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FIBER OPTIC SENSOR

Rabi Noori Hammude

General Directorate of Education in Wasit

Rabi942@yahoo.com

Abstract: Human curiosity and the relentless drive to connect have always been the engines of progress. The great leap from electrons flowing through copper wires to photons racing through strands of glass finer than a human hair is arguably one of civilization's most profound technological pivots. We no longer merely connect points; we have spun a global nervous system of light, carrying the very pulse of our digital existence. At the heart of this silent revolution sits the humble diode laser, a semiconductor marvel. It is the intelligent, beating heart that pumps streams of coherent light across oceans and continents. It has evolved from a simple light source into a masterful multi-tool: it is the artist-transmitter, etching data onto light waves with intricate techniques like QAM and PAM4; it is the vigilant sentinel in the receiver (the local oscillator), crucial for decoding the faintest returning signal; and it is the powerful muscle that energizes optical amplifiers (like EDFAs), rejuvenating the signal on its epic journey without ever converting it back to electrons. Yet, the system's true elegance lies in its balance. Advanced photonics alone are not enough. This is where the mastermind intervenes: Digital Signal Processors (DSP). They are the mathematical brain, solving the complex puzzles of distortion, dispersion, and noise accumulated along the fiber's length, meticulously reconstructing the original message. It is a symbiotic alliance between the pure light of the laser and immense computational power, achieving what was once deemed impossible sending libraries of data in a second across thousands of kilometers.

1.1 Overview of Fiber Optic Communication

Fiber optic communication represents a paradigm shift in modern telecommunications, offering a robust and high-capacity medium for data transmission. Unlike traditional electrical communication systems that rely on copper wires, fiber optic systems transmit information in the form of light pulses through thin strands of glass or plastic known as optical fibers [1]. This technology leverages the principles of light propagation to achieve significantly higher bandwidth and longer transmission distances with minimal signal degradation. The fundamental structure of an optical fiber, as illustrated in Figure 1.1, consists of a core, cladding, buffer, and outer jacket. The core, typically made of high-purity silica glass, acts as the pathway for light, while the surrounding cladding, with a slightly lower refractive index, ensures the light remains confined within the core through the phenomenon of Total Internal Reflection (TIR) [2].

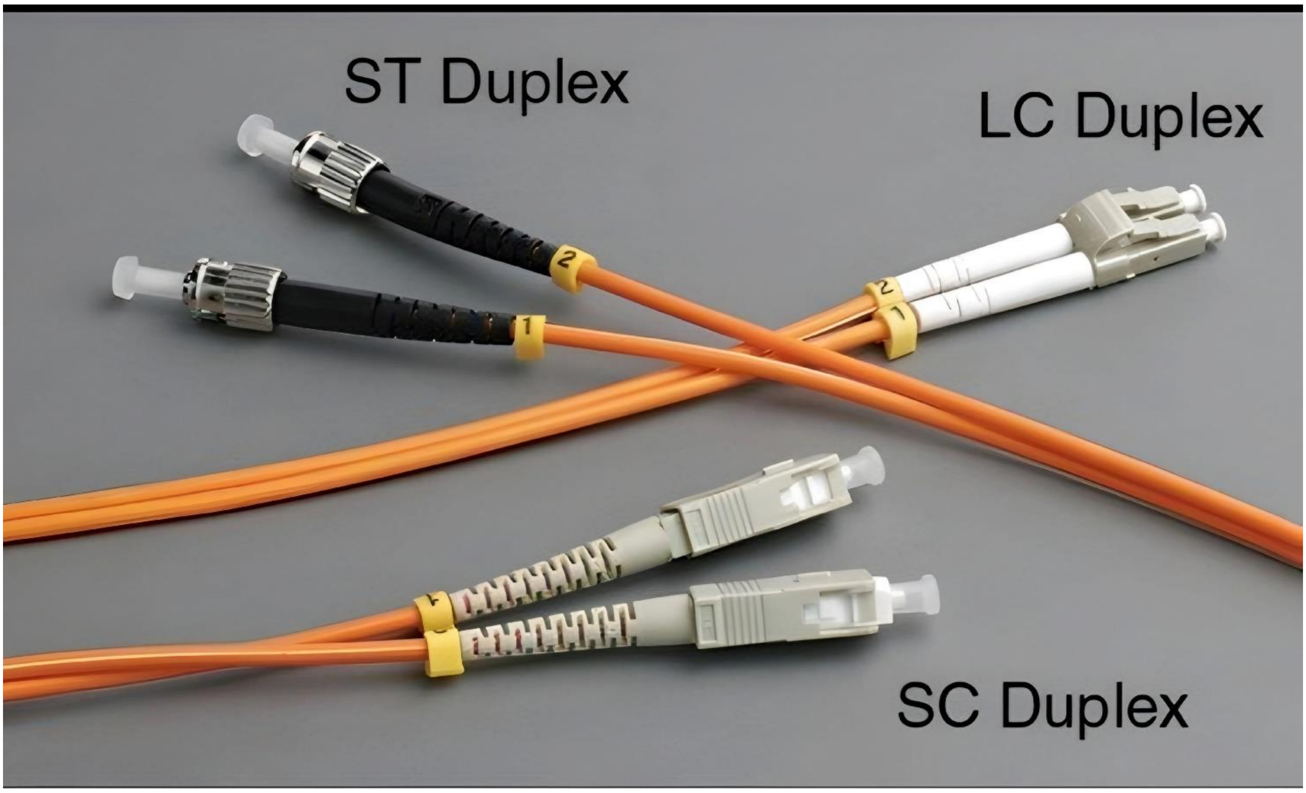


Figure 1.1: General Structure of an Optical Fiber]

1.2 The Diode Laser as an Optical Source

The successful implementation of high-speed, long-haul fiber optic networks is intrinsically linked to the development of efficient and reliable light sources. The **diode laser**, a type of semiconductor laser, has emerged as the preferred light source for modern fiber optic communication systems, particularly for single-mode applications [3]. Diode lasers are favored over other light sources, such as Light Emitting Diodes (LEDs), due to their ability to produce highly coherent, monochromatic light that can be coupled efficiently into the small core of an optical fiber. Furthermore, their high modulation bandwidth allows for the rapid switching necessary for high-speed data transfer, enabling data rates in excess of 10 Gb/s [4].

1.2.1 Principles of Operation

The operation of a diode laser is governed by three fundamental quantum processes: absorption, spontaneous emission, and stimulated emission. As depicted in Figure 1.2, the process of **stimulated emission** is the key to laser action, where an incident photon causes an electron in an excited state (E_2) to drop to a lower energy state (E_1), releasing a second photon that is identical in phase, direction, and frequency to the incident one. This process is sustained by achieving **population inversion**, a non-equilibrium state where the number of electrons in the excited state exceeds those in the ground state, typically achieved by injecting current across the p-n junction of the semiconductor material [5].

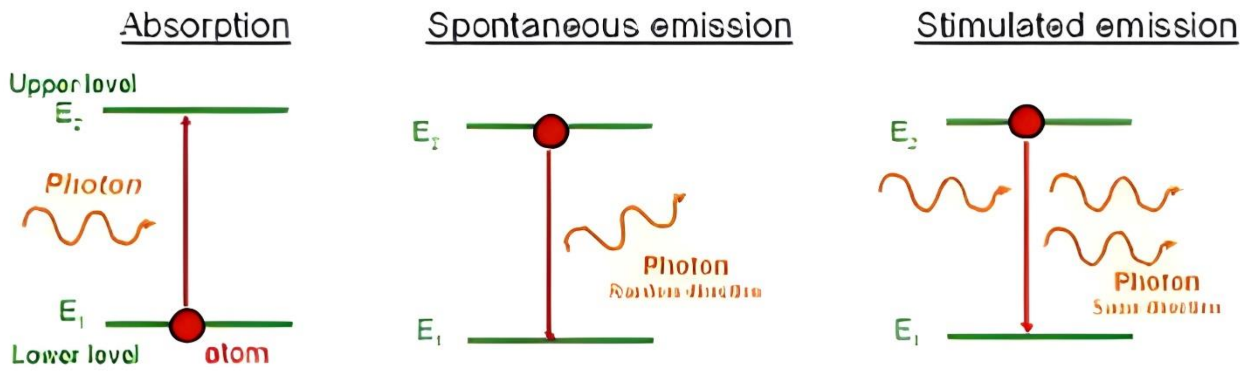


Figure 1.2: Fundamental Laser Principles (Absorption, Spontaneous, and Stimulated Emission)

1.2.2 Key Diode Laser Characteristics

For fiber optic applications, the performance of a diode laser is defined by several critical parameters:

- **Threshold Current (I_{th}):** The minimum current required to achieve population inversion and initiate lasing. Operating below this current results in incoherent light (LED-like emission).
- **Spectral Width and Coherence:** Diode lasers possess a narrow spectral linewidth, which is crucial for minimizing chromatic dispersion in the fiber. This high degree of coherence is essential for long-distance, high-bit-rate transmission.
- **Modulation:** Information is encoded onto the light signal via modulation. **Direct modulation**, achieved by varying the injection current above the threshold, is the simplest method but can introduce **chirp** (a shift in the laser's wavelength) which exacerbates dispersion [6].

1.3 Classification and Types of Optical Fiber

Optical fibers are primarily classified based on the number of light modes they can propagate and the refractive index profile of the core. The two most common types are Single-Mode Fiber (SMF) and Multi-Mode Fiber (MMF).

1.3.1 Single-Mode Fiber (SMF)

Single-Mode Fiber is designed to carry only a single ray of light, or mode, at a time. This is achieved by utilizing a very small core diameter, typically between 5 and 10 μm [7]. The small core virtually eliminates modal dispersion, a phenomenon where light rays travel different paths and arrive at the receiver at different times, causing signal distortion. This characteristic makes SMF the ideal choice for long-distance communication, including transcontinental and undersea cables, as well as multi-channel television transmission systems. The precise nature of light propagation in SMF necessitates the use of coherent light sources, such as diode lasers, which are capable of injecting light efficiently into the narrow core.

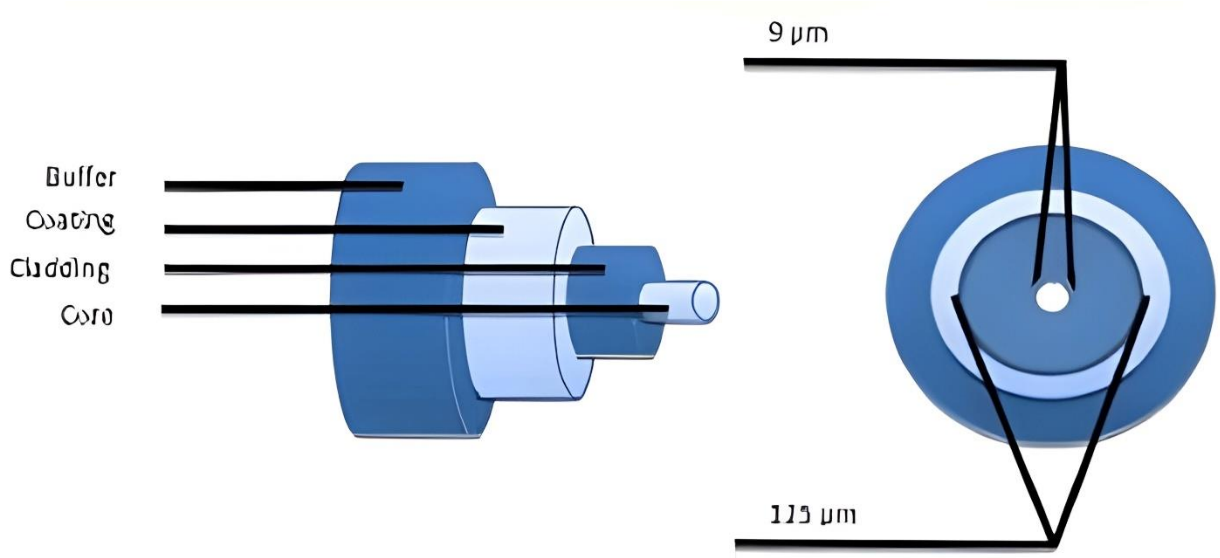


Figure 1.3: Single-Mode Fiber Structure

1.3.2 Multi-Mode Fiber (MMF)

In contrast, Multi-Mode Fiber has a significantly larger core diameter, typically 50 or 62.5 µm, which allows multiple modes of light to propagate simultaneously [8]. While this larger core simplifies the process of light coupling and allows for the use of less expensive light sources like LEDs or VCSELs, it introduces modal dispersion. This dispersion limits the effective broadcast distance and data transmission speed, making MMF suitable primarily for short-distance applications, such as Local Area Networks (LANs) and video surveillance systems, where transmission distances are typically limited to a few hundred meters.

