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High-density recording in holographic data storage system by dual 2-level run-length-limited modulation

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An angular-multiplexing holographic memory system is one candidate for future optical data storage systems because of capability for abilities of “high-density recording” and “high-speed recording and reproduction”. We have developed a high-density recording method by reducing the hologram size in a disc to half by 2-level run-length-limited (RLL) modulation. In addition, to achieve further high-density recording, we introduce 4-level recording. However, 4-level RLL modulation requires high computational complexity in general. Therefore, we developed the dual 2-level RLL modulation method that can suppress increase in computational complexity and has good compatibility with the conventional holographic data storage system (HDSS). The high-density effect of the method was experimentally confirmed by the Fourier images and SNR of reproduced images. Consequently, the dual 2-level RLL modulation enables a doubling of the recording density, this gave an inspection for realizing a next-generation HDSS with the recording density of 4.8 Tbit/in.2. © 2016 The Japan Society of Applied Physics

1. Introduction

As the amount of digital data increases, the demand for archival storage devices with larger capacities and faster transfer rates than those of current archival storage has been increasing. Optical discs are suitable for the archival storage because they are superior in terms of bit cost, lifetime and power consumption, which are important requirements for archival storage. On the other hand, improvement of their capacity and transfer rate which are inferior to those of other candidates, such as the hard-disk drive (HDD) and the tape, is expected. Therefore, we have been studying the angular-multiplexing holographic data storage system (HDSS) which is one candidate for the future optical data storage system because of its capability for “high-density recording” and “high-speed recording and reproduction”. In angular-multiplexing HDSS, a large amount of data can be recorded at the same location. Moreover, recently hundreds of holograms have been multiplexed at the same location by varying the incident angle of the reference beam. In addition to the angular multiplexing that we developed a high-density recording method in which the size of the hologram size in a disc is reduced to half by 2-level run-length-limited (RLL) modulation to increase the data capacity of HDSS.

The above two methods enable a page capacity of 0.37 Mbyte, a hologram size of 0.34 mm2, and 440 multiplexing. These specifications yield a recording density of 2.4 Tbit/in.2 in first-generation HDSS. To catch up to the market needs, the data capacity and data transfer rate of HDSS must be increased simultaneously. The data transfer rate and capacity are targeted to be doubled compared with those of the developed first-generation HDSS. For that purpose, we introduce 4-level recording for the second-generation HDSS. The signal processing for the second-generation HDSS should have compatibility with the conventional one to prevent it from develop a drastic increase of its calculation complexity. Therefore, the purpose of this study is forming a practical RLL modulation method the 4-level recording, which requires suppressing any increase in computational complexity and a compatibility with the first-generation HDSS.

2. Dual 2-level RLL modulation method

2.1 Conventional RLL modulation

Before introducing 4-level recording, the conventional high-density recording method is reviewed in this section. This method was developed to achieve a recording density of 2.4 Tbit/in.2 in the first-generation HDSS. A schematic diagram of the first-generation HDSS in recording process is shown in Fig. 1. The laser beam from a blue laser diode (LD) unit is split into signal and reference beams with a polarized beam splitter (PBS). The signal beam is modulated using the spatial light modulator (SLM) and limited by the aperture size of the spatial filter placed at the Fourier plane. The signal beam is focused into the medium through the objective lens. The reference beam is also irradiated into the medium and the beam angle can be electrically changed by adjusting the galvo mirror. Then a hologram is recorded as the fringes generated by interference between the signal and reference beams in the medium. In this system, the hologram size depends on the diffraction angle \( \alpha \) from a pixel on the SLM. The hologram size is given as

\[
(f \cdot \alpha)^2 = \frac{\lambda}{d},
\]

where \( f \) is the focal length of the lens, \( \lambda \) is the wavelength of the laser, and \( d \) is the pixel pitch of the SLM. The equation indicates that the angle spreads inversely with increasing the
For the 4-level recording of the second-generation HDSS, it is crucial that the constellation of the signal has four points in a complex plane (i.e., four levels). There are two methods of realizing 4-level recording. The first method is 4-amplitude-shift keying (4-PSK), in which the signal is recorded as amplitude-modulated pixels. The second method is 4-phase-shift keying, in which the signal is recorded as phase-modulated pixels. Examples of constellations of 4-ASK and 4-PSK are shown in Figs. 4(a) and 4(b), respectively. The horizontal axis represents the real part of the signal whereas the vertical axis represents the imaginary part of the signal. The constellation in Fig. 4(b) in particular is called quadrature phase shift keying (QPSK).

According to the previous works multi level recording methods, a 4-PSK recording has a higher signal-to-noise ratio (SNR) than a 4-ASK recording. In addition, a QPSK signal applied with 4-level RLL has the same high-density effect as that with conventional 2-level RLL. Therefore, the 4-PSK recording is applied with a 4-level RLL trellis modulation for the second-generation HDSS.

