International Journal of Advanced Engineering, Management and Science (IJAEMS)
Peer-Reviewed Journal
ISSN: 2454-1311 | Vol-11, Issue-1; Jan-Feb, 2025
Journal Home Page: https://ijaems.com/
DOI: https://dx.doi.org/10.22161/ijaems.111.6

Analyzing and Compensation of Non Linear effects on DWDM based Optical Fiber Communication System

Abdul Majid Adil

majid.adil@ptclgroup.com

Received: 23 Dec 2024; Received in revised form: 25 Jan 2025; Accepted: 29 Jan 2025; Available online: 08 Feb 2025

Abstract *— Implementing a dense wavelength division multiplexing (DWDM) configuration can substantially enhance the capacity of an optical communication system. Nonetheless, the DWDM system encounters notable challenges due to nonlinear effects that hinder its performance. Self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) are three key factors that exert a significant influence on the system's optical communication capabilities. The primary objective of this research is to tackle and alleviate the nonlinear impact of cross-phase modulation within the DWDM system through an effective approach. In this research, we introduce a method for correcting dispersion in DWDM systems. These nonlinearities, encompassing self-phase modulation, cross-phase modulation, and four-wave mixing, are common occurrences in such systems. The researcher's proposal primarily centers on addressing cross-phase modulation. To comprehensively assess the DWDM system, we explored the effects of fluctuations in power and data rates. According to the results, a 32 channel DWDM system can effectively correct nonlinearities utilizing the suggested Symmetrical-Symmetrical-Post compensation technique (SSP) up to a transmission distance of 400 km using an input power of 20mW & data rate of 100 Gbps. These characteristics are ideal for long-distance optical communication. Suitably modifying the data rate and input power, it is feasible to increase no of channels and transmission distance. The new SSP method was also found to perform better than the conventional post-compensation methodology, making it more appropriate for long-haul DWDM systems. It is crucial to understand that the SSP technique by itself is unable to fully offset the spectral broadening brought on by cross-phase modulation. In order to solve this problem, combining sophisticated modulation methods with SSP can successfully reduce the spectrum broadening. This strategy can call for the use of more amplifiers, which could result in increased power consumption. In such configurations, dynamic control of the erbium-doped fiber amplifier (EDFA) is essential.*

Keywords ***— Dense Wavelength Division Multiplexing (DWDM); Cross Phase Modulation; Nonlinearity; Self Phase Modulation; Four Wave Mixing.***

I. INTRODUCTION

- Optical Fiber Communication

Using light as the carrier signal, optical fiber communication is a technique for sending data between two points. It is a technology that allows for the transfer of high-speed data across vast distances and is widely utilized in networking, telecommunications, and internet services. Electrical signals carrying data are converted during the transmission process into optical signals, which are then sent through a glass or plastic fiber. Very little signal strength is lost as the optical impulses move through the fiber, enabling long-distance transmission without the need for frequent signal boosting or amplification.

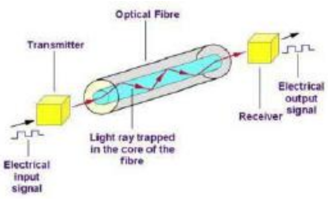

Fig.1: Optical Fibre Communication

(Source: https://www.polytechnichub.com/fiber-optic-communication/)

An introduction to optical fiber communication is provided below:

- Transmitter: Electrical signals are first created from the information to be communicated, such as data, sound, or video. The information from these electrical signals is subsequently modulated and encoded onto an optical carrier signal, typically made up of light pulses.
- Optical Fiber: A thin, glass- or plastic-made strand of optical fiber is then used to carry the modulated optical signal. Light goes through the fiber's core, which is wrapped by a cladding that bounces light back into the core to minimize signal loss.
- Signal Propagation: A phenomenon known as total internal reflection occurs when light signals repeatedly bounce off the cladding as they move through the optical fiber. when a result, there is little intensity loss when the light travels through the fiber, guaranteeing that the signal can travel over vast distances without suffering greatly.
- Receiver: A separate device known as the receiver is used to detect incoming optical signals at the receiving end. The receiver changes the optical signals it has picked up back into electrical signals so that the original data may be retrieved and further processed.

Optical fiber communication has several benefits.

- Fast Data Rates: Optical fibers can transmit data at incredibly fast rates, enabling the quick transfer of substantial volumes of data.
- Long Distances: Without the use of repeaters or signal regeneration, optical fibers may transmit signals over long distances of up to several kilometers.
- Low Signal Loss: Optical fibers have a signal loss that is substantially lower than traditional copper-based communication systems, allowing for greater transmission lengths and improved signal quality.
- Immunity to Interference: Unlike electrical communications in copper cables, optical transmissions are not hampered by electromagnetic interference. As a result, they are less vulnerable to noise and other disruptions from the outside world.
- Data transfer through optical fibers is more secure since it is difficult to intercept the

signal without physically contacting the fiber.

These benefits have made optical fiber connection the foundation of contemporary telecommunications, and it is essential for linking the entire world via the internet and other communication networks.

- **Optical Fiber Communication System**

A full network or arrangement that makes use of optical fibers to convey data between several places is known as an optical fiber communication system. To enable the effective transmission of data, sound, or video over great distances, several components must cooperate. These systems are frequently utilized in networking, cable television, internet, and telecommunications applications.

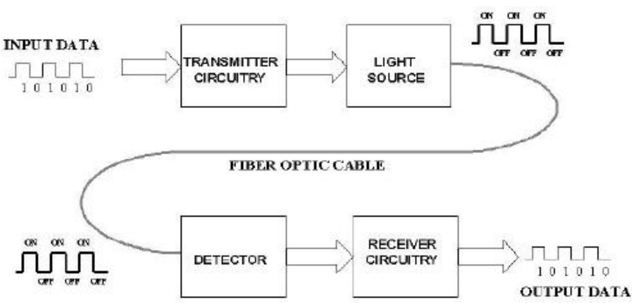

Fig.2: Optical Fibre Communication System

(Source: https://www.elprocus.com/basic-elements-of-fiber-optic-communication-system-and-its-working/)

An optical fiber communication system's essential elements include:

- The transmitter's job is to transform the input data—such as digital data, voice or video signals—into modulated optical signals that may be transmitted across the optical fiber. In order to encode the data onto the optical carrier, it normally comprises of a light source (such as a laser or light-emitting diode) and a modulator that regulates the light's intensity or phase.
- The physical medium through which modified optical signals are transmitted is an optical fiber. With a core that directs the light signals and a cladding that encloses the core to keep the light contained, it is a thin, flexible strand composed of glass or plastic. The system's capacity can be increased by joining several fibers to create an optical cable.
- Amplifiers/Repeaters: Optical signals can attenuate over long distances, resulting in a loss of signal power. Optically amplifying devices, also known as repeaters, are put at strategic points along the fiber network to make up for this loss and increase the transmission range. The optical signal is amplified by these devices without being changed back into electrical form.
- Optical Regenerators: Optical regenerators may be utilized in specific circumstances, particularly for extremely long-distance broadcasts or when the signal quality dramatically deteriorates. These devices retransmit the optical signal as a new optical signal after converting the optical signal back into an electrical signal and recovering it to its original quality.
- Receiver: At the receiving end, a receiver is used to detect the optical impulses and transform them back into electrical signals. A photodetector is commonly used in receivers to turn incoming light into electrical current. Subsequent electronic circuitry analyses and decodes the electrical signals to recover the original data.
- Multiplexers/Demultiplexers: Multiple

optical signals conveying various types of information are often integrated into a single optical fiber (multiplexing) in communication systems to make better use of the fiber's capacity. Using multiplexers and demultiplexers, the signals are divided (demultiplexed) at the receiving end.

- Optical switches provide for flexible and dynamic connections between different sites by controlling the routing of optical signals inside a network.
- Optical attenuators are used to reduce the signal strength when it is necessary to lower the signal power in a particular condition.
- Optical couplers and splitters are devices that divide or combine optical signals, enabling the connection of several fibers or the distribution of optical signals to numerous locations.

The high-speed, long-distance, and dependable communication capabilities provided by an optical fiber communication system are crucial for contemporary data transmission and telecommunications. Due to its benefits over conventional copper-based communication systems, it is a preferred option for many applications in the linked world of today.

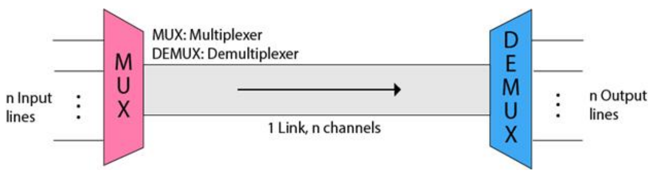

Fig.3: Multiplexing

(Source: https://www.javatpoint.com/multiplexing-in-computer-network/)

- **DWDM**

Capacity & effectiveness of optical fiber networks are increased by using the sophisticated optical communication technique known as DWDM. It enables the parallel transmission of numerous data streams or channels by enabling the simultaneous transmission of different light wavelengths (colors) across a single optical cable. The amount of data that may be transmitted across a fiber is effectively increased because each wavelength transmits a separate, independent data transmission.

