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Analysis of Various Loss Compensation Techniques in a Single Mode Fiber link

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Abstract*- The fiber optic communication system can transmit data at a rate of 10Gb/s or more ,over a maximum possible distance with less number of errors. Single mode fibers have been used as the major transmission media, especially for long haul communications. The major reason behind this is its high bandwidth, low losses and long installation lifetime compared with other fiber types. The important transmission properties of single mode fiber that affect the system performance are fiber attenuation and dispersion. Attenuation (or fiber loss) limits optical power reaching the receiver and determines the maximum transmission distance between the transmitter and receiver. Dispersion causes pulse distortion and broadening that limits the information carrying capacity of the fiber. A single mode fiber is modelled and studied the effects of dispersion and attenuation in the fiber optic link. Loss and dispersion compensation is provided in fiber optic link. Dispersion compensation is done using Dispersion compensating fiber, fiber grating and optical phase conjugator. Attenuation is compensated using lumped and distributed amplification method. The simulations have been carried out using Optisystem software version 12. Optical phase conjugator method for dispersion compensation is simulated using optsim 5.3 software.

Keywords--SMF, DCF, EDFA, distributed amplification, lumped amplification NRZ, optical phase conjugator, fiber bragg grating, Self phase modulation, Cross phase modulation, Four wave mixing, Eye diagram, BER.

I. INTRODUCTION

Optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Today, optical fibers are not only used in telecommunication links but also used in the internet and local area networks (LAN) to achieve high signaling rates. The optical fiber can be used as a medium for telecommunication and networking because it is flexible and can be bundled as cables.

A typical optical fiber bandwidth can range from approximately 100 MHz/km using multi-mode fiber to over 1000 MHz/km using single-mode fibers. Multi mode fibers are widely used for short distance (less than 100m) communications, and also in various sensing applications. Single mode fiber has a small core diameter compared to multimode fiber that allows only one mode of light to propagate. Because of this, the number of light reflections created as the light passes through the core decreases, lowering attenuation and creating the ability for the signal to travel faster. Since single mode fiber has lower attenuation and high bandwidth compared to multimode, they are typically used in long distance communications.

The important loss in the single mode fiber transmission that affect system performance are fiber attenuation, chromatic dispersion, polarization mode dispersion and nonlinearity. Attenuation limits the maximum distance. While dispersion of the optical pulse as it travels along the fiber limits the information capacity of the fiber. PMD-induced pulse broadening can move bits outside of their allocated time slots, resulting in errors and system failure in an unpredictable manner. The problem becomes serious as the bit rate increases and is of considerable concern for light wave systems in which each channel operates at a bit rate of 10 Gb/s or more.

Fiber attenuation must be compensated for transmission systems designed to operate over more than 100 km because their cumulative effects eventually make the signal so weak that information cannot be recovered at the receiver. The only loss-management technique available to the system designer until 1990 consisted of inserting an optoelectronic regenerator within the fiber link after every 80 km or so. In regenerator the optical bit stream is first converted into the electric domain and then regenerated with the help of an optical transmitter. This technique becomes quite cumbersome and expensive for WDM systems as it requires demultiplexing of individual channels at each repeater. Several kinds of optical amplifiers were developed during the 1980s to solve the loss-management problem. These amplifiers can amplify multiple WDM channels simultaneously in the optical domain itself and are much more cost-effective. The optical amplifiers can be divided into two categories, lumped and distributed amplifiers.

Optical amplifiers solve the loss problem but make the dispersion problem worse as dispersive effects can accumulate over long distances. The dispersion problem can be managed in practice through a dispersion-compensation fiber, fiber bragg grating and optical phase conjugator. The use of dispersion management can eliminate chromatic dispersion but does not affect the PMD-induced degradation of an optical signal. For this reason, PMD has become a major source of concern for modern optical communication systems. For this reason, techniques for compensating PMD attracted attention as early as 1994. PMD compensators make use of delay line to adjust differential group delay between polarization states.[1],[2]

II. MODELLING OF OPTICAL FIBER LINK

Single mode fiber link is modeled for analyzing attenuation, chromatic dispersion, polarization mode dispersion and nonlinearity effects in the link. Then dispersion and attenuation compensation methods are provided by various methods.

