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ISBN 978-981-15-3097-5 ISBN 978-981-15-3098-2 (eBook)
https://doi.org/10.1007/978-981-15-3098-2

Jointly published with Tsinghua University Press
The print edition is not for sale in China Mainland. Customers from China Mainland please order the print book from: Tsinghua University Press.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Introduction

We are in the age of information and we communicate with anyone at anytime and anywhere about anything. All information is delivered in communication systems and carried by a certain medium at different frequencies. The carrier frequency can range from a few MHz to several hundred THz, as shown in Fig. 1. An optical communication system refers to a system that uses high-frequency electromagnetic waves in the infrared, visible, or ultraviolet regions of the electromagnetic spectrum to communicate. With the invention of low-loss optical fiber, optical communication systems have been widely used since 1980 and rapidly changed the structure of communication networks around the world.

Conventional optical communication systems generally use intensity modulation and direct detection (IM/DD), in which the transmission electrical signal is used to drive an intensity modulator to generate on/off keying (OOK) optical signal at the transmitter, and the envelope detection is performed at the receiver to recover the transmitted signal. Although this strategy has the advantages of simple structure and low cost, the capacity of the transmission system is limited due to that the OOK intensity modulation format has low spectral efficiency. Therefore, the optical communication system with coherent detection has become a research hotspot

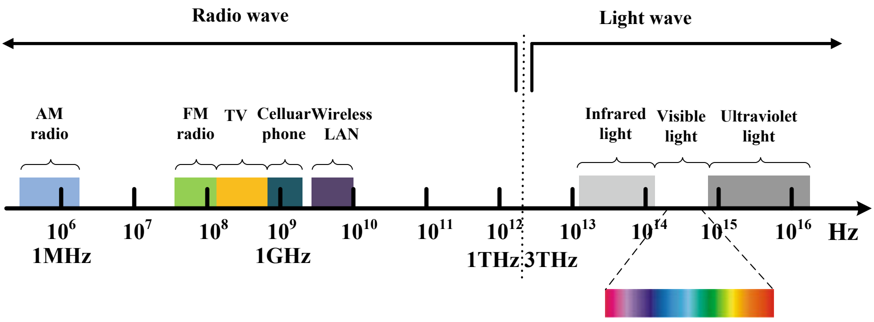


Fig. 1 Spectrum resources

nowadays due to capacity demand. In a coherent optical communication system, information is transmitted at the transmitter by modulating the frequency or phase of the optical carrier, and at the receiver, the transmitted signal is detected by using a homodyne or heterodyne technique with digital signal processing (DSP). Hence, DSP is crucial for modern optical fiber communication. Moreover, even if we use intensity modulation in the transmitter, DSP is still useful if the modulated signal is not OOK signals. For example, if the optical signals at the transmitter are pulse amplitude modulation (PAM), discrete multi-tone (DMT), or careless amplitude phase (CAP), DSP is necessary at the receiver to recover the data. This book aims to introduce modern optical communication systems with DSP to readers. We hope that readers can have an overall picture of the concept, implementation, and technology of DSP for direct detection or coherent optical communication system.

The Development and Current Status of Optical Communication

Optical communication has a long history. Broadly speaking, any communication method that uses light as a medium for information transmission can be defined as optical communication. Based on this definition, China is the first country in the world to conduct optical communications in the history that dates back to ancient times when the Chinese already knew how to use fireworks to transmit information. With the evolution of civilization, communication has also taken place by means of signal lights and semaphores. In 1880, Bell even invented the optical telephone. At this time, however, the development of optical communication has come to an end, and analog electrical communication technology has dominated in the field of communication.

It was not until the 1950s that people again investigate lightwave as a carrier for communication, though at this time there was no suitable coherent lightwave source and transmission medium. The invention of the laser in 1960 solved the problem of the lightwave source. However, the loss of the fiber is still very high, for example, the loss of the best fiber was greater than 1000 dB/km, which limits the practical use of fiber substantially. In 1966, British-Chinese scientist Charles Kuen Kao and G. A. Hockham of STC labs jointly proposed that fiber can be used as a communication transmission medium if the loss of fiber can be smaller than 20 dB/km by removing impurities in glass fiber. This research has an epoch-making significance and brought about a revolution in the field of communications, and Dr. Charles Kuen Kao won the 2009 Nobel Prize in Physics for this achievement. In 1970, Corning announced that they had produced the world's first low-loss fiber, reducing fiber loss to 17 dB/km. After that, through the intense efforts of many researchers, the transmission loss of the optical fiber has dropped significantly. So far, the loss of the optical fiber has reached the theoretical limit, as low as 0.15 dB/km.

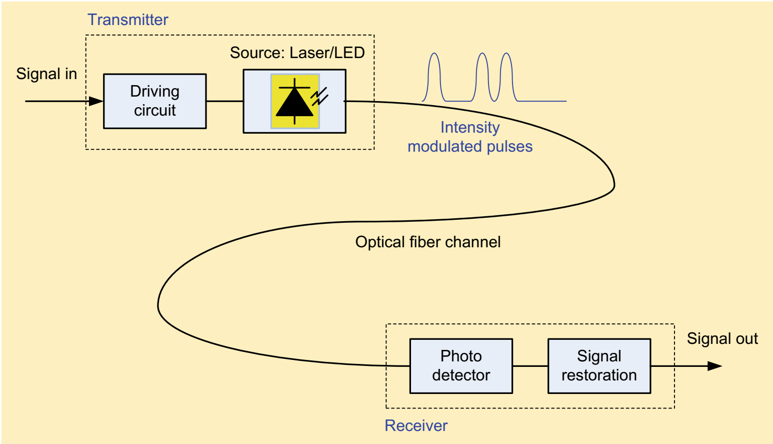


Fig. 2 The optical communication system model proposed by Charles Kuen Kao and G. A. Hockham

Dr. Charles Kuen Kao and G. A. Hockham first proposed a point-to-point optical communication system model, as shown in Fig. 2. At the transmitter, a laser or LED is used as a light source, and an input signal is used to intensity-modulate the lightwave of the laser or the LED, and then the modulated optical signal is transmitted through a fiber of several kilometers, detected by a photodetector at the receiver end, and then converted into an electrical signal. Finally, the electrical signal is recovered and measured. Dr. Charles Kuen Kao predicted that the maximal bit rate of the optical communication system could reach 1 Gb/s. Compared with the maximum communication capacity of the communication system of 100 Mbps/s in the 1970s, the predicted optical communication system showed significant capacity expansion.

Researchers have seen the considerable development prospects of optical communication systems and have devoted themselves to the research of optical communication technologies. New technologies and new devices have emerged one after another, making the communication capacity of optical communication systems increased by hundreds and thousands times within half a century, which is still growing. The structure of today's optical communication systems is very complex. Figure 3 shows a schematic diagram of a wide-area optical network with a coverage of more than one thousand kilometers and a bit rate of transmission capacity of $\sim$Tb/s. In the optical network, an optical amplifier is used to amplify the optical energy, and an optical add/drop multiplexer (ROADM) and an optical cross-connector that can be connected to the upper and lower channels are reconfigured.

The optical communication system has evolved from the originally proposed model to the complex and practical system. It has undergone several technological innovations, and each technological innovation has led to an increase in system capacity. Figure 4 shows the changes in the transmission capacity of optical communication experiments and commercial systems from 1980 to 2010. It can be

