Readout Properties of Polychromatic Reconstruction for Nondestructive Holographic Data Storage

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Abstract: Polychromatic reconstruction (PCR) is a novel nondestructive readout method that utilizes a spectrally broad light source for the probe beam. The stored image can be completely reconstructed even though the probe wavelength is very different from the recording one. The large spectral width of the polychromatic probe beam also causes adverse effect on the storage density. But this can be overcomed if an additional optical component is inserted in the imaging system. Therefore, PCR has a great potential to achieve nondestructive readout and large storage density simultaneously. In addition, PCR enables us to design a simple memory system because its readout tolerance is quite large as compared to the conventional monochromatic readout. Unique and attractive features of the polychromatic reconstruction method was theoretically and experimentally demonstrated.

Key words: holographic data storage; nondestructive readout; polychromatic light; tolerance; shrinkage; photopolymer

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0 Introduction

Holographic data storage (HDS)[1] is one of the most promising candidates for the next optical data storage system. In HDS, the information is stored as a volume hologram that is formed by an interference pattern between the signal and reference beams, and the readout is performed through the holographic reconstruction process by illuminating the hologram with a readout beam. The most characteristic feature of HDS is "multiplexing", which means that different holograms can be stored at the same location within the medium and their information can be reconstructed independently. The principle of multiplexing is usually explained by the selectivity of the Bragg diffraction. If the readout is performed with slightly different condition with the recording one, for example, at a different incident angle of the reference beam, then the diffraction will not occur from that hologram, and thus another hologram can be multiplexed at that angle. Due to the nature of the Bragg diffraction, the thicker hologram usually shows higher selectivity. In theory, if we use a 1 cm thick medium, the angle multiplexing can be performed with a very small angular separation in the range of 10^{-3} degree. Such high selectivity of the Bragg diffraction is responsible for a large storage capacity (~1 T byte/cm^3) in HDS, but it also causes two

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serious problems that prevent us from realizing the HDS in practical use.

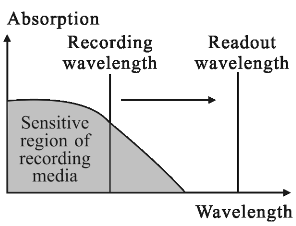
One is the destructive readout. In rewritable recording media, like photorefractive materials, illumination with a readout beam will rewrite the holograms that was recorded before, i.e., the readout will destroy the stored information. Even in a photopolymer, which is currently the most promising write-once recording material, if some monomers still exist within the volume to be read, then the readout beam will cause unintentional polymerization, which wastes the storage capacity. Clearly, such a destructive readout is caused by the readout beam having an ability to expose the recording medium. This is usually inevitable whenever the readout wavelength is same with the recording one, which is the normal choice to satisfy the Bragg condition.

To solve the above problem, several nondestructive readout methods [2-5] have been proposed so far, where the stored image can be reconstructed at a longer wavelength, outside the photosensitive spectral region of the recording material. However most of the methods may be not practical for a HDS system because the storage capacity is considerably lowered. For example, the spherical probe beam method proposed by Külich [4] enables us to reconstruct the image at different wavelength owing to the wide angular spectrum of the spherical beam, but this method tends to produce severe crosstalk noise from other multiplexed holograms, which demands a large angular separation between two adjacent multiplexed holograms, and thus results in a small storage capacity.

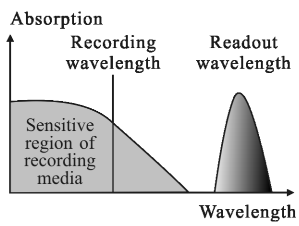
The other problem is the small tolerance of readout, i.e., the narrow acceptable range of the readout condition. This is in the trade-off relationship against the storage capacity, because the high selectivity of Bragg diffraction is responsible for achieving the large storage capacity. Thus, it is mandatory for a HDS system to control the readout wavelength and incident angle with very high accuracy, which results in the HDS becoming more high-cost, large-sized, and complicated system. In addition to such precise controls, the deformation of the recording medium must be suppressed to quite low level. The allowed volume change is typically on the order of 0.01% in a 1 cm thick hologram. Indeed, the temperature change of a few degrees causes the diffracted signal to be vanished due to the thermal expansion. High selectivity of Bragg diffraction has also affected a material design of photopolymer. Since the most photo-polymerization process tends to shrink the volume of the recording medium, the photopolymer must be designed to reduce the shrinkage even if it sacrifices the dynamic range that is directly related to the achievable storage capacity.

