Polychromatic reconstruction for volume holographic memory

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We propose a method of reconstructing an image from a volume hologram at a wavelength different from the recording one. Spectrally broad but spatially coherent light was used as a probe beam. Each angular spectral component of the recorded hologram could be Bragg matched at one particular wavelength within the broadband spectrum. We experimentally demonstrated that a whole image could be reconstructed by using polychromatic light, whereas only a partial image was obtained by using single-mode laser light. We discuss the required bandwidth of the probe beam and the deformation of the reconstructed image. © 2007 Optical Society of America

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Unintended erasure of recorded holograms during readout has been the main obstacle to rewritable holographic memories [1]. One of the simplest solutions is to read the hologram at a longer wavelength outside the sensitive spectral region of the recording media. However, reconstruction at a wavelength different from the recording one leads to deterioration of the reconstructed image, or narrowing of the image field due to Bragg's law [2]. Several papers [2–7] have addressed this issue and proposed some solutions. For example, anisotropic diffraction [3] in a birefringent crystal increases the spatial bandwidth of the Bragg-matched grating vector but is not suitable for multiplexing because it requires a specific configuration. A spherical probe beam [4] is a simple but effective way to obtain a whole image. With this method, each angular spectral component of the grating can be Bragg matched with a particular plane wave within the spherical probe beam. On the other hand, the spherical probe beam degrades the Bragg angle selectivity and produces unwanted diffraction from the other multiplexed holograms. Therefore the angular separation between the holograms should be large to avoid cross-talk noise, and as a result the storage density is substantially reduced.

In this Letter, we propose another way to reconstruct a whole image at a wavelength different from the recording one. Our method, which we call polychromatic reconstruction (PCR), utilizes a spectrally broad but spatially coherent light source for the probe beam, such as a superluminescent diode (SLD). Each angular spectral component of the grating can be Bragg matched at one particular wavelength within the broadband spectrum of the probe beam. Analogous to the spherical probe beam method, PCR is also expected to degrade the Bragg selectivity. However, PCR can improve the level of such degradation, unlike the case of the spherical probe beam. Here, we show the fundamental properties of PCR, such as the required probe bandwidth, the image properties, and the cross-talk noise from other holograms. We also describe an experiment demonstrating that the reconstructed image field was extended by using the PCR method compared with reconstruction with a monochromatic plane wave.

Figure 1 illustrates the recording and readout schemes of the PCR method. 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 probe beam is incident on the crystal at an appropriate angle. Optical waves with different wavelengths are diffracted by the hologram in different directions according to Bragg’s law and then form an image exhibiting wavelength dispersion on the detector. Note that PCR can be applied only to Fourier holograms, where a two-dimensional object is placed at the front focal plane of the Fourier transform lens so that one grating vector corresponds to one particular point on the object plane. Even though all the diffracted waves are obtained in an image hologram and a Fresnel hologram with polychromatic light, the image cannot be reconstructed, since waves with different wavelengths cannot construct a point image.

The signal beam bearing the image information includes many plane waves and creates various grating vectors after interfering with the reference plane wave, as shown in Fig. 2(a). Note that, in Fig. 2, only three angular spectral components are depicted for simplicity, but in reality an infinite number of components should exist. First, we deal with one grating component recorded by signal and reference plane waves. When a grating recorded at wavelength \( \lambda_{\text{in}} \) is read at \( \lambda_{p_{jn}} \), the Bragg condition is expressed as

\[
\theta_j = \frac{\lambda_{p_{jn}}}{\lambda_{\text{in}}},
\]

Fig. 1. Schematic diagram of (a) the recording and (b) the readout schemes in the PCR method.

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vector of the diverged signal beam, and

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the grating \( k \)
we assume that wavelength dispersion of the refractive
for all of the gratings shown in Fig.2(b). Therefore an adequate spectral width is needed for different grating vectors, which means that a monochromatic plane wave cannot satisfy the Bragg condition for all of the grating vectors shown in Fig. 2(b). Therefore an adequate spectral width is needed for the probe beam so that all of the gratings can be Bragg matched as shown in Fig. 2(c).

The spectral width required for the reconstruction of the whole image depends on the divergent angle of the signal beam. We express the signal component \( e_{dj} \) as \( e_{dj} = \mu_j (e_{sj} - e_r) \), where \( e_{sj} \) is the central direction vector of the diverged signal beam, and \( \delta e_{sj} \) is the deviation vector from \( e_{0} \). When the relation \( |\delta e_{sj}|^2 \leq 1 \) holds, the difference between \( \mu_j \) and \( \mu_0 \) is given by

\[
\delta \mu_j = -\frac{2e_{0} \cdot \delta e_{sj}}{|\hat{k}_{sj}|^2}.
\]

Equation (3) indicates that the Bragg-matched wavelength depends not only on the amplitude \( |\delta e_{sj}| \), but on the projection of \( \delta e_{sj} \) on \( e_{0} \). We assume that \( e_{0}, e_r, e_p \) lie in the same plane \( \Sigma \), and thus \( e_{0} \) also lies in the plane \( \Sigma \). If \( \delta e_{sj} \) is perpendicular to the plane \( \Sigma \), then \( \delta \mu_j = 0 \). Therefore, to estimate the required bandwidth \( \Delta \lambda_p \), it is sufficient to consider only \( \delta e_{sj} \) in the plane \( \Sigma \). Then, \( \Delta \lambda_p \) is written as

\[
\Delta \lambda_p = \frac{\sin(\theta_p - \theta_w)}{\sin^2 \theta_w} \delta \theta_{\lambda_p},
\]

