Reduction of the Resolution Losses in Dual-Wavelength Storage *

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The dual-wavelength storage for multi-page storage with the nondestructive readout is investigated in the double-doped lithium niobate crystals. The image field losses are minimized by adjusting the readout wave vectors, and the resolution is improved by optimizing the storage setup.

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Storage of volume phase holograms in photorefractive crystals is attractive because of the potential high storage capacity,[1] parallel readout of pages with short access time and high data transfer rates.[2] However, the stored information can be erased by homogenous illumination and this reversibility will lead to the destructive readout. Several methods, for example thermal fixing,[3] electrical fixing,[4] two-step recording,[5] have been proposed to fix the holograms and to realize nondestructive retrieval. Whereas all these methods make the recording process complicated and time-consuming. On the other hand, the dual-wavelength technique is another simple solution for the nonvolatile readout in which the wavelength of the readout beam is longer than that of the recording beams. Unfortunately the whole stored image could not be retrieved by this technique due to the phase mismatch. Some methods[6–9] have been proposed to solve this problem. Among them, the simplest and most effective method was the one proposed by Küich,[9] in which the Bragg mismatch was minimized by reading the holograms with a spherical wave rather than with a plane wave. But the resolution losses, which are also very important for the image reconstruction, have not been discussed. In this paper we theoretically and experimentally investigate further this simple and convenient method for the multi-page storage and its nondestructive readout. The image field losses and resolution losses are studied in details.

Supposing that the signal and reference beams are plane waves with vectors $\boldsymbol{K}_{\mathrm{s}}$ and $\boldsymbol{K}_{\mathrm{r}}$, respectively, a hologram consisting of a single grating $\boldsymbol{K}_{\mathrm{g}}$ can be recorded

$$\boldsymbol{K}_{\mathrm{g}} = \boldsymbol{K}_{\mathrm{s}} - \boldsymbol{K}_{\mathrm{r}}. \tag{1}$$

When the hologram is reconstructed at a different wavelength, the incident angle θ' of the readout beam should be adapted to the corresponding Bragg angle, which can be determined by the expression

$$\theta' = \arcsin\left(\frac{k}{k'}\sin\theta\right), \tag{2}$$

where 2θ is the intersecting angle of the two recording beams, $k(k')$ is the scale value of the wave vector $\boldsymbol{K}(\boldsymbol{K}')$. In this way, the hologram can be reconstructed by a plane wave with Bragg matched at a different wavelength. However, when we record the image, the spatial light modulator (SLM) is used to modulate the signal beam. The output light from the point on the SLM is not collimated owing to diffraction as shown in Fig. 1, and the diffraction angle α is equal to λ/d_s (λ is the wavelength of the signal beam and d_s the microstructure size of the object). Therefore, the output light includes not only one ground spatial frequency component but also many high spatial frequency components. As a result, the recorded hologram consists of multiple gratings with different grating vectors. Because each grating requires a distinct Bragg-matching condition, the plane readout wave at a different wavelength could readout only some of the gratings and the stored information could only be partly retrieved.

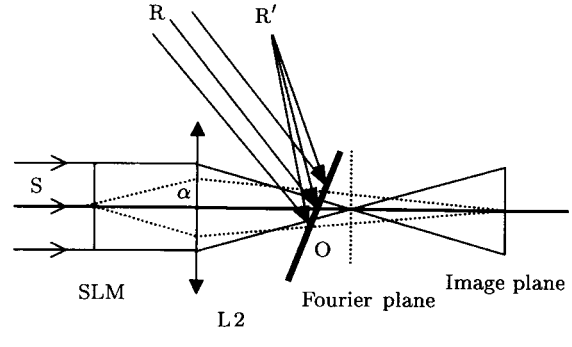

Fig. 1. General geometry for writing and reading volume holograms. R: the reference beam, S: the signal beam, R': the reading beam.

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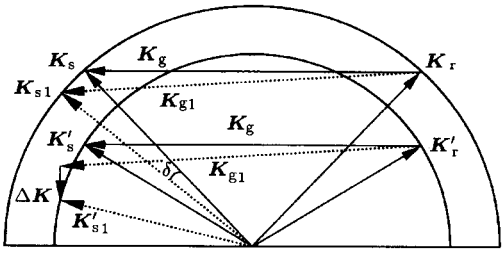

Fig. 2. Construction in the space of wave vectors for analysis of phase mismatch in the dual-wavelength recording.

