Collinear holographic data storage technologies

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In the era of information explosion, the demand of data storage is increased dramatically. Holographic data storage technology is one of the most promising next-generation data storage technologies due to its high storage density, fast data transfer rate, long data life time and less energy consumption. Collinear holographic data storage technology is the typical solution of the holographic data storage technology which owns a more compact, compatible and practical system. This paper gives a brief review of holographic data storage, introduces collinear holographic data storage technology and discusses phase modulation technology being used in the holographic data storage system to achieve higher storage density and higher data transfer rate.

Keywords: holographic data storage; collinear holography; high density; phase modulation

Introduction

With the development of information technology, the amount of data is increasing in the exploding way. International Data Corporation (IDC) forecasted that the global datasphere will grow to 163 ZB (1 ZB=10^9 TB) by 2025[1]. That is ten times the 16.1 ZB of data generated in 2016. The pressure of data storage is increasing sharply. Traditional huge data storage ways are mainly hard disc, tapes and optical disc which will be difficult to cover the demand of data growth in several years. Since cold data (data long time without use) occupies majority, the demand of data long time storage becomes more important. Traditional hard disc storage consumes huge electricity to cooling data base. The cost of electricity has been over 50% of total cost of data storage. Optical storage has the advantage of saving data for a long time due to its preserving data almost without electricity. Collinear holographic data storage technology presented mainly in the following content is one of the optical storage technolo-

gies, which also has this advantage.

Since holography was proposed by Dennis Gabor in 1948[2] and laser was invented in 1960s, holographic applications were paid attention to widely. One of its applications is the holographic data storage, an optical storage technology. The concept of holographic data storage was proposed by Van Heerden in 1963[3]. In the writing process, the data to be recorded are encoded into 2-dimensional data pattern, called 2-D signal page data. A laser beam is modulated by the signal page data, called signal beam. The signal beam interferes with another laser beam called reference beam. The interference pattern is recorded in the holographic media, as shown in Fig. 1(a). In the reading process, only the reference beam is employed to illuminate the holographic media to reconstruct 2-D page data image as shown in Fig. 1(b). After decoding the reconstructed 2-D page data image, the user data will be obtained.

There are three main characteristics in the holographic data storage including volume holographic recording,

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multiplexing recording and 2-D signal page data transfer. Compared with traditional optical data storage technologies, shown in Fig. 2, the volume holographic recording can increase the storage density, multiplexing recording can increase the storage capacity and 2-D signal page can increase the data transfer rate.
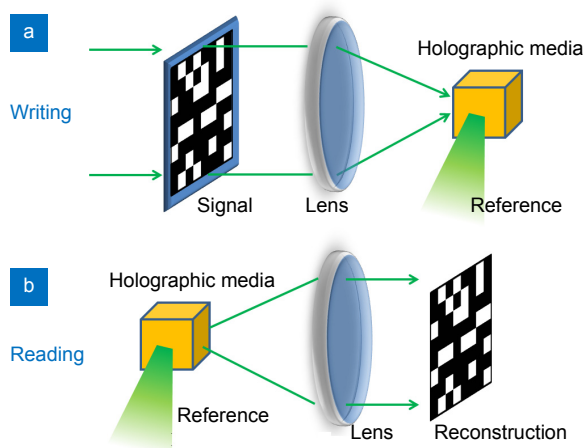
Fig. 1 | Schematic illustration of holographic data storage. (**a**) Writing process. (**b**) Reading process.
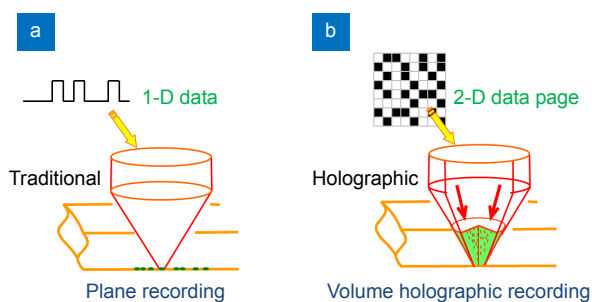
**Fig. 2 | Comparison between traditional data storage and holographic data storage.**