where \( 2\delta \theta_{\lambda_p} \) is the azimuthal divergence angle of the signal beam, \( \theta_w \) is the half-crossing angle between \( e_{0} \) and \( e_r \), and \( \theta_p \) is the incident angle of the probe beam from the bisector between \( e_{0} \) and \( e_r \), as depicted in Fig. 2. Note that all angles are measured inside the crystal. Using Eq. (4), we can estimate the allowed divergence angle \( \delta \theta_{\lambda_p} \) at a given spectral width of the probe light source. For example, when the hologram is recorded at \( \lambda_w = 532 \text{ nm} \) and at an angle of \( \theta_w = 30^\circ \), readout by polychromatic light with a center wavelength \( \lambda_{p0} \) of 810 nm requires a probe incident angle \( \theta_p = 50^\circ \). In this case, if the spectral width \( \Delta \lambda_p \) of the probe light source is 30 nm, which is a typical value of currently available SLDs, the allowed signal divergence angle \( \delta \theta_{\lambda_p} \) is estimated to be about 2°.

The image properties of the PCR were investigated by simulation, where \( e_{sj} \) and \( \mu_j \) were calculated for each \( e_{sj} \) by using Eqs. (1) and (2). We assumed that the hologram is large enough to neglect off-Bragg diffraction. The calculation was conducted under the conditions that \( \lambda_w = 532 \text{ nm} \), \( \theta_w = 30^\circ \), \( \theta_p = 50^\circ \), \( n = 1 \), and the focal lengths of the Fourier transform lenses in the recording and readout process are equal to 150 mm. The input image in our simulation was a filled square with dimensions 1 cm \( \times \) 1 cm, as shown in Fig. 3(a). Figure 3(b) shows a simulated result of the reconstructed image together with the distribution of the Bragg-matched wavelength. Since the relation \( |\delta e_{sj}|^2 \leq 1 \) held in our calculation, the Bragg-matched wavelength was dispersively aligned only in the \( x_d \) direction, as expected from Eq. (3). In contrast, enlargement of the image occurred only in the \( y_d \) direction. Such a magnification is a consequence of the readout at a wavelength longer than the recording one [8]. The magnification in the \( y_d \) direction was about 1.5, which is equal to the wavelength ratio \( \mu_j \). From geometrical considerations, the diffracted divergence angle \( \delta \theta_{d} \) is equal to \( \delta \theta_{\lambda_p} \) at any \( \theta_w \) and \( \theta_p \). Therefore the magnification in the \( x_d \) direction was always unity, independent of the recording configuration.

To investigate the cross-talk noise from the other multiplexed pages, the recorded hologram was rotated with respect to the \( y \) axis, and then \( e_{dj} \) and \( \mu_j \)
were calculated similarly. Figure 3(c) shows an image obtained from the hologram after rotation by 0.5°. The rotated gratings still satisfied the Bragg condition at other wavelengths within the broadband spectrum and constructed an image shifted along the x_d direction. Since such an image acts as cross-talk noise, similar to the case of the spherical probe beam, the rotation angle used to record the other hologram should be large enough not to prevent the signal and noise images overlapping. The required angle separation between the holograms is, in our case, about 2°, which depends on the signal divergence angle θ_s and the spectral width Δλ_p of the probe light source, and is independent of the hologram thickness. The resultant storage density in PCR decreases by at least 2 orders of magnitude in a 1 cm thick sample as compared with the case where the same wavelength is used for recording and reading. This reduction of the storage density is comparable with that in the spherical probe beam method [9]. However, PCR can reduce the angle separation between the holograms. Focusing on the Bragg-matched wavelengths at a certain point in Figs. 3(b) and 3(c), we found that there was a wavelength difference between the diffracted waves with and without rotation. For example, at the origin of the coordinates, the wavelengths of the signal and noise waves were 815 and 828 nm, respectively, and the wavelength difference was almost the same at all the points in the overlapped area. Such a wavelength difference can be used to distinguish the signal from the noise. Only the signal image would be detected if the proper optical components, such as a wavelength filter or grating, were additionally inserted into the imaging system.

To confirm the validity of the PCR, we performed an experiment using a 45°-cut Fe:LiNbO_3 crystal. The hologram was recorded in the 90° geometry with an inside crossing angle 2θ_w of 65°. The recording light source was a frequency-doubled Nd:YAG laser operating at a wavelength of 532 nm. The input image was a checkered pattern, as shown in Fig. 4(a), where the dimensions of each square were about 230 μm × 230 μm. The focal lengths of the Fourier transform lens used in the recording and readout processes were 150 and 100 mm, respectively. Readout was performed by using the SLD as a polychromatic light source. The center wavelength of the SLD was 810 nm, and its full width at half-maximum (FWHM) spectral width was 30 nm. For comparison, readout was also performed by using a single-mode laser diode (LD) with a center wavelength of 780 nm and a FWHM of about 0.1 nm. The reconstructed images obtained by using the LD and SLD are presented in Figs. 4(b) and 4(c), respectively. The SLD could reconstruct the whole image, whereas the LD could reconstruct only a portion of the input image. Comparing Figs. 4(a) and 4(c), the reconstructed image was magnified by a factor of 1.5 in the vertical direction but was almost unchanged in the horizontal direction. This deformation of the reconstructed image is consistent with our simulation of Fig. 3(b).

In conclusion, we have demonstrated the PCR method to read a volume hologram at a wavelength different from the recording one. An image recorded at a wavelength of 532 nm could be reconstructed without loss of the image field by using a polychromatic light source with a center wavelength of 810 nm. Analogous to a spherical probe beam, a polychromatic probe beam degrades the Bragg selectivity and increases the angular separation between the holograms. However, PCR could improve this by taking advantage of the wavelength difference between the signal and the cross-talk noise.

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References