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Optical Fiber Communication Technology: Present Status and Prospect

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Abstract: As an important application of laser technology, optical fiber communication is a key enabler in the current information age. With the emergence of new technologies, including the Internet of Things, big data, cloud computing, virtual reality, and artificial intelligence, society has a growing need for high-capacity information-transmission capability, which presents higher requirements for optical fiber communication technology. Based on a systematic review of the development status of this technology in China and abroad, this study analyzes the problems and challenges faced by optical fiber communications as they apply to specific scenarios, and projects the development of related technologies in the future. Through analysis, it was determined that the challenges of ultra-large–capacity optical fiber communication systems can be addressed by increasing the transmitting power, raising the bandwidth of optical amplifiers, and conducting research on low-loss optical fibers and technologies related to space-division multiplexing. The cost problems of systems in other scenarios are also considered. In general, optical fiber communication technology is evolving in the direction of ultra-large capacity, intelligence, and integration. Future goals include realizing the intelligent monitoring of network parameters, as well as ultra-long distance and ultra-large capacity transmissions. With the development of devices and integration technology, the optical fiber communication industry continues to progress toward the goal of providing high performance at low cost.

Keywords: optical fiber communications; optical networks; ultra-large capacity; integration; intelligence

1 Introduction

Since its emergence, optical fiber communication technology has brought significant changes to the areas of science and technology, as well as society. As an important application of laser technology, optical fiber communication, the main representative of laser-information technologies, establishes the framework of modern communication networks, and has become an important part of information transmission. Optical fiber communication technology is not only an important information-carrying mechanism, but also a core technology in the information age.

It is well known that the basic elements of optical fiber communication technology are a light source, optical fiber, and a photodetector. The most widely used light source is the laser. The fiber's energy-transmission efficiency is excellent, and it has the smallest transmission loss in waveguide electromagnetic transmission systems. The photodetector is a key component in the receiver of optical fiber communication.

Nowadays, all information technologies rely on communication networks. Optical fiber communications can connect to all networks, forming the main artery in the information-transmission process and playing an important role. The architecture of modern communication networks, shown in Fig. 1, mainly includes core networks (CNs), metro area networks (MANs), access networks (ANs), cellular networks, local area networks (LANs), data-center networks (DCNs), and satellite networks (SATNETs). The different networks are connected using optical fiber

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communication technology. For example, in a mobile cellular network, a part of the base station connected to MANs and CNs is also composed of optical fiber communication technology. Moreover, optical interconnects are the most widely used method in DCNs at present; that is, optical fiber communication is utilized to transmit information in intra- or inter- data centers. Thus, optical fiber communication technology not only forms the trunk road, but is also used for many key feeder roads in current communication network systems. It follows that an optical fiber transmission network is the basic bearing network of other service networks.

With the development of various emerging technologies, e.g., the Internet of Things (IoT), big data, virtual reality, artificial intelligence (AI), and fifth-generation mobile communication (5G), society demands increasingly more information exchange and transmissions. According to the research data released by Cisco in 2019, shown in Fig. 2, global annual internet (IP) traffic will grow from 1.5 ZB (1 ZB = 10^{21} B) in 2017 to 4.8 ZB in 2022, with a compound annual growth rate of 26% [1]. Faced with a high-traffic growth trend, optical fiber communication, as the backbone of communication networks, is under considerable pressure to upgrade. High-speed and high-capacity optical fiber communications systems and networks will be the main development directions in the area [2].

