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Angular multiplexed holographic memory system based on moving window on liquid crystal display and its crosstalk analysis

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Abstract. We suggested a new non-mechanical angular multiplexed holographic memory system using a moving window, which was fabricated by controlling the pixels of a liquid crystal display (LCD) electronically. If we use light passed through the window left and right, and up and down, each window makes a reference wave with a different incidence angle and we can store angular-multiplexed holograms. The feasibility of the proposed method was demonstrated through optical experiments and its crosstalk noise analysis was also presented.

Key words: crosstalk, holographic memory, LCD, moving window, multiplexing, photorefractive material

1. Introduction

Multiple holograms are useful for a broad range of applications such as parallel holographic memory, template matching, optical neural networks, optical interconnects, and correlators. Multiple holograms can be recorded in a photorefractive crystal or a polymer sequentially by using an exposure schedule which equalizes the diffraction efficiency. Among those applications, multiple holograms have been extensively studied in holographic memory systems. Volume holographic memory is expected to play an important role in the data storage hierarchy owing to its short access time, high aggregate data transfer rate, and large storage capacity (Hong *et al.* 1995). In such a memory system an object beam containing a page of information is recorded holographically in association with a uniquely oriented reference beam in volume recording materials such as photorefractive crystals. The procedure is repeated with different sets of object and reference beams to yield a volume memory in which any particular page information can be uniquely accessed by reading the hologram with the corresponding reference beam, which is called multiplexing.

After the photorefractive effect (Van Heerden 1963) was discovered, a variety of multiplexing schemes (Hong *et al.* 1995) to store a large amount of data in photorefractive materials were proposed and their feasibilities were demonstrated through optical experiments. Angular (Mok *et al.* 1991; Mok 1993), wavelength (Rakuljic *et al.* 1992) and phase code (Denz *et al.* 1991) multiplexings are the most prominent holographic multiplexing methods that allow the storage and retrieval of independent pages of data in a common recording volume. Besides those methods, shift and spatial multiplexings using the speckle patterns of optical fibers were introduced (Kang *et al.* 1997). Also, a hybrid multiplexing scheme combined with two or more multiplexing methods was proposed (Tao *et al.* 1993).

Among them, angular multiplexing is one of the most commonly used schemes of storing multiple holograms within a common volume. Angular multiplexing has the potential for recording a large number of high-resolution images in a compact volume and has been used widely. Mok (Mok *et al.* 1991; Mok 1993) reported that 500 and 5000 holograms were recorded and retrieved using multiplexing in 1991 and 1993, respectively. Angular multiplexing can store a large quantity of information by using reference plane waves with a different incidence angles. The incidence angles of the reference plane waves were changed by using a stepping motor or an acousto-optic deflector (AOD). Mechanical control of the incidence angle using a stepping motor is simple; however during data recording and retrieval, mechanical error of the stepping motor occurs, and Bragg condition is not satisfied. As a result, in the case of data retrieval, the reconstructed data contain data of another address, noises. Using AOD, the above-mentioned problem can be eliminated, but this holographic memory system is expensive and is difficult to align.

In this paper, by controlling the pixels of a liquid-crystal display (LCD) electronically, we fabricated real-time moving window on a LCD, through which light passes. Using the moving window, we suggested a new angular multiplexed holographic memory system without mechanical movement and demonstrated the feasibility of the proposed method through optical experiments. The crosstalk noise analysis of the proposed method was also presented.

2. Principle of angular multiplexing method using a moving window on a LCD

In this section, a non-mechanical angular multiplexing using a moving window on a LCD, which controls the incidence angles of reference beams electronically, is described below. The spatial light modulator such as a LCD consists of hundred of thousands pixels and on or off switching of each pixel is possible. Fig. 1 shows photograph and pixel structure of the LCD used in our experiments.

