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FIBER OPTICS IN COMMUNICATION NETWORKS: TRENDS, CHALLENGES AND FUTURE DIRECTIONS

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Abstract— Fiber optics in communication networks played a significant role as far as raising transmission rates and expanding the network. New directions address the issues of scalability and management to open the path toward the subsequent generation application across 6G, sensing, and quantum connections. This review study explores the developments, issues, and prospects of fiber optic communication technologies that comprise current high-speed low delay networks. From the study, it would be possible to analyze the most recent advancements in fiber optics, their environmental impact, and potential economic benefit, as well as possible application of future technologies, such as artificial intelligence and machine learning to enhance networks' performance. The approach entails a review of the existing literature of fiber optic systems, the latest technologies like DWDM, advanced modulation techniques, and integration of the fiber with 5G networks. These outcomes reveal that fiber optics has revolutionized data transmission through offering considerable capacity, low loss, and excellent security despite some scaling and network management challenges. The future of fiber optical communications is conditioned with the development of quantum communications, silicon photonics, and AI for optimizing the system, and the possible uses in the 6G network, sensing, and imaging. These technologies are expected to act as enablers of the next generation of communication infrastructure for the global world with speeds and heightened security measures.

Keywords— Optical fiber, Quantum Communication, Optical devices, Dense Wavelength Division Multiplexing (DWDM), Artificial Intelligence (AI).

I. INTRODUCTION

The optical data transfer system is an essential element of the global broadband network architecture. Optical fibers provide significant transmission capacity with little latency [1]. Optical communications have been widely used owing to many advantageous attributes, including the significant and rapidly growing need for limited media delivery among

consumers and enterprises. Optical fibers are ideal for gigabit transmission and are the foundation of telecommunications infrastructure. Researchers are investigating novel approaches to satisfy the increasing need for gigabit bandwidth as global data requirements increase [2]. Optical communication networks exist in many configurations. Recent advancements in optical signal technology have facilitated the creation of code divisions multiple entry networks. The security attributes of the OICI physical layer are comprehensively examined in LI [3]. At now, optical transmission has supplanted other communication methods owing to the fast expansion of data services and the resultant congestion in internet connections. Fiber optic communication, an innovative communication technology, has garnered significant interest owing to its many benefits. It has little loss, substantial communication capacity, resilience to RF interference, security, and several other superior features compared to traditional cable distribution.

As per the theory of optical fiber communication, there are two types of optical modulation: immediate and oblique modulation. First, the sound must be transferred to the point of origin. Then, electrical signals, images, and data must be converted into optical signals. Finally, these signals must be transmitted through the optical fiber to the sink. At the sink, they must be received by light, and then they must be switched back into electrical impulses [4]. The two main distinctions are as follows: first, the transmission channel is fiber optic cable, not an optical signal, and second, an electrical signal is carried by the cable instead of an optical signal. More data can be sent in the same amount of time with fiber optic communication technology due to its larger load range and broader frequency band compared to other materials. Because of its higher quality, quicker transfer rates, and more specificity, optical fiber technology outperforms both traditional cables and fiber optic cables. One of the many uses for optical fiber technology is in single-wavelength applications, which can improve data transmission quality, increase the effect of basic "Dense Wavelength Division Multiplexing (DWDM)," and expand the range of fiber loads and bandwidth features [5].

Low-loss optically transmitted fibers were essential to the significant advancement of visual communication equipment, which has altered our lives in multiple manners over the past

four decades. The exceptional achievement of optical communication methods is mostly due to the adoption of low-loss transmissible optical fibers. A passively optical system was created for the existing “Fibre-To-The-Home (FTTH)” infrastructure in the telecommunications field. The use of passively photonic hubs was crucial for the network's functionality. These hubs were constructed with “Single-Mode Fiber (SMF),” which is widely used [6].

A. Development of fiber optics

The development of FOCS started about 1975. Immigrants light wave devices generally operated within a 0.8 m range and using GaAs lasers made of semiconductors. These devices were initially launched in 1980 after several years of functional tests were carried out from 1977 to 1979. They could maintain distances of up to 10 kilometers among repeaters and function at a transmission speed of 45 Mbps. The broader repeat separation, in contrast to 1 km for cable systems, decreased setup and upkeep expenses for each repeater, influencing system designers. Scattering in fibers with multiple modes enabled the emergence of second-generation optical networks in the first half of the 1980s, while prior systems were limited to data rates under 100 Mbps [7]. Following the demonstration of the initial laser in May 1960, it was promptly characterized as a solution in quest of a problem. The increasing need to utilize connectivity, driven by the proliferation of cellphones, TV broadcasting, and other types of digital information transfer, was to be mitigated by lasers in this context. Before the 1960s, coaxial wires, lines for transmission, and RF satellites were used as immediate signal transfer in data transmission [8]. All these innovations were severely restricted. Any system using metallic conductors encounters communication losses that escalate significantly with increased data rates, requiring several repeaters over extended distances.

