Holographic diversity interferometry for optical storage

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Abstract: This study proposes holographic diversity interferometry (HDI), a system that combines information from spatially dispersed plural image sensors to reconstruct complex amplitude distributions of light signals. HDI can be used to generate four holographic interference fringes having different phases, thus enabling optical phase detection in a single measurement. Unlike conventional phase-shifting digital holography, this system does not require piezoelectric elements and phase shift arrays. In order to confirm the effectiveness of HDI, we generated optical signals having multilevel phases and amplitudes by using two SLMs and performed an experiment for detection and demodulation with HDI.

OCIS codes: (090.1995) Digital holography; (120.3180) Interferometry; (210.2860) Holographic and volume memories.

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1. Introduction

The recording capacity of optical memories with planar disk-type recording such as Blu-ray, is reaching its limit, and therefore the development of next-generation optical storage devices is expected. As an advantage, holographic memory offers a recording capacity of terabyte order by multiplex recording, and realizes a higher transfer rate than near-field optical memories and two photon absorption memories by inputting and outputting two-dimensional data pages. Presently, the recording capacity achieved by optical memories with two-dimensional data pages is around 600GB to 1TB per disc [1,2]. Although these values largely surpass the theoretical two-dimensional diffraction limit, they are still around 1/10 to 1/100 of the diffraction limit for three-dimensional optical recording. As a way to increase the recording capacity of optical memories, the multilevel modulation technique has recently attracted the attention of researchers [3–5]. In the field of communications, multilevel modulation of optical symbols, e.g., by phase shift keying (PSK) or quadrature amplitude modulation (QAM), increases the amount of information per symbol. A similar technique can be used to increase the capacities of optical memories. Although the generation of multilevel spatially phase-modulated signals is realized comparatively easily using a spatial light modulator (SLM), no optical device can directly detect the spatial distribution of light phases; thus, the development of a highly precise phase detecting method is important [6–8].

To this end, researchers are focusing on digital holography as a method to detect multilevel phases, and there have been reports of successful replay of two-dimensional data pages that were subjected to multi-valued phase modulation [5,9]. The methods for phase-shifting digital holography can be roughly divided into two categories. The first is a sequential method in which the phase of the reference light is temporally changed and holographic images are observed three or more times by sequential detection using a single imager [10–12]. The second is a parallel method in which the phase of the reference light is changed spatially and four digital holograms are generated from one detection image with single imager [13,14]. However, in the real-time operation of sequential-type detection systems, temporally changing the phase of the reference light using a device such as a piezoelectric element is difficult. In the parallel phase-shifting method, information about four pixels is required to detect one symbol, which could result in the deterioration of the detection resolution and increase in the interpolation processing load. Moreover, a phase shift array device is needed to spatially change the phase of the reference light.

To overcome the abovementioned problems, in this study, we propose holographic diversity interferometry (HDI), a method to measure the complex amplitudes of optical signals on the basis of information obtained from spatially dispersed plural image sensors. This method can be used to generate four holographic interference fringes having different phases, required for reconstructing signals in a single measurement by combining interference effects using a half mirror and polarizer. The signal pixels and detection pixels in HDI share a one-to-one correspondence, therefore, no spatial interpolation processing is needed and a reduced electrical processing load is entailed for reconstructing the original signals from the four captured images. In other words, HDI offers the advantages of both sequential-type digital holography, for which interpolation processing of images is unnecessary, and parallel phase-shifting digital holography, which records information for plural holograms at high speed as the main features in one hologram. Furthermore, unlike conventional digital holography, this method does not require piezoelectric elements and phase shift arrays to change the phase, and the interferometer can be entirely composed of standard polarizers. Therefore, it is easy to improve its accuracy and good stability can be maintained during its operation. In addition, this study proposes a method to perform HDI using only two CCD imagers even though four imagers are needed in most basic types of HDI. In order to confirm the effectiveness of this method, we performed an experiment by demodulating signals

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diffracting from an optical memory having two-dimensional data pages. In particular, the generated signals were detected by HDI and the original signals were demodulated by digital processing. Spatial quadrature amplitude modulation (SQAM) signals with multilevel phases and amplitudes were generated using two SLMs. By this method, the speed and capacity of optical memories can be improved. However, the applicability of this method is not limited to optical memories. In particular, measuring the spatial phase distribution of light is equivalent to detecting three-dimensional information about the light, and therefore, this method can be effective for real-time three-dimensional dynamic image measurements.