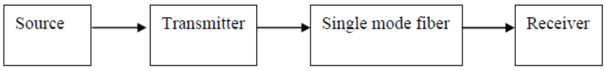


Figure 1: Single mode fiber link

Single mode fiber link in shown in Figure 1, consists of transmitter section, optical medium (single mode fiber) and receiver section. The transmitter section includes a user defined bit sequence generator, pulse generator, modulator and CW laser. User defined bit sequence generator generates a bit sequence that is defined by user. Sine pulse generator generates electrical sine waveform signal according to the input bit sequence from user defined bit sequence generator. CW laser generates a continuous wave optical signal with the given input power. Then a modulator is used to modulate optical signal from the CW laser in accordance with the electrical signal from the pulse generator.

Here external modulation is done using Mach-Zehnder modulator. It is an intensity modulator based on an interferometric principle. Then the modulated optical signal is propagated through the single mode optical fiber. Here nonlinear single mode fiber is used which takes the effect of attenuation, PMD, dispersion and nonlinearities. The fiber output signal is detected by a detector which converts the input optical signal to corresponding electrical signal. Here PIN detectors are used. Then an electrical low pass filter is used at the receiver for eliminating the low frequency noise components. The photodiode and low pass filter constitute receiver section. The visualisers used are Spectrum analyzer, BET analyzer, Oscilloscope, and Power meters.

A. *Attenuation Analysis*

Attenuation is caused by absorption, scattering, and bending losses. The effect of absorption (intrinsic and extrinsic) and Rayleigh scattering is analyzed by taking attenuation coefficient as the parameter. Attenuation coefficient is obtained from the mathematical calculation. Attenuation is also analyzed by keeping the transmitted power constant while varying the bit-rate and the length of the fiber. The reduction in power at the fiber output is measured using power meter. Since main focus here is to see the effect of fiber attenuation, dispersion and nonlinearity are ignored. [2], [3],[4]

B. *Chromatic Dispersion analysis*

Dispersion analysis is done by varying the length of the fiber. As the fiber length increases effect of chromatic dispersion increases and results in signal degradation. The main focus is to see the effect of chromatic dispersion-induced penalties; fiber-loss and non-linearity are ignored.

C. *Polarization mode dispersion analysis*

PMD is related to the differential group delay (DGD) caused by birefringence in optical fibers. It may be created by irregularities in the fiber, and causes dispersion. The average value of DGD is known as the PMD of the fiber. The polarization dependent time differential Δτ proportional to the square root of propagation distance *L*:

$$\Delta\tau = D_{PMD}\sqrt{L} \qquad (1)$$

D_{PMD} is the PMD parameter of the fiber, typically measured in ps/√km, a measure of the strength and frequency of the imperfections. The PMD parameter is varied to analyze the PMD effect in the link.

D. *Nonlinearity analysis*

The refractive index of silica fiber for communication is weakly dependent on optical intensity.

$$n = n_0 + n_2 I(t) \qquad (2)$$

Where n_o= 1.5, n_2 =2.6*10^{-20} m^2/W, and I(t) = optical intensity. At high optical power, refractive index intensity dependence induces phase modulation in the propagating optical pulse. The various nonlinearity effects are self-phase modulation, cross phase modulation and four wave mixing.

III. FIBER ATTENUATION COMPENSATION

Fiber attenuation puts limit on the transmission distance. The most common approaches for loss compensation are to use either (i) Lumped Amplification or (ii) Distributed amplification.

A. *Lumped amplification*

Optical amplifier is used in the transmission system for loss compensation. The most common optical amplifier is the erbium doped fiber amplifier. Here a single span of fiber, it has a 50 km of SMF and a forward pumped EDFA of 6 km. The model for this scheme looks is shown in Figure 2.