Higher storage density and faster data transfer rate are exactly the demand of data storage nowadays in the era of information explosion. In the past, though the demand of data storage was not huge, holographic data storage was still attractive enough. In the 1970s, some companies such as RCA[4–5], NEC[6], Hitachi[7] and 3M[8] published some early verification experiments and systems. However, experimental results were limited by the backward parameters of recording materials, modulators and detectors. With the development of recording materials and key devices especially spatial light modulator (SLM), holographic data storage technology was developed very quickly in the 1990s. In 1991, F. H. Mok et al. stored 500 holograms of military vehicles in a 1 cubic centimeter lithium niobate

crystal[9]. Two years later, they realized the experiment of storing 5000 images in 1 cubic centimeter lithium niobate crystal, and the storage capacity was increased by 10 times[10]. In 1994, Hesselink et al. of Stanford University demonstrated a full digital holographic storage system with a bit error rate of 10^{-6} [11]. In 1994, under the partial sponsorship of the Defense Advanced Research Projects Agency (DARPA), seven companies, such as IBM, Stanford University, formed a joint organization to study photorefractive information storage materials (PRISM) and applied them to holographic storage. A holographic data storage system (HDSS) with 10^{13} bits storage capacity and 1 GB/s data transfer rate was expected to be developed within 5 years. The material testing system was provided by IBM. The system can not only store and reconstruct the hologram of large data pages, but also analyze the error rate of reconstructed results[12]. The world's first complete HDSS was jointly established by Stanford University, Siros, IBM[13] and Rockwell, Thousand Oaks[14]. Researchers at California Institute of Technology and Lucent had also completed similar system demonstrations[15]. In the 2000s, holographic data storage started commercial exploration. In 2003, Aprilis Company published Vulcan™DHD driver sample with 200 GB storage capacity and 75 MB/s data transfer rate[16]. In 2005, Optware Company published collinear holographic data storage solution[17–20]. Green light sensitive to recording material was used as recording and reading light, while red light insensitive to recording material was used as addressing light[21]. A servo system was introduced to make the whole HDSS more compatible. The system stored 100 GB capacity on polymer optical discs of similar CD size. In 2006, InPhase company published a 2-axis HDSS Tapestry™HDS-300R[22–23]. Holographic Versatile Disc (HVD)[24–25] was photopolymer disc with different parameters: capacity 300 GB, data transfer rate 20 MB/s; capacity 800 GB, data transfer rate 80 MB/s; capacity 1.6 TB, data transfer rate 120 MB/s. Up to now, it is still the exploration pattern of commercialization that collinear HDSS and 2-axis HDSS develop parallel.

In this paper, we present the development of holographic data storage according to timeline and the merits of collinear holographic data storage system in detail and give a further introduction of phase-modulated collinear holographic data storage system. The phase-modulated collinear holographic system is the research hotspot in the data storage field due to its higher storage density and higher data transfer rate.
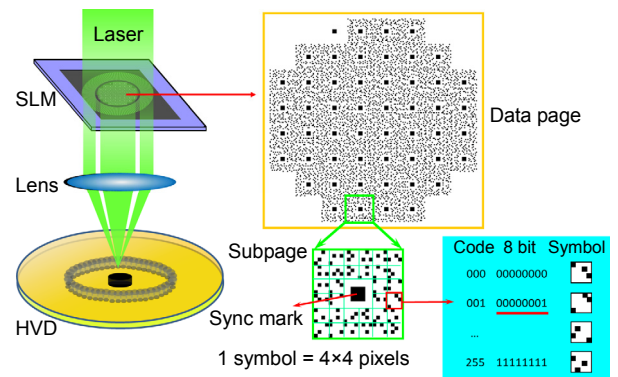
Collinear holographic data storage system