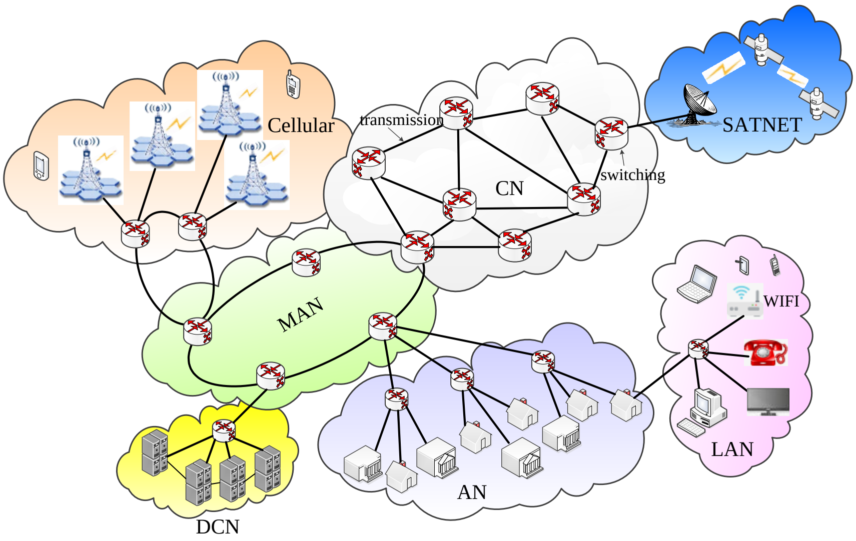

Fig. 1. Architecture of modern communication networks.

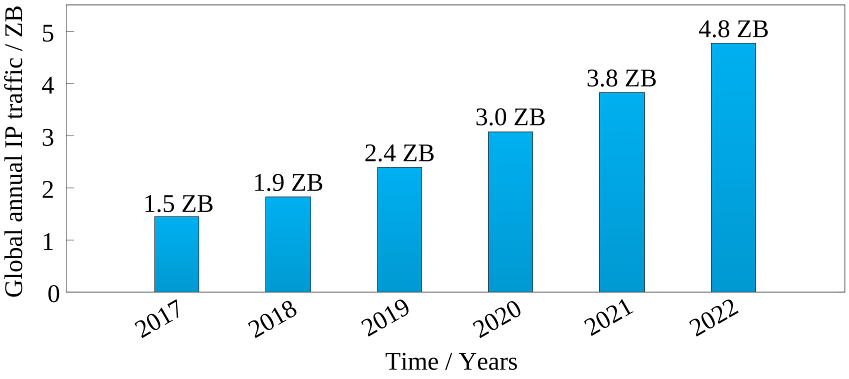

Fig. 2. Global annual IP traffic from 2017 to 2022 [1].

2 Development history and research status

2.1 Development history of optical fiber communication technology

Arthur Schawlow and Charles Townes revealed how the laser worked in 1958, and the first ruby laser was made in 1960. The first AlGaAs semiconductor laser capable of continuous operation at room temperature was developed in 1970, and a semiconductor laser that could continuously work for tens of thousands of hours in a practical environment appeared in 1977. Until then, the laser had not been used in commercial optical fiber communications. Since the invention of the laser, inventors and others have realized its important potential application in the communications field. However, it has two obvious shortcomings. One is the divergence of the laser beam, which causes it to lose considerable energy; the other is that it is more seriously affected by the application environment, e.g., the atmospheric environment, which is extremely subject to weather conditions. Therefore, a suitable optical waveguide is vital for laser communications.

Dr. Charles Kao proposed optical fibers to meet the needs of waveguides for laser communications. He proposed that the Rayleigh scattering loss of glass fiber could be very low, less than 20 dB/km. The fiber mainly lost power because the light was absorbed by impurities in the glass material; thus, material purification was the key to reducing the loss. In addition, Dr. Kao pointed out that single-mode transmission was crucial for maintaining good communication performance [3]. In 1970, the Corning glass company developed a quartz multi-mode fiber with a loss of about 20 dB/km, using Dr. Kao's purification suggestion, making optical fiber a transmission medium in reality. After continuous research and development, the power loss of quartz fiber reached 1 dB/km in 1974 and 0.2 dB/km in 1979, approaching its theoretical loss limit. Thus far, the premise of optical fiber communication has been completely satisfied.