Since the realization of the large storage capacity and above two problems are originated from the common origin, i.e., the Bragg diffraction, they are closely related to each other and cannot be treated individually. In fact, there has been no report on a HDS system realizing the large storage capacity, nondestructive readout, and large readout tolerance, simultaneously.

Polychromatic reconstruction (PCR) [6], which we have proposed as another nondestructive readout method, is a promising method to solve above issues. PCR utilizes a readout beam having some spectral bandwidth instead of monochromatic light, as shown in Fig.1. The notable feature in PCR method is that,



(a) Conventional monochromatic readout at a longer wavelength



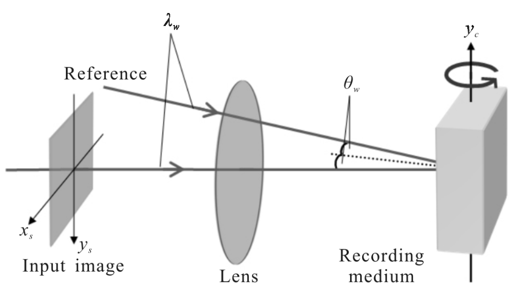
(b) Polychromatic reconstruction with a broadband readout beam

Fig.1 Concept of the nondestructive readout method

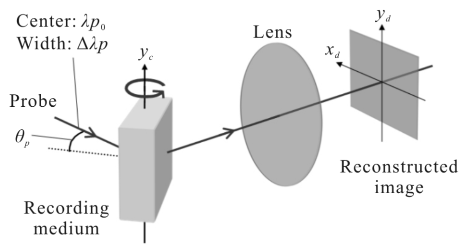
unlike the case of other nondestructive readout methods, both the nondestructive readout and a large storage capacity can be achieved simultaneously [7]. Furthermore, the readout tolerance in PCR is quite large enough to produce the diffracted signal even at the temperature change of 20 ℃ [8]. Such a large tolerance in PCR method not only makes the system simple, but also will eliminate the current constraint on the material design of photopolymer. In this paper, we present a brief review of the characteristic features of PCR method.

1 Priciple of polychromatic reconstruction

The recording and readout schemes of the PCR method are illustrated in Fig.2. In the recording process, a monochromatic signal beam bearing the image information passes through a Fourier transform lens and records a Fourier hologram in the usual way. In the readout process, the collimated polychromatic readout beam is incident on the hologram at an appropriate angle. Since the HDS usually stores 2D image information, the signal beam consists of many plane waves and creates various grating vectors after interfering with the reference plane wave, as shown in Fig.3 (a). Note that, in Fig.3, only three angular spectral components are depicted for simplicity, but in reality, a number of components should exist. Since one particular point in an input image corresponds to one grating vector in the Fourier plane, all grating components must produce the diffracted wave to reconstruct the complete image. However, when the readout wavelength is different from the recording one, the Bragg condition cannot be satisfied at all grating components, and thus only the part of the image will be reconstructed as shown in Fig.3(b). On

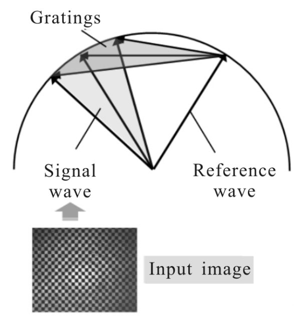


(a)

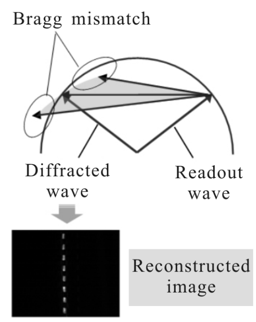


(b)

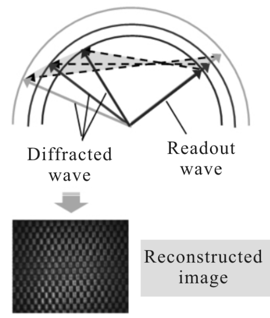
Fig.2 Schematic diagram of (a) the recording and (b) the readout schemes in the PCR method



(a) Recording process



(b) Readout process using monochromatic wave



(c) Readout process using polychromatic wave

Fig.3 Principle of PCR in K-vector diagram and reconstructed images

the contrary, if the readout beam has an adequate spectral width like in PCR method, each grating component can be Bragg-matched at one particular wavelength within the broadband spectrum of the readout beam, as shown in Fig.3(c). Thus, the whole image can be successfully reconstructed even though the readout wavelength is very different from the recording one.