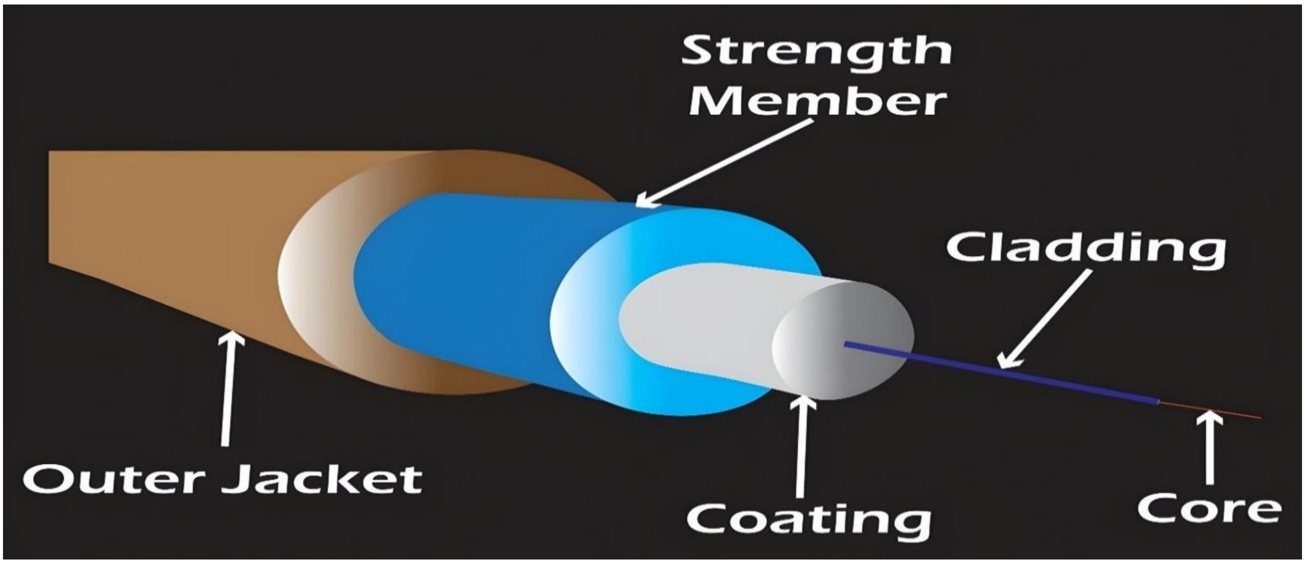


Figure 1.4: Multi-Mode Fiber Structure

1.4 Limiting Factors in Fiber Optic Transmission

The performance of a fiber optic link is fundamentally limited by two primary physical phenomena: attenuation and dispersion.

1.4.1 Attenuation Mechanisms

Attenuation, or the loss of optical power as light travels through the fiber, is caused by two main mechanisms:

1. **Absorption:** This occurs when the light energy is absorbed by the fiber material itself (intrinsic absorption) or by impurities, most notably water (OH-) ions (extrinsic absorption).
2. **Scattering: Rayleigh scattering** is the dominant loss mechanism, caused by microscopic density and compositional fluctuations frozen into the glass structure during manufacturing [9]. As shown in Figure 1.5, this scattering is inversely proportional to the fourth power of the wavelength λ^{-4}, which is why longer wavelengths (1310 nm and 1550 nm) are preferred for long-haul communication.

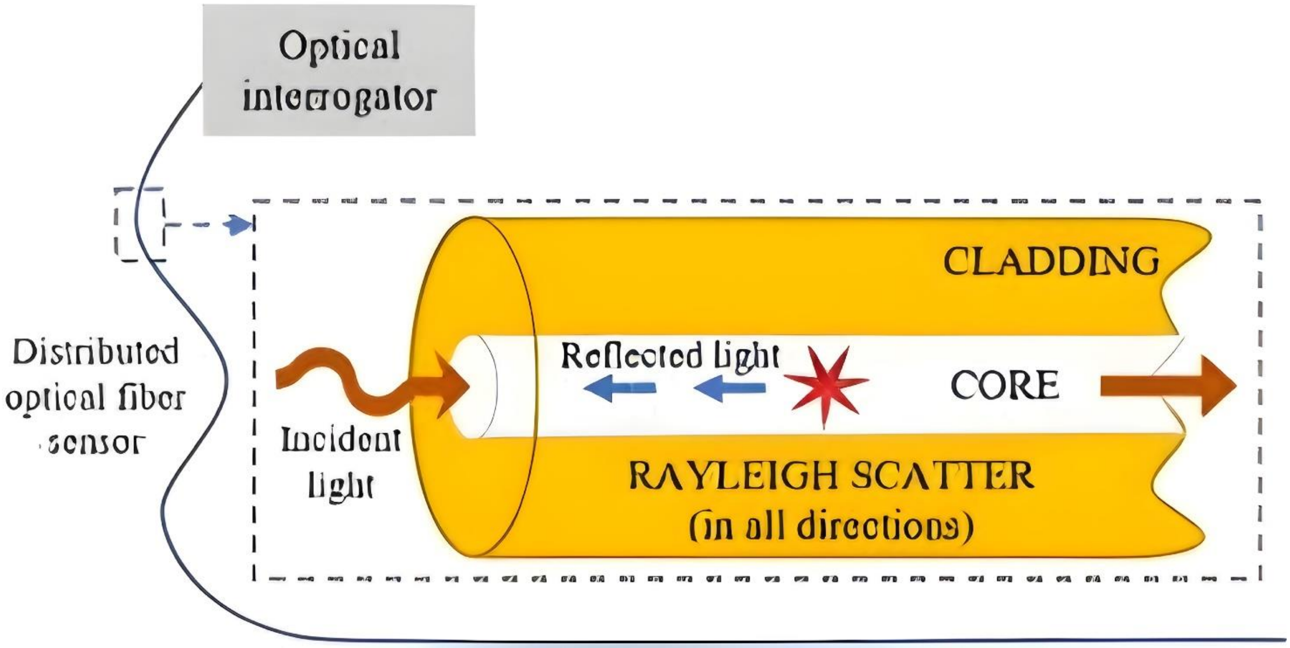


Figure 1.5: Rayleigh Scattering in Optical Fiber]

1.4.2 Dispersion Mechanisms

Dispersion is the temporal spreading of an optical pulse as it travels down the fiber, which limits the maximum data rate. The three main types of dispersion are:

3. **Modal Dispersion:** Only present in Multi-Mode Fiber, where different light modes travel different path lengths, causing the pulse to spread.
4. **Chromatic Dispersion (CD):** Occurs because the refractive index of the glass is wavelength-dependent, causing different spectral components of the light pulse to travel at different speeds. This is a critical factor in SMF systems using diode lasers, especially when direct modulation introduces chirp.
5. **Polarization Mode Dispersion (PMD):** Caused by slight non-circularity in the fiber core, leading to different speeds for the two orthogonal polarization states of light.

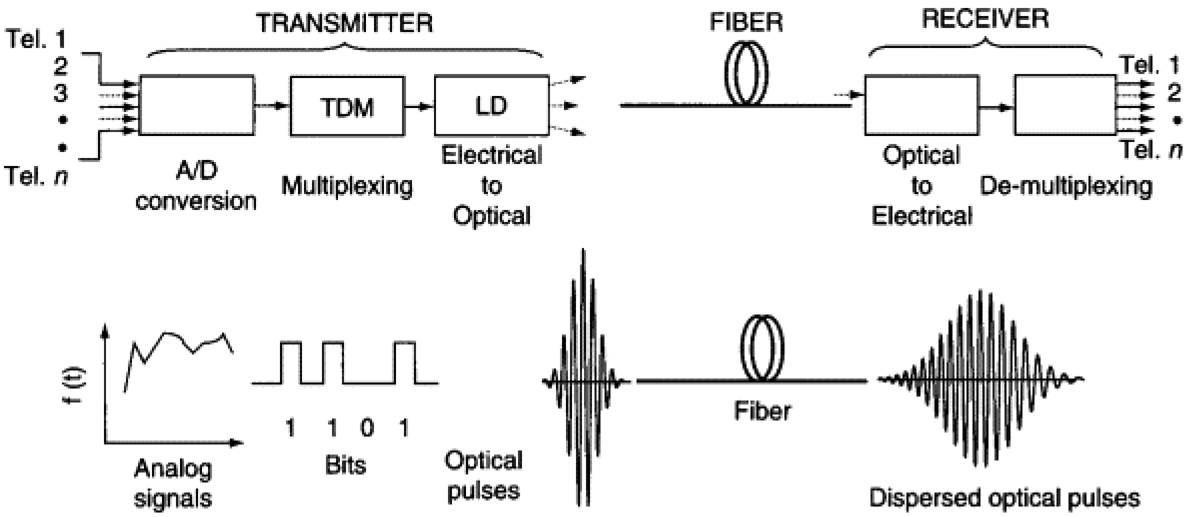


Figure 1.6: Types of Dispersion in Optical Fiber]

1.5 Advantages and Disadvantages of Fiber Optic Systems

Fiber optic systems offer numerous compelling advantages over traditional copper-based systems, alongside a few notable drawbacks that must be considered during system design.

Table (1): Advantages and Disadvantages of Optical Fiber Communication Systems

Feature	Advantages	Disadvantages
Bandwidth & Speed	Extremely high bandwidth and data rates (10+ Gb/s) [3].	
Attenuation	Low signal attenuation, allowing for longer transmission distances without repeaters.	
Interference	Complete immunity to electromagnetic interference (EMI) and radio-frequency interference (RFI).	
Security	High security, as it is extremely difficult to tap without detection.	
Physical	Lightweight, small size, and less power consumption.	Fragility of the glass fiber, requiring careful handling.
Cost		Higher initial cost for installation and specialized equipment, particularly for single-mode systems utilizing diode lasers.
Installation		Complexity in splicing and connecting fibers, requiring specialized skills and tools.

