adaptive PMD Compensation System. (PBS: Polarization beam splitter, PBC: Polarization beam combiner)

The PMD monitoring technique is based on the degree of polarization (DOP) of the received optical signal and this mechanism is bit-rate independent. Here is a brief description of how the compensation system works.

The optical signal at the output of the link, affected by PMD, is received by the E-Tek polarization controller (PC), which transforms the output PSPs of the link to align them with the input PSPs of the polarization beam splitter (PBS). The PBS has linear PSPs. The PC has four liquid crystal cells. We use three of the cells, as three are enough to achieve any SOP on the Poincare sphere. By applying varying voltages to the liquid crystal cells, different orientations of the orthogonal polarization axes can be attained. The control signals are given to the PC by the microcontroller. Figure 2.3 shows the purpose of E-Tek polarization controller in the PMD compensation system.

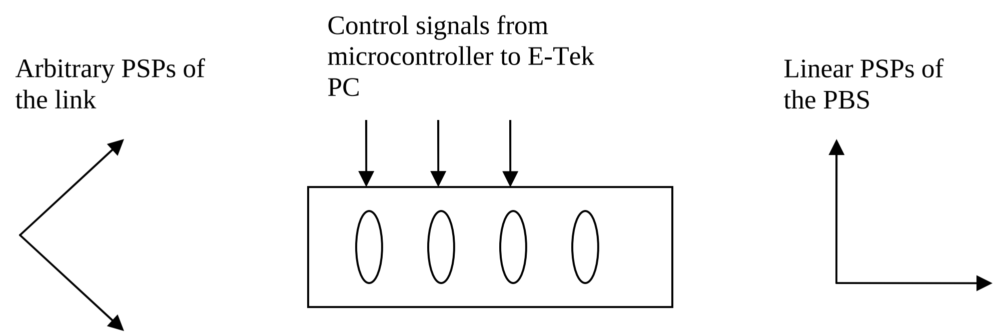

Figure 2.3 Function of E-Tek polarization controller

The PBS splits the incoming pulse along the two orthogonal axes. The slower component is made to travel along the path that contains the fixed length of polarization maintaining fiber and the faster component travels along the path that has the variable delay line. Based on the control signals from the microcontroller, the delay line is adjusted so that the faster component is slowed down and aligned with the slow component. The two components are combined on the polarization beam combiner (PBC) and the signal is fed to the polarization analyzer, which continuously measures the degree of polarization (DOP) and outputs an equivalent analog voltage. The compensation algorithm uses DOP as feedback. As the DGD increases, the DOP decreases. DOP also goes down if a good OSNR is not maintained. 0 % to 100 % DOP corresponds to an analog voltage of –10 V to 0 V as shown in Equation (3).

$$Volts = \frac{\%DOP - 100}{10} \tag{3}$$

There is a voltage inversion and scaling circuit designed to convert the analog voltage within the range 0 V to 5 V to make it acceptable to the microcontroller which sends control signals to the E-Tek PC and the variable delay line.

3 Experiments and Findings

Experiments were conducted to observe how chromatic dispersion and PMD impair the signal at 40 Gbps. DCF modules were used to compensate for chromatic dispersion and to compensate for PMD, the adaptive PMD compensation system developed in the laboratory was used to evaluate its performance at 40 Gbps.

3.1 Generation of 40 Gbps signal

The bit error rate tester (BERT) in the laboratory sends and receives data at 10 Gbps. We have to upgrade the 10 Gbps tester to 40 Gbps. The equipment needed to upgrade the pattern generator are SHF 10410 1:4 signal splitter, SHF 4005A 44 Gbps 4:1 multiplexer, SHF 5002A 50 Gbps 1: 4 demultiplexer and SHF 1020B frequency doubler.

The SHF 10410 1:4 signal splitter splits the input signal into four output signals. It receives the 10 Gbps signal from the BERT as input and outputs four 10 Gbps signals. The input peak-to-peak voltage should be less than 600 mV_{pp}. The output signals from the splitter are sent into a 4:1 multiplexer. The SHF 4005A 44 Gbps 4:1 multiplexer generates a data stream of four times the input data rate using four data signals and one clock signal at a frequency half the output bit rate. It operates up to 44 Gbps and it needs a 20 GHz clock signal to generate 40 Gbps. To provide a 20 GHz clock signal, we use a frequency doubler as the existing BERT has a clock source of only 10 GHz. The setup is shown in figure 3.1.

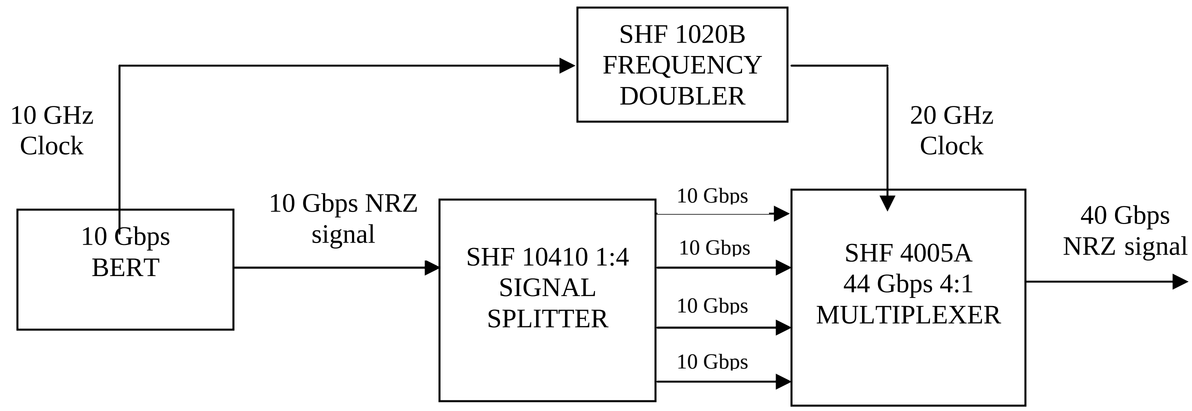

Figure 3.1 Generation of 40 Gbps signal from 10 Gbps BERT

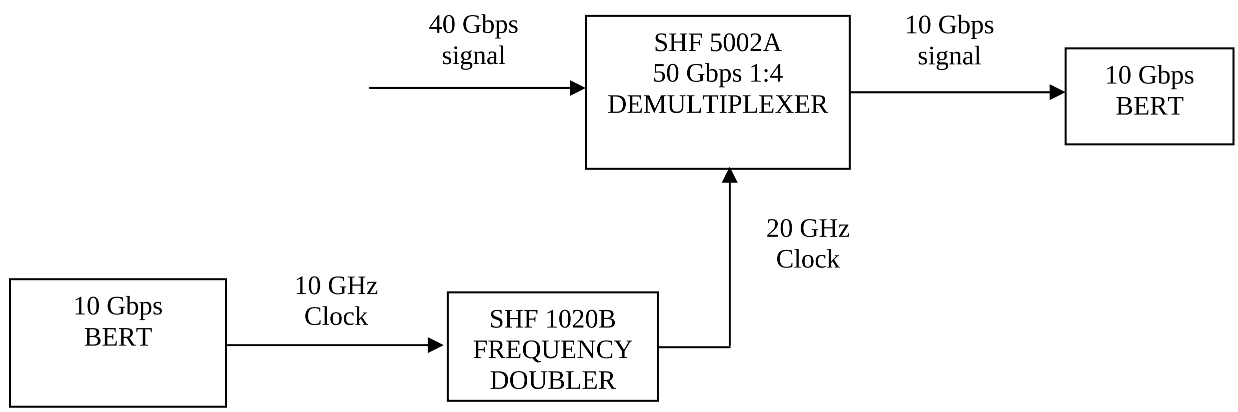

Figure 3.2 Regeneration of 10 Gbps signal from 40 Gbps signal

And finally to measure BER, the signal has to be converted back to 10 Gbps. The SHF 5002A 50 Gbps 1:4 demultiplexer outputs four data signals at one-fourth the bit-rate. If the input bit-rate is 40 Gbps, the demultiplexer extracts four signals of 10 Gbps and this also operates with half clock (i.e. 20 GHz). Figure 3.2 shows how a 10 Gbps signal is regenerated from 40 Gbps signal.

3.2 Hampering of the signal due to chromatic dispersion

At 40 Gbps, the bit period is reduced to 25 ps. We can tolerate a dispersion of only 62.5 ps/nm compared to 1000 ps/nm when operating at 10 Gbps. Thus, channel operating at 40 Gbps, is 16 times more sensitive to chromatic dispersion. Figure 3.3 shows the eye diagram for NRZ waveform when connected back-to-back at 40 Gbps. Figures 3.4 and 3.5 show how the signal gets distorted after 2 km and 5 km of SSMF. The measurement of eye diagrams show that after 5 km of SSMF spool, the signal is quite distorted by chromatic dispersion and there is a need for compensation.