A simulated result of the reconstructed image in PCR method is presented in Fig.4. In this simulation, we assumed that the input image was recorded at w 532 nm and was reconstructed with a polychromatic readout beam with a central wavelength p_0 of 815 nm. From the figure, we can see that the reconstructed image is formed with wide spectral components ranging from 795 nm to 835 nm, and image magnification occurs only in the y_d-direction. In addition to above basic imaging properties, the PCR shows several characteristic features as compared with conventional monochromatic reconstruction. So far, we have developed comprehensive theory of PCR method and derived expressions for the required spectral bandwidth, the distortion of the reconstructed image, the optimum recording configuration, the crosstalk noise, the theoretical limit of the storage density, and so on[9]. The obtained expressions are very informative for designing and constructing an actual HDS system utilizing the PCR method.

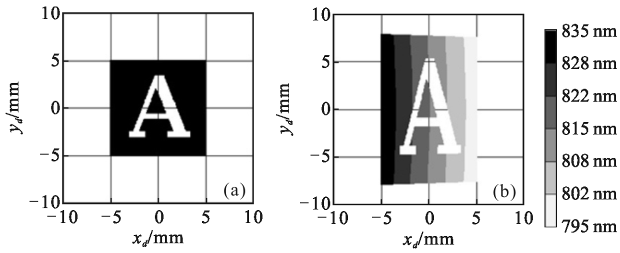


Fig.4 Simulated results of the reconstruction (a) input image and (b) the reconstructed image. The scale bar in (b) represents the Bragg-matched wavelength of each diffracted wave

2 Selective detection method for realizating a large storage density

The angular selectivity (i.e., how small the angular separation can be made) is an important figure of merit determining the total storage capacity of the system. In order to see the angular selectivity in PCR, we have simulated reconstructed images after the rotation of the hologram with respect to the y_c-axis depicted in Fig.2. The simulated results are shown in Fig.5. Even after the rotation angle of 1.0°, the image was partially reconstructed. It indicates that the rotation angle of 1.0° is not a sufficient rotation angle for multiplexing. Therefore, the angular selectivity in the PCR method is decreased by two orders of magnitude as compared with conventional monochromatic case. This reduction is comparable with that in the spherical beam method [10]. However, unlike the case of the spherical beam, such a drawback of PCR can be completely overcome by the selective detection method[7]. In PCR method, the Bragg-matched wavelength at a certain imaging position (x_d, y_d) will change after the hologram rotation as can be seen in Fig.5. Taking advantage of this wavelength difference, we can detect the signal image alone, even if the noise images overlap with the target signal image. For example, by inserting a suitable wavelength separator into the reconstructed image plane, the stored information can be retrieved without crosstalk even if the angular separation is not large enough to suppress the noise diffraction.

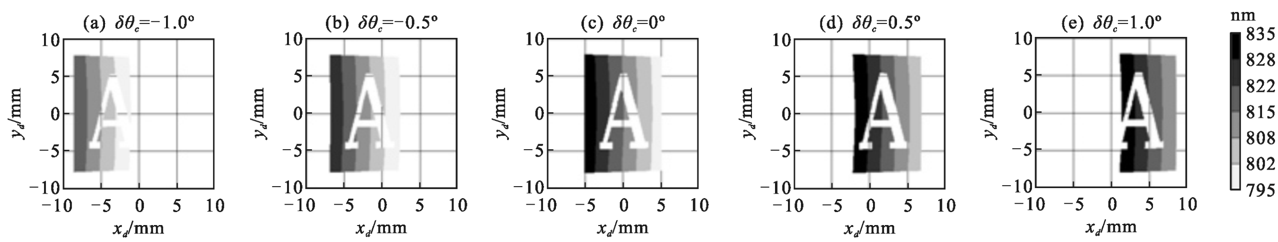


Fig.5 Simulated resutls of the angular selectivity in PCR method. $\delta\theta_c$ is the rotation angle around the y_c-axis

