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Characteristics Study of Modulation Techniques in Optical Fibers Telecommunication Systems

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Abstract

Fiber optic communication technology is essential for transmitting data at high speeds over long distances. To increase transmission capacity and quality, it is essential to use technologies that enhance these capabilities. This study investigates modulation techniques in optical fibers, including frequency modulation (FM), amplitude modulation (AM), and phase modulation (PM). The Optisystem program is used to perform design studies and analysis on a simulation model of an optical fiber communication system.

The system is equipped with a transmitting laser, 1550 nm wavelength, 20 dBm input power, and optical fiber (single mode). Modifications are analyzed and compared to achieve the highest efficiency. Two parameters are also studied: quality factor (QF) and bit error rate (BER). The results of amplitude and frequency modulation (AM and FM) techniques in optical fibers shows that FM performs best in terms of signal quality and BER, followed by AM. Phase modulation (PM) performs less effectively over long distances.

Keywords: OptiSystem; Quality factor; Bit Error Rate; Signal –to-Noise Ratio.

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دراسة خصائص تقنيات التضمين في الالياف البصرية لتطبيقات الاتصالات البعيدة المدى

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الخلاصة

تعتبر تقنية الاتصالات بالألياف الضوئية أمراً بالغ الأهمية لنقل البيانات لمسافات طويلة بسرعات عالية. ولتحسين سعة النقل وجودته، من الضروري استخدام التقنيات التي تعزز هذه القدرات. يبحث هذا البحث في تقنيات التعديل في الألياف الضوئية، بما في ذلك تعديل التردد (FM)، وتعديل السعة (AM)، وتعديل الطور (PM). يتم إجراء دراسات التصميم وتحليل نموذج محاكاة لأنظمة الاتصالات بالألياف الضوئية باستخدام برنامج Optisystem.

تم تصميم النظام باستخدام ليزر ناقل بطول موجي 1550 نانومتر، وقوة إدخال 20 ديسيبل ميلي واط، وألياف ضوئية (وضع واحد). يتم تحليل مخططات التعديل ومقارنتها لتحقيق أقصى قدر من الكفاءة. كما تتم دراسة معاملين، عامل الجودة (QF) ومعدل خطأ البت (BER). أظهرت دراسة تقنيات تعديل السعة والتردد (AM وFM) في الألياف الضوئية أن FM يوفر أفضل أداء من حيث جودة الإشارة ومعدل الخطأ في البتات، يليه AM. وأظهر تعديل الطور (PM) أداءً أقل فعالية على مسافات طويلة.

الكلمات المفتاحية: برنامج OptiSystem، عامل الجودة، معدل الخطأ في البت، نسبة الاشارة الى الضوضاء.

Introduction:

Optical fibers are increasingly important in modern society due to their role in telecommunications networks and their ability to transmit large amounts of data without signal loss or interference [1]. They are cost-effective and more efficient than radio frequency and free space technologies, making them suitable for remote areas and limited situations. Optical fibers use light to transmit data through small filaments made of glass or plastic, offering faster transmission speeds and maintaining signal integrity over long distances [2]. The material is affordable, compact, strong, and flexible due to its composition of silica glass or plastic surrounded by multiple protection layers. The use of polymers in outer layers enhances durability [3]. Optical fiber communication systems offer high capacity and low transmission loss, serving as the foundation of the global communication system. The Internet, a term used to describe the digital communication system, has significantly transformed our lives through optical communication [4]. Despite these benefits, fibers are sensitive to damage and require power stations for long-distance signal transmission, requiring specialized technicians and tools for installation and maintenance, as they can easily break and lose performance when bent [5]. Research and development are crucial for improving the performance and development of optical fibers in long-distance communications, as they have significantly impacted our lives and interactions. [6]. Researchers like Liu et al. (2022) and Hasan (2023) have highlighted the importance of optical fibers in efficient data transmission over long distances, citing their high efficiency and flexibility compared to conventional communication technologies. Studies on the durability of optical fibers have mainly focused on their physical and structural aspects, as discussed by Elsherif et al., 2022 and Singh, 2023. However, most of these studies have primarily addressed the physical and structural aspects of optical fibers, without delving into the impact of various modulation techniques on transmission performance in long-distance optical communication systems. The study compares the performance of Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM) modulation schemes in a simulated environment using OptiSystem software. The evaluation is based on Q-factor and Bit Error Rate (BER), aiming to fill a research gap in long-haul optical fiber communication and enhance the design and efficiency of modern optical networks.