Early optical fiber communication systems adopted the direct-detection (DD) receiving method, shown in Fig. 3. This is a relatively simple form. The photodetector is a square-law detector, which can only detect the intensity of an optical signal. In other words, it can only modify the light intensity to convey information in the transmission. The receiving sensitivity of this method depends on the data-transmission rate, and the transmission distance is determined by the data-transmission rate, together with the thermal noise of the trans-impedance amplifier (TIA) in receiver. The DD method continued from the first-generation optical fiber communication technology in the 1970s to early 1990s. The corresponding specific technical indexes changed from a 45-Mbps data transmission over a 10-km fiber link without a repeater, emitted by a 0.8-μm GaAs semiconductor laser to a 2.5-Gbps data transmission over a 100-km fiber link without a repeater, emitted by a 1.5-μm GaAs semiconductor laser.

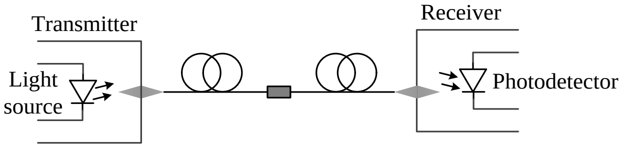

Fig. 3. Schematic diagram of the DD optical fiber communication system.

Since the 1990s, coherent-detection technology in optical fiber communication has gradually become a research hotspot [4]. A schematic diagram of the initial coherent detection is shown in Fig. 4, which is also the first generation of a coherent-detection system. Using coherent detection, the optimal detection sensitivity can be achieved with a high-power local oscillator, although it is limited by scatter noise. Only optical power P_S is detected in a DD system, while a $2\sqrt{P_S P_{LO}}$ signal can be detected in a coherent system, in which P_{LO} is the power of the local oscillator. If the power of the local oscillator is sufficiently large, the detection sensitivity can reach the limit. The sensitivity of the receiver is significantly improved by introducing the coherent-detection technique.

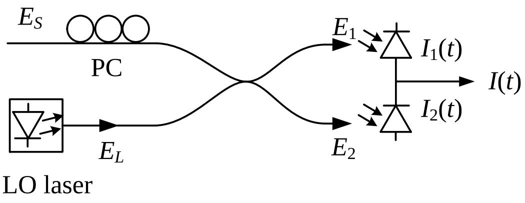

Fig. 4. Schematic diagram of coherent detection.

Heterodyne and homodyne detection were used in the early phase of coherent detection. Heterodyne detection means that the frequency difference between the signal carrier and the local carrier is an intermediate frequency, while homodyne detection means that the signal-carrier and the local-carrier frequencies are exactly the same and the phase difference is fixed. To ensure the frequency lock and restore the carrier phase of the received signal, early coherent-detection technology required complex optical phase-locked loops. In addition, a polarization controller (PC) was needed to keep the polarization state of the signal light consistent with that of the local oscillator to achieve the maximum receiving efficiency.

The optical amplifier is also a vital achievement in the history of optical fiber communication technology. Optical fiber links that use optical amplifiers can also overcome the limited detection sensitivity caused by scatter noise and remove the need for electrical repeaters, to eventually realize long-distance transmissions. The concept of optical amplification was suggested in the earliest laser patents and was finally realized by the University of Southampton and Bell Labs in 1987 [5,6].

2.2 Research status of optical fiber communication technology

Since the 1990s, with the rapid development of the Internet, users' demands for Internet bandwidth have been increasing daily, bringing an urgent requirement for greater optical fiber communication capacity. At first, when 2.5 Gbps optical fiber communication appeared, it was widely believed to be sufficient to support the Internet for generations; however, the growing demand for capacity soon dispelled that idea.

