Optical Wireless Communication Theory and Technology

Xizheng Ke
Jiali Wu

Coherent Optical Wireless Communication Principle and Application

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Series Editor

Xizheng Ke, School of Automation and Information Engineering, Xi'an University of Technology, Xi'an, Shaanxi, China

The book series Optical Wireless Communication Theory and Technology aims to introduce the key technologies and applications adopted in optical wireless communication to researchers of communication engineering, optical engineering and other related majors. The individual book volumes in the series are thematic. The goal of each volume is to give readers a comprehensive overview of how the theory and technology in a certain optical wireless communication area can be known. As a collection, the series provides valuable resources to a wide audience in academia, the communication engineering research community and anyone else who are looking to expand their knowledge of optical communication.

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Xizheng Ke
School of Automation and Information Engineering
Xi'an University of Technology
Xi'an, Shaanxi, China

Jiali Wu
School of Automation and Information Engineering
Xi'an University of Technology
Xi'an, Shaanxi, China

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Preface

The rapid development of artificial intelligence has resulted in higher requirements for the communication industry. The optical communication industry is focusing on larger channel capacities, longer transmission distances, higher data transmission rates, and better transmission quality. The intensity modulation/direct detection method adopted by the traditional optical communication technology cannot cope with this high-speed communication, owing to its limited single-channel bandwidth.

Coherent optical communication is favored by researchers because of its unique advantages of rich modulation modes, large communication capacity, and high receiving sensitivity. It can fundamentally improve the selectivity of the receiver and increase the relay-free transmission distance of optical signals. To achieve more accurate, effective, and reliable coherent optical communication, breakthroughs are needed in corresponding key technologies, such as carrier frequency stability, beam coupling, and the correction of the polarization direction and wavefront distortion of the signal light at the receiving end.

The book is divided into nine chapters, which provide an overview of optical wireless coherent detection, coherent optical communication, spatial optical-fiber coupling and beam control, beam polarization control technology, double-balanced detection, adaptive optics correction, wavefront sensorless correction, spatial coherent optical communication wavefront correction of LC-SLM-R, and the influence of the beam mode on the performance of coherent detection systems. The principles and key technologies of coherent optical wireless communication are also introduced. Array coupling reception and large aperture coupling are proposed for spatial optical coupling. To improve the mixing efficiency of coherent detection receivers, signal optical polarization control and adaptive optics technology are proposed.

This book is a result of the dedicated efforts of the author and his graduate students, from the Optoelectronic Technology Research Center of Xi'an University of Technology. The author and his graduate students have conducted a considerable amount of theoretical research and a number of experiments on the coherent optical wireless communication in recent years. Their efforts have contributed to the further development of optical wireless communication technology.

The related work of this book has been supported by the Shaanxi Provincial Key R&D Program (Key Industrial Innovation Chain) Project (2017ZDCXL-GY-06-01), the research plan project of the Shaanxi Provincial Department of Education (18JK0341) and the Xi'an science and technology plan project (2020KJRC0083).

This book is a preliminary summary of the research conducted by the author on coherent optical wireless communication. Due to the limited knowledge of the author, there may be some inevitable inconsistencies in the book. Readers are welcome to suggest corrections.

Xi'an, China
Spring 2022

Xizheng Ke
Jiali Wu

Introduction

This book focuses on optical wireless communication. It introduces beam coupling, polarization control, and wavefront correction of signal light in detail. Further, it discusses the basic principles and heterodyne detection conditions of coherent optical communication, space optical-fiber coupling by array coupling reception, and large aperture coupling. The use of simulated annealing, particle swarm optimization, and single particle swarm optimization algorithms for controlling the polarization state of signal light is discussed. The stochastic parallel gradient descent algorithm, adaptive optics correction, liquid-crystal spatial light modulation for signal light wavefront distortion correction, and the influence of beam modes on coherent detection performance are also discussed. This book provides both theoretical deductions and experimental results, which can enhance the reader's understanding of the theories presented herein.

This book is suitable for engineering and technical personnel, college and university teachers, graduate students and undergraduate students in their final year, who are engaged in the field of optical wireless communication.

Contents

Chapter 1
Optical Wirelss Coherent Detection: An Overview

Contents

1.1 Optical Wireless Coherent Communication

Free-space optical communication (FSOC), also known as optical wireless communication (WOC), is a communication technology that uses laser beams as information carriers to directly transmit data, audio, and video signals in space [1]. With the development of the high-capacity, long-distance communication technology, WOC has broad application prospects in the fields of inter-satellite communication and the last-kilometer access of local networks. Therefore, WOC has become a research hotspot in optical communication technology [2].

Generally, WOC adopts intensity modulation/direct detection (IM/DD) and subcarrier modulation (SCM)/DD. IM refers to the use of the intensity of light to carry information, including the on–off keying (OOK) mode and pulse-position modulation (PPM) mode. DD refers to direct detection, using a photoelectric detector, of

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the intensity of a laser converging on a photosensitive surface. The IM/DD mode has the advantages of its simple principle and low cost; however, it has the disadvantages of low frequency band utilization and poor reception sensitivity [3]. In SCM, the binary bit information is modulated to the carrier frequency. Thereafter, the modulated subcarrier is used to modulate the optical carrier [4]. This modulation technology can use the spectrum resources effectively through the wavelength division multiplexing technology and improve the capacity of transmission [5].