A communication system comprises a transmitter, medium, and receiver, as illustrated in Figure (1), with the transmitter being the primary component and the medium being the communication channel [7].

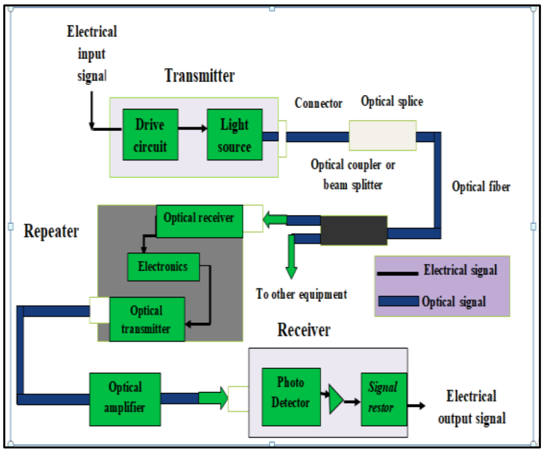

Fig. (1): Block Diagram of Optical Communication System [7].

Fundamentals of optical fiber telecommunication systems:

Optical telecommunication uses light sources like LEDs, lasers diodes, and PIN/APD photodetectors to convert electrical signals to light and vice versa, using channel modulation techniques like direct, external, and circularly polarized light [8].

Optical fiber communications are increasingly important in communication and signal processing due to their high bandwidth and low loss. They offer practical advantages such as low loss, ease of coupling to light sources, compactness, low dispersion, low nonlinearity, and immunity to electromagnetic interference, making them an attractive medium for guided light wave communication [9].

Basic components: Optical fiber communication systems convert electrical signals into light signals through thin glass fibers, then back into electrical signals at the destination.

These systems generally consist of the following components [10]:

(1) LED or laser are used for transmitting low-energy and high-energy signals, respectively.

(2) The modulator converts electrical signals into light signals, altering their properties to represent data.

(3) The optical fiber, a thin glass thread, transmits light through internal reflection and consists of a core, cladding, and buffer coating.

(4) An amplifier enhances the quality of optical signals during long-distance transmission.

(5) The photodetector converts optical signals from optical fibers into electrical signals for processing and utilization.

(6) Connecting devices and connectors are essential for optical fibers and other system devices.

Modulation techniques in optical fibers systems: Optical fiber systems use light as a carrier wave for transmitting information, with various modulation techniques used to encode data onto this wave. Key modulation parameters include amplitude, phase, and frequency. Amplitude refers to the intensity of the light wave, phase is its position within its cycle, and frequency is the number of cycles per second [11].

Amplitude Modulation (AM):

The principle involves altering the amplitude of light waves to represent data, such as zeros and ones, However, it is less common due to its susceptibility to noise. It offers simplicity, ease, and low cost, but is susceptible to noise and interference [12].

Frequency Modulation (FM):

Frequency modulation is a method where the frequency of a light wave is altered to represent data, making it more noise-resistant than amplitude modulation but requiring more complex circuits, despite its advantages over amplitude modulation [13].

Phase Modulation (PM):

The principle involves changing the position of a light wave within its cycle to represent data, enhancing its noise resistance and enabling higher data rates. However, this method requires precise phase control, requiring a more complex approach. [14].

Performance metrics in modulation techniques: Transceivers in optical communication systems account for over 50% of total power consumption, making improving their power efficiency in long-range communications challenging. To optimize and design transceivers, advanced optical transmitters and receivers need to adapt performance characterizations from short - reach to long - range communications. Modulation techniques of metrics should be redefined to guide optimization and architectural design. Performance is evaluated based on four metrics: power penalty, energy per bit, power tolerable capacity, and amplifier consumption efficiency. In real long-range optical fiber communications, the power penalty is determined by receiver feedback processes like clock synchronization, sampling timing recovery, and automatic gain control [15].

Signal –to-Noise Ratio (SNR):

The signal quality ratio is a measure of the clarity of a signal compared to surrounding noise, indicating its quality. A higher ratio indicates better signal quality, indicating a clearer reception of the signal.

The signal-noise ratio (SNR) is calculated by comparing the signal strength to the noise strength, expressed in decibels (dB) [16].

$$SNR = \frac{P_{signal}}{P_{noise}} \cdots\cdots (1)$$

Where:

$\boldsymbol{P_{signal}}$ is the power of the desired signal.

