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Image Retrieval by Holographically-Generated Phase Conjugate Wavefronts

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ABSTRACT

Holographically-generated conjugate wavefronts have been used for realising optical associated memory elements which can reproduce complete stored information when addressed only by a partial information.

1. INTRODUCTION

Holograms have been used as optical associated memory elements which can reproduce complete stored information when addressed by only a partial information in a manner similar to that of the human brain[1-7]. The images in the memory can be recalled, not only by simple plane or spherical wavefronts but also by complicated reference images. The images that can be stored in the memory can be 2D binary, grey tone transparencies, or 3D objects with high spatial frequencies with the possibility of multiplexing. This is in contrast to the matrix-based associative memory system using feed-back and thresholding in which even storage of 2D images would result in a complicated associative matrix becoming very difficult to handle. Phase conjugate mirrors have been used along with holographic memories to achieve association.

Four-wave mixing in nonlinear media is one of the methods widely used for phase conjugation[8,9]. The similarities and parallelism between four-wave mixing in nonlinear crystals and holography are so intense that the idea of four-wave conjugation was evident in the work of pioneers of holography. Kogelnik was the first, who suggested to combine in time the recording and reconstruction of a holographic process to yield a dynamic hologram. The conjugate wavefront generated by a hologram was used as early as 1960s for the correction of aberrations of imaging system[10-12]. With the advent of real-time recording media, such as photothermoplastics, dichromated gelatin, photorefractive crystals etc, there has been renewed interest in holographically-generated phase conjugated wavefronts.

This paper describes the application of holographically-generated phase conjugate wavefronts to associative memory without using four-wave mixing in nonlinear crystals.

2. GENERATION OF CONJUGATE WAVEFRONTS BY HOLOGRAPHY

The photorefractive crystals have been used both for dynamic holography and four-wave mixing experiments[8,9,13]. The behaviour of photorefractive crystal in four-wave mixing has been explained with the analogy of holography. Sometimes, it does not become immediately clear whether the particular use of the crystal has been made as a recording medium for holography or as a four-wave mixing device. To

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understand this, one must keep in mind the basic differences between the two which are shown in Table 1.

Recording and reconstruction of a conventional hologram involves interference of two complex amplitudes $O(x, y)$ and $R(x, y)$. When the recorded hologram is irradiated by one of the two waves, say R, the transmitted light field is

$$E = (|O|^2 + |R|^2)\,R + R^2O^* + |R|^2O \qquad (1)$$

where $(|O|^2 + |R|^2)R$ is proportional to the incident field and R^2O^* corresponds to a time reversed phase conjugate replica of the original object field O. This image is nothing but the conventional pseudoscopic image. The last term $|R|^2O$ is equivalent to the original object field. In the off-axis hologram, third and fourth wavefields are separated. In thick holograms, the term R^2O^* is phase mismatched and not radiated.

For many applications of phase conjugate wavefronts, such as imagery through phase distorting media and associated memory, reconstruction of the hologram (Eqn (1)) by the conjugate of the reference beam, i.e., R^* is of importance. In this case, the transmitted light through the hologram is

$$E_c = |O|^2 + |R| \quad R^* + (R^*)^2O + |R|^2O^* \qquad (2)$$

where $|R|^2O^*$ corresponds to the time reversed phase conjugate replica of the original object field and $(R^*)^2O$ is not radiated in thick holograms.

When the hologram is irradiated by both R and O beams, the transmitted light through the hologram is

$$E_c = R(|R|^2 + 2|O|^2) + O^2R^* + O(2|R|^2 + |O|^2) + R^2O^* \qquad (3)$$

The R^2O^* in Eqn (3) is the phase conjugate of the object O. Figure 1 shows various wavefields produced when the hologram is reconstructed by the both reference and object beams. A plane reference beam is conjugated simply by using a plane mirror so that the wave is reflected back on to itself. Similarly, a spherical wave is conjugated by using a concave mirror.