Improving the capacity of optical fiber communication became an urgent problem to be solved. Claude Shannon, the father of information theory, determined the channel-capacity limit. No communication system that transmits information can exceed this limit, which is related to the system bandwidth and the signal-to-noise ratio (SNR) in the channel. When the system bandwidth is larger and the SNR is higher, the capacity limit will increase. According to Shannon's theory, the capacity limit of a single fiber core can be expressed as:

$$C = 2B\log_2\left(1+S/N\right) \qquad (1)$$

where 2 denotes polarization division multiplexing (PDM). *B* is the system bandwidth in the fiber link, which depends on the optical amplifier, and the C+L band is about 95 nm in total. *S* is the power into the fiber, limited by the fiber nonlinearity. *N* is the noise power, depending on the noise coefficient, fiber loss, length, and number of segments.

The bandwidth of a typical C-band erbium-doped fiber amplifier (EDFA) is 35 nm, or about 4375 GHz. With such a huge bandwidth resource, the key problem is making full use of it to realize large-capacity transmission. Thus, the idea of wavelength-division multiplexing (WDM) appeared. It enables carriers on different wavelengths to carry signals simultaneously and transmit them together in a single optical fiber. In addition, the invention of fiber Bragg grating (FBG) also facilitated WDM, which can be used for dense wavelength-division multiplexing (DWDM) filters, increasing or decreasing multiplexers, and EDFA gain equalizers [7,8]. Fig. 5 shows a schematic diagram of a WDM optical fiber communication system.

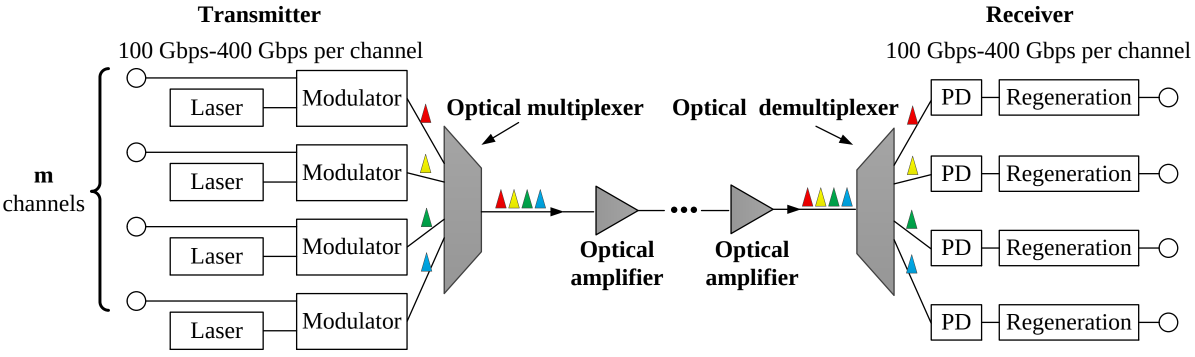

Fig. 5. Schematic diagram of a WDM optical fiber communication system.

From another angle, Shannon's formula can be expressed as:

$$C/B = 2\log_2\left(1+S/N\right) \qquad (2)$$

where C/B is the frequency efficiency, the unit of which is bit/s/Hz, and S/N is the electric SNR of the signal. For example, when the electric SNR is 10 dB, the frequency-efficiency limit of the system is 6.9 bit/s/Hz. Because the bandwidth of the system is limited by the EDFA, optical fiber communication can only obtain limited bandwidth; however, the channel capacity can be increased by improving the spectral efficiency.

There are two methods for increasing the frequency utilization within the bandwidth B. First, DWDM,

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high-order modulation formats, Nyquist shaping, super channels, faster-than-Nyquist (FTN), forward error correction (FEC), and probability shaping are used to approach the Shannon limit. However, increasing the spectrum efficiency will increase the electric SNR requirement, thereby reducing the transmission distance. The second method involves making full use of the information-carrying capacity of the transmission phase and polarization states, which is the second-generation coherent optical communication system. The receiver is shown in Fig. 6 [4].