When compared with the DD technology, the coherent optical detection technology can improve the receiver sensitivity and signal-to-noise ratio (SNR), realize multiple modulation modes [6], ensure appropriate selectivity [7] and increased communication capacity [8], and improve the performance of the WOC system. The requirements of coherent light detection for light sources, modulation, transmission, and reception are significantly stricter than those for DD [9]. It is necessary to address the problem of light source stability to realize coherent optical detection [10]. The frequency stabilities of the transmitter and receiver light sources are significantly high in a coherent optical communication system. Furthermore, wavefront matching and polarization matching of the received signal light and local oscillator light are necessary to ensure that the receiver has high detection sensitivity [11]. However, the atmospheric environment significantly affects the detection sensitivity of coherent light, thereby limiting the popularization and application of the coherent light detection technology. To mitigate the effects of the atmospheric turbulence, developed countries such as the United States, Europe, and Japan have adopted some atmospheric-disturbance-compensation technologies in the design of WOC systems [12, 13]. Some research progress in this direction has been made also in China [14]. Notwithstanding these developments, mitigating the effects of the atmospheric turbulence and improving the received SNR and optical detection sensitivity remain open areas in the field of wireless laser communication. Therefore, in-depth research in these areas has potential theoretical and application values.

1.2 Optical Wireless Communication: Development Status

In the 1980s, some countries began to study the theory and engineering of the FSOC technology using various modulation methods. The United States, Japan, and some European countries have a leading position in the research on optical communication technology.

In the early 1980s, the MIT Lincoln Laboratory (MIT-LL) and National Aeronautics and Space Administration (NASA) jointly developed the NASA-ACCS communication satellite demonstration system [15]. The transmitter in this system adopts differential phase shift keying (DPSK) modulation and receives through optical heterodyne detection. The collaboration successfully launched a satellite loaded with the system in 1989. In 1995, the Jet Propulsion Laboratory (JPL), supported by NASA and managed by the California Institute of Technology, developed a laser communication demonstration system (LCDS) [16], which adopted OOK modulation for the signal light and continuous wave modulation for the beacon light. The data transmission rate of the system was 750 Mbit/s. In 1995, the US Ballistic Missile Defense Organization implemented the Space Technology Research Vehicle 2 (STRV-2) experimental plan. The communication unit of STRV-2 adopted the IM/DD mode semiconductor laser emission and avalanche photodiode reception [17]. Its designed data transmission rate was 1 Gbit/s. In 2000, Lucent and Astro Terra successfully realized a commercial WOC experimental system with four wavelengths near 1550 nm, wavelength-division multiplexing of 10 Gbit/s, and a transmission distance of 5 km [18]. In October 2013, NASA successfully realized a laser communication link between the lunar laser communication terminal and the ground station [19]. Its data transmission rate was 622 Mbit/s. The project adopted 16-PPM, superconducting nanowire single-photon detection and ground terminal array transceiver technology, which effectively mitigated the problems of the light intensity flicker and low receiving power density in the atmospheric turbulence channel. Photon reception with high sensitivity was realized. In the late 1980s, the European Space Agency (ESA) began to formulate the semiconductor laser inter-satellite link experiment (SILEX) [20] plan to establish laser communication links between satellites and develop the required subsystems and communication units. In 1994, British, Canadian, and Belgian companies jointly developed a small optical user terminal (SOUT) and very small optical user terminal (VSOUT), which realized an inter-satellite communication link using IM/DD [21, 22]. The communication terminal developed in the SILEX program in 2001 successfully realized the first inter-satellite laser link experiment [23]. A binary phase shift keying (BPSK)/coherent detection mode was adopted, and the communication rate was 50 Mbit/s. In 2005, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany, developed a BPSK modulation/homodyne detection optical-communication terminal, called laser communication terminal (LCT). The data transmission rate in this communication experiment reached 5.625 Gbit/s. In 2006, Davis [25] reported that the sensitivity of polarization modulation was approximately 3 dB higher than that of OOK modulation. In 2009, Popoola [26] of Northumbria University reported that atmospheric turbulence significantly reduced the performance of the DD system, and SCM was better than OOK, which is a modulation method that effectively suppresses the effect of atmospheric turbulence. In November 2014, a second generation LCT [24] laser communication was established between the AlphaSat satellite and Sentry 1A [27]. BPSK modulation/homodyne detection was adopted in that study, and the test rate was 600 Mbit/s.

In 1995, the IM/avalanche photodiode (APD) DD communication terminal laser communication equipment developed by Comprehensive Communication Research Laboratory, Japan, successfully performed two-way laser communication with an American atmospheric observation satellite for 8 min [28]. In May 2006, a laser communication experiment was successfully realized between the Optical Inter-orbit Communication Engineering Test Satellite (OICETS) and the National Institute of Information and Communication Technology (NICT) ground station in Japan. The laser-utilizing communication equipment (LUCE) laser communication terminal onboard OICETS [29, 30] used an optical power of 100 MW and an 847-nm laser with left-handed circular polarization modulated by non-return to zero-code direct IM. Its data rate was 49.3 Mbit/s and the bit error rate (BER) was 10^{-6}.