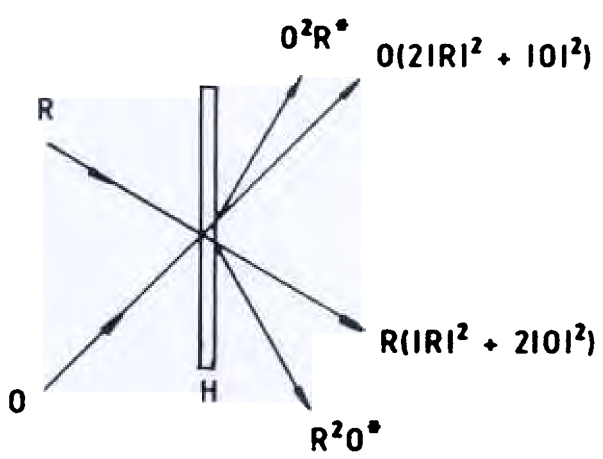


Figure 1. Generation of phase conjugate beam by the reconstruction of the hologram by reference and object beams.

3. HOLOGRAPHIC ASSOCIATED MEMORY

When recorded hologram is reconstructed by a part of the object beam, i.e., by $O'(x, y)$, the amplitude transmitted by the hologram will be

$$E_c = O'(|O|^2 + |R|^2) + O'OR^* + O'O^*R \qquad (4)$$

The $O'O^*R$ involves the correlation of O and O' and convolution of this correlation with R. If O' and O are similar their correlation will form a sharp peak and will be reconstructed.

Table 1 Difference between holography and four-wave mixing

Holography	Four-wave mixing
In conventional holography, object and reference beams must be of same frequency and polarity.	The pump and signal waves need not be of same frequency. The polarisation may even be orthogonal.
Recording involves change in some property of recording material, i.e. in refractive index or transmission or both.	The process is the result of tensorial properties of the nonlinear susceptibility of the medium.
Object and reference beams not present with readout and conjugate object beams.	Simultaneous presence of the pump and probe waves in nonlinear crystal.

Thus, by a partial input (object), the other beam (reference) can be reconstructed (Fig. 2). To reconstruct the complete object from the partial input, the recorded hologram is reconstructed by $O'O^*R$ producing

$$\begin{aligned} E_c &= O'O^*R(|O|^2+|R|^2) + O'O^*RO^*R \\ &\quad + O'O^*ROR^* \\ &= O'O^*R(|O|^2+|R|^2) + O'O^{*2}R^2 \\ &\quad + O'O^*|R|^2O \end{aligned} \tag{5}$$

The term $O'O^*|R|^2O$ in Eqn (5), provides the reconstructed object O provided O' is close to O with $O'O^{2*}R^2$ providing a uniform background.

If the phase conjugated object O^* is desired then the recorded hologram is reconstructed with $(O'O^*R)^*$. This is similar to the case when the hologram is illuminated by R^* when O and O' are close to each other.

$$\begin{aligned} E_c &= O'^*OR^*(|O|^2+|R|^2) + O'^*OR^*OR^* \\ &\quad + O'^*OR^*RO^* \\ &= O'^*OR^*(|O|^2+|R|^2) + O'^*O^2R'^{*2} \\ &\quad + (O'^*O)\,|R|^2O^* \end{aligned} \tag{6}$$

The term $(O'^*O)|R|^2O^*$ gives the phase conjugate O^*.

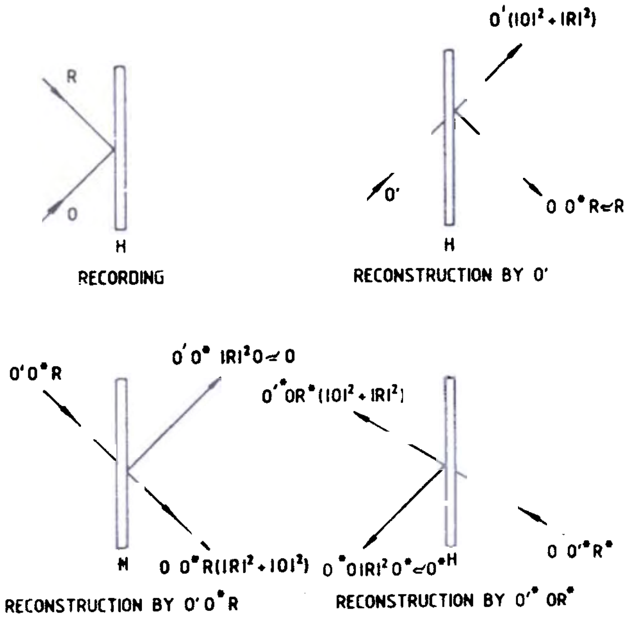


Figure 2. Principle of complete reconstruction of information by partial input.