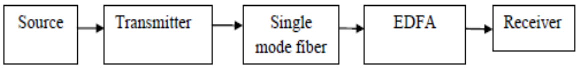


Figure 2: Model for lumped amplification

B. Distributed amplification

Distributed amplification is based on Stimulated Raman Effect. So high power pump signal is needed. Pump power and signal is injected in to the fiber using pump coupler. Pump coupler can control the attenuation of the signal and pump independently. Figure 3 illustrate the distributed amplification. Here pump power is taken as 117.5mW and pump wavelength is selected 100nm below signal wavelength to get maximum gain at the output. Fiber length is 50km. [5]

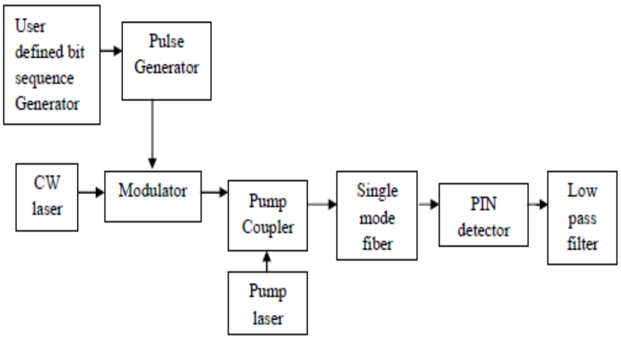


Figure 3: Model for Distributed amplification

IV. CHROMATIC DISPERSION COMPENSATION

A. Dispersion compensating fiber (DCF)

The most common dispersion compensation technique used in long-haul links uses short lengths of DCFs followed by relatively longer lengths of transmission fibers in each span. This is also known as post-compensation of chromatic dispersion.

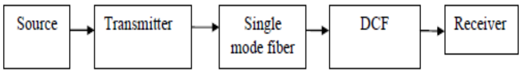


Figure 4: Model for dispersion compensation using DCF

B. Fiber Bragg grating

The fiber bragg grating is a versatile device that can be used for dispersion compensation. A chirped bragg grating can introduces different delays at different frequencies. In regular fiber, chromatic dispersion introduces larger delays for the lower frequency component in the pulse. To compensate this effect, a chirped fiber grating can be designed that do exactly opposite – namely, introduce larger delays for the high frequency components. Figure 5 illustrates fiber bragg grating method.

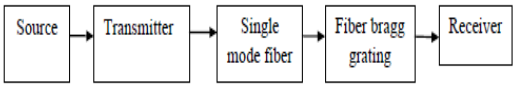


Figure 5: Model for dispersion compensation using fiber bragg grating

C. Optical phase conjugator

Optical phase conjugator act as mirror which reverses the propagation direction and phase variation of a beam of light. It is placed at the middle of the link,so dispersion accumulated in the first half of the fiber link is compensated by propagating through next half after conjugation. Figure 6 shows optical phase conjugation method.

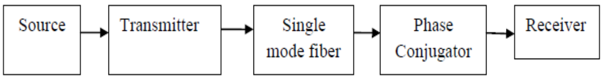


Figure 6: Dispersion compensation using Optical phase conjugator

V. POLARIZATION MODE DISPERSION COMPENSATION

A. Delay method

This method makes use of a delay line. The linearly polarized input pulse has two components along the two axes called principle state of polarization (PSP). The distorted signal from the fiber is separated in to two along PSPs using polarization controller and beam splitter. Adjustable delay is introduced in one of the branch using variable delay and is combined using polarization combiner. The model delay method is shown in Figure 7.[6]

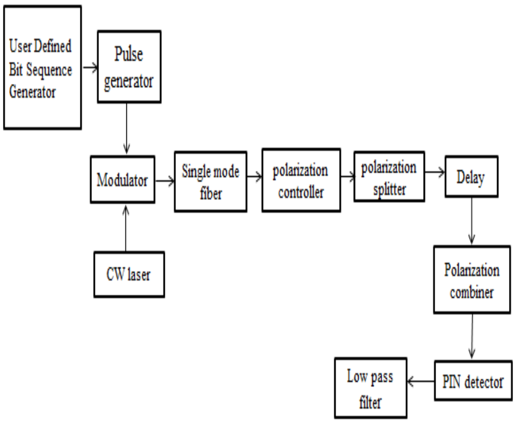


Figure 7: Model for delay method

B. Phase shift method

The polarization rotator rotates the SOP of the signal from the fiber with different angle. Due to this rotation a delay will be introduced. This delay can be adjusted by varying angle of rotation. The model for phase shift method is shown in Figure 8. [7],[8].