B. Basic principles of communication using optical fibers

The optical network employs a fiber optic connection that transmits data via light waves between locations. The sent information mostly comprises digital data generated by machines, cable TV suppliers, and telecommunication networks. An optic fiber is a low-loss cylinder resonator composed of silicon dioxide. The waveguide core's somewhat elevated refractive index compared to the cladding facilitates total internal reflection, guiding pulses of light down the fiber's axis. The optical converter in an optical system of communication converts the electrical impulse into a signal that is optical prior to its transmission over optical fibers. The optical signal gets further amplified by optical amplifiers and ultimately transformed back into a signal of electricity at the receiver's end. The cable comprises numerous strands of optical fibers. The fibers themselves may be categorized into

two main types: graded-index optical fibers which include single-mode or multi-mode fibers, and step-index optical fibers [10].

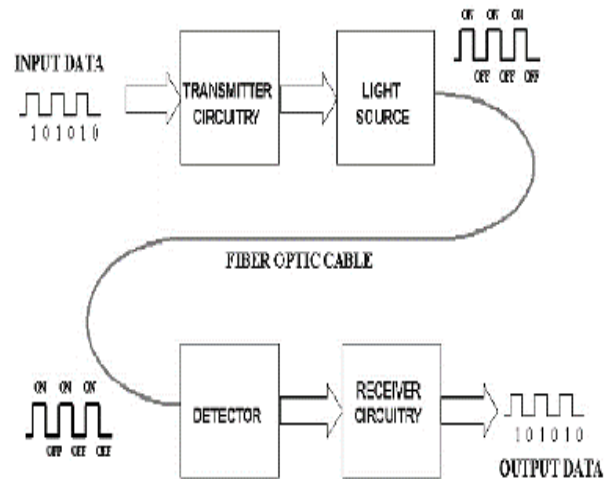


Figure 1: Basic fiber optic communication system [11]

The core diameter of a multiple modes index optical cable is a minimum of 50 mm, allowing many light pathways that result in modal dispersion. Evaluated index wavelengths include a core reflecting index that gradually decreases from the core's center. The enhanced diffraction at the core's center causes some light beams to move at a reduced velocity, allowing all light rays to arrive at the point of reception almost simultaneously and reducing dispersion.

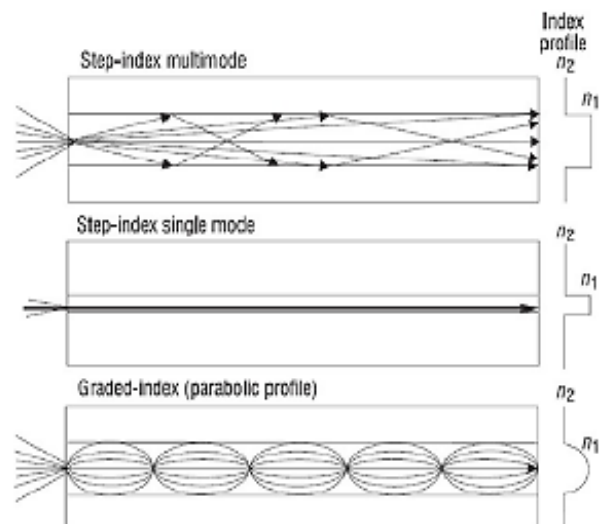


Figure 2: Fiber Optic Modes

a. Optical devices

Optical communication technologies are being advanced by “Photonic Integrated Circuits (PICs)” or “Planar Lightwave

Circuits (PLCs),” often called integrated optics [10]. When it comes to improving the operation of telecommunications networks, reducing the quantity of carbon emissions generated by power consumption, and eventually lowering the cost of producing optical equipment, integration has shown to be a crucial instrument. Current hybrid systems will be supplanted by less expensive monolithic ones, according to predictions made by optical circuit development [12]. The current state of the art in hybrid integrated circuit technology combines several optical and electrical functions performed by discrete or integrated circuits. One optical chip will house both the active and passive components of future macroscopic integrated circuits. Presently, researchers are aiming to find a way to integrate light from laser resources, senders, digital signal processing elements, regulators, receivers, demodulating devices, and sensors on a single semiconductor substrate. Because of the delicate nature of optical receivers and the fact that their signals are the weakest part of the total communication chain, they will keep drawing more and more attention [13].