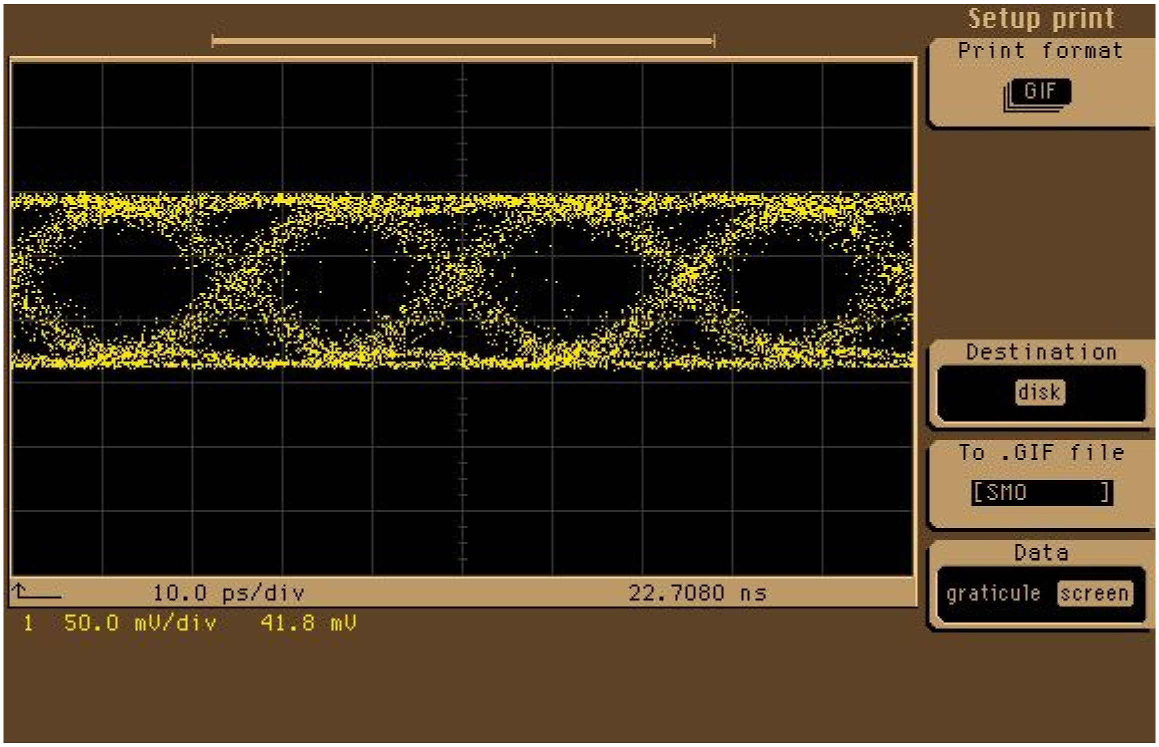

Figure 3.3 Eye-Diagram when connected back-to-back at 40 Gbps

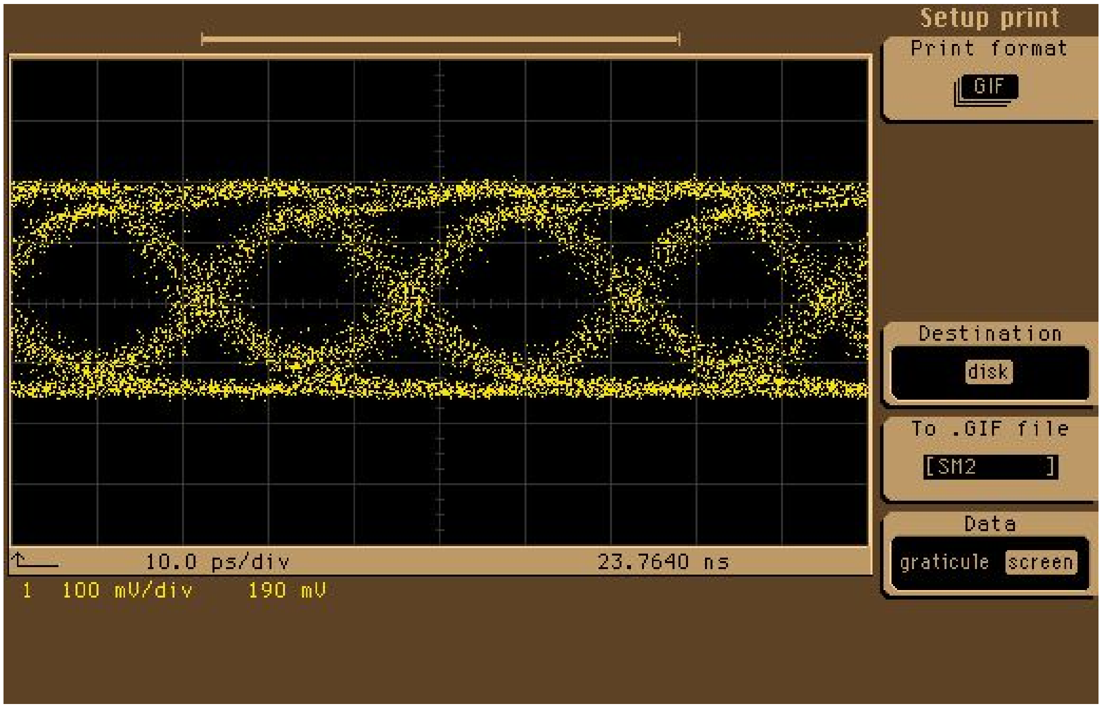

Figure 3.4 Eye-Diagram at 40 Gbps after 2 km transmission of SSMF

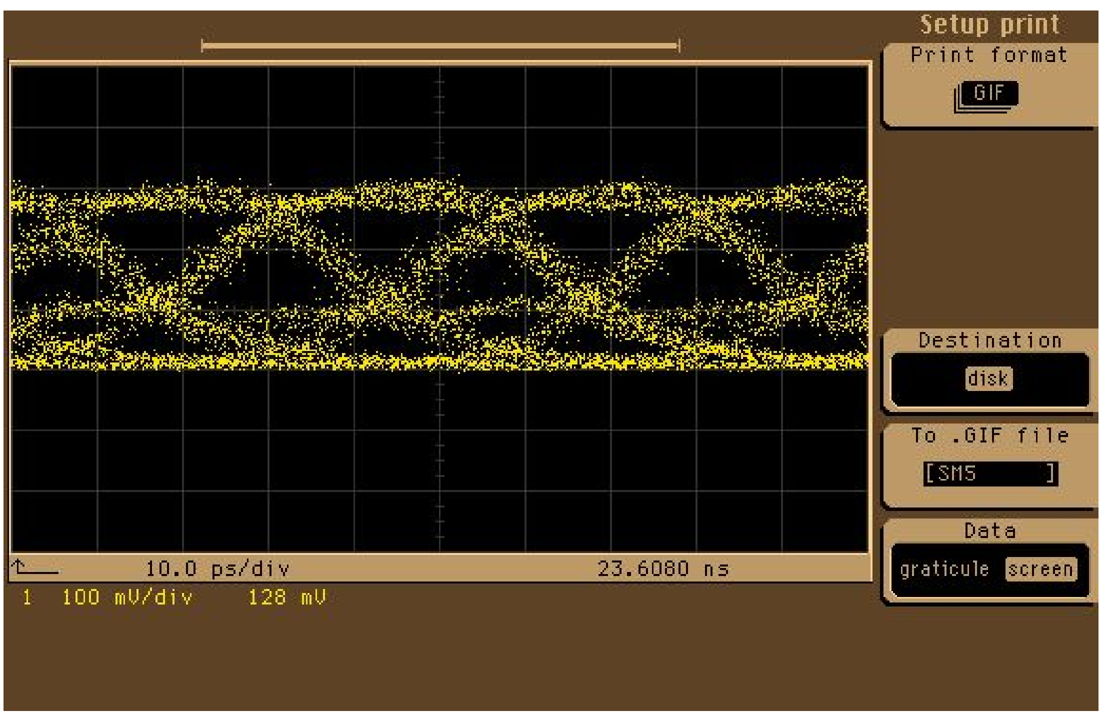

Figure 3.5 Eye-Diagram at 40 Gbps after 5 km transmission of SSMF

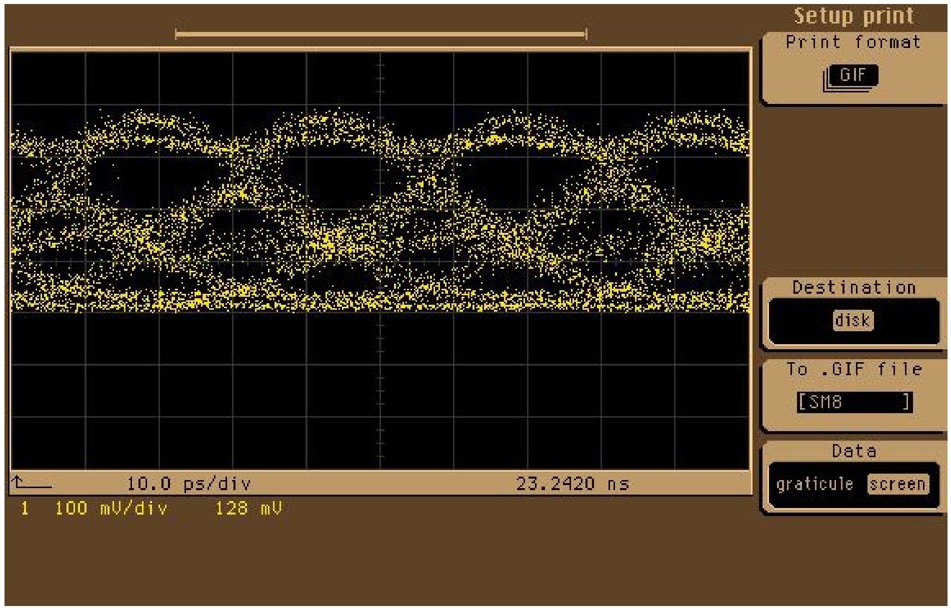

Figure 3.6 Eye-Diagram at 40 Gbps after 8 km transmission of SSMF

Observing the eye-diagram after 8 km of SSMF in figure 3.6, we see that the signal is largely affected by chromatic dispersion. The dispersion is approximately 136 ps/nm and we can tolerate only 60 ps/nm. Therefore, we employ DCF modules to nullify the effect.

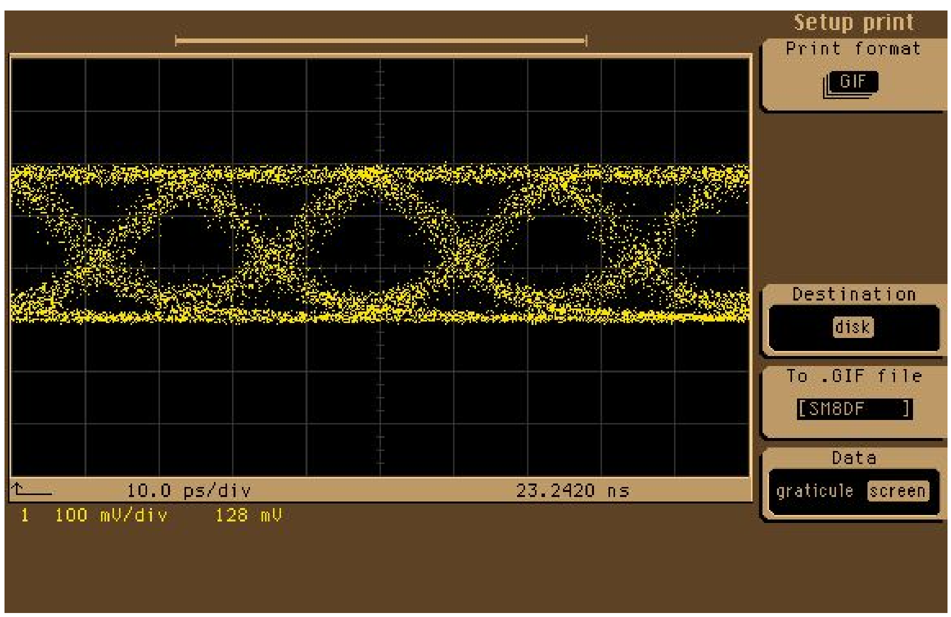

Figure 3.7 Eye-Diagram at 40 Gbps after 8 km transmission for SSMF and DCF-10

In figure 3.7, we observe that there is a significant opening of the eye when we introduced DCF modules. The eye is slightly distorted because we used DCF-10 for 8 km of SSMF. DCF-10 compensates chromatic dispersion for 10 km of SSMF.

3.3 Hampering of the signal due to PMD

As we know PMD is a random and stochastic process, it varies randomly with environment fluctuations and it is a serious limitation in high bit-rate systems. Pulse broadening due to PMD results in intersymbol interference (ISI). To see the effects of PMD, we emulated different amounts of DGD using the PMD emulator from JDS FITEL, which can emulate up to 120 ps of DGD and observed the eye-diagrams. Figures 3.9, 3.10 and 3.11 illustrate how the eye signal quality degrades when we introduce 10 ps, 20 ps and 30 ps of DGD.

