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Introduction

1.1 Big Data Era

Information has long been regarded as an important resource, and with the continuous development of information technology, information protection, mining, and data storage have become particularly important. The year 2012 was declared as the Big Data Meta Year with the sudden explosion in the amount of global data generated and the advent of the big data era has forced us to prioritize data storage. According to the research results of International Data Corporation (IDC), the total amount of data generated worldwide in 2010 was 1.2 ZB (1 ZB = 10^3 EB = 10^6 PB = 10^9 TB), the data volume in 2013 was 4 ZB, and that in 2018 was 33 ZB. The latest forecast of IDC predicts that by 2025, the total global data will exceed 175 ZB.

Today's data storage technology is still dominated by magnetic storage devices, such as hard disk storage and magnetic tape storage. Although this technology has matured, its data storage capacity has only increased by about 20% each year, which is far from keeping up with the current rate of data growth. Moreover, its limitation of two-dimensional storage still persists. For further increasing the magnetic storage density, the size of the recording magnetic particles needs to be continuously reduced. However, when the magnetic particles are small enough, they are affected by the superparamagnetic effect, making it difficult for the recording particles to maintain magnetic stability even at normal temperatures. The traditional magnetic storage density has approached its theoretical limits. In practice, to ensure data redundancy, three hard disks are generally required to back up one copy of the data simultaneously, and the data in each hard disk need to be transferred to a new hard discovery four to five years; otherwise, the information will likely be lost forever. Professionally stored tape storage also needs to be transferred every 10 years or so to avoid data loss. Therefore, companies with large data centers, such as Google, require a large server scale, and the annual cost of data transfer is huge, accounting for about one-third of the total cost of data storage. Additionally, during magnetic data writing and reading, the driver radiates a large amount of heat, and an exorbitant amount of power is consumed to cool the server. Accordingly, the power cost also accounts for about one-third of the total cost. Therefore, the data

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storage cost of the magnetic storage technology is in sync with the amount of data growth, and both are exploding, and as a result, the pressure on magnetic storage technology is increasing.

Optical storage is another important data storage technology. At present, the most common optical storage technology is optical disks. If light with a wavelength of λ is used as a light source for data storage, its theoretical storage area density is nearly $1/\lambda^2$. From the earliest compact disc (CDs) to video compact (VCDs), digital video discs (DVDs), and now Blu-ray discs, the density of disc storage is also increasing. However, the optical discs are still two-dimensional surface storage devices based on bit storage (although some optical discs can achieve multilayer storage, but the number of layers is limited); each recording bit represents only a 0 or 1 state, and its storage density is affected by the record. Moreover, although a smaller-sized recorded bit results in a greater data storage density, the size of the bit is limited. Each recording bit is etched by converging the energy of an incident laser light. To obtain a smaller recording bit size, the numerical aperture of the recording objective lens must be increased, and a shorter wavelength laser should be used as the recording light source. At present, the numerical aperture of the data recording objective lens in the most advanced Blu-ray disc has reached about 0.85, and the laser wavelength has also been shortened to 405 nm. Now a single-sided single-layer Blu-ray disc can have a storage capacity of 25 GB, while a double-sided four-layer Blu-ray disc can exhibit a storage capacity of 200 GB. Therefore, the famous data company Facebook started to build a Blu-ray disc-based database with a total capacity of 1000 PB in 2014. Its data access energy consumption is 80% lower than that of the magnetic hard disks. The Blu-ray disc can be stored for 30–50 years, and the cost of data transfer is greatly reduced. This Facebook storage system uses a very cost-effective redundant backup method, which can achieve a data backup redundancy with a coefficient lower than two to ensure data security and not cause performance degradation due to scale expansion.