b. Communication Techniques

Hence, expanding the audience reach and enhancing the transmission capacity of optical networks are the goals of optical communications research and development. It is remarkable and noteworthy that coherent optical systems are already in operation. Though it made an appearance in the early 1980s, the idea "disappeared" when optical amplifiers were developed. Efficient data transfer is guaranteed by a number of communication mechanisms. Despite its simplicity, "Amplitude Shift Keying (ASK)" is susceptible to noise and signal distortion [14]. It represents digital data by varying the amplitude of the optical signal. In comparison to ASK, "Frequency Shift Keying (FSK)" offers superior noise resistance due to its usage of distinct frequencies for each binary state. The use of phase modulation in Phase Shift Keying (PSK) allows for more efficient data transmission over a wider spectrum, but it is also more vulnerable to phase aberrations [15]. Combining amplitude and phase modulation, "Quadrature Amplitude Modulation (QAM)" maps several bits to a single symbol, improving transmission speeds and spectral efficiency.



Figure 3: Optical communications technique
Source: Authors' own elaboration

Other techniques are OFDM which partitions the bandwidth into small subcarriers, each of which modulates the information using PSK or QAM to reduce the impact interferences on spectrum utilization. "Wavelength Division Multiplexing (WDM)" means the transmission of many optical signals on a single fiber at different wavelengths, thus greatly increasing the overall capacity of the fibers [16]. TDM is a classic type of DS, where signals are divided into particular time slots and many signals can be transmitted simultaneously in one channel. The Code Division Multiple Access (CDMA) is another method used in the optical communication networks since the channels are distinguished with codes and there is provision of many more available access points [17].

C. Characteristics of optical fiber communication technology

Competence in fending against anti-em intrusion Because of its strong insulating properties and capacity to sufficiently insulate the fiber, quartz is often used as the main component of the insulating material for optical fibers. Therefore, as compared to traditional cable interaction, an optical network connection shows better resilience to electromagnetic interference during data transfer. They completely ensure the transfer speed and quality of data, even in dangerous locations or during bad weather. Because this insulating material is so responsive to a unique sound wave, fiber optic communication equipment has greatly improved accuracy [18].

Extensive range of frequencies and high data transfer rates Optical fiber transmission uses very high-energy invisible radiation with frequencies of 850 nm and 1311 nm. The result is a dramatic improvement in both the capacity to communicate and the rate of data transfer when compared to ordinary copper wire [19].



a. Low losses and cost savings

Presently, SiO₂ is a popular raw material for electronic fibers, and fiber losses may be drastically reduced by improving the quality of glass fibers. Reducing optical fiber loss allows for longer distances between transmitting stations, which in turn reduces manufacturing costs and improves data and communication quality.

b. Good confidentiality

Constrained optical signal structures inside optical waveguides can only propagate within the fiber core, as optical waves are mainly used for signal transmission in optical fiber communication. Any light that manages to escape is absorbed by the sheathing that extends beyond the fiber line. It would not release any electromagnetic radiation so as to prevent leakage and crosstalk [20]. It is rather difficult to go into the fiber's core and disrupt the light data transmission due to the electromagnetic radiation spectrum's dissimilarity to visible light. Therefore, fiber optic communication technology provides an advantage in terms of secrecy over traditional cable connection.

c. Rich sources of raw materials

In contrast to the large amounts of non-ferrous metals required for wired and wireless electronic communication, the glassy silica used to make optical fibers is both abundant and difficult to create.

d. Low weight and small dimensions

The diameter of the fiber is less than 50 microns, making it almost as small as human hair. Because of this, it is very practical for transportation and packing, and each step may be done separately. The plastic jacket may be used to attach a lightweight, compact, non-bending, long-lasting cable; the communication line can be set up on many kinds of terrain; and the installation is a breeze.

