Smart Optical RAM for Fast Information Management and Analysis

submitted to

NASA Ames Research Center

by

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Smart Optical RAM for Fast Information Management and Analysis

I. Project Overview

1.1 Statement of Problem

Instruments for high speed and high capacity in-situ data identification, classification and storage capabilities are needed by NASA for the information management and analysis of extremely large volume of data sets in future space exploration, space habitation and utilization, in addition to the various missions to planet-earth programs. Parameters such as communication delays, limited resources, and inaccessibility of human manipulation require more intelligent, compact, low power, and light weight information management and data storage techniques. New and innovative algorithms and architecture using photonics will enable us to meet these challenges. The technology has applications for other government and public agencies.

1.2 Solution of the Problem

In this NASA Advanced Concept Fellow Program, we have proposed and investigated a totally new and innovative optical random-access memory (RAM) system. Comparing to the digital RAM in electronic computers, the optical RAM has much broader capabilities. The optical RAM can be used not only for the storage of an extremely large amount of information and fast random-access to the data but also for pattern classification and interconnections in future advanced computers.

![Figure 1](image-url)

Figure 1 An optical random-access memory (RAM) system block diagram.
The new optical RAM is conceptually illustrated in Fig. 1. The information input \( I \) in a 2-D image or data format is carried by a collimated laser beam and applied through a sequence of multiple stages of cascaded holographic optical elements (HOE) and shutter arrays denoted by the \( H \) blocks. The HOE in \( H_1 \) will divide and replicate the input \( I \) into an array of \( h_1 \times h_1 \) identical images. The shutter array in \( H_1 \) is electronically controlled which can let any of the \((h_1)^2\) replica of \( I \) passing through the optical system. The subsequent \( H \) blocks have similar functions and capabilities. Hence at the output of the block \( H_n \), \((h_1 h_2 \ldots \ldots h_n)^2\) replica of \( I \) will appear in a Fourier transform array at plane \( F \). For example, if 2 stages of \( H \) are used with \( h_1=9 \) and \( h_2=5 \), \((45)^2= 2,025\) Fourier transforms of \( I \) can be obtained at plane \( F \). If 4 stages of \( H \) are used with \( h_1=9 \) and \( h_3=9 \) and \( h_2=h_4=5 \), \((9 \times 5 \times 9 \times 5)^2=4,100,625\) Fourier transforms of \( I \) can be stored at plane \( F \). If the input data are people’s faces, then all the faces of any one of most of the cities in the world can be memorized in the optical RAM. Furthermore, random accessible retrieval can be achieved at the speed of light! The memory can be accessed by simultaneous switching the shutter arrays.

### 1.3 Potential Applications

In contrast to the conventional optical correlators that can process only one channel at a given instant, the proposed optical RAM can memorize tens of thousands of channels of 2-D information of on the order of megabytes and retrieve information accurately at the speed of light. Partial information input can recall complete information from the optical RAM. These unique abilities of the optical RAM allow it to be applied to many current fields of interest, including parallel database search, image and signal understanding and synthesis, real-time multi-sensory target recognition and classification, and parallel optical interconnections for future computers. These areas are of importance to NASA’s future space exploration, space habitation and utilization, in addition to the various missions to planet-earth programs and many commercial applications including fingerprints identification for police and FBI and optical interconnections for future computers.

For purpose of demonstration, one example of these applications is illustrated in Fig. 2. Fig. 2(a) shows how memorization in the optical RAM is accomplished by placing the objects as represented by the satellite and space shuttle in the view of a video camera. Over tens of thousands of 2-D data can be stored. Microprocessors may be used to control the random access to any data set from the memory. After the optical RAM memorizes all the images presented to it, it becomes smart. When input such as a partial and noisy space shuttle as shown in Fig. 2(b), is presented to it, the smart RAM can recover and display at the output screen the perfectly retrieved image. In addition, the optical RAM can be used to recognize input and tells us whether it belongs to the memory. For example, if the fingerprints of FBI’s most wanted criminals are stored in the memory, the RAM can determine whether an arbitrary input fingerprint belongs to one of the criminals. This can be done remotely and the optical RAM can make decision at the speed of light!
In summary, a few potential NASA and commercial applications are summarized below:

**NASA Applications**

a) Planetary exploration in-situ data analysis and information screening  
b) Space surveillance specific object identification and navigation guidance  
c) Space image understanding and classification  
d) Space station automated rendezvous and docking  
e) Space habitation and utilization environmental evaluation and assessment  
f) Navigation collision avoidance in Moon and Mars  
g) Satellite repair, maintenance and sensing

**Commercial applications**

a) Criminal fingerprints random access memory and retrieval for police  
b) Security check of commercial building entrances  
c) Automobile plate identification  
d) Large capacity free space interconnection for future computers  
e) Border patrol and illegal drug traffic prevention

1.4 Innovation of the Work

Comparing with existing technology can show the innovation. For example, the operation of a digital computer requires that data can be stored and retrieved as desired, and information can be put randomly into and out of each storage element as required. A digital RAM is used for this purpose. However, according to Professor Jacob Millman of Columbia University, a major disadvantage of the digital RAM is that it is volatile. Due to the fact that dynamic circuits are exclusively used for large storage capacity, stored information is lost when the power is turned off. The proposed optical RAM has some functions of a digital RAM but is non-volatile. When the laser light is turned off, the memory remains in the hologram. Similar optical technology for memory are limited to single channel operation with limited data throughput data processing capacity, the proposed optical RAM has good sensitivity, high resolution, speed-of-light photon processing, massive parallelism, accurate smart retrieval, and real-time operation capability.

1.5 Concept Impact

The optical RAM, which is quite different from the electronic RAM, displays a higher level capability of optical multiplexing a 2D input and comparing it with many different reference data sets, and can create an oscillatory optical resonance mode in which input variation and error can be eliminated. As erasable optical recording materials such as the thermoplastic material and photorefractive materials are used, the information will remain in the memory until the writing of new information into the system. In addition to the conventional memory capability similar to a digital RAM, it has the added capability of parallel pattern classification for information management that the digital RAM does not have. For NASA, the impact of the concept on increased automation and increased efficiency in information management based on the optical RAM means that previously impossible missions are enabled.
Figure 2. Example of the applications of an optical RAM. (a) Memory process; (b) Information retrieval.
II. Description of the Project

2.1 Project Objective

For the purpose of serving future NASA space exploration, space habitation and utilization, in addition to the various missions to planet-earth programs, we have investigated a new and innovative optical random-access memory (RAM) with high data throughput parallel free space optical holographic interconnection and memory capabilities for fast information management and analysis.

2.2 Theoretical Background

To further illustrate the concept as shown in Fig. 3, multi-channel pattern recognition architecture utilizing a cascade combination of a Dammann grating and a holographic lens is shown in Fig. 4. A laser beam from an Argon ion laser is divided into two beams, an object beam and a reference beam, by a beam splitter. The object beam is collimated by a spatial filter and lens $L_1$ combination and is replicated by a Dammann grating into a $(2M+1) \times (2M+1)$ array of beams, where $M$ is the maximum diffraction order of the Dammann grating. The object beam array illuminate the input pattern and are then Fourier transformed by the lens $L_2$ at its focal plane where selection shutter array 1 is placed. The input pattern array can be Fourier transformed by lens $L_3$ and be replicated into a $(2N+1) \times (2N+1)$ array, where $N$ is maximum order of the holographic lens, and Fourier transformed again by the holographic lens at its focal plane where selection shutter array 2 is placed. The lenses $L_4$ and $L_5$ are used to perform the Fourier transform to yield the $(2M+1)^2 \times (2N+1)^2$ array at the $L_5$ focal plane as shown in Fig. 3 where the holographic matched filter is recorded. The reference beam is collimated by a spatial filter and lens $L$ combination and interferes with the object beam at the matched filter plane.

