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All-Optical Implementation of Volume Holographic Associative Memory

(부피격자형 연상메모리의 광학적 구현)

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要 約

본 논문에서는 광굴절 매질과 반사경을 사용한 부피 격자 홀로그램 연상 메모리에 대하여 기술하였다. 광원으로는 0.6328μm 파장의 He-Ne 레이저를 사용하였고, Fourier 변환된 물체빔과 각 다중화 기록빔으로써 $BaTiO_3$ 결정에 다중 홀로그램을 형성하였다. 기억된 영상의 1/6부분 입력으로도 원하는 원래의 영상이 재생되었으며, 실시간 연상 메모리 뿐아니라 주소 지정메모리도 가능하였다.

Abstract

We describe a volume holographic associative memory using photorefractive material and conventional planar mirror. Multiple hologram is generated with two angular multiplexed writing beams and Fourier transformed object beam in $BaTiO_3$ crystal at 0.6328 μm. Complete image can be recalled successfully by partial input of the original stored image without any additional thresholding and optical feedback process.

It is proved that our system is useful for optical implementation of real-time associative memory and location addressable memory.

I. Introduction

The human brain is the most sophisticated and powerful computing machine. It is believed to self-organize by modifying the synaptic weight of connection between neurons. The brain processes data in an associative manner, which is significantly different from the electronic computer. It can recall complete data by partial or distorted version of original data via association.

The additive equation for binary neural signal processing was first introduced by W.S. McCulloch and W. Pitts[(1)] in 1943. T. Kohonen[(2)] explained the properties of outer-product model in 1972. Since J.J. Hopfield[(3)] suggested Hopfield model in 1982, several holographic associative memories using conventional dichromatic gelatine plate hologram and phase conjugate mirrors hav been investigated recently.[(4-6)]

But it is impossible to implement a real-time associative memory with these methods, because the formation of a hologram requires much

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time and stored data can not be altered. If photorefractive materials, $BaTiO_3$, BSO ètc, are used for holographic memory, it is expected that real-time associative memory can be possible.[7]

In this paper, we describe a Fourier transformed volume holographic associative memory in correlation domain. Volume grating is formed in a $BaTiO_3$ crystal with angular multiplexed writing beams. We perform all-optical associative memory successfully without any thresholding and iteration process.

II. Volume holographic associative memory

Holographic system is similiar in many respects to the outer-product neural network model. An advantage of the holographic system is the ease with two dimensional objects can be stored. And also it has wider shift invariant range. If photorefractive material is used as a holographic storage medium instead of DCG(dichromatic gelatine) plate, it is possible to store and erase the data in real-time. When light beam is incident in the nonlinear material ($BaTiO_3$, BSO etc) which has large electro-optic coefficient, charge migrates in the medium due to the incident light energy and results in a strong electric field. The refractive index of medium is varied by this induced space charge field, so volume grating which enables to record the amplitude and phase information of object image is formed dynamically.[8]

In the case of DFWM (degenerate four wave mixing) in which frequencies of the four incident beams are the same, the variation of the refractive index $\triangle n$ is given by

$$\begin{aligned}\triangle n = n_0 &+ \frac{n_I e^{i\phi_I}}{2}\frac{(E_1^* E_4 + E_2 E_3^*)}{I_0}\exp(ik_I\cdot r) + c.c.\\ &+ \frac{n_{II} e^{i\phi_{II}}}{2}\frac{(E_1 E_3^* + E_2^* E_4)}{I_0}\exp(ik_{II}\cdot r) + c.c.\\ &+ \frac{n_{III} e^{i\phi_{III}}}{2}\frac{(E_1 E_2^*)}{I_0}\exp(ik_{III}\cdot r) + c.c.\\ &+ \frac{n_{IV} e^{i\phi_{IV}}}{2}\frac{(E_3^* E_4)}{I_0}\exp(ik_{IV}\cdot r) + c.c.,\end{aligned} \quad (1)$$

where Ei (i=1,2,3,4) is electric field of the incident beam, $Io = \sum_{i=1}^{4} Ei$, phase $\phi_I, \phi_{II}, \phi_{III}, \phi_{IV}$ are real, index variation n_I, n_{II}, n_{III}, n_{IV} are real and positive, k_I, k_{II}, k_{III}, k_{IV} are grating wave vectors, respectively.