2. Holographic diversity interferometry

HDI is a new method to reproduce the complex amplitude of an optical signal by combining information from imagers arranged spatially and by irradiation with one reference light. This method is suitable for the high-speed real-time observation of light amplitude and phase, because four holographic interference fringes with different phases can be generated simultaneously without the need for a variable phase shifter and phase-shifting array device used in conventional digital holography. The structure and operating principle of HDI are shown below.

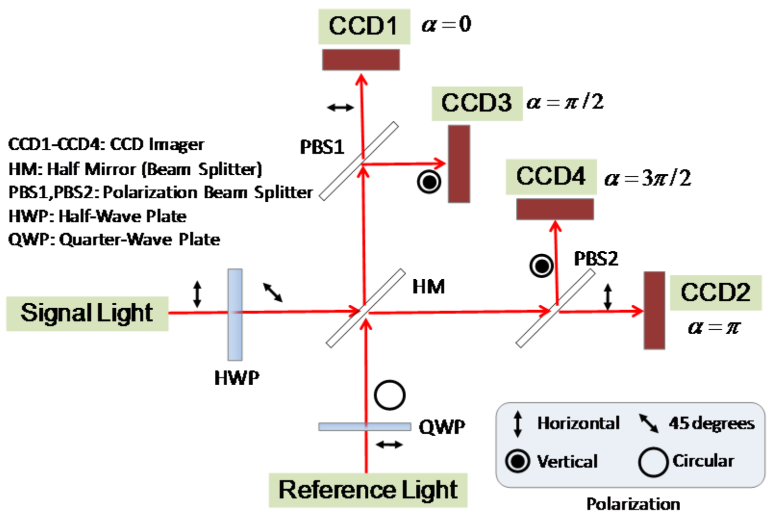

Fig. 1. Conceptual diagram of holographic diversity interferometry.

The observed light signal or optical image enters a half mirror (HM) or beam splitter from the left side, as shown in Fig. 1. The amplitude transmittance and amplitude reflectance of the HM for the light from this direction (rightward in the figure) are denoted by t and r, respectively. Moreover, the holographic reference light enters the HM from the bottom (as seen in the figure). The amplitude transmittance and amplitude reflectance of the HM for the light from this direction (upward in the figure) are denoted by t' and r', respectively. In this case, the Stokes relationships [15]

$$t^*t'+r^*r=1, \quad t^*r'+r^*t=0 \tag{1}$$

and the energy conservation law

$$t=t' \tag{2}$$

are generally satisfied.

When the signal and reference lights entering the HM are horizontally polarized light from the same laser source, the amplitude of the holographic interference occurring on CCD1 is expressed as

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$$I_{CCD1}(x,y) = \left|rA\exp(i\phi) + t'R_0\right|^2 \\ = |r|^2 A^2 + |t|^2 R_0^2 + 2AR_0\left|rt^*\right|\cos(\phi+\gamma) \tag{3}$$

and the holographic amplitude occurring on CCD2 is expressed as

$$I_{CCD2}(x,y) = \left|tA\exp(i\varphi) + r'R_0\right|^2 \\ = |t|^2 A^2 + |r'|^2 R_0^2 - 2AR_0\left|rt^*\right|\cos(\gamma+\varphi) \\ = |t|^2 A^2 + |r'|^2 R_0^2 + 2AR_0\left|rt^*\right|\cos(\gamma+\varphi-\pi) \tag{4}$$

where $A(x,y)\exp\{i\phi(x,y)\}$ is the signal light with amplitude $A(x,y)$ and phase $\varphi(x,y)$, R_0 is the amplitude of the reference light, and γ denotes the phase angle of the product of reflectance and transmittance. Comparing Eq. (3) with Eq. (4), the phase of the holographic interference is shifted by π. In other words, this difference suggests that the interference fringes with phases of $\alpha = 0$ and $\alpha = \pi$ can be generated simultaneously, where the phase α is based on the interference fringe on CCD1. For instance, when there is a bright pixel on CCD1, the corresponding pixel on CCD2 is dark. To measure complex amplitude precisely, it is necessary to equalize the first and second terms on the right side of Eq. (3) and Eq. (4), $|r|^2 = |r'|^2 = |t|^2$ in other words. In HDI, it is necessary to use a HM, which satisfies this assumption.