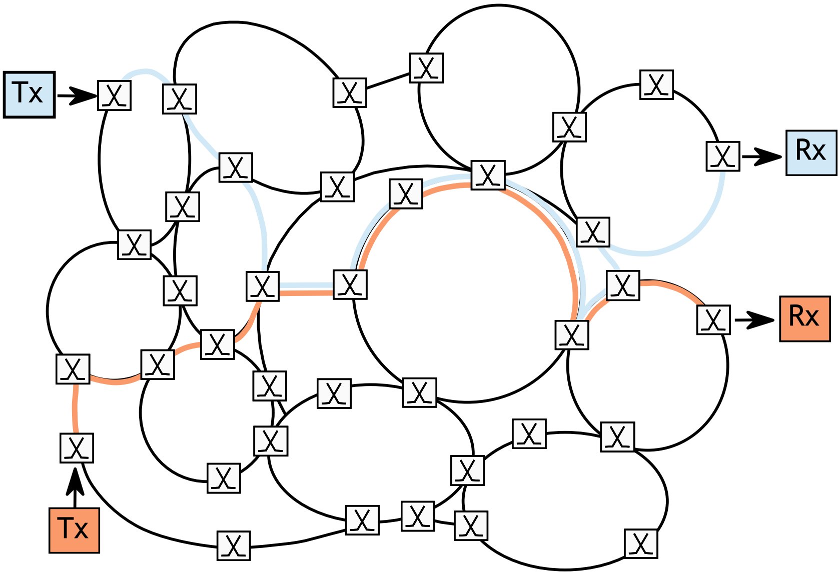


Fig. 3 The modern optical fiber communication system

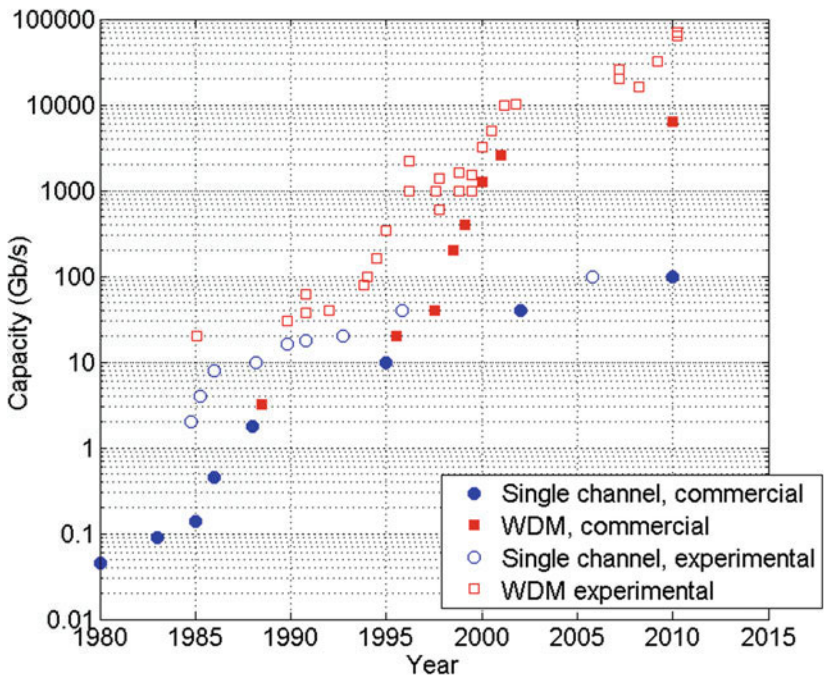


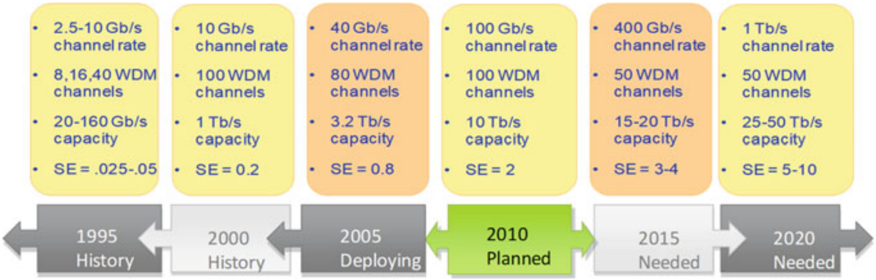
Fig. 4 Optical communication system capacity from 1980 to 2010

seen that the transmission capacity of optical communication systems has grown tremendously within half a century.

The first generation of practical optical communication systems was put into commercial use in 1978. The system works at 0.8 μm and uses multimode fiber with a bit rate of 20 ~ 100 Mb/s. With the advent of single-mode fibers and the development of lasers and photodetectors, the second-generation optical communication system was put into commercial operation in 1987. The system operates at 1.3 μm and uses single-mode fiber with a bit rate of up to 1.7 Gb/s. The third-generation optical communication system works at 1.55 μm. Because the minimum loss of the fiber appears at around 1.55 μm, the bit rate of the system can reach more than 10 Gb/s. These three generations above of optical communication systems use intensity modulation/direct detection (IM/DD), and their system capacity encountered bottlenecks in the late 1980s. Researchers began to explore new directions to further improve system performance that have a major impact on the development of optical communications. The researchers' ideas are mainly classified into two categories. One is to develop new devices to increase the transmission distance. Optical amplifiers were born during this period, especially the Erbium-doped fiber amplifier (EDFA) is one of the most important inventions in the history of optical communication. It is still the most widely used amplifier in optical communication systems. Another idea is to modifiy the system structure and explore new technologies like wavelength division multiplexing (WDM) technology and coherent optical communication technology. The fourth-generation optical communication system is characterized by the use of optical amplifiers and wavelength division multiplexing. At this time, although coherent optical communication systems have emerged, due to the complexity of the system and the level of the devices, direct detection of optical communication systems remain as the most popular schemes in the 1990s. After a period of silence, the coherent optical communication with DSP technology has become a research hotspot in the twenty-first century due to the development of the device level and the need for system expansion, and further improved the transmission rate of the system.

We focus on the development of optical communication systems from the 1990s to the present, as summarized in Table 1. In the late 1980s, WDM technology was introduced, but due to the additional insertion loss of the WDM multiplexer, the transmission rate of the wavelength division multiplexing system was limited. In the early 1990s, the rapid commercialization of EDFA solved the insertion loss problem. EDFA can provide a large power gain, and its amplification bandwidth is high, which can simultaneously amplify multiple signals, which is very suitable for WDM systems. As a result, the development of WDM technology has embarked on a fast lane, and the data rate of optical communication systems has rapidly multiplied.

Table 1 Development of commercial optical communication systems from 1990 to the present



In the 1990s, the single-channel rate of optical communication systems was increased from 2.5 to 10 Gb/s, mainly by improving the stability of the laser output wavelength and optical filtering techniques such as flat-top filters. During this period, optical communication systems was dominated by direct detection. The simple OOK intensity modulation format and direct detection technology were used to transmit multiple channels of data on one fiber through WDM technology. The total communication rate of the direct detection system reached 160 Gb/s. In 2000, by increasing the degree of wavelength division multiplexing, the number of transmission channels on a single fiber was increased to 100, achieving a total communication rate of 1 Tb/s. Then, by adopting a spectrally more efficient modulation format (such as dual binary, DPSK, DQPSK, and PDM-QPSK which can be directly detected or coherently detected), the single-channel communication rate is further increased from 10 Gb/s to 40 Gb/s. In order to increase the system capacity, higher order modulation formats (such as PM-8QAM, PM-16QAM, and PM-64QAM) can be applied for coherent detection. Currently, commercial WDM systems have achieved a single-carrier 400 Gb/s bit rate with a total system capacity of 20 Tb/s or more.

Coherent optical communication with DSP technology improves spectral efficiency by adopting high-order modulation formats such as phase shift keying modulation (PSK), QAM, polarization multiplexing modulation, and orthogonal frequency division multiplexing (OFDM), thereby improving system single-channel transmission rate and communication capacity. By adopting new technologies, the spectrum efficiency of optical communication systems could be increased. Throughout the 1990s to the present, the spectrum efficiency has increased by almost 10 times every ten years. The spectrum efficiency in the past 20 years is shown in Fig. 5. According to this trend, the spectrum efficiency in 2020 will reach 100 bit/s/Hz. It seems difficult to imagine how to achieve such high spectral efficiency.

In recent years, researchers have seen a series of breakthroughs in high-speed coherent optical communication systems. In 2007, Coreoptics first realized the transmission of QPSK signals of 100 Gb/s polarization multiplexing over 1600 km. In 2008, NEC Labs and AT&T Labs combined PDM-RZ-8PSK modulation and coherent detection to achieve 161 $\times$ 114 Gb/s DWDM transmission via 662 km ultra-low-loss fiber, creating a record that a C-band optical bandwidth (4.025 THz) is with a capacity of 17 Tb/s. In 2010, NTT completed the single-channel

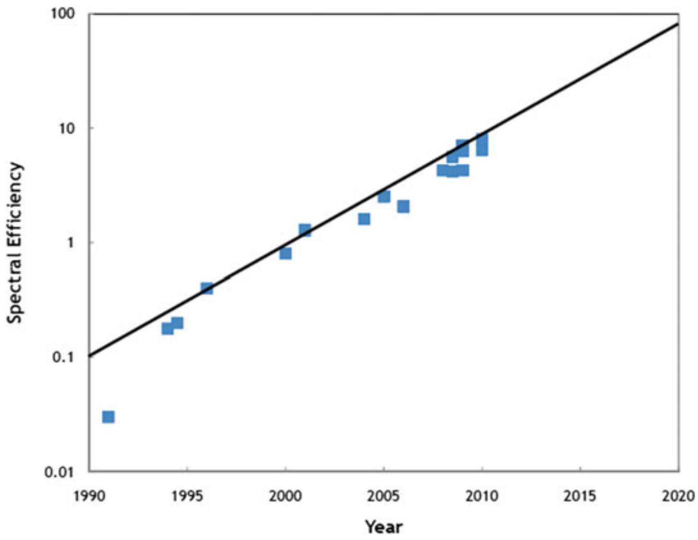


Fig. 5 Changes in spectral efficiency from 1990 to 2010

transmission of 160 Gb/s PDM-16QAM signals on optical fibers with a length of 3123.9 km, which is the longest transmission distance achieved by the current 16QAM modulation format. In 2012, NTT Labs in Japan adopted PDM-64QAM to achieve a 240 km transmission of 102.3 Tb/s C+L band optical signals. Recently people to use multicore and multimode, over 5 Pbit/s capacity has been demonstrated, which is the fifty times of the capacity record in 2013.