PDM has been widely used to double the channel capacity by adopting two orthogonal polarization states to carry information separately. The second-generation coherent optical communication system adopts a hybrid for intra-dyne detection and polarization-diversity receivers; that is, the signal light and local-oscillator light are decomposed into two beams with orthogonal polarization states at the receiver; the frequency beat in the two polarization directions can be achieved in this manner. In addition, it is very important that frequency tracking, carrier-phase recovery, equalization, synchronization, polarization tracking, and de-multiplexing at the receiver can all be accomplished by digital signal-processing (DSP) technology, which greatly simplifies the receiver's hardware design and improves the signal-recovery capability [9,10].

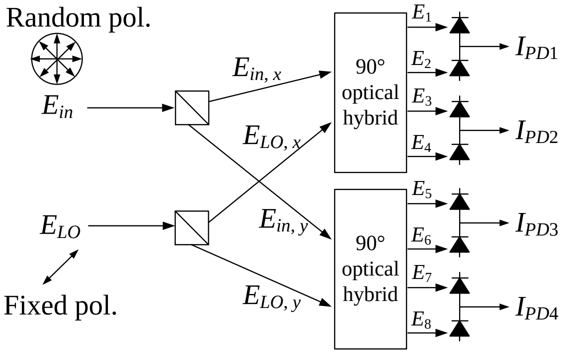

Fig. 6. Schematic diagram of second-generation coherent detection.

Representing the current status of commercial products, China Telecom and Huawei achieved 50-GHz channel spacing and single-channel 200-Gbps polarization-multiplexed 16-QAM signal transmissions via a 1142-km optical fiber link through probabilistic constellation shaping and Nyquist shaping; the indicator is 1920 km in the laboratory, and the total capacity of a single fiber is 16 Tbps. The latest research achievements in the industry include the following: Bell Labs and others used SOA and Raman amplification to achieve a 300-km transmission of a 107-Tbps signal with a 103-nm (1515 nm–1618 nm) band [11]; Huawei used an EDFA in a C+L band to realize the 600-km transmission of 124-Tbps signals.

3 Challenges and thoughts on development

3.1 Ultra-large–capacity optical fiber communication systems

By applying various technologies, academic circles and the industry have basically reached the spectrum-efficiency limit of the optical fiber communication system. To continue to increase the transmission capacity, it is necessary to increase the system bandwidth B (linear increase in capacity) or increase the SNR (increase in power, logarithmic increase in capacity). The specifics are discussed below.

3.1.1 Increasing the transmission power

Because properly increasing the effective area of the fiber cross-section can reduce the nonlinear effects of a high-power transmission [12], it is possible to use few-mode fiber instead of single-mode fiber to increase the transmission power. In addition, the most common solution to nonlinear effects is to use the digital back-propagation (DBP) algorithm; however, the algorithm's performance improvement leads to an increase in the computational complexity. The original DBP algorithm can only deal with nonlinear effects within one channel; it cannot compensate for nonlinear effects, e.g., cross-phase modulation (XPM), between channels. While the multi-channel DBP algorithm can be used to compensate for nonlinear effects among channels, e.g., XPM and four-wave mixing (FWM), the complexity increases significantly. Recently, machine-learning technology research in the nonlinear-compensation field has shown good application prospects, significantly reducing the algorithm complexity. Thus, in the future, machine learning can be used to assist in the design of DBP systems.

3.1.2 Increasing the bandwidth of optical amplifiers

Increasing the bandwidth can break through the limitation of the EDFA frequency band. In addition to the C-band and L-band, the S-band can also be included in the application range, using a semiconductor optical amplifier (SOA) or Raman amplifier for amplification [11]. However, the optical-fiber loss outside the S-band is relatively large. For example, the optical fiber loss in the O-band near 1310 nm reaches 0.3 dB/km, and new optical fiber needs to be designed to reduce the transmission loss. However, for the remaining bands, commercial-quality optical amplification technology is also a challenge. Compared with EDFAs, these optical amplification technologies have the problems of a small gain and a large noise figure. For example, the gain of a praseodymium-doped O-band fiber amplifier (1280 nm–1320 nm) is 10 dB to 25 dB, and the noise figure is 7 dB. A thulium-doped S-band fiber amplifier (1477 nm–1507 nm) has a gain of 22 dB and a noise figure of 6 dB. The SOA has a similar noise figure, and WDM systems have cross-gain modulation problems.