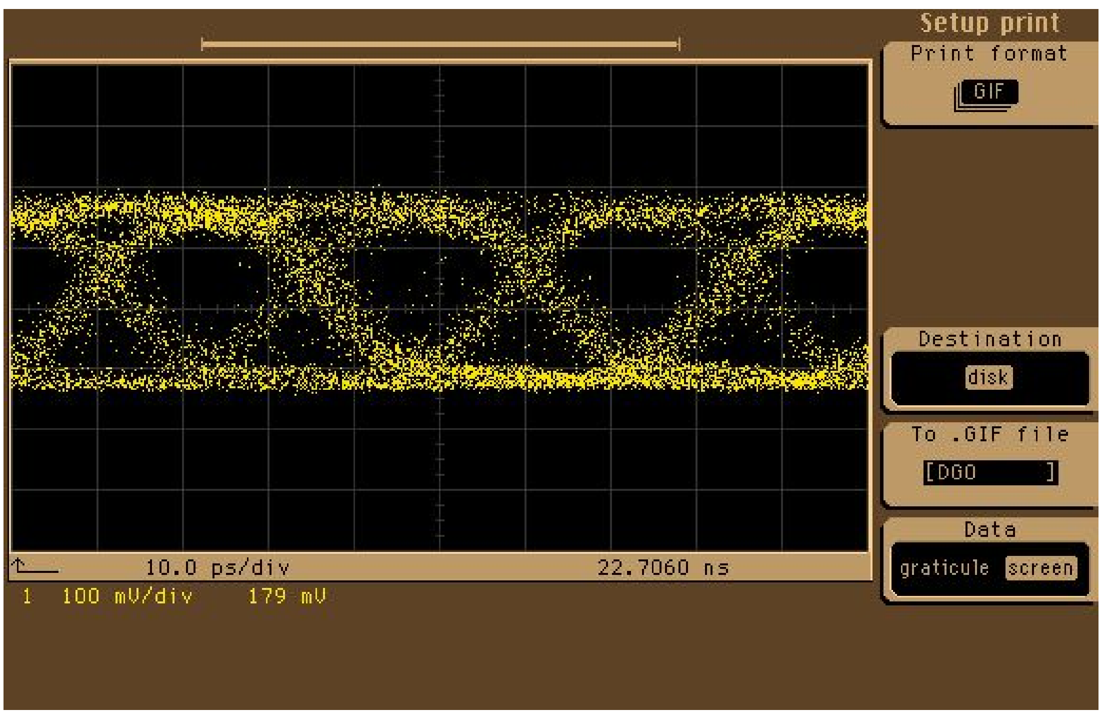

Figure 3.8 Emulated PMD: 0 ps

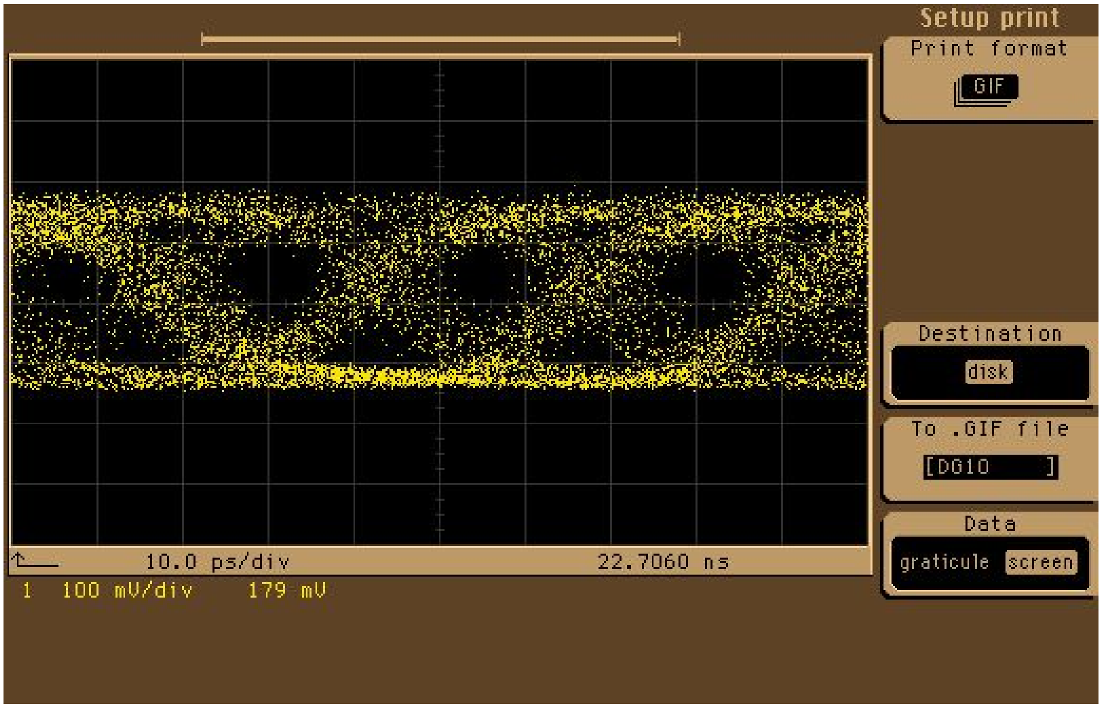

Figure 3.9 Emulated PMD: 10 ps

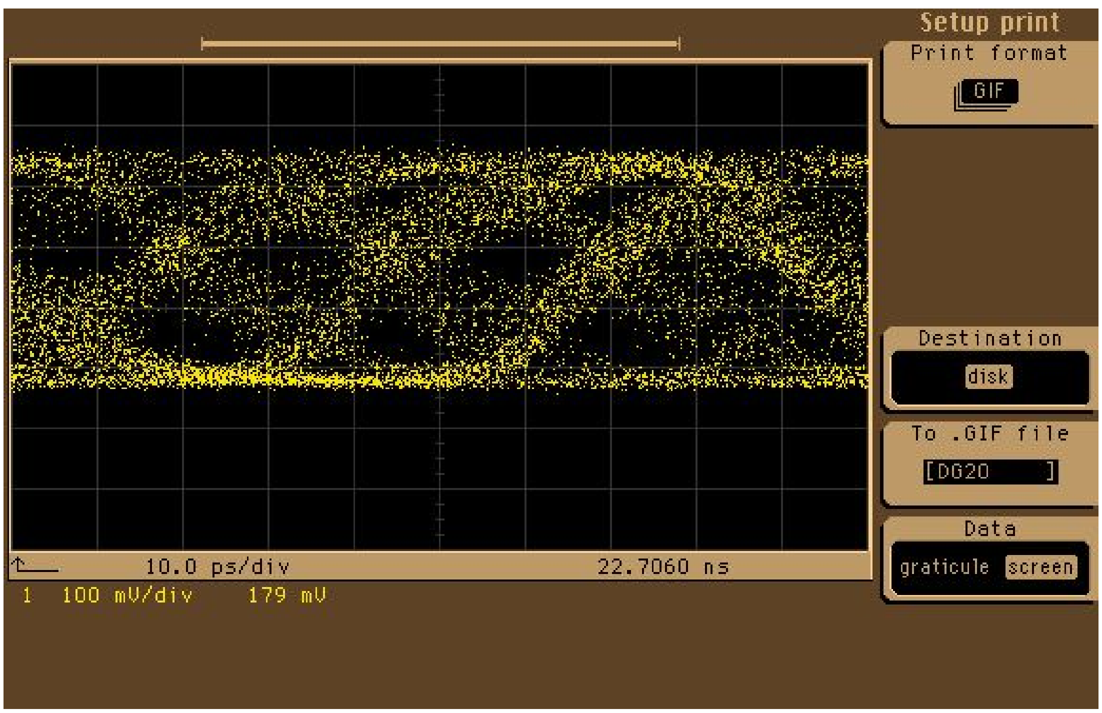

Figure 3.10 Emulated PMD: 20 ps

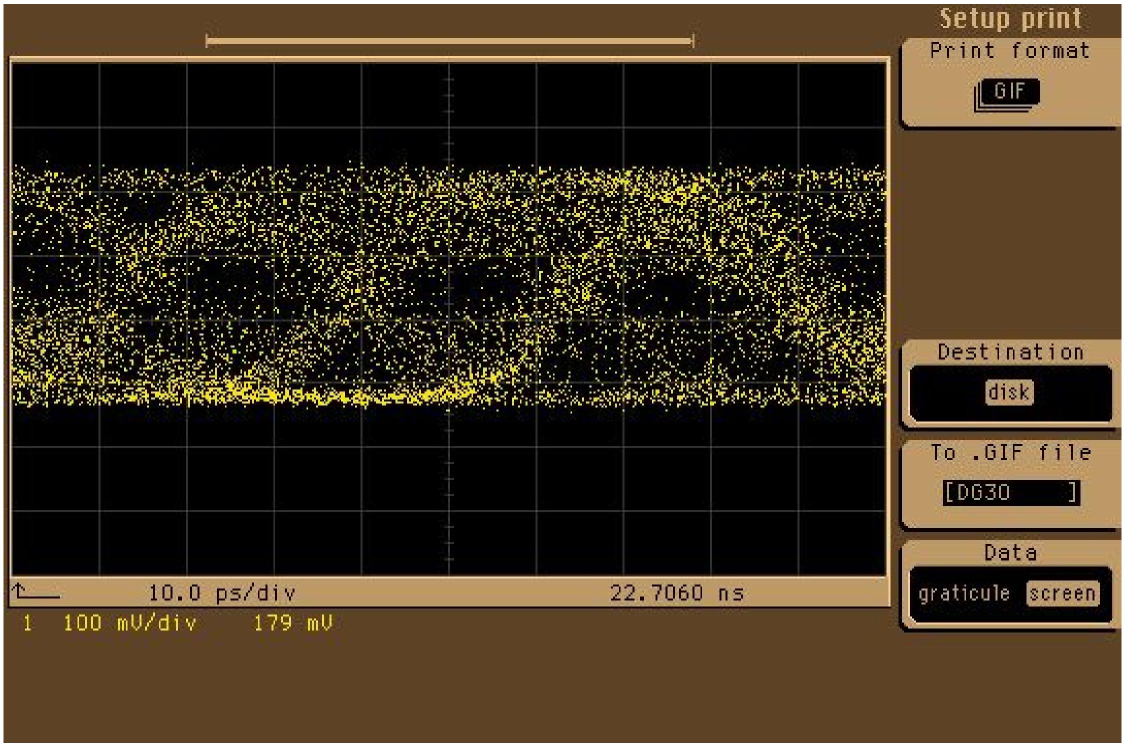

Figure 3.11 Emulated PMD: 30 ps

PMD depolarizes the optical signal. As the amount of optical power in the polarized state reduces, the DOP goes down. Table 3.1 shows the variation of DOP with emulated DGD. As the DGD increases, the DOP goes down.

Table 3.1 DOP measured before PMD compensation

Emulated DGD (ps)	DOP (%)
10	76.5
20	67.5
30	60.0

The adaptive PMD compensation system was tested at 40 Gbps. As this mechanism is based on degree of polarization, which is independent of the bit-rate, we expect to see considerable rise in the DOP values, which implies the PMD in the system, has been successfully compensated for. The eye diagrams have been monitored and the results are as follows. The improvement in performance after compensating for PMD is observed in figures 3.12, 3.13 and 3.14.

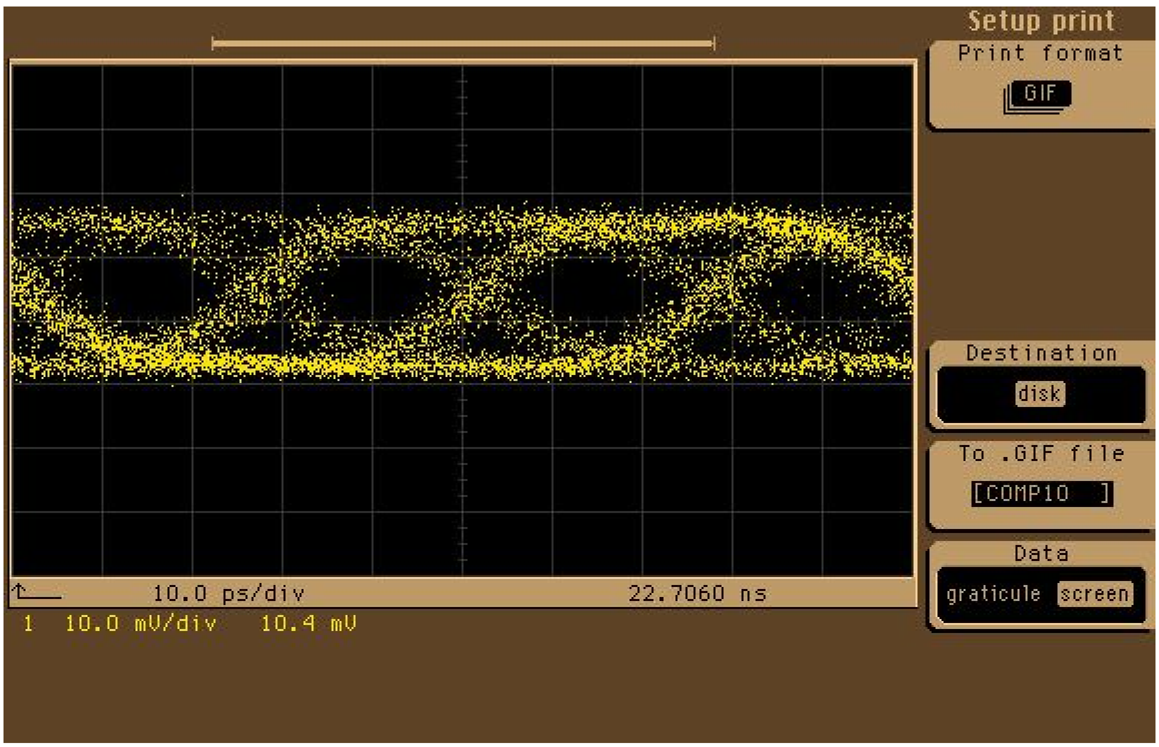

Figure 3.12 Eye-diagram after compensation. Emulated PMD: 10 ps

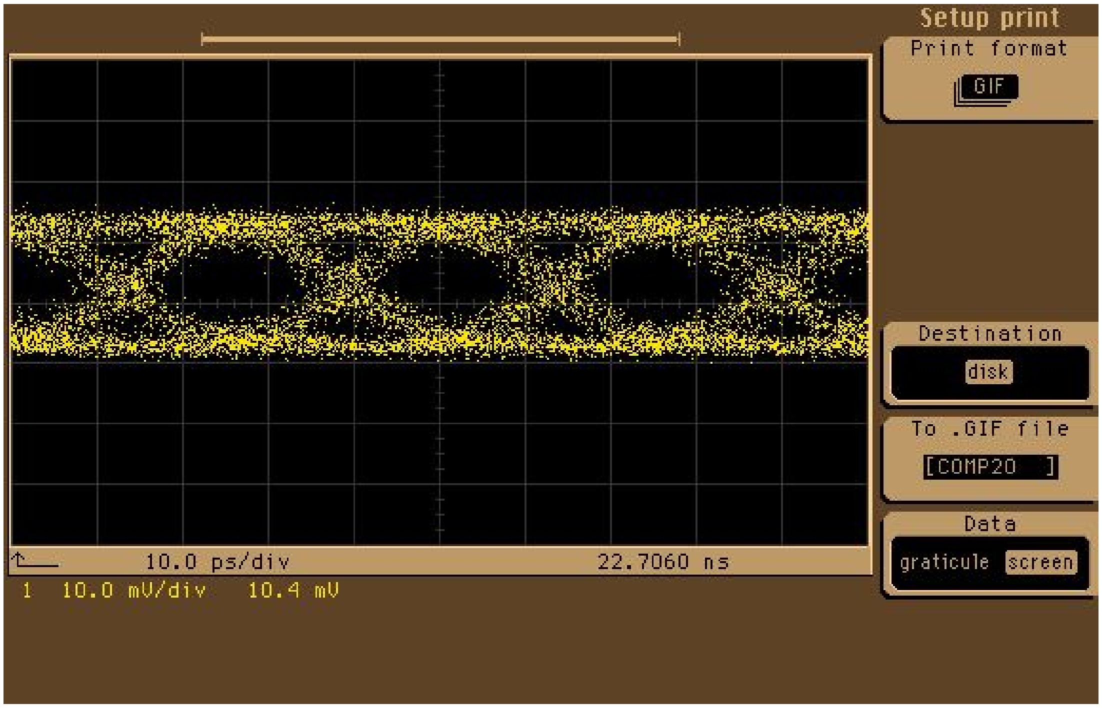

Figure 3.13 Eye-diagram after compensation. Emulated PMD: 20 ps

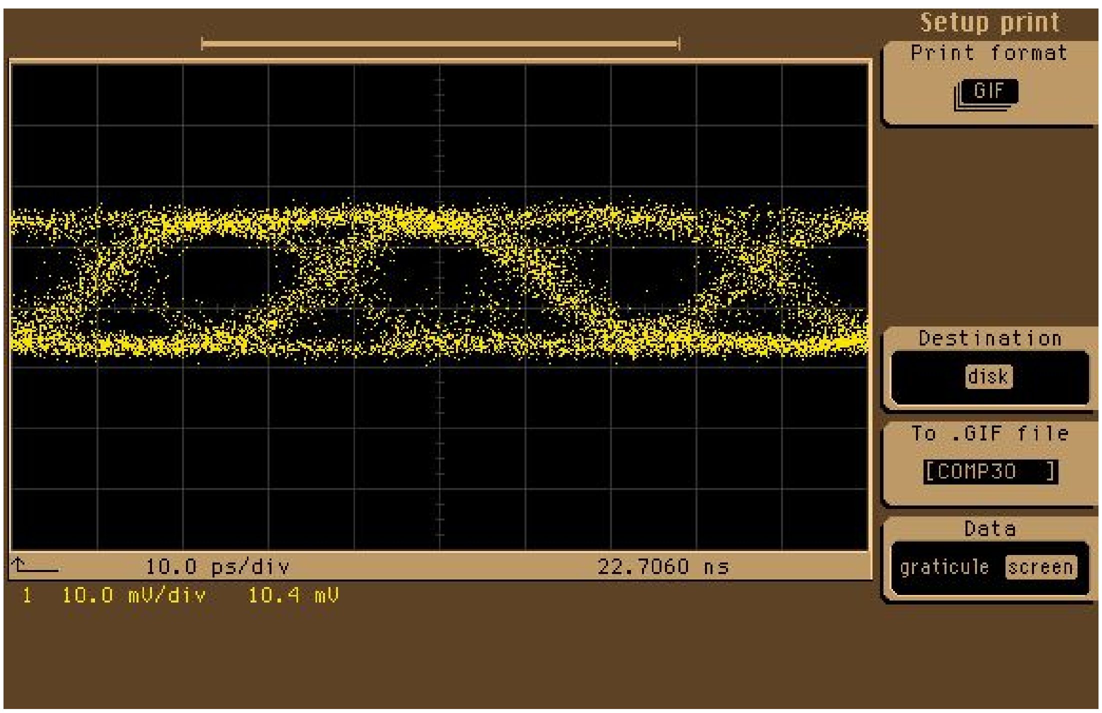

Figure 3.14 Eye-diagram after compensation. Emulated PMD: 30 ps

Table 3.2 lists the DOP measurement for different values of DGD, when we run the compensation algorithm.

Table 3.2 DOP measured after PMD compensation

Emulated DGD (ps)	Compensated DGD (ps)	DOP (%)
10	7	82
20	20	81
30	30	80

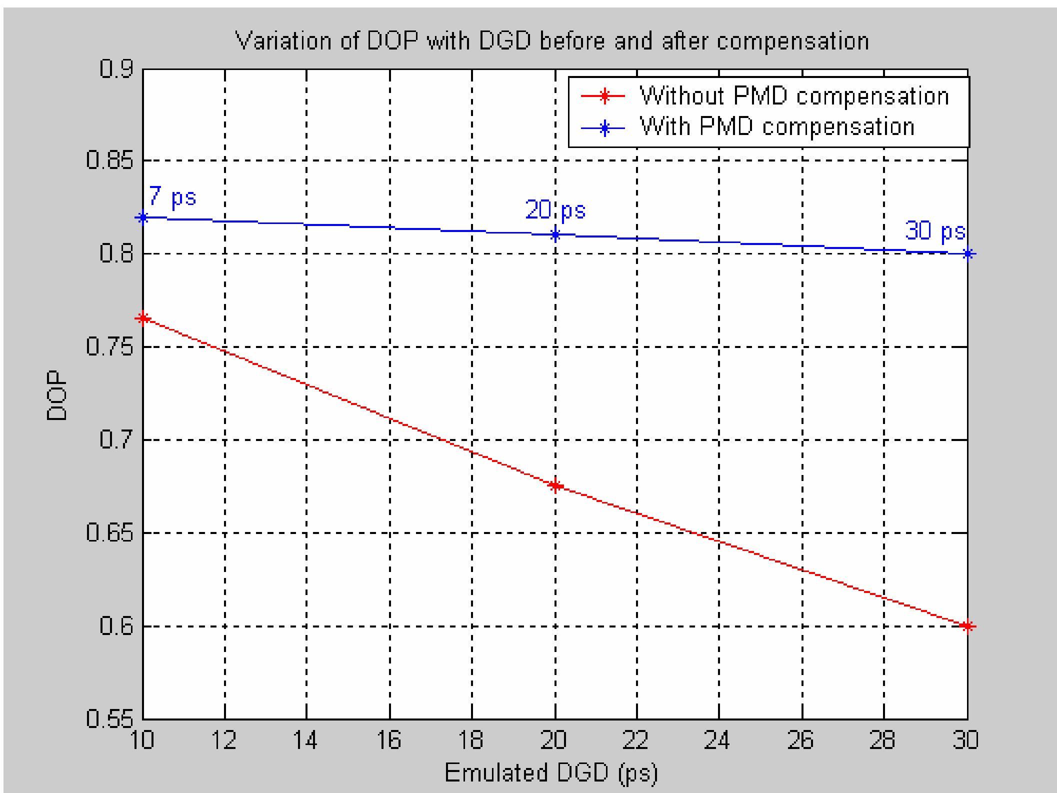

Figure 3.15 Variation of DOP with DGD before and after compensation

In figure 3.15 we observe a significant increase in the DOP values when we run the compensation algorithm. Thus, the adaptive PMD compensation system was tested successfully at 40 Gbps.