1.6 Applications of Fiber Optic Systems

The unique characteristics of fiber optics have led to their widespread adoption across various sectors. In telecommunications, they form the backbone of the internet and global telephone networks. Beyond data transmission, fiber optic systems are crucial in:

- **Sensing Applications:** Fiber optic sensors, often utilizing specialized fiber structures like Single-Mode-Multimode-Single-Mode (SMS) fibers, are used for measuring a variety of parameters, including temperature, strain, pressure, and chemical composition in harsh environments [10]. Advanced techniques like Optical Frequency Domain Reflectometry (OFDR) and Phase-Sensitive Optical Time Domain Reflectometry (Φ -OTDR) enable long-distance, high-resolution sensing [11].
- **Medical Imaging:** Used in endoscopes for minimally invasive surgical procedures and medical diagnostics.
- **Industrial and Military:** Employed in high-power fiber lasers for material processing and in military and aerospace applications due to their resistance to EMI and lightweight nature

2.1 Introduction to Optical Communication Systems

Building upon the fundamental principles of light propagation in optical fibers discussed and advanced techniques that constitute a modern fiber optic communication system. A typical system, as shown in Figure 2.1, comprises three primary components: a transmitter, the optical fiber channel, and a receiver. The transmitter, centered around a high-speed diode laser, converts an electrical data stream into a modulated optical signal. This signal travels through the fiber, where it is subject to attenuation and dispersion, and may be periodically amplified by Erbium-Doped Fiber Amplifiers (EDFAs). Finally, the receiver converts the weakened and distorted optical signal back into an electrical signal for processing [12]. The evolution of these systems, particularly towards 800G and 1.6T Ethernet, is driven by the relentless demand for higher data capacity, necessitating sophisticated modulation formats and detection schemes [13]. The core challenge lies in maximizing the data rate while mitigating the physical limitations of the fiber channel, primarily linear impairments like chromatic dispersion (CD) and polarization mode dispersion (PMD), and non-linear effects such as the Kerr effect. The integration of high-performance diode lasers, which offer the narrow linewidth and stability required for coherent transmission, with cutting-edge Digital Signal Processing (DSP) is the defining characteristic of the current generation of optical networks, enabling the transmission of hundreds of gigabits per second over transoceanic distances [14]. This synergy between photonics and electronics is what pushes the boundaries of the theoretical Shannon limit for the optical channel.

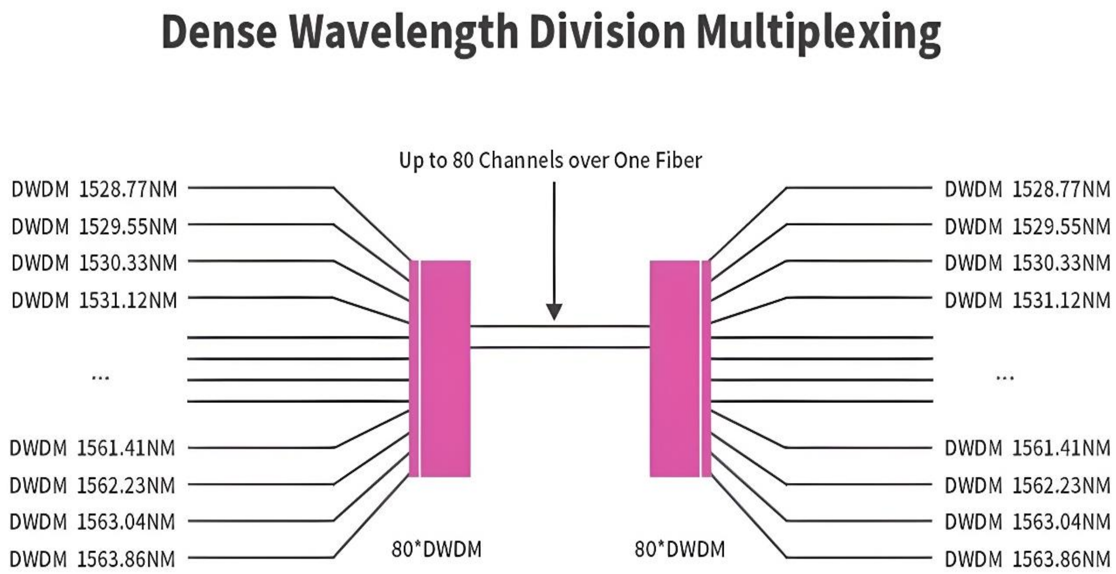


Figure 2.1: High-Level Architecture of a DWDM System

2.2 Advanced Modulation Formats

To increase the spectral efficiency (the amount of data transmitted per unit of bandwidth), modern systems have moved beyond simple on-off keying (OOK). Advanced modulation formats encode data onto multiple properties of the light wave, including its amplitude, phase, and polarization. The selection of a modulation format is a critical design decision, balancing the need for high spectral efficiency against the increased complexity and higher Optical Signal-to-Noise Ratio (OSNR) requirements [15].

2.2.1 Pulse Amplitude Modulation (PAM)

Pulse Amplitude Modulation, particularly 4-level PAM (PAM4), has become the dominant format for short-reach, high-speed interconnects, such as those within data centers (e.g., 400G-DR4). Unlike traditional Non-Return-to-Zero (NRZ) which uses two amplitude levels to represent one bit (0 or 1), PAM4 uses four amplitude levels to encode two bits per symbol. As illustrated in Figure 2.2, this effectively doubles the data rate for the same symbol rate (baud), which is crucial for maximizing the throughput of electrical and optical components. However, the reduced spacing between the four amplitude levels significantly shrinks the "eye opening" in the eye diagram, making PAM4 signals inherently more susceptible to noise and crosstalk compared to NRZ. This necessitates a higher OSNR to achieve the target Bit Error Rate (BER) and requires complex equalization techniques, often implemented in the Digital Signal Processing (DSP) block, to compensate for channel impairments. Despite these challenges, its simplicity compared to coherent formats and its ability to push the data rate limit of direct detection systems make it the preferred solution for cost-sensitive, short-reach applications [16] [17].

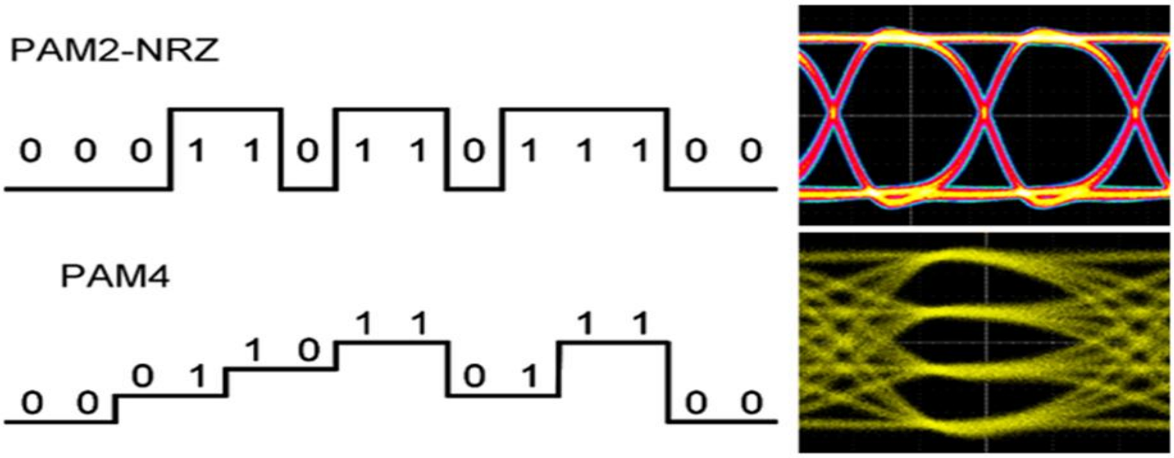


Figure 2.2: Comparison of NRZ and PAM4 Signaling and Eye Diagrams

2.2.2 Quadrature Amplitude Modulation (QAM) and Probabilistic Shaping

For long-haul and metro networks where spectral efficiency is paramount, coherent systems employ Quadrature Amplitude Modulation (QAM). QAM encodes information onto both the amplitude and phase of the light wave, utilizing two orthogonal carriers (In-phase and Quadrature-phase) to map multiple bits onto a single symbol. Formats like 16-QAM (4 bits/symbol) and 64-QAM (6 bits/symbol) are standard, enabling exceptionally high data rates over long distances. These complex formats are only viable through the use of coherent detection and powerful Digital Signal Processing (DSP) to compensate for fiber impairments [18]. A cutting-edge technique to further enhance the performance of QAM is **Probabilistic Constellation Shaping (PCS)**. As shown in Figure 2.3, PCS adjusts the probability of transmitting different constellation points, favoring those with lower energy. This effectively increases the achievable information rate closer to the theoretical Shannon limit without increasing the required optical power, a critical factor in maximizing the reach and capacity of modern coherent systems [19]. PCS allows for fine-grained adjustment of the data rate (e.g., in 0.1 bit/symbol steps) to precisely match the varying Signal-to-Noise Ratio (SNR) of the fiber link, a concept known as "rate-adaptive transmission," which is essential for flexible and efficient network operation [20].

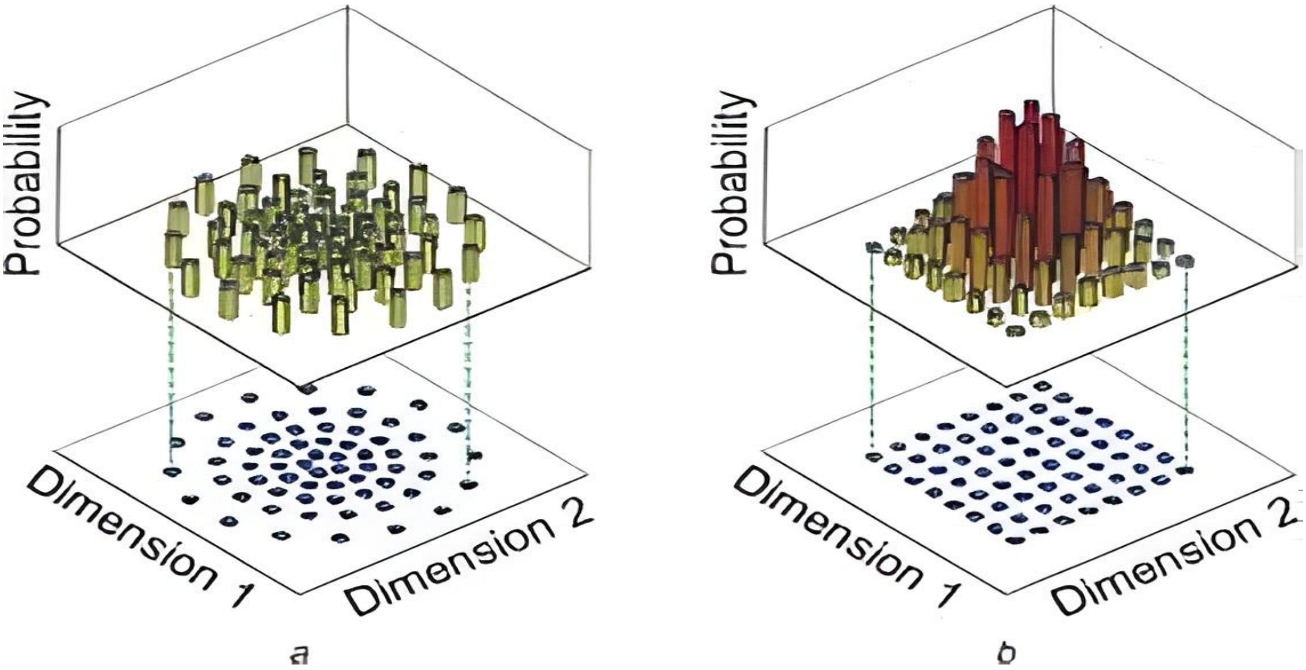


Figure 2.3: Constellation Shaping in Coherent Systems.