$\boldsymbol{P_{noise}}$ is the power of noise or interference in decibels (d B):

$$SNR_{dB} = \left(\frac{P_{signal}}{P_{noise}}\right) log_{10} X10 \ldots\ldots (2)$$

Signal strength, distance, interference, and equipment quality are all factors that affect the signal-to-noise ratio (SNR). Signal strength increases with higher transmission, distance decreases signal strength and increases noise:

Interference increases noise and reduces SNR. Equipment quality affects transmission and reception and is crucial in optical fibers and communication systems. SNR is a decisive factor in determining data transmission quality, as noise levels can affect system performance [17].

Bit error rate (BER): The Bit Error Rate (BER) is a crucial metric in digital communications that measures the frequency of errors during data transmission. The BER is calculated by dividing the number of incorrectly received bits by the total number of bits transmitted [18]. Mathematically, it can be expressed as:

$$\text{BER} = \frac{number\ of\ error\ bits}{total\ number\ of\ transmitted} \ldots (3)$$

BER is a crucial metric for evaluating the quality of digital communications, influenced by various factors such as noise, interference, attenuation, and channel impairments. A lower BER indicates higher quality communication, and it can be measured using specialized equipment. Other factors can also affect BER, affecting the overall quality of digital communication [19].

A higher Q-factor generally means better signal quality and lower bit error rate (BER) [20] .

$$Q - Factor = \frac{V_H - V_L}{\sigma_L + \sigma_H} \ \ldots . (4)$$

Where V_H and V_L is the voltage sent by the transmitter of two levels. σ_L and σ_H are standard deviations of the noise at the receiver.

Applications and future developments: Optical fiber is a critical technology in long-distance communications, with significant advancements in recent decades. It is essential for supporting 5G and 6G communication networks, enabling ultra-fast data transfer speeds, facilitating services like high-speed internet, cloud gaming, and virtual reality. Dense Wavelength Division Multiplexing (DWDM) technologies allow the transmission of vast amounts of data through a single optical fiber by using multiple wavelengths, enhancing efficiency [21].

Spectrum efficiency improvement and signal distortion reduction are achieved through advanced modulation techniques, which enhance spectrum efficiency and reduce errors caused by noise and interference. Reducing optical noise is achieved by improving receiver devices and increasing the sensitivity of receivers [22].

Nonlinear optical fibers and optical dispersion technologies are being developed to improve photonic techniques and reduce signal losses over long distribution among optical pulses [23].

Simulation Work: OptiSystem Systems software tool was used to design and simulate an optical fiber optical communication system. The system consisted of an optical source based on a CW laser, connected to various modulation components for different techniques. A single mode fiber (SMF) was used to represent the optical fiber with different lengths, simulating a long-distance communication environment.

An optical amplifier compensated for power losses over the fiber, while an optical attenuator controlled signal power. A photodetector APD converted the optical signal into an electrical signal, followed by a low-pass Bessel filter to ensure signal purity. The received signal was then analyzed using a BER analyzer and oscilloscope visualizer. Figures 2,3, and 4 illustrate the simulation designs of AM, FM, and PM techniques respectively.