By applying voltage to the electrode of the LCD in the Fig. 1, we can switch each pixel of the LCD on or off. By switching specific pixels of the LCD on and the rest off, we can fabricate a window on the LCD, through which light passes. By controlling the window electronically, we can move it on the LCD, and call it a moving window. Fig. 2 shows that the window is moving on the LCD. In this figure, the window consists of 2×2 pixels, and the rest of the pixels are off. The size of window can be controlled electronically and varied arbitrarily.

As shown in Fig. 2, by controlling electronically which pixels of the LCD are switched on and off, the window can be moved left and right, and up and down by its number order. Then each window makes a reference wave with a different incidence angle, and by using the window in this manner, we can store angular-multiplexed holograms. Figure 3 shows that when light passing through windows of the LCD is transformed by Fourier transform (FT) and interferes with object waves in the photorefractive material, the light beam passing through each window has a different wave vector. In Fig. 3(a), the windows do not overlap with each other and can move left and right. If we move the windows left and right and store holograms, no crosstalk will be observed in the reconstructed information. Figure 3(b) shows the reference and object waves in Fig. 3(a) represented as wave vectors. As shown in Fig. 3(b), when we use the lights passing through the windows as reference waves, the reference waves are focused at the same location but the direction of the wave vector of each reference wave is different. Accordingly, interference of the object wavers with the same wave vector and reference waves with different wave vectors makes

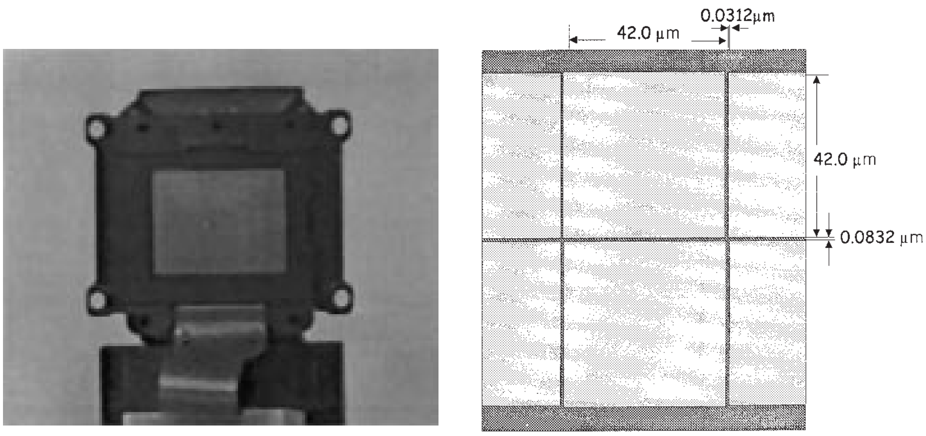

Fig. 1. Photograph and pixel structure of a LCD.

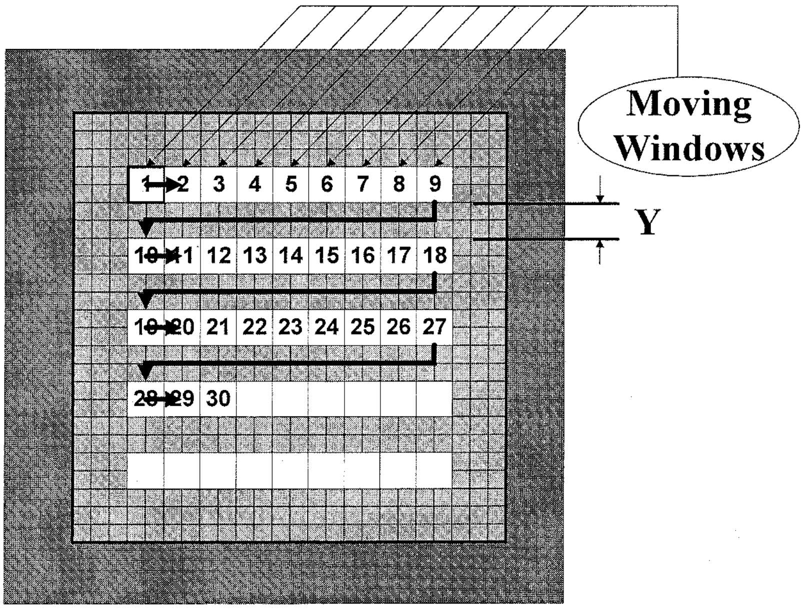

Fig. 2. Schematic diagram of moving windows on a LCD.