4. EXPERIMENTAL

All the holograms were recorded in photothermoplastic recyclable medium using a 15 mW *He-Ne* laser.

As pointed out, the phase conjugate of the object beam is obtained when the hologram is illuminated by the phase conjugate of the reference beam. The reference beam can be conjugated by using a phase conjugate mirror or simply by a plane mirror if the reference beam is collimated. Therefore, before carrying out actual experiments the laser beam is made perfectly collimated. The collimation and the alignment can be checked by recording a two-beam hologram using plane beams. The reconstruction is done with the object beam itself for all the experiments.

To further check the alignment of the reference beam, an experiment was performed for imaging through a phase distorting medium (Fig. 3). Basically the arrangement is that of recording Fourier transform hologram with a distorting glass plate inserted in the object beam. The object beam while travelling through the distorting plate, acquires additional undesirable information. The effects of distorting medium are cancelled when the complex conjugate of this wave travels through the same distorting medium in opposite direction. The hologram H produces the desired complex conjugate (Fig. 4). The extent of restoration of the image shows that the collimation and the alignment of the reference beam was perfect.

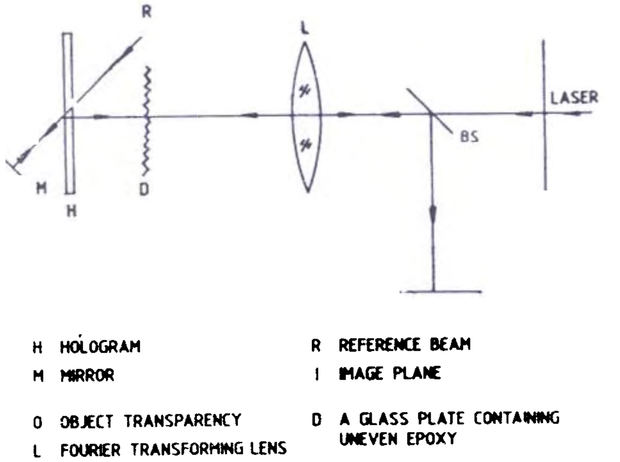
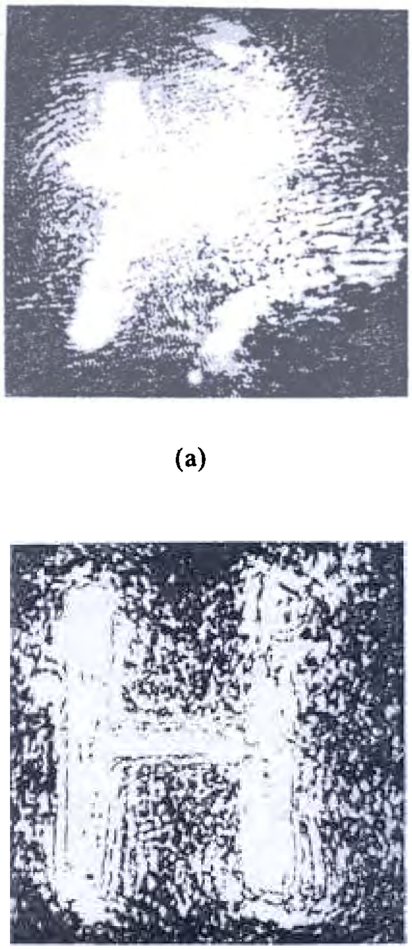