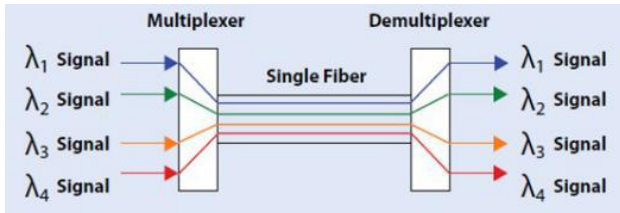

Fig.4: WDM Multiplexing

(Source: https://www.fibermall.com/blog/cwdm-dwdm-mux-demux-technology.htm)

The fundamental idea behind DWDM is to divide an optical fiber's bandwidth into a number of tiny channels, each of which operates at a different wavelength. These wavelengths are usually in the electromagnetic spectrum's infrared region, which is invisible to the human eye. Since the distances between these wavelengths are typically between 0.8 and 0.4 nanometers, the optical spectrum is able to accommodate a large number of channels that are close together. Monochromatic colors don't contain white, black and grey shades and have dominant only single light wavelength with some saturation and intensity level and blue, yellow, green and red absolute hues. However, achromatic light contains the colors which chromatic light don't contains, namely; white, black and grey. Achromatic light possesses all light wavelengths, do not contain saturation and vividness and do not have dominant hues.

DWDM systems' essential characteristics and elements include:

- Multiplexing and demultiplexing: The DWDM system mixes (multiplexes) numerous data streams from various sources onto various light wavelengths at the transmitting end. The system divides (demultiplexes) the wavelengths at the receiving end and directs each channel to the right place.
- DWDM systems produce the optical signals at certain wavelengths using precise and reliable laser sources and tunable transmitters. Tunable transmitters, which offer flexibility and simple network configuration, can change their wavelength to match any channel within the DWDM spectrum in some systems.
- Optical Amplifiers: In order to increase the signal strength without transforming the optical signal into an electrical signal, optical amplifiers (such as erbium-doped fiber amplifiers, or EDFA) are utilized because optical transmissions may travel over long distances and experience signal attenuation.
- Filters that multiplex and demultiplex several wavelengths are known as mux/demux filters. While demux (multiplexer) filters split the signals at the receiving end, mux (multiplexer) filters combine the signals into a single fiber.
- Different modulation formats, such as intensity modulation, phase modulation, or amplitude modulation, are used to encode data onto the optical carriers.

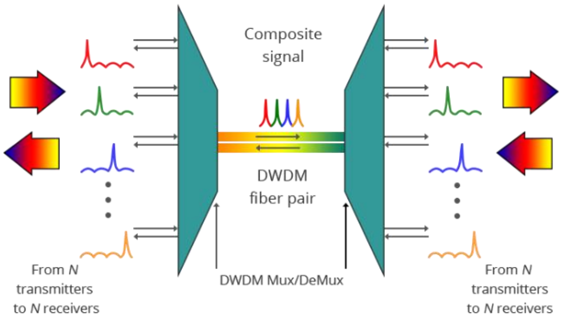

Figure 5: DWDM System

(Source: https://www.cables-solutions.com/capacity-expansion-and-flexibility-dwdm-network.html)

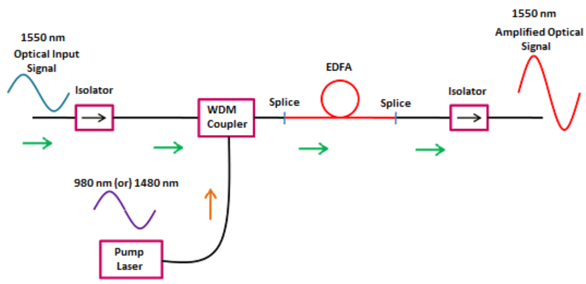

Fig.6: Erbium Doped Fiber Amplifier (EDFA) Block Diagram

(Source: https://www.physics-and-radio-electronics.com/blog/edfa-erbium-doped-fiber-amplifier/)

Benefits of DWDM

- High Data Capacity: DWDM systems are capable of supporting data transmission rates of up to several terabits per second, greatly enhancing the capacity of optical fiber networks.
- Transmission over a long distance: DWDM signals can be sent across distances of thousands of kilometers without the requirement for regeneration when employing optical amplifiers.

- Scalability: DWDM networks are scalable because they can simply be improved and expanded by adding more wavelengths and channels.
- Efficiency: DWDM is a very efficient technology because it allows numerous channels to be transmitted simultaneously over a single fiber, maximizing the fiber's bandwidth utilization.
- Cost-effective: DWDM makes high-capacity data transmission possible without the need to install several fibers.

In backbone networks, data centers, long-haul telephony, and other high-capacity communication applications, the need for quick and effective data transfer is crucial. DWDM plays a crucial role in these applications.

Table 1: Benefits of DWDM System

Specifications/Features	DWDM
Full form	Dense Wavelength Division Multiplexing, WDM system having more than 8 active wavelengths per optical fiber
characteristic	Defined by frequencies
capacity	higher
cost	high
Distance	long range communication
Frequencies	uses narrow range frequencies
Wavelength spacing	less, hence can pack 40+ channels compare to CWDM in the same frequency range
Amplification	light signal amplification can be used here
Drift	Precision lasers are needed to keep channels on the target
Spectrum utilization	dices the spectrum into small pieces
No. of active wavelengths per fiber	More than 8

(Source: https://www.fiberopticshare.com/a-comparison-between-cwdm-and-dwdm.html)

- **Non Linear Effects on DWDM**

Non-linear effects in DWDM-based optical fiber communication systems might develop as a result of interactions between different light wavelengths inside the fiber. The overall effectiveness of the communication system may be restricted by these effects, which can lead to distortions and signal deterioration. Analyzing and making up for these non-linear effects is crucial for maintaining the system's quality and dependability. Let's look at the most significant non-linear impacts and how they are handled.

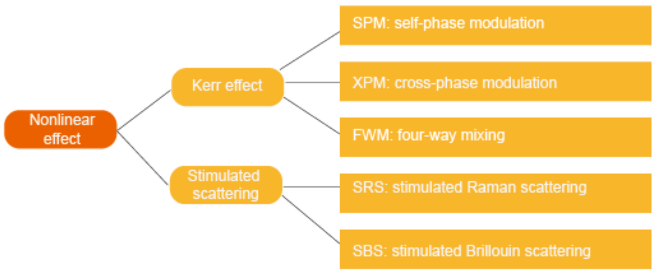

Fig.7: Non Linear Effects

(Source: https://info.support.huawei.com/network/ptmngsys/Web/WDMkg/en/21_nonlinear.html)

1. Four-Wave Mixing (FWM): Four-wave mixing is the process through which signals with various wavelengths interact inside a fiber to produce new frequencies. Crosstalk between channels might result from this effect, which would degrade and interfere with the signal.

2. Stimulated Raman Scattering (SRS): SRS is a non-linear phenomenon where new wavelengths are produced as a result of the interaction between the optical signal and the molecular vibrations of the fiber. The signal power of the desired channels may be decreased as a result of power transfer between various wavelengths.

3. Stimulated Brillouin Scattering (SBS): When an

optical signal interacts with acoustic waves in a fiber, new frequencies are created. Power transmission between channels and spectral widening may result from this effect.

4. Self-Phase Modulation (SPM): SPM is a nonlinear phase modulation that happens when an optical signal's intensity changes the phase of the signal. Signal distortion and spectrum broadening may result from this phenomenon.

5. Cross-Phase Modulation (XPM): XPM happens when the intensity of one wavelength influences the phase of another. This effect has the potential to deteriorate and interfere with signals.

DWDM-based optical fiber communication systems use advanced simulations and modeling approaches to research non-linear phenomena. The physical qualities of the fiber, the characteristics of the light sources (such as laser diodes), and the particular system configuration are all taken into account in these simulations. Engineers can forecast the performance impact of non-linear effects and tune different settings to lessen their effects by running these simulations. In DWDM systems, a variety of compensation strategies are used to reduce non-linear effects. Here are a few typical methods:

1. Dispersion Compensation: Non-linear effects and dispersion, or the spreading of light pulses, are frequently closely associated. The system can lessen the effect of non-linarites by utilizing dispersion compensation techniques, such as dispersion compensating fibers or dispersion compensating modules.

2. Optical Phase Conjugation: In this method, non-linear effects are used to counteract one another. To correct the phase distortions brought on by SPM and XPM, optical phase conjugation devices can be strategically positioned across the fiber network.

3. Raman Amplification: Raman amplifiers can be used in place of conventional optical amplifiers. Raman amplification reduces the effects of SRS by compensating for the power transfer between channels by amplifying the signals at various wavelengths in a dispersed way.

4. Non-linear Fiber with Modified features: The behavior of the system can be customized and the effects of non-linearity's can be minimized by using non-linear fibers that have been specifically developed with certain features.

5. Advanced Modulation Formats: The system can be strengthened against non-linear effects by using advanced modulation formats like polarization division multiplexing (PDM) and quadrature amplitude modulation (QAM).

6. Adaptive Equalization: To reduce non-linear distortions in the received signals, adaptive equalization techniques can be used in the receiver.

In order to assure high-quality, dependable, and effective data transmission in DWDM-based optical fiber communication systems, it is essential to analyze and correct for non-linear effects. System performance can be improved, and the effects of non-linearity's can be reduced, with the use of simulation, good system design, and compensating methods.