Next, it is assumed that the signal light $A(x,y)\exp\{i\phi(x,y)\}$ and holographic reference light R_0 are linearly polarized light (horizontally polarized light) from the same laser source. However, for the signal the angle of polarization is rotated through 45 degrees by a half-wave plate (HWP) as shown in Fig. 1. This means that after passing through the HWP the signal has a horizontally polarized component and vertically polarized component that are in phase with each other. The holographic reference light, which is horizontally polarized light, is converted into circularly polarized light by passing through a quarter wave plate (QWP). Here, circularly polarized light means a state of polarization in which the phase difference between the horizontally polarized component and vertically polarized component is $\pi/2$.

Under the optical conditions described above, consider first the two light beams that exit toward the upper side of the HM after the signal light and holographic reference light enter the HM. The horizontally polarized component of the signal light and that of the circularly polarized reference light generate a holographic interference corresponding to $\alpha = 0$ on CCD1. At the same time, the vertically polarized component of the signal light and that of the circularly polarized reference light reflected from a polarization beam splitter (PBS1) and propagate toward the right side of the figure. Since a phase difference of $\pi/2$ exists between the horizontally and vertically polarized components of the circularly polarized light, a holographic interference corresponding to $\alpha = \pi/2$ is generated on CCD3 and can be expressed as

$$I_{CCD3}(x,y) = \left|rA\exp(i\varphi) + t'R_0\exp(i\frac{\pi}{2})\right|^2 \\ = |r|^2 A^2 + |t|^2 R_0^2 + 2AR_0\left|rt^*\right|\cos(\varphi+\gamma-\frac{\pi}{2}) \tag{5}$$

Similarly, consider next the two light beams that exit toward the right side of the HM after the signal light and reference light enter the HM. The horizontally polarized component of the signal light and that of the reference light pass straight through PBS2 and generate a holographic interference corresponding to $\alpha = \pi$ on CCD2. At the same time, the vertically polarized component of the signal light and that of the reference light reflect from PBS2 and propagate toward the upper side of the figure. According to the relationships of Stokes and the property of circularly polarized light, a holographic interference corresponding to $\alpha = 3\pi/2$ is generated on CCD4 and can be expressed as

$$\begin{aligned} I_{CCD4}(x,y) &= \left| tA\exp(i\varphi) + r' R_0 \exp(i\frac{\pi}{2}) \right|^2 \\ &= |t|^2 A^2 + |r'|^2 R_0^2 + 2AR_0 |rt^*| \cos(\varphi + \gamma - \frac{3\pi}{2}) \end{aligned} \tag{6}$$

When the signal light and holographic reference light are added to this holographic diversity detection system, a different holographic interference is simultaneously generated on each CCD, as though the phase of the holographic reference light were changed from $\alpha = 0$ to $\alpha = \pi/2$, π, and $\alpha = 3\pi/2$, but without the need to adjust the optical path length.

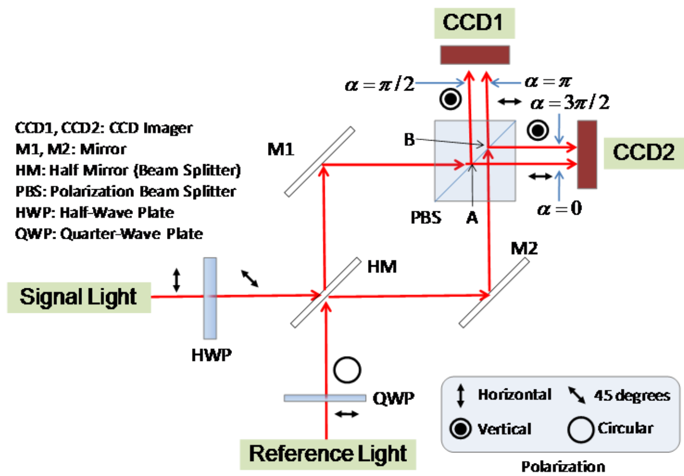

Fig. 2. HDI with two CCD imagers.