In 2002, the Chengdu Institute of Optoelectronic Technology, Chinese Academy of Sciences, developed a WOC terminal with a transmission rate of 10 Mbit/s, working wavelength of 850 nm, transmission distance of 1–4 km, and transmission power of 3–30 mW [31]. In 2002, the University of Electronic Science and Technology developed a ground demonstration system for satellite optical communication verification [32]. Wuhan University is engaged in research on atmospheric laser communication and beacon light acquisition and tracking. It performed an atmospheric laser communication experiment in 2002 [33], adopted the IM /DD mode, completed the ground simulation test of an automatic tracking servo system of space optical communication in 2008 [34], realized a 4.6 km FSOC link, and completed 5 Gbit/s data transmission using dense wavelength division multiplexing in 2011 [35]. In 2009, Guangxi Guilin Laser Communication Research Institute developed a laser atmospheric communication system with a communication distance of 5 km, communication rate of 155 Mbit/s, and BER of less than 10^{-7} [36]. In October 2011, a satellite-to-ground communication terminal developed by the Harbin University of Technology was launched on the Ocean 2 satellite. It achieved a single-channel data transmission rate of 504 Mbit/s [37]. In September 2013, the Changchun University of Technology successfully completed an aircraft-to-aircraft long-distance laser communication test [38].

The Xi'an University of Technology has been studying the atmospheric laser communication system since 2000 and has made significant progress in optical design, coding, and modulation [39]. A wireless laser communication system terminal has been successfully developed. The system has common digital interfaces, including serial and parallel ports and Ethernet. The system can realize full-duplex communication between computers or terminal equipment and reliable transmission of data, audio, and video. Its transmission rate and distance are 20 Mbit/s and 1 km, respectively. At present, it has been applied to expressway video monitoring systems.

It is evident that the transmitter used in the FSOC technology has developed from the initial OOK modulation mode to other reliable modulation technologies such as SCM [40], PPM [41], multi-pulse position modulation [42], digital pulse position modulation [43], and BPSK modulation. Such reliable modulation technologies with high efficiencies and strong anti-interference abilities facilitate a high transmission rate and low BER communication and play an important role in improving the performance of communication systems. The receiver of FSOC also develops into a coherent detection owing to the low sensitivity of direct detection.

1.3 Research Status at Home and Abroad

In this section, we summarize the research status of inter-satellite coherent optical detection and allied technologies at home and abroad.

1.3.1 Inter-Satellite Coherent Optical Detection

1.3.1.1 Abroad

The United States, Europe, Japan, and other developed countries have performed extensive research on the coherent optical detection technology in the field of inter-satellite optical communication. Recently, they have entered the experimental stage of inter-satellite coherent optical communication systems.

(1) United States

In the mid 1980s, the MIT-LL performed a laser inter-satellite transmission experiment (LITE) and developed an optical heterodyne detection communication terminal. This experimental device is depicted in Fig. 1.1. The transmitter used in this device uses the DPSK modulation method. The experiment used a 30 mW semiconductor laser, 200 mm telescope system with a data rate of 220 Mbit/s, communication distance of 40,000 km, and modulation rate of up to 1 Gbit/s [44].

JPL successfully performed a 64-PPM coherent optical communication experiment in 2004. The experimental device is depicted in Fig. 1.2. In this experiment, two Nd-doped yttrium aluminum garnet lasers with a wavelength of 1064 nm were used as signal light and local oscillator light sources. The optical heterodyne detection method was used at the receiving end, with an intermediate frequency (IF) of 6 MHz [45].

(2) Germany

In Germany, Lange successfully realized 5.625 Gbit/s BPSK-modulated homodyne detection optical communication in October 2006 [46]. Two LCTs were used for ground-to-ground coherent optical communication experiments between Canary

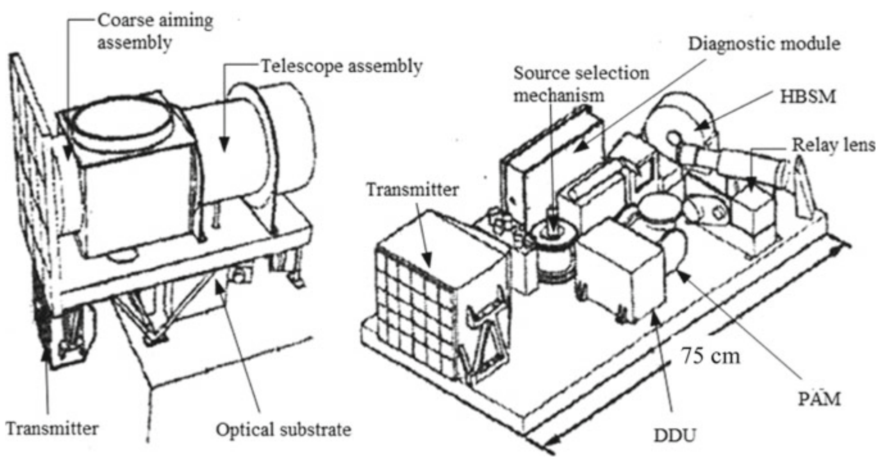

Fig. 1.1 Sketch of MIT Lincoln laboratory LITE [44]