When reading beam E_3 is blocked using shutter, and only writing beam E_1 and object beam E_4 are used to record a image, ie $E_2 = E_3 = 0$, then

$$\triangle n = \frac{n_I e^{i\phi I}}{2}\frac{E_1 {}^*E_4}{I_1 + I_4}\exp(jk_1 .r) + c.c. \quad (2)$$

The formation of the multiple hologram is illustrated in Fig.1. In order to store one image, writing beam R_2 is blocked by shutter. Image positioned at (a_1, b_1) on input plane P_1 is Fourier transformed by lens L, and it is recorded by object beam and writing beam R_1 for a sufficiently long time enough for grating to reach a steady state. At P_2 plane, following hologram is formed.

$$Fm(u, v) \exp[-j(u a_1 + v b_1)] + \exp(-j u) \quad (3)$$

where Fm is Fourier transformation of the input image fm.

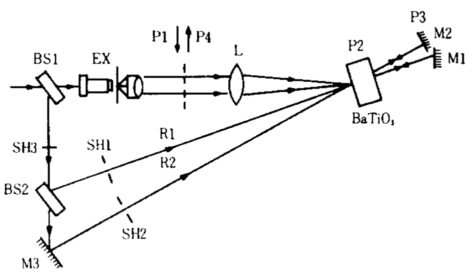


Fig.1. Construction of the multiple image hologram.

As a similiar manner, another image positioned at (a_2, b_2) is stored using writing beam R_2, then hologram formed in $BaTiO_3$ crystal is given by

$$Fm(u, v) \exp[-j(u a_2 + v b_2)] + \exp(-j u) \quad (4)$$

After multiple image hologram is formed, two writing beams are blocked by shutter SH_3. When a partial input image which is one of the stored images, is Fourier transformed and directed to $BaTiO_3$ crystal, then incident beam is diffracted by volume grating. At P_3 plane, desired output due to auto-correlation and undesired noise due to adjacent stored images are output. Only a diffracted beam due to auto-corralation between input image and stored image is sampled using pinhole array positioned at opposite direction to the corresponding writing beam and this beam is retraced to the $BaTiO_3$ crystal using planar mirror M in order to obtain output image. Therefore, at P_4 output plane, desired image is recalled and ghost image is also appears.

When hologram is addressed by $\hat{f}mo$, a partial or distorted input of the original stored image fmo, the recalled output image $\mathring{f}mo$ at P_4 plane is given by[9]

$$\mathring{f}_{mo} = (f_{mo} * \hat{f}_{mo}) \star \hat{f}_{mo} + \sum_{m \neq mo} (fm * \hat{f}_{mo}) \star \hat{f}_{mo} \tag{5}$$

where *, ⋆ denote correlation and convolution, respectively.

The first term of the equation (5) is a desired image due to auto-correlation and the second term is undesired noise due to cross-correlation. To reduce cross-correlation noise and to increase auto-correlation peak, edge enhancement technique,[10],[11] in which object beam is focused and the intensity of the object beam is sufficiently larger than that of the writing beam, can be applied. Then dc term of the Fourier transformed object is reduced and higher-order terms which play an important role in distinguishing objects, are enhanced. So unwanted cross-correlation noise is greatly reduced, and equation (5) is given by

$$\mathring{f}_{mo} = (f_{mo} * \hat{f}_{mo}) \star \hat{f}_{mo} \tag{6}$$

As a result, only desired image without ghost image is recalled by partial input of the stored image.

$BaTiO_3$ crystal is illuminated uniformly with additional laser (erase beam) to clear the previously stored image and another image is recorded by the same procedure, so real-time process is possible.

Formation of the multiple hologram in photorefractive material using angular multiplexed writing beams allowed access to the correlation domain where the use of nonlinearities can greatly increase the storage capacity. In DCG hologram, the incident angle between object beam and writing beam must be large enough to reduce the cross-correlation noise between adjacent images. But in $BaTiO_3$, it is preferable to make incident angle between object and writing beams be small as 5°-20°, at which a volume grating having a large diffraction efficiency is formed. In conventional hologram, the additional thresholding process using PCM (phase conjugate mirror) is required, because the diffraction efficiency of it is order of 10% in optimal condition. But if photorefractive material is used as a memory, complete image can be recalled successfully by partial input without any thresholding and iteration process.

III. Exprimental results

In our experiment, volume hologram is formed in $BaTiO_3$ crystal (7.8 x 5.5 x 5.1 mm) by intensity interference pattern of object beam and writing beam. To determine the optimal condition, the characteristics of the $BaTiO_3$ crystal is observed first. When the intensities of the object and writing beams are adjusted to 1.24 mW/cm^2, 0.606 mW/cm^2, respectively, and image is recorded for 5 sec, diffraction efficiency and intensity of the diffracted beam are shown in Fig.2. When incident angle is fixed at 8°, diffraction efficiency according to the recording time is shown in Fig.3. As a experimental result, intensity of the diffracted beam is maximum at incident angle 10° and maximum efficiency is 33.47%. In addition, it increases as recording time increases. And it is proved that time required to reach a steady state is 7 sec.