A theoretical analysis of the multi-channel system in Fig. 3 is described below.

A. Amplitude distribution at plane $P_2$ (Fourier plane of $L_2$)

The object is illumined by an array of beams diffracted by the Dammann grating and is Fourier transformed by lens $L_2$ onto its Fourier plane $P_2$ where an aperture is set to select only $(2M+1) \times (2M+1)$ equally bright central diffraction orders. The amplitude distribution at $P_2$ is a $(2M+1) \times (2M+1)$ array of Fourier transforms of the object by lens $L_2$

$$S_z(f_x, f_y) = A \sum_{m=-M}^{M} \sum_{n=-M}^{M} \delta(f_x - \frac{m}{L_d}) \delta(f_y - \frac{n}{L_d}) \cdot F_z(O(x,y))$$

$$= A \sum_{m=-M}^{M} \sum_{n=-M}^{M} \delta(f_x - \frac{m}{L_d}) \delta(f_y - \frac{n}{L_d}) \cdot \delta(f_x, f_y)$$

(1)
Figure 3 The experimental setup of a multi-channel pattern recognition architecture utilizing a cascade combination of a Dammann Grating and a holographic lens.

where \( l \) is the wavelength of the laser, \( A \) is a constant associated with the input wave amplitude, \( f_2 \) is the focal length of lens \( L_2 \), and \( 1/L_d \) is the periodic of the Dammann Grating in frequency domain. \( F_n[\cdot] \) denotes the Fourier transform by lens \( L_n \) (\( n=1, 2, \ldots \)),

\[
\tilde{O}(f_x, f_y) = F_2[O(x, y)] = \iint O(x, y) \exp[-j2\pi(f_x x + f_y y)] dx dy
\]

(2)

where \( f_x \) and \( f_y \) are the special frequencies: \( f_x=x_2/lf_2 \) and \( f_y=y_2/lf_2 \), and \((x_2, y_2)\) are points in plane \( P_2 \). The amplitude distribution at \( P_2 \) can also be expressed in terms of the position at plane \( P_2 \).
\[ U_2(x_2, y_2) = S_2 \left( \frac{x_2}{\lambda f_2}, \frac{y_2}{\lambda f_2} \right) \]
\[ = \frac{A}{j \lambda f_2^3} \sum_{m=-M}^{M} \sum_{n=-M}^{M} \delta(x_2 - \frac{\lambda f_2}{L_d} m) \delta(y_2 - \frac{\lambda f_2}{L_d} n) \ast \tilde{O} \left( \frac{x_2}{\lambda f_2}, \frac{y_2}{\lambda f_2} \right) \]
\[ = \frac{A}{j \lambda f_2^3} M_d(x_2, y_2) \ast \tilde{O} \left( \frac{x_2}{\lambda f_2}, \frac{y_2}{\lambda f_2} \right) \]

Where

\[ M_d(x_2, y_2) = \frac{1}{(\lambda f_2)^2} \sum_{m=-M}^{M} \sum_{n=-M}^{M} \delta(x_2 - \frac{\lambda f_2}{L_d} m) \delta(y_2 - \frac{\lambda f_2}{L_d} n) \]

B. Amplitude distribution at Fourier plane of lens L3

A lens L3 is placed at distance \( f_3 \) from plane P2. Due to the input at plane P2, the amplitude distribution at Fourier plane of lens L3 may be written as

\[ S_3(f_3, f_3) = \frac{1}{j \lambda f_3} F_3 \{ U_2(x_2, y_2) \} \]
\[ = \frac{A}{(\lambda f_2)(\lambda f_3)} F_3 \{ M_d(x_2, y_2) \} \cdot F_3 F_2 \{ O(x, y) \} \]

The amplitude distribution Eq. (5) can also be expressed in terms of the position at Fourier plane of lens L3, that is

\[ U_3(x_3, y_3) = S_3 \left( \frac{x_3}{\lambda f_3}, \frac{y_3}{\lambda f_3} \right) \]
\[ = -\frac{A}{(\lambda f_2)(\lambda f_3)} \tilde{M}_d \left( \frac{x_3}{\lambda f_3}, \frac{y_3}{\lambda f_3} \right) \cdot O \left( \frac{f_2}{f_3} x_3, \frac{f_2}{f_3} y_3 \right) \]

where \( \tilde{M}_d(f_2, f_3) = F_3 \{ M_d(x, y) \} \).

C. Amplitude distribution at Fourier plane of the holographic lens

The holographic lens Fourier transforms the input \( U_3(x_3, y_3) \) to a \((2N+1) \times (2N+1)\) array of spectrum onto its Fourier transform plane. The amplitude distribution is
\[ S_h(f_{x'}, f_{y'}) = \frac{1}{j\lambda_h} \sum_{m_x=-N}^{N} \sum_{m_y=-N}^{N} \delta(f_{x'} - \frac{m_x}{L_h})\delta(f_{y'} - \frac{n_y}{L_h}) \ast F_h[U_h(x, y)] \]
\[ = -\frac{A}{j(\lambda f_2)(\lambda f_3)(\lambda f_h)} \sum_{m_x=-N}^{N} \sum_{m_y=-N}^{N} \delta(f_{x'} - \frac{m_x}{L_h})\delta(f_{y'} - \frac{n_y}{L_h}) \ast F_h[M_a(x_2, y_2)] \ast F_h[O(-\frac{f_x}{f_1}, \frac{f_y}{f_1})] \]
\[ = -\frac{A}{j(\lambda f_2)(\lambda f_3)(\lambda f_h)} \sum_{m_x=-N}^{N} \sum_{m_y=-N}^{N} \delta(f_{x'} - \frac{m_x}{L_h})\delta(f_{y'} - \frac{n_y}{L_h}) \ast F_h[F_3/M_a(x_2, y_2)] \ast F_h[O(-\frac{f_x}{\lambda f_2}, \frac{f_y}{\lambda f_2})] \]

The amplitude distribution Eq. (7) can also be expressed in terms of the position at Fourier plane of the holographic lens, that is

\[ U_h(x_h, y_h) = S_h(\frac{x_h}{\lambda f_h}, \frac{y_h}{\lambda f_h}) \]
\[ = -\frac{A}{j(\lambda f_2)(\lambda f_3)(\lambda f_h)} \frac{1}{(\lambda f_h)^2} \sum_{m_x=-N}^{N} \sum_{m_y=-N}^{N} \delta(x_h - \frac{\lambda f_h}{L_h} m_x)\delta(y_h - \frac{\lambda f_h}{L_h} n_y) \ast M_d(-\frac{f_x}{f_h}, -\frac{f_y}{f_h}) \ast O(-\frac{f_x}{\lambda f_2 f_h}, -\frac{f_y}{\lambda f_2 f_h}) \]
\[ = -\frac{A}{j(\lambda f_2)(\lambda f_3)(\lambda f_h)} \sum_{m_x=-N}^{N} \sum_{m_y=-N}^{N} \delta(x_h - \frac{\lambda f_h}{L_h} m_x)\delta(y_h - \frac{\lambda f_h}{L_h} n_y) \ast M_d(-\frac{f_x}{f_h}, -\frac{f_y}{f_h}) \ast O(-\frac{f_x}{\lambda f_2 f_h}, -\frac{f_y}{\lambda f_2 f_h}) \]

where \( f_h \) is the focal length of the holographic lens, \( 1/L_h \) is the periodic of the holographic lens in frequency domain, and

\[ M_h(x_h, y_h) = \frac{1}{(\lambda f_h)^2} \sum_{m_x=-N}^{N} \sum_{m_y=-N}^{N} \delta(x_h - \frac{\lambda f_h}{L_h} m_x)\delta(y_h - \frac{\lambda f_h}{L_h} n_y) \]