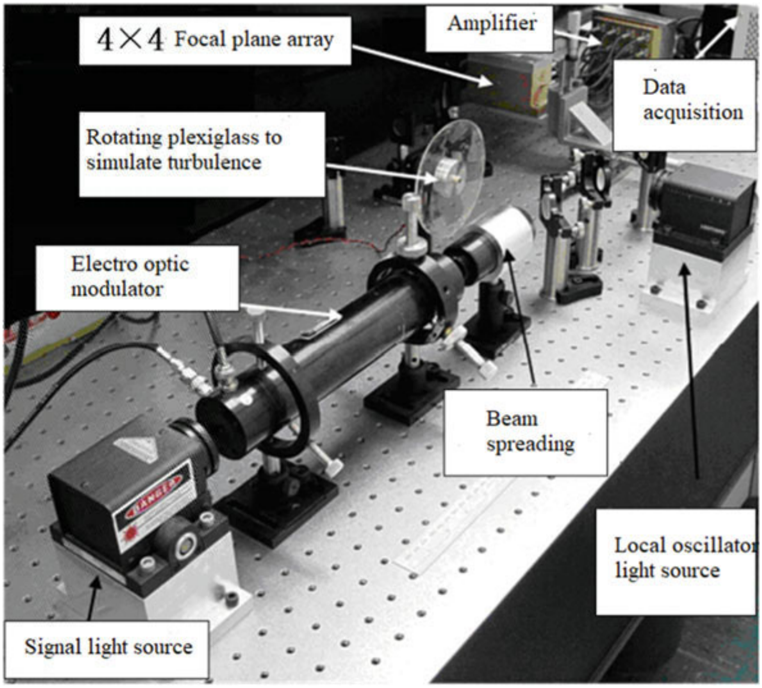

Fig. 1.2 Coherent light detection experimental device at JPL [45]

Islands, Spain, and La Palma and Tenerife islands 142 km away. The homodyne BPSK receiver used in the LCT is depicted in Fig. 1.3. The actual communication bit rate reached 5.625 Gbit/s without optical filtering, and the BER was between 10^{-6} and 10^{-4}.

In 2008, the near-field infrared experiment (NFIRE) of the Ministry of Defense successfully realized two-way broadband data transmission with a transmission rate of up to 5.6 Gbit/s. BPSK modulation/homodyne coherent optical detection was adopted, and the BER was better than 10^{-9}. This was the first time that a long-distance spatial coherent optical communication experiment was realized [47] in Germany. And, a laser link to realize satellite-to-ground bidirectional laser communication was successfully established between the terraSAR-X satellite and an optical ground station (OGS) in Germany. The link holding time was 8 min, and the data transmission rate was 5.6 Gbit/s. Experimental results indicated that the BER of the uplink was greater than 10^{-5}. The LCT homodyne coherent optical detection terminal was used at the transmitter and receiver [48]. An image of the LCT terminal, which comprises a coarse aiming device, telescope, and receiver, is depicted in Fig. 1.4.

In the same year, the infrared reconnaissance satellite NFIRE of the US Department of Defense established two-way laser communication with the OGS in Germany. The data transmission rate was 5.625 Gbit/s, and the link holding time

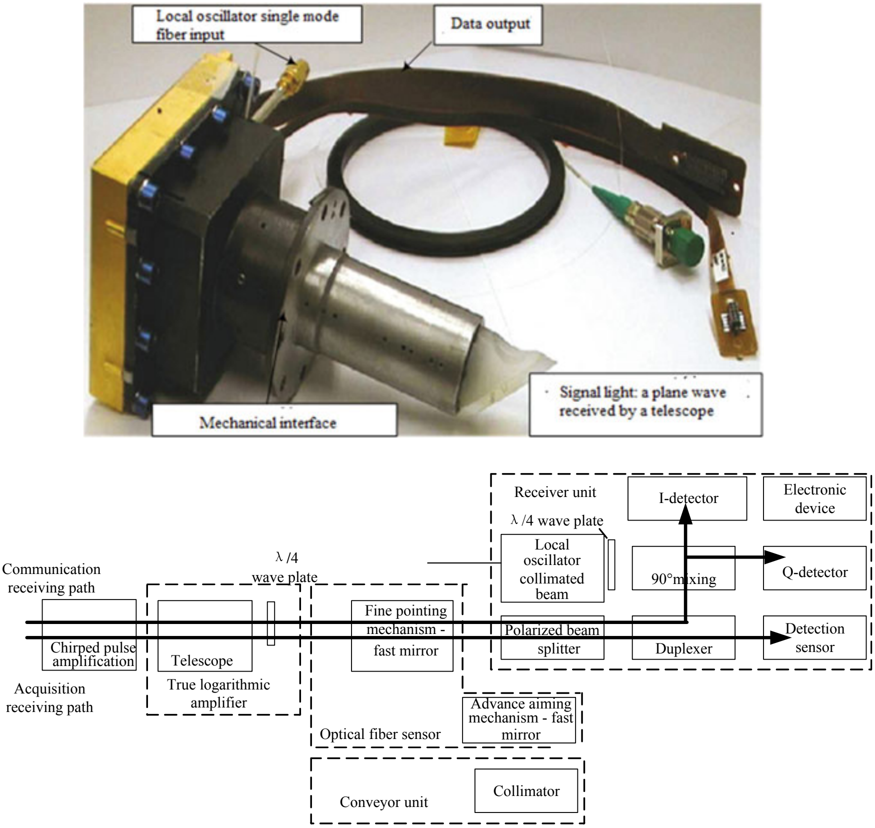

Fig. 1.3 LCT homodyne BPSK receiver [46]