3.4 Variation of DOP with SNR and PMD

DOP degradation occurs due to presence of PMD and poor SNR. An experiment was conducted to see how DOP varies with SNR and find out what is the minimum signal-to-noise ratio that should be maintained to get a good polarized signal.

Laser was used as the signal source and an erbium doped fiber amplifier was used as a source of noise. A 2×2 coupler was used to couple the signal power and noise power and this was fed as input into the polarization analyzer, which would measure the DOP. Table 3.3 lists the DOP values for different values of SNR.

Table 3.3 Variation of DOP with SNR

SNR (dB)	DOP (%)
3.16	13.1
4.13	13.2
5.82	14.2
7.81	25.0
9.39	26.3
11.08	33.2
12.45	40.0
13.62	44.4
14.91	53.3
16.65	63.0
18.79	72.9
19.56	76.7
21.83	85.7
23.04	87.4
24.23	90.9
25.50	93.2
26.30	93.6
28.65	97.0
34.12	99.2

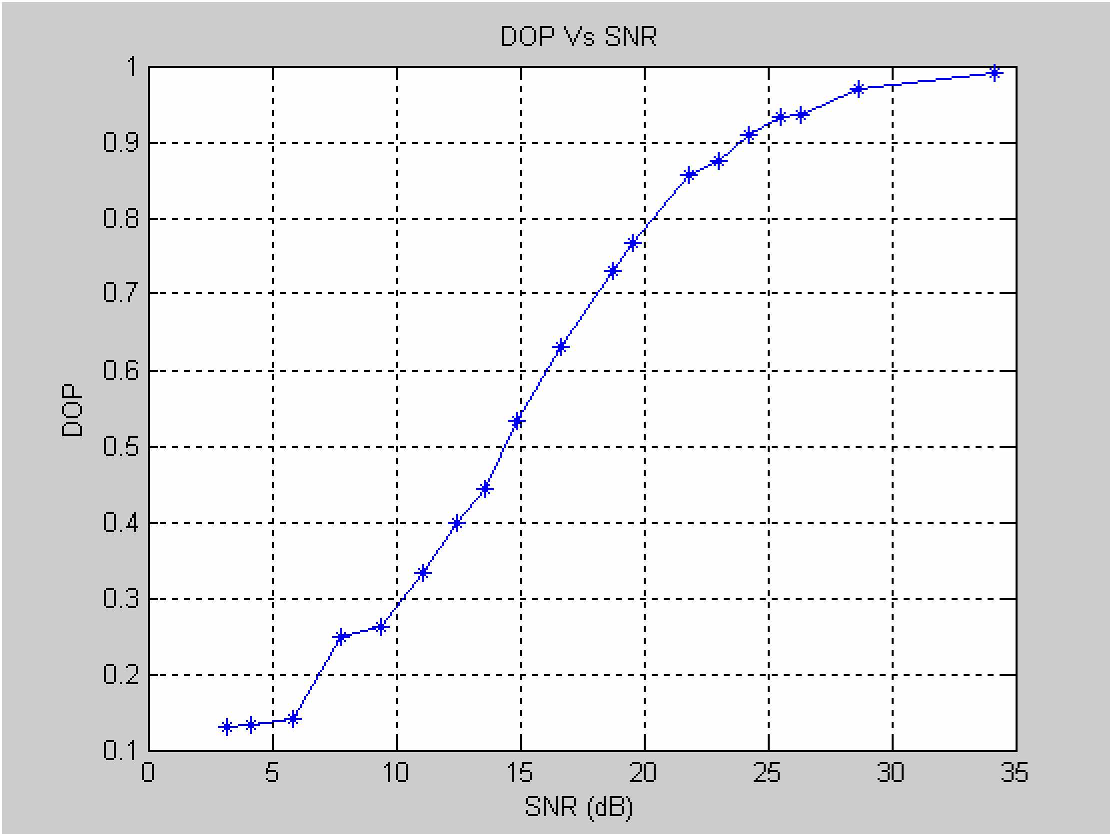

Figure 3.16 Variation of DOP with SNR

As seen in figure 3.16, to get a DOP of 90 % and higher, SNR of about 25 dB should be maintained.

We saw the variation of DOP with PMD in section 3.3.

3.5 Device under test: 10 km of single mode fiber

Prior to sending data at 40 Gbps on 95 km of buried single mode fiber, we tested the 40 Gbps system in the laboratory on 10 km of SSMF.

3.5.1 Experimental setup

The experimental setup to test the 40 Gbps system along with the PMD compensation system at this bit-rate is shown in figure 3.17.

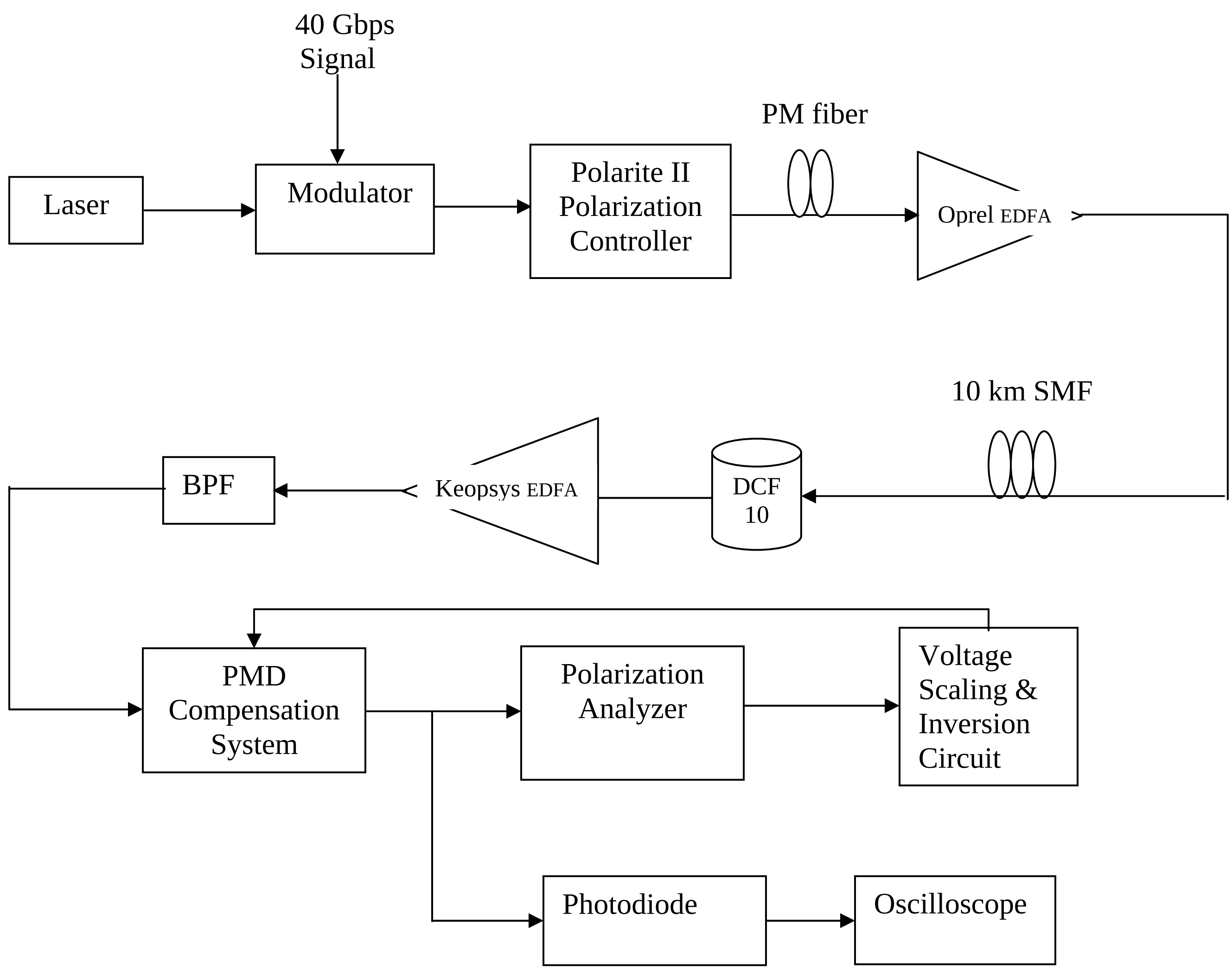

Figure 3.17 Experimental setup to test the PMD compensation system at 40 Gbps

3.5.2 Description and Results

The 10 Gbps pattern generator was used for transmitting a pseudo-random bit sequence (PRBS, 2^7-1) at an OC-192 data rate. With the help of a 1:4 signal splitter and 4:1 multiplexer, a 40 Gbps NRZ modulated signal is generated which is transmitted through 10 km of single mode fiber. The polarization controller is used for scrambling. One axis scrambling is performed at a frequency of 100 Hz. DCF 10 module is employed to compensate for chromatic dispersion. To emulate PMD in the system, we used polarization-maintaining (PM) fiber, which has a PMD of around 17 ps. The eye diagram monitored before introducing the PMD compensation system is shown in figure 3.18.

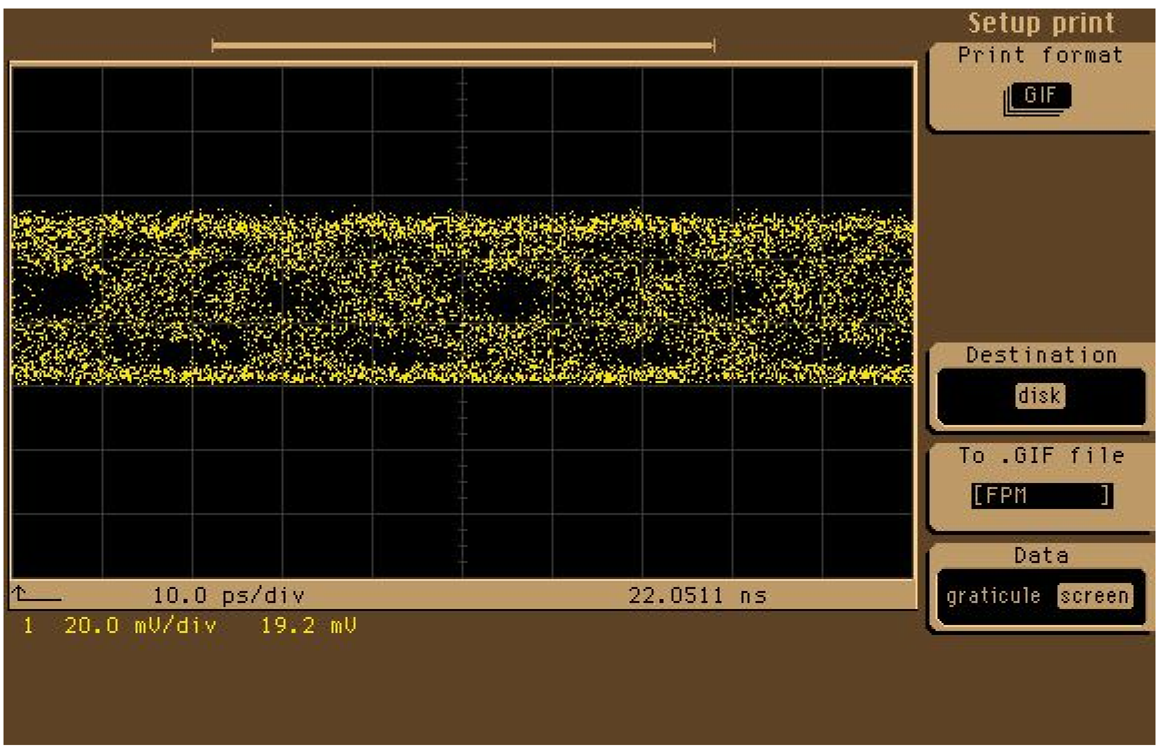

Figure 3.18 Eye diagram after 10 km of SMF and DCF 10 without PMD compensation

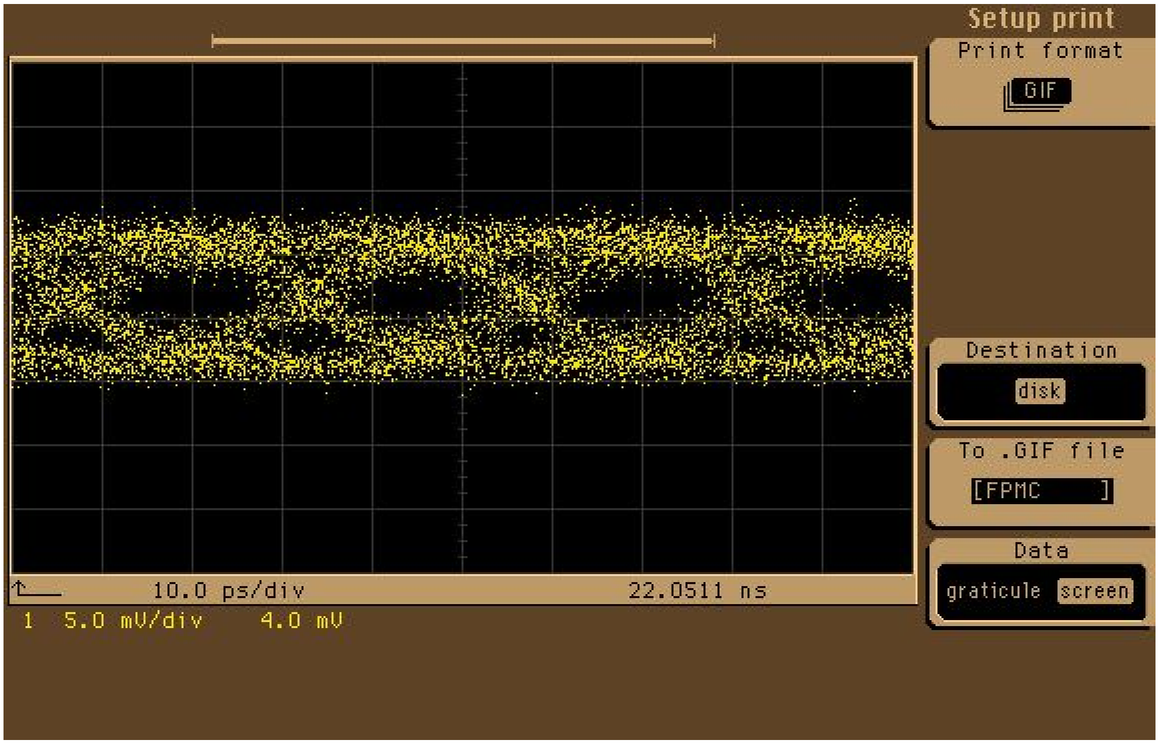

Figure 3.19 Eye diagram after 10 km of SMF and DCF 10 and PMD compensation

Figure 3.19 shows the eye diagram after running the PMD compensation algorithm. We observe a significant opening of the eye.