3.1.3 Research on low-loss optical fiber

Low transmission-loss fiber is one of the most critical issues in this field. Hollow-core fiber (HCF), with the possibility of lower transmission loss, will reduce the time delay of fiber transmissions, and can eliminate the nonlinear problem of fiber to a great extent. A new research result shows that hollow-core nested anti-resonant node-less fiber (NANF) achieves a transmission loss of 0.28 dB/km in the 1510 nm to 1600 nm band [13], and theoretical predictions show that the structure has the possibility of continuously reducing the loss to 0.1 dB/km [14], which is below the material-loss limit of quartz fiber (the limit is 0.145 dB/km, caused by Rayleigh scattering). In addition, NANF has the possibility of a wider low-loss window, and the currently reported bandwidth has reached 700 nm [15].

3.1.4 Research on technologies related to space-division multiplexing

Space-division multiplexing (SDM)–related technology is an effective solution for increasing the capacity of a single fiber [16]. There are two main directions. First, multi-core fiber can be used for transmissions, and the capacity of a single fiber is multiplied. The core issue is related to the more efficient optical amplifier; otherwise, it is only equivalent to multiple single-core fibers. Second, using the linear-polarization mode (LP mode), an orbital angular-momentum (OAM) beam based on the phase singularity, or a cylindrical vector beam (CVB) based on the polarization singularity in the SDM can increase its capacity.

Such technologies provide new degrees of freedom for beam multiplexing and increase the capacity of optical communication systems. They have broad application prospects; however, the related optical-amplifier research is also a challenge. In addition, balancing the system complexity caused by the differential-mode group delay (DMGD) and multiple-input multiple-output (MIMO) digital equalization technology are also worthy of attention. In the future, it is hoped that the research and development related to SDM can form an evolution route like that of the WDM system, promoting the progress of optical fiber communication technology.

3.2 Optical fiber communication systems in other scenarios

Ultra-large–capacity optical fiber communication systems are mainly used in backbone network scenarios and do not consider the cost. The current optical fiber communication technology has been applied to many different scenarios, most of which have the practical dilemma of cost sensitivity. For this reason, the authors will list several cost-sensitive scenarios and systems, and briefly analyze their development prospects.

3.2.1 Systems with different combinations of modulation and detection

Owing to the different modulation and detection methods, the application cost of optical fiber communication technology varies considerably. At present, in some extremely cost-sensitive scenarios, the earliest optical communication technology is still used, namely, intensity modulation–direct detection (IMDD). However, in environments with strict communication-performance requirements, the most complicated traditional coherent communication method is employed. In the future, there may be many transition schemes between these two communication methods, and it is urgent to consider the performance and cost tradeoffs to find a scheme suitable for the specific scenario. This specifically involves systems that use in-phase and quadrature (IQ) modulation and direct detection, e.g., single-sideband (SSB) modulation with direct detection [17]. Another example is using intensity modulation with coherent detection, which employs a direct-modulation laser (DML) chirp to produce a certain modulation of the signal phase, and finally detects the corresponding information with the coherent

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receiver [18].

Several special types of optical fiber communication system also exist, e.g., the system based on Stokes-vector direct detection (SVDD) receivers [19], the system based on Kramer-Kronig (KK) relationship receivers [20], and the newly proposed carrier-assisted differential detection (CADD) receiver system [21]. The SVDD receiver is simpler than the traditional coherent system; however, the received signal can only contain information from one polarization state and cannot achieve complete PDM. It is urgent to develop an SVDD receiver–based silicon optical integrated chip for promotion and application. The KK system is based on the KK relationship of a special signal, usually a single sideband one, and the phase is calculated from the received signal amplitude to achieve the effect of coherent detection in a DD system; however, the spectrum efficiency is only half that of the traditional coherent-detection system. The CADD system uses a special receiver to achieve a spectrum efficiency close to 100%, compared to coherent detection; however, this system currently only receives the result of the single polarization state, and temporarily cannot obtain PDM results. It is hoped that, in the future, a simplified coherent communication method with PDM and 100% spectrum efficiency will be developed. Although the above systems have their advantages and disadvantages, combining the costs to make a fair comparison is a key issue in different application scenarios, as devices and integration technologies continue to develop.