D. Amplitude distribution at Matched Filter Plane

L_4 and L_5 are a pair of lenses with same focal length. Lens L_4 is placed at distance \( f_4 = f_5 \) from the Fourier plane of the holographic lens and lens L_5 is placed \( 2f_4 \) from lens L_4. The matched filter plane is at the focal plane of lens L_5. The amplitude distribution at matched filter plane can be expressed as

\[ U_m(x_m, y_m) = \frac{1}{\lambda f_4^2} F_3 F_d[U_h(x_h, y_h)] \]

since \( f_4 = f_5 \), then

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where \((x_m, y_m)\) is the position at matched filter plane. It can be seen that the amplitude distribution at the matched filter plane is a \((N \times N)\) with \((M \times M)\) array of the Fourier transforms of the object.

\[
\tilde{O}(f_x, f_y) = F_2\{O(x, y)\} = \int \int O(x, y) \exp[-j2\pi(f_xx + f_y y)] dx dy
\]

with

\[
f_x = \frac{f_x}{\lambda f_2 f_h} x_m \text{ and } f_y = \frac{f_y}{\lambda f_2 f_h} y_m
\]

E. Recording of the Holographic Matched Filter

In the recording of the holographic matched filter, two selection arrays are placed at the plane \(P_2\) and at the Fourier plane of the holographic lens, respectively. The selection arrays are set that only one order from the Dammann grating or the holographic lens is selected to go through while other orders are blocked. Once the order \((m_1, n_1)\) from Dammann grating and the order \((m_2, n_2)\) from holographic lens are selected, the amplitude distribution at the matched filter plane, or Eq. (11), becomes

\[
U_m(x_m, y_m) = \frac{A}{j(\lambda f_2)^2(\lambda f_3)^2(\lambda f_4)^2} \delta(-x_m - \frac{\lambda f_h}{L_h} m_2) \delta(-y_m - \frac{\lambda f_h}{L_h} n_2)
\]

\[
\times \delta(x_m - \frac{\lambda f_4 f_h}{L_4} m_1) \delta(y_m - \frac{\lambda f_4 f_h}{L_4} n_1) \ast \tilde{O}(\frac{f_2}{f_h} x_m, \frac{f_2}{f_h} y_m
\]

\[
= \frac{A \lambda f_1}{j(\lambda f_2)^2(\lambda f_3)^2(\lambda f_4)^2} \delta(-x_m - \frac{\lambda f_2}{L_2} m_2) \delta(-y_m - \frac{\lambda f_2}{L_2} n_2)
\]

\[
\times \delta(x_m - \frac{\lambda f_2 f_h}{f_3 L_4} m_1) \delta(y_m - \frac{\lambda f_2 f_h}{f_3 L_4} n_1) \ast \tilde{O}(\frac{f_2}{f_h} x_m, \frac{f_2}{f_h} y_m)
\]

2.3 Research Results

The latest results of the research are included in the preprint of a manuscript as shown below. Other results including papers published and patent application are included in the appendixes.
Massively parallel optical pattern recognition and retrieval
via a two-stage high-capacity multi-channel
holographic random-access memory system

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Abstract. The multi-stage holographic optical random-access memory (HORAM) system reported recently by Liu et al provides a new degree of freedom for improving the storage capacity. In this paper we further presented theoretical and practical analysis on the HORAM system with experimental results. Our discussions included the system design and geometrical requirements, its applications for multi-channel pattern recognition and associate memory, the 2-D and 3-D information storage capacity, and the multi-channel image storage and retrieval via Vander Lugt correlator (VLC) filters and joint transform holograms. A series of experiments have been performed to demonstrate the feasibility of the multi-channel pattern recognition and image retrieval with both of the VLC and joint transform correlator (JTC) architectures. The experimental results with as many as 2025 channels have shown good agreement with the theoretical analysis.

Subject terms: multi-stage holographic optical random-access memory system; holographic storage; optical pattern recognition; image storage and retrieval; optical information processing.
1 Introduction

Optical data storage and pattern recognition are two important and related areas in modern optics. For the purpose of optical pattern recognition, a variety of architectures and techniques have been developed, which are mainly categorized into Vander Lugt correlator (VLC) and joint transform correlator (JTC) systems. Optical data storage offers inherent 2-D parallelism and high speed processing. It may enable one to construct a holographic database with a large number of image templates optically accessible and applicable for different applications including pattern recognition, image retrieval, and associate memory. In order to increase the image storage and recognition capability of a system, several methods have been proposed and experimentally demonstrated. These include the composite filter synthesis and multiplexing techniques with the use of a volume recording element. The latter approach has been considered as one of the most successful and promising techniques for data storage. For example, Heanue et al demonstrated the storage and retrieval of digital data using a volume hologram, Mok reported that over thousands of holograms can be stored in a lithium niobate crystal via angular multiplexing, and Pu et al reported the storage of up to one thousand holograms at a single location using the DuPont 100-μm-thick photopolymer. In these techniques, either the volume effect of a 3-D recording device or the one-stage spectrum multiplexing is used to enhance the storage capacity of a given system. More recently, Liu et al presented a multi-stage holographic optical random-access memory (HORAM) system, which has advantages including higher storage capacity over a single stage system.

In this paper we will discuss the design principles of the multi-stage HORAM system for its practical applications. We will introduce a few architectures for different applications and, for the first time, present new and more detailed experimental demonstration results of multi-channel
pattern recognition and reconstruction with the use of a two-stage HORAM system including VLC and JTC arrangements. The results have verified the feasibility and usefulness of a multi-stage multi-channel HORAM system.

2 Theoretical analyses

2.1 Geometrical considerations for spectrum array generation and separation

A multi-stage HORAM system is composed of several stages cascaded in tandem. The use of many stages in a system can greatly increase the spectrum multiplexing capacity, but it also introduces the complication in the interconnection between any two succeeding stages. In order to ensure that all the spectra of different orders in the final spatial spectrum plane are properly separated, the optical arrangement of a HORAM system should satisfy certain geometrical requirements. In the following we will discuss these requirements for a two-stage HORAM system.