different grating vectors. On reconstruction, we can predict that different object waves will be reconstructed with each reference wave. We can also multiplex the holograms by moving the window up and down. In this case, only when we move the windows at their width apart up and down or more than two times the horizontal angular selectivity, the crosstalk in reconstructed data will not occur (Lee *et al.* 1989; Mok 1993). We can therefore see that holograms can be angularly multiplexed by the moving window.

3. Experimental results

To implement the proposed method, we set up the system as shown in Fig. 4. In this figure, we used a NdYAG laser (Model DPSS532, COHERENT) with wavelength and output power of 532.8 nm frequency doubled and 100 mW, respectively. The total pixel number of the LCD (Model P13VM215, Epson) used is 307, 200 (480 × 640) pixels and the size of each pixel is 42 μm × 42 μm. The photorefractive material is a $FeLiNbO_3$ crystal and its size is 1 cm cube. The focal length of FT lens is 120 mm. In this figure, light expanded by the beam expander is divided into reference and object waves by the beam splitter. Polarization of the laser is vertical. The reference wave polarization changes into horizontal polarization after passing through the LCD. The object wave polarization changes into horizontal polarization

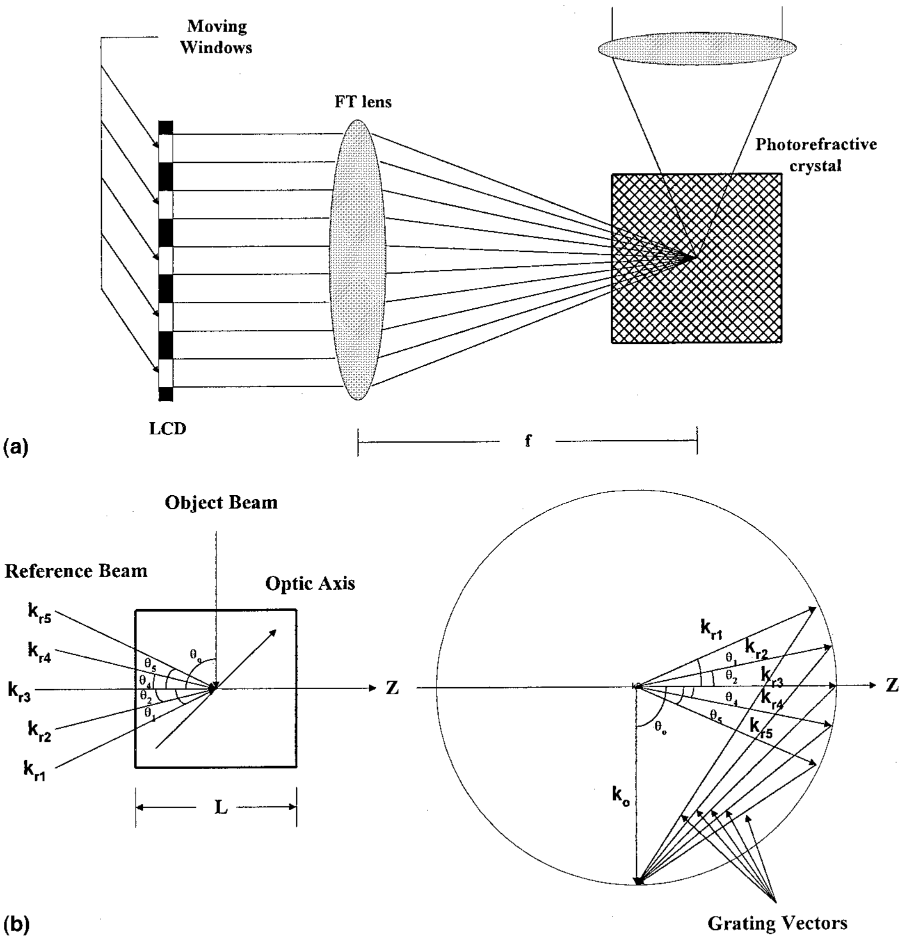

Fig. 3. Principle of angular multiplexing by moving windows (a) Interaction geometry in photorefractive material (b) Wave vector space description of holographic interaction.