Self-Phase Modulation (SPM)

When powerful optical pulses pass through optical fibers, a non-linear optical phenomena known as self-phase modulation (SPM) takes place. An optical pulse's phase in SPM is altered as a result of the interaction between the pulse's intensity and the fiber's refractive index. The Kerr effect, a non-linear optical response that most transparent materials, including the glass in optical fibers, display, is the cause of this effect. The leading edge of an intense optical pulse has a greater refractive index than the trailing edge as it passes through an optical fiber. The leading edge of the pulse moves through the fiber more slowly than the trailing edge due to this discrepancy in refractive index. This causes the pulse to lengthen in duration and flatten its intensity profile, a phenomenon known as temporal broadening. A self-induced effect, or one that completely depends on the properties of the optical pulse as it travels down the fiber, is the temporal broadening caused by SPM. Broader pulses have the potential to interact with other non-linear fiber phenomena including stimulated Raman scattering (SRS) and cross-phase modulation (XPM), adding to the system's complexity and signal distortions.

Self-phase modulation's (SPM) main characteristics are:

- Phase shift that is intensity-dependent: The optical pulse's intensity directly affects how much phase shift it experiences. The magnitude of the phase shifts increases with increasing pulse intensity.
- The powerful optical pulse goes through a process called temporal broadening, which alters the pulse's duration.
- Frequency Broadening: The SPM-induced temporal broadening also causes the pulse's frequency spectrum to enlarge.
- Phase Distortions: SPM may cause phase distortions in the optical signal, which may impair the signal's ability to be transmitted accurately.
- SPM can occasionally result in pulse compression, in which the pulse's duration is shortened as a result of the non-linear interaction.

SPM has been used in some applications, despite being generally regarded as an undesirable phenomenon in optical fiber communication systems:

- Optical Solitons: In some circumstances, the dispersion effect in the fiber can counteract the non-linear effects of SPM, resulting in the generation of optical solitons. Solitons are excellent for long-distance communications because they are self-sustaining, steady pulses that may go a long way without much distortion.
- Supercontinuum Generation: Supercontinuum light sources can be created using SPM in conjunction with other non-linear effects. Wide-ranging, coherent spectral output from supercontinuum sources is used in fields including optical frequency metrology, spectroscopy, and optical coherence tomography (OCT).

SPM is, nevertheless, regarded in the majority of optical communication systems as a degradation that requires mitigation or compensation. Through methods like dispersion compensation, the use of fiber designs with particular qualities, or the use of advanced modulation formats that are less vulnerable to non-linear effects, its impacts can be controlled. Engineers can create optical fiber communication systems with high data transmission quality by comprehending and managing SPM.

Self-Phase Modulation (SPM)

When two or more powerful optical signals—often referred to as "pump" and "probe" signals—travel through the same fiber at the same time, cross-phase modulation (XPM), a non-linear optical phenomenon, takes place. In XPM, the strength of one signal modulates the phase of the other, changing the properties of how both signals propagate. The Kerr effect, a non-linear optical response that most transparent materials, including the glass in optical fibers, show, serves as the foundation for the underlying process of XPM. The refractive index of the fiber is intensity-dependent as a result of the Kerr effect. Consequently, when two powerful optical signals co-propagate through the fiber, they create a change in the refractive index of the fiber that affects the phase of the signals.

Cross-phase modulation (XPM)'s main attributes are:

- Phase shifts: An optical signal's strength causes the other signal to shift in phase. The pump signal's intensity directly relates to how much phase shift the probe signal experiences.
- Intersymbol Interference (ISI) is a phenomenon caused by temporal changes in the probe signal brought on by the phase modulation introduced by XPM. The quality of the data received can be lowered by this interference, and the data transfer speeds can be constrained.
- The probe signal's center frequency may change as a result of phase modulation, which can also cause a frequency shift in the signal.
- Bidirectional Effect: XPM is a bidirectional phenomenon, which means that it happens regardless of which way the pump and probe signals propagate.

In optical fiber communication systems, XPM is typically seen as an unwanted phenomenon, although it also has several intriguing implications and applications:

- Wavelength Conversion: XPM can be used to change an optical signal's wavelength in some wavelength conversion methods. A weaker probe signal can have its frequency changed, altering its wavelength, by being phase-modulated by a strong pump signal.
- All-Optical Switching: XPM is applicable to all-optical switching situations where the presence of a powerful control signal (pump) may affect the transmission or blockage of a weaker signal (probe).
- In nonlinear interferometers, such as the nonlinear Mach-Zehnder interferometer (N-MZI) or the Sagnac interferometer, XPM is one of the nonlinear effects that is employed to carry out a variety of tasks, including signal regeneration and wavelength conversion.

Researchers use a variety of strategies, such as the following, to mitigate the impacts of XPM and lessen its influence on communication systems:

- Optimizing Wavelength Allocation: It is possible to lessen the possibility of major XPM interference between signals by selectively allocating wavelengths to various channels.
- Advanced Modulation Formats: Using advanced modulation formats and coding techniques can reduce the likelihood of XPM-induced distortions in the signals.
- PDM (Polarization Division Multiplexing): PDM can separate signals that are polarized in opposite directions, which minimizes XPM interactions.
- Nonlinear Fiber Designs: By increasing the effective area of the fiber core, for instance, special fiber designs can be utilized to lessen XPM and other non-linear effects.

In general, XPM management and comprehension are essential for developing effective and dependable optical fiber communication systems, particularly in high-capacity DWDM networks.

Four-Wave Mixing (FWM)

When numerous optical signals with various wavelengths interact with one another in optical fibers, a non-linear optical phenomenon known as four-wave mixing (FWM) takes place. In FWM, three optical signals acting as the "pump," "signal," and "idler" waves interact with one another inside the fiber to produce a fourth output signal with a different frequency. To create the new frequency, the input frequencies are nonlinearly mixed in this procedure. The third-order non-linear susceptibility of the fiber material, which is in charge of how the optical fields interact, is the basis of FWM. Energy is transmitted amongst the waves as the pump, signal, and idler waves co-propagate through the fiber, creating the fourth frequency component.

The energy conservation law, which states that the total of any two input waves is equal to the sum of the other two output waves, is followed by the FWM process. This relationship can be modeled mathematically as:

$\omega\_pump + \omega\_signal = \omega\_idler + \omega\_output$

Where:

ω_pump = Frequency of the pump wave

ω_signal = Frequency of the signal wave

ω_idler = Frequency of the idler wave

ω_output = Frequency of the output wave (generated by FWM)

Four-wave mixing's (FWM) main characteristics are:

- FWM can be utilized in frequency conversion applications, which involve shifting the signal's frequency up or down to produce new wavelengths.
- Phase Matching Requirement: For effective FWM to take place, the phases of the involved waves must match, which means that they must align in a way that maximizes energy transfer between the waves.
- Phase Conjugation: In some circumstances, FWM can result in phase conjugation, in which the phase of the output wave is the conjugate of the phase of the input signal. For signal adjustment and correction, phase conjugation can be used.
- Effects between individual channels and between channels in a multi-channel system are referred to as intrachannel and interchannel FWM, respectively.

FWM has some useful implications and applications even though it is typically thought of as an undesirable impact in optical fiber communication systems:

- Crosstalk and Interference: FWM can deteriorate the signal quality in a multi-channel communication system by causing crosstalk and interference between several channels.
- Wavelength Conversion: FWM can be used for wavelength conversion, which enables signals in DWDM systems to be transferred to different channels by creating a new wavelength.
- Signal regeneration and reshaping are two examples of nonlinear optical signal processing applications where FWM can be applied.
- Optical parametric amplifiers (OPAs) use FWM to enhance optical signals at particular wavelengths. FWM is the underlying principle of OPAs.

Researchers employ strategies like the following to control the effects of FWM and lessen its influence on communication systems:

- Wavelength Separation: The FWM effect can be reduced by carefully choosing the wavelengths of the pump, signal, and idler waves.
- Fiber Design and Dispersion Management: To lessen FWM and other non-linear effects, special fiber designs and dispersion management strategies can be used.
- Advanced Modulation forms: By using advanced modulation forms, the signals may be less prone to distortions brought on by FWM.

In general, FWM control and understanding are crucial for developing effective and dependable optical fiber communication systems, particularly in high-capacity DWDM networks.

Stimulated Raman Scattering (SRS)

When bright light interacts with the material's molecular vibrations, a non-linear optical phenomenon known as stimulated Raman scattering (SRS) takes place in optical fibers and other transparent materials. In SRS, an incident optical wave transmits energy to the material's vibrational modes, causing inelastic scattering to produce new optical frequencies (wavelengths).

The following is a description of stimulated Raman scattering:

- Incident Pump Wave: The pump wave is a powerful optical wave that travels through the optical fiber.
- Molecular Vibrations: The molecular vibrations (phonons) of the fiber material are in contact with the pump wave. Due to the atoms' thermal motion, this material naturally experiences these vibrations.
- Energy Transfer: The vibrational modes receive some of the energy from the pump wave, which excites them.
- New Optical Frequencies: The excited vibrational modes produce photons at new frequencies that are either lower or higher than the frequency of the pump wave when they revert to their initial condition. Stokes and anti-Stokes frequencies are the names given to these new frequencies.

The frequency of the molecular vibrations is equal to the frequency difference between the pump wave and the generated Stokes/anti-Stokes waves. The Raman shift is a frequency shift that depends on the characteristics of the substance.