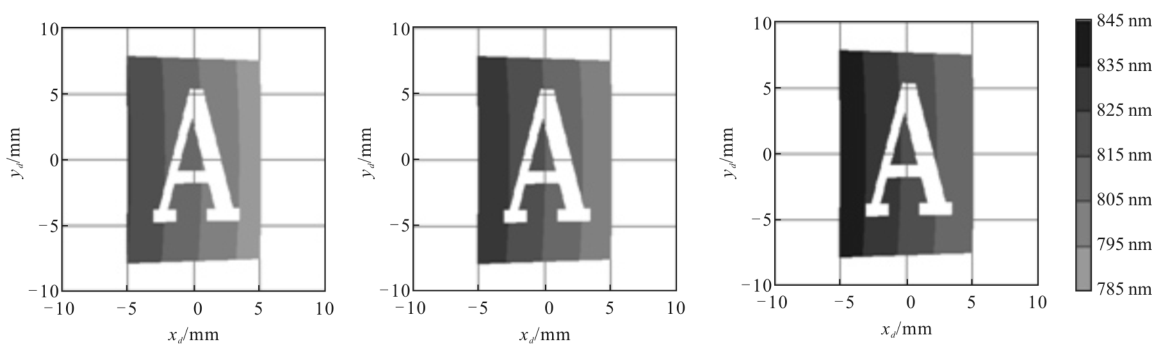
To confirm the validity of the selective detection method, we performed experiments employing a band-pass Linear Variable Filter (LVF) as a wavelength separator. The three different images, "ABC", "abc", and "123", were recorded with an angular separation of 0.6°. The reconstructed images obtained without- and with the LVF are shown in Figs.6 (b) and 6(c), respectively. Since the angular separation of 0.6° was not a sufficient rotation angle, the severe crosstalk noise disturbed the detection of the target signal image. Employing the LVF, however, although the polychromatic beam produced noise images from the other multiplexed holograms, only the target signal image was successfully detected as shown in Fig.6(c). Since the degree of improvement depends on the transmitting bandwidth of the wavelength separator, the storage capacity in the PCR method will be completely recovered if we use an LVF having a sufficiently small bandwidth. Therefore, PCR has a great advantage in the storage capacity compared with other nondestructive readout methods proposed so far.

(a) Target signal image to be read (b) Reconstructed images without LVF (c) Reconstructed images with LVF

Fig.6 Reconstructed images of multiplexed holograms.

3 Readout tolerance

As was seen in the previous section, PCR method has quite low angular selectivity unless the selective detection method is applied. In other words, it indicates that PCR method has intrinsically large readout tolerance as compared to the conventional monochromatic readout. In addition, our theoretical study shows that PCR method has a quite large readout tolerance also for the deformation of the hologram. Figure 7 shows the reconstructed images after the medium expansion by using PCR method. In this simulation, an input image was recorded at $\lambda_w=$ 532 nm and was reconstructed with the polychromatic probe beam with center wavelength λ_{p0} of 815 nm and full spectral width $\Delta\lambda_p$ of 60 nm. The image was reconstructed even at the expansion factor γ_0 of ±1.0%. Furthermore, the imaging position was not changed with the isotropic volume change, but the wavelength of the diffracted wave was shifted about ±8 nm at the



(a) (b) (c)

Fig.7 Reconstructed images after the medium expansion in PCR method. The expansion factor 0 are (a) 1.0%, (b) 0.0%, and (c) 1.0%, where the minus sign of the expansion factor represents shrinkage of the recording medium expansion factor γ_0 of ±1.0%. Therefore, as is similar to the tolerance for the incident angle of the polychromatic probe beam, the readout tolerance for the volume change in PCR method is quite large and depends on the spectral width of the polychromatic probe beam. If the spectral width of the polychromatic readout beam is sufficiently large, the stored information can be successfully reconstructed even at the volume change of 1.0%. In order to confirm the large tolerance in PCR method, we performed the readout experiments by using 1 cm thick photorefractive crystals. The results are shown in Fig.8. In this experiment, Single hologram was recorded at crystal temperature of 35 ℃. And then, the readout performed at several increased temperatures. Due to the severe selectivity of Bragg diffraction, the temperature change of 2 ℃ made the image almost disappear in the conventional monochromatic readout. In contrast, the stored image could be successfully reconstructed in PCR method even at a temperature change of 20 ℃.

We also experimentally demonstrated the large tolerance for the media shrinkage in PCR method. Figure 9 shows experimental results of the holographic reconstruction with a large shrinkage medium. In this experiment, a single hologram was recorded in unexposed 1 mm thick photopolymer, and then the images were obtained after certain amounts of post exposure. In conventional monochromatic case, the image cannot be obtained after some exposure. However, PCR can reconstruct the image even at a medium shrinkage of 0.37%. This result clearly shows that PCR have a large readout tolerance as compared to the monochromatic readout. It may release us from the severe restriction against the shrinkage in the material design of photopolymer.