after passing through the $\lambda/2$ wave plate. The polarizer in front of the LCD was used to improve the contrast. The digital computer controls electronically so that the window on the LCD moves left and right, and up and down. The reference wave interferes with the object wave in the photorefractive material and forms the grating. To make reference waves with different wave vectors, we moved the window consisted of 20×20 pixels electronically. In this case, one row and one column of our LCD can address 24 and 16 holograms, respectively. Accordingly, the total number of addresses is 384. The maximum number of holograms that can be multiplexed is dependent on the size of the moving window and the focal length of the FT lens. And also, the size of object is another important parameter that determines the maximum number of holograms, because the vertical angular separation that is

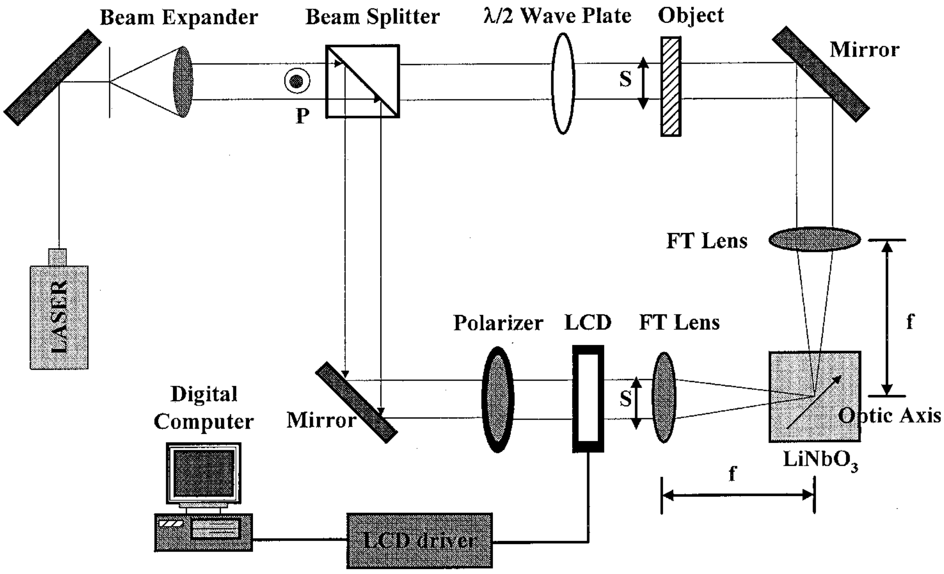

Fig. 4. System diagram for implementing angular multiplexing by moving window.

required to avoid the overlap of the degenerate reconstruction of the neighboring object images is directly dependent on it. If we use the lens of focal length of 120 mm, the angular separation is 3.5×10^{-4} rad for one pixel apart in our proposed scheme. And angular selectivity can be found using the equation of angular selectivity in first paragraph of the Section 4. The wavelength of laser is 532.8 nm, the refractive index of the photorefractive crystal is 2.2, and θ_R and θ_O are both 45°, so that the angular selectivity is 1.7×10^{-5} rad. Therefore, in our case the number of holograms that can be multiplexed is limited by the window size, the object size, and the focal length of the lens.