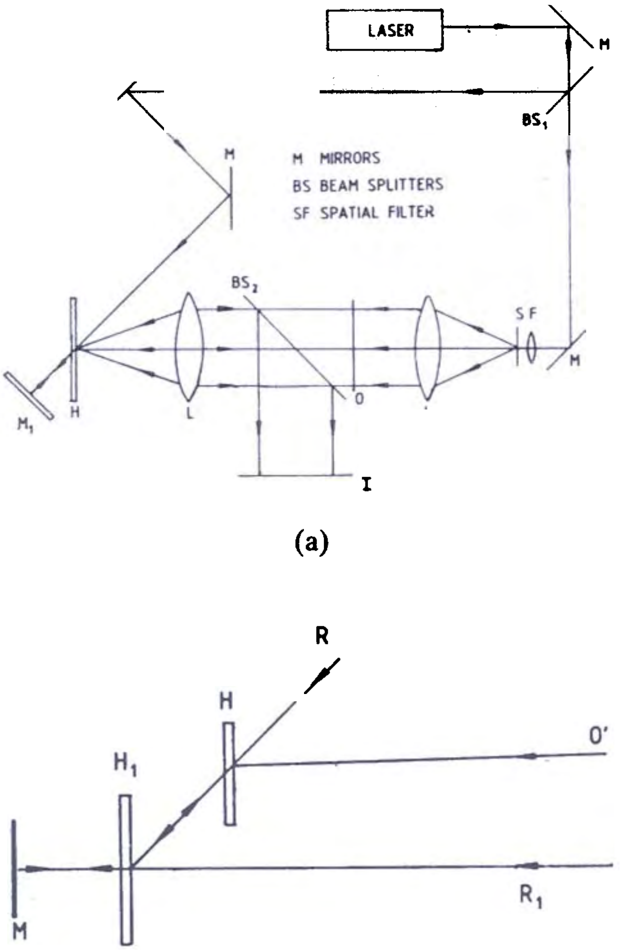
Figure 3. Schematic diagram of imaging through phase distorting medium.



(a)

(b)

Figure 4. Results of experiment for imaging through phase distorting medium : (a) holographic image without correction, (b) image with correction obtained at I, in Fig. 3.



(a)

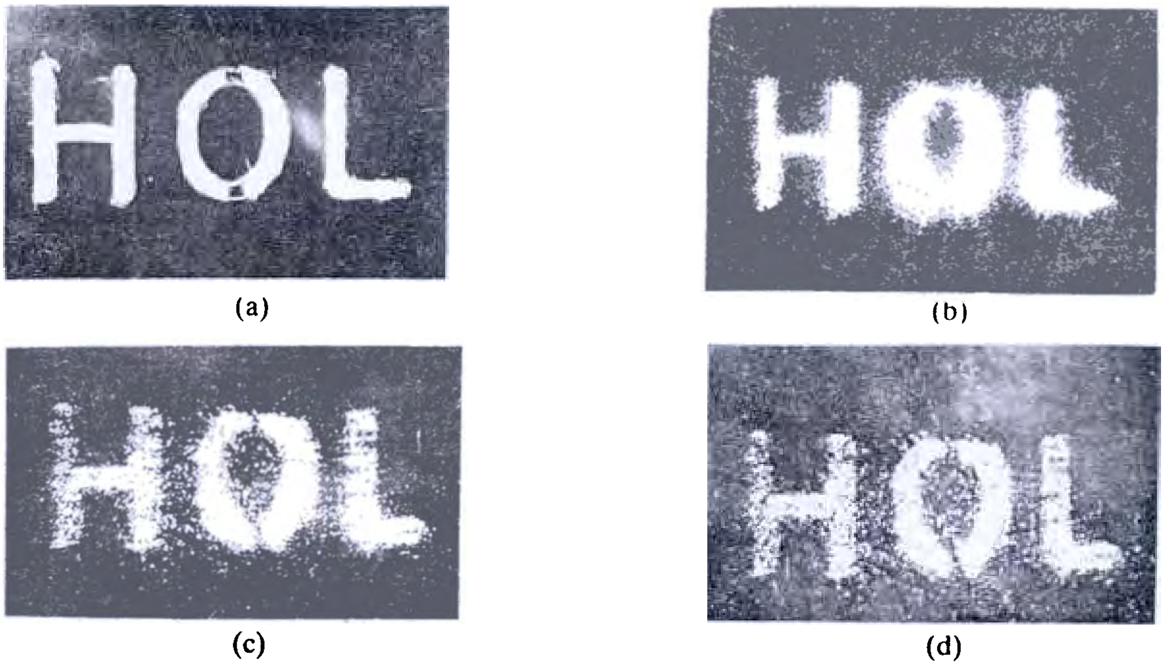
(b)

Figure 5. (a) Schematic diagram for holographic associated memory, and (b) when input object differs too much from the stored object, an additional hologram H is used.

