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REVIEW ARTICLE

High density collinear holographic data storage system

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Abstract Holographic data storage system (HDSS) has been a good candidate for a volumetric recording technology, due to their large storage capacities and high transfer rates, and have been researched for tens of years after the principle of holography was first proposed. However, these systems, called conventional 2-axis holography, still have essential issues for commercialization of products. Collinear HDSS, in which the information and reference beams are modulated co-axially by the same spatial light modulator (SLM), as a new read/write method for HDSS are very promising. With this unique configuration, the optical pickup can be designed as small as DVDs, and can be placed on one side of the recording media (disc). In the disc structure, the preformatted reflective layer is used for the focus/tracking servo and reading address information, and a dichroic mirror layer is used for detecting holographic recording information without interfering with the preformatted information. A 2-dimensional digital page data format is used and the shift-multiplexing method is employed to increase recording density. As servo technologies are being introduced to control the objective lens to be maintained precisely to the disc in the recording and reconstructing process, a vibration isolator is no longer necessary. Collinear holography can produce a small, practical HDSS more easily than conventional 2-axis holography. In this paper, we introduced the principle of the collinear holography and its media structure of disc. Some results of experimental and theoretical studies suggest that it is a very effective method. We also discussed some methods to increase the recording density and data transfer rates of collinear holography.

Keywords holographic data storage system (HDSS), holography, optical memory, volumetric recording, optical disc, high density recording

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1 Introduction

With the development of digital and internet technologies, we have entered into the big data era. The necessity for large capacity, high transfer rates and long-term data storage systems has been increased. But, the main storage media we rely on currently are magnetic technology, like hard disk drives (HDD) and tape, which life times are several years only. They cannot satisfy the demand of prolonged preservation. Optical discs based on the bit-by-bit method, such as CD, DVD and Blu-ray Disc, for storing sound, movies, photos and other digital contents are widely used in our daily life. The long-term life time is one of the properties. The optical disc should be a good candidate of data storage system for big data preservation. However, to increase the recording density, the spots size has to become smaller and smaller; to minimize the spots size, the numerical aperture of the objective lens has become larger and larger; the wavelength of the laser has become shorter and shorter because optical resolution is limited by wavelength. In addition, to diminish aberrations caused by disc tilt, the protective layer has become thinner and thinner. To increase the data transfer rate, the rotation speed of the disc has become higher and higher. The Blu-ray Disc achieves up to 25 GB high-density recording on a single-sided single-layer disc, by employing a short wavelength blue-violet laser (λ = 405 nm), a large numerical aperture (NA = 0.85) field lens, and a 0.1 mm protective layer. For this reason, the limits of the bit recording method are looming on the horizon. Now, we are faced with the questions: how to increase the capacity? And what is the next generation of optical discs?

On the other hand, there is a different optical storage system, called holographic data storage system (HDSS). In the holographic technology, two coherent beams are necessary. One is information beam including user data we want to record, the other is reference beam. During the recording process, they interfere with each other and the interference pattern is recorded in the media, called hologram. In the reconstructing process, the information beam can be reconstructed when the reference beam incident on the hologram. Because the two beams are separate, we call this HDSS conventional 2-axis holography. This method was first proposed in the 1960s [1]. In this method, data are recorded in the media volumetrically (3-D) and transformed 2-dimensionally (2-D). Due to their large storage capacities and high transfer rates, HDSS should become a promising candidate of next-generation of storage system. Within the last decade, unique demonstration platforms using holography have been proposed [2–4]. However, these 2-axis HDSS still have essential issues for practicality [5]. Holographic recording has been known for 50 years and never been commercially available. It is clear that a technological breakthrough is necessary.

Collinear HDSS is proposed and demonstrated by OPTWARE Corporation [6]. This technology can produce a small, practical HDSS more easily than conventional 2-axis holography. In this paper, we introduced collinear technology and reported the structure of media. And we discussed some methods to enlarge the recording density and increase data transfer rate of the collinear HDSS.

2 Collinear technology and media structure

Collinear technology, as a new reading and writing method for HDSS, is very promising and differs from conventional 2-axis holography. The structure of collinear HDSS is shown in Fig. 1. The unique feature of this technology is that 2-D page data are recorded as volume holograms generated by a co-axially aligned information beam and a reference beam, which are modulated simultaneously by the same spatial light modulator (SLM). The information pattern in the center and the reference pattern circling it interfere with each other in media through a single objective lens. In reconstructing process, only the reference pattern, outer ring pattern, is used for creating a reference beam. The reconstructed image beam is sent back to the same lens as used in the recording process by a reflective interlayer in media, and reflected to a complementary metal oxide semiconductor (CMOS) image sensor by a polarized beam splitter.