However, the 4-level RLL trellis is formed by expanding the RLL trellis, resulting in a trellis that consists of a large number of states and paths, as follows. In the conventional RLL trellis 1 bit is regarded as 1 symbol; in contrast, in the 4-level RLL trellis 2 bits must be regarded as 1 symbol. An example of input and output for the 4-level RLL trellis is shown in Table I. The table indicates that the 2-symbol input has 16 combinations and the 3-symbol output has 28 combinations that satisfy the RLL constraint. Eventually, the number of paths of the 4-level RLL trellis is at least 256 as mentioned in Sect. 2.1. Consequently, the complexity of the 4-level RLL trellis will become at least 11 times as high as that of the conventional RLL trellis. A 4-level RLL modulation method is shown in Fig. 5. In this method, a 4-level pattern is directly generated by the complicated 4-level RLL trellis modulation, and restricted to the RLL pattern.

2.3 Dual 2-level RLL
As previously mentioned, the 4-level RLL modulation method shown in Fig. 5 can generate the RLL code; however, the complexity of the modulation will be much higher than that of 2-level DLL modulation. Thus, to reduce the complexity, a new modulation method was devised as follows. The QPSK signal has the constellation shown in Fig. 4(b) such as \((1 + i)/\sqrt{2}, (1 - i)/\sqrt{2}, (-1 + i)/\sqrt{2}, \text{ and } (1 - i)/\sqrt{2}\). Then, the QPSK signal can be divided into a complex plane (i.e., four levels). There are two methods of realizing 4-level recording. The first method is 4-amplitude-shift keying (4-PSK), in which the signal is recorded as amplitude-modulated pixels. The second method is 4-phase-shift keying, in which the signal is recorded as phase-modulated pixels. Examples of constellations of 4-ASK and 4-PSK are shown in Figs. 4(a) and 4(b), respectively. The horizontal axis represents the real part of the signal whereas the vertical axis represents the imaginary part of the signal. The constellation in Fig. 4(b) in particular is called quadrature phase shift keying (QPSK).

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2.2 Single 4-level RLL modulation
For the 4-level recording of the second-generation HDSS, it is crucial that the constellation of the signal has four points in a complex plane (i.e., four levels). There are two methods of realizing 4-level recording. The first method is 4-amplitude-shift keying (4-PSK), in which the signal is recorded as amplitude-modulated pixels. The second method is 4-phase-shift keying, in which the signal is recorded as phase-modulated pixels. Examples of constellations of 4-ASK and 4-PSK are shown in Figs. 4(a) and 4(b), respectively. The horizontal axis represents the real part of the signal whereas the vertical axis represents the imaginary part of the signal. The constellation in Fig. 4(b) in particular is called quadrature phase shift keying (QPSK).

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real part and an imaginary part. A constellation of the real part is shown in Fig. 6(a), and consists of $1/\sqrt{2}$ and $-1/\sqrt{2}$. On the other hand, a constellation of the imaginary part is shown in Fig. 6(b), and consists of $i/\sqrt{2}$ and $-i/\sqrt{2}$. Therefore, the 4-level RLL modulation must be explained by the two 2-level RLL modulations. This method is named “dual 2-level RLL modulation”. The dual 2-level RLL modulation method is shown in Fig. 7. In this method, a 4-level pattern of QPSK (a) is divided into a 2-level patterns of the real part and the imaginary part (b). Both have undergone 2-level RLL modulation applied (c). Moreover, the two modulated patterns are combined as real and imaginary parts of the QPSK signal. The modulated 4-level pattern (d) includes isolated pixels but they are not allowed in the 4-level RLL modulation method. This means that the advantage of the dual 2-level RLL modulation is not only the ease of modulation but also the flexibility of modulation. Moreover, this method must have the same effect as the 2-level RLL modulation, namely, the intensity distribution of the Fourier image must be concentrated in the center as much as that of the 2-level RLL modulation. When a Fourier image of a SLM image “A” is described as $F[A]$, the Fourier image resulting from the dual 2-level RLL modulation can be given by

$$F[A + iB] = F[A] + iF[B],$$

where $[A + iB]$ is the image generated with the dual 2-level RLL modulation and A, B are the images generated by the conventional RLL modulation, because the Fourier transformation is a linear mapping method. In Eq. (2), $F[A]$ and $F[B]$ are the conventional RLL modulated images. As a result, $F[A + iB]$ has analytically the same effect as the conventional RLL modulation.

### 3. Results and discussion

To confirm the effect of the dual 2-level RLL modulation, the following three methods were evaluated by a simulation and experiment. The example patterns generated by the three methods are shown in Figs. 5(a), 5(b) and 7(d).

(A) QPSK without RLL modulation [Fig. 5(a)]

(B) QPSK with 4-level RLL modulation [Fig. 5(b)]

(C) QPSK with dual 2-level RLL modulation [Fig. 7(d)]

#### 3.1 Comparison of intensity distribution on Fourier plane

As mentioned in Sect. 2.1, the high-density effect of RLL modulation can be observed as Fourier images. The intensity distribution of the Fourier images corresponds to the concentration of the signal beam in a disc. Simulated Fourier images of the above three methods are shown in Figs. 8(a)–8(c). The rectangular line shows the aperture size of the spatial filter. As a result, transmittances of the spatial filters were as follows: (A) 36.63%, (B) 67.98%, and (C) 67.99%. This result indicates that the dual 2-level RLL modulation (C) has almost the same distribution as the 4-level RLL modulation (B). Thus, the dual 2-level RLL modulation has the same effect as the conventional RLL modulation.