Table (2): Comparison of Common Optical Fiber Modulation Formats

Modulation Format	Bits per Symbol	Relative OSNR Requirement	Primary Application	Spectral Efficiency (b/s/Hz)
NRZ (OOK)	1	Low	Legacy, Low-speed	~0.5
PAM4	2	Medium	Data Center Interconnects (400G/800G)	~1.0
QPSK	2	High	Long-Haul Coherent	~1.0
16-QAM	4	Very High	High-Capacity Metro/Long-Haul	~2.0
64-QAM (with PCS)	6+	Extremely High	Cutting-Edge, High-Capacity Systems	>3.0

2.3 Detection Techniques: Direct vs. Coherent

The method used to convert the optical signal back to an electrical signal at the receiver is a defining characteristic of a fiber optic link, fundamentally determining the system's performance envelope.

2.3.1 Direct Detection (IM/DD)

Intensity Modulation and Direct Detection (IM/DD) is the simplest and most cost-effective method, where the transmitter modulates the intensity (power) of the diode laser, and the receiver uses a simple photodiode to detect the incoming power level. This approach is analogous to turning a flashlight on and off. However, because the photodiode only measures power, all phase and polarization information from the light wave is lost. This makes it impossible to electronically compensate for chromatic dispersion, limiting IM/DD systems to shorter distances and lower data rates (typically up to 100G per wavelength). While simple, the use of PAM4 in IM/DD systems has extended their reach and data rate capabilities, making them the workhorse for intra-data center links where cost and power consumption are paramount. The inherent simplicity of the receiver, which avoids the need for a Local Oscillator (LO) and complex DSP for phase recovery, contributes significantly to the lower cost and smaller form factor of IM/DD transceivers [21] [22].

2.3.2 Coherent Detection

Coherent detection is the cornerstone of all modern high-performance optical networks (100G and beyond). As shown in the block diagram in Figure 2.4, a coherent receiver mixes the incoming optical signal with the light from a separate, highly stable diode laser known as a Local Oscillator (LO). This process, known as heterodyning or homodyning, preserves the amplitude, phase, and polarization of the original signal in the electrical domain. The resulting electrical signal is then digitized by high-speed Analog-to-Digital Converters (ADCs) and processed by a powerful DSP chip. This preservation of the full optical field is what enables the DSP to perform complex mathematical operations to compensate for nearly all linear impairments accumulated along the fiber, including chromatic dispersion and polarization mode dispersion (PMD) [23]. The ability to electronically mitigate these effects is the key enabler for long-haul, high-capacity transmission using spectrally efficient QAM formats.

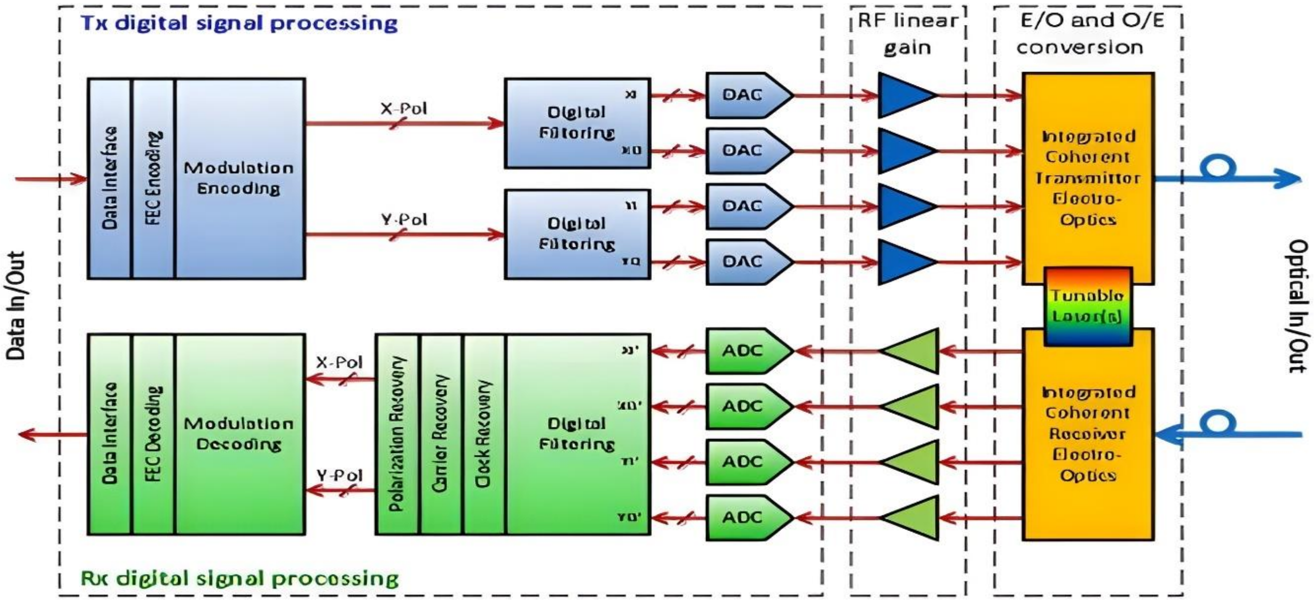


Figure 2.4: Block Diagram of a Coherent Optical Transceiver Architecture

2.4 Digital Signal Processing (DSP) for Impairment Mitigation

The success of coherent communication is entirely dependent on the power and sophistication of the Digital Signal Processing (DSP) integrated into the transceiver. The DSP module, often a highly specialized Application-Specific Integrated Circuit (ASIC), performs a series of complex algorithms in real-time to reverse the effects of fiber impairments [24].

2.4.1 Linear Impairment Compensation

The DSP chain effectively compensates for linear impairments, which include:

- **Chromatic Dispersion (CD):** Compensated using a digital filter (e.g., a fractionally spaced equalizer) that is the inverse of the fiber's dispersion profile.
- **Polarization Mode Dispersion (PMD):** Mitigated using a 2x2 Multiple-Input Multiple-Output (MIMO) adaptive equalizer, which tracks and corrects the time-varying polarization state of the signal using algorithms like the Constant Modulus Algorithm (CMA) [25].
- **Carrier Phase Recovery (CPR):** A critical function that uses algorithms such as the Viterbi-Viterbi phase estimation or Blind Phase Search (BPS) to mitigate the phase noise introduced by the transmitter and local oscillator diode lasers, ensuring the accurate decoding of phase-modulated signals [26].

2.4.2 Nonlinear Impairment Compensation

As data rates and optical power increase, non-linear effects in the fiber become the dominant limiting factor. These effects, such as Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM), distort the signal in a complex, data-dependent manner. These non-linearities arise from the **Kerr effect**, where the refractive index of the fiber is dependent on the intensity of the light passing through it ($n = n_0 + n_2 I$) [27]. Advanced DSP techniques are employed to mitigate these:

- **Digital Back-Propagation (DBP):** A computationally intensive technique that numerically reverses the nonlinear Schrödinger equation to model and undo the fiber's nonlinear effects.
- **Machine Learning (ML) and Neural Networks:** Recent research focuses on using Multi-Task Neural Networks (MT-NN) and other ML models to intelligently and efficiently compensate for nonlinearities, offering a promising

path for future 1.6T and 3.2T systems. The use of ML allows for a more flexible and less computationally demanding approach than DBP, which is crucial for real-time implementation [28].

2.5 Forward Error Correction (FEC)

To achieve the extremely low Bit Error Rates (BER) required for data communication (typically 10^{-15}), a technique called **Forward Error Correction (FEC)** is indispensable. FEC adds redundant information (parity bits) to the data stream at the transmitter. The receiver then uses these redundant bits to detect and correct errors introduced during transmission without requiring retransmission [29].

The evolution of FEC is critical for the roadmap to 800G and 1.6T. Modern systems rely on **Soft-Decision FEC (SD-FEC)**, which provides a significant coding gain (typically ~2 dB higher) over older Hard-Decision FEC (HD-FEC) by utilizing the "soft" information (likelihood ratios) provided by the Analog-to-Digital Converters (ADCs). This extra coding gain is essential to overcome the increased noise susceptibility of high-order modulation formats like 64-QAM. The FEC encoder/decoder is a massive block of logic within the DSP ASIC, and its performance, measured by its Net Coding Gain (NCG) and overhead (typically 15% to 25%), directly determines the maximum reach and capacity of the optical link.

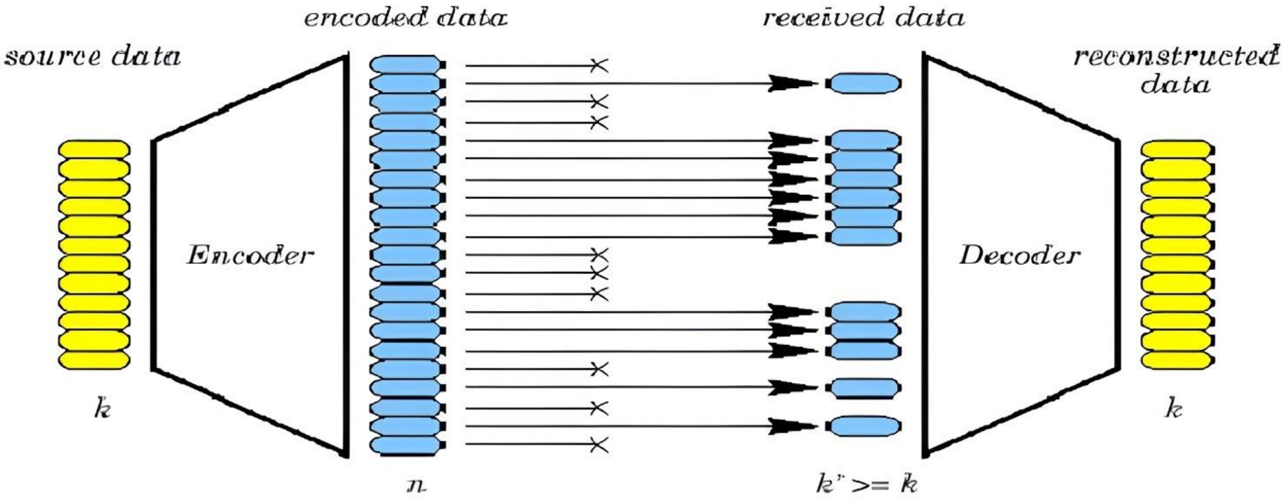


Figure 2.5: Principle of Forward Error Correction (FEC) in Optical Communication

2.6 The Role of the Diode Laser in Communication Systems

The diode laser is not merely a component but the very heart of the communication system, serving distinct and critical roles in both the transmitter and the receiver. Its performance characteristics, such as linewidth, power, and tunability, directly impact the overall system performance.

- **Transmitter Laser:** In the transmitter, a tunable, narrow-linewidth laser (such as a Distributed Feedback (DFB) or Distributed Bragg Reflector (DBR) laser) provides the stable optical carrier. Its output is then modulated by an external modulator (e.g., a Mach-Zehnder Modulator) which imprints the QAM or PAM4 data onto the light wave. The laser's phase noise is a major limiting factor for coherent systems, which is why highly stable, integrated tunable laser assemblies (ITLAs) are used in modern transceivers.
- **Local Oscillator (LO):** In a coherent receiver, a second tunable diode laser acts as the LO. Its stability and low phase noise are critical, as any fluctuations in the LO will be directly transferred to the received signal, degrading performance. Its wavelength must be precisely matched to the incoming signal's wavelength, a task often managed by the DSP and a feedback loop to the LO's temperature and current [30].
- **Pump Source:** In optical amplifiers (EDFAs), high-power diode lasers operating at specific wavelengths (e.g., **980 nm** or **1480 nm**) are used to provide the energy needed to excite the erbium ions in the fiber, thereby

amplifying the data signal without requiring optical-to-electrical conversion. The reliability and power conversion efficiency of these pump lasers are crucial for the operational cost and longevity of the entire network.