In collinear HDSS, the green (or blue) 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. A red laser that is not sensitive for recording medium is used for optical servo control to adjust the focal point of the objective lens onto the disc correctly and to locate the holograms address in media disc. For this reason, a special disc structure of media has been designed. The six layers structure is shown in Fig. 2 schematically. On the base layer, there are preformatted emboss pits and meta-data layer. The material in the meta-data layer is a rewritable phase change material, like CD-RW. It is used to write address information by red laser and reflect red laser for servo and locate holograms. To eliminate the diffraction noise into the recording media caused by the embossed pits, a dichroic mirror interlayer is placed between the recording layer and the reflective layer. The red laser beam for optical servo control will pass through this layer and reach to the preformatted meta-data reflective layer. The green (or blue) laser beam for forming hologram is perfectly reflected by this dichroic mirror interlayer. Figure 3 shows image quality comparison between Fig. 3(a) with and Fig. 3(b) without dichroic mirror interlayer, respectively. The dichroic mirror interlayer eliminates diffraction noise effectively [5]. The holographic material used in the recording layer is photopolymer, which has a dynamic range (M/#) more than 10.

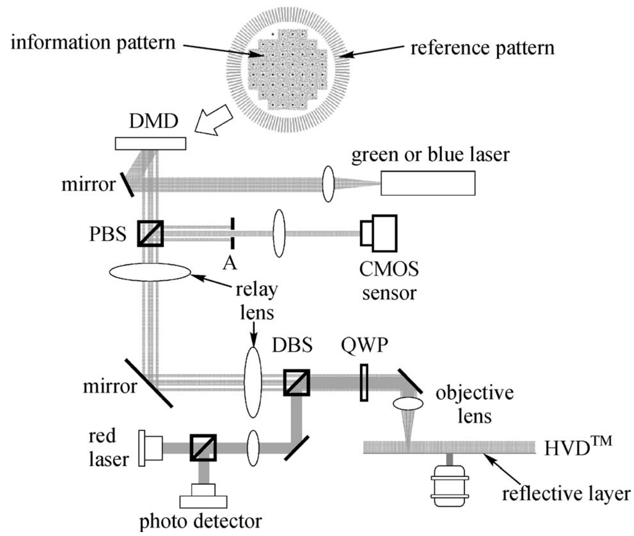

Fig. 1 Optical configuration of HDSS using collinear technology. In recording process, information pattern, in the center and reference pattern, out ring, are displayed simultaneously by the same SLM, and information beam and reference beam interfere with each other in the media through a single objective lens. In reconstructing process, only the reference pattern is displayed on the SLM. The reconstructed beam is sent back to the same lens by a reflective layer, and reflected to a CMOS image sensor by a polarized beam splitter. Red laser and photo detector are used to servo control and locate holograms. DMD: digital micro mirror device; PBS: polarizing beam splitter; DBS: dichroic beam splitter; QWP: quarter wave plate; HVD: holographic versatile disc

On the other hand, shift multiplexing method is used in collinear HDSS [7,8]. Because the hologram recording layer is separated optically by dichroic interlayer, the shift pitch can be arbitrarily adjusted based on the location information obtained from the preformatted meta-data layer, and the storage capacity can be changed freely, this is the concept of the selectable capacity recording format [5,7].

With the special structure, the holograms can be located by retrieving address information on the preformatted meta-data layer. In addition, based on this layer, focusing servo and tracking servo technologies which are widely used in existing optical disc, like CD and DVD, can be