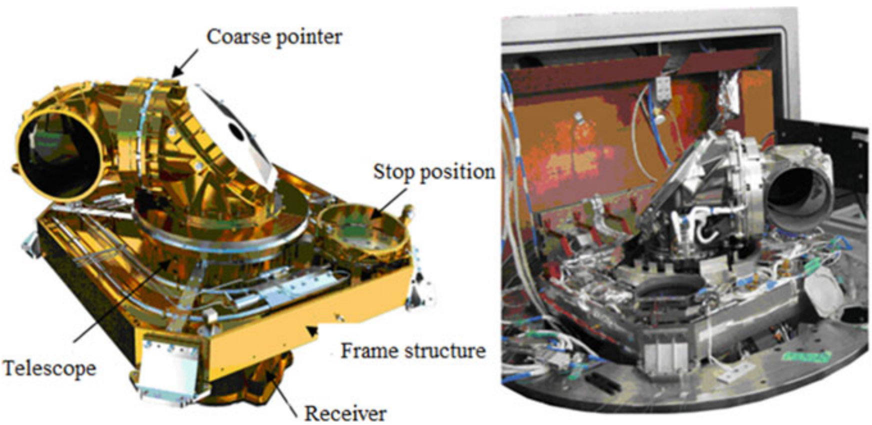

Fig. 1.4 LCT structure [48]

was 177 s. The experiment used the BPSK modulation/homodyne coherent optical detection technology [49].

(3) Japan and other countries

In 1997, the National Institute of Information and Communication Technology of Japan began to implement a development plan for the next-generation LEO system (NeLS). The objective of this plan was to realize satellite-to-ground and inter-satellite laser links. A DPSK/coherent detection system was used for this purpose. The communication data rate was 2.4 Gbit/s, and the laser wavelength was 1550 nm. The terminal demodulated the signal using a plane optical wave interferometer to recover the data stream with a detection limit of 56 photos/bit [50, 51]. The NeLS plan was originally expected to be officially put into commercial operation in 2010. Although the plan remains suspended as of now, it acts a reference for subsequent projects. In 2011, the University of Tokyo reported a digital optical heterodyne receiver suitable for intersatellite communication. It was based on BPSK modulation, with a data transmission rate of 12 Gbit/s. It may be noted that digital coherent optical detection is the core technology for next-generation intersatellite optical communication [52].

Based on various research breakthroughs-the short-range optical inter-satellite link (SROIL), intersatellite link front end, and optical cross links-of several collaborations, Contraves Space AG (a Swiss company) has designed and developed the OPTEL series laser communication terminals for commercial use to meet the requirements of various space applications [53]. The key technology used in this series is the high bit rate homodyne coherent optical communication technology. The OPTEL series meets the requirements of the miniaturization, high bit rate, and low energy consumption. These terminals use the 1064 nm laser BPSK modulation/homodyne detection. The OPTEL-25 communication laser uses a diode-pumped single-frequency single-mode tunable Nd-doped yttrium aluminum garnet laser as the main vibration amplification structure of the fiber laser amplifier. It uses emission wavelength of 1064 nm, 808 nm laser diode as the pumping source, 977 nm laser diode as the pumping source for the ytterbium-doped fiber amplifier, output optical power of 1.25 W, and laser diode as beacon laser. It has a wavelength of 808 nm, maximum output power of 7 W, and transmitting aperture of 135 mm. A variable-window charge coupled device (CCD) detector is used for acquisition and coarse tracking, and a micromechanical optical fiber scanning position detector is used for communication and fine tracking.

1.3.1.2 China

In the 1980s, the University of Electronic Science and Technology studied the heterodyne atmospheric laser communication system with a CO_2 laser as the light source. This study laid the foundation for the research on coherent optical communication systems [54]. In 2007, Wang [55] designed and simulated an optical heterodyne detection system for atmospheric laser subcarrier multiplexing. In 2007, Zhao [56] proposed a receiver scheme integrating heterodyne detection and optical power tracking, established a light-field distribution model on the detector surface, and analyzed the heterodyne efficiency of signal light and local oscillator light under the best matching and several incomplete matching. In 2008, Zhang [57] used experiments to prove that heterodyne signals can be obtained when the signal optical power in heterodyne detection is six orders of magnitude lower than the local oscillator optical power. Furthermore, they verified that the light source and spatial conditions for coherent detection were significantly higher than those for DD. In 2009, Wang [58] of the University of Electronic Science and Technology analyzed the optical coherence system based on BPSK modulation/homodyne detection, focusing on the design and implementation of the optical phase-locked loop technology. In 2010, Zhao [59] of the Changchun University of Technology studied the heterodyne asynchronous demodulation reception scheme and reported that the mixing efficiency decreases sharply with an increase in the mismatch angle when a spatial mismatch angle exists between the signal light and the local oscillator light. When the wave surface of the local oscillator Gaussian light bends, the mixing efficiency is maximized when the radius of curvature tends to infinity. In 2014, Luo [60] of the Beijing University of Posts and Telecommunications designed and built a spatial coherent optical communication experimental platform and performed indoor and outdoor spatial optical transmission experiments of 10 GBaud quadrature phase shift keying (QPSK) modulation. The indoor and outdoor distances were approximately 6 m and 600 m, respectively. Luo concluded that the BER was 10^{-6} at approximately −17.6 dBm outdoors and the indoor turbulence was weak, with its sensitivity being approximately 7 dB higher than that of outdoor.