At present, coherent optical communication with DSP has become the mainstream scheme in the field of optical communication. Coherent detection was adopted in almost all experiments on high-speed transmission. 100 G and 400 G per channel coherent detection systems have been widely deployed all over the world. The single-channel transmission rate of optical communication systems with 1 Tb/s will be commercialized soon. It is foreseeable that coherent optical communication technology has a bright future, and the future optical communication field will be the world of coherent optical communication systems.

Signal Degradation in Optical Communication Systems

When an optical signal is transmitted in an optical communication system, noise existing in the optoelectronic device, as well as loss, dispersion, and nonlinearity of the optical fiber may cause damage to the signal, and thus the signal may inevitably deteriorate. The compensation for these factors that cause signal degradation largely determines the communication capacity of the system. In this section, we will briefly describe the signal degradation and its solutions in optical communication systems.

The main cause of signal degradation in an optical communication system is the interference caused by the noise of the optoelectronic device, and the signal attenuation and signal distortion caused by the optical fiber transmission. The noise of optoelectronic devices comes mainly from optical amplifiers. Signal attenuation, also known as fiber loss, is one of the important characteristics of fiber optics, which largely determines the maximum distance that a signal in an optical communication system can transmit without an optical amplifier and optical repeater. The signal distortions caused by optical fibers come in two basic classes: linear distortion and nonlinear distortion. Linear distortion refers to the broadening of the optical pulse caused by the dispersion of the fiber, and the nonlinear distortion refers to the signal distortion caused by the nonlinear effects of the optical fiber. The dispersion and nonlinear effects of the fiber, when the system transmission distance is long enough, will have a significant impact on signal transmission and limit the transmission capacity of the system.

Since Dr. Charles Kuen Kao made the first fiber that can be used for communication in 1966, in the next decade or so, the loss of multimode fiber has been reduced to 0.6 ~ 0.7 dB/km around 1.3 μm. The loss of single-mode fiber is reduced to 0.2 dB/km around 1.55 μm. Figure 6a shows the change of loss spectrum of multimode fiber from 1972 to 1982, and Fig. 6b shows the loss spectrum of single-mode fiber using different methods in 1982 (MCVD Modified Chemical Vapor Deposition method, OVD Outside Vapor Deposition method, VAD vapor-axial epitaxy method). Although the loss of fiber at that time was already low, for long-distance transmission systems, fiber loss was still a key factor limiting system capacity growth.

In the 1990s, with the invention of optical amplifiers and its rapid commercialization, the problem of fiber loss was completely solved. Long-distance transmission can be achieved by compensating for fiber losses with optical amplifiers. Erbium-doped fiber amplifier (EDFA) is one of the most important optical amplifiers. It has been widely used in optical communication systems. Its structure is shown in

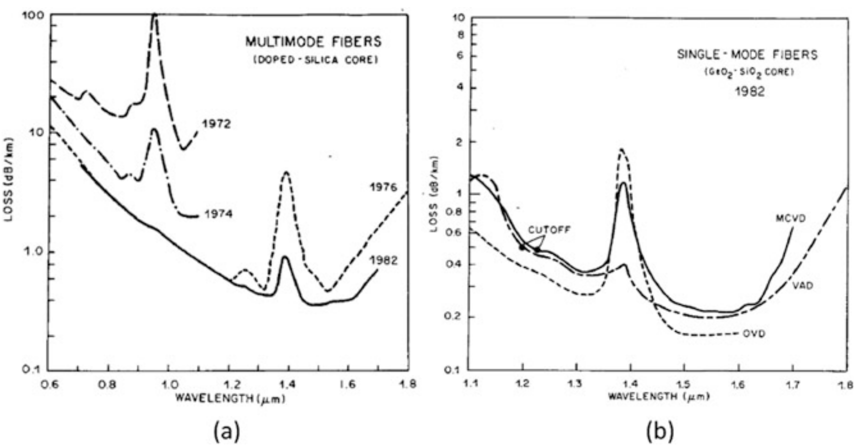


Fig. 6 **a** Loss spectrum of multimode fiber, **b** Loss spectrum of single-mode fiber

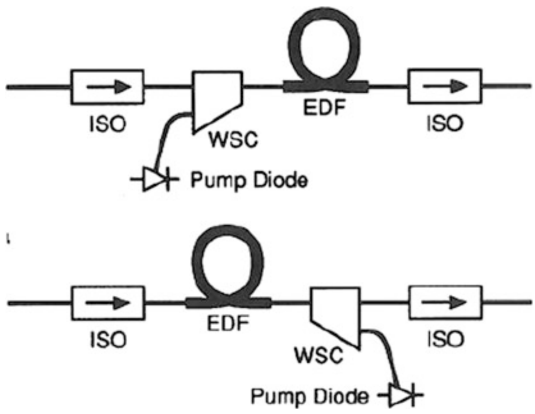


Fig. 7 Basic structure of an Erbium-doped fiber amplifier

Fig. 7. EDFA uses Erbium-doped single-mode fiber as the gain medium, and the population inversion occurs under the excitation of pump light, and the stimulated radiation amplification is realized by signal light induction. EDFA has excellent performances such as high gain, high power, and wide bandwidth. It is very suitable for WDM systems and promotes the commercialization of WDM technology. It has brought a huge revolution in the field of optical communication, which has doubled the communication capacity in ten years. It is worth mentioning that when using an optical amplifier (EDFA) in a WDM system, the non-uniform gain of the WDM link within the EDFA amplification bandwidth will result in a difference in channel quality. In this case, the equalization technique is very necessary.

The invention of optical amplifiers solves the problem of fiber loss, but another important parameter of fiber, fiber dispersion, still limits communication capacity and communication distance. Fiber dispersion is the broadening of the light pulse transmitted in the fiber as the transmission distance increases. When the distance of transmission is long enough, adjacent optical pulses may overlap due to broadening, resulting in a false decision of the receiver, and thus fiber dispersion limits the information-carrying capacity of the optical fiber.

Fiber dispersion mainly is chromatic dispersion (including material dispersion and waveguide dispersion), modal dispersion, and polarization dispersion. Chromatic dispersion refers to the broadening of the optical pulse caused by the difference in group delays in which different frequency (wavelength) components of the source spectrum propagate in the fiber. The material dispersion is caused by the nonlinear change of the refractive index of the material with the change of wavelength. And the waveguide dispersion is due to the nonlinear variation of the propagation constant of the guided wave mode with the change of wavelength. The modal dispersion refers to the dispersion caused by the different propagation constants of different modes at the same wavelength. In a single-mode fiber, there are two polarization modes in which the degenerate polarization directions are orthogonal. When the fiber has birefringence, the propagation speeds of the two degenerate modes are not the same, causing random spreading of optical pulses, so it is called polarization dispersion. Strictly speaking, polarization dispersion is also a kind of modal dispersion. In general, in multimode fibers, there are modal dispersion and chromatic dispersion, but mainly modal dispersion. In single-mode fibers, there are material dispersion and waveguide dispersion, which are generally dominated by material dispersion.

Most fiber-optic communication systems use single-mode fiber as the transmission medium. Therefore, we mainly introduce the dispersion compensation methods for single-mode fiber. The system's dispersion requirements have been the main driving force behind the development of single-mode fiber, as shown in Fig. 8. In order to solve the problem of dispersion of optical fibers, researchers have continuously improved the structure and parameters of optical fibers and manufactured a variety of new optical fibers.

We know that the zero-dispersion point of ordinary single-mode fiber is around 1.3 μm, but the optical communication system operating at 1.3 μm is limited by the fiber loss around 1.3 μm (typically 0.5 dB/km); the minimum loss of single-mode fiber is near 1.55 μm, but the fiber dispersion at 1.55 μm is very high (typically 17 ps/(nm km)). Based on the analysis and calculation of the dispersion formation mechanism, the researchers improved the structure and parameters of the common single-mode fiber and shifted the zero-dispersion wavelength to the vicinity of 1.55 μm to achieve a dispersion-shifted fiber (DSF) with zero dispersion and low attenuation. By adopting DSF, the communication distance and data rate of the optical communication system can be simultaneously increased.