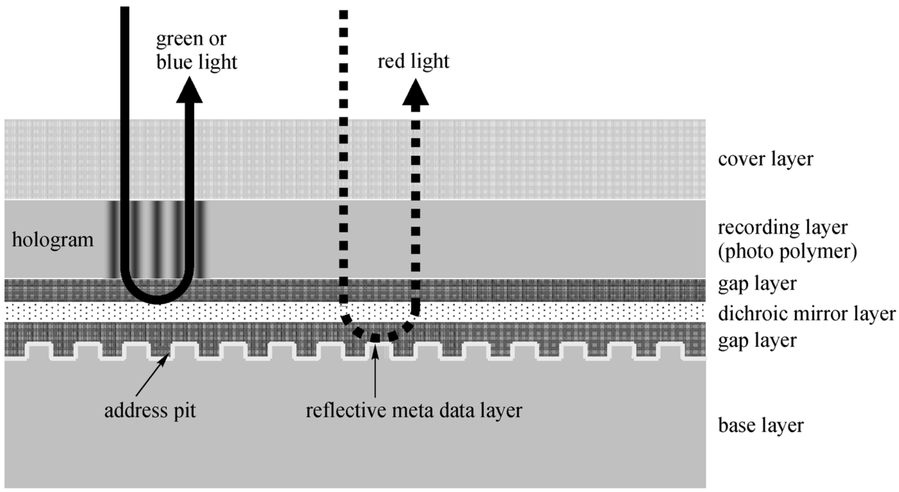

Fig. 2 Schematic illustration showing a reflective structure of collinear holographic media. Base layer, which contains preformatted emboss pits and meta data reflective layer, is used to reflect red laser for servo and locate holograms. Dichroic mirror layer eliminates the diffraction noise caused by embossed pits. Recording medium layer is photo polymer

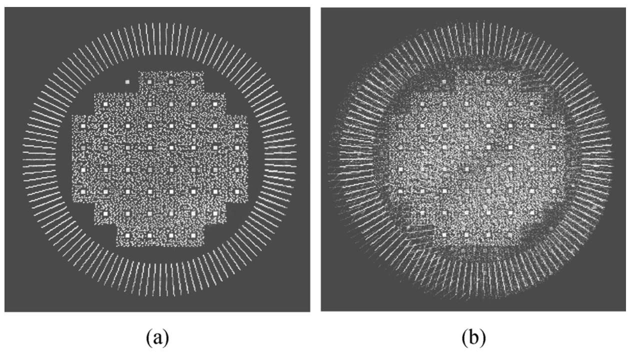

Fig. 3 Reconstructed images from HVD™ (a) with and (b) without dichroic mirror interlayer. The result is very clear that dichroic mirror interlayer eliminates diffraction noise effectively

used in the recording and the reconstructing process. This will precisely maintain the distance and the relative position of the objective lens and the disc, and the holograms can be recorded and reconstructed in a disc accurately even if there is axial deflection or radial runout. Furthermore, a vibration isolator is no longer necessary [7]. Figure 4 shows the schematic optical configuration of actuator used in collinear holography. This technology will enable us to construct a small volumetric optical disc storage system, compatible with existing disc storage systems, like CD and DVD.

3 High density recording methods

There are generally several kinds of methods to increase the HDSS recording density on the recording media. These methods include multiplexing holograms to increase the number of holograms recorded in the same region of the media, saving the dynamic range of media, so called M number (M/#), to increase the multiplexing recording number, and increasing the amount of information in a data page, etc.

3.1 Multiplexing recording

A high density recording method can be realized by recording multiple holograms in the same region of the media. Many kinds of multiplexing methods are employed normally, for example: angle multiplexing [2], phase-coded multiplexing [3], wavelength multiplexing [4], and other methods [8,9]. Shift-multiplexing method can be used to record holograms continually by rotating the media disc [10], and it is suitable for collinear technology [7]. The shift-selectivity, the smallest shift-pitch between two holograms, using collinear technology has been investigated. When shifting 3 μm in both radial and tangential directions of disc, the reconstructed image disappears completely, indicating that collinear technology allows us to record holograms by overlapping at a pitch of at least 3 μm [11]. An orthogonal reference pattern (RP) modulated shift multiplexing method by hybridization of these two multiplexing methods is also proposed [12]. The holograms are multiplexed by not only using different reference patterns, but also shifting the media with a small distance separately in the recording process. The inter-page cross-talk due to Bragg degeneracy and Bragg mismatch readout can be substantially attenuated by utilizing the shift selectivity of hologram. The shift pitch for this hybrid shift multiplexing method can also be substantially reduced by utilizing shift selectivity in conjunction with Bragg selectivity, which offers a potential to significantly increase the data density and transfer rate of the collinear HDSS.