The ground spatial frequency components from all points on the object plane play a key role in the image field losses of the dual-wavelength method. Therefore, when we study the image field losses, the signal beam can be considered as a spherical beam consisting of only the ground spatial frequency components. Using the approximation of local plane waves and elementary holograms, the intensity distribution I'_s of the spherical signal wave reconstructed with a plane wave at a different wavelength can be easily obtained by Kogelnik's theory.[10] In the case of small diffraction efficiencies without absorption, it could be expressed by

$$I'_s = I'_r \eta_0 \mathrm{sinc}^2\left(\frac{\Delta k d}{2}\right), \tag{3}$$

where I'_r is the intensity of the readout plane wave, η_0 the diffraction efficiency of the gratings, d the thickness of the crystal, Δk the amplitude of the off-Bragg vector $\Delta \boldsymbol{K}$. For simplicity, in our analysis the signal beam could be represented as an on-axis wave vector $\boldsymbol{K}_s$ and an off-axis wave vector $\boldsymbol{K}_{s1}$ as illustrated in Fig. 2. Because different wave vectors are corresponding to the different spatial points of the photorefractive medium, $\boldsymbol{K}_s$ and $\boldsymbol{K}_{s1}$ interfere with K_r in different points of the sample to form the gratings $\boldsymbol{K}_g$ and $\boldsymbol{K}_{g1}$, respectively. When the grating K_g is readout by a plane wave K'_r at different wavelength under the Bragg condition, the grating K_{g1} could not be retrieved effectively under this condition. The off-Bragg vector ΔK for a readout wave at an arbitrary hologram location could be expressed as

$$\Delta \boldsymbol{K} = \boldsymbol{K}'_{s1} - (\boldsymbol{K}_g + \boldsymbol{K}'_r). \tag{4}$$

The amplitude Δk of the off-Bragg vector can be calculated as

$$\Delta k = \delta k \sin\theta \left(1 - \frac{k\cos\theta}{k'\cos\theta}\right) = \delta k_m, \tag{5}$$

where δ is the crossing angle between $\boldsymbol{K}_{s1}$ and $\boldsymbol{K}_s$. When $k' = k$, $\Delta k \equiv 0$, i.e. the Bragg condition is fulfilled while the hologram is readout with the reference wave. When $k' \neq k$, the Bragg mismatch readout angle in the horizontal plane, i.e. the horizontal angular selectivity $\beta_{\|}$ can be deduced from Eqs. (3) and (5) as

$$\beta_{\|} = \left|\frac{2\pi}{dk_m}\right|. \tag{6}$$

Due to the grating degeneracy, the readout wave vectors, which fulfill the Bragg condition, form a cone rather than a plane. Thus we could obtain the expression of the Bragg vertical angular selectivity as[11]

$$\beta_{\perp} = \sqrt{\frac{2\beta_{\|}}{\tan\theta}}. \tag{7}$$

From Eqs. (6) and (7), we can get $\beta_{\perp} \gg \beta_{\|}$, which definitely shows that only a strip of the original image could be retrieved and the horizontal width of the reconstructed image is proportional to $\beta_{\|}$ while the vertical width is proportional to $\beta_{\perp}$ as observed in Ref. 9. In the case of symmetric incidence with respect to the normal of the sample and with the approximation of small angle, we can calculate the distance R between the readout point source and the point O of the sample as shown in Fig. 1,

$$R = \frac{2a\lambda\cos^2\theta'}{\cos\theta(\lambda\cos\theta' - \lambda'\cos\theta)}, \tag{8}$$

where a is the distance between the point O and the Fourier plane. From the sign of R we can know at which side of the sample the readout point source has to be placed. In our experiment, the readout point source should be put on the opposite side of the sample with respect to the signal source. By adjusting the readout wave vectors at as many points as possible to fulfill the Bragg condition for the ground spatial frequency components, the holograms can be readout without image field losses.

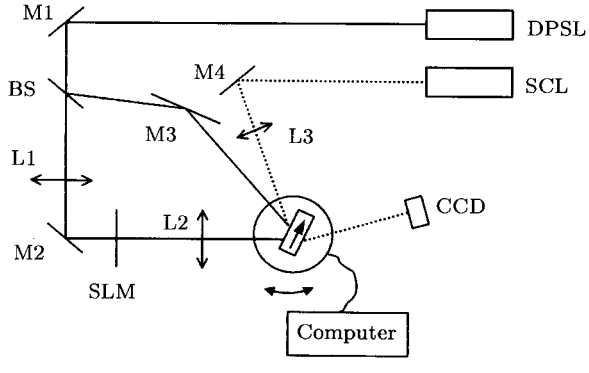

Fig. 3. Experimental setup. DPSL: the diode pumped solid laser, SCL: the semi-conductor laser. M's: mirrors. L's: lens. BS: beam splitter, SLM: spatial light modulator. The crystal is mounted on a rotation stage, which can be rotated around the vertical axis.