With the commercialization of WDM technology, dispersion-shifted fibers induce serious nonlinear problems. The nonlinear effects of optical fibers can be divided into two categories according to their physical characteristics. The first category covers nonlinear inelastic scattering processes, namely stimulated Raman

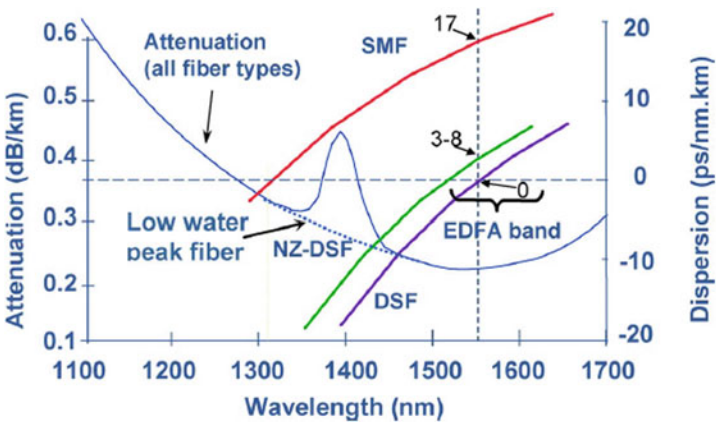


Fig. 8 Dispersion characteristics and attenuation characteristics of various single-mode fibers

scattering (SRS) and stimulated Brillouin scattering (SBS). The second type is the change of refractive index related to the light intensity in an optical fiber, including self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). The current nonlinear effect that has the greatest impact on optical communication systems is four-wave mixing, which we will focus on.

The WDM system requires both high input power and low dispersion, resulting in the four-wave mixing effect (FWM) that produces a new spectrum. The new spectrum can interfere with the operation of the WDM system, resulting in system performance degradation. Four-wave mixing is a third-order nonlinear effect in an optical fiber, which is similar to intermodulation distortion in electrical systems. In a multi-channel system, the mixing of three optical frequencies produces a fourth optical frequency $fg = fi + fj - fk$. The lower the dispersion is, the higher the new frequency energy generated by the four-wave mixing effect, the greater the interference to the communication. When WDM technology is applied to the DSF, a severe four-wave mixing effect is produced. For a system with N channels, the number of new frequencies generated by four-wave mixing is $M = 1/2\ (N^3 - N^2)$, that is, for two-channel and three-channel systems, 2 and 9, respectively, will be generated. The new frequency is shown in Fig. 9. Figure 10 shows the optical

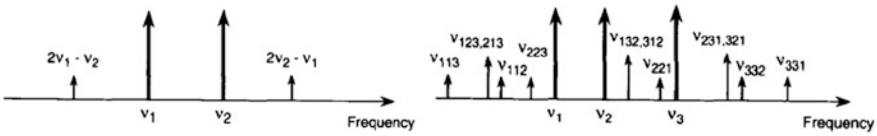


Fig. 9 Schematic diagram of four-wave mixing effect for two-channel and three-channel WDM systems

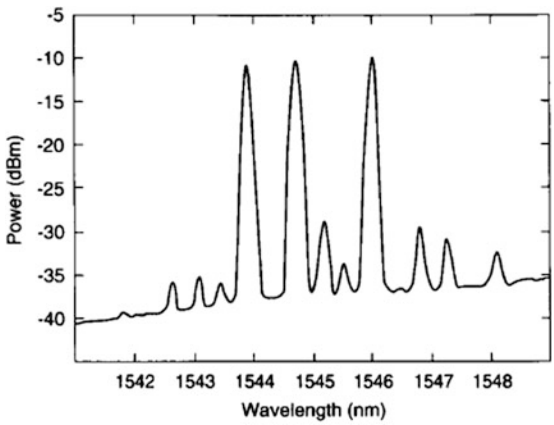


Fig. 10 Output optical power spectrum of a 3 mW/channel, three-channel WDM system after 25 km DSF transmission

power spectrum measured at the output after a 25-km DSF transmission for a three-channel WDM system with an input power of 3 mW per channel.

Due to the severe four-wave mixing effect when applying WDM technology on DSF, DSF is not suitable for WDM systems and is therefore not widely used. In order to suppress the four-wave mixing effect which is generated when WDM technology is applied within the EDFA bandwidth, a certain degree of dispersion is necessary, but at the same time, the dispersion must be small enough to reduce the dispersion loss, so researchers designed a new type of fiber, the non-zero dispersion-shifted fiber (NZDSF). In the NZDSF design, the zero-dispersion point is moved from 1.55 μm to the spectrum beyond the amplification bandwidth of the EDFA. As shown in Fig. 8, the typical dispersion value at 1.55 μm is 3 ~ 8 ps/(ns km). The application of NZDSF is very suitable for WDM systems, while the standard single-mode fiber has a high dispersion limit at 1.55 μm and a nonlinear effect due to four-wave mixing.

Since the nonlinear effect is inversely proportional to the effective area of the fiber, increasing the effective area of the fiber can reduce the nonlinear effect. Most NZDSFs have an effective area of 50 μm^2, which is much smaller than standard single-mode fibers. In order to increase the effective area, the researchers designed and manufactured a large effective area of NZDSF, called Large Effective Area Fiber (LEAF), with an effective area of 72 μm^2. Therefore, when transmitting the same optical power, LEAF can reduce the power density and nonlinear effects in the fiber and is more suitable for use in WDM systems.

A large number of dispersion-shifted fibers have been laid around the world for single-wavelength transmission systems. When upgrading to WDM systems, four-wave mixing has become a serious problem requiring dispersion management. Dispersion management is to suppress the FWM by properly arranging the fibers with different dispersion characteristics to obtain a locally higher but overall lower dispersion. The lower average dispersion broadens the light pulse, and the higher local dispersion can destroy the phase matching relationship of the carrier frequency at which the FWM intermodulation products are formed. One of the methods of dispersion management is to use passive dispersion compensation, that is, inserting an optical fiber with negative dispersion characteristics in the fiber link to cancel the cumulative dispersion of the transmission fiber. The inserted negative dispersion characteristic fiber is called a dispersion compensation fiber (DCF). After this method, the total dispersion of the system is zero, but the absolute dispersion at each frequency point in the fiber is not necessarily zero. The non-zero dispersion destroys the phase matching between the wavelength channels, thus destroying the condition of FWM generation.

At present, optical communication systems have evolved from analog communication to digital communication. Digital signal processing (DSP) such as dispersion compensation, carrier recovery, and polarization demultiplexing at the digital end is relatively mature. However, the nonlinear effect of optical fiber still limits signal rate and transmission distance. Researchers have done a lot of research on the compensation of nonlinear effects and have achieved a series of results. Volterra filtering and digital back propagation (DBP) have been proposed for nonlinear compensation and have formed a theoretical system. In 2011, the researchers used Volterra filters to mitigate nonlinear effects. The simulation realized a 14 GBd/s DP-16QAM signal transmission of 500 km and a 28 GBd/s DP-QPSK signal transmission of 1200 km. In 2012, Bell Labs used a digital phase conjugate to compensate for the nonlinear effects of the fiber. The experiment demonstrated the transmission of 40-Gb/s CO-OFDM-16QAM signals over 10,400 km. The NEC lab America used the simplified DBP algorithm to effectively compensate the nonlinear effect of the fiber. T. Kobayashi uses RF pilot to compensate for the nonlinear effect, achieving 1,200 km transmission of 538 Gb/s/ch PDM-64QAM SC-FDM signal. The compensation algorithm for nonlinear effects is still in the experimental stage. Due to the complexity of the algorithm and the limitations of the device, it is still not practical. We hope that in the near future, breakthroughs will be made in this area so that the system capacity can be increased.

Optical Communication System

The basic components of an optical communication system are shown in Fig. 11. The optical communication system is mainly composed of three basic units: an optical transmitter, a fiber channel, and an optical receiver. This block diagram is only a simplified diagram of the principle. The actual optical system also includes some optical interconnect and optical signal processing devices, such as fiber jumpers, optical couplers, optical beam splitters, optical amplifiers, regenerative repeaters, and so on.