3.2 Saving M/#

The maximum attainable number of multiplexed holograms depends mainly on the media and optical system. From the viewpoint of media development, the number of multiplexed holograms increases with the dynamic range (M/#) of the media, which increases with medium thickness and maximum achievable refractive index changes. From the viewpoint of optical system, the number of multiplexed holograms increases with the high signal-to-noise ratio (SNR) of reconstructed holograms at limited M/# of recording material. For this reason, in the recording process, the holograms are recorded as weak as we can in order to save the M/#, and in the reconstructing process, the holograms is retrieved by high power reference beam in order to get a bright image and high SNR. In collinear holography, the information and reference beam are co-axially aligned, and in the reconstructing process, the reconstructed information image beam is also co-axially aligned with reference beam. Decreasing the optical scattering noise from the reference beam in the reconstructing process is very useful for high density recording. Here we propose a method to increase recording density and data transfer rate.

We put a polarization selective patterned absorber (PSPA) at the front of quarter wave plate (QWP) set at the front focal plane of the objective lens. The pattern of absorber is a ring-shaped with an inner ratio similar to that of reference pattern. The schematic optical diagram is shown in Fig. 5. The center part of the PSPA is a transmission area. However, at the ring-shaped area, the *p*-polarized beam can pass through it and *s*-polarized beam is absorbed. In the recording process, the information beam (center part) and the reference beam (outer ring part), with *p*-polarization, pass through the PSPA and are then incident upon the QWP. The laser beams, whose polarizations are converted from the *p*-polarized state to a circularly polarized state, are focused and interfere with themselves in the holographic recording media by an objective lens. The interference pattern is recorded as a volume hologram in the media. In the reconstructing process, only the outer ring reference beam is used. The *p*-polarized laser beam passes through the PSPA and then converted to circularly polarized state by the QWP, and focused by the same objective lens as used in the recording process. The circularly polarized reconstructed information beam, which is diffracted from the hologram and reflected by dichroic mirror layer in the media, is sent back to the objective lens and passed through the QWP again. The polarization is converted from circularly polarized state to *s*-polarized state. The reconstructed information beam goes through the transmissive area of the PSPA, and the reflected reference beam is absorbed at the ring-shaped area of the PSPA. As a result, only the reconstructed information beam can be received by CMOS image sensor. Figure 6 shows the read out pattern detected at the CMOS image sensor without and with the PSPA. Using the PSPA,

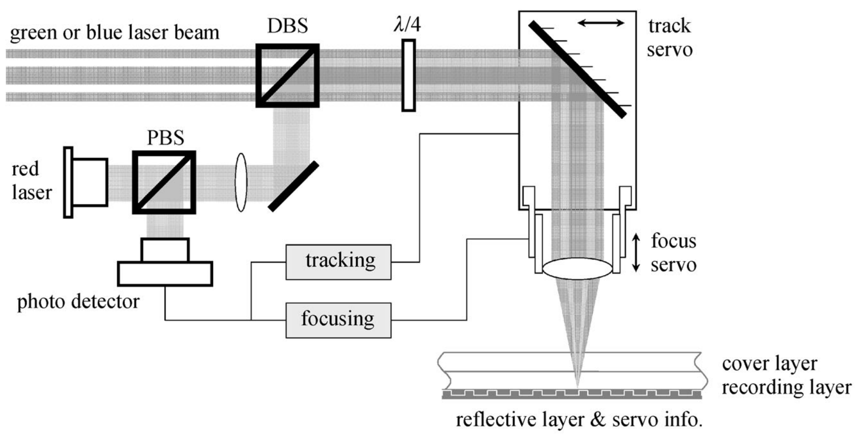

Fig. 4 Optical configuration of collinear holographic actuator used in HDSS. Green or blue laser is used to read and write holograms, red laser is used to control tracking and focusing servos. The objective lens can be maintained at the relative position to disc precisely even if there is axial deflection or radial runout. Furthermore a vibration isolator is no longer necessary