Collinear holographic data storage system (CHDSS) is a more compact, compatible and practical HDSS. The illustration of CHDSS is shown in Fig. 3. The unique feature of CHDSS is that 2-D data pages are recorded by an interferometry structure. The volume holograms generated by a co-axially aligned information beam and a reference beam, which are modulated simultaneously by the same SLM. In the writing process, the information pattern in the center and the reference pattern circling it are used, and two parts of modulated laser beam interfere with each other in the recording media called holographic versatile disc (HVD) through a single objective lens. In the reading process, only the reference pattern is used. The modulated laser beam illuminates the volume hologram in the HVD. The reconstructed image beam is passed back to the same objective lens with a reflective interlayer in HVD, and is received by a complementary metal oxide semiconductor (CMOS) image sensor. In the CHDSS, the green (or blue) laser and red laser beams are combined to the same axis and are transmitted through a single objective lens. The green (or blue) laser is used to read and write holograms because it is sensitive to recording media. A red laser which is not sensitive for recording media is employed for adjusting the focal point of the objective lens correctly in optical servo control system and locating the holograms address in the HVD.
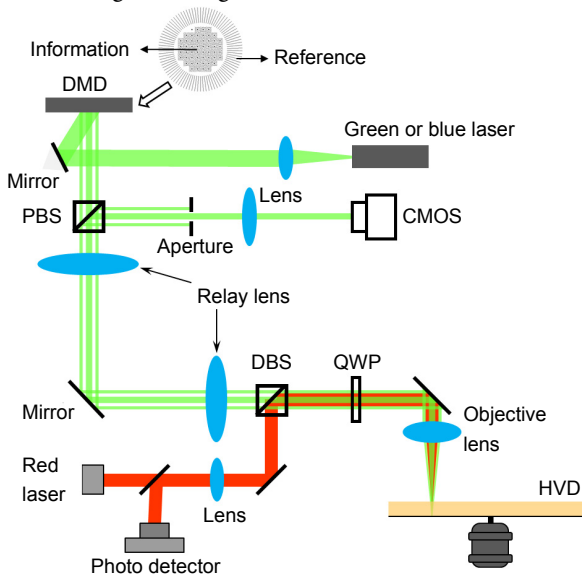
HVD is designed to be a special six-layered structure[17]. On the base layer, there are preformatted address pits and reflective meta-data layer. The material in the meta-data layer is a rewritable phase change material, like DVD-RW. It is used to write address information by red laser to locate holograms and reflect red laser for servo control. The diffraction noise caused by address pits is eliminated by placing a dichroic mirror interlayer placed between the reflective layers. The red laser beam will pass through this layer and reach to the reflective layer while the green (or blue) laser beam will stay in the recording layer due to reflection by this dichroic mirror interlayer. The image quality with the dichroic mirror interlayer is much better than without one[19]. The disk structure is generated by the simplified optical systems of CHDSS, characterized as small volumetric optical disc storage system, allowing small and compact packaging on the same side of the disk. Besides, the generated disk structure is compatible with the already existent storage disc systems, such as CD and DVD.

The format of data page will greatly influence the amount of recording information. In the conventional CHDSS, the code is amplitude modulation. Here, the subpage format is designed to eliminate the problems such as illuminated intensity distribution in a data page, the distortion, the tilting and the aberration of the optical system, as well as the estimation error caused by amplification. As shown in Fig. 4, one data page is made of 51 subpages and 1 synchronous mark. One subpage is made of 32 symbols (4×4 pixels) and 1 synchronous mark (8×8 pixels). The synchronous mark, which includes a 4×4 pixels rectangular block, is used to locate the subpage and to provide the necessary coordinate information for data decoding. The symbol includes 4×4 pixels. There are only 3 ON-pixels in the symbol and others are OFF-pixels.

Fig. 3 | Optical configuration of CHDSS. Photo detector and red laser are utilized to servo control and locate holograms. QWP: quarter wave plate; HVD: holographic versatile disc; DMD: digital micro mirror device, one kind of SLM; PBS: polarized beam splitter; DBS: dichroic beam splitter.