To demonstrate the proposed method, we made a window consisted of 20×20 pixels and moved it to the right without overlap. Figure 2 shows locations of 30 windows used in our experiment. The size of each window is 20×20 pixels and its area is 840 μm × 840 μm. In this figure, light passes through only the bright parts of the LCD and not through the other parts. Therefore, if we move the window left and right without overlap, we can make reference waves with different incidences angles.

In this study, we stored 30 input images using 30 windows in Fig. 2. The size of the input image in our experiment is 5 mm × 5 mm. Ten images from the reconstructed images using different reference windows are shown in Fig. 5. The numbers shown on the photographs indicate the order of the recorded and reconstructed images. From those results, we can see that data storage and retrieval using the window on the LCD is possible and angular

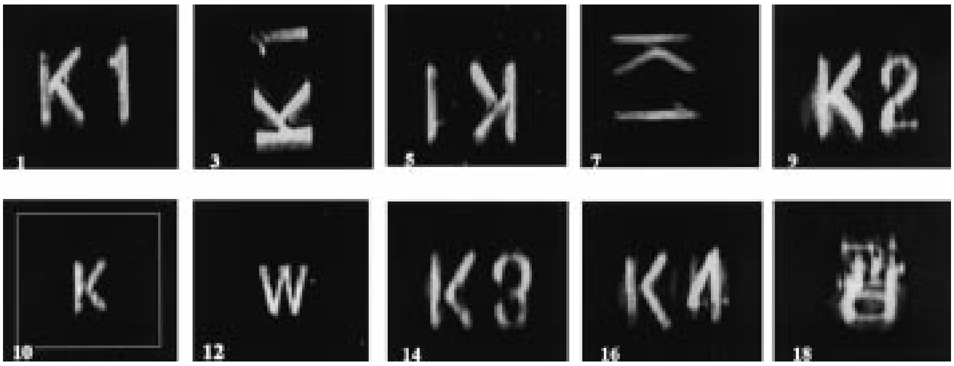

Fig. 5. Reconstructed images using moving windows.

multiplexing using the moving window is valid. Using a diffuser on the record of the hologram, we will obtain a clear image on reconstruction.

Using the method proposed here, we can make reference waves as many as pixel number of the LCD theoretically. But the number of reference wave is limited by two parameters. First, the number of reference wave is limited by the lens aperture of Fourier transforming the light passing through the window on the LCD. Because the diameter of lens used in this paper is 1 inch, only the lights passing through windows on the LCD within the diameter of the lens can be used as reference waves. Accordingly, using the lens with diameter larger than the diagonal of the LCD, we may use the lights passing through all windows on the LCD as reference waves. Another limitation is that windows must be at window width apart in vertical direction. Otherwise, the reconstructed images contain noise (Mok 1993).

In addition to the above-mentioned parameters, an allowed minimum size of the window for a certain background light should also be considered. Because there is no perfect on-off SLM, the SLM has a finite extinction ratio. Thus there is an allowed minimum window size to overcome the noise from the background light. The extinction ratio of the SLM used in our experiment is about 200:1 due to poor polarizer. If we use the polarizer of good quality instead built-in polarizer, we can obtain the extinction ratio of 25,000:1 for crossed pair polarizers. If the pixel numbers of one window is N_{win} and the total number of pixels within beam size is N_{tot}, and the power ratio of on to off is $R_{on/off}$, then the ratio of signal to background noise is presented by $N_{win}/(N_{tot} - N_{win}) \times R_{on/off}$. Considering that $R_{on/off}$ of the SLM is 25,000, N_{win} should be about 5908 pixels for $N_{tot} = 153{,}600$ (considering the angular selectivity in the vertical direction) to obtain 30 dB of signal-to-background noise ratio. That is, the number of pixel of the window should be more than 5908 pixels in order to obtain over 30 dB of signal-to-background noise. In the case of 20×20 window, the signal-to-background noise is about 18 dB. If we increase the extinction ratio of the SLM by adding the polarizers, the window size for obtaining over 30 dB of signal-to-background noise can be reduced.