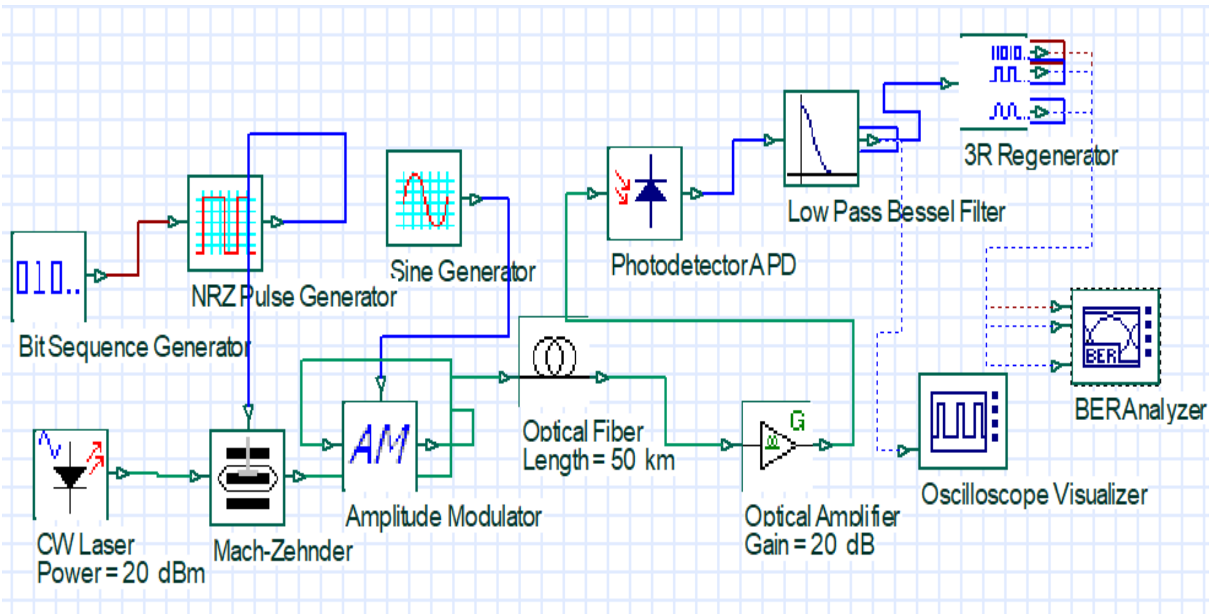

Fig. (2): Simulation setup for AM technique.

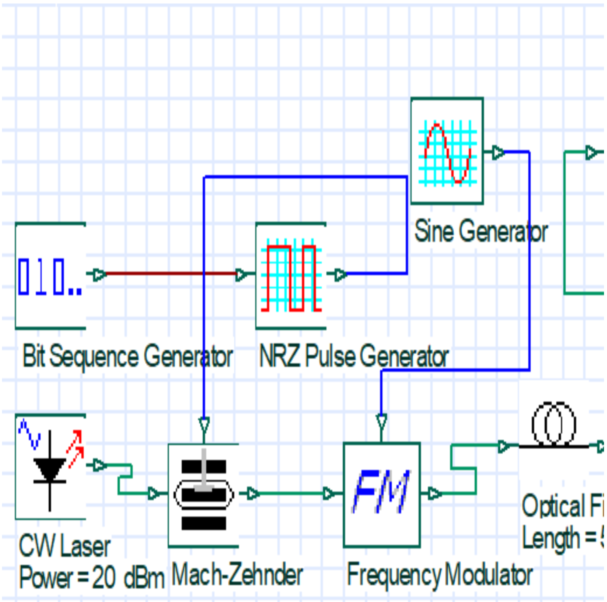

Fig. (3): Simulation setup for FM technique.