There are two methods for coherent optical detection. In one method, the signal light and local oscillator light coherently generate differential frequency signals on a photosensitive surface. However, when part or all of the space laser communication link is in the atmosphere, atmospheric absorption or scattering causes serious attenuation of the intensity of the laser, and atmospheric turbulence causes the beam drift, light intensity flicker, angle-of-arrival fluctuation, and wavefront distortion. Consequently, the sensitivity of heterodyne detection is significantly reduced. The other method is based on coupling the space light into the optical fiber, and then making the space light coherent with the local oscillator light through a 90° mixer. However, the fiber coupling efficiency and Doppler shift in atmospheric turbulence are two main factors that affect the performance of space optical communication.

1.3.2 Coherent Optical Detection in Optical Fiber Communication

Coherent optical fiber communication technology was a research hotspot in the field of optical fiber communication in the 1980s. At that time, this technology mainly used the advantages of high coherent receiving sensitivity to increase the transmission distance of optical fiber communication. However, with the emergence of Er-doped fiber amplifiers, coherent optical communication lost favor during the 1990s and the IM/DD mode became the primary transmitting/receiving technology for optical fiber communication [61].

In 2003, Taylor was the first to demonstrate a 10-Gbit/s DPSK modulation homodyne digital coherent optical detection system [62]. The block diagram of this digital coherent receiver is depicted in Fig. 1.5. The laser linewidth of the signal light and local oscillator light generated by the system was 100 MHz. Taylor used the electrical domain equalization technology to compensate for the dispersion effect in the fiber. In 2006, a company in the United States launched an optical heterodyne detection receiver with a bandwidth of 10 Gbit/s, with the sensitivity reaching −30 dBm when the BER was 10^{-9} [63]. In 2007, the Nortel Network realized a 40-Gbit/s dual-polarization four-phase shift keying optical transmission technology [64]. The receiver in this scheme is a real-time homodyne detection system. The receiver uses a distributed feedback laser with a linewidth of 100 kHz. The signal light and local oscillator light are mixed through an asymmetric optical fiber coupler, and the IF signal is obtained on the photosensitive surface of the photoelectric detector. The signal is collected using an analog-to-digital converter (A/D), and the QPSK signal is demodulated using a digital signal processor (DSP). In 2008, the AT and NEC Laboratory collaborated for an experiment of a 640-km single-mode ordinary optical fiber transmission and coherent light detection of 8 × 114 Gbit/s polarization multiplexed 8-PSK signal with an interval of 25 GHz. At the receiving end, a 90° mixer was used to accomplish polarization and phase diversity reception, and an adjustable external cavity semiconductor laser was used as the local oscillator laser with a linewidth of 100 kHz. Automatic polarization control was achieved through electrical domain processing [65]. In 2010, Masato [66], in Japan, reported a transmission experiment of 140 Gbit/s with a transmission distance of 150 km by using polarization multiplexing and homodyne optical coherent detection. The local oscillator at the receiving end used a wavelength-adjustable local oscillator laser; the bandwidth was adjusted to 4 kHz; optical mixing was achieved using a 90° mixer; and the local oscillator phase locking was realized through the pilot optical signal and detected using a balance detector. In 2011, a successful homodyne detection experiment, with a 1550-nm, 5-Gbit/s 40-km bidirectional transmission optical network, was reported in Denmark [67]. In 2011, Alcatel-Lucent collaborated with Bell Laboratories to accomplish a 160-Gbit/s time division multiplexing QPSK coherent optical detection experiment over a transmission distance of 2400 km [68].

In 2007, Feng et al. studied digital optical coherent detection [69] and made a polarization diversity optical 90° mixer in a digital coherent receiver, as depicted in Fig. 1.5, using optical fiber devices. The difference between the four output losses was less than 0.3 dB, and the delay difference was less than 5 ps. They achieved in-phase quadrature (IQ) of optical mixer, digital dispersion compensation. The basic digital signal processing algorithm modules such as digital polarization demultiplexing and carrier phase recovery realize the 40-Gbit/s polarization multiplexed QPSK signal loop transmission of 1200 km, and the received BER is less than 10^{-3}. In 2008, Zeng [70] simulated an asynchronous demodulation coherent optical heterodyne balanced receiver in an optical fiber communication system. Their results indicate that the

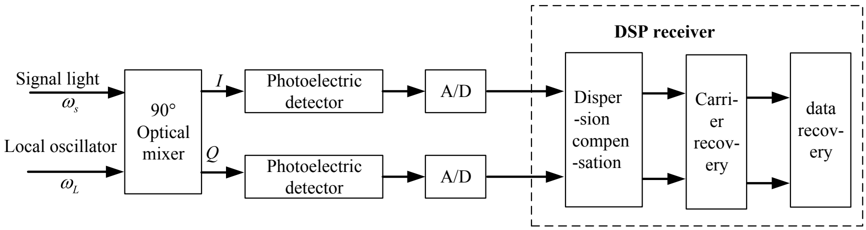

Fig. 1.5 Block diagram of digital coherent receiver [62]

quality factor Q value and receiver sensitivity of the coherent optical receiver decrease significantly with an increase in the linewidth of the light source laser. Increasing the IQ power to a certain extent can improve the sensitivity of the receiver: the higher the modulation rate, the lower the sensitivity of the receiver. In 2008, Zhu studied the heterodyne detection technology of a single-channel 2.5-Gbit/s signal-quadrature amplitude modulation and realized a 10-GHz IF signal. Zhu reported a sensitivity of -21.4 dBm at a BER of 10^{-8}. In 2011, Luo [71] studied a 40-Gbit/s coherent optical detection polarization multiplexing QPSK optical fiber communication transmission system. They used the back-propagation algorithm based on the Markov equation to achieve nonlinear compensation.