D. Application of optical fiber communication technology

a. Military field

Modern Chinese military technology and economic growth are incompatible with the capabilities of outdated military network systems. Optical fiber operations technology for engineering has the potential to greatly improve military communications by adapting to the demanding environmental conditions of numerous societal concerns. Communication using optical fiber networks in the railway industry. The use of fiber optic connection technology allows for faster data transmission rates while also ensuring consistent data transport. Fiber optic technology has several real-world uses, despite its relatively recent use in China's rail network [21]. It is common practice to use technology like wavelength division multiplexed. The railway ministry mostly utilizes it in low loss zones to guarantee signal consistency. Thanks to

spectrum multiplexing, which may expand pathways for communication, visitors can now completely immerse themselves in the online world.

b. Force communication

Power connections may keep moving toward grids if this technology is used extensively in power communications. Utility sector competitors are starting to see the importance of optical technology in energy communications. Along with substations and the national grid, optical fiber is used by several agencies. Verify that the power source will be delivered punctually. Also, the use of optical fiber helps reduce energy accident occurrences and external factors' impact on the delivery of energy [22].

c. Radio and Television

The media industry is actively pushing FOCS, with network television serving as a notable example. FOCS is relied upon by radio and television for reliable network transmission, enables the swift transmission of broadcast information [23]. Improving the quality of radio and television services while simultaneously providing the audience with high-quality visuals and audio is achievable via effective utilization of broadcasting data.

E. Future trends in optical communication

Future trends in optical communication are based on developments in fiber optic technologies with consideration of future possibilities of future developments. It is further predicted that more efficiency in data transmission will be achieved where transmission speeds will rise from terabits to petabytes due to persistent high demand. Current backbone transmission aims to guarantee reliable, high-speed wireless access in 6G [24]. ML is considered to be vital to enhance PNYC performance. Issues like signal transmission through different barriers or high-speed systems with non-linear capability also continue to pose challenges to research makers. There is also green fiber optics that are still blossoming is more on energy effectiveness and sustainability. Optical fiber-based quantum communication is expected to provide greatest security and bandwidth in the future while the flexible and reconfigurable systems promised to meet the future requirements of the networks. Apart from optics communication and medical applications, fiber optics seems to have a future in sensing and imaging. Lastly, the field needs to merge photonics with electronics to overcome the current obstacles in order to develop new fiber optic networks [25, 26].

Research in fiber optics for network connectivity has led to significant advancements in high-capacity transfer and scalability, especially via techniques like DWDM and "Space-Division Multiplexing (SDM)." Advancements in coherence imaging and sophisticated modulation have enhanced signal



integrity and efficiency in long-distance networks. The amalgamation of fiber optics with nascent technologies such as 5G is augmenting network backhaul and decreasing latency [27]. Nonetheless, obstacles like scaling of networks and signal loss persist, prompting investigation into advanced materials and photonic switching technologies. Future trajectories include quantum computing and photonics made of silicon to further transform global data transport. This review article titled “Fiber Optics in Communication Networks: Trends, Challenges, and Future Directions” begins with an overview of the significance of fiber optics in contemporary communication networks and outlines pertinent research concerns. It subsequently presents an exhaustive literature assessment, including current developments and pinpointing significant difficulties within the domain. After that the discussion and conclusion integrate the results and propose future research avenues to enhance FOCS.

II. RESEARCH QUESTION

The presented study marks the resolutions for the research questions provided below:

- i. What are the latest advancements in fiber optic technologies and their impact on modern communication networks?
- ii. What are the environmental and economic impacts of fiber optic infrastructure deployment, and how can these challenges be mitigated?
- iii. How can machine learning and artificial intelligence be leveraged to optimize the performance and management of fiber optic communication networks?
- iv. What are the potential future directions for fiber optic technology, including innovations in materials, components, and system integration?

III. REVIEW OF LITERATURE

Lakhan et al., (2024) [28] proposed the “Adaptive Security Deep Q-Learning Network (ASDQN)” algorithm to facilitate the implementation of telemedicine apps under defined QoS constraints, which included time constraints, delay, safety, and budget limits. Simulation results indicated that ASDQN had surpassed all applications for telemedicine in terms of QoS and goals when compared to the current DQN and “State-Action-Reward-State (SARSA)” rules throughout execution and planning across numerous nodes.