Despite the rapid development in the optical disc storage, it is still a two-dimensional surface bitwise storage device. To further increase the storage density, the numerical aperture of the recording objective lens needs to be increased further, and the recording light wavelength should be further shortened. However, the theoretical aperture of the objective lens in air is less than or equal to one. To develop a numerical aperture greater than one, only the method of immersion can be used. The application environment for such a storage device is limited, and the implementation cost will be exorbitant. With the increase in the numerical aperture, the thickness of the protective layer on the surface of the optical disc needs to be reduced excessively, which in turn will eventually result in the loss of the protective effect. The wavelength of the recording light is currently close to the range of invisible light, and the cost of using violet or extreme ultraviolet lasers is also very high. Therefore, further increasing the storage density of the traditional optical disc is an arduous task. According to the current 200 GB data storage capacity of a Blu-ray disc, by 2020, the number of optical discs required to store the global data is expected to exceed 500 billion, and their combined thickness will exceed the distance between the Earth and the Moon. Therefore, traditional optical disc storage is unable to meet the growing requirements of big data storage, and the discovery and development of new technologies is imminent.

Optical holographic data storage is an optical storage technology that follows the principle of holography for data storage and reproduction. The most noticeable feature of the optical holographic storage is that it breaks through the two-dimensional surface storage mode of the traditional optical disc storage and adopts the three-dimensional volume storage mode. Further, its theoretical storage density is $1/\lambda^3$. By increasing the storage density by one dimension, the existing optical storage density can be increased by several orders of magnitude.

The optical holographic data storage technology records the amplitude and phase information of objects in the form of holograms in holographic materials. As shown in Figure 1.1, during the recording process, the light passes through a spatial light modulator (a two-dimensional optical element that can display the two-dimensional pattern that you want to upload), and the information carrying the two-dimensional pattern is called the object light. This object light interferes with another beam of the known light field (reference light) in the holographic material to form a complex light field distribution. The holographic material responds to the light fields of different intensities accordingly, resulting in changes in the material and finally forming some kind of stable structure, namely a hologram. This hologram records the object light information in the holographic material. During the reading process, only the hologram in the material needs to be irradiated with the same reference beam in the same state as that used during the recording process, and the light energy is coupled to the object light through the coupling effect of the holographic structure on the reference light. In the field, diffraction of light occurs, and the diffracted light is also

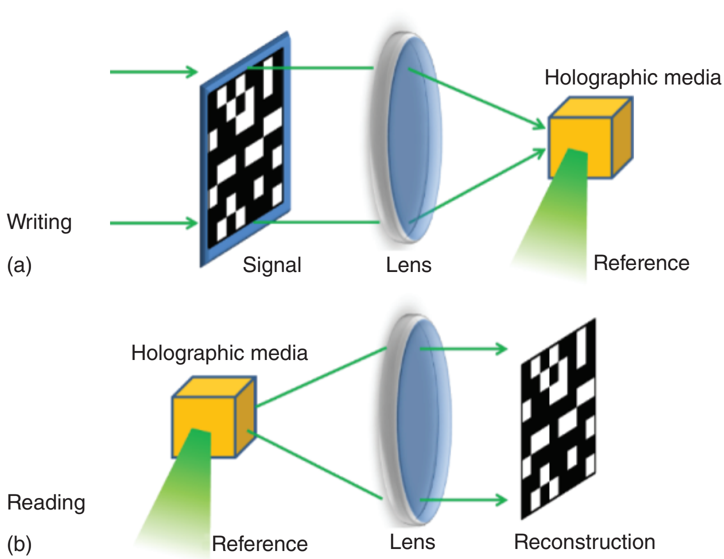

Figure 1.1 Schematic illustration of holographic data storage: (a) writing process and (b) reading process. Source: Xiao Lin.

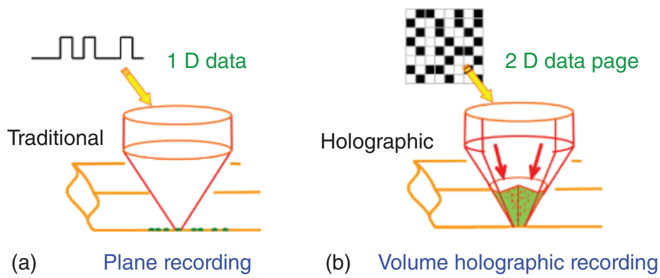

Figure 1.2 Comparison between traditional data storage and holographic data storage. Source: Xiao Lin.

called as the reconstructed light, which is actually consistent with the distribution of the original light field, enabling readout of the object light information.