The function of the optical transmitter is to convert the electrical signal into an optical signal and inject the optical signal into the optical fiber for transmission, generally consisting of a light source, a modulator, and a channel coupler. Light-emitting diodes (LEDs) and semiconductor laser diodes (LDs) are used as light sources because their emission wavelengths are adapted to the fiber channel. The communication channel is an optical fiber, and its basic characteristic parameters are loss and dispersion. In order to achieve high-speed long-distance transmission, the fiber is required to have low-loss and low-dispersion characteristics. The function of the optical receiver is to convert the optical signal output from the optical fiber into an electrical signal, generally consisting of a channel coupler, a photodetector, and a demodulator. A semiconductor photodiode is used as a photodetector because its response characteristic is adapted to the optical communication wavelength. The design of the demodulator depends on the modulation format

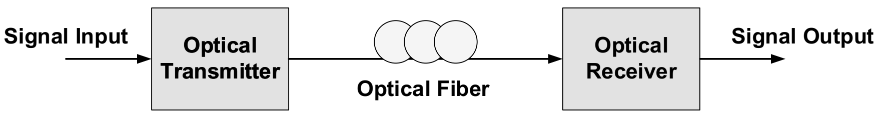


Fig. 11 Block diagram of the optical communication system

used by the system. According to the demodulation method, the optical communication system can be classified into a direct detection optical communication system and a coherent detection optical communication system.

Direct Detection Optical Communication Systems Without DSP

Most of the commercial optical communication systems are still direct detection systems without DSP at the receiver side. In this section, we will briefly introduce the composition and principle of direct detection optical communication systems. The block diagram of the direct detection optical communication system is shown in Fig. 12. The transmitter of the direct detection optical communication system uses intensity modulation, and the receiver is a direct detection receiver. The input electrical signal is intensity-modulated by the drive circuit and converted into an optical signal for transmission on the optical fiber. The light source generally adopts a light-emitting diode (LED) or a semiconductor laser diode (LD), while the light source is selected according to different performance requirements of the system. After the optical signal is transmitted on the optical fiber, it is input to the optical receiver, and the optical signal is converted into an electrical signal by the photodetector. After the electrical signal is amplified, the signal is shaped by the signal recover, and finally the electrical signal is output. The photodetector can use a photodiode (PIN) or an avalanche photodiode (APD), where PIN is more commonly used.

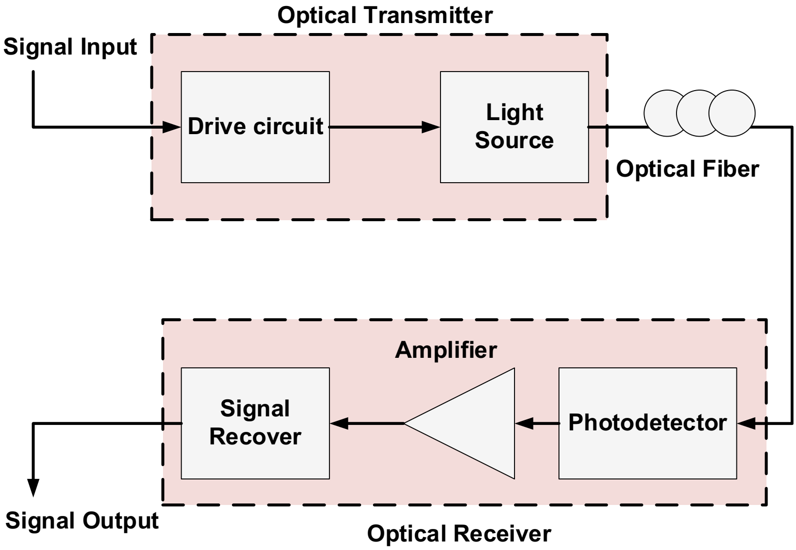


Fig. 12 Block diagram of direct detection optical communication system

The direct detection optical communication system without DSP has been widely used due to its simple structure and low cost. Most of the commercial optical communication systems with a bit rate of 40 Gb/s or lower are direct detection systems, nonetheless the direct detection receiver has low sensitivity and low-frequency band utilization, which cannot give full play to the superiority of fiber-optic communication. Today, with the rapid increase of information, direct detection of optical communication systems without DSP has gradually failed to meet people's communication requirements, and the era of optical communication systems with DSP has arrived.

Direct Detection Optical Communication Systems With DSP

For short-reach data center interconnect or passive optical networks (PON) in the near future, the bit rate can go up to 100 Gb/s. In these networks, the cost, size, and power consumption are very important. The coherent detection system can easily get this bit rate, but it is more expensive, has larger size, and needs more power. Therefore, coherent detection is difficult in employing these cost-sensitive networks. IM/DD is still a better choice. But if we use low spectral efficiency OOK modulation, the baud rate is very high. For 100 Gb/s optical signal, the baud rate is over 100 Gbaud if we consider forward error correction (FEC) overhead. The required bandwidth of the optical and electrical components is up to 50 GHz. The components with this bandwidth are very expensive. Therefore, modulation formats with high spectral efficiency such as PAM, DMT, and CAP are introduced. Usually, to generate these signals, DSP is needed at both transmitter and receiver sides. However, if the bandwidth of components is large enough, PAM does not need DSP. But PAM with DSP usually can get better performance because PAM is sensitive to nonlinear effects in optical and electrical components. The distortion caused by these nonlinear effects can be compensated by DSP.

Coherent Detection Optical Communication System With DSP

The coherent optical communication system was developed around the world in the 1980s, but its system structure is more complicated at higher costs. Due to the limitation of the devices (digital to analog converter or analog to digital converter) at the time and the advent of EDFA, WDM techniques brought direct detection optical communication system's capacity to a new record, so the coherent optical communication has been silent for a long time. In the twenty-first century, due to the development of the devices, coherent optical communication has come back. The coherent optical communication system has high sensitivity, long relay distance, good selectivity, large communication capacity, and many other advantages such as that various modulation methods could be adopted, thus it has a good application prospect.

Figure 13 shows the block diagram of a coherent optical communication system. The main difference from the direct detection system is the modulation and detection. The transmitter of the coherent optical communication system generally adopts external modulation. We can modulate the optical carrier by frequency, phase, or amplitude. The specific advanced modulation formats will be introduced in detail in Chap. 2. The direct detection system generally employs IM/DD. The receiver of the coherent system uses coherent detection, and the main difference from direct detection is the addition of the local oscillator source. The local oscillator and the received signal light are mixed by an optical mixer, and the signal is down-converted from the optical carrier frequency to the microwave carrier frequency, and then the center frequency of the signal is detected by the photodetector, which is the difference of the signal light and the local oscillator light frequency. Then, the intermediate frequency signal is amplified by the intermediate frequency amplifier and demodulated to obtain the baseband signal. If the signal light is equal to the frequency of the local oscillator, this detection is called "homodyne detection"; if the signal light and the local oscillator light are not equal, it is called "heterodyne detection". Coherent detection technology is the core technology of the coherent optical communication system. Next, we will focus on the principle of coherent detection.

The general process of coherent detection is that the transmitted optical signal at the receiver and the local oscillator generated by the local oscillator are interfered by the optical mixer, and then the photocurrent is output via the photodetector, and finally the photocurrent is processed by DSP and the baseband signal is generated. Since the IF signal can carry the amplitude, frequency, or phase information, the coherent detection is suitable for all modulation formats.

Coherent detection can be divided into heterodyne detection and homodyne detection according to the local oscillator frequency and the signal light frequency are different or the same. The former after optical/electrical (O/E) converter obtains an intermediate frequency (IF) signal, and the second demodulation is required to convert it to be a baseband signal. The latter is directly converted into a baseband signal after the O/E converter, but it requires the local oscillator frequency to match the signal frequency.