Stimulated Raman Scattering's (SRS) main characteristics are:

- SRS can result in frequency conversion, where the energy of the pump wave is changed into new frequencies (Stokes and anti-Stokes waves).
- SRS has a threshold power level, which has an effect. It only becomes meaningful when the intensity of the pump wave exceeds a particular cutoff point. The scattering impact is minimal below this point.
- SRS is a bi-directional process, which means it can move along the fiber in both the forward and reverse orientations.
- Dependence on Material Properties: The molecular characteristics of the material, such as its Raman gain coefficient, affect the Raman shift and the effectiveness of SRS.

Despite being typically regarded as an unwanted result in optical fiber communication systems, stimulated Raman scattering has the following practical implications and applications:

- Raman amplification is a technique used to increase the strength of optical signals in fibers, and it makes use of SRS. Energy is supplied to the signal, amplifying it through the Raman effect, by pumping the fiber with a high-power laser at a particular wavelength (usually in the 1400–1500 nm region).
- Similar to Stimulated Brillouin Scattering (SBS), SRS can be used for wavelength conversion. In this process, the energy of the pump wave is transmitted to the signal, creating new wavelengths.
- Raman Fiber Lasers: Raman fiber lasers are efficient and portable light sources that operate at specified Raman-shifted wavelengths and employ stimulated Raman scattering.

Researchers employ strategies like the following to mitigate SRS's effects and lessen its influence on communication systems:

- Raman Pump Deposition: By strategically positioning the Raman pump laser along the fiber, it is possible to maximize Raman amplification while limiting undesirable effects.
- Depending on the needs of the system, special fiber patterns can be utilized to either strengthen or weaken the Raman effect.
- Optimized Wavelength Allocation: The overlap with Raman-shifted frequencies can be reduced by carefully choosing the signal wavelengths.

In conclusion, Stimulated Raman Scattering is a crucial non-linear phenomenon in optical fibers, with both difficulties and useful applications. Designing effective and dependable optical fiber communication systems, especially those that make use of Raman amplification, requires a thorough understanding of and management of SRS.

Stimulated Brillouin Scattering (SBS)

When powerful light interacts with acoustic waves (phonons) in a material, a non-linear optical phenomenon known as stimulated Brillouin scattering (SBS) takes place in optical fibers and other waveguides. In SBS, an incoming optical wave transfers energy to the acoustic waves, resulting in an inelastic scattering process that scatters light at a little lower or higher frequency.

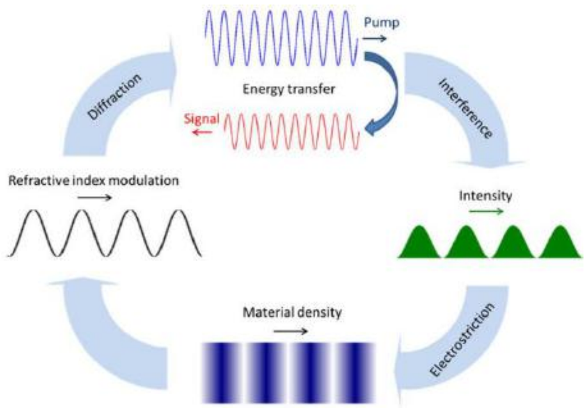

Fig.8: Stimulated Brillouin Scattering Process

(Source: Primerov, Nikolay & Thévenaz, Luc. (2013). Generation and application of dynamic gratings in optical fibers using stimulated Brillouin scattering.)

Following is a description of stimulated brillouin scattering:

- Incident Pump Wave: The pump wave is a powerful optical wave that travels through the optical cable or waveguide.
- Phonons, or mechanical vibrations that naturally arise in materials as a result of changes in temperature or other causes, interact with the pump wave.
- Energy Transfer: The pump wave transfers

some of its energy to the acoustic waves, which stimulate them.

- The excited acoustic waves produce photons at a lower frequency than the pump wave when they revert to their initial condition, creating a new optical frequency (Stokes wave). The Stokes frequency is the name given to this new frequency.

The frequency of the acoustic waves is equal to the frequency shift between the pump wave and the generated Stokes wave. The Brillouin shift is a frequency shift caused by changes in the refractive index and acoustic velocity of the material.

Stimulated Brillouin Scattering's (SBS) main characteristics are:

- SBS can result in frequency conversion, where the energy of the pump wave is changed into a new frequency (the Stokes wave) through the scattering process.
- SBS has a threshold power level, or effect. It only becomes meaningful when the intensity of the pump wave exceeds a particular cutoff point. The scattering impact is minimal below this point.
- Phase Conjugation: Phase conjugation is a fascinating feature of SBS. The initial pump wave and the Stokes wave produced by SBS are phase-conjugate. Accordingly, at the point of scattering, the Stokes wave's phase is the pump wave's phase inverted. Signal adjustment and correction can be accomplished via phase conjugation.
- SBS is a bi-directional process, which means it can move along the fiber in both the forward and reverse orientations.

Stimulated Brillouin Scattering has some useful implications and applications even though it is typically regarded as a negative phenomenon in optical fiber communication systems:

- Stimulated Brillouin Scattering is employed in Brillouin fiber lasers, which are efficient and portable light sources that produce Stokes-frequency radiation.
- SBS-Based Sensing: SBS can be utilized for distributed fiber sensing applications, which use the scattering process to gauge temperature or strain changes throughout the fiber.

Researchers employ strategies like the following to mitigate SBS's effects and lessen its influence on communication systems:

- Depending on the needs of the system, special fiber patterns can be utilized to either strengthen or weaken the Brillouin effect.
- Brillouin Pump Deposition: By strategically placing the Brillouin pump laser along the fiber, it is possible to improve SBS-based sensing or lessen its negative effects on signal transmission.
- Maximizing Wavelength Allocation: The Brillouin-shifted frequencies can be avoided as much as possible by carefully choosing the signal wavelengths.

In conclusion, Stimulated Brillouin Scattering is a significant non-linear phenomenon in optical fibers that has both difficulties and useful uses. Designing effective and dependable optical fiber communication systems and other related technologies requires an understanding of and management of SBS.

Problem Statement

Dense Wavelength Division Multiplexing (DWDM) systems, which are widely used in optical communication networks, have critical difficulties that severely restrict their overall performance due to nonlinear effects. The capacity and effectiveness of optical communication are significantly influenced by these nonlinear phenomena, specifically SPM, XPM & FWM. To lessen the consequences of these nonlinear effects and realize the full potential of optical communication technology, researchers in the field are constantly investigating cutting-edge techniques. These strategies include nonlinear compensation and optimized fiber designs. We can make way for more stable and dependable DWDM systems, enabling seamless and quick data transfer over very long distances, by skillfully handling these difficulties.

Research Purpose

The objective of the research is to present DWDM systems with 4, 8, 16, and 32 channels that are the focus of two main examinations. The research explores the consequences of dispersion at various data rates after first exploring the effect of dispersion brought on by the launched input power. The major goal is to put forth a dispersion correction technique that is especially made for the DWDM system and is intended to deal with cross-phase modulation. Additionally, the project aims to evaluate effects of power/data rate variations. The ultimate objective is to develop a novel SSP (Symmetrical-Symmetrical-Post) method that successfully mitigates spectrum broadening when paired with cutting-edge modulation techniques. Following parameters will be measured:

- Output Optical Signal-to-Noise Ratio (OSNR) of 4/8/16/32 channels WDM measured at various power levels with/without dispersion compensation.
- Output OSNR of 4/8/16/32 channels WDM measured at various data rates with/without dispersion compensation.
- Eye-diagram channel system.
- Comparison of post & proposed SSP compensation technique.
- Channel spectrum at the receiver.

Research Significance

The suggested approach proves to be better suited for long-haul DWDM systems when compared to conventional post-compensation method. While the SSP technique is effective in mitigating spectral broadening caused by cross-phase modulation, it alone cannot fully compensate for it. However, when combined with advanced modulation techniques, SSP can efficiently reduce spectral broadening effects. To accommodate this setup, a larger number of amplifiers are utilized, leading to higher power consumption, making dynamic control of Erbium-Doped Fiber Amplifiers (EDFA) a critical aspect of the system.

II. LITERATURE REVIEW

Data traffic over optical networks has increased dramatically as a result of the widespread use of the internet. It has become necessary to increase the optical bandwidth within the Wavelength Division Multiplexing (WDM) system in order to effectively manage this growing demand. The system can now support high baud rate data transmission as a result [1]. Compressed Wavelength Division Multiplexing (DWDM) systems have more wavelengths as data traffic on optical fibers increases. However, this rise in nonlinear effects due to the increase in optical fiber impedance can negatively affect signal efficiency and ultimately jeopardize performance of system [2].

Many nonlinear effects, including stimulated Raman dispersion (SRS), stimulated Brillouin dispersion

(SBS), SPM, XPM & FWM, are present in DWDM systems. FWM is particularly important and crucial among them [3]. When two waves interact, two or more extra waves of various frequencies are produced, leading to FWM. The operation of the system is significantly hampered by this phenomena, which causes data loss and reduced signal efficiency. Numerous methods have been proposed to lessen the effect of FWM on DWDM systems in order to solve this problem [4].

Data traffic on optical networks has significantly increased as a result of the internet's quick growth in popularity. Dense Wavelength Division Multiplexing (DWDM) technology is used to meet this expanding demand, effectively increasing the data rate by supporting a greater number of channels [5]. However, because they lower the signal power of the receiver, nonlinearities in DWDM systems present a significant problem. Although optical amplifiers have been created to extend transmission distances, completely eliminating fiber losses is still not feasible [5].