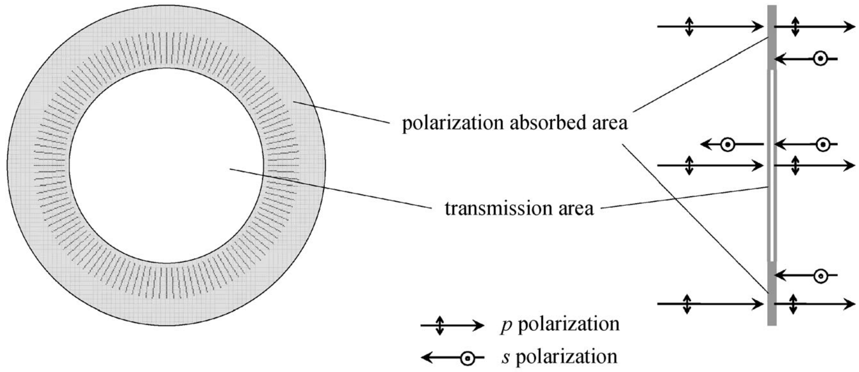

Fig. 5 Schematic diagram showing spatial relation between the patterned polarization selective absorber and the reference pattern on the left hand and the optical diagram of the function of the polarization selective absorber on the right hand

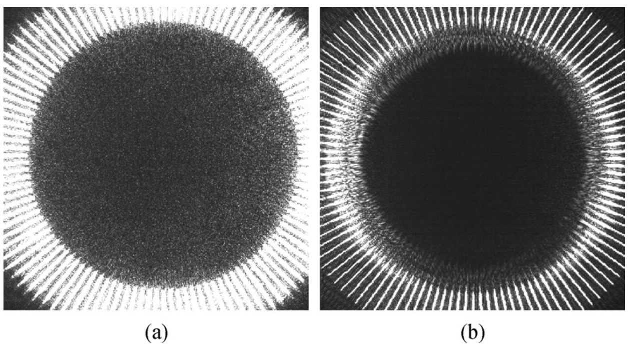

Fig. 6 Images of reconstructed reference pattern detected by the CMOS image sensor. (a) Without and (b) with the polarization selective patterned absorber

the optical scattering noise was drastically suppressed.

In collinear HDSS, as shown in Fig. 1, data pages are recorded as Fourier holograms inside the recording media. As shown in Fig. 7(a), the DC components of the Fourier-transformed signal and reference beams, which are much higher in intensity than other Fourier components, consume a large amount of M/#. For increasing data capacity, this M/# loss should be reduced. Therefore, using high-pass filter to remove DC components in recording process has been proposed to help suppress the loss of M/# [13]. There are also some other methods to reduce the center intensity of the DC components by random phase mask to modulate the amplitude data page. We have investigated the influence of the phase modulation at different rate of 0 and π [14]. Figure 7 shows the result of data page modulated by amplitude only and phase with the 0 and π at the rate of 5/5 and 3/7.

3.3 Improving information of data page

The amount of recording information in a data page is determined by its format. In the collinear HDSS, the data page format based on the subpage is designed to eliminate the problems of illuminated intensity distribution in a data page, of distortion and aberration of the optical system, of tilting, and of the estimation error caused by amplification. As shown in Fig. 8, the size of a subpage (24 × 24 pixels is used) depends on the parameters and the magnitude of the inhomogeneity of a system. In each subpage, there are 32-byte data symbols (4 × 4 pixels) and a synchronous mark (8 × 8 pixels) in its center. The synchronous symbol, which includes a 4 × 4 pixel rectangular block, is used to

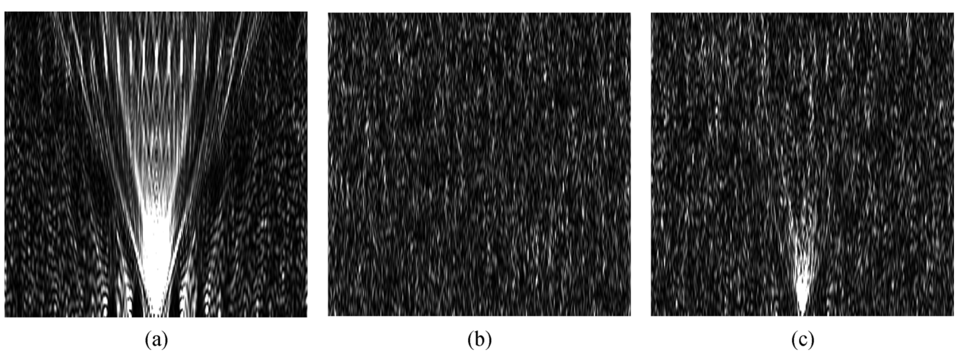

Fig. 7 Simulated intensity profiles in the media of collinear HDSS. Data page modulated by (a) amplitude only, the DC components of the Fourier-transformed signal and reference beams are much higher in intensity than other Fourier components; (b) phase with same number of 0 and π; (c) phase with the 0 and π at the rate of 3/7