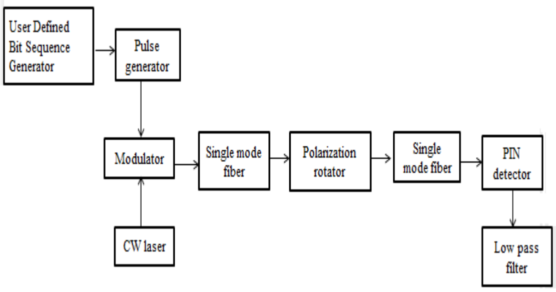


Figure 8: Model for phase shift method

VI. SIMULATION RESULTS

A. *Attenuation analysis*

The result obtained for attenuation analysis is shown in Table 1.Reduction in output power due to various fiber induced losses such as absorption and Rayleigh scattering is obtained from power meter at the receiver output.

TABLE 1
ATTENUATION ANALYSIS

Wavelength (nm)	Output power due to UV absorption	Output power due to IR absorption	Output power due to Rayleigh scattering
800	$1.789*10^{-6}$	$434*10^{-3}$	$1.89*10^{-12}$
1310	$433.86*10^{-6}$	$433.86*10^{-3}$	$6.7*10^{-12}$
1550	$416.96*10^{-3}$	$416.96*10^{-6}$	$112*10^{-9}$
1700	$2.250*10^{-3}$	$2.25*10^{-6}$	$79*10^{-9}$

UV absorption is high at lower wavelength and it decreases with increase in wavelength. IR absorption is negligible at lower wavelength and its effect is dominated at wavelength above 1200nm. Rayleigh scattering increases with increase in wavelength.

B. *Dispersion analysis*

Eye diagram obtained for dispersion analysis is shown in Figure 9.

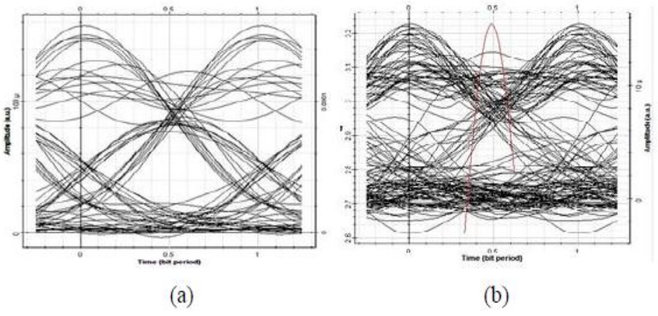


Figure 9: Eye diagram at (a) 100km and (b) 150km

The BER of the transmission system with 150 km fiber is increased to 0.487 as compared to BER at 100km, which is $5.37 * 10^{-7}$. Quality factor at 150km reduced to 3.25 from 5.87 at 100km. This gives the result as the distance increases the chromatic dispersion the fiber also increases.

C. *Polarization mode dispersion analysis*

PMD effect is analyzed by varying the PMD coefficient. As the PMD coefficient increases from $0.5ps/\sqrt{km}$ to 50 $ps/\sqrt{km}$ distortion increases. Figure 10 illustrates PMD analysis.

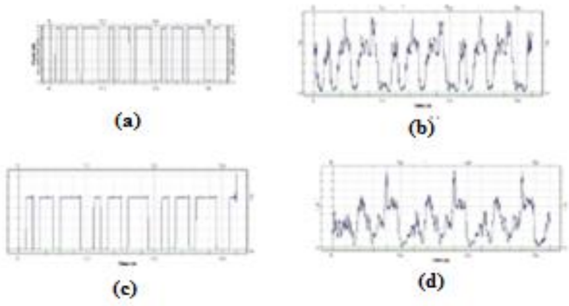


Figure 10: Oscilloscope output for (a) input waveform, Output at (b) *10 $ps/\sqrt{km}$ (b) 0.5$ps/\sqrt{km}$ (c)40$ps/\sqrt{km}$ (d) 50$ps/\sqrt{km}$*