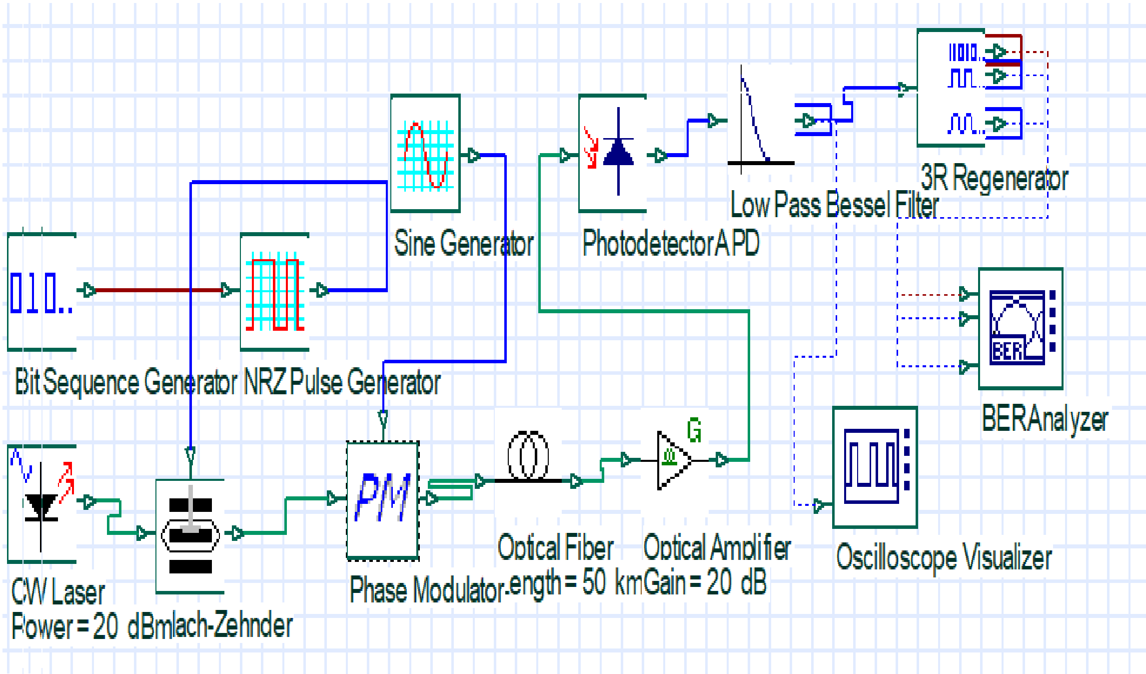

Fig. (4): Simulation setup for PM technique.

Results and Discussion:

1. Amplitude Modulation (AM): Amplitude modulation performed well and stably up to a distance of 70 km, with quality factor values remaining within acceptable limits and the error rate remaining relatively low. However,

performance began to deteriorate significantly beyond this distance, as the Q-factor decreased and the BER increased, reducing signal reliability. Therefore, this type is suitable for use in medium-haul links.. Table 1 illustrates the Q factor and BER results using optisystem of optical fiber communication link with different lengths in C- band communication window.

2. Frequency Modulation (FM): Frequency modulation demonstrated the best performance among the three modulation types, maintaining a very high Q-factor up to 90 km, and an extremely low BER over most distances, demonstrating signal purity and high transmission reliability. Performance only began to deteriorate at 100 km, making it the ideal choice for long-distance links in optical communications systems. Table 2 clear the Q factor and BER results using optisystem of optical fiber communication link with different lengths in C- band communication window.

3. Phase Modulation (PM):

Phase modulation showed the poorest performance in this comparison, with the quality factor beginning to decline rapidly after 40 km and reaching zero after 70 km. The BER also increased significantly with increasing distance, indicating a significant degradation in signal quality and making this type of modulation unsuitable for long-distance data transmission. Therefore, it is only suitable for short distances where high reliability is not required. Table 3 shows the Q factor and BER results using optisystem of optical fiber communication link with different lengths in C- band communication window.

Table 1.Q-Factor and BER for AM Technique in the C- Band Communication Window at P=20dBm.

Link length (km)	QF	BER
10	24.708	4.0043e-135
20	9.2606	7.70441e-021
30	7.6572	8.80182e-015
40	6.35497	1.029e-010
50	6.10337	5.13254e-010
60	5.69649	6.08734e-009
70	5.65901	7.39136e-009
80	4.8723	5.25985e-007
90	2.81781	0.00189697
100	2.61429	0.00343264

Table 2.Q-Factor and BER for FM Technique in the C- Band Communication Window at P=20dBm.

Link length (km)	QF	BER
10	36.3288	2.83814e-89
20	19.8956	2.22174e-088
30	18.9532	1.98692e-080
40	11.6563	8.97056e-032
50	7.25604	1.70798e-013
60	7.22598	1.78968e-013
70	6.6615	9.17679e-012
80	6.37914	8.03751e-011
90	5.566	1.20562e-008
100	0	1

Table 3.Q-Factor and BER for PM Technique in the C- Band Communication Window at P=20dBm.

Link length (km)	QF	BER
10	9.76314	8.07327e-023
20	3.49394	0.000237645
30	3.47673	0.000236392
40	3.20726	0.000560664
50	2.81795	0.00240983
60	2.59082	0.0077067
70	2.44947	0.00712376
80	0	1
90	0	1
100	0	1

Figures 5 and 6 show the Q factor and BER behavior for different optical communication link lengths.