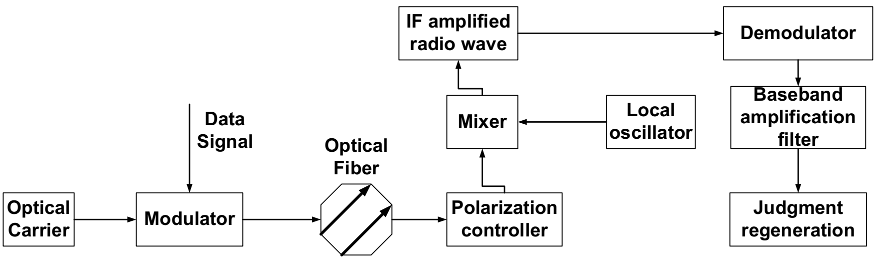


Fig. 13 Block diagram of a coherent optical communication system

Homodyne Detection

For homodyne detection where the local oscillator frequency is equal to the signal optical frequency, the IF frequency $\int_{IF}$ is zero. The corresponding photocurrent expression after O/E is

$$I(t) = R(P_s + P_{LO}) + 2R\sqrt{P_s P_{LO}}\cos(\varphi_s - \varphi_{LO}) \quad (1)$$

In the above formula, R is the responsivity of the photodetector, P_s and P_{LO} are the power of the signal lightwave and the local oscillator lightwave, respectively, and φ_s and φ_{LO} are the phases of the signal lightwave and the local oscillator lightwave, respectively. The first term of (1) is an almost constant DC term that is easily filtered out. The last term of (1) contains the transmitted information and provides it to the decision circuit application. Considering the phase lock of the local oscillator on the phase of the signal, it can be seen that the expression of the photocurrent obtained by the homodyne detection is

$$I_p(t) = 2R\sqrt{P_s P_{LO}} \quad (2)$$

We know that the expression of the signal current in the case of direct detection is

$$I_{dd} = RP_s(t) \quad (3)$$

By comparing (2) and (3), one significant advantage of homodyne detection can be obtained: the magnitude of the output photocurrent is proportional to the product of the signal optical power and the local oscillator power after coherent mixing in homodyne detection. And the local oscillator power is much larger than the signal light power, which greatly improves the sensitivity of the receiver. In addition, it is clear from Eqs. (2) and (3) that with the homodyne detection, the average electrical signal power is increased by 4 P_{LO}/P_s times. Since 4 P_{LO}/P_s can be artificially set to be much larger than 1, this increase can be several orders of magnitude. Although the shot noise is also increased, the SNR is still improved in the case of homodyne detection.

From (1), we can also observe another advantage of homodyne detection: since the last term contains the phase of the signal light, it is possible to transmit information by modulating the phase of the optical carrier. Direct detection does not allow phase or frequency modulation due to the phase information after directed detection in a photodiode.

The disadvantage of homodyne detection also comes from a high sensitivity to phase. We can see from (1) that its last term contains the phase φ_{LO} of the local oscillator, which obviously should be controlled. In the ideal circumstance, both φ_s and φ_{LO} should be a constant value except for intentionally modulating φ_s. But in fact, both φ_s and φ_{LO} are randomly floating with time. Although the optical PLL can make the difference $\varphi_s - \varphi_{LO}$ of φ_s and φ_{LO} nearly constant, it is not simple to implement such a phase-locked loop, and it also makes the design of the homodyne detection optical receiver quite complicated.

Another disadvantage of homodyne detection is that since the homodyne detection matches the transmitter frequency to the frequency of the receiver's local oscillator, this imposes stringent requirements on the two sources. But these problems can be solved by using advanced DSP or heterodyne detection.

Heterodyne Detection

For heterodyne detection where the local oscillator frequency and the signal optical frequency are not equal, the intermediate frequency $\int_{IF}$ falls within the microwave region. The expression of the photocurrent in this situation is

$$I(t) = R(P_s + P_{LO}) + 2R\sqrt{P_s P_{LO}}\cos(\omega_{IF}t + \varphi_s - \varphi_{LO}) \quad (4)$$

In the above formula, ω_{IF} is the IF angular frequency. Similarly, the first term in Eq. (4) is easily filtered out as an almost constant DC term. Thus, the heterodyne signal is given by the alternating term in equation (4), namely

$$I_{ac}(t) = 2R\sqrt{P_s P_{LO}}\cos(\omega_{IF}t + \varphi_s - \varphi_{LO}) \quad (5)$$

For heterodyne detection, information can be transmitted by modulating the amplitude, phase or frequency of the optical carrier. In addition, similar to homodyne detection, the local oscillator amplifies the received signal, which can significantly improve the sensitivity of the receiver and improve the signal-to-noise ratio SNR. Heterodyne detection improves the signal-to-noise ratio SNR by a factor of 2 (or 3 dB) compared to homodyne detection. This reduction is called a 3 dB heterodyne detection penalty. The 3 dB heterodyne detection penalty can be seen from the signal power proportional to the square of the current.

However, the advantage of 3 dB heterodyne detection cost is that the receiver design is greatly simplified because the optical phase-locked loop is no longer required. Although the random variations of φ_s and φ_{LO} still need to be controlled by a narrow linewidth semiconductor laser diode, in the discussion of the next section, we can see that the asynchronous demodulation technique can relatively alleviate the linewidth requirement. In summary, in practical applications, heterodyne detection is more advantageous than homodyne detection. Therefore, coherent detection optical communication generally adopts heterodyne detection.

The electrical signal obtained by heterodyne detection is a microwave intermediate frequency signal, which needs to be demodulated to the baseband. The demodulation of the optical signal can employ a synchronous or asynchronous scheme.

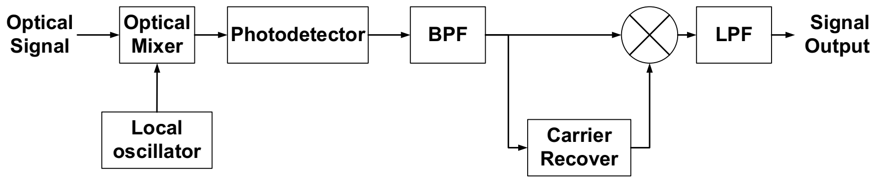


Fig. 14 Block diagram of the heterodyne asynchronous receiver

Figure 14 shows a block diagram of the heterodyne asynchronous receiver. Heterodyne asynchronous demodulation does not require recovery of the IF microwave carrier, so the design of the receiver is much simpler. In the outer heterodyne asynchronous demodulation, the output signal after the bandpass filter is restored to the baseband signal by using an envelope detector and a lowpass filter which is immediately following it. The signal received by the decision circuit is exactly I_f, obtained by Eq. (6). Then I_d can be given by

$$I_d = |I_f| = \left[\left(I_p \cos \varnothing + i_c\right)^2 + \left(I_p \sin \varnothing + i_s\right)^2\right]^{1/2} \tag{6}$$

The main difference between the heterodyne asynchronous receiver and the heterodyne synchronous receiver is that the heterodyne asynchronous receiver can affect the signal by the in-phase and inverting quadrature components of the receiver noise. Therefore, the signal-to-noise ratio (SNR) of asynchronous demodulation is reduced. And because of the SNR reduction, the sensitivity of the asynchronous receiver also decreases. However, the amount of decrease in sensitivity is quite small, approximately 0.5 dB. And in the case of asynchronous demodulation, the linewidth requirements for the transmitter and local oscillator are not that strict. Therefore, in the coherent optical communication system, the heterodyne asynchronous receiver is a practical solution and plays an important role.

Advantages of Coherent Detection

The advantages of coherent detection can be summarized in the following four aspects:

(1) It can significantly improve receiver sensitivity and increase non-relay transmission distance. As we mentioned earlier, the magnitude of the output photocurrent after coherent detection is proportional to the magnitude of the product of the signal light power and the local oscillator power. Since the local oscillator power is much larger than the signal light power, the sensitivity of the receiver is greatly improved. The high sensitivity of coherent detection makes the coherent receiver more suitable for the detection of weak light signals, while direct detection is only suitable for the detection of stronger signals. Under the

same conditions, the coherent receiver improves the sensitivity by about 20 dB compared with the conventional receiver and can achieve high performance close to the shot-noise limit. Therefore, the high sensitivity of the coherent receiver also increases the non-relay transmission distance of the optical signal.

(2) It leads to good selectivity and large communication capacity. Another major advantage of coherent detection is the ability to increase the selectivity of the receiver. In the coherent heterodyne detection, the mixed light of the signal lightwave and the local oscillator is detected, so only the noise in the IF band can enter the system, and other noises are filtered by the narrow bandwidth microwave IF amplifier. It can be seen that the heterodyne detection has good filtering performance. In addition, due to the excellent wavelength selectivity of coherent detection, the coherent receiver can substantially reduce the frequency separation of the frequency division multiplexing system, that is, dense wavelength division multiplexing (DWDM), which replaces the large frequency spacing of the conventional optical multiplexing technology. Small frequency spacing achieves the potential advantage of higher transmission capacity.

(3) A variety of modulation methods are available. In direct detection systems, only the intensity modulation can be used to modulate the lightwaves. In the coherent detection system, in addition to the amplitude modulation of the lightwave, frequency shift keying (FSK) or phase shift keying (PSK) modulation formats can be performed, that is, a plurality of modulation formats can be adopted, which is advantageous for flexible engineering applications, although the system complexity is increased in this scenario. Relative to the change of optical power in the IM/DD system, coherent detection can detect all the information carried by the amplitude, frequency, phase, and polarization state of the optical signal, so coherent detection is a holographic detection technique, which is not available in the IM/DD system.