Fiber losses can be roughly divided into linear and nonlinear categories. Attenuation and dispersion are examples of linear effects, whereas nonlinear effects include SRS, SBS, FWM, XPM, & SPM [5]. FWM is particularly important and difficult to address among these. Data loss and decreased signal effectiveness result from the interaction of two waves, which might generate two or more additional waves with differing frequencies [7]. Fiber nonlinearities are caused by a number of phenomena, including as inelastic scattering and variations in refractive index with optical intensity [6].

The capacity of DWDM systems is improved by raising the data rate and the quantity of channels. Employing efficient modulation techniques, heavily reliant on electronics, and raising the launching power are required to achieve larger data speeds. However, additional nonlinear effects are brought on by increasing transmission input power [7]. It is vital to choose the proper laser and optical filters since increasing the channel spacing to accommodate more channels might also affect the nonlinear effects [8, 9].

The Kerr effect, inelastic scattering, and the effective cross-sectional area of the fiber are the main contributors to the nonlinear effects in DWDM systems [6]. Multiple in-line amplifiers can be added to lessen nonlinear effects, but they come with higher installation costs [6]. The interaction of higher intensity sections of an optical pulse with the fiber's refractive index results in self-phase modulation (SPM), another nonlinearity that causes frequency chirping and a dispersion penalty with rising input power [10].

When many optical pulses propagate simultaneously, cross-phase modulation (XPM) takes place, which affects other co-propagating beams and results in spectrum widening and pulse shape distortion [13]. On the other hand, four-wave mixing (FWM), which is strongly reliant on channel spacing but independent of data rate, can deplete power and impair system performance as it increases [14].

Different compensation approaches, including dispersion compensating fiber, pump pulses, and dispersion-shifted fiber, have been investigated to address these nonlinear effects [15, 14]. Nevertheless, getting the best pay is still difficult. In addition, the system is complicated and losses are added by SRS & SBS [6], which necessitates careful adjustment of power levels and channel spacing to lessen their impacts [15, 16].

Numerous strategies, such as modulation techniques, fiber Bragg gratings, and symmetric compensation techniques, have been investigated recently in studies to reduce nonlinearities in DWDM systems

[17, 18, 19, 20]. Support vector machines and the optimization of 44 channels have showed promise in enhancing performance [18, 19]. Further highlighting the ongoing attempts to solve these issues is the investigation of a 64-QAM-based radio over fiber system with SVM-based nonlinearity mitigation [17].

When dealing with a greater number of channels and greater distances, modern telecommunication systems significantly rely on DWDM technology for transmission. However, both linear and nonlinear impairments have a major impact on the overall signal quality and may cause the receiver to reject the signal. Attenuation losses and dispersion effects are two categories for linear effects [21]. The length of the fiber cable affects signal power losses, which cause attenuation losses. Signal-boosting amplifiers can be used to fix this problem. Contrarily, chromatic dispersion (CD) and polarization mode dispersion (PMD) are two types of dispersion effects. As a result of CD, distinct wavelengths move at varying speeds, arrive at the receiver at various times, and spread out and overlap one another. To account for CD effects, negative dispersion compensation fiber (DCF) and fiber Bragg gratings (FBG) are used [22].

The two types of nonlinear effects are parametric effects and scattering effects [23]. When the optical pulse strength reaches a particular point, parametric effects, also referred to as refractive index phenomena, take place. This intensity changes the characteristics of the fiber medium, which then has an impact on the propagation of the optical signal [24]. The "non-linear Kerr effect" [25] is the name given to the refractive index change brought on by an increase in pulse intensity. The nonlinear portion of the refractive index (n), which is controlled by this effect, causes it to rise with high signal power and produce unwanted effects including FWM, SPM & XPM [26].

The interaction of atoms and molecules within the material results in scattering effects, which reduce optical power. Both SRS & SBS are additional categories for these events [27].

The growing demand for high-bandwidth applications from end users has fueled advancements in optical components, subsystems, systems, and networks. Next-generation optical communication systems are anticipated to operate at data rates of 40 to 100 Gb/s per channel for long-distance transmissions, while existing 40 to 80 channel optical communication systems with 10 Gb/s transmission speeds struggle to meet the requirements of high-capacity transmission [28]. This trend is further fueled by the explosive development of broadband applications and high-speed online services like teleconferencing and ultra-high-definition television (UHDTV), which will require future data transmission technologies with increased capacity, speed, and range.

The International Telecommunication Union (ITU-T)'s standardization of DWDM technology has been essential in enabling the administration of services employing different light wavelengths carried through the same optical fibers. This enables the transmission of a sizable volume of data for various communication services and applications [4].

In the late 1990s and early 2000s, the second generation of optical networks appeared. These networks brought about innovations that moved security and recovery tasks to the optical portion of the network, greatly enhancing optical communication networks [28].

DWDM technology has advanced significantly toward the goal of entirely transparent optical networks, allowing the transmission of multiple optical waves in the C-band and L-band across a single fiber because of their low transmission attenuation loss [31]. The quality level of the network is assessed using qualitative measures like the Q factor or BER, and network planning and capacity planning are crucial during operation [32].

It is simple to integrate DWDM networks into existing optical networks; all that is needed are upgrades to the transmission systems; the fibers themselves need not be modified. As a result, DWDM technology is now frequently used [29-33].

DWDM systems need to be adjusted and modified in order to satisfy the requirements of the expanding multimedia landscape. Multichannel optical transmission is complicated by the signal's structure, the transmission medium's dispersive and nonlinear properties, and the simultaneous high-speed transmission of many optical channels. The intention is to minimize signal deterioration while increasing the system's transmission capacity [34].

In both terrestrial and transoceanic communication systems, the use of optical fiber cables enables high-capacity optical transmission over great distances. However, both linear and non-linear influences limit the performance. The presence of Amplified Spontaneous Emission (ASE) noise from Erbium-Doped Fiber Amplifiers (EDFAs), SRS, SBS, SPM, XPM & FWM are among the main non-linear effects [35] [36].

Dense Wavelength Division Multiplexing (DWDM) technology is used to increase the overall bandwidth of single-mode optical fibers. However, when sending data across long distances at rates more than 2.5 Gbit/s, the effects of dispersion and nonlinearities start to matter. While EDFAs enhance transmission distances and make up for fiber losses, they also increase ASE noise and nonlinearities. Numerous fiber kinds have been developed to lessen the impacts of dispersion and nonlinearities in order to address these issues [37] [38] [39].

Numerous research on nonlinear impairments have been done, emphasizing their significance and complexity in the context of DWDM systems [40] through [45]. The need of resolving these phenomena to guarantee the best performance and efficiency of DWDM technology is highlighted by these investigations.

Optical Signal to Noise Ratio, which is also known as OSNR, is used to measure the quality of signal in far long range optical fiber communication system. Amplified Emission Noise, which is termed as ASE, is a major contributor to the performance of OSNR, which got added due to the noise of optical components and in turn reduces the OSNR and hence signal quality.

In conclusion, as internet usage continues to rise, creative methods are needed to control the growing data traffic on optical networks. Even though DWDM technology greatly increases capacity, nonlinear effects must still be taken into account to ensure effective and trustworthy optical communication. For more reliable and high-performance DWDM systems, ongoing research and development are crucial to optimizing modulation and compensation strategies.

III. RESEARCH METHODOLOGY

- **Methodology**

The effects of greater power levels at different data rates were investigated using a DWDM system with 4/8/16/32 channels. The system was initially simulated using the traditional "post" compensation method. The improvements in performance were then evaluated by comparing the findings to those obtained from the suggested compensating design.

The effects of XPM (Cross-Phase Modulation) are addressed in the literature using a variety of traditional methodologies. To reduce nonlinearity in the DWDM system, the researcher suggests a brand-new symmetrical-symmetrical-post compensating technique. In this method, single-mode fiber (SMF), erbium-doped fiber amplifier (EDFA), and dispersion compensating fiber (DCF) are all integrated.

This approach produces a good Signal-to-Noise Ratio (SNR) by passing the SMF data through the EDFA, which offers strong optical gain while preserving low noise. The figure below shows experimental configuration for a 4-channel WDM (Wavelength Division Multiplexing) system with compensation. It is made up of a compensation, receiver & transmitter blocks.

The transmitter block consists of a Mach-Zehnder (MZ) modulator, 4-channel WDM multiplexer, a continuous wave (CW) laser, a Non-Return-to-Zero (NRZ) pulse generator, and a pseudo-random binary sequence (PRBS) generator. The receiver part, on the other hand, is made up of a Fabry-Perot filter, a demultiplexer, a PIN receiver, and a BER analyzer. Wherever necessary, optical power meters, a WDM analyzer & optical spectrum analyzers are also attached to make system evaluation easier.

The compensating block subsequently receives optical signal generated in transmitter portion. It moves through a single-mode fiber (SMF) that is 16 km long and has dispersion of 16 ps/nm-km. To maintain optical signal-to-noise ratio (OSNR), EDFA must give a significant gain. In order to provide equal and opposite dispersion compensation, the accumulated dispersion is finally eliminated using the dispersion compensating fiber (DCF).