However, the resolution losses are not discussed in Ref. 9, which should be very important for the image reconstruction. Here we study the resolution losses in details. At any point of the sample, most high spatial frequency waves are not readout, which will result in resolution losses. The Bragg condition plays

a role of a spatial frequency filter and suppresses the high-spatial-frequency components to reduce the resolution. The resolution of reconstructed image can be analyzed based on the Bragg mismatch angle. The minimum distance of the object, which may be distinguished, can be calculated by

$$d_{\parallel} = \frac{\lambda f}{a\beta_{\perp}}, \tag{9}$$

$$d_{\perp} = \frac{\lambda f}{a\beta_{\parallel}}, \tag{10}$$

where f is the focus length of the lens (L2) and equal to 300 mm in our experiment. Therefore, we could easily get the result of $d_{\parallel} \ll d_{\perp}$ and understand why the horizontal structure of image has a higher resolution than the vertical structure, which is often observed in the experiments. When $k' = k$, $d_{\perp} = d_{\parallel} = 0$, i.e., the retrieval process does not reduce the image resolution.

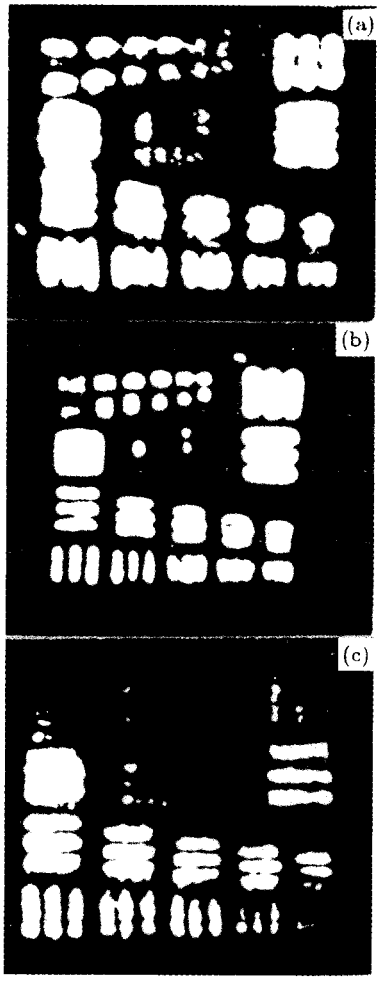

Fig. 4. Reconstructions of a U. S. Air Force test target recorded at 532 nm: (a) a = 10 mm, readout at 670 nm; (b) a = 10 mm, readout at 532 nm; (c) a = 15 mm, readout at 670 nm.

Our experimental setup is sketched in Fig. 3. A diode pumped solid laser (DPSL) at 532 nm is used to record holograms. The crossing angle between the two recording beams is 45° in air. The signal beam, which is expanded and collimated, passes through a computer-addressed SLM. A co-doped $LiNbO_3$:Fe,Mg (0.05 wt.%Fe, 0.8 mol%Mg) crystal[12] with the thickness of 4.5 mm is used as the storage medium. The c-axis lies in the incident plane. A light beam at 670 nm from the semi-conductor laser (SCL) reads out the recorded holograms for retrieval. The CCD camera is used to detect the retrieved image.

In order to adapt the readout wave front, a spherical lens (L3) is added to the readout light path to focus the readout beam to a point behind the sample with a distance 57.8 mm when the distance a is equal to 10 mm. The retrieved image is shown in Fig. 4(a). For a judgment of image quality the retrieval with the original reference wave is shown in Fig. 4(b), from which we could see that the image can be retrieved without image field losses as expected in Ref. 9. By increasing the magnitude of a, we can minimize the magnitude of $d_{\perp}$ to improve resolution, as shown in Fig. 4(c) while the distance a is equal to 15 mm.

In the common angular multiplexing storage system, the multi-page storage is realized by changing the incident angle of the reference beam. Because the distance R changes with the intersecting angle between the reference beam and the signal beam, all recorded holograms could not be retrieved by a readout point source at a fixed position. It is easily found that this problem could be solved via rotating the crystal instead of changing the intersecting angle. Even though the crossing angle between the reference beam and the signal beam in crystal changes with the rotation, it is so small that all the stored holograms could be reconstructed with the same distance R. We have recorded 100 holograms with high resolution in one position of the sample using our storage system by angular multiplexing technique, which shows that our proposed technique is effective.

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