3.6 Description of field trial and results obtained

A field trial was conducted on 95 km of buried single mode fiber link. Experiments were done to calculate the loss through the link, measure chromatic dispersion and polarization mode dispersion in the link. Following which a link budget analysis was done to send data at 40 Gbps on the link and the BER of the system was calculated.

3.6.1 Characteristics of the link

Length of the link is ~ 95 km. The loss through the link including connectors is ~ 40 dB. A test method has been developed to measure chromatic dispersion in the laboratory, the description of which is given in detail in the Appendix. DCF modules were employed to mitigate the effects due to chromatic dispersion and a plot of dispersion after compensation versus wavelength was obtained which is as shown in figure 3.20.

Chromatic dispersion versus wavelength on 95 km of buried SMF-28 after compensation

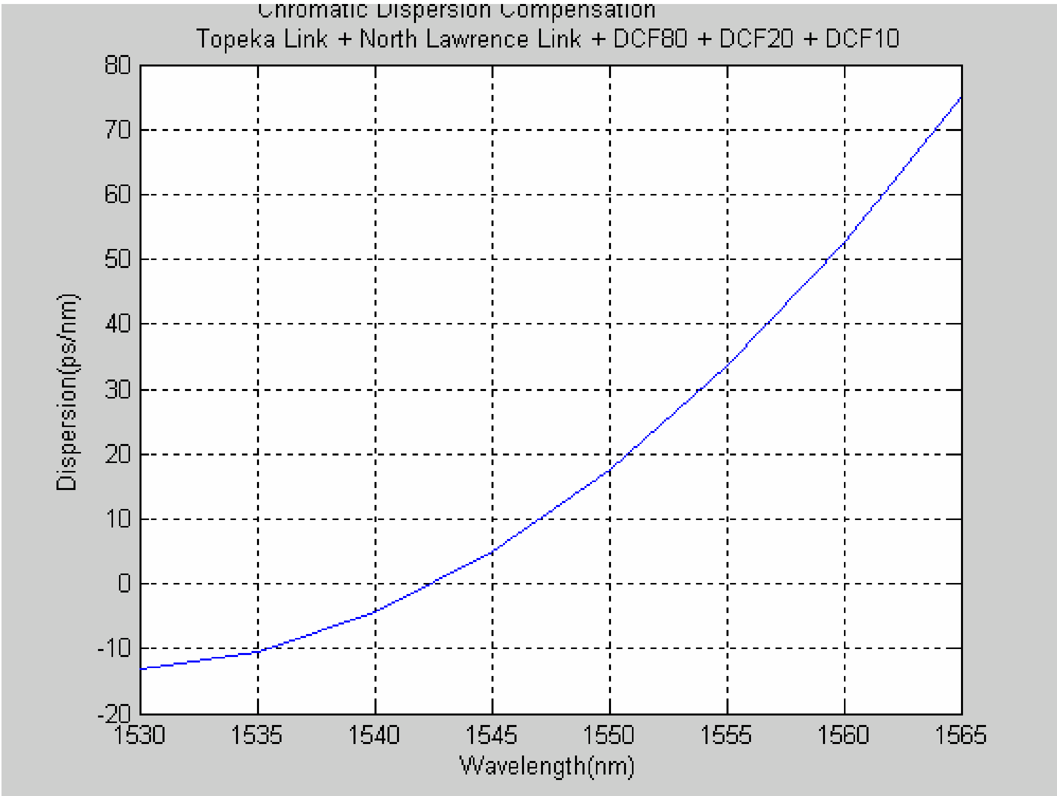

Figure 3.20 Plot of chromatic dispersion vs. wavelength on 95 km of buried SMF-28 after compensation

Zero dispersion can be achieved at around 1542 nm. To reduce the detrimental effects due to chromatic dispersion when sending data at 40 Gbps, we choose to operate at 1542 nm. Then to measure the PMD on the link, we used the jones matrix eigenanalysis method. The normalized DGD on the link was found to be 1.11 ps at the zero dispersion wavelength. Figure 3.21 shows the plot of normalized DGD versus wavelength on 95 km of buried single mode fiber.

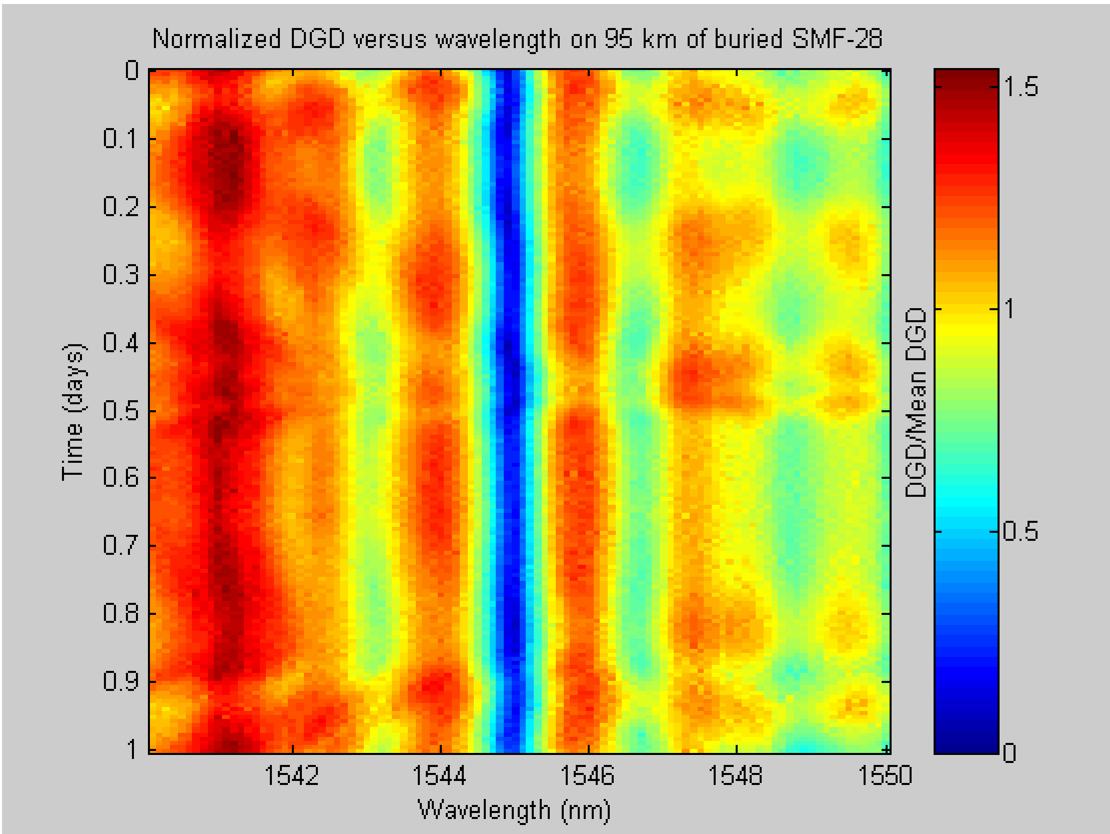

Figure 3.21 Normalized DGD versus wavelength on 95 km of buried SMF-28

3.6.2 Link budget analysis

The output power is maintained much below 10 dBm to avoid nonlinearities. We need not worry about cross phase modulation and four wave mixing as we are using just one channel. DCF modules are more susceptible to nonlinearities, as they have a smaller core diameter.

Therefore, the power entering the DCF modules is kept very low. The loss through the different components and gain of the amplifiers is given in the following table.

Table 3.4 Link budget analysis

Components	Loss (dB)	Gain (dB)
95 km buried SMF link	40	
18 km buried SMF link	7	
DCF 80	8.03	
DCF 20	2.94	
DCF 10	1.68	
Modulator	11.9	
Oprel EDFA		17.5
Keopsys EDFA 1		42
Keopsys EDFA 2		26

3.6.3 Experimental setup and description

The experimental setup for the field trial is shown in figure 3.22.

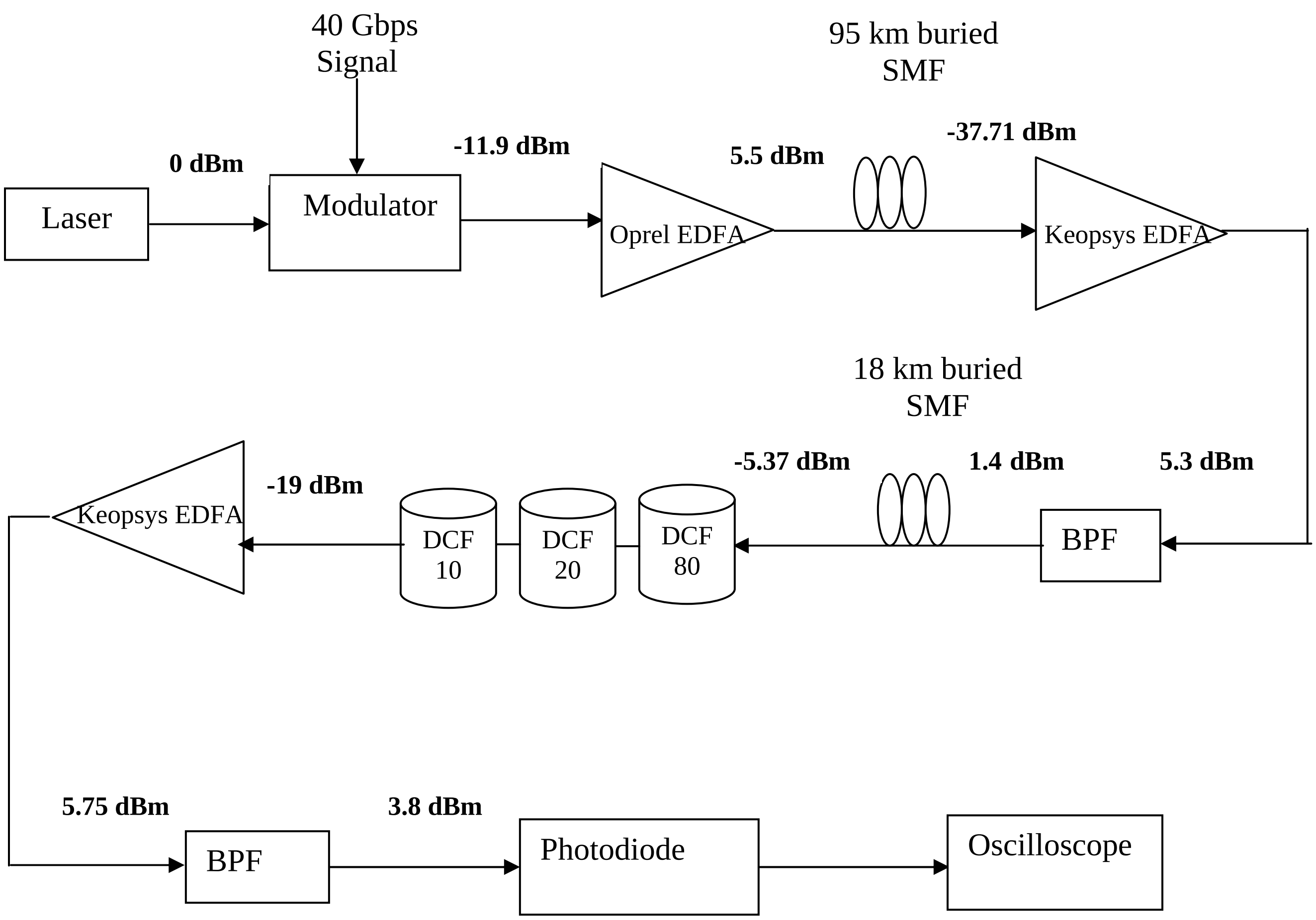

Figure 3.22 Experimental setup to send data at 40 Gbps on 95 km of buried SMF-28

The laser was operated at a wavelength of 1543 nm. The 10 Gbps pattern generator was used for transmitting a pseudo-random bit sequence (PRBS, 2^7-1) at an OC-192 data rate. With the help of a 1:4 signal splitter and 4:1 multiplexer, a 40 Gbps NRZ modulated signal is generated, which is fed into the 95 km fiber link. For management of chromatic dispersion, we need to include 18 km of buried fiber link and DCF 80, 20 and 10 modules. At the output of first Keopsys EDFA, the signal power is 5.3 dBm and the noise power is -10.38 dBm, which gives a SNR of 15.68 dB. The noise figure of Keopsys EDFA at 1543 nm is 4 dB. Therefore, the SNR at the output of second Keopsys EDFA comes out to be 11.68 dB. From figure 3.16, we observe that at a SNR of around 11.68 dB, the DOP is only 35 %. There is a huge reduction in DOP due to poor SNR. Due to this, we cannot see the effect of PMD on DOP.