Figure 2 shows that by partially changing the composition of the optical system in Fig. 1 a method for HDI with four holographic interference images on two CCDs is possible. The signal light and the reference light pass through the HM to enter the same PBS. At this point, two different holographic interference images are generated on one CCD by moderately separating the positions at which the light beams enter from the lower side and the left side, as shown in Fig. 2 by points A and B. Thus, holographic interference corresponding to $\alpha = \pi/2$ and $\alpha = \pi$ is generated, respectively, on the left and right portions on CCD1, while that corresponding to $\alpha = 3\pi/2$ and $\alpha = 0$ is generated on those of CCD2.

In these examples of HDI, the calculation that recovers the phase and the amplitude of the original signal from the four interference images V_n $(n = 1,2,3,4)$ is similar to that of the standard phase-shifting digital hologram, as follows [16]:

$$\phi(x,y) = \tan^{-1} \frac{\sum_n V_n \sin\alpha}{\sum_n V_n \cos\alpha} \tag{7}$$

$$A(x,y) \propto \sqrt{\left(\sum_n V_n \sin\alpha\right)^2 + \left(\sum_n V_n \cos\alpha\right)^2} \tag{8}$$

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The amplitude of the original signal can also be measured by detecting directly the signal light without making the reference light be incident on.

Comprising only two or four CCD imagers and standard polarizing elements is the most characteristic feature of HDI. The interference pattern, which is needed to reconstruct the phase distribution of the original signal, is automatically generated by one reference beam on each imager. With regard to its signal processing load, HDI has an advantage similar to that of sequential phase-shifting digital holography, in that one signal pixel may correspond to one detection pixel. In parallel phase-shifting digital holography, the signal processing of the interpolation becomes complex, as one detection pixel receives any of four different phases in the reference light to generate the digital hologram by the phase-shifting array device [14]. Moreover, four holographic interference images can be detected simultaneously by HDI, since the phase retardations among holographic interference fringes are obtained in parallel by diversity interferometry using two or four image sensors, even though in principle the difference at detection time is found in a digital hologram of the sequential type [10].

3. Experimental

For the purpose of confirming the operation of HDI, we performed an experiment in which optical signals having multiple values of the phase and amplitude were generated using two SLMs. These signals were detected and demodulated with HDI, simulating the case of demodulating signals from an optical memory having two-dimensional data pages. QAM is a modulation technique in which amplitude modulation (AM) and phase modulation (PM) are combined. For radio communication and optical communication, this modulation technique can transmit plural information by changing both the amplitude and phase [17]. In communication technologies the signals are modulated along the direction of a temporal axis, whereas in optical memories the information is recorded and replayed by modulating signals along the directions of spatial axes in two dimensions (x, y). Therefore, in this study, we refer to spatial quadrature amplitude modulation (SQAM) to distinguish this technique from the QAM defined for communication technologies.

The SQAM signals used for the experiment were light information having six values of symbolic points generated by two values of intensity and three values of phase, as shown in the constellation diagram at the left side of Fig. 3. The horizontal I and vertical Q in the figure are defined as follows:

$$\begin{aligned} I &= A(x,y)\cos\phi(x,y) \\ Q &= A(x,y)\sin\phi(x,y) \end{aligned} \tag{9}$$

The reason that the symbolic points do not extend into the lower half of the figure is because the phase change width of the SLM used in the experiment was restricted, not because of any theoretical restriction on the method. The page data used in the reproduction experiment are shown at the right side of Fig. 3.

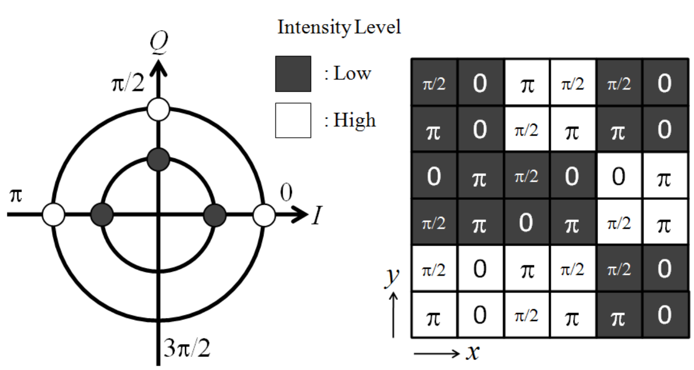

Fig. 3. Constellation diagram of SQAM signal and page data with 6 × 6 symbols.