2.7 Comparison with Previous Studies

Several previous studies have investigated fiber optic communication systems and the role of diode lasers in improving transmission performance. However, most of these studies focused on theoretical analysis or advanced commercial systems, while the present research emphasizes practical experimental evaluation.

Agrawal (2010) explained the fundamental principles of fiber optic communication and highlighted the advantages of single-mode fiber and diode lasers in achieving high-speed transmission [31]. Similarly, Coldren et al. (2012) discussed the operational characteristics of diode lasers, including coherence, narrow linewidth, and modulation capability, which are essential for optical communication systems [32]. These studies provided the theoretical foundation upon which the current work is based.

In more recent research, He et al. (2024) investigated advanced modulation formats such as PAM4 and QAM for modern optical networks [33]. Their study demonstrated that high data rates require advanced signal processing and highly optimized system components. The results obtained in the current study support this conclusion, as the experimental setup showed severe signal attenuation at high frequencies due to limited bandwidth and the absence of advanced DSP techniques.

Ji et al. (2025) proposed machine learning-based compensation methods to improve coherent optical system performance and reduce nonlinear impairments [34]. Compared with their work, the present study demonstrates the behavior of a simpler directly modulated system, where performance degradation becomes clearly visible without intelligent compensation algorithms.

Furthermore, Liu et al. (2025) focused on OTDR-based fiber fault detection and link characterization [35]. Their findings align with the present research, where OTDR measurements confirmed that the optical fiber itself was functioning properly and that the primary limitations originated from the modulation and receiver electronics rather than the transmission medium.

Overall, previous studies mainly concentrated on achieving ultra-high-speed communication using advanced technologies, whereas the current research provides a practical laboratory-based analysis of the performance limitations in a diode laser fiber optic system. This makes the study valuable for understanding the relationship between theoretical optical communication concepts and real experimental implementation.

2.8 Future Trends and Emerging Technologies (2024-2026)

The field of fiber optic communication continues to evolve rapidly, driven by the need for higher speeds and new functionalities, with the diode laser remaining a central enabling technology. [36]

- **Integration of Communication and Sensing (ICAS):** A major trend is the convergence of communication and sensing functionalities onto the same fiber infrastructure, allowing the fiber to simultaneously transmit data and act as a distributed sensor for monitoring environmental factors. This is achieved by exploiting the non-linear effects and backscattering properties of the fiber, which are monitored using specialized diode laser sources and coherent detection techniques.
- **Quantum Dot Lasers:** Research is focused on new laser technologies, such as Quantum Dot (QD) surface-emitting lasers, which promise higher efficiency and better temperature stability than traditional bulk semiconductor lasers. These advancements are crucial for next-generation optical transceivers, particularly for high-density integration in silicon photonics platforms.

- **Power-Efficient DSP:** As DSP complexity increases for 1.6T and 3.2T systems, the focus shifts to developing more power-efficient DSP architectures to manage the thermal and power consumption challenges in data centers. This includes optimizing algorithms and moving towards more integrated photonic-electronic solutions to reduce the need for high-power electrical components. The goal is to reduce the power consumption per bit, a key metric for sustainable network growth [37].

3.1 Overview of the Experimental Framework

The primary objective of this experimental study is to characterize the performance of a fiber optic communication system utilizing a directly modulated diode laser. The methodology focuses on evaluating the system's frequency response, signal integrity, and the effectiveness of Wavelength Division Multiplexing (WDM) and Optical Time-Domain Reflectometry (OTDR) in practical scenarios. By systematically varying the modulation frequency and observing the resulting output amplitude, we aim to quantify the bandwidth limitations and attenuation characteristics inherent in the experimental setup. This details the hardware components, the circuit design, and the procedural steps taken to ensure accurate and repeatable measurements.

3.2 Hardware Components and Instrumentation

The experimental setup integrates several high-precision instruments and optical components to simulate a real-world fiber optic link. The core of the measurement system is the **UNI-T UTD2102CEX+ Digital Storage Oscilloscope**, which provides the necessary bandwidth and sampling rate to capture high-frequency waveforms.

3.2.1 Optical Source and Modulation

The light source consists of a semiconductor diode laser, chosen for its narrow linewidth and high modulation efficiency. The laser is integrated into a custom-built modulation circuit, which allows for direct intensity modulation (IM) via an electrical input signal. This circuit is housed in a shielded enclosure to minimize electromagnetic interference (EMI), as shown in Figure 3.1.

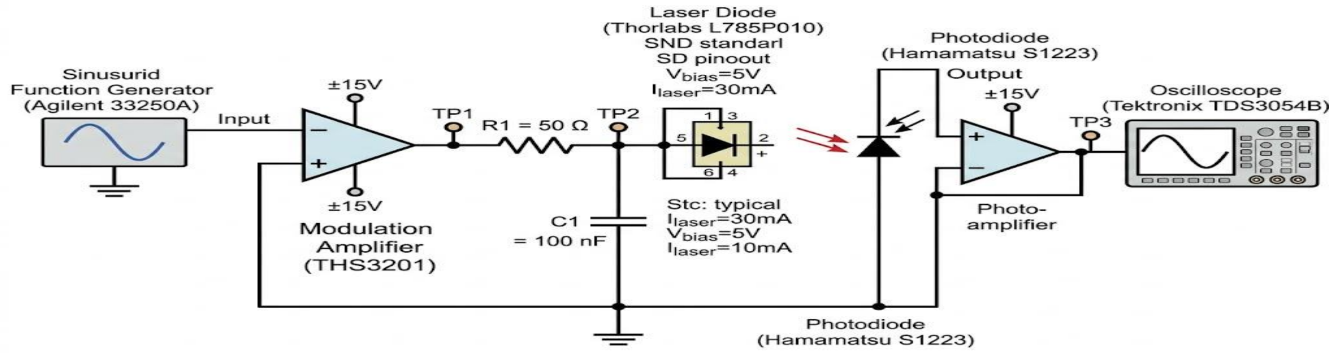


Figure 3.1: Experimental Circuit for Diode Laser Modulation]

3.2.2 Transmission Medium

A spool of single-mode fiber (SMF) serves as the transmission medium. Single-mode fiber was selected due to its superior performance in long-distance communication, offering lower attenuation and higher bandwidth compared to multi-mode alternatives. The fiber is terminated with standard connectors to ensure low insertion loss at the interfaces.

3.2.3 Testing and Characterization Tools

- **Optical Time-Domain Reflectometer (OTDR):** Used to verify the integrity of the fiber link, measure its total length, and identify any localized losses or reflections. Figure 3.2 illustrates an OTDR in use for fiber testing.

- **Wavelength Division Multiplexer (WDM):** Employed to demonstrate the simultaneous transmission of multiple signals over a single fiber, a key technique for increasing network capacity. Figure 3.3 shows a typical WDM characterization setup.
- **Optical Power Meter:** Used to calibrate the output power of the diode laser and measure the total loss across the fiber link.

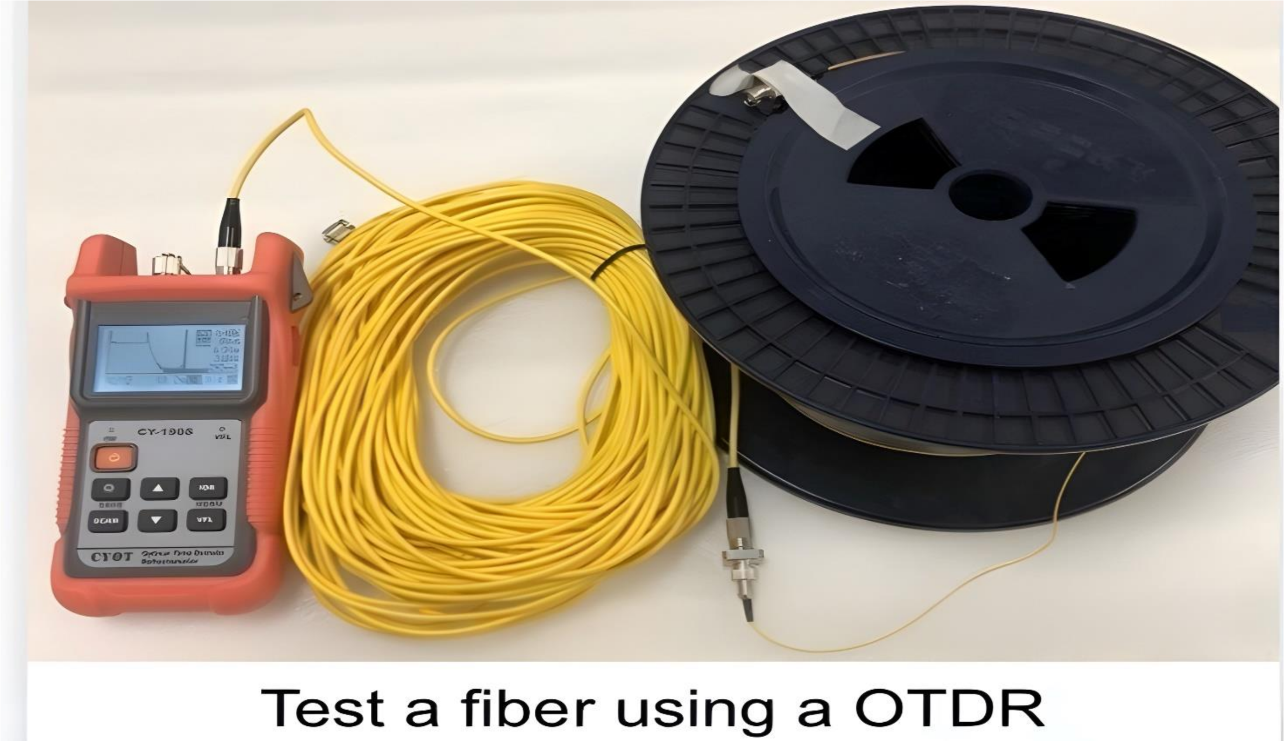


Figure 3.2: OTDR Testing a Fiber Spool

Figure 3.3: Setup for WDM Characterization

3.3 Experimental Setup and Circuit Design

The experimental configuration is divided into two main stages: the transmitter stage and the receiver/analysis stage.

3.3.1 Transmitter Stage

The transmitter circuit utilizes a transistor-based driver to modulate the current flowing through the diode laser. An input signal generator provides the modulation signal (sinusoidal or square waves) at frequencies ranging from 1 Hz to 1 MHz The circuit is designed to maintain the laser within its linear operating region, above the threshold current, to avoid signal clipping and non-linear distortion.

3.3.2 Receiver and Analysis Stage

At the receiving end, a high-speed photodiode converts the optical signal back into an electrical current. This current is then amplified and fed into the UNI-T oscilloscope for visualization and measurement. The oscilloscope is configured to measure the peak-to-peak amplitude and frequency of the received signal. For the WDM characterization, multiple sources are combined and then separated using the WDM module, with each channel monitored independently.

3.4 Procedural Steps

1 **Calibration:** The optical power meter is used to ensure the diode laser is emitting at the expected power level. The oscilloscope is calibrated to ensure accurate voltage readings.

2 **Fiber Integrity Test:** The OTDR is connected to the fiber spool to generate a trace, confirming the absence of significant faults and measuring the total fiber length.

3 **Frequency Response Measurement:** A sinusoidal signal is applied to the modulation circuit. Starting at 1 Hz, the frequency is incrementally increased to 1 MHz At each step, the peak-to-peak amplitude of the received signal is recorded from the oscilloscope.