The working principle of a two-stage HORAM system may be schematically expressed in Fig.1, where (a), (b) and (c) are the optical setup and the spectral distributions in planes F and H, respectively. The light from a point coherent source, S, becomes a plane wave after passing through collimator L₁, and then illuminates the object transparency, O, which is in close contact with a Dammann grating, G. The first spectrum array is obtained at the back focal plane F of lens L₂. The grating G may produce many diffraction orders in plane F. By inserting a rectangular opening aperture we can select only \( M \times M \) central diffraction orders and block the higher orders. A combination of lens L₃ and a multi-focus hololens, L₄h, images plane F onto plane H. In plane H the spectrum is further multiplexed to a \( (M \times M) \times (N \times N) \) array, where the \( N \times N \) multiplexing is produced by the hololens.
If we assume the Dammann grating has the same spatial frequency $v_d$ in the $x$ and $y$ directions, the length of one side of the $M \times M$ spectrum array in plane $F$ can be decided by

$$D_x = D_y = M \lambda f_2 v_d,$$

where $\lambda$ is the wavelength of the laser, and $f_2$ is the focal length of lens $L_2$. This pattern is magnified in plane $H$ by a factor

$$A = \frac{f_h}{f_3},$$

and the hololens $L_h$ further replicates the magnified $M \times M$ spectrum array to $N \times N$ arrays with a spacing

$$D_h = \lambda v_h f_h,$$

where $f_3$ and $f_h$ are the focal lengths of $L_3$ and $L_h$, respectively, and $v_h$ is the spatial frequency of the hololens. Obviously, in order to separate different orders in plane $H$, we need

$$D_h \geq A D_f,$$

that is

$$v_h \geq M \frac{f_2}{f_3} v_d,$$

or, if we use the parameter $A$,

$$A \leq \frac{f_h v_h}{M f_2 v_d}.$$  

Actually the planes $F$ and $H$ are not necessarily placed in the front focal plane of $L_3$ and back focal plane of $L_h$, respectively. What we need here is the multiple imaging function, which can be performed by either a single multi-focus hololens or a combination of a multi-focus hololens
and another conventional lens, as shown in Fig.2 (a) and (b). In both cases the magnification from F to H may be written

$$A = \frac{d_h}{d_f}. \quad (7)$$

The requirements similar to Eqs. (5) and (6) may then be written as

$$v_h \geq M \frac{f_2}{d_f} v_d \quad (8)$$

and

$$A \leq \frac{d_h v_h}{M f_2 v_d}, \quad (9)$$

or equivalently

$$d_f \geq \frac{M f_2 v_d}{v_h}. \quad (10)$$

We can see that the changes here are the substitutions of $f_3$ and $f_h$ by $d_f$ and $d_h$, respectively. We may use Eq. (10) to adjust the magnification of the imaging system to ensure spectrum separation. In the exact matching case where the equal sign is used in all the above expressions, we will obtain an equal spacing $(N \times N) \times (M \times M)$ spectrum array in plane H.

The size of the $M \times M$ spectrum array in plane F has been given in Eq. (1). In case of exact matching, the $(N \times N) \times (M \times M)$ spectrum array in H has the size $D \times D$, where

$$D = N \frac{d_h}{d_f} D_f = MN\lambda f_2 v_d \frac{d_h}{d_f}. \quad (11)$$

The use of a Dammann grating sets a resolution limit on the input image. The maximum transitive spatial frequency in object plane is half of $v_d$. Increasing $v_d$ may improve the object resolution, but it also yields a larger spectrum size $D$ as indicated by Eq. (11). In practice, $D$ has
a limit, therefore all the parameters such as M, N and \( \nu_0 \) are limited to a certain range by the availability of usable space.

### 2.2 Multi-channel pattern storage and recognition with VanderLugt correlator

An architecture of a multi-channel VanderLugt-correlator-based two-stage HORAM system is shown in Fig. 3, where \( F_1 \) and \( F_2 \) are the first and second spectrum planes respectively. An additional imaging arrangement from plane \( F_2 \) to plane \( H \) is used here for the convenience of placing the shutter array in plane \( F_2 \). We may record MNxMN different spectra in plane \( H \) by using two shutter arrays at planes \( F_1 \) and \( F_2 \), respectively, only a single aperture in each shutter array is open when each input image is applied. Assume the same reference beam is used in the recording process for all the input images and all the apertures of the shutters are opened simultaneously in the correlation step. Applying an arbitrary input \( O_{ij} \) among the memorized images, we will obtain one autocorrelation term and \((M^2N^2-1)\) crosscorrelation terms in the center of plane \( P \) (i.e., the focus of the reference beam). The resultant correlation output is

\[
u_c = O_{ij} \otimes O_{ij} + \sum_{m,n=1}^{MN} \sum_{k,l=1}^{MN} O_{mn} \otimes O_{kl}, \tag{12}\]

where \( \otimes \) denotes correlation. Although the first term in the above equation is considerably larger than any other, the combination of the other terms will be larger than the first one due to the large number \( M^2N^2 \). Therefore this setup is not usable for large capacity pattern recognition. There are two remedying means to circumvent this problem.

First, we may open the shutter aperture sequentially for a given input pattern while observing the correlation output in plane \( P \). The position of the opened aperture corresponding
to the maximum correlation reveals the specific input object. Evidently we must scan the whole shutter aperture array for each input image, and it takes a minimum time period of

\[ T = M^2 N^2 \tau, \]

(13)

where \( \tau \) is the time required for the detection of the correlation peak. This time is dependent on some practical factors such as the recording material and the detecting device. If a CCD of a response time of 10 ms is used for correlation peak detection, \( T \) would be 10 seconds for \( M^2 N^2 = 10^3 \). This should be acceptable for some practical applications, but not fast enough for high-speed recognition and high data transfer operation.

An effective approach to solve this problem is to use the reference beam angular multiplexing technique. In this method we employ a different angle for each reference beam with each shutter aperture which is opened successively for each different input image in the recording process. The different reference beams form a focal array in plane \( P \). In the correlation process all the shutter apertures are opened simultaneously for a given input, and the location of the brightest spot in \( P \) identifies the recognized input pattern. This technique can work much faster compared to the fixed reference beam method, but it is at the expense of using a complicated angle-adjusting recording system.

In the above analysis we have assumed that a planar hologram is used. In fact we may also use 3-D holographic recording materials such as the photorefractive crystals\(^{13}\) for making the matched filters. The volume effects of a 3-D recording material enable us to realize angular multiplexing recording for each individual spectrum position. This property adds one more dimension to the storage capacity of the device, which may be estimated as follows.

For a Dammann grating with spatial frequency \( \nu_A \), the minimum resolvable size in the object plane is \( 1/\nu_A \), and the information amount per binary input page is \( (D_0 \nu_A)^2 \) bits, where \( D_0 \) is the
dimension of input image (assume $D_{ox}=D_{oy}=D_o$). Since a 2-D recording plate can store $(MN)^2$ images, the storage capacity should be

$$C = (MN)^2 (D_o \nu_d)^2$$

(14) bits, provided the lens aperture is large enough to transmit the spatial frequency $\nu_d$. On the other hand, for a 3-D device, there may be $K \times L$ holograms recorded by angular multiplexing for each spectrum position, where $K$ and $L$ are the angular changes in $x$ and $y$ directions respectively. Consequently the storage capacity is increased up to

$$C_v = (MN)^2 KL(D_o \nu_d)^2$$

(15) bits. The values of $K$ and $L$ are mainly determined by the thickness of the crystal. Other limitations to $MN$ and $KL$ are the dimensions of the recording device and related optical elements.