4. Crosstalk noise analysis of the moving window holographic memory system

As shown in Fig. 2, if we move the window left and right without overlap and store holograms, no crosstalk will be observed in the reconstructed information. Horizontal angular selectivity of the proposed scheme is generally as the same; $\Delta\theta_R = \lambda \cos\theta_O / nL_z \sin(\theta_R + \theta_O)$ where θ_R and θ_O are the incidence angles of the reference and object waves with respect to *c*-axis, respectively, L_z is the thickness of plate, n is the refractive index of the medium, and λ is the free space wavelength of light (Hong *et al.* 1995).

We can also multiplex the holograms by moving the window up and down. In this case, only when we move the windows by a distance equal to their width up and down or more than two times the horizontal angular selectivity, crosstalk will not occur in the reconstructed data. Figure 6 shows crosstalk effect in reconstructed image. This is the reconstructed image using 9th window after storing images using 9th and 18th windows in Fig. 2, in which case the spacing of the vertical window rows is smaller than the object width.

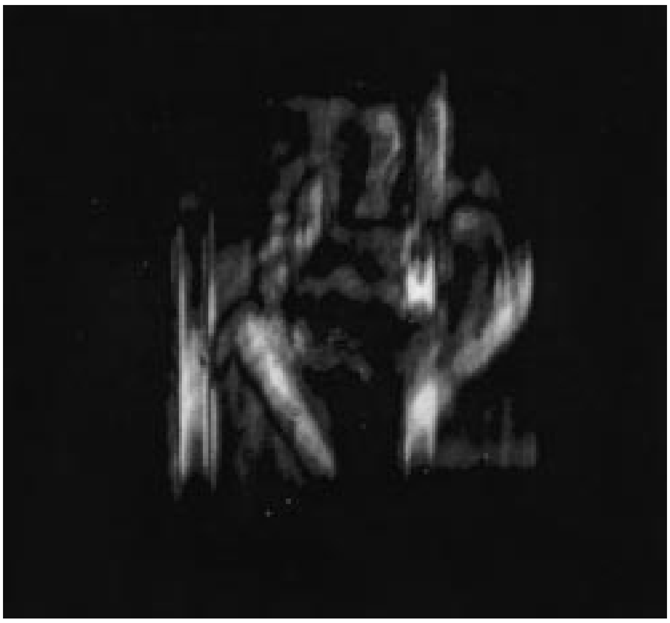

Fig. 6. Crosstalk effect in the reconstructed image using moving window with *Y* separation less than object width.

Therefore, to obtain crosstalk-free images, Y in Fig. 2 must at least be separated by a distance equal to the width of the window or more than two times the horizontal angular selectivity.

The crosstalk noise analysis is performed to confirm the validity of the proposed system. This scheme has fatal demerits that it uses only small parts of the reference beam power and the total number of multiplexed holograms is limited by the total pixel number of the LCD. Under these limitations, it is very important to know the crosstalk noise of hologram memory that limits the memory capacity.

The proposed system is similar to the angular multiplexing scheme. Therefore, the crosstalk noise analysis for angular multiplexed Fourier hologram can be applied to the proposed one. The simple and easy method used in the crosstalk noise analysis of Fourier hologram was presented by Gu *et al.* (1992).

The reference beam R_m is presented by Equation (1), which represents a plane wave with wavevector k_m. 'm' denotes each hologram that is stored with each reference window.

$$R_m = \exp(jk_m \cdot r). \tag{1}$$

We calculate the noise-to-signal ratio(NSR) by Equation (2).

$$\mathrm{NSR} = \sum_{m \neq j} \left| \mathrm{sinc}\left[\frac{t}{2\pi} \left((\Delta K_{mj})_z + \frac{1}{F}\left((\Delta K_{mj})_x x_2 + (\Delta K_{mj})_y y_2 \right) + \frac{\lambda}{4\pi}\left((\Delta K_{mj})_x^2 + (\Delta K_{mj})_y^2 \right) \right) \right] \right|^2, \tag{2}$$

where t is photorefractive crystal thickness, λ is wavelength, $\Delta K_{mj} = k_m - k_j$ is the mismatch between a recording reference beam (m) and a retrieving beam (j). x_2 and y_2 are the distance from the center in the output plane.