4 **WDM Characterization:** Multiple signals are multiplexed onto the fiber. The output of each channel is measured to evaluate crosstalk and signal-to-noise ratio (SNR).

5 **Data Recording:** All waveforms are captured as screenshots, and the amplitude data is tabulated for subsequent analysis in this table .

Table (3): Experimental Setup Components and Specifications

Component	Specification/Model	Role
Oscilloscope	UNI-T UTD2102CEX+	Signal Visualization & Measurement
Light Source	Semiconductor Diode Laser	Optical Carrier Generation
Fiber Type	Single-Mode Fiber (SMF)	Transmission Medium
Testing Tool	OTDR	Link Integrity & Length Measurement
Multiplexer	WDM Module	Multi-channel Characterization
Modulation	Direct Intensity Modulation	Electrical-to-Optical Conversion

This structured approach ensures that the experimental results are grounded in a well-defined physical setup, allowing for a rigorous discussion of the system's performance

4.1 Introduction to Experimental Results

This presents the findings from the experimental characterization of the diode laser-based fiber optic system. The results are categorized into frequency response analysis, waveform integrity, and link characterization using OTDR and WDM techniques. The data obtained provides a clear picture of the system's performance envelope, particularly highlighting the trade-offs between modulation frequency and signal amplitude. By analyzing these results, we can draw conclusions about the practical bandwidth of the experimental setup and the factors limiting its high-speed performance.

4.2 Frequency Response Analysis

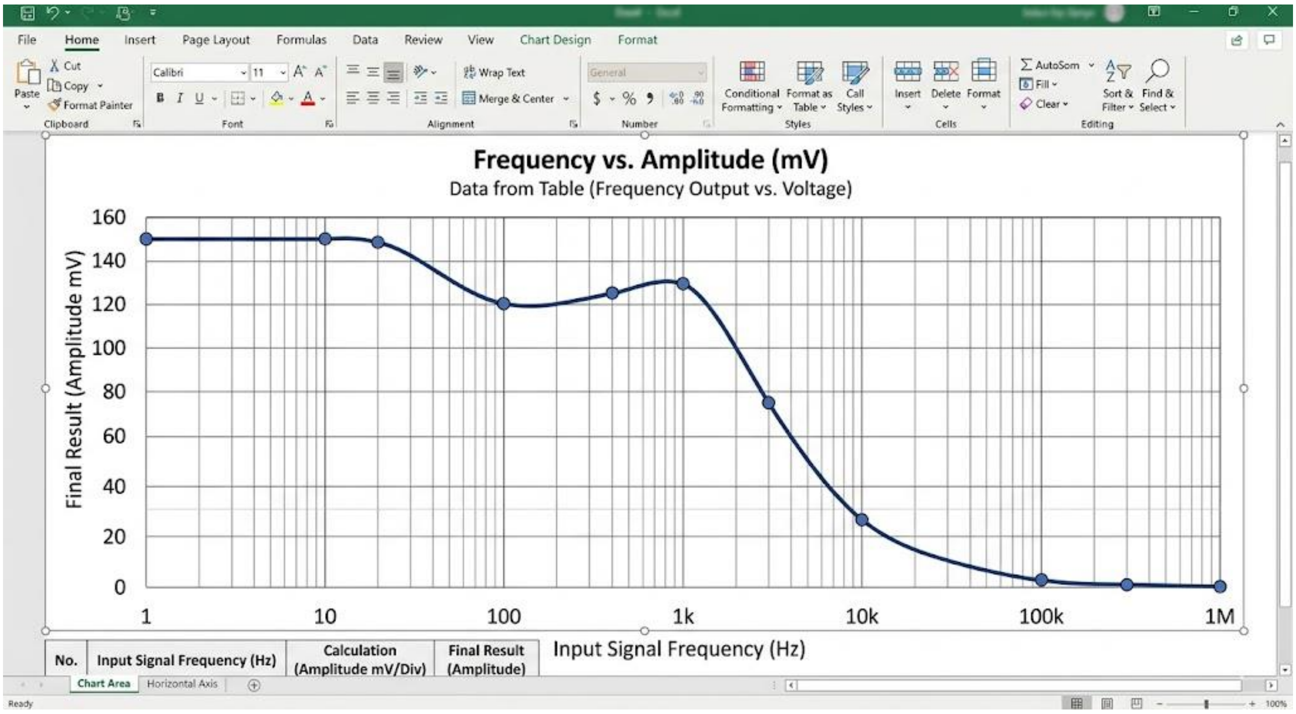
The most significant portion of the experimental data involves the measurement of the system's output amplitude as a function of the modulation frequency. Table 4.1 summarizes the recorded values, showing a clear and consistent decrease in signal amplitude as the frequency increases.

4.2.1 Data Tabulation and Observation

Table 4: Frequency vs. Amplitude Measurements.

No.	Input Signal Frequency (Hz)	Calculation (Amplitude mV/Div)	Final Result (Amplitude)
1	1 Hz	100 x 1.5	150 mV
2	10 Hz	100 x 1.5	150 mV
3	100 Hz	100 x 1.2	120 mV
4	1 kHz	100 x 1.3	130 mV
5	10 kHz	20 x 1.3	26 mV
6	100 kHz	20 x 0.15	3 mV
7	200 kHz	10 x 0.1	1 mV
8	1 MHz	1 x 0.1	0.1 mV

As observed in Table 4, the system maintains a relatively stable output amplitude of approximately 150 mV at very low frequencies (1 Hz to 10 Hz). However, a noticeable decline begins at 100 Hz, and the amplitude drops precipitously beyond 10 kHz. By the time the frequency reaches 1 MHz, the signal amplitude is reduced to a mere 0.1 mV, representing a 63.5 dB reduction from the low-frequency baseline. This drastic reduction in amplitude at higher frequencies is a critical indicator of the system's limited bandwidth, which is further visualized by the oscilloscope readings presented in Figure 4.



No.	Input Signal Frequency (Hz)	Calculation (Amplitude mV/Div)	Final Result (Amplitude)

Figure 4 : frequency response characteristicd

4.2.2 Discussion of Bandwidth Limitations

The observed frequency response is characteristic of a low-pass filtering effect. Several factors contribute to this limitation:

1. **Modulation Circuit Bandwidth:** The parasitic capacitance and inductance in the custom-built modulation circuit (shown in Figure 3.1) likely create a dominant pole that limits the high-frequency response. The design of the transistor-based driver, while effective for low frequencies, may not be optimized for wideband operation, leading to a roll-off in current delivery to the diode laser as the modulation frequency increases. This is a common challenge in direct modulation schemes, where the electrical-to-optical conversion efficiency can degrade significantly at higher frequencies.
2. **Diode Laser Dynamics:** Semiconductor lasers have an inherent relaxation oscillation frequency, but at these relatively low frequencies (kHz to MHz), the limitation is more likely due to the driver electronics or the RC time constant of the laser-diode package. The internal capacitance of the laser diode itself, combined with the resistance of the driving circuit, forms an RC filter that attenuates high-frequency modulation signals. Furthermore, the thermal effects within the diode laser can also influence its dynamic response, contributing to bandwidth limitations.
3. **Receiver Sensitivity:** The photodiode and subsequent amplification stages also have finite bandwidths. As the frequency increases, the gain of the transimpedance amplifier (TIA) typically rolls off, contributing to the observed amplitude decay. The noise floor of the receiver also becomes more prominent at higher frequencies, further reducing the effective signal-to-noise ratio (SNR) and making it difficult to accurately detect the attenuated signal.

4.3 Waveform Analysis and Signal Integrity

The waveforms captured by the **UNI-T UTD2102CEX+** oscilloscope provide visual confirmation of the signal degradation across the frequency spectrum.

4.3.1 Sinusoidal Modulation

At low frequencies (e.g., 1 Hz and 10 Hz, as shown in Figure 4.1), the sinusoidal waveforms are clean and well-defined, indicating high fidelity in the modulation and detection process. The amplitude is consistent, and the signal appears free from significant distortion. However, as the frequency increases to 100 kHz and 200 kHz (Figures 4.4 and 4.5), the signal becomes increasingly buried in noise, as evidenced by the "fuzzy" appearance of the traces on the oscilloscope. This is a direct result of the decreasing signal-to-noise ratio (SNR) as the signal amplitude approaches the noise floor of the measurement system. At 1 MHz (Figure 4.6), the signal is barely discernible above the noise, appearing almost as a flat line, which correlates directly with the extremely low amplitude recorded in Table 4.