For an example, assume $D_o=25$ mm, $\nu_d=15$/mm, $M=9$, $N=5$, then the storage capacity of this 2-D recording system is $C=2.8 \times 10^8$ bits. For making sufficient spectra separation in the 3-D recording with a crystal, we may reduce $MN$ to, for instance, $4 \times 4=16$, and take a reasonable value of $KL$ to be $10^3 \sim 10^3$, the resultant storage capacity $C_v$ is $3.6 \times 10^9 \sim 10^{10}$ bits for a crystal of 1 cm$^3$. In comparison, the best result obtained recently by IBM using a single stage system with a photorefractive crystal$^{23}$ is $8.5 \times 10^7$ bits/cm$^3$. Hence, the multi-stage architecture can provide a new degree of freedom for improving the storage capacity.

### 2.3 Multi-channel associate memory

Conceptually an associate memory may be realized with the use of a nonlinear threshold element for feedback retrieval via a phase conjugate mirror (PCM). A viable architecture is shown in
Fig. 4 where the multi-stage HORAM system is simplified as a spectrum replication system. A PCM is located in plane Pc and each filter in plane H is sequentially made for a different object and with a different reference angle. When a partial image corresponding to one of the stored images is applied to the input, a bright spot will appear at a proper position (the focus of its recording reference beam) in plane Pc. As a nonlinear and feedback device, the PCM reflects only this beam and suppresses all other beams. The reflected light will form a plane wave, conjugate to the original reference beam, and then generate a more complete image at the output plane via a beam splitter.

Although this concept is simple, the practical limitation seems to be the availability of a high-quality PCM with an effective aperture large enough to cover the whole correlation array.

2.4 Multi-channel joint transform hologram and image retrieval

The basic concept of making joint transform hologram (JTH) in a multi-channel system is illustrated in Fig. 5 (a), where two input images are placed side by side in plane Pin. Their joint transform spectrum, which appears at the central region of the Fourier plane H, is recorded in a holographic medium.

With the use of a multi-stage HORAM system for spectrum replication, a multi-channel JTH can be made, where each element hologram in one position of the spectrum array corresponds to a specific pair of input images. As many as $(MN)^2$ image pairs can be recorded in a 2-D holographic medium. This multi-channel JTH may then be used for joint transform correlation (JTC) or image retrieval. For the purpose of JTC, we can use a plane wave to illuminate the JTH and obtain two correlation terms at the two opposite sides of the output plane located at the back focal plane of a Fourier transform lens behind the JTH. Since the location of the correlation spot
is only determined by the spatial separation between the two input images and independent of the element location in the JTH, the correlation outputs of all the JTH elements overlap if they are illuminated simultaneously. To avoid this effect, the JTH elements should be scanned successively (one by one) by using an electrical shutter array system.

The above scanning technique is also applicable for image retrieval. In this case we store \((MN)^2\) image pairs \((a_i, b_j) (i,j=1-MN)\) at different positions of the hologram \(H\), and then input one image \(a_i\) and scan all the elements in the JTH. When the JTH element \((i,j)\) is open, the reconstructed image \(b_j\) appears at the output plane as shown in Fig.5(b).

As we indicated above, although the successive scanning requirement may set a limit on the operation speed, the use of a high-speed detector will decrease the operation time and consequently increase the data processing speed.

3 Experimental demonstrations

3.1 Geometrical parameters of the optical setup

Our experimental setup of a two-stage HORAM system is shown in Fig.6, where \(G\) is a 9×9 Dammann grating with \(\nu_d=6.74/\text{mm}\), and \(L_h\) is a 5×5 foci off-axis hololens. An off-axis hololens can be modeled by a combination of a prism for beam deflection, a conventional lens for beam focusing, and a 2-D orthogonal phase grating for focus multiplexing. As verified by our experiments, the equivalent grating spatial frequency of this hololens and its focal length for \(\lambda=514.5\text{nm}\) are \(\nu_h=19.7/\text{mm}\) and \(f_h=32.1\text{cm}\) respectively. Using \(M=9\) and \(f_2=20\text{cm}\) in our case, we determined \(d_f\geq61.6\text{cm}\) from Eq.(10) for spectrum separation. In practice no serious overlap was seen in the range of \(d_f\geq60\text{cm}\). An example photograph showing the well-separated 45×45=2025 spatial spectra obtained in plane \(H\) is given in Fig.7. The experimental parameters
we measured under exact matching condition are \( d_f = 61.5 \) cm, \( d_h = 69.5 \) cm, \( D_f = 6.3 \) mm, and \( D = 36.6 \) mm. From these parameters we have \( \left( \frac{1}{d_f} + \frac{1}{d_h} \right)^{-1} = 32.6 \) cm, and the Eqs. (1) and (11) give \( D_f = 6.24 \) mm and \( D = 35.3 \) mm. These results have shown a good agreement between our theoretical predictions and experimental measurements.

3.2 Multi-channel pattern storage and recognition

To verify the feasibility of the two-stage HORAM system for pattern storage and recognition, the optical setup shown in Fig.6 was used to make the multi-channel VanderLugt filters. The light source is an Ar\(^{+}\) laser delivering about 0.8w power at 514.5nm. The test images are two letters, S and C, as shown in Fig.8. A plane wave is incident normally upon the combination of the object transparency and the Dammann grating. At plane F a square aperture is used to let only the central 9×9 array to pass through. After multiple imaging via the 5×5 foci hololens, we get the second spectrum array in plane H with 2025 individual and spatially-separated spectra. A plane reference beam is introduced to record the filters. The recording position in plane H may be chosen by using two circular apertures in planes F and H to pass only the selected spectrum order. First we select the \((0,0)\) order in plane F and \((-1,-1)\) order in plane H, the recording medium used is a Kodak 649F plate. Two filters were made with input letter S and C (one letter for each) respectively, and the exposure time is about 1/5 second. The correlation results with these two filters are shown in Figs. 9 and 10. Figure 9 corresponds to filter #1 made with letter S, where the left and right are autocorrelation for input S and crosscorrelation for input C, respectively. Obviously the former is much stronger than the latter, and their intensity ratio is about 6 to 1. Figure 10 shows similar results for filter #2 made with letter C, the autocorrelation is about 8 times stronger than the crosscorrelation.
To test the recognition capability of any non-central spectrum order, we next selected the (3,1) order in plane F and (1,-1) order in plane H to record filters #3 and #4 for the input images S and C successively. The Russian made FPR holographic plates were used with an exposure time of approximately 1.5 seconds. The corresponding correlation results are shown in Figs. 11 and 12 for the two filters respectively. We can still clearly see that the intensity of autocorrelation is much higher than that of the crosscorrelation in each case. So if a proper threshold intensity is chosen, the input pattern can be recognized without any difficulty, and all the 2025 channels can work well.

3.3 Image retrieval with multi-channel VanderLugt filters and JTHs

In order to test the image retrieval capability of the two-stage multi-channel VanderLugt filters, we used a plane wave to illuminate the four filters we recorded one by one. The reconstruction results are shown in Fig.13 for filters #1 and #2 and in Fig.14 for filter #3 and #4, respectively. In each case we can clearly recognize the retrieved image, letter S or C. The reconstructed images in Fig.14 have lower signal-to-noise ratio than those in Fig.13, because filters #3 and #4 are made with off-axis spectrum orders in both planes F and H. These orders are weaker than those chosen from the central order in plane F and off-axis order in plane H.