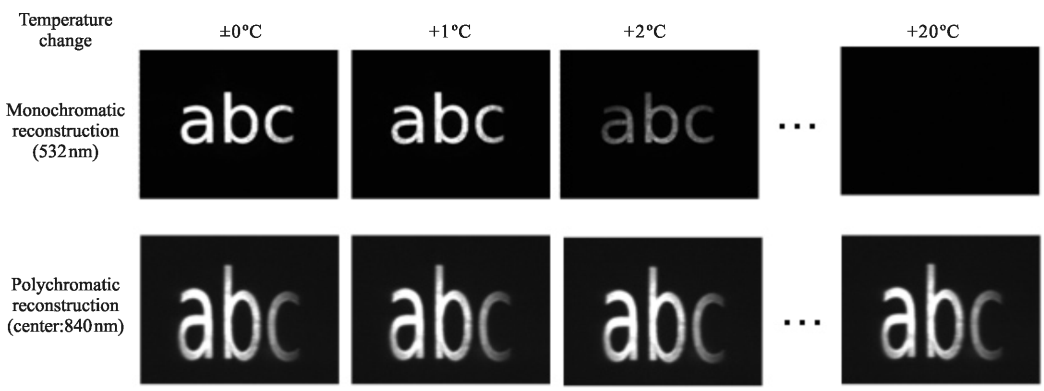


Fig.8 Experimental results of the readout tolerance for the temperature change

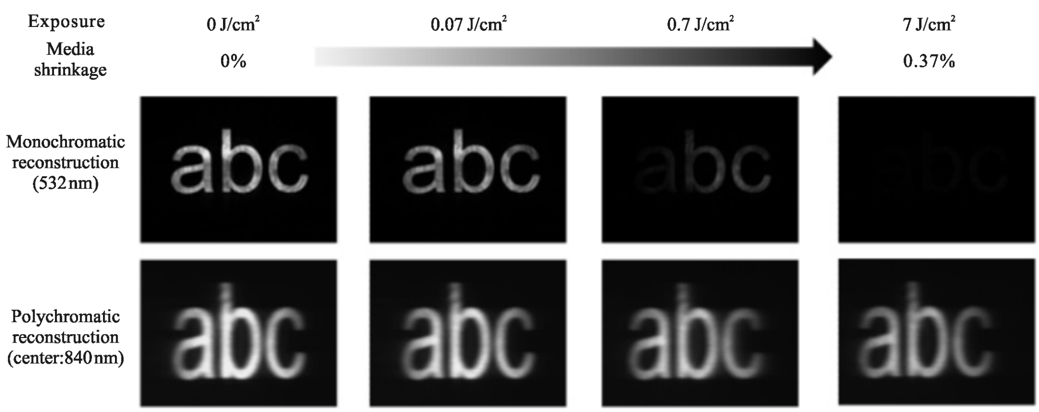


Fig.9 Experimental results of the readout tolerance for the media shrinkage

4 Conclusion

Polychromatic reconstruction is a novel readout method that utilizes a broadband readout beam instead of monochromatic light. Its characteristic features and impacts are summarized as follows.

(1) Nondestructive readout

The stored holograms can be reconstructed at any desired wavelength. It means that the nondestructive readout is possible if the readout wavelength is selected from an insensitive spectral region of a recording material. Since the readout will not cause any influence on the recording materials, a bulk-shaped recording medium, such as a spherical or cubic shaped photopolymer, can be adopted instead of the conventional disk-type recording medium. Higher angular selectivity and larger diffraction efficiency are expected in bulk-shaped thick recording medium owing to the nature of the Bragg diffraction. Furthermore, because the separate light sources are used for the recording and readout processes, real-time data verification can be performed simultaneously with recording a hologram. A lot of benefits can be received from the nondestructive readout.

(2) Storage capacity

The large spectral width of the polychromatic probe beam causes deterioration of the angular selectivity and results in considerable lowering of the storage capacity. However, such a drawback can be overcome by using a selective detection method. By inserting a suitable wavelength separator into the reconstructed image plane, we can retrieve the stored information without crosstalk even if the angular separation is not large enough to suppress the noise diffraction. While other nondestructive readout methods have failed to achieve a high storage capacity, the polychromatic reconstruction employing the selective detection method has a great potential to achieve both nondestructive readout and a high storage capacity, simultaneously.

(3) Readout tolerance

Readout tolerances for wavelength shift, incident angle change, ambient temperature, and media shrinkage are very large in polychromatic reconstruction method due to the wide spectral width of the readout beam. Such a large tolerance in PCR method should be a great advantage because it enables us to construct a simple memory system. Furthermore, if the tracking mark is additionally embedded in the input images, the characteristic of large tolerance can be utilized in a tracking system, that is, readout conditions are detected and corrected by using the information from the tracking mark.

In summary, polychromatic reconstruction is a quite promising method in holographic memory system. It is a simple but effective way to solve the longtime difficulties in a holographic data storage system.

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