Fig. 4 | Data page format in the CHDSS.

The combination of ON-pixels' positions denotes different 8-bit code. In this data page format, the code rate is 8/16=0.5, and the white rate is 3/16=19% approximately.

Multiplexing technology which records multiple holograms in the same region of the media is an effective way to increase storage density. Until now, varieties of multiplexing methods are employed such as phase coded multiplexing[26], angle multiplexing[10], wavelength multiplexing[27], and so on[28–29]. The shift-multiplexing method which is by rotating the media disc continually can be applied to record holograms[30], and it is suitable for CHDSS[31]. The shift-selectivity means when shifting 3μm in both radial and tangential directions of disc, the reconstructed image disappears completely. The shift-pitch between two holograms is a pitch of at least 3 μm usually, which has been investigated in reference[17].

An orthogonal reference pattern modulated shift multiplexing method by hybridization of these two multiplexing methods has been proposed[32]. The holograms are multiplexed by not only shifting the media with a small distance separately, but also using different reference patterns in the recording process. By utilizing the shift selectivity of hologram, the inter-page crosstalk due to Bragg degeneracy and Bragg mismatch readout can be substantially attenuated. In this hybrid shift multiplexing method, the shift selectivity in conjunction with Bragg selectivity is utilized to reduce the shift pitch, which offers a potential to significantly increase the data density and transfer rate of the CHDSS.

In the CHDSS, the multiplex recording process has been demonstrated[17]. Three 2-D images from 20 multiplex recording holograms at the recording order of the first, tenth, and twentieth are reconstructed respectively. The intensity distribution analysis indicated that the ON-pixels and the OFF-pixels are clearly separated. Though the symbol error rate of reconstruction of all 20 multiplex is different from 10^{-3} to 10^{-2}, as expected, if symbol error rate is less than 10^{-2}, the user data can be decoded from the reconstructed page-data images[33].

Phase-modulated CHDSS

As conventional CHDSS is coded by amplitude code, where the code rate can hardly exceed 1, for instance, typical 3/16 amplitude code owns only 0.5 code rate. In holographic data storage, phase modulation methods were proposed to increase the storage capacity, which has the advantage of providing higher storage density and data transfer rate than conventional amplitude modula-

tion shown in Fig. 5. In the calculation, if we use 4-level phase and 8-level phase adding on 3/16 amplitude code, the code rate will be 0.875 and 1.0625 respectively. Besides, phase modulation can provide higher signal noise ratio (SNR) by homogenizing intensity in the center of recording hologram. In Fig. 5, phase modulation with 3/7 rate of 0 and π worked well compared with amplitude modulation obviously. The influence of the phase modulation at different rate of 0 and π has also been investigated[34].
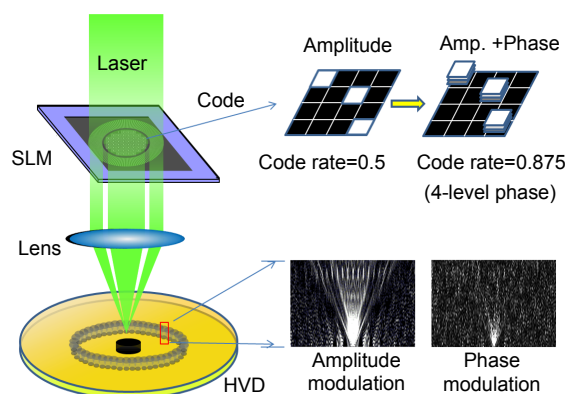

Fig. 5 | The comparison between amplitude modulation and phase modulation.