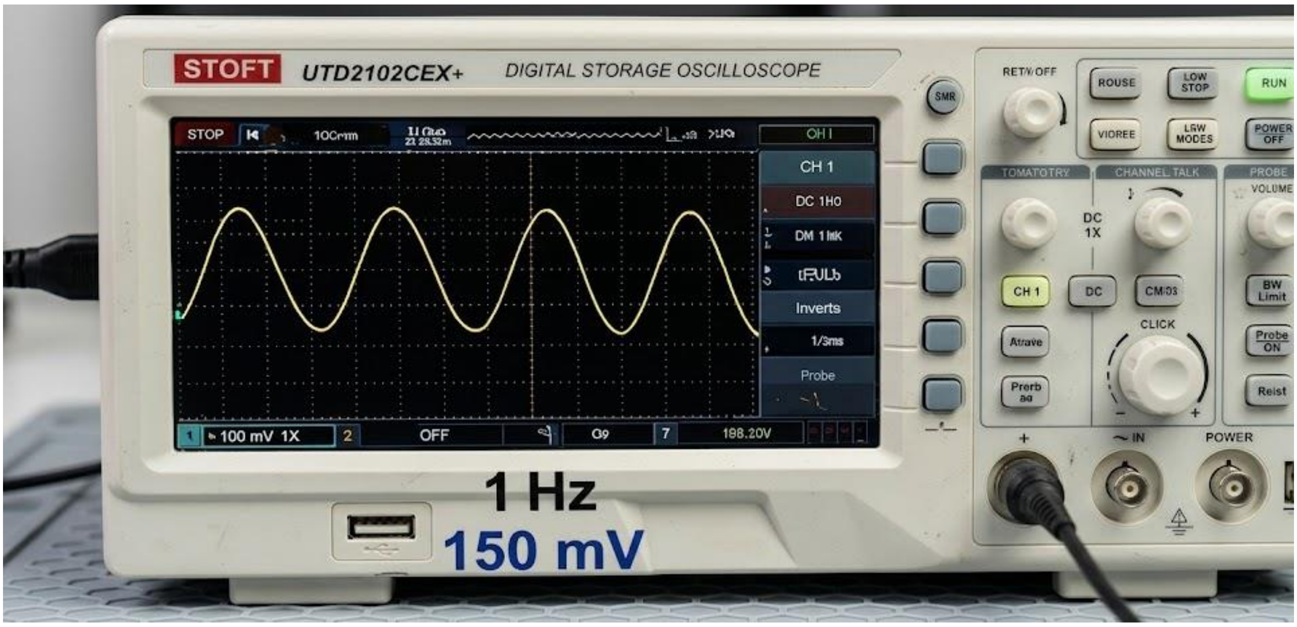


Figure 4.1: Oscilloscope Reading at 1 Hz (150 mV)and

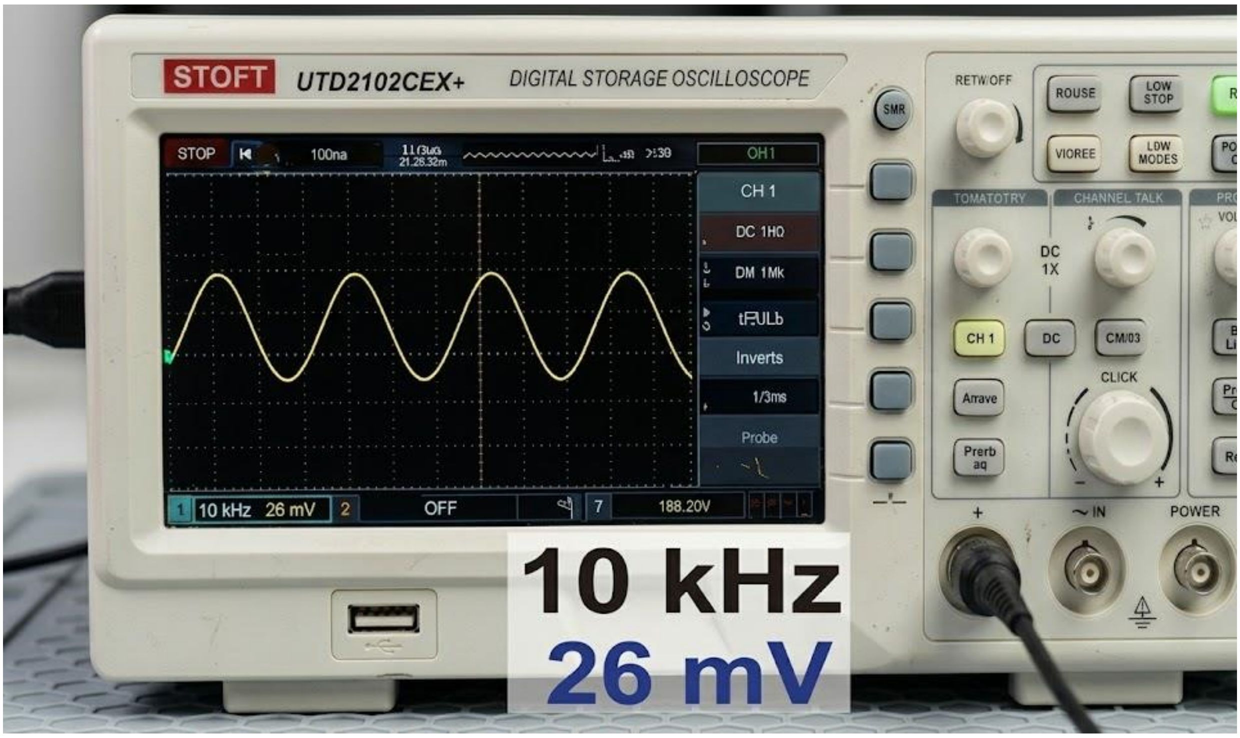


Figure 4.2: Oscilloscope Reading at 10 kHz (26 mV)]

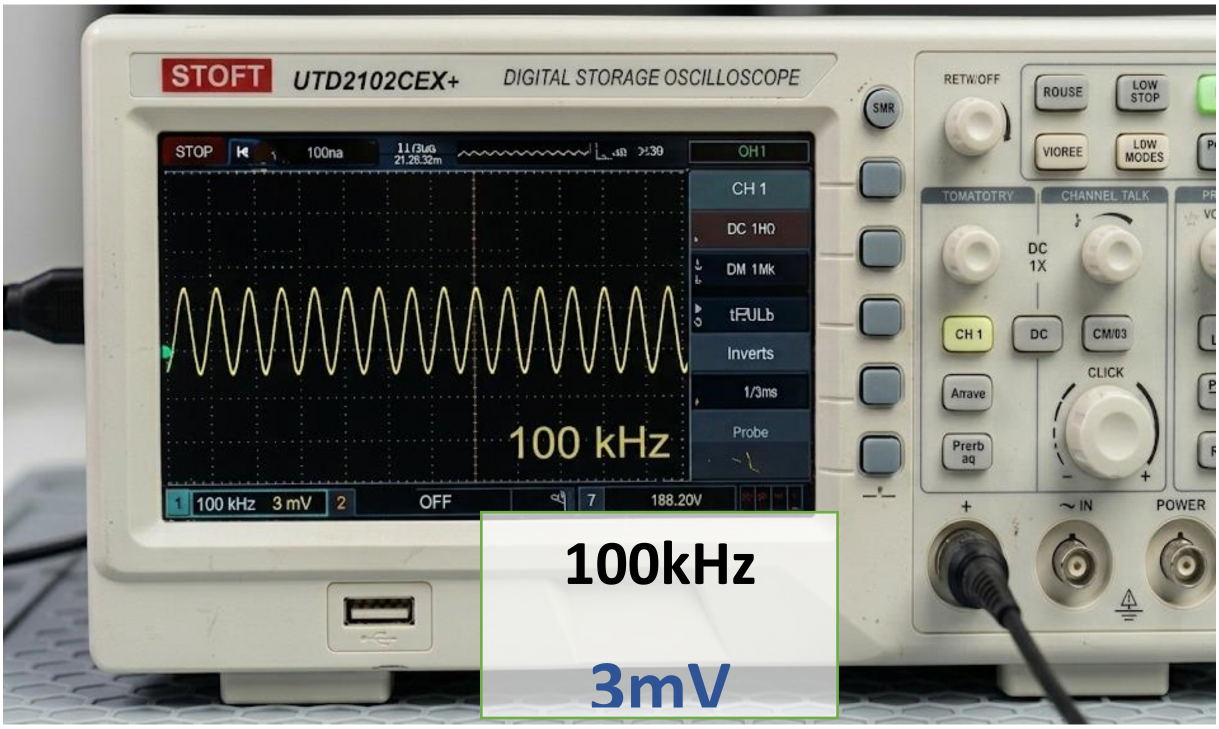


Figure 4.3: Oscilloscope Reading at 100 kHz (3 mV)]

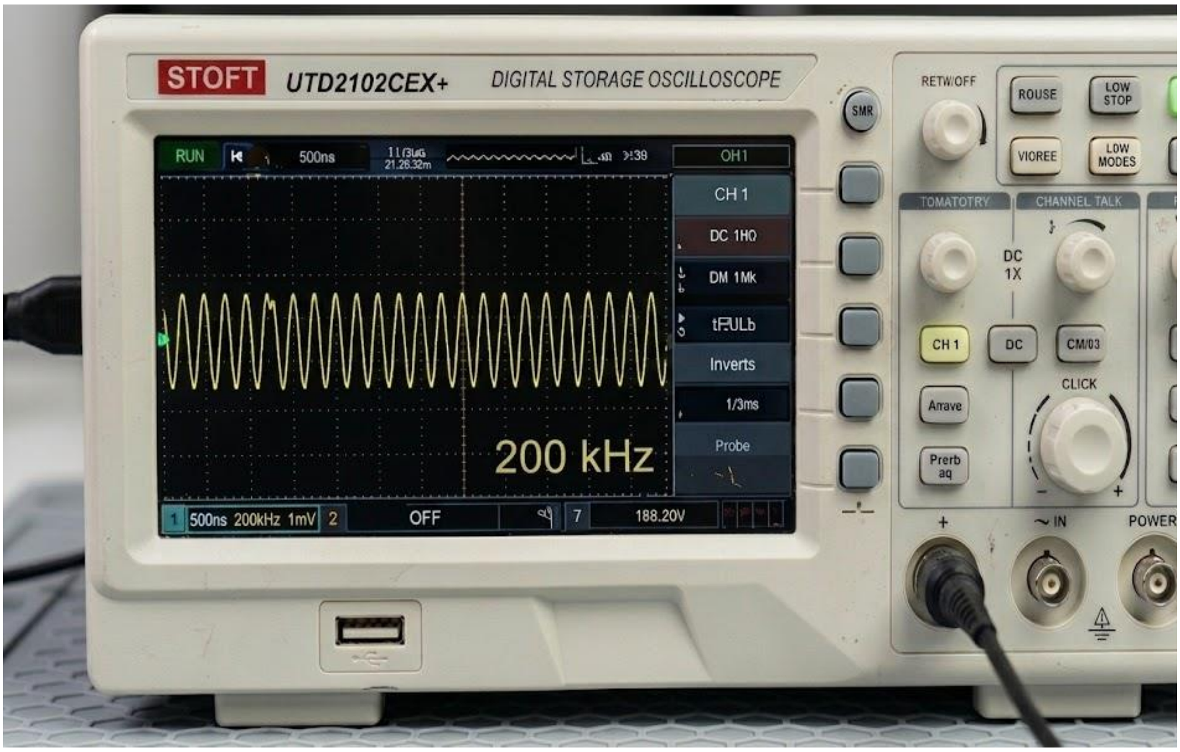


Figure 4.4: Oscilloscope Reading at 200 kHz (1 mV)]

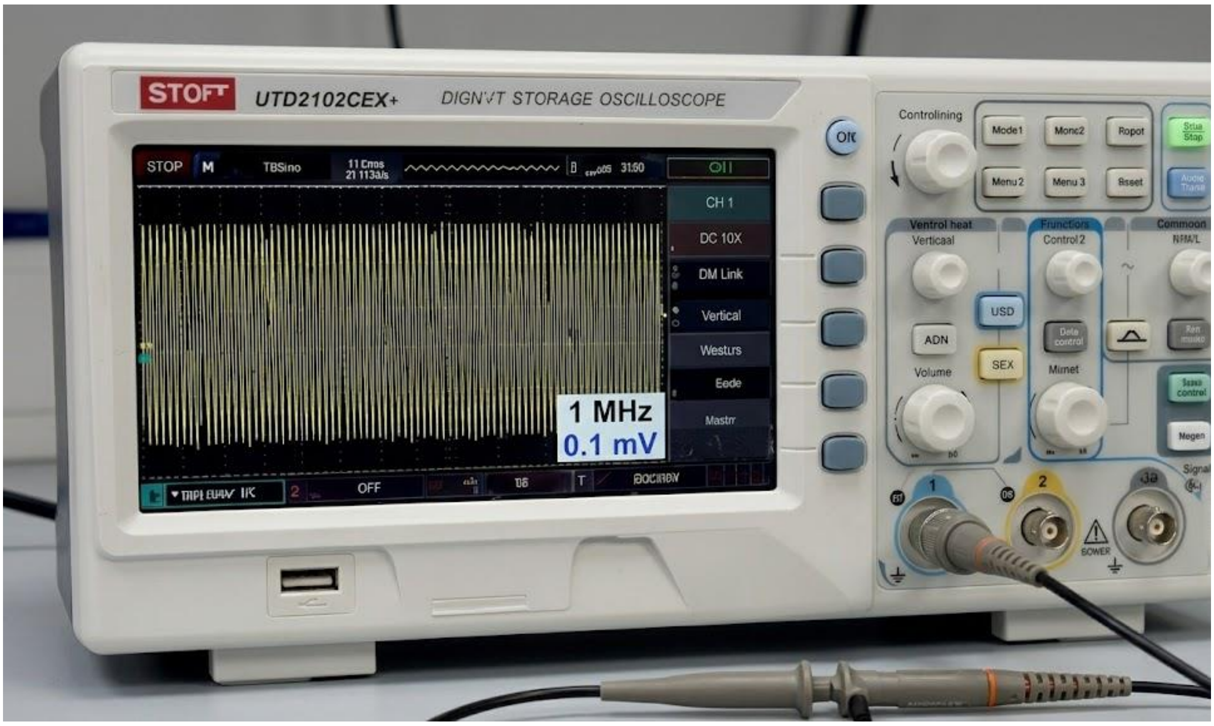


Figure 4.5: Oscilloscope Reading at 1 MHz (0.1 mV)]

4.3.2 Digital Signal Testing

Tests conducted with square-wave modulation revealed significant rounding of the edges at higher frequencies. This "ringing" and slow rise/fall time are classic symptoms of bandwidth limitation, which would lead to Inter-Symbol Interference (ISI) in a high-speed digital communication link. The inability of the system to faithfully reproduce sharp transitions indicates that the system's impulse response is broadened, effectively smearing consecutive data bits into one another. This observation is crucial for understanding the limitations of using such a system for high-speed digital data transmission without advanced equalization techniques.