Optical holographic storage can get rid of the one-dimensional data storage limitation of bit storage. Each recording position represents a two-dimensional coding pattern, as shown in Figure 1.2. Further, because the holographic storage has the characteristics of reusable recording, the recording bit and its area can be superimposed on each other, which leads to a large recording holographic storage density of the order of TB/in^2. Simultaneously, the data reading conversion rate can also reach the order of 10 GB/s, because each recording position readout is a two-dimensional encoding pattern. Additionally, the performance of the materials used for holographic storage is significantly improved. The materials, viz. the early photorefractive crystals to the current photopolymers, are easy to prepare and cost effective, and the life of data can be as long as 50 years. Therefore, holographic storage is considered to be the most promising and a key optical storage technology in the era of big data.

1.2 History of Holographic Data Storage

As early as 1948, Dennis Gabor proposed the concept of holography, involving only the method of wavefront reconstruction. This method did not link holography with data storage, but used holographic technology for the magnification of X-ray images [1, 2]. The primary drawback of this method was the unavailability of a good coherent light source; thus, conjugate images appeared in the coaxial wavefront reconstruction systems. Previously, Gabor [3] and other scientists, such as Kirkpatrick and Hussein El-Sum [4, 5], Baez [6], Gordon Rogers [7], and others, attempted to solve this problem, albeit with poor results. With the discovery of lasers in the early 1960s, a good coherent light source was discovered, and holography entered a stage of rapid development. The recording and reconstruction of clear images became a reality, and because of the excellent coherence of the light source, E.N. Leith and J. Upatnieks proposed a reference light off-axis holographic recording system [8, 9] that overcame the drawback of Gabor hologram, in which the reconstructed conjugate images are aliased in one place. In 1963, van Heerden formally proposed the concept of holographic data storage [10]. He attributed holographic data storage to three-dimensional solid-state optical information storage and estimated that its storage density limit was V/λ^3 (V is the volume of the recording material, and λ is the wavelength of the recording light). Subsequently, van Heerden also discussed the possibility of multiplexing with the reference light angle and the wavelength in holographic data storage. Leith et al. also proposed and validated the technique of recording disk rotation multiplexing in the early developmental stages of holographic data storage [11]. At this time, the holographic technology had been quite embryonic, but owing to the lack of effective recording materials, most of the research on holographic data storage stayed was confined only to the discussion of methods. In 1966, Ashkin et al. of Bell Labs unexpectedly discovered the photorefractive effect while performing frequency doubling experiments with lithium niobate crystals [12]. These crystals have been extensively studied as photorefractive crystals and applied to holographic data storage [13–16], making three-dimensional volume holographic data storage once again a research hotspot. Due to the development of materials, a series of verification experiments on holographic data storage have been published, and more reuse technologies have been studied.

In 1973, researchers at the American RCA Corporation designed and verified a holographic memory that could read and write 10^6 bit data [17]. In 1973, the Japanese company NEC proposed a holographic data storage system (HDSS) with read-only holographic encoder disks, but stored in two dimensions, on a 128 mm × 128 mm surface, with a storage capacity of 2.5×10^5 bits at a resolution of 1 line/mm [18]. In 1974, the American 3M company, Strehlow, and others designed a 7 MB holographic memory [19]. In 1973, Huignard and coworkers first demonstrated the law of angular multiplexing, and proposed that recording 100 holograms in one location can reach a total storage capacity of 10^{11} bits [20], and then experimentally demonstrated the angular multiplexing scheme in iron-doped niobium. Ten holograms were reused in the lithium acid crystals [21]. In 1975, Amodei and Staebler of RCA Corporation, for the first time, recorded 500 holograms in 1 cm^3 of iron-doped lithium niobate crystals [14]. In 1978, Andrei Mikaeliane described a rewritable holographic storage system based on iron-doped lithium niobate crystals [22]. In 1976, Hitachi, Japan reported a holographic video disc, which stored a 30 minutes color video in a disc of 300 mm diameter; a total of 54 000 holograms were recorded on the disc [23]. In 1980, Kubota et al. of NEC Company developed a one-dimensional Fourier transform hologram optical disc for recording audio information; this disc could achieve a data conversion rate of 256 Mb/s [24].