(4) It can improve bandwidth utilization. Optical coherent detection technology converts optical frequency signals of the order of frequencies up to 10^{14} Hz into electrical intermediate frequency (RF) signals of the order of frequency 10^9 Hz, while electrical IF filters have unmatched frequency selection performance of optical filters. The wavelength (frequency) selectivity of the optical receiver is greatly improved. In principle, the system can adopt a dense wavelength division multiplexing technology with a channel spacing as small as $1 \sim 10$ GHz, and the utilization of the optical fiber bandwidth can be further improved by the multi-channel multiplexing technology.

The Trend of Optical Communication System

If you consider signal transmission bandwidth requirements to grow by 40−50%/year, and computing and storage capacity to grow at a rate of 60% per year, these factors will directly lead to an increase in Internet bandwidth at a rate of 60%.

According to Moore's Law, the demand for single-channel 1 Tb/s will appear in 2020. It can be seen that large-capacity transmission is undoubtedly the most important target of the transmission network, and only the optical communication system has the potential to carry such large-capacity information. At present, 100 Gb/s optical transmission systems are being largely deployed, and single-carrier 400 G transmission is becoming a commercial product. 800 Gb/s, 1 Tb/s, and even 10 Tb/s per channel transmission is an optional single-channel rate after 400 G.

The invention of fiber amplifiers has promoted the use of WDM technology in optical transmission systems, and with the widespread adoption of WDM equipment, the single-channel rate has also doubled, enabling transmission capacity to increase hundreds of thousands. However, after the single-channel rate has exceeded 10 G, the simple NRZ pattern and direct detection technology have been difficult to meet the long-distance transmission requirements. Therefore, in the future commercial 800 G or 1T systems, new modulation and demodulation technologies and detection technologies are needed. Coherent optical communication systems will become inevitable. In order to further increase the single-channel rate, such as 1T or higher, considering the availability of high-speed optoelectronic devices, especially the ADC bandwidth limitation, the current research direction mainly includes high-order modulation format, Nyquist WDM technology and orthogonal frequency division multiplexing (OFDM) technology.

The use of high-order modulation formats improves spectral efficiency and enables higher bit rate transmissions with limited bandwidth. However, high-order modulation formats such as 64QAM are more sensitive to nonlinear distortion caused by optoelectronic device bandwidth limitations, and the accuracy requirements for laser linewidth and high resolution of the ADC are also increased.

Optical OFDM technology uses multi-carrier dense modulation, and there is no crosstalk between each carrier, so it can achieve higher spectral efficiency. At present, multi-subcarriers still suffer from stability, performance, and cost problems. It is necessary to study new methods to generate high-performance, high-reliability multi-subcarriers. At the same time, when detecting OFDM modulated signals, multiple subcarriers need to be detected at the same time (generally three need to be detected), which also has certain requirements on the ADC bandwidth of the receiver.

To meet the ADC bandwidth requirements, the researchers proposed Nyquist WDM technology. Nyquist WDM technology uses strong filtering technology, and the bandwidth occupied by each subcarrier is equal to the baud rate of each subcarrier signal. Through strong filtering techniques, the crosstalk between subcarriers is already small, so each subcarrier receiver needs to detect the subcarrier at the receiving end, thus reducing the bandwidth requirement of the ADC. However, because of the strong filtering, it also brings a large optical signal-to-noise ratio (OSNR) cost.

In order to reduce the baud rate of the optical signals, people investigate to use multicore and multimode fiber to deliver high-speed optical signals. New fiber with more cores or modes is invented. Few-mode multicore fibers (FM-MCFs) have been reported with up to 19-core and 6-mode FM-MCF (114 spatial channels). The transmission capacity can go up to 10 Pb/s with an average data rate per spatial channel of 89.1 Tb/s and average spectral efficiency of 1099.9 b/s/Hz. The key components such as multimode or multicore optical amplifier, multiplexer, demultiplexer are becoming mature. But fiber splicing and stability are not well solved. Since 2007, coherent detection communication systems with DSP have become a hot research direction due to their transmission capacity. With the development of broadband optical and electrical device and the emergence of new DSP technologies, coherent optical communication systems with DSP is still the sole solution for large-capacity system. For short reach such as data center interconnect or passive optical networks (PON), multilevel modulation formats in the transmitter to reduce baud rate and direct detection with DSP are the main research areas. It is anticipated that single channel with bit rate up to 100 G will be widely deployed very soon.

Structure of the Book

This book includes 19 chapters.

Chapter 1, advanced modulation. This chapter mainly introduces the principle and methods of generating various modulation signals.

Chapter 2, the basic algorithm of single-carrier coherent optical transmission system. The basic algorithms of single-carrier coherent optical transmission system are introduced, including I/Q imbalance compensation, orthogonal normalization, dispersion compensation, clock recovery, channel equalization, carrier recovery, and phase compensation algorithm. For channel equalization, blind equalization algorithm based on the statistical properties of signal is introduced, from classic CMA algorithm to CMA algorithm in polarization multiplexing signal. However, CMA algorithm has constant amplitude, so it cannot make a good recovery to the high-order signal. This book further introduces CMMA algorithm which aims at high-order modulation of inconstant, this algorithm utilizes angle and the modulus value. Further more, there are too many reference levels of CMMA, so we introduce an improved cascade multimode algorithm MCMMA algorithm. MCMMA changes the diversified angle and modulus values to the orthogonal real and imaginary components, which reduces the reference level and has more obvious performance in high-order signal optimization. In addition, ICA algorithm (Independent component analysis) is introduced. At the end of this chapter, the basic digital signal processing algorithm introduced in this chapter is arranged and compared, and the relevant constellation diagrams are displayed, showing more intuitively the functions of each algorithm.

Chapter 3, quasilinear coherent optical transmission system and digital signal processing. This chapter focuses on the study of quasilinear coherent optical detection system based on advanced digital signal processing technology, including the front-end linear pre-equalization algorithm. The bandwidth limitation of the device and the nonlinear damage of the optical fiber link are two important factors that restrict the transmission of high-speed optical signal. The former limits the bandwidth and baud rate generated by the signal, while the latter limits the transmission distance of high-speed optical signal. This chapter first introduces the basic digital signal processing of coherent optical communication, and then introduces a new front-end digital time-domain pre-equalization scheme based on this. Finally, simulation and experiment are conducted to verify the compensation performance of time-domain data pre-equalization for coherent optical communication.

Chapter 4, the exploration of the high spectral efficiency super-Nyquist wavelength division multiplexing system. Aiming at high spectral efficiency and high-speed optical transmission, a new multimode blind equalization algorithm for super-Nyquist spectrum compression signal is firstly introduced. This algorithm can effectively suppress noise and crosstalk between channels, so as to realize super-Nyquist WDM signal transmission. At the same time, the experimental results show that the algorithm has better anti-noise, anti-filter, and anti-channel interference performances than the ordinary equalization algorithm. In this chapter, the experiment of super-Nyquist signal digital generation and 4-carrier 400 G optical transmission based on front-end filtering and ultra-high-speed PDM-QPSK coherent transmission system up to 110 GBaud will be introduced. By using this system, the world's first 400 G optical transmission system based on a single-carrier super-Nyquist, and the world's highest baud rate of 110 GBaud was created. The carrier interval was compressed to 100 GHz, the transmission capacity reached 8.8 Tb/s, and the signal spectrum efficiency was greater than 4 bit/s/Hz. Finally, the performance of super-Nyquist filter signal in multiple reconfigurable optical division and interpolation multiplexers (ROADMS) is experimentally studied. We also demonstrated the high anti-filtering property of the 9QAM super-Nyquist signal in the experiment. The content of Chap. 4 provides effective theoretical and technical support for realizing high-frequency efficient optical transmission.

Chapter 5, the production and processing of all-light Nyquist signals. All-optical signal processing technologies are explored, mainly for the generation, transmission, and signal detection of all-optical Nyquist signals. First, the principle of all-optical Nyquist signal pulse generation, signal modulation, and multiplexing mechanism will be introduced. This chapter also provides the theoretical basis for realizing frequency locked, linear phase, and equal amplitude optical comb based on a single MZM. Then, the first full light Nyquist signal generation and coherent detection system is introduced. The full light Nyquist QPSK signals up to 62.5 GBaud, 75 GBaud, and 125 GBaud are generated and coercively detected by the full light comb spectrum. Finally, the research work on polarization-multiplexed all-light Nyquist signal long-range and high-order modulation schemes is introduced, including the production, transmission, and full-band coherent detection of 37.5 and 62.5 Gbaud all-light Nyquist PDM-QPSK and 16QAM signals. Aiming at all-optical Nyquist signals, we can not only realize the generation and transmission of high-frequency efficient optical signals, but also improve the signal generation and processing rate by breaking through the bandwidth limitation of electronic devices.