Yang et al., (2024) [29] presented an “Optical Phased Array (OPA)” that had fast beam-switching capabilities for use in dynamic mobile communication systems. A setup had been put in “Place for Point-to-Multi-Point (P2MP)” scenarios that made use of OPA for quick beam switching between two receivers that were aligned. An experiment was carried out to demonstrate the stability of shifting through lossless image transmission. Furthermore, a way was developed to follow the

paths of things that moved utilizing the fast-switching OPA, allowing them to engage in agile random-access shifting. These findings led to more adaptable, user-friendly, and rapidly-changeable urban wireless optic telecommunications. Iqbal et al., (2024) [30] achieved the goal of utilizing DL models to decrease the frequency of symbol errors in short-range optical transmission settings. It faithfully reproduced a variety of channel defects, including nonlinearity, “chromatic dispersion (CD),” and attenuations. The primary focus was the representational difficulties of a nonlinear channel. The analysis and improvement of the symbol error rate in relation to fiber optic length became the ultimate result of this work. Hugar et al., (2024) [31] discovered that the power of light levels, diminution, variation, noise, and component quality were the important components impacting “Bit Error Rate (BER)”. Two-dimensional graphs, “Bit Error Rate Testers (BERTs),” and eye diagrams served as some of the BER measurement tools utilized in OptiSystem simulations for accurate system efficiency assessment. With reduced BER, data reliability and transmission speed improved, and research simulations provided insight into how to build optical fiber communication systems to achieve that.

Al Dujaili et al., (2023) [32] stated that a plan for an optical low both bandpass filters made of two-dimensional polymeric stones, which was intended for communicating using optical fiber, had been laid out. The plane-wave expansion method was employed to evaluate the bands and calculate the optical band gap. At its core wavelength of 1570 nm, this design functioned as a highly discriminating optical band pass filter, according to simulation data. A voltage transduction efficiency of 96.4 percent was achieved with a focal plane of the course size as small as only 0.3 nm.

Alsharari et al., (2023) [33] proposed that the 5G capability of the FSO/fiber optic idea was tested using the “New radio (NR)” sub-THz links. Optic wireless, half-meter RF, and twenty-five kilometers of single-mode fiber all function effectively in the integrated paradigm. To achieve 22 Gbps transmission rates at four sub-THz frequency ranges, NR-based 5G FSO systems utilized 64-quadrature intensity modulation-orthogonal multiplexing for frequency division at 125, 150, 175, and 200 GHz. Three metrics have been used to evaluate the simulation results: BER, FEL, and EVM. The high data speeds achieved by NR 5G sub-THz with MIMO transmissions were demonstrated using a connected fiber-free orbital optical networking terminal.

Li et al., (2022) [34] determined that the “polarization-maintaining fiber optical gyro (PMFOG)” utilizing orthogonal polarization states had been built by us. A PMFOG utilized the same fiber coil for both the clockwise and counterclockwise light directions, but with different polarizations. The study's findings greatly affected the minimization of fiber optic gyroscopes, the improvement of signal-to-noise ratios, and the optimization of adaptability to environments.



Pan et al., (2021) [35] demonstrated the use of ML in optical network communications technologies. Three use cases were outlined to evaluate the feasibility of the proposed architecture. The PCA based phase estimation method was used for phase noise restoration in coherence optical systems within the communication layer, while the K-means technique was applied to alleviate the impact of nonlinear distortion in stochastic shaping devices. The results illustrated the effectiveness of three applications. ML techniques applied at the transmission layer substantially improved the effectiveness of digital signal analysis without making it more complicated. Sasai et al., (2021) [36] disclosed a “Channel Reconstruction Method (CRM)” that employed “Receiver-side (Rx), Digital Signal Processing (DSP)” of data-carrying signals to ascertain the material properties of link parts such as long-term fiber losses, CD, gain spectrum from several amplifiers, as well as responses of various filters. CRM elucidated the multi-span

attributes of fibers, boosters, and filtering in Rx DSP, detecting abnormal elements without observation, in contrast to optical time-domain form reflect meters and optically spectra testers.

Burdin et al., (2020) [37] suggested a new kind of “Laser-Optimized Multimode Optical Fibers (LOMF)” made of silica grading index, which had a core diameter that increased to 100 μm and a cladding diameter that was often used in telecommunications, which was 125 μm . The rigorous requirements of Ethernet networks and gigabit onboard cable systems inspired the development of that optical fiber. Reasons for the variation included a graded refraction profile that had been fine-tuned to provide little “Differential Mode Delay (DMD)” for certain directed modes. Results of tests that were performed on a 520 m long LOMF 100/125 pilot, with an emphasis on geometry and key transmission parameters, including impedance and DMD map.