3.2.2 Systems with different transmission distances

Optical fiber communication technology can be divided into different categories, according to the transmission distance and application scenario. Typical short-distance optical transmission systems include data-center optical interconnection and access networks. At present, most short-distance transmissions use the IMDD method. As the transmission distance increases, the communication method gradually moves closer to coherent communication. The optical interconnections for intra data centers mainly use the IMDD system, based on a vertical-cavity surface-emitting laser (VCSEL) and multimode fiber link [22]. Some optical interconnections among the data centers adopt IMDD, while some are expected to use a transition scheme between direct detection and coherent detection, or a simplified coherent-detection scheme [23]. Medium-distance transmission systems, including the links used in metro area networks, are gradually evolving to coherent systems. Long-distance transmission systems include core network-transmission links and transoceanic transmissions; they have high transmission-performance requirements and are not cost-sensitive.

4 Development prospects

Optical fiber communication technology, from low speed to high speed, has become a backbone technology supporting access to information in society and is now a major research field. In the future, with the ever-increasing demand for information transmissions, the technologies will evolve toward ultra-large capacity, intelligence, and integration. While improving transmission performance, they will continue to reduce costs, support people’s livelihoods, and play an important role in bringing the benefits of the information age to every nation.

4.1 Intelligent optical networks

Compared with wireless communication systems, intelligent optical networks are still in the early stages in terms of network configuration, network maintenance, and fault diagnosis, and the intelligentization of the networks is insufficient. Owing to the huge capacity of a single fiber, which may be greater than 100 Tbps, the failure of any fiber will have a great impact on economy and society. Therefore, monitoring the network parameters is crucial to future development. The research directions that need to be considered in the future include system-parameter monitoring utilizing simplified coherent technology and machine learning, and monitoring technology based on coherent signal analysis and phase-sensitive optical time-domain reflection (OTDR).

4.2 Integration technology and systems

Device integration reduces costs. Short-distance and high-speed signal transmissions can be achieved through continuous signal regeneration. However, owing to the problems of phase and polarization recovery, integrating coherent systems is currently difficult. In addition, if a large-scale integrated optical-electrical-optical (OEO) system can be realized, the system capacity will also be significantly improved. However, owing to certain factors, e.g., low technical efficiency, high complexity, and difficulty of integration, the optical communication field is unlikely to widely promote all-optical signal-processing technology, e.g., all-optical 2R (re-amplification, re-shaping) and 3R (re-amplification, re-timing, re-shaping).

Therefore, in terms of integration technology and systems, the future research directions are as follows. First, although existing research on SDM systems is already abundant, academic circles and the industry still lack sufficient research and technological breakthroughs on the key components, such as integrated lasers and modulators, two-dimensional integrated receivers, and energy-efficient integrated optical amplifiers. Second, new optical fibers may significantly expand the system bandwidth; however, in-depth research is still required to ensure that their comprehensive performance and manufacturing process can match the existing single-mode optical fiber. Third, various devices that can be used with new optical fibers in communication links also require systematic research.

4.3 Optical communication devices

Among optical devices, the initial research and development of silicon optical devices has shown promising results. However, the current related research in China is mainly based on passive devices, and research on active devices is relatively weak. To address this issue, future research directions include the following. First is the integration of active devices and silicon optical devices. Second is researching non-silicon optical device-integration technologies, e.g., integration based on III-V material substrates. Third is developing new devices, e.g., the integrated lithium niobate optical waveguide that combines the advantages of high speed and low power consumption [24].

Acknowledgments

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