We deal with the one-dimensional reference, that is, we ignore the x-coordinate in Equation (2). We calculated the signal to noise ratio (SNR) for the cases of variations in the focal length, the distance between windows and the number of holograms change and showed in Figs. 7–9. In Figs. 7–9, the worst SNR means the minimum value of the SNRs that are calculated by Equation (2) for the reference beams ($j = 1 \sim N$). Figure 7 shows the relation between the focal length and SNR. As expected, as the focal length increases, the effective angular separation of each hologram decreases in Fourier plane and the crosstalk noise increases. In Fig. 7, the dashed and solid lines represent SNR of 50 and 100 holograms, respectively. The SNR decreases from 55 dB to 41 dB as focal length increases from 20 mm to 120 mm. The number of holograms has small effect on the SNR: $N = 50$ and $N = 100$ have nearly the same values as shown in Fig. 7.

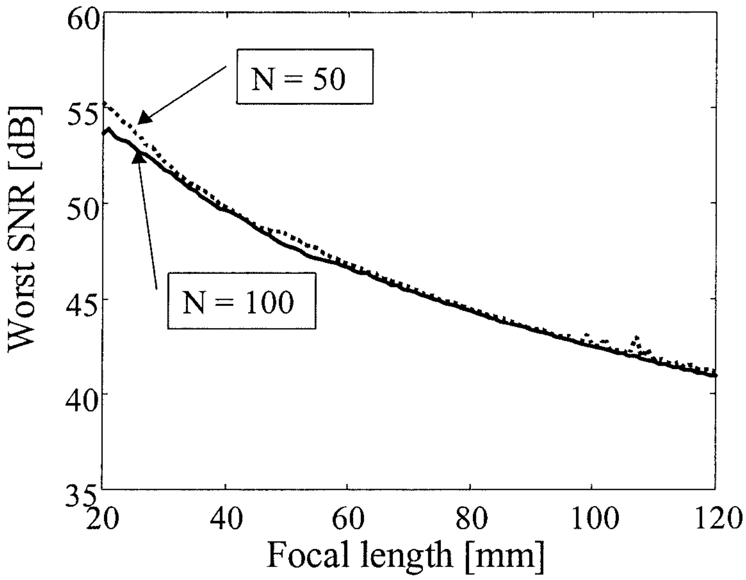

Fig. 7. The worst SNR as a function of focal length. Window distance is fixed to 420 μm for both cases.

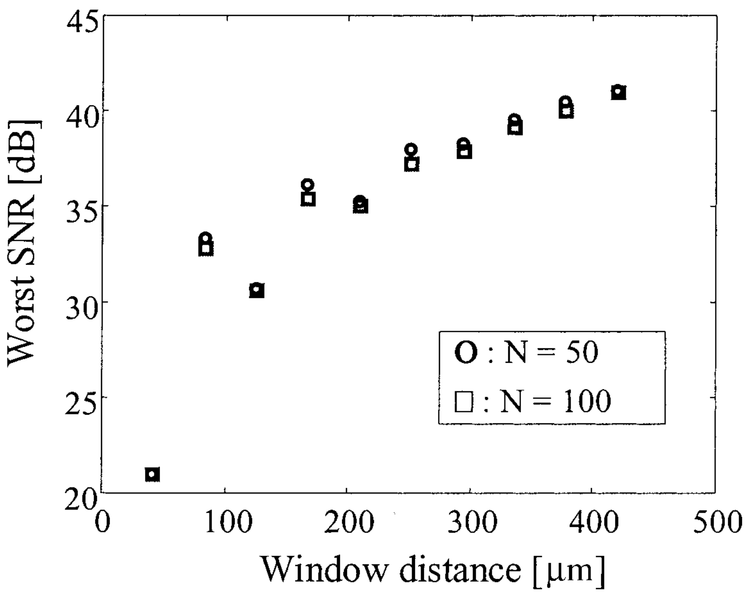

Fig. 8. The worst SNR as a function of the distance between two neighboring windows. Focal length is fixed to 120 mm for both cases.