Table 1: Synthesis of Review of Literature

Sr. no.	Authors name	Year	Method Used	Findings
1	Lakhan	2024	ASDQN	The findings from the simulation indicated that ASDQN surpassed all telemedicine services in terms of QoS.
2	Yang	2022	OPA	Results led to more versatile, user-centric, and swiftly modifiable urban optical wireless services.
3	Iqbal	2024	DL models	The results showed the analysis and enhancement of the symbol error rate concerning fiber optic duration.
4	Hugar	2024	BER	A decreased BER enhanced data dependability and transmission velocity.
5	Al Dujaili	2023	Plane-wave expansion method	A voltage transduction effectiveness of 96.5% was achieved with a focus plane size as small as 0.3 nm.
6	Alsharari	2023	New radio (NR)	Findings showed that even at large capacity channel communication, the proposed architecture maintained efficient and dependable outputs.
7	Li	2022	PMFOG	The study's results significantly influenced the reduction of fiber optic gyroscopic, the enhancement of signal-to-noise percentages, and the optimization of environmental adaptability.
8	Pan	2021	ML, PCA	ML methods applied at the transmission layer significantly enhanced the efficacy of digital signal evaluation without increasing its complexity.
9	Sasai	2021	CRM	Experimentation demonstrated that CRM depicted multi-span characteristics of fibers, boosters, and filtering in Rx DSP, while also localizing anomalous elements



				without directly measuring them.
10	Burdin	2020	LOMF	Outcomes of assessments that were conducted on a 520 m long LOMF 100/125 pilot focused on geometry and essential transmitting characteristics, including resistance and DMD map.

IV. DISCUSSION

Network optimization, hardware design, and deep learning in optical communication systems are the papers mentioned above. Lakhan et al. (2024) discuss on Asynchronous deep reinforcement learning approach for adaptive security in telemedicine application based on an interesting ASDQN method to consider QoS parameters such as deadline, latency, security, and resource availability. In contrast with Yang et al. (2024) who focus on improving optical communication through the fast beam-switching in optical phased arrays for flexible wireless networks, an idea that is closer to what may be explained as real-time data transmission optimization. On similar lines, Iqbal et al. (2024) discuss how deep learning can be used for minimizing symbol error rate in short reach optical system addressing channel impairment in optical fiber. Hugar et al. (2024) use a conventional approach to examine the performance of the optical communication system that involves use of bit error rate (BER) and their minimization through modeling. However, Al Dujaili et al. (2023) and Alsharari et al. (2023) turned their attention to hardware, where the former constructed an optical narrow-bandpass filter for optical communication and the latter combined free-space optics with fiber optics for 5G high-speed. Optical gyro design is further enriched and advanced by Li et al. (2022) with developments that focus on miniaturization and environment compatibility for sensor applications. In recent work, Pan et al. (2021) and Sasai et al. (2021) combine machine learning with optical systems to reduce nonlinear noise and enhance phase estimation and, respectively, to model the optical channel from the receiver side data. Finally, Burdin et al. (2020) describe a new form of graded-index multimode fiber with improved transmission characteristics fit for industrial use.

V. CONCLUSION

Fiber optic communication has over the years revolutionized global telecommunications due to speeds, reliability and security offered as compared to other modes of transmission. In military, railway, electricity, and broadcasting industries, as well as the other modern communication networks, it provides high bandwidth, low loss transmitting capacity, along with its immunity to electromagnetic interference, making it the backbone technology of the present age. Further development of fiber optic communication embedding new technologies including DWDM, coherent optical systems along with new developments including AI, 5G and quantum communication

are driving the establishment of highly scalable low latency networks. However, problems such as installation costs, network scalability, and signal attenuation still exist; there is still much work to be done with the development of new material and efficient optical switching as well as energy efficient systems. Future trends sight further development of ultra-high-speed fibre networks and systems for terabit and petabit data rates as well as the integration of photonics and electronics to create more effective and efficient platforms for multimegabit networks of the future. Quantum communication and using of optical fibers for sensing and imaging will open new options in using fibre optical beside from the data transmission, this will make centre of future technologies. Moreover, the fiber optics increases progressively, and it can revolutionize the outlook of the global communication networks in the future.

The research focuses specifically on fiber optics while excluding other future technologies like 5G and satellite communications, which are used in modern networks. The words “trends and future directions” can be somewhat synonymous with each other, so they are used interchangeably when considering the present and future events. Moreover, it does not have a geographical or application-oriented focus that can possibly limit broad experiences of problems that can be met in different regions or sectors. The study also does not allow solving environmental, economic, and regulatory issues that are also important for consideration of the full range of fiber optic development. Last but not the least there will not be enough of inter-disciplinary views and some evolving fields like quantum communication or silicon photonics may not be able to develop enough to provide deeper insight into the study.

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