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Figure 4 shows the experimental arrangements. The light emitted from the laser was passed through a beam expander and then was split in two directions with PBS1. The light wave that propagated leftward in the figure was used for signal light generation. First, intensity modulation was performed on this light with SLM1, which was a transmission-type spatial modulation device. After that, phase modulation was performed with SLM2, which was a reflective-type spatial modulation device, and SQAM signals were generated. Next, the signal light generated in this way was detected and reconstructed by HDI. The signal light was converted to linearly polarized light at 45 degrees by passing through HWP2. Moreover, the reference light for interference was generated with the light wave that propagated downward from PBS1 in the figure and was converted into circularly polarized light by passing through the QWP. The interference patterns with the phases shifted by π with respect to each other were generated from the signal light and reference light incident on BS2. Furthermore, the interference patterns with the phases shifted by π/2 were generated by making the light beams that exited BS2 enter PBS2 at slightly different places. Two holographic interference images with α = π/2 and α = π were captured simultaneously on the right and left regions of CCD1, and those of α = 3π/2 and α = 0 were similarly captured on CCD2. Lenses L5 and L6 were used to form images on the image sensor being combined with the lenses L7 and L8, respectively.

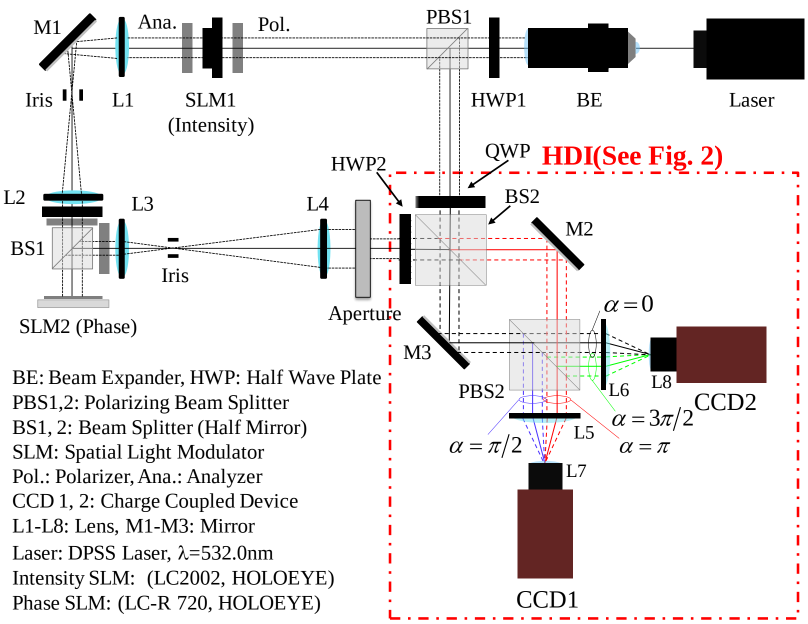

Fig. 4. Experimental arrangements.

In this experiment, light intensity was adjusted using ND filters not shown in Fig. 4, so the intensities of the signal beam and the reference beam that entered into HDI were 350 μW and 300 μW, respectively. Each signal beam consisted of a 6 × 6 symbol. The pixel pitch of the SLM used for the intensity modulation was 32 μm, and one symbol of the signal corresponded to 14 × 19 pixels on this SLM. Moreover, the pixel pitch of the SLM used for the phase modulation was 20 μm, and one symbol corresponded to about 22 × 30 pixels on this SLM.

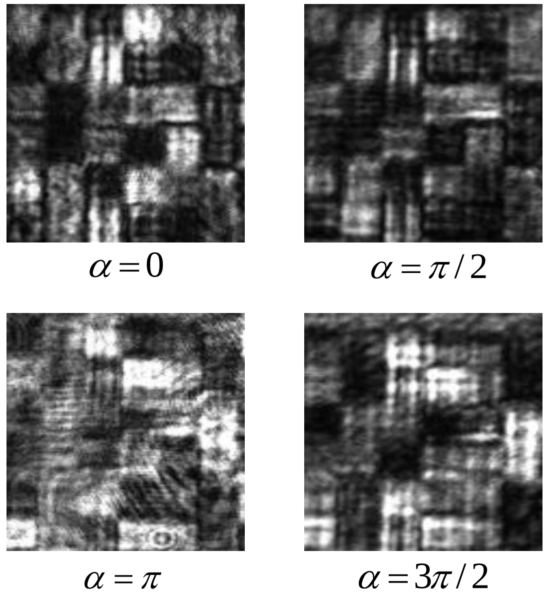

Fig. 5. Holographic interference patterns captured by CCDs in HDI.