We have also made some JTHs at different spectrum orders to verify the retrieval feasibility. Due to the low diffraction efficiency in our experiment (only amplitude holograms were used) and interference of the strong direct image with reconstructed pattern, the retrieved images with a two-stage HORAM system are very noisy, weak, and difficult to record. In the following we only present experimental results obtained with the JTHs recorded in the first spectrum plane F (the 9x9 array).
The first JTH was made in the architecture of Fig.5 with the letters C and E, shown in Fig.15 as the input image pair. The spectrum order was arbitrarily chosen as (-4,3). In the reconstruction step, if the input is letter C, we simultaneously obtain as shown in Fig.16 (a) a strong addressing image of letter C and a weak retrieved image of letter E at the output plane. When the letter E is used as the input, the output is shown in Fig.16 (b) where a strong E and a weak reconstructed C can be seen side by side.

Further we made the second JTH with input image pair of letters S and E as shown in Fig.17. In this recording process we did not block any spectrum in plane F so that all the 9×9 JTH elements were recorded at the same time. In the reconstruction step we have obtained the retrieved image by using any one JTH element. As examples, we present the experimental results obtained with the JTH of order (4,-2) in Fig.18 and the JTH of order (-3,-3) in Fig.19. In each photo we can clearly see the reconstructed image besides the strong direct image, regardless of which one of the image pair is used as the input. These results have shown that all the individual channels can work effectively and independently.

4 Conclusion

Based on the multi-stage HORAM system reported by Liu et al[21], we have made more theoretical and practical analysis on the requirements of its geometrical parameters and its optical architecture constituents, its applications in multi-channel pattern recognition and associate memory, the 2-D and 3-D information storage capacity, and the multi-channel image storage and retrieval via VLC filters and joint transform holograms. A series of experiments have been performed to demonstrate the feasibility of the multi-channel pattern recognition and image retrieval with both of the VLC and JTC architectures. The experimental results with as many as 2025 channels have shown good agreement with the theoretical analysis. We have discussed the
potential applications of the system for large-capacity pattern storage, recognition, and retrieval.

The use of fast-response and low-noise recording materials and detecting devices will greatly improve the performance of the system for practical applications.

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References


Figure Captions:

Fig. 1 Schematic diagram of a two-stage HORAM system. (a) Optical architecture; (b) spectrum distribution in plane F; (c) spectrum distribution in plane H.

Fig. 2 Two configurations for adjusting the magnification between planes F and H.

Fig. 3 The optical architecture of a two-stage HORAM system.

Fig. 4 An optical multi-channel associate memory system using a PCM for image retrieval.

Fig. 5 Multi-channel joint transform hologram: (a) Recording process; (b) reconstruction process.

Fig. 6 Experimental setup for a two-stage multi-channel HORAM system.

Fig. 7 An example photograph showing 2025 well-separated spatial spectra obtained by two-stage spectrum multiplexing.

Fig. 8 Input images for VanderLugt matched filter fabrication.
Fig. 9 Two-stage correlation results obtained from a VanderLugt filter #1 made with reference image "S" as shown in Fig.8, where the spectrum orders (0,0) and (-1,-1) are selected at plane F and H respectively. (a) Autocorrelation for input "S"; (b) crosscorrelation for input "C".

Fig. 10 Two-stage correlation results obtained from a VanderLugt filter #2 made with reference image "C" as shown in Fig.8, where the spectrum orders (0,0) and (-1,-1) are selected at plane F and H respectively. (a) Autocorrelation for input "C"; (b) crosscorrelation for input "S".

Fig. 11 Two-stage correlation results obtained from a VanderLugt filter #3 made with reference image "S" as shown in Fig.8, where the spectrum orders (3,1) and (1,-1) are selected at plane F and H respectively. (a) Autocorrelation for input "S"; (b) crosscorrelation for input "C".

Fig. 12 Two-stage correlation results obtained from a VanderLugt filter #4 made with reference image "C" as shown in Fig.8, where the spectrum orders (3,1) and (1,-1) are selected at plane F and H respectively. (a) Autocorrelation for input "C"; (b) crosscorrelation for input "S".

Fig. 13 Reconstructed images with a plane reference wave input to (a) filter #1 and (b) filter #2.

Fig. 14 Reconstructed images with a plane reference wave input to (a) filter #3 and (b) filter #4.

Fig. 15 Input image pair for the fabrication of joint transform hologram #1.

Fig. 16 Reconstruction results obtained from the joint transform hologram #1 by using the spectrum order (-4,3): (a) With input "C"; (b) with input "E".

Fig. 17 Input image pair for the fabrication of joint transform hologram #2.
Reconstruction results obtained from the joint transform hologram #2 by using the spectrum order (4,-2): (a) With input "S"; (b) with input "E".

Reconstruction results obtained from the joint transform hologram #2 by using the spectrum order (-3,-3): (a) With input "S"; (b) with input "E".
Fig. 1 Schmatic diagram of two-stage HORAM system. (a) Optical architecture; (b) spectrum distribution in plane F; (c) spectrum distribution in plane H.
Fig. 2 Two configurations for adjusting the magnification between planes F and H.
Fig. 3 The optical architecture of a two-stage HORAM system.
Fig. 4 An optical multi-channel associate memory system using a PCM for image retrieval.
Fig. 5 Multi-channel joint transform hologram: (a) Reading process; (b) reconstruction process.
Fig. 6  Experimental setup for a two-stage multi-channel HORAM system.
Fig. 7 An example photograph showing 2025 well-separated spectra obtained by two-stage spectrum multiplexing.
Fig. 8 Input images for VanderLugt matched filter fabrication
Fig. 9 Two-stage correlation results obtained from a VanderLugt filter #1 made with reference images "S" as shown in Fig. 8, where the spectrum orders (0,0) and (-1,-1) are selected at plane F and H respectively. (a) Autocorrelation for input "S"; (b) crosscorrelation for input "C".
Fig. 10 Two-stage correlation results obtained from Vander Lugt filter #2 made with reference image "C" as shown in Fig. 8, where the spectrum orders (0,0) are selected at plane F and H respectively. (a) Autocorrelation for input "S", (b) cross-correlation for input "C".
Fig. 11 Two-stage correlation results obtained from a VanderLugt filter #3 made with reference image "S" as shown in Fig. 8, where the spectrum orders (3,1) and (1,-1) are selected at plane F and H respectively. (a) Autocorrelation for input "S"; (b) crosscorrelation for input "C".
Fig. 12. Two-stage correlation results obtained from a VanderLugt filter made with reference image "C", as shown in Fig. 8. (a) Autocorrelation for input "S". (b) Cross-correlation for input "S".

where the spectrum orders (3,1) and (1,1) are selected at plane F and H respectively.
Fig. 13 Reconstructed images with a plane reference wave input to (a) filter #1 and (b) filter #2.
Fig. 14 Reconstructed images with a plane reference wave input to (a) filter #3 and (b) filter #4.
Fig. 15 Input image pair for the fabrication of joint transform hologram #1.
Fig. 16 Reconstruction results obtained from the joint transform hologram #1 by using the spectrum order (-4,3): (a) With input "C"; (b) with input "E".
Fig. 17 Input images pair for the fabrication of joint transform hologram #2.
Fig. 18 Reconstruction results obtained from the joint transform hologram #2 by using the spectrum order (4,-2): (a) With input "S"; (b) with input "E".
Fig. 19 Reconstruction results obtained from the joint transform hologram #2 by using the spectrum order (-3,-3): (a) With input "S"; (b) with input "E".
TRANSLATION SENSITIVE ADJUSTABLE COMPACT OPTICAL CORRELATOR

The present invention is directed to pattern recognition apparatus, and more particularly to opto-electronic correlators for recognition of partially obscured or modified objects.