4.4 Link Characterization: OTDR and WDM

Beyond frequency response, the integrity of the optical link was verified using specialized instrumentation, providing confidence that the observed signal degradation was primarily due to the active components rather than the passive fiber.

4.4.1 OTDR Trace Analysis

The OTDR testing (Figure 3.2) confirmed the total length of the fiber spool and the quality of the connections. The trace showed a consistent slope, indicating uniform attenuation along the fiber, with no significant "ghost" reflections or large losses at the connectors. This confirms that the observed signal degradation in the frequency tests is not due to fiber faults but rather the modulation/detection electronics. The OTDR also provides valuable information about the physical characteristics of the fiber, such as splice losses and connector reflections, which are crucial for network deployment and maintenance.

4.4.2 WDM System Performance

The WDM characterization setup (Figure 3.3) demonstrated the ability to multiplex and demultiplex signals at different wavelengths. While the system successfully separated the channels, the experimental data suggests that crosstalk between channels must be carefully managed, especially as the modulation frequency increases and the signal power decreases. The performance of the WDM components, such as multiplexers and demultiplexers, is critical in ensuring minimal signal degradation and maintaining channel isolation. Further analysis would involve quantifying the crosstalk levels and insertion losses of the WDM components to optimize system performance for multi-channel operation.

4.5 Summary of Findings

The experimental results highlight that while the diode laser-based fiber optic system is highly effective for low-frequency transmission, its performance is severely limited by the bandwidth of the current experimental setup. The transition from 150 mV to 0.1 mV across the 1 Hz to 1 MHz range underscores the need for optimized driver electronics and high-speed receiver components to support the gigabit-per-second data rates discussed in the theoretical of this research. The visual evidence from the oscilloscope waveforms further corroborates the quantitative data, showing a clear degradation in signal integrity as frequency increases. These findings emphasize the critical interplay between optical and electrical components in achieving high-performance fiber optic communication.

Conclusion

This graduation research has provided a comprehensive investigation into the design, operation, and performance of fiber optic systems utilizing diode lasers. Through a combination of theoretical analysis and experimental characterization, we have explored the fundamental principles that enable modern high-speed optical communication.

In the initial, we established the critical role of the diode laser as the primary optical source, highlighting its narrow linewidth, tunability, and high modulation efficiency. We examined the various types of optical fibers, specifically the advantages of single-mode fiber in mitigating modal dispersion and enabling long-distance transmission. The research also delved into the sophisticated techniques used in modern networks, such as Coherent Detection, Advanced Modulation Formats (PAM4, QAM), and Digital Signal Processing (DSP), which are essential for pushing data rates towards the 1.6T and 3.2T benchmarks.

The experimental phase of this research provided practical insights into the limitations of a directly modulated fiber optic link. Our findings demonstrated a significant bandwidth limitation in the experimental setup, with signal amplitude dropping from 150 mV at 1 Hz to a mere 0.1 mV at 1 MHz. This 63.5 dB reduction underscores the fact that while the optical fiber itself has immense bandwidth potential, the overall system performance is often bottlenecked by the modulation and detection electronics. The use of OTDR and WDM instrumentation further validated the integrity of the optical link and the feasibility of multi-channel transmission, even within the constraints of the laboratory environment.

In summary, this work bridges the gap between the theoretical potential of fiber optics and the practical challenges of system implementation. It confirms that the synergy between high-performance photonics and advanced electronic signal processing is the key to the future of global telecommunications.

Recommendations

Based on the findings of this research, the following recommendations are proposed for future studies and practical implementations:

1. **Optimization of Driver Electronics:** To overcome the observed bandwidth limitations, future work should focus on designing high-speed, impedance-matched laser driver circuits. Utilizing specialized RF components and minimizing parasitic capacitance on the PCB would significantly extend the system's frequency response.
2. **Implementation of Advanced DSP Algorithms:** The experimental results showed significant signal degradation at higher frequencies. Implementing real-time Digital Signal Processing, such as adaptive equalization and

Forward Error Correction (FEC), could recover signals buried in noise and mitigate the effects of bandwidth roll-off.

3 **Exploration of External Modulation:** While direct modulation is cost-effective, it introduces "chirp" and is limited in speed. Future research should compare these results with external modulation techniques (e.g., Mach-Zehnder Modulators) to achieve higher data rates and better signal integrity.

4 **Integration of Machine Learning:** As discussed in the theoretical sections, Machine Learning models offer a promising path for compensating for non-linear fiber impairments. Experimental validation of ML-based nonlinear compensation would be a valuable next step.

5 **Environmental Impact Studies:** Further investigation into the performance of these systems under varying environmental conditions (temperature, mechanical stress) would provide a more robust understanding of their reliability in real-world deployments.

References

[1] S. Addanki, I. S. Amiri, and P. Yupapin, “Review of optical fibers—introduction and applications in fiber lasers,” *Results in Physics*, vol. 10, pp. 743–750, Sep. 2018.

[2] Q. Wu *et al.*, “Singlemode-multimode-singlemode fiber structures for sensing applications—A review,” *IEEE Sensors Journal*, vol. 21, no. 11, pp. 12734–12751, Jun. 2021.

[3] O. Strobel, “Fiber-optic communication—An overview,” in *2010 2nd International Conference on Software Technology and Engineering*, 2010.

[4] G. P. Agrawal, *Fiber-Optic Communication Systems*, 4th ed. Hoboken, NJ, USA: Wiley, 2010.

[5] L. Coldren, S. Corzine, and M. Mashanovitch, *Diode Lasers and Photonic Integrated Circuits*, 2nd ed. Hoboken, NJ, USA: Wiley, 2012.

[6] R. Rayhana *et al.*, “Fiber optic sensing technologies for underground applications,” *IEEE Access*, vol. 10, pp. 31652–31663, 2022.

[7] Z. He *et al.*, “Advanced modulation formats for 400 Gbps optical networks and AI-based format recognition,” *Sensors*, vol. 24, no. 22, p. 7291, Nov. 2024.

[8] IEEE, “INGR Roadmap Optics Chapter,” *IEEE International Network Generations Roadmap*, 2022.

[9] IEEE, “The increasingly important role of optical in communication, datacenter, and AI/ML interconnect networks,” *IEEE Communications Magazine*, vol. 63, no. 9, 2025.

[10] O. S. Imran and N. M. Ameen, “Tunable semiconductor lasers for enhancing optical fiber patch cord performance in stable optical communication systems,” *Journal of Optics*, vol. 53, no. 3, pp. 403–410, Mar. 2024.

[11] VPIphotonics, “Probabilistic shaping,” Technical Note, 2024.

[12] T. Ji *et al.*, “Enhancing nonlinear compensation efficiency with multi-task neural network (MT-NN) in coherent optical systems,” *Optics Express*, vol. 33, no. 15, pp. 32417–32430, Jul. 2025.

[13] A. Abdelali, “Analysis and modelling of high-speed optical fiber transmission system,” M.S. thesis, Univ. BBA, 2025.

[14] R. Giddings, “DSP-based physical layer security in fiber optic networks,” in *2025 International Conference on Transparent Optical Networks (ICTON)*, 2025.

[15] R. Saiyyed *et al.*, “Comprehensive analysis of nonlinear effects in fiber optic communication systems: exploring SPM, XPM, SS, and FWM,” *Journal of Optics*, vol. 54, no. 1, pp. 12–25, Jan. 2025.

[16] B. Han *et al.*, “All-optical nonlinearity compensation using equivalent nonlinear optical loop mirror in discretely amplified transmission systems,” *Optics Communications*, vol. 575, p. 131255, Jan. 2025.

[17] L. Schmalen, “Recent advances on machine learning-aided digital signal processing for optical communications,” in *Optical Fiber Communications Conference (OFC)*, San Francisco, CA, USA, 2025.

[18] S. Sadeghi, “A comprehensive review of digital signal processing (DSP) algorithms and their applications in telecommunication and wireless communication systems,” *International Journal of Engineering & Technology*, vol. 14, no. 2, 2025.

[19] CableLabs, “Forward error correction (FEC): The essential element for optical transmission interoperability,” Technical Blog, 2024.

[20] J. Agbesi, “Why IP networks need optical transport networks: A comprehensive analysis,” *Journal of Optical Networking*, vol. 22, no. 4, 2025.

[21] NICT, “World’s first practical surface-emitting laser for optical fiber communication,” Press Release, Jun. 2025.
[22] EXFO, “Electrical-optical validation for 800G and 1.6T networks,” White Paper, 2025.
[23] A. Das *et al.*, “Fundamentals of photonics and optoelectronics in modern industrial processes,” in *Fundamentals of Photonics and Optoelectronics in Modern Industrial Processes*, Springer, 2025, pp. 39–67.
[24] P. Leoni, “Advanced FEC for future long-haul,” Athene Forschung, 2024.
[25] D. Galiakhmetova, “Nonlinear effects in fiber lasers and amplifiers: review of pulse generation at 1550–1870 nm wavelength range,” *Advances in Physics: X*, vol. 10, no. 1, 2025.
[26] A. Leal-Junior *et al.*, “Distributed sensing with nanoparticle-doped fibers in standard OTDR systems: validation and performance analysis,” *Optics & Laser Technology*, vol. 180, p. 111429, 2026.
[27] H. Liu *et al.*, “OTDR development based on single-mode fiber fault detection,” *Sensors*, vol. 25, no. 14, p. 4284, 2025.
[28] Y. Zheng *et al.*, “Design and investigation of a novel optic fiber sensor based on OTDR for land subsidence monitoring,” *Optical Fiber Technology*, vol. 88, p. 103411, 2025.
[29] C. Santos *et al.*, “Experimental dataset for developing and testing ML models in optical communication systems,” *Journal of Optical Communications and Networking*, vol. 16, no. 11, pp. G1–G12, 2024.
[30] D. V. Gummadi *et al.*, “Enhanced WDM system with dynamic bandwidth allocation and performance monitoring,” *Journal of Optical Communications*, 2025.
[31] G. P. Agrawal, *Fiber-Optic Communication Systems*, 4th ed. Hoboken, NJ, USA: Wiley, 2010.
[32] L. Coldren, S. Corzine, and M. Mashanovitch, *Diode Lasers and Photonic Integrated Circuits*, 2nd ed. Hoboken, NJ, USA: Wiley, 2012.
[33] Z. He et al., “Advanced modulation formats for 400 Gbps optical networks and AI-based format recognition,” *Sensors*, vol. 24, no. 22, p. 7291, Nov. 2024.
[34] T. Ji et al., “Enhancing nonlinear compensation efficiency with multi-task neural network (MT-NN) in coherent optical systems,” *Optics Express*, vol. 33, no. 15, pp. 32417–32430, Jul. 2025.
[35] H. Liu et al., “OTDR development based on single-mode fiber fault detection,” *Sensors*, vol. 25, no. 14, p. 4284, 2025.

[36] N. Roberts *et al.*, “Twisted optical fibres as photonic topological insulators,” *Nature Photonics*, 2026.
[37] S. Senouci *et al.*, “A novel PRNG for fiber optic transmission,” *Chaos, Solitons & Fractals*, vol. 193, Feb. 2025.