As depicted in Fig. 1.5, the digital coherent optical detection technology used in optical fiber communication systems comprises an optical 90° mixer, a balanced detector, a high-speed A/D, and a DSP processing algorithm. The optical 90° mixer and digital signal processing algorithm form its core. Digital optical coherent detection mainly includes the following digital processing algorithms: polarization control [72, 73], chromatic dispersion and polarization mode dispersion compensation [74–76], and carrier phase estimation algorithms [77].

In summary, there are many similarities and differences between the coherent optical detection system and the spatial coherent optical detection system used in optical fiber communication systems.

The similarities are as follows:

1. The coherent optical detection technology in optical fiber communication and in space is based on the principle of coherent optical detection, which uses signal light and local oscillator light to coherently generate differential frequency signals.
2. The homodyne detection requires optical phase-locked loop technology, and the heterodyne detection technology requires a narrow linewidth and high stability laser.
3. Both use multilevel digital phase shift keying (MPSK) demodulation technology or quadrature amplitude modulation and demodulation technology.

The differences are as follows:

1. The spatial coherent optical detection system suffers from the problem of beam alignment.

2. To improve the detection sensitivity of coherent optical at the receiving end, the optical fiber coherent optical detection system must control the polarization state and compensate for the dispersion and polarization mode dispersion. The spatial coherent optical detection system requires considering compensating for any interference such as wavefront distortion, random polarization change, and Doppler frequency shift caused by the atmospheric channel.

1.3.3 Free-Space Coherent Detection Communication System

1.3.3.1 Development Status Abroad

(1) United States

In the mid-1980s, the MIT-LL in collaboration with NASA, Aerospace Corporation, US Air Force, Missile Defense Agency, and JPL set up LITE using the FSK modulation mode and a modulation rate of up to 220 Mbit/s. The performance and space environment of each module of the system were tested. However, the project failed to perform the actual test and performed only a demonstration experiment on ground [78]. Figure 1.6 depicts the experimental device used in LITE.

In the late 1980s, NASA developed a new laser communication program. The objective of this program was to relay communication from the geostationary earth orbit (GEO) using an advanced communications technology satellite (ACTS) terminal laser to a ground station. ACTS laser communication experiments included DD and coherent detection experiments on ground and airborne counter terminals. Based on the experience of the LITE program, MIT-LL developed an APT system, an optical platform, and a heterodyne receiver. In the early 1990s, the JPL performed research on the inter-satellite coherent optical communication system and realized communication using a PSK modulation communication experiment demonstration of an inter-satellite coherent detection system with a code rate of 100 Mbit/s [79].

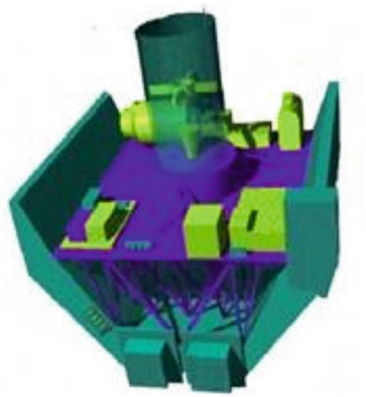

Fig. 1.6 Experimental device used in LITE [78]

Table 1.1 Parameters for laser communication system

Parameter	Value
Communication wavelength	0.8 μm
Detector response	0.517
Receiver optical efficiency	0.8
Transmitter optical efficiency	0.8
Bit error rate	10^{-6}
Inter-satellite transmission distance	3000 km
Transmission speed	2 Gbit/s

However, JPL shifted its focus to the IM/DD communication system until the end of the twentieth century. To improve the channel capacity of inter-satellite communication, the JPL laboratory shifted its research focus back to the coherent optical communication system. During this period [80], the LL developed a communication system with a communication rate of up to 1 Gbit/s. Simultaneously, the convolutional coding and decoding technology of the space channel was also being studied in depth [81]. In 1999 [82], for the low earth orbit (LEO) under the vibration condition of the inter-satellite platform, LL analyzed the SNR, BER, and other performance parameters of the coherent optical communication system under various modulation modes. The parameters of the laser communication system used in the test are listed in Table 1.1.

In 2008, NASA launched the Deep Space Optical Communication (DSOC) program, including Lunar Laser Communication Demonstration (LLCD). Its purpose was to verify the feasibility of laser communication between the Earth and Moon using small and light communication terminals. A schematic of this system is depicted in Fig. 1.7. The Laser Communication Relay Demonstration (LCRD) project can be considered as an extension of the LLCD program. The main objective of the LCRD program is to use a GEO satellite as a relay to realize continuous communication between two on-ground terminals. As depicted in Fig. 1.8, the LCRD program is an important step for NASA to improve its space laser communication capability.