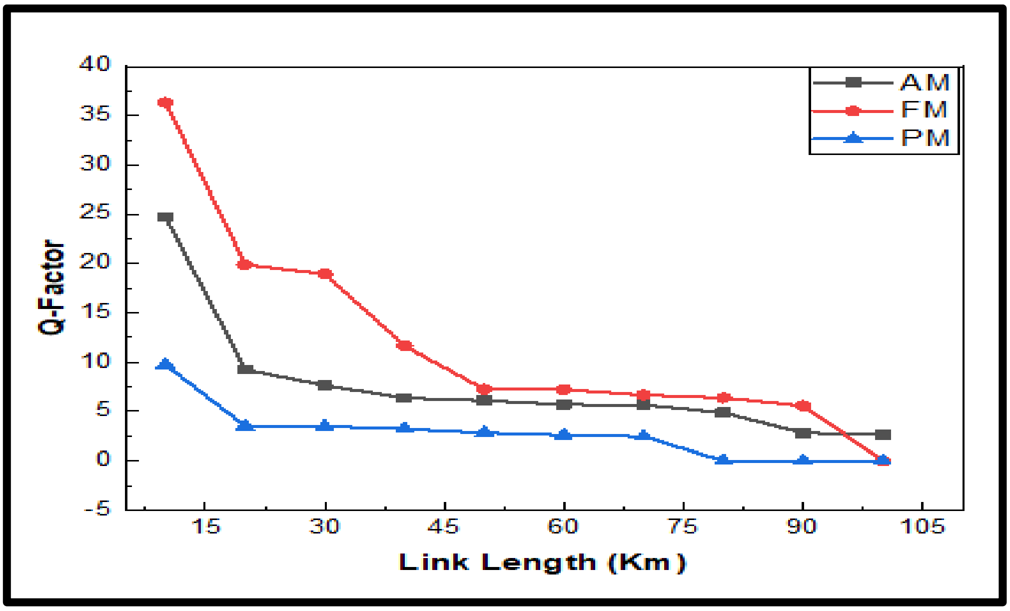

Fig. (5): Q- factor of different optical communication link lengths for (AM, FM, PM) techniques.

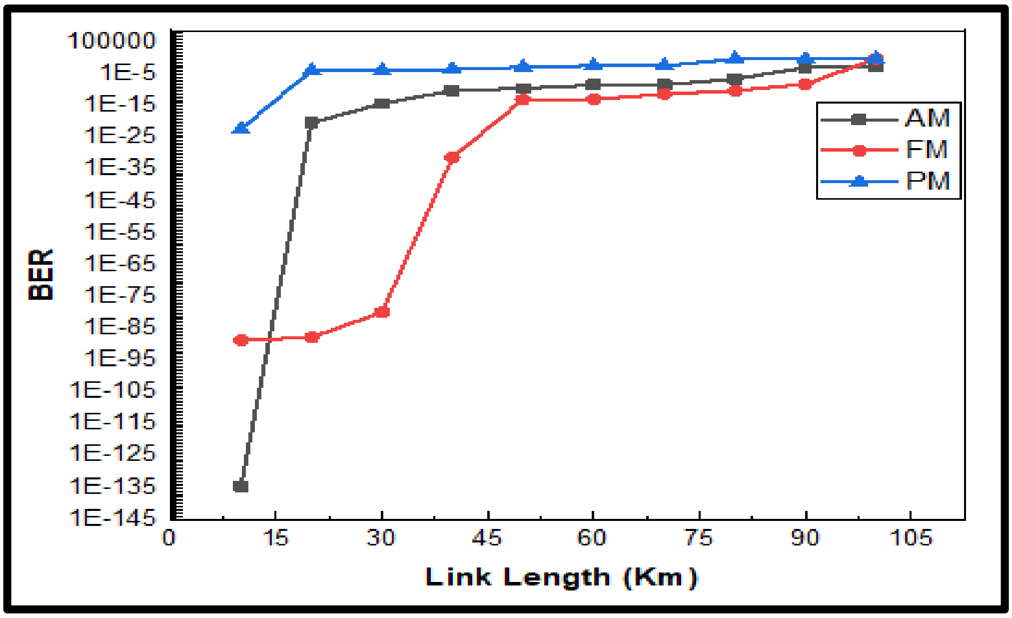

Fig. (6): BER of different optical communication link lengths for (AM, FM, PM) techniques.

Conclusion:

The study of amplitude and frequency modulation techniques

(AM and FM) in optical fibers found that FM Frequency modulation is best for long distances, maintaining high quality and low error up to 90 km, while amplitude modulation starts to deteriorate after 70 km, and phase modulation is weakest and deteriorates after 40 km.

The results suggest that frequency modulation is the most suitable choice for long-distance optical communication systems due to its high signal quality and stable performance over distances up to 90 km.

The attenuation and dispersion were the most serious problems which the optical fiber communication likes suffered. This problem is overcome using optical amplification and dispersion compensation techniques.

Conflict of Interest:

The authors declared no conflict of interest.

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