Although there was a rapid development of the holographic storage theory in the 1970s, it was still limited by the backward effects of recording materials, modulators, and detectors at that time, and a satisfactory storage density could not be achieved in the early works.

Until the early 1990s, with the development of recording materials, spatial light modulators, charge-coupled device detectors, and other key materials and devices, the storage density of the HDSSs could be greatly increased, and the optical holographic data storage entered a period of accelerated development. Overall, the materials used and the reuse theory have been comprehensively improved.

In 1991, Mok et al. stored 500 holograms of military vehicle shapes in 1 cm^3 of iron-doped lithium niobate crystals [25], and only two years later, F.H. Mok achieved the storage of 5000 images in 1 cm^3 of iron-doped lithium niobate crystals, indicating a 10-times-increased storage capacity [26]. In 1994, Hesselink and coworkers from Stanford University showed a full digital holographic storage system that converts images and videos into multiple data pages, and the bit error rate can reach 10^{-6} [27]. In 1994, IBM and Stanford University and other seven companies and university research groups formed a joint agency under the partial sponsorship of the United States Defense Advanced Research Projects Agency (DARPA). They expect to develop a HDSS with 10^{13} bit storage capacity and 1 Gb/s data conversion rate within five years. The material test system is provided by IBM. This system can not only store and reconstruct holograms of large data pages, but also perform bit error rate analysis on the reconstruction results [28]. The world's first complete HDSS was jointly established by Stanford University, Siros, IBM [29] and Rockwell, Thousand Oaks [30], and other companies. Researchers at Caltech and Lucent also completed similar system demonstrations [31].

In 1997, CIT's Allen Pu and D. Psaltis used a spherical reference light to obtain a volume holographic storage with an area density of 100 bits/μm^2 on a 1-mm-thick iron-doped lithium niobate crystal via shift multiplexing [32]. In 1998, Bell Labs' K. Curtis and coworkers used a similar multiplexing technology to store the areal density in iron-doped lithium niobate crystals at a rate exceeding 350 bits/μm^2 [33].

In terms of recording materials, in addition to photorefractive materials that have been studied since the 1970s [21, 22, 34], in 1994, the United States DuPont company developed a radical polymerizable photopolymer [35]. Pu et al. conducted an in-depth study on the holographic storage characteristics of this photopolymer material product, and performed holographic storage experiments using cyclic and angular multiplexing techniques. Subsequently, Allen Pu and Demetri Psaltis converted this material into a holographic disc, and multiplexed and stored 32 holograms in each flat cell area, and obtained a storage area density of 10^9 bit/cm^2 [36]. Even though the sensitivity of the photopolymers is one to two orders of magnitude higher than that of the photorefractive crystals, the problem of material shrinkage is also severe. Therefore, the dynamic response range and shrinkage of the material must be balanced, as explained in detail by T. Bieringer [37]. The researchers at the Polaroid and Bell Labs took different approaches to materials research. Polaroid used experimental cationic ring-opening materials for the experimental verification [38, 39], whereas Bell Labs and Lucent used free radiating media [33]. Later, Stanford University and Aprilis Company (continued to develop after Polaroid) used a cationic open-loop material to record 250 GB of information on a DVD-sized disc with a data transmission rate of 10 Gb/s. In 2003, Waldman et al. used a photopolymer material, HMD-050-G-C-400 manufactured by Aprilis Company, with a thickness of 400 μm to achieve a holographic storage area density greater than 100 bits/μm^2 [40].