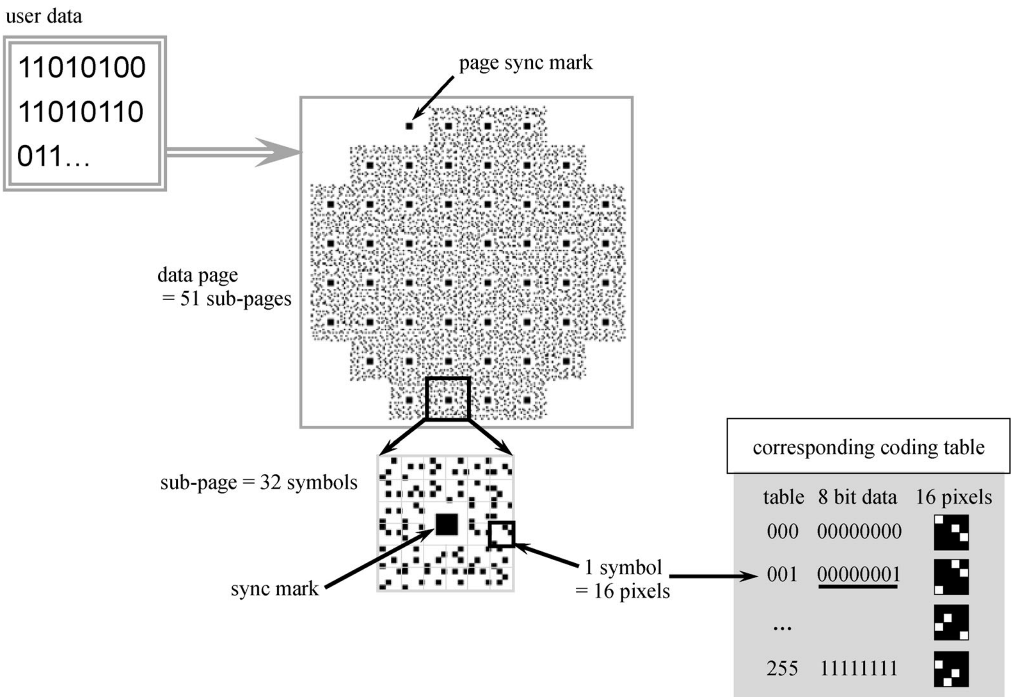

Fig. 8 Data page format, based on sub-page, encoded from the user data to be used in the collinear HDSS. There are 51 sub-pages, 32 symbols included in each sub-page, and 1 symbol represents 8 bit data using 256 patterns, which are combined by 3 ON-pixels and 13 OFF-pixels, the patterns are defined in a corresponding coding table. The code rate is 0.5, and the white rate is approximately 19%

locate the subpage and to provide the necessary coordinate information for data decoding. The sorting method and correlation technique that differ from the threshold method are used to distinguish the ON-pixel and OFF-pixel states from the reconstructed image in the decoding process. In collinear HDSS, 3 pixels ON and others are OFF. In this data page format, the code rate is $8/16 = 0.5$; and the white rate is $3/16 \approx 19\%$ approximately [11].

To improve the information content within a data page, an effective method is to elevate the code rate. The multiple gray coding method and phase modulated data page are used. In the format of the data page, as shown in Fig. 8, there are only three ON-pixels in a symbol. If the gray coding method is used, if all 16 pixels are modulated by phase, the code rate should be increased.

4 Conclusions

In this paper, we have reviewed collinear HDSS. Using the collinear technologies, 2-D page data can be recorded as volumetric holograms generated by an information beam and a reference beam that are bundled on the same axis, and irradiated on the media through a single objective lens. The optical configuration and disc structure are indeed very effective for materializing a small optical storage system with huge density. With its unique selectable capacity recording format of media shows both downward and upward compatibility of different disc capacities. Based on collinear technologies, we discussed many kinds of methods to increase the density and reduce the noise in the reconstruction process. These methods allow us to read low intensity hologram with high SNR.

Further investigations are underway to develop the high power, small size and low cost laser, to test the reliability of the media, to balance the data density and the transfer rate by incorporating newly designed optical and electronic components. Theoretical discussion is necessary to elucidate why collinear HDSS has significant advantages compared to other HDSS.

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