Figure 5 shows four holographic interference patterns captured by CCDs with spatial phase shifts α of 0, π/2, π, and 3π/2. These images were taken simultaneously with two image sensors, each a 1/3-inch progressive scanning CCD with an intensity resolution of 16bit. We observe that the image brightness of the symbol changes with the phase α of the detecting sensor. This means the different holographic interference that accompanies a different phase-shift is produced by a different sensor. In other words, even without time series phase-shifting or spatial phase array, the four holographic interference images necessary for phase-shifting digital holography are generated by HDI. Figure 6 shows the intensity and phase data extracted from these holographic interference images by Eq. (7) and Eq. (8). Finally, a conversion is necessary to recover the original digital signal, because the holographic image contains analog data. Threshold processing was performed on these raw data using a PC, and the restorations of the original symbols are shown in Fig. 7. In this case, the SQAM signal was detected by the HDI without error. Although the number of symbols in this experiment was small, the accuracy of reconstruction in a practical optical memory is associated with an increased size of page data. To maintain high accuracy, two SLMs with finely matched pixels and an optical system with high spatial coherence will be required.

Positional gap of the signal light and the reference light, which are incident on the HM, cannot be a large problem since the reference light with a beam diameter that is greater than that of the signal light is used. It is necessary to make angle of the signal light equal to that of the reference light so that variation of interference fringe in one pixel can become small enough when these lights were incident on the image sensors. However, since values of each pixel can be calculated independently in HDI, it is not necessary to make phase of the reference light uniform over plural pixels on the image sensor for accuracy. In addition, a relative shift between the different image sensors greatly affects the measurement accuracy of complex amplitudes in HDI. To perform the detection with high precision, it is necessary to adjust the positions and angles of the image sensors by giving a signal to be basis beforehand and examining where the signal is detected on the image sensors. Furthermore, for application to optical memory, in the case that there is a distance between data symbols constituting signals or that one data symbol can be received on plural pixels on the image sensor, it is possible to ease the precision required for this adjustment.

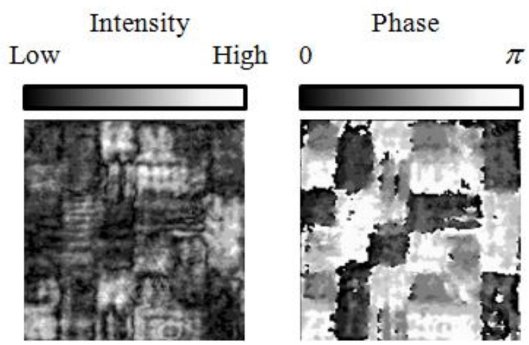

Fig. 6. Result of data extraction.

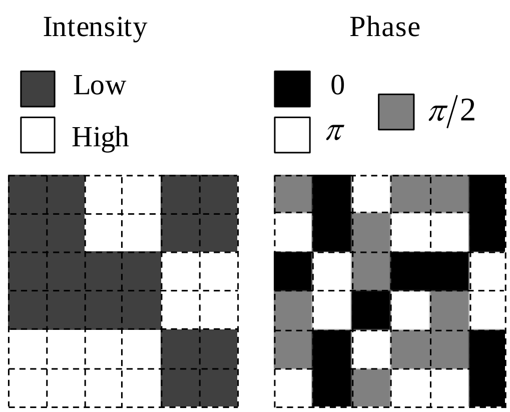

Fig. 7. Result of restoring the original symbols.

4. Conclusion

In this study, we have proposed HDI as a light amplitude measuring technique that has many advantages over the conventional phase-shifting interference measurement techniques. In addition, we performed experiments to evaluate its effectiveness and succeeded in not only generating SQAM signals with multi-valued phases and amplitudes using two SLM, but also detecting the signals with HDI and demodulating them by digital processing. Although two CCD cameras were used in our experiments, it is possible to generate four holographic interference images in different regions of a single CCD by using an optical system. As regards future developments for optical memories, we plan to demonstrate replaying of SQAM signals obtained by HDI after recording on media such as photopolymers. Moreover, because HDI can be used widely for measurements of light spatial amplitudes, we anticipate its application to real-time measurements for medical analyses and product inspection, as well as three-dimensional dynamic image measurements of living cells.

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