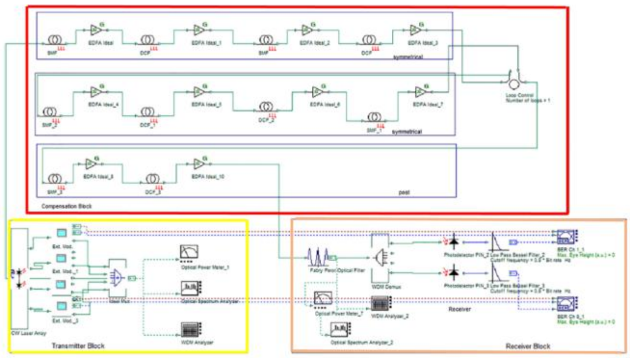

Fig.9: Experiment Setup: 4 Channel WDM system with compensation

- **Parameters**

Table below shows the parameters used for experimental setup.

Table 2: System Parameters

S/NO	Parameters	Value
1	Transmitter Parameters	
	Pseudo Random Binary Sequence Bit Rate	20 - 100 Gbps
2	Receiver Parameters	
	PIN Responsivity	1 A/W
	Dark Current	10 nA
3	Single Mode Fibre (SMF) Parameters	
	Length	16 – 20 Km
	Effective Area	80 μ m^2
	Attenuation	0.20 dB/km
	Dispersion	16 ps/nm-km
	Differential Group Delay	0.20 ps/km
	Dispersion Slope	0.075
4	Dispersion Compensating Fiber (DCF) Parameters	
	Length	4 – 5 km
	Attenuation	0.50 db/km
	Dispersion	- 64 ps/nm-km
5	Erbium Doped Fiber Amplifier (EDFA) Parameters	
	Gain	2 – 4 dB
	Noise Figure	2 dB
	Power	10 dBm
6	Wavelength Division Multiplexing (WDM) Parameters	
	Channel Spacing	200 GHz
	Number of Channels	4, 8, 16, 32

A transmitter in optical fiber communication is a device or system that generates, encodes, and launches optical signals into an optical fiber in order to convey data. Transforming electrical impulses (data) into optical signals (light) that can pass through the optical fiber is the transmitter's primary job.

A receiver is an essential component in optical fiber communication and is in charge of identifying, decoding, and transforming incoming optical impulses into electrical signals. Its main job is to take in sent optical signals that have passed through the optical fiber and turn them into usable electrical data so that electronic devices may process and interpret it.

An optical fiber known as a single-mode fiber (SMF) in optical fiber communication enables the transmission of light signals through a single, clearly defined mode of propagation. Single-mode fibers have a small core diameter, typically approximately 9 micrometers, as opposed to multimode fibers, which permit several light propagation routes (modes). Due to the limited number of supported modes due to the small core size, only one mode of light can efficiently propagate through the fiber.

A form of optical fiber called a dispersion compensating fiber (DCF) is used in optical fiber communication systems to compensate for the chromatic dispersion that happens when light signals are sent across conventional single-mode fibers (SMFs). When various light wavelengths move through a fiber at slightly different speeds, a phenomenon known as chromatic dispersion, the light pulses spread out and overlap.

An optical amplifier called an erbium doped fiber amplifier (EDFA) is used in optical fiber communication systems to increase the power of optical impulses without converting them to electrical signals. In long-distance and high-capacity optical communication networks, it is a crucial element. The optical amplification that occurs when erbium ions are doped (introduced) into the core of a specially created optical fiber is the foundation of the EDFA's working principle. The erbium ions operate as the amplification medium and interact with the optical signals coming in, collecting energy from pump lasers at particular wavelengths and then emitting this energy as additional photons that are in line with the wavelengths of the signal. The optical signals are amplified using this method while still maintaining their original data content.

Wavelength division multiplexing (WDM) is a technique used in optical fiber communication to multiply the number of optical signals being sent through a single optical fiber at the same time, increasing their number and efficiency. Multiple optical signals—also known as channels—can coexist and travel down the same fiber without interfering with one another because each optical signal, also known as a channel, contains distinct data.

The intended loop control & accompanying fiber length are shown in following table. The PIN detector in the reception section transforms the optical signal into an electrical signal.

Table 3: Loop Control Details

S/No	No of SMF	Total Length SMF (Km)	No of DCF	Total Length DCF (Km)	Total Length (Km)
1	5	80	5	20	100
2	10	160	10	40	200
3	15	240	15	60	300
4	20	320	20	80	400

Using the traditional "post" correction technique, the researcher compared the optical signal-to-noise ratio's (OSNR) performance. The Dispersion Compensating Fiber (DCF) was linked in this comparison after the Single-Mode Fiber (SMF) and Erbium-Doped Fiber Amplifier (EDFA) were combined. The researcher used identical simulation circumstances for the studies to validate the suggested strategy.

The transmitter section feeds data into the compensation block using a series of single-mode fiber (SMF) and dispersion compensating fiber (DCF) with negative dispersion of - 64 ps/nm-km & 0.50 dB attenuation, respectively, in the proposed symmetrical-symmetrical-post (SSP) compensation technique. Optical amplifiers are positioned after each fiber to compensate for the signal loss; the gain is denoted by the letter L. The SMF's 16 km length and 16 ps/nm-km dispersion is balanced by the DCF's 4 km length and -64 ps/nm-km dispersion. As demonstrated in Tables 3 and 4, the Dispersion Compensating Fiber (DCF) imparts equal and opposite dispersion, effectively counteracting pulse broadening over a 100 km span. When additional loops are incorporated, researchers note dispersion effects extending over greater distances. Additionally, the research takes into account the influences of Cross-Phase Modulation (XPM) under varying launching power levels and data rates.

- **MATLAB Simulation**

The simulations were done using MATLAB. The MathWorks company created MATLAB, often known as "Matrix Laboratory," which is a potent programming environment and computer platform. It is widely utilized in many different industries, including engineering, math, physics, finance, image and video processing, and many more. MATLAB is recognized for its simple syntax, big function library, and superior numerical processing abilities.

Key MATLAB Features include:

- Numerical computations: MATLAB is excellent at doing numerical calculations, making it the best choice for handling challenging calculations involving matrices, vectors, and arrays. It has many built-in functions for things like integration, optimization, and linear algebra.
- Interactive Command-Line Environment: The Command Window in MATLAB allows users to enter commands, run them, and immediately view the results. It is a fantastic tool for quick prototyping and data exploration because of its interactive nature.
- MATLAB provides script files (sometimes known as "m-files"), which let users compose a series of commands and save them in a script for later use. Additionally, MATLAB provides function files (m-files), which let users design unique functions that can be utilized frequently throughout various program sections.
- Graphics and visualization: MATLAB has robust visualization features that let users design stunning plots, charts, and graphs to display data and outcomes. It has a number of charting options and tools for adjusting how plots look.
- Toolboxes: To enhance its capability for certain applications, MATLAB provides a wide range of toolboxes. These toolboxes include sections on machine learning, control systems, image processing, signal processing, optimization, and more.
- Block diagrams can be used to describe, simulate, and analyze dynamic systems using Simulink, a graphical extension to MATLAB. It is frequently employed in the design of control systems, simulations, and the creation of embedded real-time systems.
- GUI development is made feasible by MATLAB's tools for constructing Graphical User Interfaces (GUIs), which allow interactive programs to be built without a deep understanding of programming.

MATLAB is used in a variety of academic, research, and commercial contexts. It is utilized by engineers, scientists, researchers, and students for a variety of tasks, including algorithm development, simulation, prototyping, data analysis, and more. Its capabilities are expanded by the availability of specific toolboxes, making it a flexible and extensively used software tool for a variety of purposes.

In conclusion, MATLAB is a robust, user-friendly software environment with numerous libraries, visualization tools, and numerical computation capabilities, making it a top choice for a variety of scientific and engineering jobs. Its widespread community support and simplicity of usage have boosted its acceptance in global academia and business.

IV. RESULTS AND DISCUSSION

In this research, the DWDM system is the main topic of investigation, and the features of systems using 4, 8, 16, and 32 channels are examined. The research explores two important topics for discussion:

(i) The effect of dispersion brought on by the launched signals' input power.

(ii) A thorough examination of the consequences of dispersion at various data rates.

In order to understand how the DWDM system behaves with regard to dispersion, the researcher investigates how the system functions under various channel configurations. The effects of changing input power on dispersion can be studied to learn more about the capabilities and limitations of the system. A thorough grasp of how the DWDM system manages signal degradation and dispersion difficulties is provided by the investigation's further exploration of the dispersion impacts across various data speeds.

- **Launched Power Effects**

Through simulations at various power levels and measurements of the Optical Signal-to-Noise Ratio (OSNR) over a range of distances, specifically between 100 km and 400 km, researcher sought to investigate the effects of DWDM system in this research. The simulations were conducted at a data rate of 20 Gbps, with the aim of investigating the implications of a novel dispersion compensation technique known as "Self-Phase Modulation (SSP) compensation." In these simulations, the researcher emulated the DWDM system with post-compensation, utilizing identical simulation parameters to implement the proposed SSP compensation, subsequently assessing the resulting Optical Signal-to-Noise Ratio (OSNR).