D. *Nonlinearity analysis*

a. Self-phase modulation

At high optical power phase shift due to self phase modulation is high. So it can be analyzed by varying the optical power. Figure 11 shows the result obtained. [6]

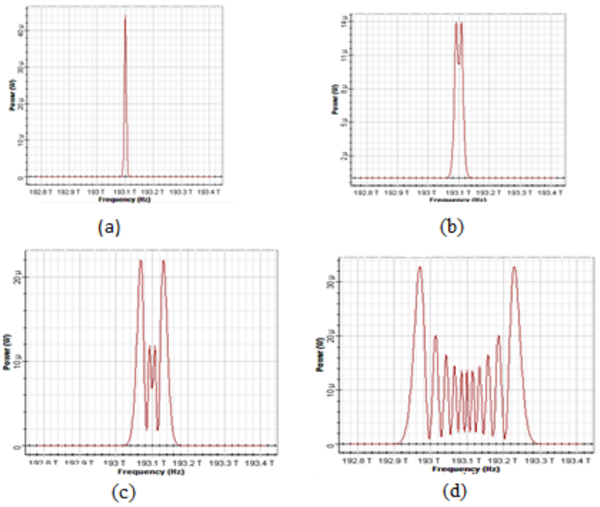


Figure 11: (a) Input spectrum, Output spectrum (b) at 5mW (c) at 10mW (d) at 50mW.

b. Cross phase modulation

Cross phase modulation occurs due to refractive index dependence not only on intensity of optical signal but also on intensity of other co propagating signal at different wavelength. Cross phase modulation induces coupling between the optical fields. Result obtained from oscilloscope is shown in Figure 12. [9], [10], [11]

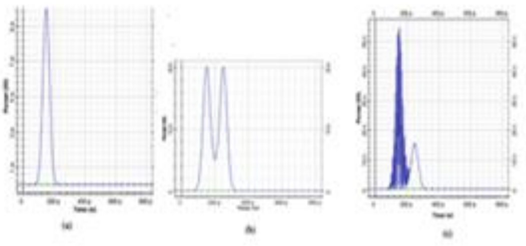


Figure 12 :(a) Input waveform at 1550nm (b) Input waveform at 1540nm(c) Output waveform

c. Four wave mixing

The FWM process can generate a new wave at the frequency whenever three waves of frequencies co propagate inside the fiber. Oscilloscope result obtained in shown in Figure 13.

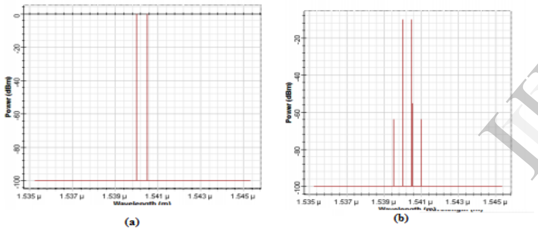


Figure 13 : (a) Input waveform (b) Output waveform

E. *Attenuation Compensation*

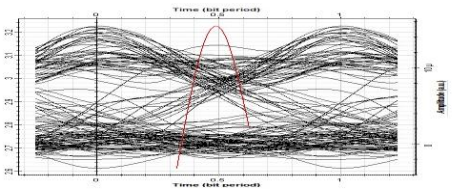


Figure 14: Eye diagram before compensation

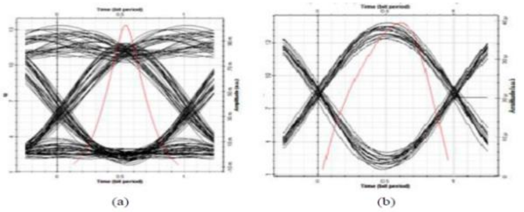


Figure 15: Eye diagram for (a) Lumped amplification And (b) Distributed amplification

TABLE 2
BER and Quality factor obtained before and after amplification

	Before amplification	After compensation	
		Lumped Amplification	Distributed Amplification
Q Factor	3.22	13.36	14.76
BER	0.00622	6.22×10^{-41}	1.1771×10^{-49}

From the eye diagrams shown in Figure 15, the eye opening for distributed amplification is more compared to lumped amplification Thus performance of distributed amplification is better compared to lumped amplification. But Rayleigh scattering and high power requirements limits distributed amplification.