The realization of phase retrieval is one of the challenging aspects in phase modulation, as the detectors such as CMOS cannot detect phase information intuitively. The interferometry method is a solution which transforms the undetectable phase information into intensity signal[35]. However, the interferometric results are influenced by the environmental disturbance, as subtle vibration can cause undesirable results. In previous work, a phase modulation method for holographic data storage has been proposed. At the same medium location, two sequential recording processes locked the phase-retrieval reference beam with its corresponding data page. It makes the system more compact and phase retrieval easier by avoiding complicated interferometric components such as piezoelectric elements, phase shift arrays and extra interference beam. With this method, the bit error rate (BER) for 4-level, 8-level, and 16-level phase modulation can be achieved to be 0.3%, 1.5% and 6.6%, respectively[36].

Figure 6 shows the complex amplitude data page and the interference data page (IDP). In the recording process, the signal data page with phase modulation and the IDP with uniform phase are recorded at the same location sequentially. As shown in Fig. 6, half of the reference region A, B, C and D in Fig. 6(a) are used to record the data

page with phase modulation. The other half of the reference region E, F, G, and H in Fig. 6(b) are used to record the IDP following the data page recording. In the reconstruction process, the encoded phase value is transferred into intensity with the IDP as the phase retrieval reference beam. As shown in Fig. 6 all the reference region from A to G are uploaded to the SLM to reconstruct and interfere the data page and the IDP simultaneously, forming an intensity image that can be captured by the CMOS.
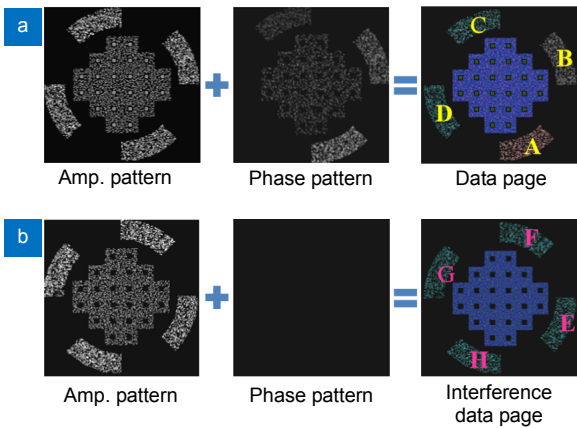

Fig. 6 | The complex amplitude data page and interference data page. (**a**) Data page. (**b**) Interference data page (IDP).

To solve another problem that IDP consumes media, one IDP corresponding to multiple data pages recording method is proposed to reduce IDP consumption. For reconstructing these data pages independently without causing cross-talk between multiple data pages recorded at the same position, an orthogonal reference encoding method is introduced. This method is based on phase-retrieval reference beam locking modulation. The illustration of orthogonal reference encoding method is shown in Fig. 7. In the regions of the reference pattern for data page, 4 kinds of different phase combination P-1, P-2, P-3 and P-4 correspond to 4 different data pages Data A, Data B, Data C and Data D, respectively. During the reconstruction process, the corresponding data page can be reconstructed by the reference pattern with identical phase distribution.

In the experiment, four data pages and one IDP are recorded at the same medium location and four data pages are read one by one. Figure 8 illustrates the experimental phase histogram results for four data pages with orthogonal phase encoding recording. The BER of page 1 to page 4 are calculated to be 3.55%, 2.64%, 4.54%, 8.02%, respectively. Compared with single data page recording, the multiplexing results bear higher error. However, the phase statistical distribution is still distinguishable and the phase distributions of four data pages are quite similar.

The above-mentioned method with phase retrieval reference beam locking and orthogonal reference encoding, leading a stable interferometric result. However, the accurately matching between amplitude SLM and phase SLM is difficult and make the system complex. Besides, the code rate of amplitude plus phase is still not high enough. Actually, pure phase code has higher code rate. If we use pure phase code, only one phase-only SLM is needed which makes the system simple. Except for interferometric method, a non-interferometric phase