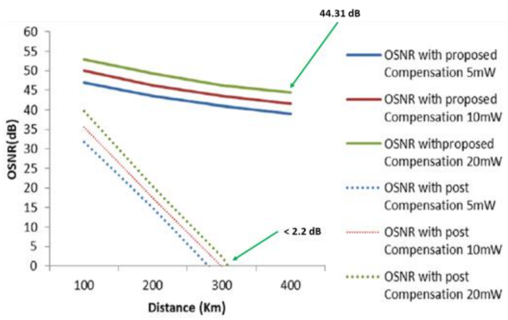

Fig.10: Output OSNR

(4 channel WDM (measured at various power levels) with/without dispersion compensation - DC)

The output OSNR when utilizing dispersion correction is shown in Figure as solid lines, while the output OSNR when using the standard "post" dispersion compensation technique is shown as dotted lines. Analysis of the results shown in Figure revealed that nonlinearity develops with transmission distance, resulting in a drop in OSNR. Furthermore, we observed that the OSNR increases with power. It was also clear that the conventional post-compensation method had its limits. It could only sustain a transmission distance of up to 300 km, even with a power input of 20 mW, and at this point, the achieved OSNR was below the intended range, measuring less than 2.2 dB.

On the other hand, when using the suggested SSP compensation strategy, performance significantly improved. The recorded OSNR impressively reached a value of 44.31 dB at a transmission distance of 400 km and an input power of 20 mW, proving the efficiency and superiority of the SSP compensating methodology over the conventional method. Overall, these findings show the benefits of using the ground-breaking SSP compensation technique to achieve improved performance over longer transmission distances and offer useful insights into the behavior of the DWDM system under various circumstances.

It is crucial to carefully regulate the number of channels while preserving an acceptable Optical Signal-to-Noise Ratio (OSNR) while using Dense Wavelength Division Multiplexing (DWDM). In order to fully understand the implications of nonlinearities over greater transmission lengths, we carried out a thorough analysis of the DWDM system in this work, looking at its behavior with 4, 8, 16, and 32 channels. Research identified an important pattern: the OSNR significantly declines as the number of channels rises. With increased transmission distance, this degradation is even more obvious. Figures (8-channel DWDM), (16-channel DWDM), and (32-channel DWDM), where we noted the declining OSNR values, provide a clear illustration of this phenomenon.

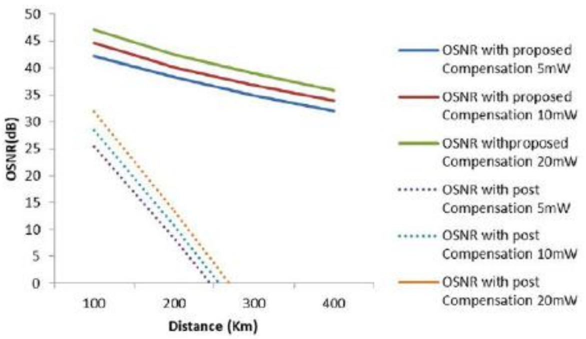

Fig.11: Output OSNR

(8 Channel WDM measured at various power levels with/without DC)

Researcher suggests a unique compensation method termed "Self-Phase Modulation (SSP) compensation" to address these problems and contrasted it with the traditional post-compensation method. A detailed comparison of the two methods' output OSNR, as measured at various power levels, is shown in Figure. Analysis showed that proposed SSP technique performs much better than post compensation technique. Recorded OSNR utilizing the SSP technique at a transmission distance of 400 km was 32 dB with an input power of 5 mW, whereas at an input power of 20 mW, it was 35.8 dB. The OSNR values for the post-compensation technique were much lower, coming in at 7 dB and 11 dB for input powers of 5 mW and 20 mW, respectively. The post-compensation technique was unable to handle transmission beyond 200 km.

In addition, researcher looked at Figure OSNR performance for 16 channels. The OSNR for the suggested SSP approach at 400 km was 23.8 dB with 5 mW input power, and it increased to 26.9 dB with 20 mW input power. On the other hand, the post-compensation technique could only sustain transmission up to a distance of 200 km and delivered OSNR values of only 7 dB and 11 dB for 5 mW and 20 mW input powers, respectively.

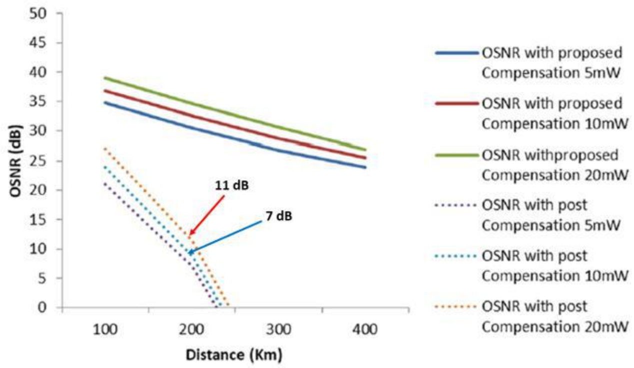

Fig.12: Output OSNR

(16 channel WDM measured at various power levels with/without DC)

As a result, our research emphasizes how crucial it is to keep the OSNR levels in DWDM systems at an adequate level while also regulating the number of channels. A possible way to improve the system's performance over longer transmission lengths and with more channels is provided by the proposed SSP compensation methodology, which performs better than the conventional post-compensation method.

Using only the post-compensation strategy may not be sufficient as Dense Wavelength Division Multiplexing (DWDM) systems add more channels. When analyzing the OSNR performance of a 32-channel DWDM system (as depicted in Figure), this constraint becomes clear. With an input power of 5 mW and a transmission distance of 400 km, the OSNR obtained with the ground-breaking SSP compensation technique measured 19.11 dB. The OSNR increases to 21.6 dB at 20 mW of input power. OSNR values produced by the conventional post-compensation method, on the other hand, are lower, only reaching 5.2 dB at 200 km with 5 mW input power and 8.8 dB with 20 mW input power.

These results underline how crucial it is to implement the suggested SSP compensation technique in order to successfully handle the difficulties brought on by more channels in DWDM systems. For durable and dependable DWDM transmission, the SSP compensation technique turns out to be essential in obtaining the appropriate OSNR levels. By using the SSP compensation method, DWDM systems can maintain acceptable OSNR values and improve performance even when supporting more channels. The increased OSNR levels at greater transmission lengths and under various power input conditions show how effective and appropriate the SSP technique is for addressing the needs of contemporary high-capacity DWDM networks.

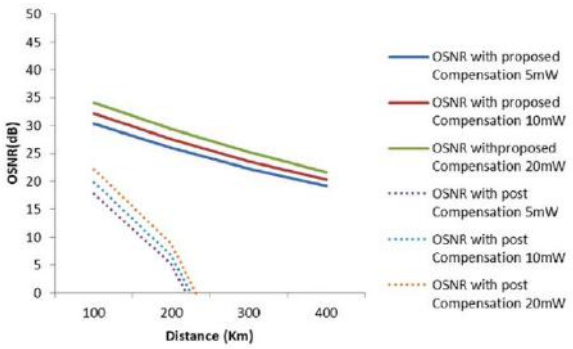

Fig.13: Output OSNR

(32 channel WDM measured at various power levels with/without DC)

In conclusion, as the number of channels rises, it becomes clear that the post compensation technique has limits, necessitating the use of proposed SSP compensation technique as a vital means of achieving the appropriate OSNR values in DWDM systems. The performance and dependability of DWDM networks can be significantly improved by embracing the benefits that come with SSP compensation, putting them in a better position to handle the increasing demands of high-bandwidth communication.

- **Effects due to Data Rate**

It becomes essential to increase the data rates in DWDM systems in order to make full use of the optical capacity and improve data transmission capabilities. We looked closely at the DWDM system in our analysis, taking into account several channel configurations (4/8/16/32 channels) and increasing the data rates to 20 Gbps, 40 Gbps, and 100 Gbps. Main goal was to evaluate how well the suggested compensatory mechanism handled these higher data rates. The performance of increasing data rates when combined with more channels must be understood in order to maximize DWDM networks. As a result, we carefully examined how increased data rates would affect both the effectiveness of the suggested compensation mechanism and the overall performance of the system.

As the number of channels increases from 4 to 32, there is a discernible rise in nonlinearity, which is a significant finding from our research. This result highlights the need for rigorous nonlinearity management in the system when introducing more channels. The research provides a useful understanding of the behavior of DWDM systems at larger data rates and with more channels, setting the groundwork for practical nonlinearity-related problem mitigation solutions.

Overall, this thorough analysis clarifies the critical significance that data rate increases play in efficiently utilizing optical capacity. To assure the best performance and reliability in high-capacity optical communication networks, we can create reliable compensation approaches by analyzing the effects of various data rates on DWDM systems with diverse channel configurations.

Results for DWDM systems with 4, 8, 16, and 32 channels are shown in Figures, respectively. We started running simulations using the post compensation method to assess the effectiveness of the suggested compensation strategy. We then tested the performance of the suggested Self-Phase Modulation (SSP) approach with an input power of 10 mW under the identical simulated settings. Throughout the course of our investigation, we kept a careful eye on how distance and data rate affected the degree of nonlinearity seen in the DWDM systems. Our research uncovered an interesting pattern: as distance and data rate increased, so did the nonlinearity inside the systems.