Like the case of the focal length, the distance between neighboring windows affects the SNR. If the window distance increases, the effective angular separation of each hologram increases and crosstalk noise decreases as shown

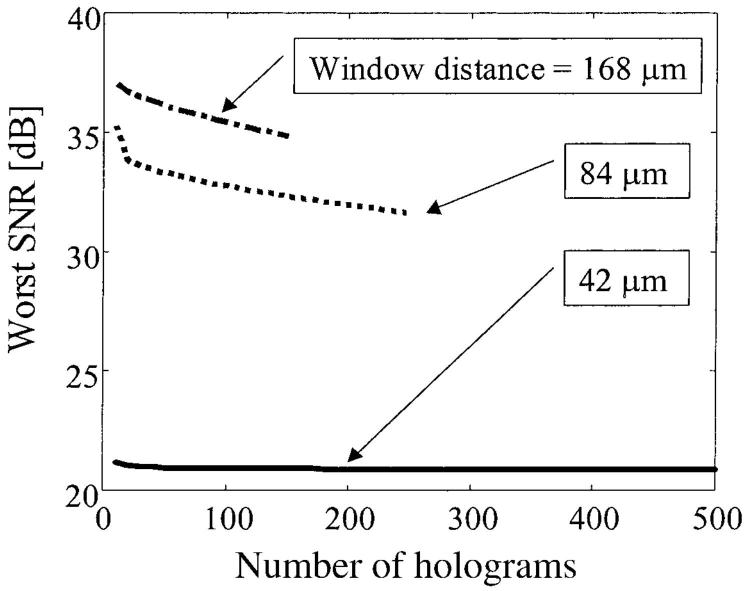

Fig. 9. The worst SNR as a function of the hologram number. Focal length is fixed to 120 mm for all cases.

in Fig. 8. There are small differences between the cases of hologram number $N = 50$ and $N = 100$. Because of the fixed pixel size, the distance can only be the integer multiple of the pixel size. For the convenience of calculation, the window is assumed to be a point source and be placed at the given distance apart. Therefore, we cannot involve the effect of window to the SNR. But, we can obtain the tendency of the effect of the window distance to the SNR.

If we use the LCD of 480×640 pixels and each pixel size is 42 μm × 42 μm, the maximum number of hologram multiplexed by windows in the x-direction is 480. The broader the window size, the lower the number of windows. Therefore, we calculated the SNR for fixed window size as a function of the number of holograms. If the window size is 42, 84 and 168 μm, then the maximum number of windows is 480, 240, and 120, respectively. As shown in Fig. 9, the crosstalk noise increases as the number of hologram increases. The effect of window distance on the SNR is larger than that of the number of holograms.

5. Conclusions

An advantage of the method is that the simpler and more exact addressing compared with the conventional methods is possible. That is, by controlling reference wave electronically, this method can eliminate the crosstalk due to mechanical movement in the case of using the stepping motor to control the incidence angle of reference wave.

Angular selectivity of the proposed memory system is the same as that of general angular multiplexing. Crosstalk noise analysis shows that as the focal length increases, the crosstalk noise increases, and as the distance between two neighboring windows increases, crosstalk noise decreases. The effect of the window distance on the SNR is larger than that of the hologram number. If the proposed memory system is combined with spatial multiplexing, high density storage in compact volume is possible. Using a multi-focus lens in place of general FT lens behind LCD of Fig. 2, spatial multiplexing in which angular multiplexed holograms are stored at multiple locations is possible with no moving parts. Then we can store and retrieve the data in the given holographic memory system by full electronic mechanism.

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