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### Table I. Input and output for 4-level RLL modulation.

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Fig. 5. 4-level RLL modulation method.

Fig. 6. (Color online) Constellation of QPSK signal. (a) Real part of signal and (b) imaginary part of signal.
Figure 9 shows a schematic diagram of an experimental system for measuring Fourier images obtained by the above three methods. The laser beam from a red-LD unit was modulated using a 512 × 512-pixel-phase-modulation SLM with a 15-µm pixel pitch. The SLM displayed patterns generated by the above three methods. The modulated beam was focused on a 2048 × 2048-pixel camera with a 5.5-µm pixel pitch using the relay lens. Then, the camera captured the Fourier image.

Experimental Fourier images for the above three methods are shown in Figs. 10(a)–10(c). The intensity distribution of the simulation result shown in Fig. 9 and the experimental result shown in Fig. 10 agree well. Therefore, the dual 2-level RLL modulation was experimentally confirmed to have the same effect as the conventional RLL modulation.

3.2 Comparison of SNRs
The high-density effect of the dual 2-level RLL modulation was confirmed by the Fourier image in Sect. 3.1. In addition, the above three methods were compared in terms of SNR by simulation. In the first-generation HDSS, we found that the reproduced images with more than 2.4 dB can be completely correctable. The SNR is given by

$$20 \log_{10} \left( \frac{\mu_{\text{on}} - \mu_{\text{off}}}{\sigma_{\text{on}} + \sigma_{\text{off}}} \right)$$

where $\mu_{\text{on}}$ and $\mu_{\text{off}}$ are the means of the distributions of “0”s and “1”s of a reproduced image, respectively, and $\sigma_{\text{on}}$ and $\sigma_{\text{off}}$ are standard deviations of “0”s and “1”s of a reproduced image, respectively. 2-level reproduced signal is required to decode the signal and calculate the SNR. Therefore, a 4-level reproduced signal must be divided into two 2-level signals as well as the recoded signal.

A flow diagram for the SNR calculation of the dual 2-level RLL modulation is shown in Fig. 11. 2-level RLL patterns were modulated by the method of the first-generation HDSS shown in Figs. 11(a) and 11(b). The two patterns were merged into a dual 2-level RLL pattern (c), filtered with the spatial filter (d), and random-complex noise was added to the filtered pattern (e). The dual 2-level pattern was divided into 2-level patterns (f), and then each 2-level pattern was resampled (g) and the SNR was calculated (h). By this process, the encoding and decoding signal processing of first-generation HDSS is easy to apply to the process of the
We investigated the 4-level recording methods to achieve further high-density recording, and we have developed the dual 2-level RLL modulation method suited to QPSK. The high-density effect of the method was confirmed experimentally by the Fourier images and SNR of reproduced images. Moreover, the method consists of two conventional 2-level RLL modulations used in the first-generation HDSS; this method can suppress increases in computational complexity and has good compatibility with the first-generation HDSS.

Consequently, the dual 2-level RLL modulation enables the doubling of the recording density; this gave us an inspiration for realizing a second-generation HDSS with the recording density of 4.8 Tbit/in.2.

**Fig. 12.** (Color online) Relationship between SNR and aperture size of spatial filter. (A) QPSK without 4-level RLL modulation, (B) QPSK with 4-level RLL modulation, and (C) QPSK with dual 2-level RLL modulation.

4. **Conclusions**

We investigated the 4-level recording methods to achieve second-generation HDSS. Thus, the compatibility among the two generations is satisfied.

In addition, the relationship between the SNR and the aperture size of the spatial filter is shown in Fig. 12. The horizontal axis represents the size of the aperture size normalized with the Nyquist size of the signal without RLL modulation, whereas the vertical axis represents the SNR. As a result, the dual 2-level RLL modulation (C) has almost the same characteristics as the 4-level RLL modulation (B). Thus, it becomes clear that the dual 2-level RLL modulation (C) achieves the same effect as the first generation HDSS, in consideration of shrinking a recoded hologram. As mentioned, the criterion of error correction is 2.4 dB; therefore, in method the case of (A) can be used the aperture size is only 0.96, whereas the methods the cases of (B) and (C) aperture size of 0.48. This result indicates that the dual 2-level RLL modulation can reduce the hologram size to half compared with case of the 4-level without RLL modulation.

Consequently, the feasibility of the 4-level RLL modulation was verified. Moreover, we will soon realize the 4-level RLL modulation and demodulation circuits by using circuits of the first-generation HDSS, because the developed dual 2-level RLL modulation consists of the RLL of first-generation HDSS.

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