The memory experiment was performed by a set-up, as shown in Fig. 5, which is similar to that in Fig. 3 except that no distorting medium has been used. To introduce some redundancy, the Fourier spectrum can be slightly defocused. When only a partial object is available in the object plane with no reference beam, the memory hologram reconstructs a plane reference beam which is reflected back by the mirror. This reference beam travelling in the reverse direction produces the complete object at plane I (Fig. 6).

A hologram of a transparency containing letters HOL was recorded. Figure 6(b) shows the reconstructed object at plane I by the reference beam. When the reference beam is blocked and the memory element interrogated by HOL, the image of HOL was reproduced as shown in Fig. 6(c). When only OL was input, still complete image of HOL was reconstructed with slightly reduced brightness (Fig. 6(d)). When the object O and its partial version O' differ too much, a simple plane mirror M will not produce the desired R^*. Instead a real-time hologram can be used as shown in Fig. 5(b). The output of H, when illuminated by O' is recorded as a Hologram H_1 by using a plane reference beam R_1. This hologram will exactly produce the desired beam $(O'O^*R)^*$ in Eqn (6). A phase conjugated mirror based on four-wave mixing has been used by many workers.

The system performance can be improved by adding one more interconnected branch of memory (Fig. 7). The reconstructed object travels to the second memory



(a) (b)

(c) (d)

Figure 6. Results of associated memory experiment; (a) object in holographic memory, (b) reconstruction by reference beam, (c) reconstruction by complete object (HOL), and (d) reconstruction by partial object (OL).

element and produces a reference beam which is again reflected back to the hologram producing the object beam. The information circulates between the two memory elements. In each cycle the object is improved if the memory elements themselves do not introduce noise.

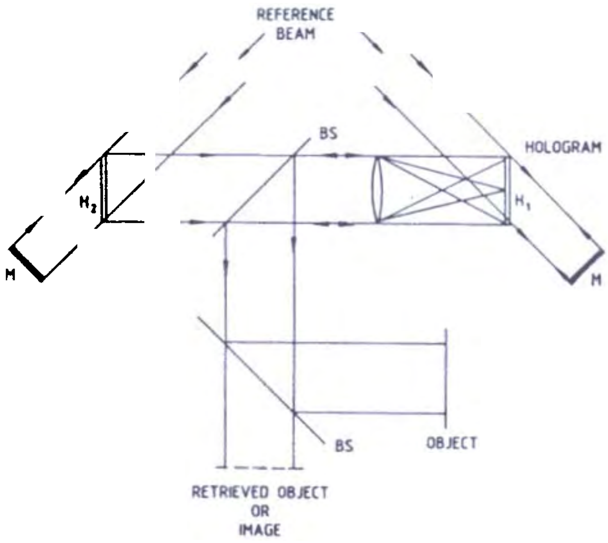


Figure 7. Information circulation using two holograms H_1 and H_2

5. DISCUSSION

A Fourier transform hologram was used as the memory element because it has an advantage of having a large zero order amplitude requiring a large dynamic range of the recording medium. Limited dynamic range materials would therefore, not record the low order frequencies thus enhancing the higher frequency components in the reconstructed image improving the discrimination.

The generation of conjugate wavefronts by holographic techniques and their various applications require real-time recording media. Dichromated gelatin and photopolymers are good media for recording holograms but these materials, though ideal for permanent storage purposes, are not recyclable. Photothermoplastic is a recyclable recording material but it backscatters light too much specifically in a Fourier transform hologram, which is collected by the Fourier transforming lens superimposing on the conjugate wavefronts. When real-time operation is not required as in the case of the associated memory, many of the experiments involving phase conjugate by nonlinear crystals can be performed by a thermoplastic film, photopolymer and dichromated gelatin.

The method reported though does not require accurate alignment of the object, lacks in thresholding operations which may call for nonlinear media. Further work is in progress to store and retrieve multiple objects and also to use available light energy efficiently.

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