In 2002, Suzuki et al. first doped TiO_2 nanoparticles into methacrylate photopolymer films and found that the volume shrinkage of the materials during the holographic exposure was suppressed [41]. Since then, the method of nanoparticle doping to modify materials has been the focus of many studies. In 2008, Goldenberg et al. studied the doping of metal nanoparticles and modified gold nanoparticles. It has been proven that nanoparticles, when mixed with carboxyl functional acrylate monomers, can affect the structure of the material, inhibit shrinkage, and increase the stability of the material [42]. In 2010, Koji Omura and Yasuo Tomita studied the properties of ZrO_2 nanoparticle polymer composite films under a 404 nm laser and proposed that the shrinkage of the material was suppressed owing to the increase in the gel point [43]. In 2011, Hata et al. introduced thioolefin monomers into silica nanoparticle polymer composites, investigated their photopolymerization kinetics and volume holographic recording characteristics, and found that the material shrinkage and thermal stability were greatly improved [44]. In 2014, the research group of Chengming Yue and others proposed a holographic kinetic model to represent the kinetics of the hybrid grating in bulk polymer doped with photopolymers of gold nanoparticles quantitatively and described the polymerization of the gold nanoparticles. Further, because of the multicomponent diffusion behaviors, a mixed circular polarization-angle volume holographic multiplexing recording was then achieved in the prepared gold nanoparticle-doped phenanthrenequinone/polymethyl methacrylate (PQ/PMMA) photopolymer [45, 46]. In 2016, Tomita et al. introduced hyperbranched polymers, with ultrahigh refractive indices, as organic nanoparticles, and prepared nanoparticle–polymer composite holographic gratings, achieving a significant increase in the refractive index modulation and diffraction efficiency (close to 100%) at a wavelength of 532 nm [47]. In 2018, Liu et al. prepared a new material by dispersing silver nanopillars in a photopolymerizable mixture, and demonstrated the grating of this nanopillar-doped polymer composite under the exposure of an ultrafast nanosecond laser. To study the formation, they analyzed the causes of reciprocity failure and the improvement in the polymer holographic properties by the doped silver nanoparticles; the diffraction efficiency of the optimized polymer was as high as 51.4% [48].

In addition to incorporating nanoparticles into photopolymers, many optimization attempts have been made on photopolymer systems. In 2012, Ortuño et al. developed a new dry photopolymer called bio-photoelectronics, which has a low toxicity. This photopolymer was developed with the aim to counter the toxicity and poor environment compatibility exhibited by most of the photopolymer components. Additionally, its high thickness makes it ideal for holographic data storage applications [49]. Subsequently, in 2013, Ortuño et al. also proposed a new chain transfer agent 4,4′azo-bis-(4-cyanovaleric acid) (ACPA) with a polyvinyl alcohol (PVA)/acrylamide (AA) photopolymer, whose performance can be improved by the initiator ACPA [50]. In 2016, Cody et al. studied a novel composition of a low-toxic water-soluble holographic photopolymer and obtained a bright reflection grating with a recording diffraction efficiency of up to 50% [51]. Later, the research team of Fan Fenglan and others proposed to modify the material components via chemical methods to prepare PQ-supported dimonomer photopolymer materials, which improved the solubility of the photoinitiator in the photopolymer, thereby achieving material optics, as an improvement of features [52]. In 2018, Liu et al. proposed a new type of photosensitizer-doped photopolymer and proposed an optimized three-step thermal polymerization preparation method. The thermal initiators with different concentrations and the photoinitiator characteristics of the photopolymers [53] were studied in detail.

By doping nanoparticles and optimizing the polymerization methods, the current recording materials have been significantly improved to better meet the needs of optical holographic data storage. The next step is to steadily increase the diffraction efficiency while further enhancing the material stability and corresponding rate as well as improving the data storage density.

The supreme advantage of volume holographic storage is its ability to use a variety of multiplexing technologies to increase the storage density. The multiplexing technology of volume holographic storage was well developed in the 1990s [27, 54, 55].

Angular multiplexing is one of the more widely used off-axis HDSSs. It uses plane waves of the same wavelength as the reference light and forms multiple holograms at different angles of incidence in the same area. With a 1 cm thick lithium niobate crystal as the recording material and a 500 nm wavelength laser as the recording and reading light, the angular selectivity is approximately 50 μrad. Thus, 10 000 holograms can be recorded within 30° of the reference light angle multiplex.