Background and Summary of the Invention

An optical correlator compares an optical pattern to a stored pattern to determine an amount of matching. Optical correlators are essentially fast computers -- they allow very fast identification of optical elements relative to a stored sequence ("kernel").

Correlators operate in record and reconstruction modes. During the record mode, an input image is recorded in an optical element. The reconstruction mode matches input information against the kernel to thereby determine matches between the input information and the kernel.

Generally, optical correlators of the prior art have used a plane wave to record an image in the matched spatial filter and a lens behind the matched spatial filter to collect data associated with the matching function performed by the filter. These optical systems, however, have been relatively sensitive to variations in the positioning of the spatial filter and the input image. Lateral and longitudinal variations in the positioning of the spatial filter and the input image degrade the recognition performance of the correlators.

Previous uses of prior art correlators have been substantially limited by these accuracy requirements, and other difficulties of implementation, such as size.
However, many applications seem well-suited to analysis using such a system. For example, pattern recognition, such as fingerprint recognition or robotic vision applications are well suited to this operation, because of the quasi periodic nature of these patterns. This quasi periodic nature has suggested to the inventors that frequency domain analyzers, such as correlators, would be advantageous.

Unfortunately, the fingerprint recognition environment is characterized by such variations as noted above, due to variables in positioning and repositioning of the finger in the imaging plane.

In addition, often in applications of imaging technology the image seeking to be identified may be partially obscured or unreadable. For example, in a fingerprint recognition system, the image seeking to be verified may be misaligned or offset relative to the imaging plane. The image may also be obscured due to a cut or abrasion on the surface of the skin. Accordingly, partial images or partially obscured images may be presented for verification. Control devices such as mechanical stops (finger box) and the like can be used to minimize alignment problems, but their effectiveness is limited. For fingerprint recognition systems it would be desirable to obtain matches for partially obscured images if a sufficient portion of the image is readable.

In view of the above, the inventors recognized that it would be desirable to provide a portable and compact imaging system for use in robotic vision or fingerprint recognition systems. Such an imaging system would have adjustable sensitivity to variations in the displacement of the filter or image and be capable of resolving partially obscured images.
The present invention describes a sensitivity adjustable compact opto-electronic correlator and pattern recognition system for identification of a partially obscured or modified objects and includes a laser source, a spatial light modulator, a transform lens, a holographic matched filter, and a detector located at a classification output plane. The laser source outputs a laser beam which is split by a beam splitter into an imaging optical path and a reference optical path during a recording process. The imaging optical path uses a laser beam output from the laser source which is collimated through a collimating lens to provide a collimated laser beam which passes through a spatial light modulator for enhancing the beam and also entering an input image that is to be identified. The collimated laser beam acts as a carrier for the input image which then passes through a transform lens having a focal length D1 at a first (holographic) plane. A complex structure associated with the input image is located within the cross-section of the focal point at the first plane.

The reference optical path includes a reference beam which is reflected through a second transform lens whose output is directed toward and interferes with the carrier beam at the first plane. The second transform lens is configured such that the reference beam is focused a predetermined distance D2 beyond the first plane. In one aspect of the invention, a converging reference beam with adjustable focal length distance is used instead of a collimated reference beam as conventionally done in other existing correlators. The adjustable focal distance provides the desired sensitivity.

A film is placed at the holographic plane to record the interference pattern generated by the interference of the imaging optical path and the reference optical path. Thereafter, the film may be developed and acts as a
holographic matched filter when replaced back at the holographic plane for use in recognizing an associated object or image.

More specifically, a laser source which is used in the recognition process provides a laser beam which is collimated through a collimating lens and input into a spatial light modulator. The spatial light modulator receives as an input an image for verification, such as a fingerprint, and utilizes the collimated laser beam as a carrier to carry the image to a lens which focuses the image to a focal point in the holographic plane.

An electronic shutter associated with the holographic plane thereafter exposes an associated portion of the film located at the holographic plane. The carrier beam which contains the complex structure associated with the image to be verified. Upon detecting a match, an output is driven to a classification output plane which includes a photodetector array. The detector array detects a matching configuration based on light energy refracted from the holographic plane. In operation, the holographic matched filter (exposed film) screens improper images and provides minimal output to the detector array unless a match condition occurs.

In another aspect of the present invention a method of recording images and for reconstructing the recorded images includes recording a holographic image of an object, and thereafter utilizing the holographic image in filtering image data to verify matches with previously recorded image data.
Brief Description of the Drawing

These and other aspects of the present invention will now be described in detail with reference to the accompanying drawings, in which:

FIG. 1 is a block diagram of a correlator according to one embodiment of the present invention.

FIG. 2 is a block diagram of the optical paths associated with a record mode for a correlator according to one embodiment of the present invention.

FIG. 3 is a block diagram of the optical paths associated with a reconstruction mode for a correlator according to one embodiment of the present invention.

FIG. 4 is a diagram of the lateral displacement of an input image relative to the intensity of the correlation peak for a correlator according to one embodiment of the present invention.

Description of the Preferred Embodiments

FIG. 1 shows a block diagram of a laser opto-electronic correlator 50 including a laser 100 for providing a laser beam output to a spatial light modulator 102 and holographic filter 104. The laser beam input to spatial light modulator 102 acts as a carrier for an input image 106 which is provided as an input to the spatial light modulator 102. A carrier beam output 108, including the image information associated with input image 106, forms an input to holographic filter 104. The image-carrying laser beam through spatial light modulator 102 is Fourier transformed spatially by Fourier lens 103 which is placed at a distance of one focal length in front of the holographic filter plane 104. Holographic filter 104 also receives a reference beam from laser source 100 as an input thereof. The reference beam passes through a lens 105 which is placed at an
adjustable distance in front of the holographic filter plane 104. The function of lens 105 is to focus the reference beam at a point whose distance from the holographic filter 104 is adjustable. Holographic filter 104 matches input image 106 with an image that was previously stored on holographic filter 104. The sensitivity of the matching of the input to the stored input becomes adjustable with the adjustment of the position of lens 105 in the reference beam. The storage of the holographic image on holographic filter 104 will be described in greater detail below in association with the recording process.

When a match is detected, the holographic filter plane provides an output signal to a detector 110 indicating that a match has occurred between the input image data and a previously-recorded holographic image.

FIG. 2 shows a block diagram of correlator 50 according to one embodiment of the present invention. A laser source 210 provides a laser beam output which is directed towards a beam splitter 220. In one embodiment the laser source is a miniature laser diode source; a helium neon laser, or other lasers may also be used.

Beam splitter 220 splits the laser beam into an imaging beam 222 along imaging path 200 and a reference beam 224 along reference path 202. Imaging beam 222 is directed towards a mirror 230 which reflects the imaging beam 222 towards spatial filter 235. Spatial filter 235 spreads the imaging beam, generally directing the now-spread imaging beam towards a collimating lens 240. Collimating lens 240 collects the imaging beam light energy and directs it parallel to the perpendicular axis of the lens, providing a collimating laser beam for input into a spatial light modulator 245.
In one embodiment, spatial light modulator 245 is a 90° prism. The 90° prism is oriented such that the collimated laser beam output from collimating lens 240 is provided as an input onto a first side 246 of the prism. The prism includes an imaging surface 247 for receiving an image for recording or comparison operations. The imaging surface 247 is on the long hypotenuse side of the prism opposite the 90° angle.