	P-1	P-2	P-3	P-4
A	0	0	0	0
B	0	0	π	π
C	0	π	0	π
D	0	π	π	0
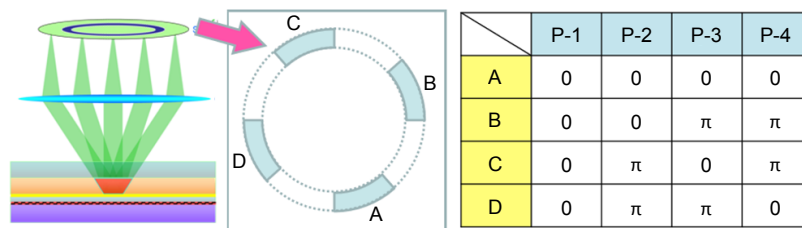
Fig. 7 | Phase modulation of reference pattern for data page pattern.
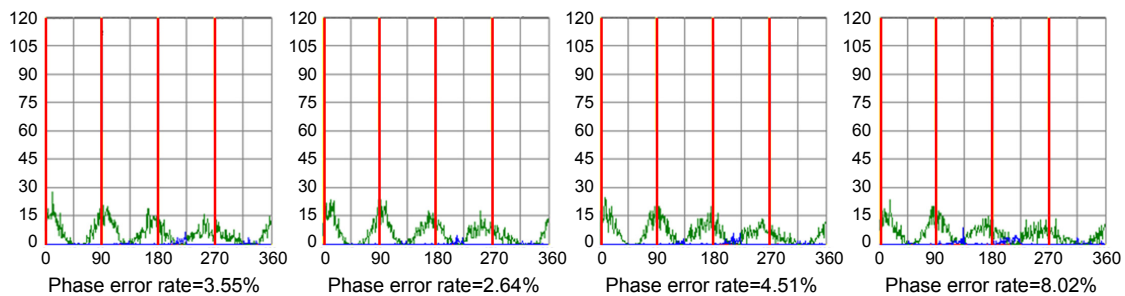
Fig. 8 | The phase demodulation histogram of four different data pages.

readout method is also proposed which has the advantages of easy implementation, simple system setup and robust noise tolerance[37].

The non-interferometric phase readout method based on iterative Fourier transform (IFT) algorithm is an iterative single operation method[38−40], which is proposed by R. W. Gerchberg and W. O. Saxton in 1970s and modified by James R. Fienup in 1980s. Until now, the IFT algorithm and its derivative algorithms have large amount of applications such as digital encryption, image resolution enhancement, wavefront shaping and so on[41−44]. Generally, the reconstruction of relative faithful phase information require hundreds of iterations, which casting a heavy burden on computation time and reducing the data transfer rate eventually. For this reason, the application dependent prior phase information is utilized to speed up the convergence. In holographic data storage, certain positions of the data page which named as embedded data can be set as the mark or calibration points with fixed and known phase values. During the encoding process, portion of embedded data can be controlled.

In our phase retrieval algorithm, the input captured by CMOS is the Fourier transformation of reconstructed beam, which is more concentrated than the original reconstructed beam itself. Therefore, in our method both dynamic range of recording media and data storage density can be increased greatly.

Figure 9 shows the phase readout scheme of non-interferometric system. In the recoding process, the original phase data page with certain portion of embedded data is addressed on the SLM. The original phase data as the signal beam will be recorded in the media when it interferes with the reference beam. In the reading process, after reading out by the reference beam, the original phase data page is reconstructed as illustrated red dotted line area in Fig. 9. By placing a CMOS at the back focal plane of the lens, the intensity distribution will be captured. In the phase retrieval processes, the remained unknown phase data in the original phase data from an initial guess distribution will be retrieved by using captured intensity distribution and embedded data constraints in the IFT algorithm.