Relative intensity of the object beam and writing beam is adjusted to 2.2:1, and incident angle between them if fixed at 12°. Edge enhanced image and output waveform detected by

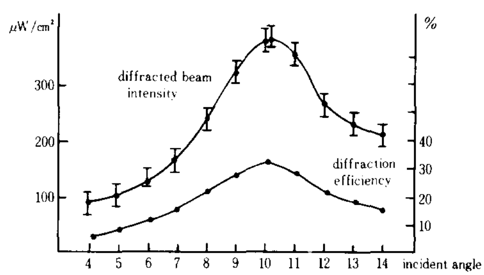


Fig.2. Intensity of the diffracted beam and efficiency as a function of the incident angle.

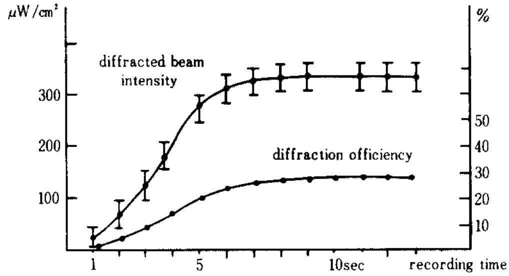


Fig.3. Intensity of the diffracted beam and efficiency as a function of the recording time.

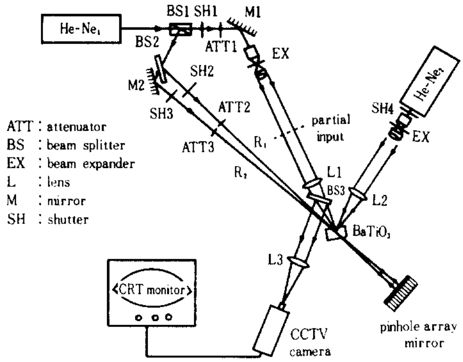


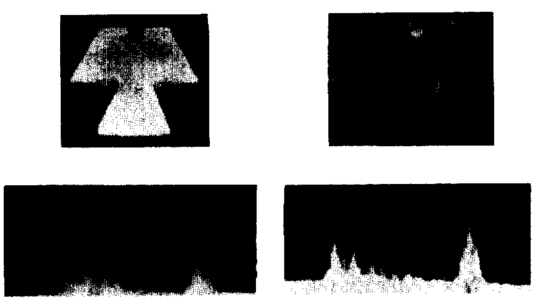
Fig.5. Experimental set-up for real-time associative memory.

Fairchild CCD 133 image sensor and displayed on oscilloscope are shown in Fig.4. Intensity of the edge is about 14 dB larger than that of the center.

The experimental set-up for real-time associative memory is illustrated in Fig.5. The size of the original images, PARKHK and OHCHAS, is 28 x 12 mm (each character, 3 x 4 mm). All of object and writing beams are derived from 5.3 mW He-Ne laser operating at 0.6328 μm.

The angle between object beam and writing beams R_1, R_2 are 8°, 14°, respectively, at which strong beam coupling occurs.

After erasing beam and writing beam R_2 are blocked, object beam passes through beam splitter BS_1-beam attenuator ATT_1-mirror M_1-beam expander Ex. PARKHK image is Fourier transformed by lens L_1 and focused in the $BaTiO_3$ crystal exatly. Writing beam R_1 passes through BS_1-BS_2-ATT_2, and incidents at angle 8°. In order to increase the auto-correlation peak and to reduce the cross-correlation noise, the dc term of Fourier transformed object is slightly suppressed and high order terms of it are enhanced by edge enhancement mechanism. So intensities of the object beam and writing beam R_1 are adjusted to $1.20mW/cm^2$, $0.606mW/cm^2$ using beam attenuators ATT1, ATT2, respectively. And this image is recorded for 12 sec, so as to reach a steady state. When second image, OHCHAS, is recored, writing beam R_1 is blocked by SH_2 and writing beam R_2 is incident at angle 14° through BS_1-M_2-ATT_3. At this time, to prevent the erasing effect of previously stored image, intensity of the writing beam R_2 is adjusted to 0.30 mW/cm^2 and image is recorded shortly for 5 sec. Two images stored in $BaTiO_3$ crystal is maintained by closing all shutters.