F. *Chromatic dispersion compensation*

The eye diagram for various chromatic dispersion techniques are shown in Figure 16 and Figure 17.

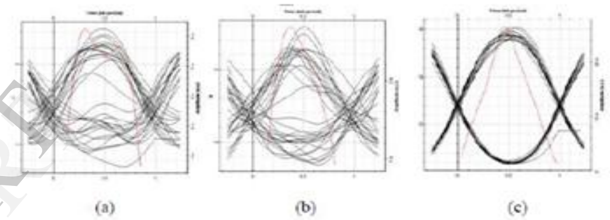


Figure 16 : Eye diagram of receiver output at 130 km fiber length (a) without compensation (b) with DCF (c) with Fiber grating

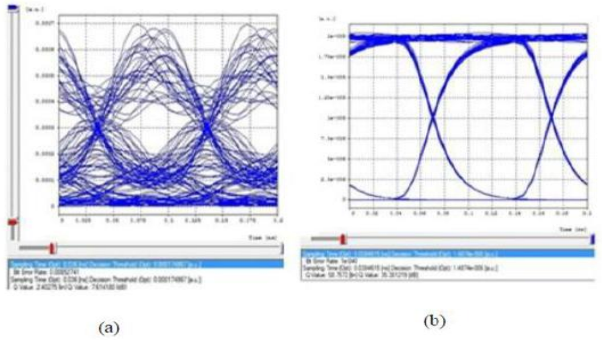


Figure 17: Eye diagram of receiver output at 130 km fiber length (a) without compensation (b) with Optical phase conjugator

TABLE 3
COMPARISON OF DISPERSION COMPENSATION METHODS

	without compensation	With compensation		
		DCF	Fiber grating	Optical phase conjugator
BER	.000294	0.000178	$2.66 \times e^{-205}$	1×10^{-240}
Q Factor	3.43	3.56	30.54	35.3

The eye diagram for various chromatic dispersion techniques are shown in Figure 16 and Figure 17. The result shows that, optical phase conjugator has high performance (high quality factor and low BER) compared to DCF and fiber bragg grating. But optical phase conjugator has high cost and third order dispersion compensation is not possible. DCF is cheaper but its performance is limited by high insertion loss and attenuation (0.5dB/km). Fiber bragg grating has less insertion loss compared to DCF, but it has limited bandwidth.

G. Polarization mode dispersion compensation

Eye diagram obtained before and after compensation is shown in Figure 18.

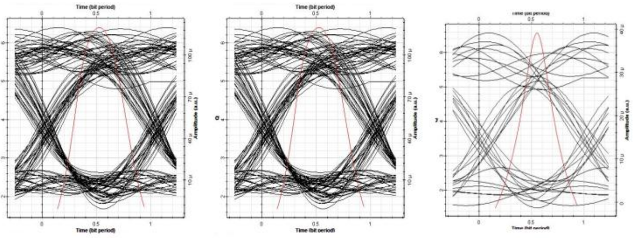
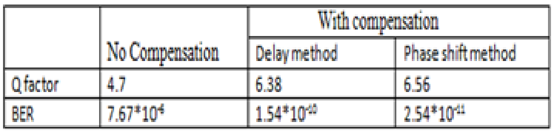


Figure 18: Eye diagram (a) without compensation (b) with delay method (c) with phase shift method.

TABLE 4
Q-FACTOR AND BER AFTER AND BEFORE COMPENSATION



	No Compensation	With compensation	
		Delay method	Phase shift method
Q factor	4.7	6.38	6.56
BER	$7.67*10^{-6}$	$1.54*10^{-10}$	$2.54*10^{-11}$

From the eye diagrams shown in Figure 18, the Q factor and BER for phase shift method is better to delay method.

CONCLUSION

A single mode fiber link is simulated to study the effect of attenuation, chromatic dispersion, nonlinearity and polarization mode dispersion. For chromatic dispersion compensation optical phase conjugator is the better method compared to fiber bragg grating and DCF. Distributed amplification is better method compared to lumped amplification for attenuation compensation. For polarization mode dispersion phase shift method shows better performance compared to delay method.

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