The proportion of the embedded phase data is a crucial factor for the IFT algorithm. Convergent curves with different proportions of embedded phase data is shown in Fig. 10. It is clear that the higher proportion of embedded phase data, will speed up the degree of phase retrieval convergence. However, the higher proportion of embed-

ded phase data means lower code rate. Therefore, we need to make a balance between the code rate and proportion of embedded data. Due to the requirement of high data transfer rate, we believe that iteration number should be around 10 and phase error before error correction should be smaller than 0.05, respectively.
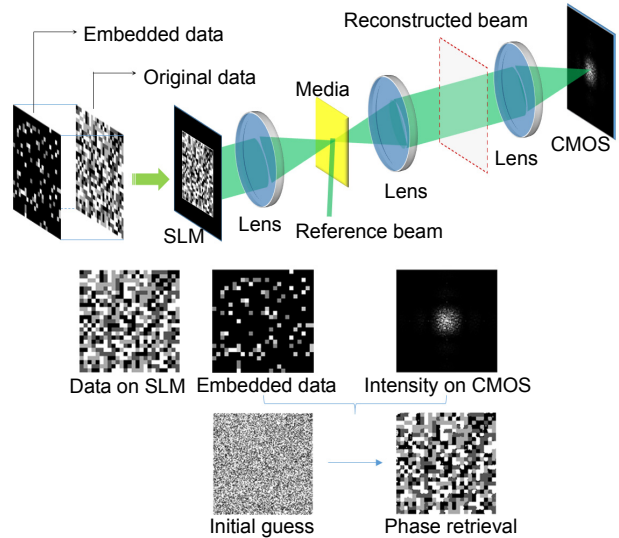
Fig. 9 | The diagram of non-interferometric system for phase retrieval based on IFT algorithm.
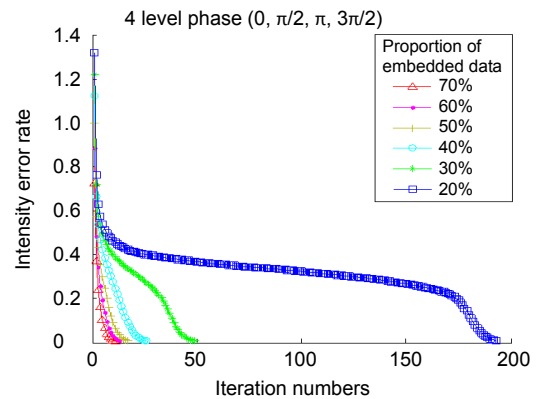
Fig. 10 | Convergent curves with different proportions of embedded phase data.

In the experiment, 4-level phase with 50% embedded data was used where the code rate is 1. After 10 iterations, the BER was reduced to 4.7% from 87% without iteration[37]. This result can be accepted. In the near future, higher lever number of phase code and less iterations should be researched in the CHDSS.

Some developed and developing technologies of holographic data storage are introduced briefly above. Since holographic data storage technology has been researched for more than fifty years, the developments of theory and system are mature relatively. Under the background of Big

Data, there is no doubt that the technology will go into commercialization. The possible bottlenecks for commercialization are two aspects. One is the performance and cost of recording material which is the most important. Recently, more researchers put their eyes on the photopolymer which is a very cheap holographic material and owns high dynamic range. The performance of photopolymer is also better and better with the new technologies such as doping nanoparticles in the material[45]. The other is the detection method of multi-dimensions such as phase and polarization. Multi-dimensional modulation can increase storage density, but meanwhile bring challenges on the detection. Dimension reduction detection method will be a thought. The non-interferometric phase retrieval method introduced in this paper is one kind of dimension reduction detection method.

Conclusions

In the era of Big Data, the demand of data storage is increased dramatically. Holographic data storage technology is one of the most promising next-generation data storage technologies. This paper gives a brief review of holographic data storage according to time line from the start of this technology to the development of its commercial application. Collinear holographic data storage technologies as the typical solutions of the HDSS are introduced. CHDSS owns more compact, compatible and practical system for fitting the requirement of commercial data storage product. To increase storage density further, phase-modulated CHDSS is proposed to achieve higher storage density and higher data transfer rate. The key problem of phase readout rapidly and correctly has been researched in this paper. Relative works by using interferometric method and non-interferometric method are reviewed respectively.

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Competing interests

The authors declare no competing financial interests.