For instance, the observed OSNR attained a remarkable value of 39.5 dB when using the suggested SSP compensation technique for a four-channel system at a data rate of 100 Gbps and a transmission distance of 400 km. In contrast, the achieved OSNR while using the post correction technique at a data rate of 100 Gbps and a distance of 200 km was just 13.5 dB. Furthermore, even when the data rate was reduced to 20 Gbps, we saw that the post compensation technique was unable to adequately compensate for signal losses beyond 200 km.

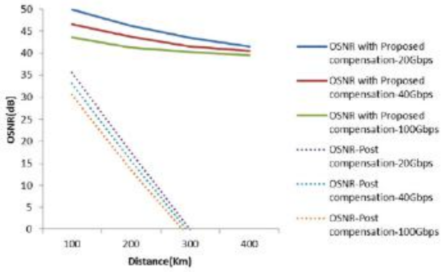

Fig. 14: Output OSNR

(4 channel WDM measured at various data rates with/without DC)

Similar to this, we investigated the performance of an eight-channel system in Figure. At data rate of 100 Gbps and a transmission distance of 400 km, the proposed compensatory technique showed an OSNR of 32.2 dB. In comparison, with data rate of 100 Gbps and a distance of 200 kilometers, the post correction technique produced an OSNR of only 7.2 dB.

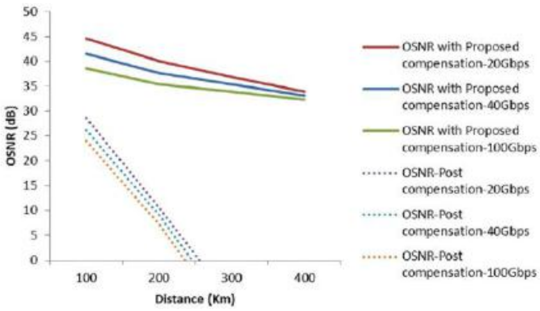

Fig.15: Output OSNR

(8 channel WDM measured at various data rates with/without DC)

Regarding 16-channel system shown in Figure, our research showed that the proposed method was able to achieve an OSNR of 24.2 dB at 400 km and data rate of 100 Gbps, but post compensation method was unable to do this beyond 200 km.

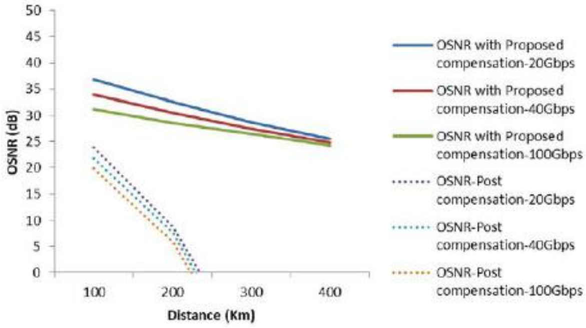

Fig.16: Output OSNR

(16 channel WDM measured at various data Rates with/without DC)

32-channel system was the main focus of Figure, where the suggested SSP compensation technique produced an OSNR of 19.6 dB at a data rate of 100 Gbps and a distance of 400 km. The OSNR values were lower at 6.8 dB at 20 Gbps data rate and 4.7 dB at 100 Gbps data rate due to the post correction method's limited ability to support networks beyond 200 km.

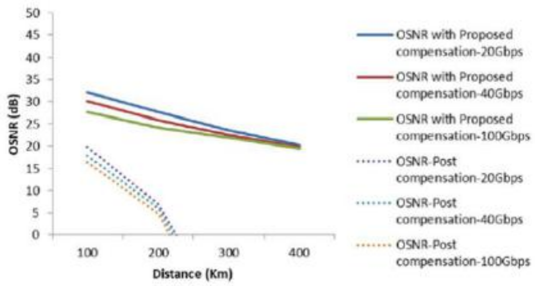

Fig.17: Output OSNR

(32 channel WDM measured at various data rates with/without DC)

The results of our research highlight importance of the suggested SSP compensation technique in reducing nonlinearity problems and expanding the transmission range in DWDM systems with different channel layouts and data rates. The performance of high-capacity optical communication networks can be improved using this knowledge as a foundation for the implementation of strong compensating mechanisms.

A brief summary of the Optical Signal-to-Noise Ratio (OSNR) values for various data speeds is provided in Table 4.

Table 4: Comparison of the post compensation & proposed SSP compensation technique

Compensation	Number of Channels	OSNR		
		20 Gbps	40 Gbps	100 Gbps
Proposed SSP Technique	4	46.27	43.69	41.20
	8	40.05	37.65	35.35
	16	32.51	30.52	28.52
	32	27.66	25.86	24.26
Post Compensation Technique	4	17.48	15.68	13.57
	8	10.65	9.15	7.25
	16	8.87	7.67	5.97
	32	6.87	5.97	4.77

(Distance 200 km; Launched Power 10 mW)

The eye diagrams in Figure give a visual depiction of the data that was received for 32-channel DWDM system over a 100 kilometer distance. Figure also shows associated spectrum at receiver. In particular, wide eye-opening seen in Figure shows that the received data benefits from less jitter, noise, and nonlinearities, which is mainly related to the application of the Self-Phase Modulation (SSP) compensation approach. This demonstrates the enhanced signal integrity attained using SSP compensation.

It is interesting that comparable eye diagrams were also generated for the 4, 8, and 16 DWDM channels, demonstrating the SSP compensation technique's consistent and advantageous effects across a range of channel configurations. These eye diagrams' wide eye openings show that the SSP compensation efficiently reduces impairments, resulting in improved reception quality and system performance as a whole.

These eye diagrams demonstrate the system's resistance to signal deterioration by using the SSP compensation technique, producing well-defined eye patterns with minimal distortions. This in turn shows how the suggested SSP compensation technique effectively improves the performance of DWDM systems over a wide range of channel configurations and distances.

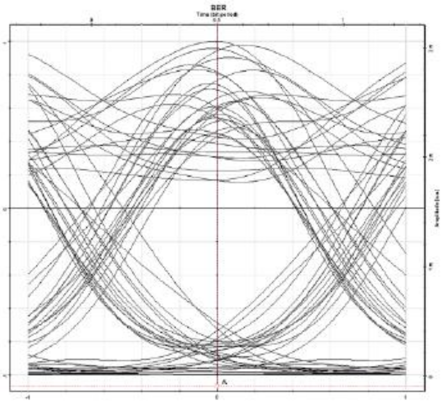

Fig.18: Eye-diagram

(32 channel system at a distance of 100 km)

Figures show DWDM systems to retain steady and reliable signal reception even in the presence of difficult transmission conditions, provide clear proof of the advantages offered by the SSP compensation technique. The proposed compensation technique's effectiveness in minimizing distortions and guaranteeing ideal signal quality in high-capacity optical communication networks is visually validated by the eye diagrams.

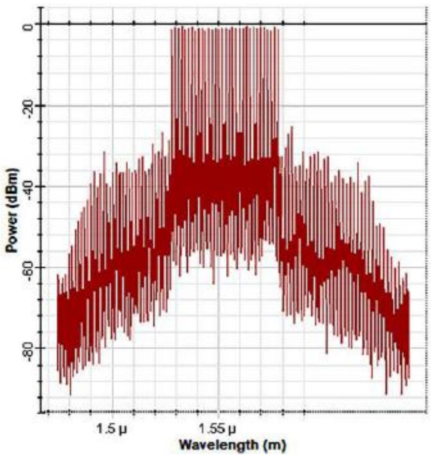

Fig.19: 32 Channel spectrum at the receiver.

V. CONCLUSIONS

DWDM system, which is prone to nonlinearities such as CPM, SPM, & FWM, is addressed in this research with a unique dispersion compensation technique. Our suggested method focuses primarily on compensating for cross-phase modulation with the goal of enhancing system performance and reducing the negative consequences of nonlinear phenomena.

This research focused on the fluctuations in data rates and power levels to perform a thorough examination of the DWDM system. Promising results were seen, especially in a 32-channel DWDM system, according to our observations. We successfully compensated for nonlinearities over an amazing transmission distance of up to 400 km by using our suggested Self-Phase Modulation (SSP) approach. Additionally, this was accomplished utilizing characteristics that are ideal for enabling long-haul optical communication, namely an input power of 20 mW and a high data throughput of 100 Gbps.

It's interesting to note that researchers have shown that no of channels and the transmission distance may both be increased by carefully altering data rate and input power. Due to its adaptability, the DWDM system may be customized to meet particular communication needs and adjust to shifting network requirements.

Our research also showed that the suggested SSP strategy performs better than the conventional post-compensation method, making it more appropriate for long-haul DWDM systems. Despite the fact that some nonlinearities are adequately addressed by the SSP compensation, we accept that the spectrum broadening brought on by XPM cannot be fully corrected by SSP technique alone. We suggest combining cutting-edge modulation techniques with the SSP compensation to get over this restriction. This combination strategy improves spectrum broadening mitigation while also improving system performance.

However, because they typically use more power, it's crucial to think about the effects of utilizing additional amplifiers. As a result, dynamic management of Erbium-Doped Fiber Amplifiers (EDFA) is essential for maintaining appropriate signal amplification and successfully managing power consumption.

The results of this research demonstrate the viability of the suggested dispersion correction method in DWDM systems. In order to achieve long-haul optical communication with high data rates and various channels, the SSP method appears to be a promising approach. The performance of DWDM systems can be further improved, making them well-suited for a variety of optical communication applications by integrating modern modulation techniques with the SSP compensation and assuring effective control of amplifiers.

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