3.6.4 Analysis

The digital receiver performance is governed by the bit-error-rate (BER). BER is the probability that a bit is identified incorrectly by the decision circuit of the receiver. In fiber optic communication systems, the error rates usually range from 10^{-9} to 10^{-12}. This value depends on the signal-to-noise ratio at the receiver. The BER can be calculated from the Q-factor as shown in [2]

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}} \frac{e^{-\frac{Q^2}{2}}}{Q} \quad \textbf{(4)}$$

Q is defined as

$$Q = \frac{I_1 - I_0}{\sqrt{\sigma_1^2} + \sqrt{\sigma_0^2}} \quad \textbf{(5)}$$

I_1 and I_0 are the average values when the bits transmitted are 1 and 0 respectively in the bit stream. σ_1^2 and σ_0^2 are the corresponding variances when 1 and 0 are received. Figure 3.23 (a) shows schematically the fluctuating signal received by the decision circuit. The circuit compares the sampled value I with a threshold value I_D and decides on bit 1 if I > I_D or bit 0 if I < I_D. Figure 3.23 (b) shows how P(0/1) and P(1/0) which are the probabilities of deciding 0 when 1 is received and vice versa, depend on the Gaussian probability density function of sampled value I and the dashed region shows the probability of incorrect identification.

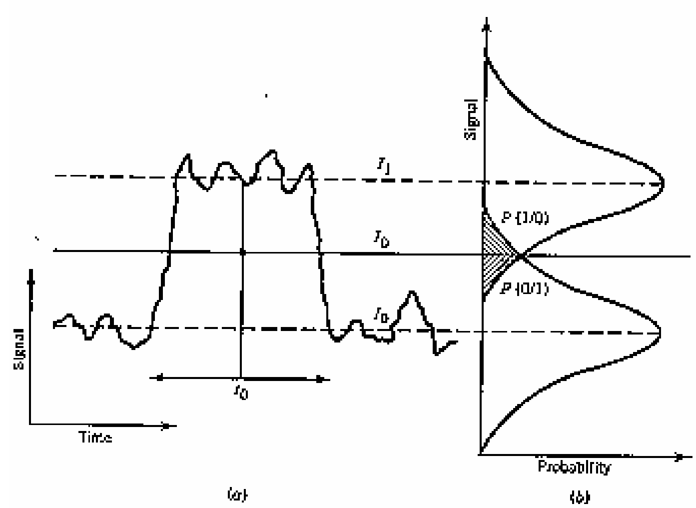

Figure 3.23 (a) Fluctuating signal generated at the receiver. (b) Gaussian probability densities of 1 and 0 bits. The dashed region shows the probability of incorrect identification.

The following plot figure 3.24 shows the averaged bit pattern after sending data at 40 Gbps through 95 km of buried SSMF.

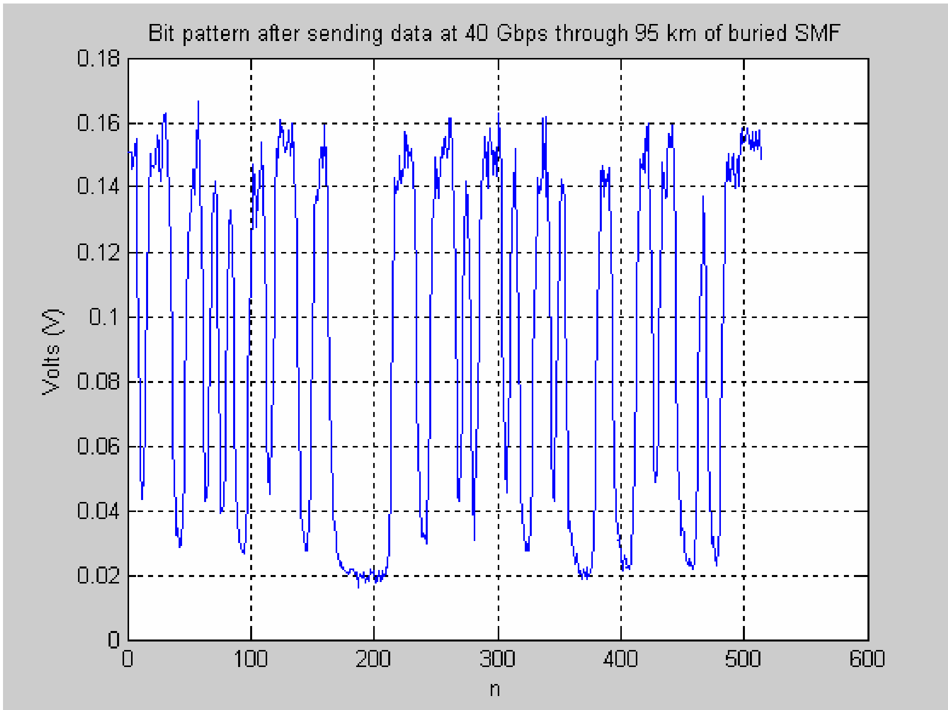

Figure 3.24 Averaged Bit pattern after sending data at 40 Gbps through 95 km of buried SMF-28

This is the bit pattern obtained after an averaging of 16 is done. While calculating Q, σ_1^2 and σ_0^2 are multiplied by 16 to get the actual value of variances. Using Equation (4), the value of Q is calculated to be 1.6537. From Equation (5), the BER of the system is 6.1×10^{-2}. This corresponds to an average of 6 errors per 100 bits. This shows that the SNR of the system is very poor and the system is noise limited. Figure 3.25 shows the eye diagram generated from the bit pattern.

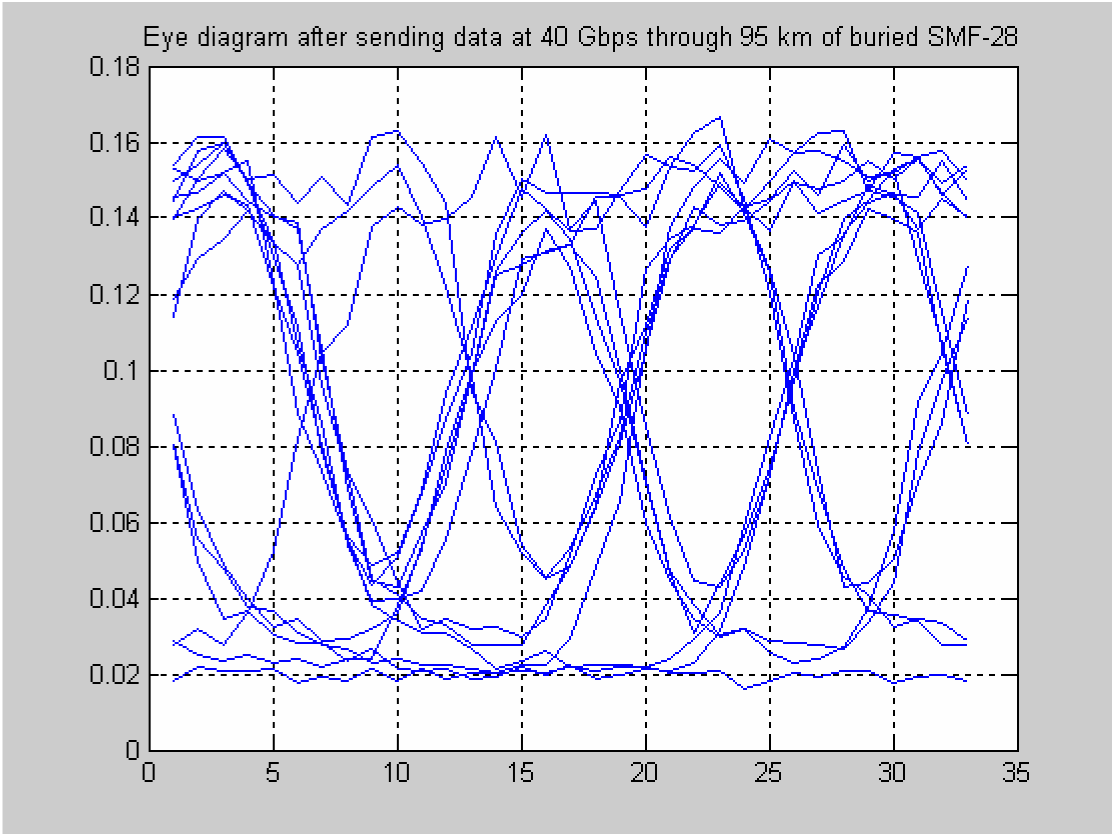

Figure 3.25 Eye diagram after sending data at 40 Gbps through 95 km of buried SMF-28

To improve the SNR of the system, erbium doped fiber amplifiers should be placed along the real link (95 km of fiber) to boost the signal periodically and avoid signal degradation.

4 Conclusion and future work

The 10 Gbps BERT was upgraded to generate a 40 Gbps NRZ signal. Tests were conducted to see how a channel operating at 40 Gbps is affected by chromatic dispersion, polarization mode dispersion and how these issues could be resolved.

Experiments showed that when operating at this high bit rate, the signal is largely affected by chromatic dispersion. Even after 5 km transmission through SSMF, the signal gets degraded and dispersion compensation has to be employed even for such short distances, as the channel is 16 times more sensitive to dispersion at 40 Gbps when compared to 10 Gbps.

To see the effect of polarization mode dispersion, a PMD emulator was used to introduce DGD in the system. We tested the adaptive PMD compensation system at 40 Gbps. There was an increase in DOP when we ran the compensation system.

When a field trial was performed on 95 km of buried single mode fiber, a BER of 6.1×10^{-2} was achieved. This is attributed to a poor SNR. The performance is mainly limited by noise. To improve the SNR of the system, erbium doped fiber amplifiers should be placed along the link to boost the signal periodically.

The adaptive PMD compensation system was not included in the setup as the SNR was very poor. The compensation system could not be tested for the field trial because the PMD monitoring mechanism is based on the DOP of the received signal and in this case, inferences cannot be made from the DOP measurement as there was a significant reduction in DOP due to SNR and hence the reduction due to PMD could not be observed.

We could not measure the BER along the link due to the following reason. We are not recovering the clock from the signal and are using the clock from the BERT. The alignment between the clock and signal might drift in time due to variations in temperature and this will result in misinterpretation of the data.

To do further experiments at 40 Gbps, EDFAs should be placed along the link and we need a clock recovery unit. To compensate accurately at 40 Gbps, tunable chromatic dispersion compensation is recommended as changes in temperature can lead to variations in dispersion, which becomes significant in 40 Gbps systems [8]. The 40 Gbps system with the PMD compensation system can be tested for different modulation formats such as RZ and CS-RZ (carrier suppressed return-to-zero).

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5 Appendix

The block diagram of the system used to measure chromatic dispersion in the laboratory is shown in figure 5.1.

5.1 Experimental setup to measure chromatic dispersion

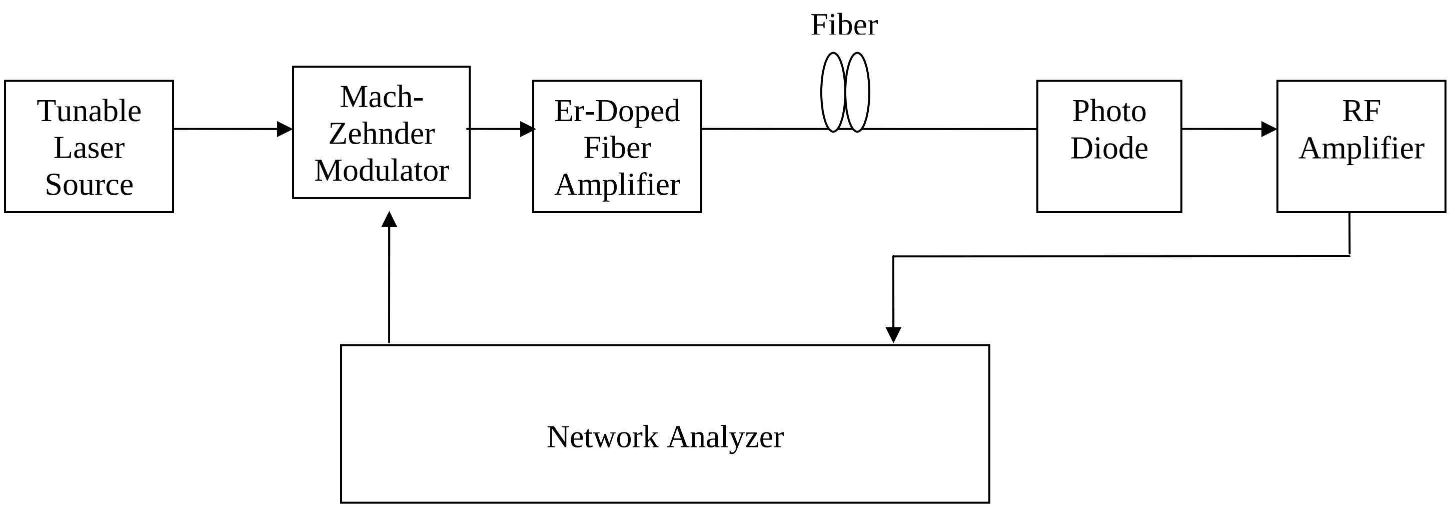

Figure 5.1 Experimental setup for measuring Chromatic Dispersion

5.2 Required Equipment

1. Tunable Laser Source: should be able to vary the wavelength over a range of at least 30 nm.

2. Mach-Zehnder Modulator: Bandwidth of 6 MHz.

3. EDFA: Optical Bandwidth: 1535-1565 nm

   Small Signal Gain: > 30 dB

4. Photo Diode: Bandwidth of 6 MHz.

5. Network Analyzer: Frequency of 6 MHz.

5.3 *Employing phase shift method to measure chromatic dispersion*

1. Calibrate the Network Analyzer.

2. Sinusoidal wave (f_m = 1 GHz) from the Network Analyzer is used to modulate the light coming out of a tunable laser source (variable wavelength light source). We vary the wavelength from 1520 nm to 1580 nm. Step size used is 0.5 nm.

3. The modulated laser light from the Mach-Zehnder modulator is then passed through an EDFA and then sent through the spool of fiber.

4. The optical signal is converted to an electrical signal by passing it through a photodiode. The signal is amplified with a RF amplifier and then sent back to the Network analyzer.

5. The phase of a signal at a particular wavelength is measured directly from the Network Analyzer. Phase of the signal at different wavelengths is measured.