Wavelength multiplexing uses plane waves of different wavelengths as the reference light, which is incident at the same angle, to form multiple holograms [56]. This multiplexing technique is usually more suitable for inorganic photorefractive crystal materials, as organic photopolymer materials have different sensitivity to different wavelengths and do not exhibit a simple linear response.

Phase code multiplexing uses phase coding of the reference light of the multiplexed hologram to prevent crosstalk with each other to the greatest extent. In particular, the orthogonal phase multiplexing of the reference light can effectively suppress the cross-page crosstalk. Moreover, the introduction of phase modulation improves the signal-to-noise ratio [57, 58].

Displacement multiplexing involves the separation and multiplexing of different holograms in space; that is, after recording a hologram somewhere, a certain distance is moved, and then the next hologram is recorded. The sharp drop in the diffraction efficiency after the Bragg mismatch is used so that one hologram does not affect the other when it is read. The displacement multiplexing technology is mostly used for organic photopolymer materials, which can be well matched with optical disc-type HDSSs, and is highly compatible. Moreover, the smaller the shift distance, the higher the multiplexing number [59–61]. The aforementioned methods are the main multiplexing methods used for optical holographic storage, while some systems use random phase multiplexing and other hybrid multiplexing methods [62–64].

Optical holographic data storage technology moved out of the laboratory after the year 2000 and became commercialized. In 2000, Stanford University developed the HDSS [59] with a storage area density of 70 bits/μm^2, and a continuously improved data transmission rate (up to 10 Gb/s) [65]. The Aprilis Company in the United States of America intensively researched materials for such a storage device. In 2002, it developed a photopolymer disc with a storage capacity of 200 GB, while in 2003, it launched a Vulcan^{TM} drive hearing device prototype, but the transmission rate was only 75 Mb/s [40]. In 2005, Japanese Optware proposed a coaxial holographic data storage scheme [66–69], in which green light, which is sensitive to the recording material, is used as the recording read light, and red light, which is insensitive to the material, is used as the address light [70]. The optical path for reading and writing was improved, and a servo system was introduced to generate the entire holographic data. The storage system is more compatible with the widely accepted CD-ROM systems. The system stored 100 GB of data on a similar-sized polymer disc. In 2006, the American company InPhase, separated from Bell Labs, launched Tapestry™ HDS-300R, which was the first commercial HDSS [71, 72]. It matched with three types of photopolymer holographic versatile disc (HVD) [73, 74] with different capacities and different data transmission rates. The device featured a storage capacity of 300 GB, transmission rate of 20 MB/s, capacity of 800 GB, transmission rate of 80 MB/s, capacity of 1.6 TB, and transfer rate of 120 MB/s. For storage, an off-axis original "polytopic" method was adopted [75]. Since then, a parallel market exploration pattern has been formed for the coaxial HDSS represented by Optware and the off-axis HDSS represented by InPhase.

However, the research on optical holographic storage encountered a low tide after the successive collapse of both InPhase and Optware, further indicating that the technology at that time was not mature enough, especially in terms of materials. Although photorefractive crystals have the characteristics of recording and erasing, the data cannot be recorded and stored for a long time. Moreover, the problem of shrinkage and low efficiency of organic photopolymers need to be solved as well, and the storage method is still based on the amplitude and does not fully utilize the advantages of holographic storage. Another critical issue was that the data storage requirements at that time were not very large, and mature technologies, such as hard disks, could cover the storage requirements of that time.

After 2012, the era of big data arrived, and the market for data storage grew drastically. Additionally, the synthesis of organic photopolymer materials has progressed considerably in recent years. In later years, Tan Xiaodi's team proposed and demonstrated a phase-type holographic data storage method [76–79], which is fast becoming a research hotspot because of its high storage capacity and higher signal-to-noise ratio.