Chapter 6, research on nonlinear compensation algorithm of fiber channel. In this chapter, the nonlinear compensation algorithm is introduced, and the performance of nonlinear compensation is verified from theory, simulation, and experiment. Then, a new DBP nonlinear compensation algorithm based on improved log-step distribution is introduced, and its compensation effect in Nyquist wavelength division multiplexing system (N-WDM) is studied and analyzed. Finally, an improved digital nonlinear compensation algorithm based on logarithmic step size is introduced.

Chapter 7, research of probability shaping technology. The probabilistic shaping technique introduced in this chapter is an optimization one for advanced modulation formats, which has the advantages of high transmission capacity and low system complexity. Based on the basic principles of probabilistic shaping, this chapter explores the optimization of RoF system from the perspectives of algorithm, simulation, and experiment.

Chapter 8, ultra-high baud rate optical signal transmission technology. This chapter introduces and analyzes the experiment of ultra-high baud rate optical signal transmission. This chapter mainly introduces three different experiments from the perspective of experimental setup and analysis of experimental results. The first is an experiment of 110 Gbaud polarization-multiplexed QPSK signal transmission of 3000 km. The second experiment is 128 GBaud polarization-multiplexed QPSK signal transmission of 10,000 km. The third experiment is 128 GBaud polarization-multiplexed 16QAM signal long-distance transmission experiment. In this chapter, the feasibility and prospect of ultra-high baud optical transmission system are proved by experiments.

Chapter 9, advanced modulation code optical signal transmission technology. This chapter also verifies from the experimental perspective. First, it verifies the generation experiment of 34 GBaud PM-256QAM signal, and then it verifies the transmission experiment of single-carrier 400 G PM-256QAM signal. Experimental results show the advantages and prospects of advanced modulation code optical signal transmission technology.

Chapter 10, carrierless amplitude phase modulation (CAP) techniques. This chapter mainly introduces the short distance high-speed optical transmission. Firstly, the modulation and demodulation principle and realization method of new efficient modulation format CAP are introduced, including the generation and reception of single-band CAP-mQAM and the generation and reception of multi-band and multi-order CAP signal. Then, through experimental research, a WDM-CAP-PON multi-user access network based on multi-order multi-band CAP modulation was introduced, and its high-speed access performance was verified, and the high-speed multi-order multi-band CAP signal was first demonstrated for the WDM-CAP-PON experimental system. Then, the experiment of wireless access network transmission based on high-order modulation CAP-64QAM is introduced. Then, a high-speed CAP-64QAM system based on DML and digital equalization is introduced. CAP-64QAM signal is equalized with the improved DD-LMS. Finally, CAP long-distance transmission of 100 G signal with dispersion compensation is introduced. The digital signal processing of CAP, SSB signal generation, experimental equipment, and results are introduced in detail. In addition, the performance of DDMZM pre-dispersion, dispersion compensation fiber, SSB, and IQ modulator are compared.

Chapter 11, PAM4 signal modulation and detection techniques based on digital signal processing. This chapter mainly introduces PAM4 signal modulation and corresponding digital signal processing algorithm and PAM4 high-speed transmission system experiment. First, PAM4 principle, DD-LMS algorithm, and pre-dispersion compensation principle are introduced. In addition, a simple lookup table (LUT) algorithm is introduced, which can pre-distort the signal at the transmitter end and resist all kinds of nonlinear damage in the direct detection system. Then, the four-channel IM/DD 112-Gbit/s PAM-4 system is introduced, and a series of algorithms such as dispersion pre-compensation (pre-CDC), pre-equalization, lookup table (LUT), and DD-LMS are applied to realize the 400 Gbit/s high-capacity high-speed system. Finally, the polarization-multiplexed 400 G PAM4 signal coherent system is introduced, this system use time division multiplexing (TDM) and polarization multiplexing (PDM), and the use of pre-emphasis technology to overcome the photoelectric device bandwidth limit, to achieve 120 GBaud PDM-PAM4 signal transmission, its data rate is up to 480-Gb/s, and can still reach 400-Gb/s net bit rate considering 20% FEC overhead. These results show that it has a broad application prospect in short distance access network and metropolitan area network.

Chapter 12, optical OFDM principle. In this chapter, the basic principle of optical OFDM (orthogonal frequency division multiplexing) system technology is introduced, and the basic structure and principle of optical OFDM system based on direct detection and optical OFDM system based on coherent detection are, respectively, introduced.

Chapter 13, basic digital signal processing technology of direct detection OFDM. This chapter mainly studies the basic digital signal processing technology of direct detection OFDM system. First is the introduction of the system principle. Secondly, the research on the elimination of DDO-OFDM sub carrier interbeat effect based on Half-cycled technology is introduced, and the experimental equipment and results are, respectively, presented. Then, the research of direct detection of high-order QAM-OFDM signal transmission is introduced, the experimental equipment and results are also introduced, and the experimental results are analyzed and summarized. Finally, the research of DDO-OFDM signal transmission based on DFT-spread is introduced. The optimization of training sequence in the system is introduced, and then the effects of pre-emphasis and DFT-spread in DDO-OFDM are compared.

Chapter 14, intensity modulation and direct detection of the high-speed optical fiber access system. In this chapter, the bandwidth shortage, strong nonlinear effect, and fiber dispersion in the direct detection system of intensity modulation are investigated systematically, and the corresponding solutions are proposed from the aspects of system structure, modulation coding technology, and digital signal processing algorithm. First, Nyquist modulation and super-Nyquist modulation techniques with high spectral efficiency are introduced, and then Volterra series and equal-like coding are introduced. Then, the modulation technology of DFT-S OFDM with low power peak average ratio and high spectral efficiency is introduced. Based on this technology, a series of advanced digital signal processing algorithms, including pre-equalization, nonlinear compensation, DD-LMS, and other technologies, are combined to realize the transmission of single-mode fiber signals of over 100 Gb/ S over 320 km.

Chapter 15, high-speed optical fiber access system based on I/Q modulation direct detection. This chapter introduces an optical access system architecture based on I/Q modulator that generates independent double-sideband signals in detail and carries out direct detection at the receiver end, respectively. By adopting a new Image elimination algorithm, the generation and detection of single-carrier 64 Gb/s CAP4 signals and multi-carrier 300 Gb/s DFT-S OFDM signals based on two independent sideband can be successfully realized. The 240 Gb/s 16QAM DFT-S OFDM signal based on two independent sideband can be transmitted over 160 km in single-mode fiber without dispersion compensation.

Chapter 16, forward error correction code. This chapter introduces several common coding techniques in FEC algorithms. The application of LDPC cascade TCM encoding modulation technique in OFDM-ROF system and Turbo equalization technique to reduce the dispersion effect of optical transmission system is introduced. Forward error correction (FEC) technology finds and corrects the error caused by reasons of the dispersion and nonlinearity by adding a small amount of redundant information in the signal optical transmission process. In addition, the influence of dispersion and nonlinearity on transmission system performance is reduced. The FEC technology lowers the OSNR tolerance at the receiver end through the sacrifice of the signal transmission rate, thereby it gains coding gain, reduces the error rate, and improves the reliability of communication system.

In Chap. 17, the principle and key technology of high spectral efficiency four-dimensional modulation. This chapter introduces the basic principle and key technology of high spectral efficiency 4-dimensional modulation. Firstly, the distribution and performance analysis of 2-D and 3-D constellations are introduced, and then the principle and realization of 4-D multi-order modulation are studied. Then it expands from 4 dimensions to multiple dimensions and introduces the design consideration of multi-dimensional modulation constellations. Finally, the performance of the typical multi-dimensional multi-order constellation diagram is analyzed.

Chapter 18, machine learning algorithm in optical communication system. This chapter mainly introduces the machine learning algorithm applied in optical communication system. Firstly, support vector machines are introduced. Based on the principle of structural risk minimization, it minimizes the actual risk of the learning machine by properly selecting the subset of functions and the discriminant functions in the subset, thus ensures the small error classifier obtained from the limited training samples, and the test error of the independent test set is still small. Then, BP neural network, which is one of the most widely used neural network models, is introduced. It is a multi-layer feedforward network trained by error back propagation algorithm. BP network can learn and store a large number of input–output pattern mapping relationships without revealing the mathematical equations describing such mapping relationships in advance. Then, the clustering algorithm is