Chromatic dispersion is calculated using the following formula:

$$D(\lambda_i) = \frac{\left[\phi(\lambda_{i+1}, f_m) - \phi(\lambda_i, f_m)\right]}{\left[2\pi f_m \Delta\lambda_i\right]} \qquad \textbf{(2)}$$

Where:

- λ_I = laser wavelength
- f_m = intensity modulation frequency = 1 GHz
- $\phi(\lambda_i, f_m)$ = phase
- $\Delta\lambda_i = \lambda_{i+1} - \lambda_i$ = 0.5 nm

5.4 Experimental Results

- Device under test: SMF-28 fiber (length = 5.458 km)
- Chromatic dispersion vs. Wavelength (f_m = 1 GHz, $\Delta \lambda_i$ = 0.5 nm)

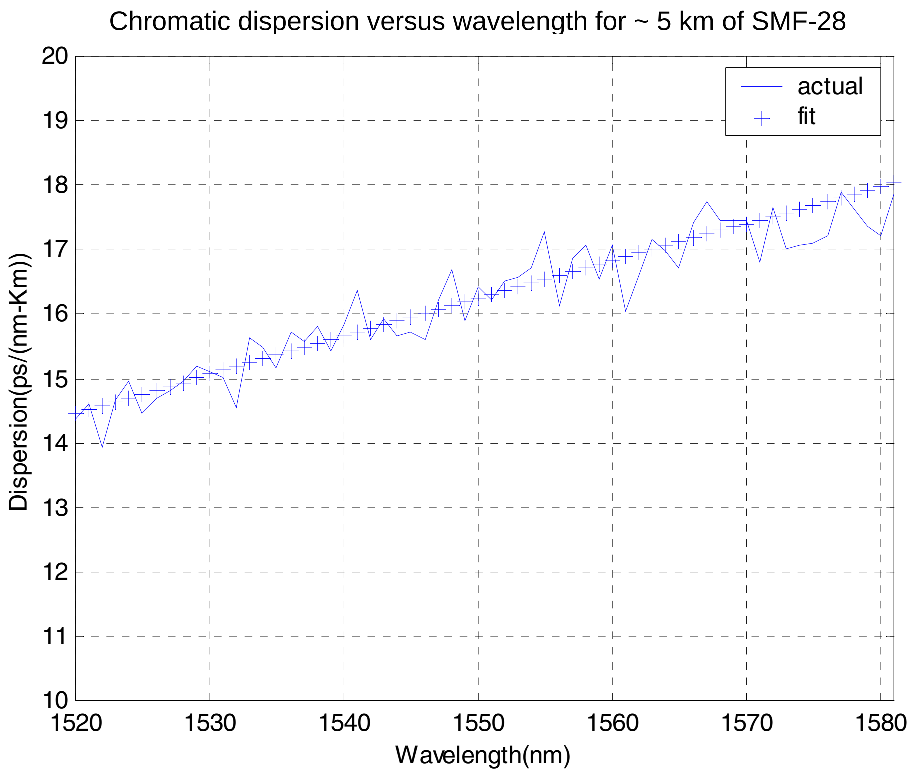

Figure 5.2 Plot of chromatic dispersion versus wavelength for 5 km of SMF-28

Equation used for curve fitting:

$D(\lambda) = (S_o \lambda / 4)(1 - \lambda_o^4 / \lambda^4)$

S_o = 0.09 ps/nm^2 km

λ_o = 1325 nm

5.5 Chromatic Dispersion Measurements over 95 km of buried SSMF

- SMF-28 Fiber (length ~ 95 km)
- $f_m = 2$ GHz, $\Delta \lambda_i = 0.1$nm

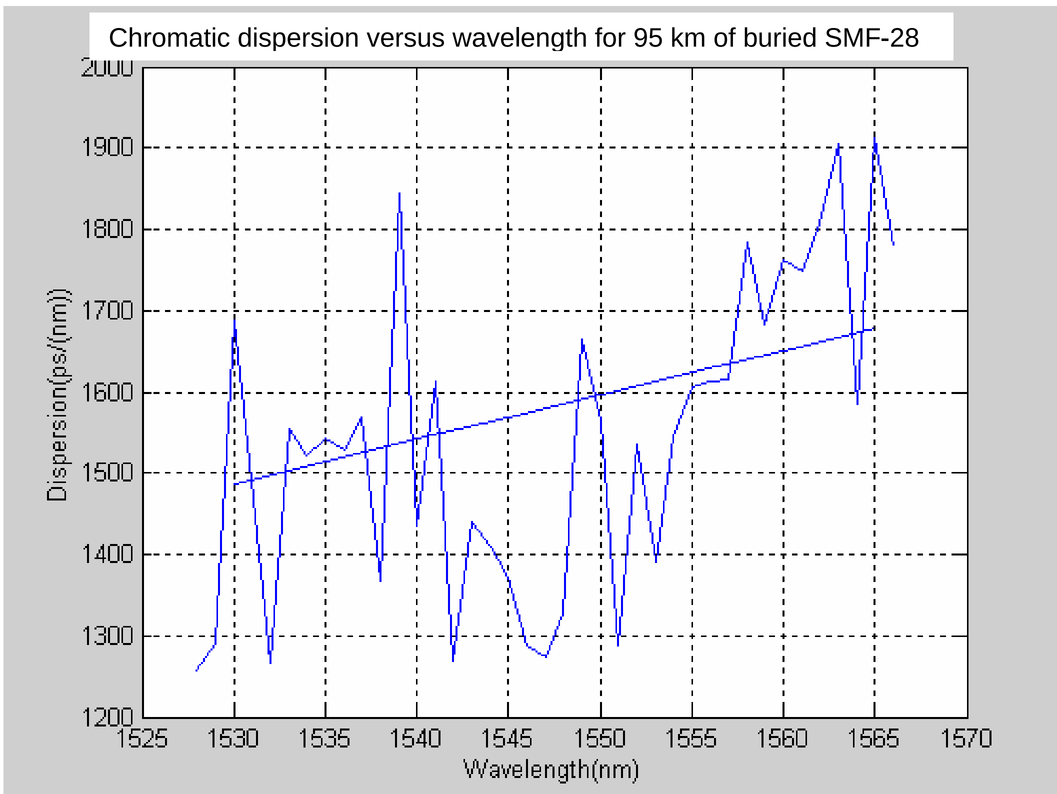

Figure 5.3 Plot of chromatic dispersion versus wavelength for 95 km of buried SMF-28

Equation used for curve fitting:

$D(\lambda) = (S_o \lambda /4)(1- \lambda_o^4 / \lambda^4)$

$S_o = 0.09$ ps/nm^2 km

$\lambda_o = 1315$ nm

5.6 Chromatic Dispersion Measurements over 18 km of buried SSMF

- SMF-28 Fiber (length ~ 18 km)
- $f_m = 1$ GHz, $\Delta \lambda_i = 0.5$ nm

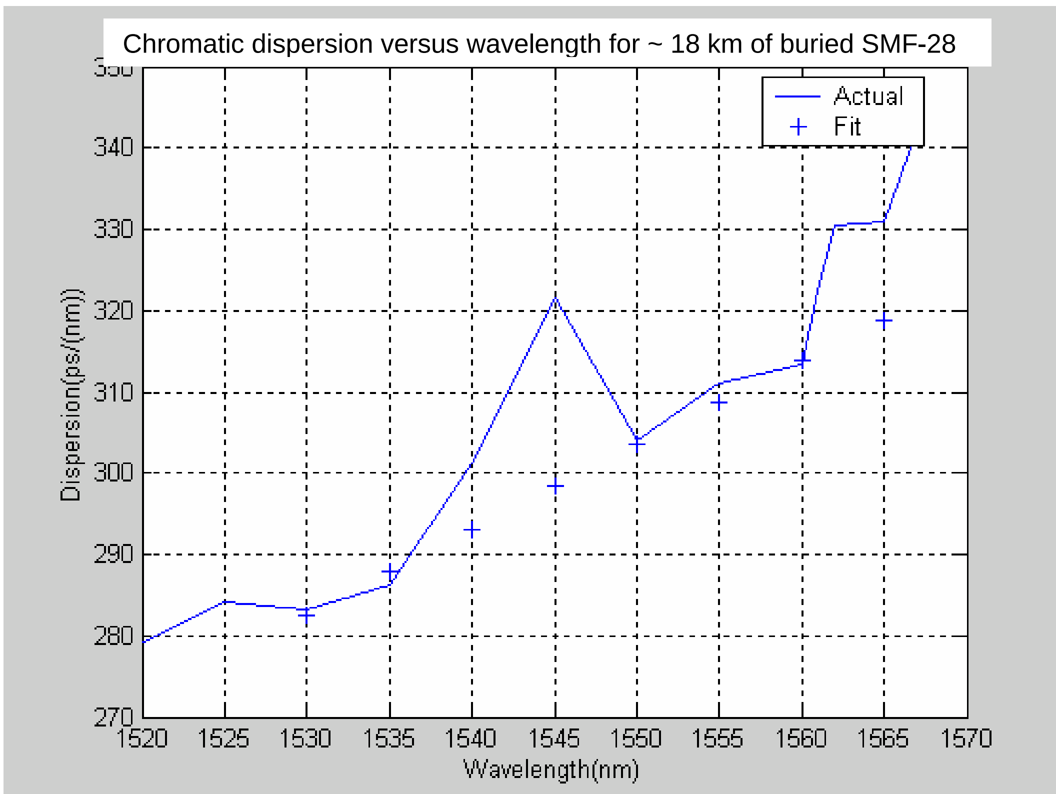

Figure 5.4 Plot of chromatic dispersion versus wavelength for 18 km of buried SMF-28

Equation used for curve fitting:

$D(\lambda) = (S_o \lambda /4)(1- \lambda_o^4 / \lambda^4)$

$S_o = 0.09$ ps/nm^2 km

$\lambda_o = 1314$ nm

As expected, standard single mode fiber has zero dispersion wavelength of about 1.325 μm and positive chromatic dispersion of about 17 ps/nm-km at 1.55 μm and DCF has negative chromatic dispersion at 1.55 μm. Therefore dispersion compensating fiber (DCF) is used to compensate this positive dispersion with its negative dispersion.

The following plots show how dispersion varies with wavelength for dispersion compensating modules.

- DCF10 (length ~ 3.476 km)
- $f_m = 1$ GHz, $\Delta \lambda_i = 0.5$ nm

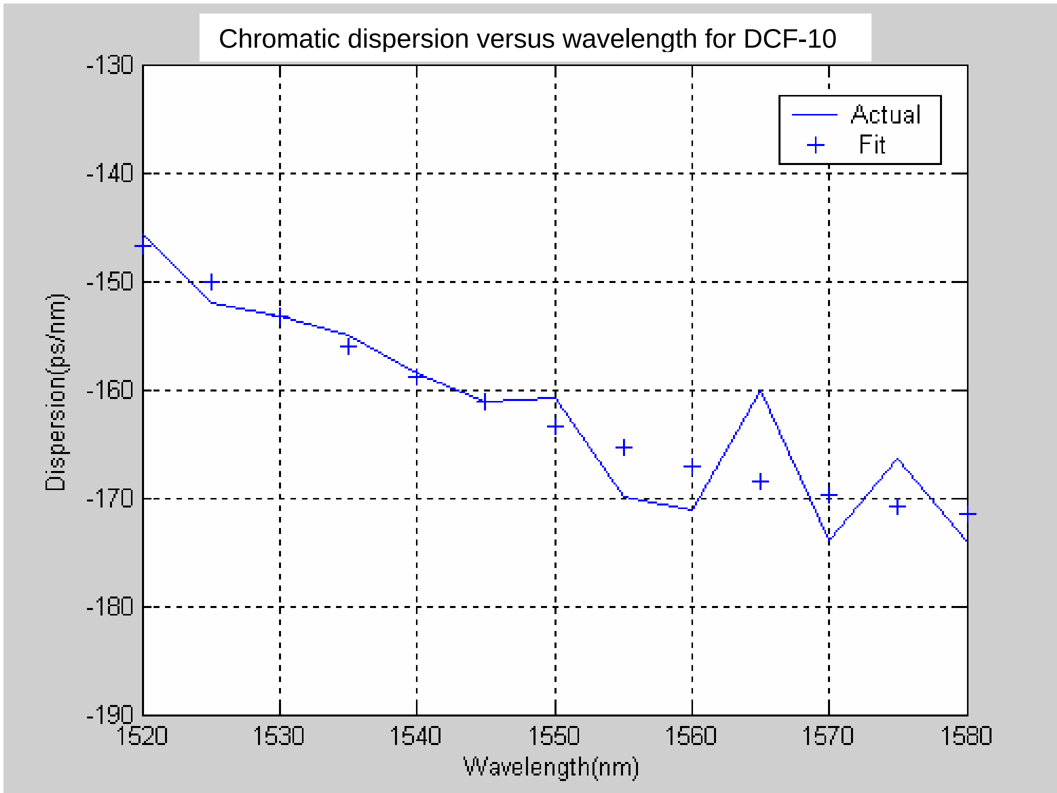

Figure 5.5 Plot of chromatic dispersion versus wavelength for DCF-10

Equation used for curve fitting:

Used a polynomial fit

y1 = ax^2 + bx + c

where

a = 0.00085037363

b = -2.71044549450

c = 2128.76094835080

- DCF20 (length ~ 3.556 km)
- f_m = 1 GHz, $\Delta \lambda_i$ = 0.5 nm

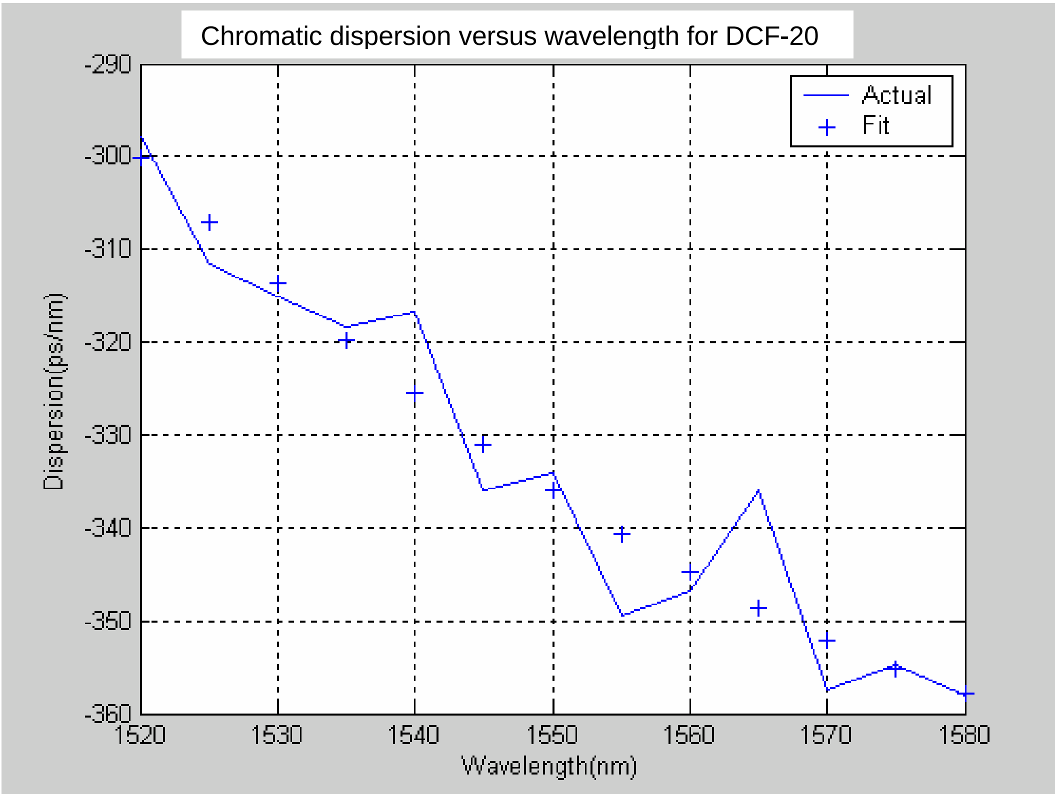

Figure 5.6 Plot of chromatic dispersion versus wavelength for DCF-20

Equation used for curve fitting:

Used Polynomial Fit

y2 = ax^2 + bx + c

where

a = 0.00139088911

b = -4.48461118881

c = 3549.06375024921

- DCF40 (length ~ 7.755 km)
- f_m = 1 GHz, $\Delta \lambda_i$ = 0.5 nm

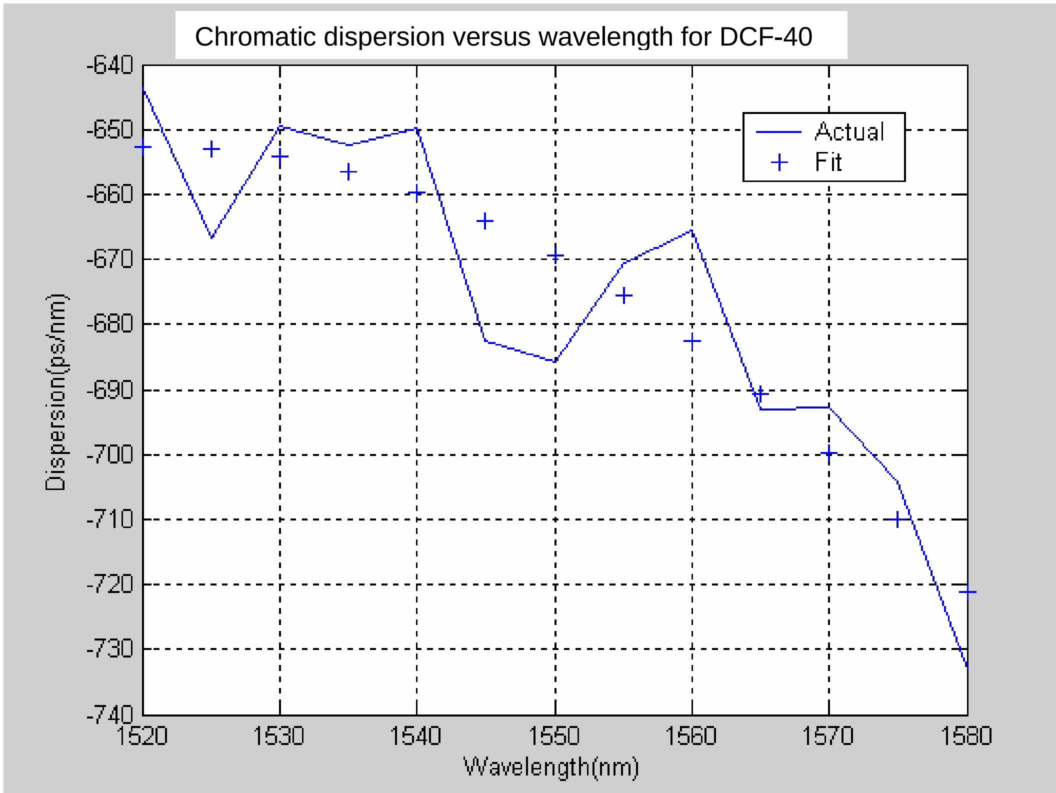

Figure 5.7 Plot of chromatic dispersion versus wavelength for DCF-40

Equation used for curve fitting:

Used polynomial fit

y3 = ax^2 + bx + c

where

a = -0.003526212188

b = 10.72544551447

c = -8273.39818490022

- DCF80 (length ~ 14.18 km)
- f_m = 1GHz, $\Delta \lambda_i$ = 0.5 nm

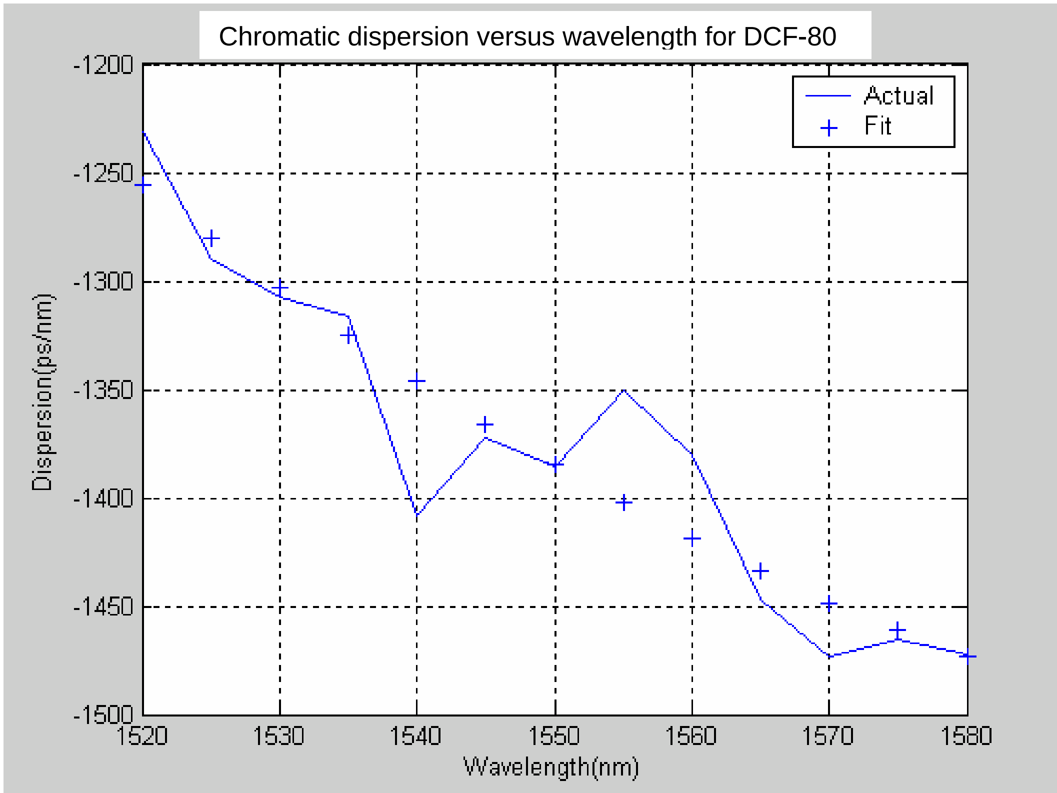

Figure 5.8 Plot of chromatic dispersion versus wavelength for DCF-80

Equation used for curve fitting:

Used polynomial fit

y4 = ax^2 + bx + c

where

a = 0.0041529071

b = -13.5268152847

c = 10739.9042677308

Observing the combined dispersion versus wavelength of DCF80, DCF20 and DCF10 modules. DCF10 means it can compensate chromatic dispersion for about 10 km of SMF-28 fiber. We need to compensate for 113 km of SMF-28 fiber (Topeka link + North Lawrence link)

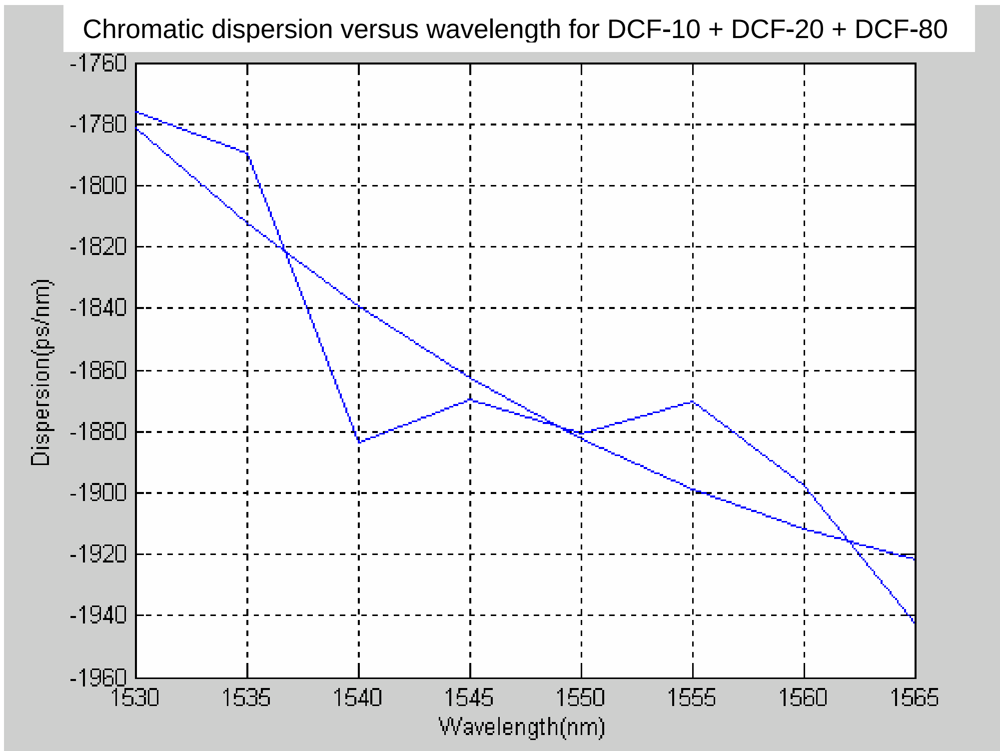

Figure 5.9 Plot of chromatic dispersion versus wavelength for DCF-10 + DCF-20 + DCF-80

Equation used for curve fitting:

Used polynomial fit

$y = y1 + y2 + y3$

From the following figure we observe that zero dispersion is achieved at around 1542 nm.

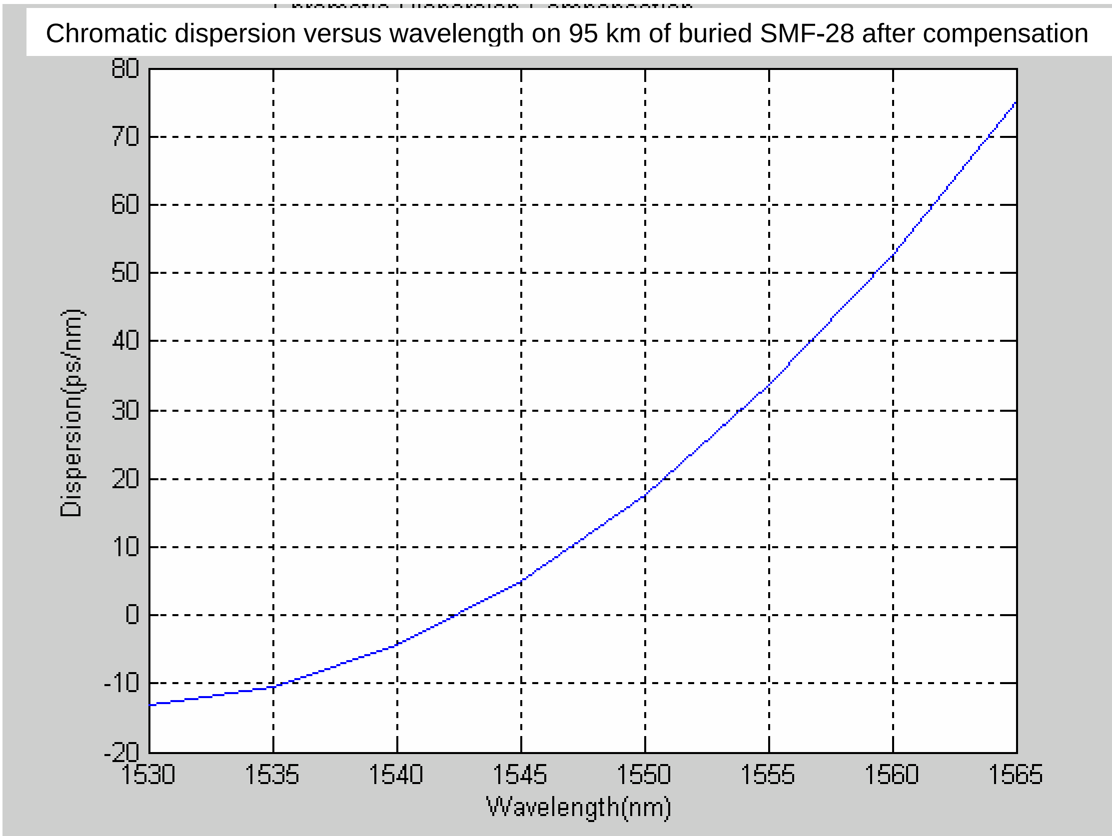

Figure 5.10 Plot of chromatic dispersion versus wavelength for 95 km of buried SMF-28 after compensation

5.7 Conclusion

We have seen that chromatic dispersion causes the pulse to broaden as it travels along the length of the fiber and we can compensate for this by using dispersion compensating fiber (DCF) modules. To compensate for the chromatic dispersion on 95 km of buried SMF-28, we need to use DCF80, DCF20 and DCF10 modules. We observe that zero dispersion is attained at ~ 1542 nm.