1.3 Present Problems

1.3.1 Recording Medium

The recording medium may be the most important factor. In the past, it was thought that photorefractive crystals were the main materials for holographic data storage recording, because a large change in the refractive index could be obtained with a weakly intense light. However, the photorefractive crystal exhibits a severely deteriorated reproduction, indicating that the reading light makes the recording hologram gradually disappear. Therefore, although the recording speed of the photorefractive crystal is very fast, the data storage life is short. In addition, the photorefractive crystal is not suitable for a rotating disk structure, and thus impedes its application. In recent years, the research on holographic materials has gradually shifted to photopolymers, whose refractive indices change due to irreversible chemical changes. Therefore, once the holographic structure is formed using such a material, its structural stability can be maintained for a long time, and it is less affected by the reading light. However, the photopolymers are characterized by a low refractive-index modulation as well as a low photosensitivity, which result in a long recording time. Additionally, the volume of the photopolymer material shrinks after light exposure, which in turn changes the recorded diffraction grating pitch, resulting in a significant deviation from the Bragg condition. Consequently, the reading light fails to reconstruct the original information correctly. Although the shrinkage can be compensated by adjusting the wavelength of the reading light and the angle of the beam incident on the material, this compensation is limited for more complex structures. In general, a material shrinkage below 0.5% is acceptable, and the higher the refractive index modulation of the photopolymer material, the higher the shrinkage rate. Therefore, disentangling this contradictory behavior is a major challenge for future of materials research.

1.3.2 Multiplexing Diffraction Efficiency

Theoretically, multiple multiplexed recording is expected to reduce the diffraction efficiency of holographic data storage as the diffraction efficiency is inversely proportional to the square of the number of multiplex recordings. A reduction in the diffraction efficiency leads to a reduction in the intensity of the light reaching the photodetector, and even a reduction in the signal-to-noise ratio. Because the intensity of the reading light is limited, the required diffraction efficiency also has a lower limit, and consequently, the number of multiplexing has an upper limit.

1.3.3 Media Duplication

Another problem with multiplexing holograms is media duplication. Flat optical storage devices, such as CDs, can be copied in large quantities at high speed through injection molding. For multiple recording media, sequential writing is inevitable, and thus, a very high writing speed is required for holographic recording.

1.3.4 Pixel Matching

Pixel matching arises while reading data. A photodetector pixel matching of 1 : 1 is required for ideally reproducing a two-dimensional data page. However, realizing this condition in actual optical systems is difficult because of aberrations. Theoretically, according to the sampling theorem, if the pixel pitch of the photodetector is smaller than that of the reproduced image, then the signal can be reproduced by image processing even if the pixels are not completely matched. However, this approach is anticipated to increase the amount of calculation. Thus, the situation of the optimal pixel matching is determined by the performance of the optical system and the computer.

1.3.5 High-Speed Reading

Even though the reading speed of light is sufficiently fast enough, the data reading speed of the actual system depends only on the refresh speed of the connected electrical devices, such as spatial light modulators and photodetectors. Currently, a digital micromirror device (DMD) is the only spatial light modulator that can achieve high-speed modulation. A DMD can reach a refresh rate above 20 kHz, but it can only modulate the amplitude. To modulate information such as phase, usually liquid crystal on silicon (LCOS) is used as the spatial light modulator, whose refresh rate can reach only up to 180 Hz; this rate is exceedingly below the speed required to match the amplitude. In addition, high-speed photodetectors have been extensively developed, exhibiting a data throughput of 128 Gb/s. Nevertheless, it is necessary to further reduce the volume and cost of the high-speed cameras. In addition, a camera with a higher refresh rate usually requires a larger luminous flux to ensure sufficient illumination, enforcing higher requirements on the diffraction efficiency of the material and the laser power.

In general, fulfilling the recording material requirements is still the last hurdle in the direction of efficient big data storage. To mitigate the material-related deficiencies, an amalgamation of materials research and optics is indispensable. Optics expert should focus on improving the optical storage systems and provide clear guidelines, which will aid the material specialists engaged in holographic data storage research in realizing practical applications of this technology.

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