(a)　　(b)

Fig.4. Output images and waveforms according to the relative intensity Ir.
(a) Ir=1:2.
(b) Ir=2.2:1.

Two writing beams being blocked by shutters SH_1 and SH_2, a partial input image is also Fourier transformed by lens L_1 and directed to $BaTiO_3$ crystal. The first order of diffracted beam generated by the correlation between stored image and partial input image is sampled by pinhole array which extracts a desired auto-correlation between them. Extracted beam which acts as a reading beam is retraced to the $BaTiO_3$ crystal by conventional planar mirror. Phase conjugated beam being generated via DFWM configuration is inverse Fourier transformed by lens L_3 and reconstructed output image is detected by CCTV camera through a beam splitter BS_1. And recalled image is displayed on CRT monitor. Two stored images, partial input image and recalled output image are shown in Fig.6. Complete image can be reconstructed by 1/6 partial input of the stored image without any additional thresholding and iteration process successfully.

An additional 2 mW He-Ne laser is used to erase the volume grating rapidly for the purpose of real-time process. Using this erasing beam, $BaTiO_3$ crystal is illuminated uniformly for 10 sec to clear the previously stored images. And new images are recorded with same procedure. When $BaTiO_3$ crystal is addressed by writing beam, corresponding image (shown in Fig.7.) can be recalled. From this mechanism, our system is useful for optical implementation of real-time associative memory and location addressable memory.

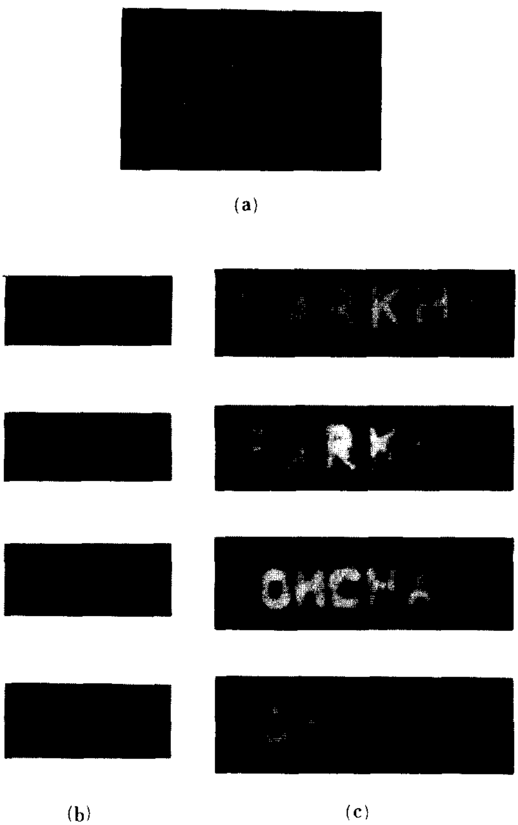


Fig.6. Recalled image via association.
(a) stored images in $BaTiO_3$.
(b) partial input.
(c) output image.

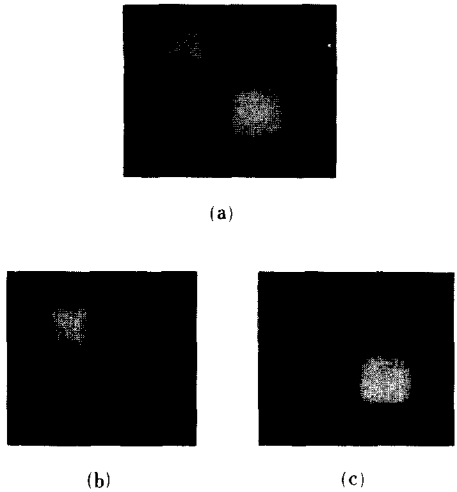


Fig.7. Recalled image via addressing.
(a) stored images.
(b) output image by R_1.
(c) output image by R_2.

IV. Conclusion

In our system, two images can be stored effectively by angular multiplexed writing beams in $BaTiO_3$ crystal. Complete image can be recalled successfully by partial input without any thresholding and iteration process. More efficient methods to record many images in photorefractive materials is our future interest. And also, if three phase conjugate mirrors, one for volume holographic memory and the others for thresholding and feedback devices, are used, good quality of real-time associative memory will be possible. It is expected that associative memory is applicable to optical pattern recognition and many other optical signal processing fields.

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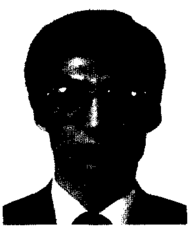

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