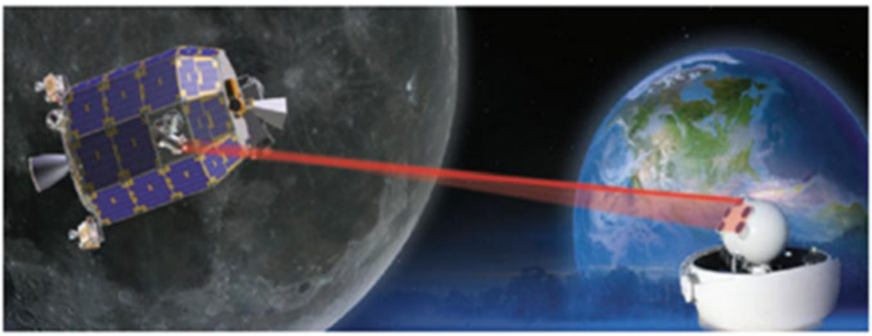

Fig. 1.7 Schematic of LLCD [86]

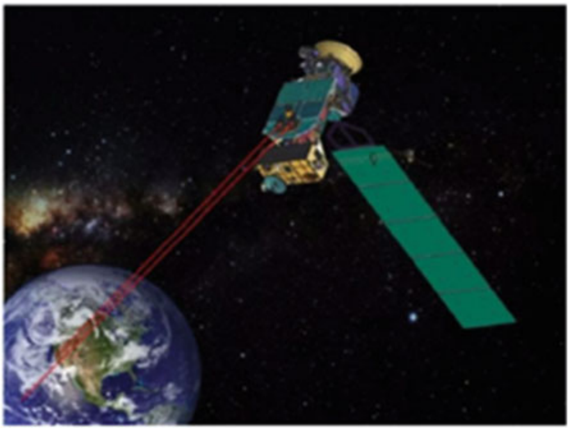

Fig. 1.8 Schematic of LCRD plan communication [86]

In 2013, as a prototype of the LCRD program, NASA announced that it had successfully established a duplex communication link between the Lunar Atmosphere and Dust Environment Explorer operating in the lunar orbit and the on-ground terminal for the first time. This project used pulse PPM, with the uplink and downlink communication rates being 20 Mbit/s and 622 Mbit/s, respectively [19, 83–85]. The DSOC program is part of the space exploration mission of NASA. In 2017, DSOC was expected to return data from Mars at a rate higher than 250 Mbit/s, with a communication distance of approximately 630 million kilometer, a terminal mass of 28 kg, and a power of 76 W. The system will continue to carry aircraft for deep space laser communication technology verification in 2023 [86]. Figure 1.9 depicts the schematic of the planned DSOC link.

In the mid-1980s, the MIT-LL used the semiconductor laser and heterodyne detection technology to successfully develop a coherent optical communication prototype [15, 38, 87–89]. This prototype was used for the LITE. The prototype comprised a

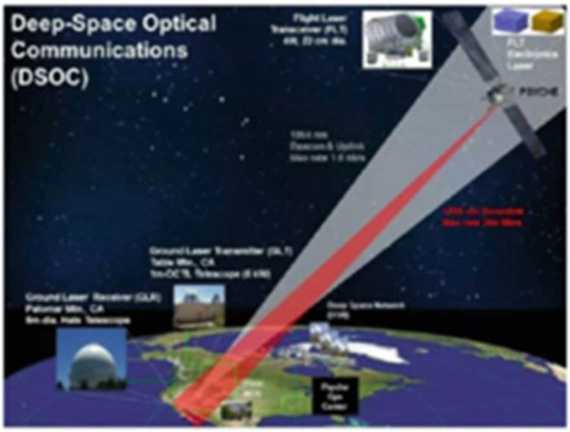

Fig. 1.9 Schematic of the planned DSOC link [86]

30-mW semiconductor laser transmitter, an Er-doped fiber amplifier with a wavelength of 1550 nm, and a telescope system of 200 mm diameter. It employed DPSK, with the modulation rate reaching up to 1 Gbit/s. The uplink communication rate was 220 Mbit/s, and the receiver adopted the heterodyne detection technology. However, no flight experiments were performed as part of this project.

In 2004, a 64-PPM coherent optical communication experiment was successfully performed by JPL. Both the signal light and the local oscillator light used a laser of 1064 nm wavelength. The output power of the signal laser was 2–3 mW, and the maximum output power of the local oscillator laser was 50 mW. There was a certain difference between the ground frequencies of the two lasers. The optical heterodyne detection method was used at the receiving end. A least square algorithm was used to track the differential frequency signal. The mixer output the frequency of a differential frequency signal of 6 MHz [90].

(2) Europe

Europe has also made some breakthroughs in the field of free-space coherent optical communication [91–99]. Some major research institutions in Europe are the ESA, DLR, and French military. ESA began research work in the field of space optical communication in 1977. In 1985, it started SILEX [100]. As part of SILEX, ESA launched Artemis into the GEO on November 20, 2001. For the first time, laser inter-satellite communication was realized between a satellite and the French SPOT-4 satellite in LEO. The communication setup is depicted in Fig. 1.10. The communication distance in this experiment was 45,000 km, and the BER was less than 10^{-6} [101]. The preferred communication scheme for SILEX was the homodyne coherent detection system with a communication wavelength of 1064 nm. Finally, the advanced DD scheme was used because the technical specifications of the lasers available at that time did not meet the requirements of the experiment.

Since 1989, ESA has performed in-depth research on coherent optical communication systems and other key technologies based on YAG solid-state lasers as part of SILEX. In 1996, the SROIL plan was officially launched in Switzerland. The plan is

Fig. 1.10 Schematic of inter-satellite communication between GEO and LEO in SILEX [91]