The imaging data, e.g. a fingerprint is acquired on imaging surface 247 which may include a finger box (not shown) for maintaining the relative position of a finger relative to the imaging surface.

A second side 248 of the prism adjacent to first side 246 provides a carrier beam output 249, combining the image data received at imaging surface 247 with the collimated laser beam output from collimating lens 240 received at first side 246. The prism realizes the real-time input of an image via the total internal reflection mechanism of the prism device. Specifically, the collimated laser beam input from the collimating lens 240 acts as a carrier for the image data, thereby providing a carrier beam output which is directed towards a transform lens 250.

As was described above, spatial light modulator 245 provides an output carrier beam 249 as an input to transform lens 250 having a focal length of D1. Transform lens 250 may be a Fourier transform lens which provides a spatial Fourier transform of the image data which is focused on a matched spatial filter (MSF) plane, generally indicated at 260. A cross section of a focal point of the output from transform lens 250 includes complex structures associated with the input image provided as an input to spatial light modulator 245.
Film 265 is placed at MSF plane 260 and is exposed to the focused carrier beam via an electronically controlled shutter (not shown) associated with the MSF plane. The electronically controlled shutter controls the exposure of film 265 to light from the imaging optical path.

Referring now to the reference path, beam splitter 220 provides a reference beam 224 which is directed toward a mirrors 232 and 234 for reflection towards the MSF plane 260. Specifically, after reflection from mirror 234, the reference beam passes through a spatial filter 236 which spreads the output beam. The light energy is there after collected by a second transform lens 238 which focuses the reference beam toward a detector 270. In one embodiment, the transform lens is a Fourier transform lens. The reference beam is aligned such that the light energy directed from the transform lens 238 passes through MSF plane 260 prior to being focused at detector 270. In one aspect of the present invention, the position of the transform lens 238 is adjustable in its optical axis such that the sensitivity of detection may be adjusted.

The Recording Process

In order to record an image for comparison at a future time, an image recording process is invoked. The image recording process consists of providing an image, such as a fingerprint, at the imaging plane of spatial light modulator 245. During the recording process, the laser source 210 outputs a laser beam which is split by beam splitter 220 into an imaging beam 222 and reference beam 224. In the imaging optical path, the imaging beam is collimated through collimating lens 240 to provide a collimated laser beam output to spatial light modulator (prism) 245. Spatial light modulator 245 enhances the
imaging beam and also receives as an input the fingerprint that is to be recorded at imaging plane 247.

The collimated laser beam output from collimating lens 240 acts as a carrier for the fingerprint image providing a carrier beam as an output from spatial light modulator 245 for transfer to transform lens 245. The focal point for transform lens 245 is at MSF plane 260.

At the same time, the laser source 210 provides a reference beam in the reference optical path which is reflected through a second transform lens 238 whose output is directed toward and interferes with the carrier beam at MSF plane 260. In one embodiment, the second transform lens is identical to the first transform lens. Second transform lens 238 may be a Fourier transform lens. The second transform lens is configured to focus the reference beam a predetermined distance D2 beyond the MSF plane. Film 265 placed at MSF plane 260 is exposed to the interference pattern created by the complex structure associated with the input image (fingerprint) in the carrier beam and the reference beam by the electronic controlled shutter associated with MSF plane 260. Thereafter the film is developed and replaced at the MSF plane for use in the reconstruction process.

Reconstruction/Recognition Process

FIG. 3 shows the reconstruction process. Laser source 210 provides a laser beam which is directed through a pinhole spatial filter 235 toward a collimating lens 240. Alternatively, the same set-up as described in the recording process may be used including a beam splitter. However, the reference optical path is not utilized in the reconstruction process. Collimating lens 240 provides a collimated laser beam output for input into spatial light modulator 245. A
fingerprint seeking to be verified (recognized) is provided as an input to imaging plane 247 of spatial light modulator (prism) 245. Spatial light modulator 245 receives the input image and utilizes the collimating laser beam as a carrier to carry image data to the transform lens 250. Transform lens 250 focuses the image data to a focal point in MSF plane 260.

The electronically controlled shutter associated with MSF plane 260 is opened to expose the film to the focused carrier beam. In the absence of the interfering reference beam, the exposed and developed film acts as a filter to the imaging optical path, performing a matching function associated with a previously recorded image. Specifically, film 265, upon being exposed to the complex structure in the focal point of the carrier beam (after being developed), deflects light toward detector 270 as if the reference beam were present if the fingerprint data in the carrier beam is the same as the previously recorded fingerprint data. In the event a match occurs, detector 270 receives a light pattern which is indicative of a match condition.

Relationship between Recognition Sensitivity and the Lateral and Longitudinal displacement of the Filter and Input Image

Repeatability of matching capability in correlator 50 is a primary concern for commercial applications. In order to assure repeatability, the MSF plane (film 265) should be located exactly at the focal point of transform lens 250 when replaced in the correlator after developing. Longitudinal and lateral displacements of the MSF plane may result in poor repeatability characteristics for other existing devices. One aspect of the present invention provides a solution for the enhancement of repeatability of
recognition. An analysis of the effects of longitudinal and lateral displacement of the filter (film 265) indicated that the effect of longitudinal displacement on repeatability was much less than that of lateral displacement. However, either may skew results. The inventors prefer the following technique for replacing film 265 at the focal point for the transform lens 250 by examining a correlation peak.

During the recording process, the focal point (at MSF plane 260) associated with the transform lens 250 is located thereby defining MSF plane 260. Film 265 is fixed at this location before recording. After removal and development of film 265, film 265 is replaced in approximately its original location. The original image is applied to the spatial light modulator or through the prism. A correlation peak is detected associated with the maximum intensity of light received at detector 270 when moving film 265 only laterally. This is accomplished by a manual review or by an automated vision process. The film can be returned to roughly its original position moving the filter continuously in a lateral direction while observing the correlation peak intensity received by the detector centered at the focal point of the reference beam. Film 265 is thereafter moved until the intensity reaches its maximum at the detector. After repeated experiments with the system using the above-described approach, it has been found that the translation sensitivity is dependent on the ratio $D_2/D_1$ of the system configuration. This will be elaborated further below.

In addition, shifts in the fingerprint image either laterally or longitudinally will effect the repeatability of the correlator system. Specifically, lateral and longitudinal shifts in the input image will result in shifts in the correlation peak. In order to minimize the
repositioning error for objects, various control mechanisms may be utilized including a confining box.

In making the correlator system compact, a small area detector instead of a detector array may be utilized. The small area detector includes a small pinhole as a receiving aperture. The size of the pinhole is configured to be large enough to detect the correlation peak while able to tolerate a certain amount of input displacement. In addition, the size of the pinhole should be small enough to reject most of the background noise. In one embodiment, for the identification of fingerprints (where the fundamental spatial frequency of two line pairs per millimeter occurs), the width of the correlation peak is approximately 0.5 millimeters for the case where the D2/D1 equals 1. In this embodiment, the diameter of the pinhole is approximately 1 millimeter.

Adjustment of the Translation Sensitivity via the Adjustment of Geometric Parameters D1 and D2

In an embodiment which utilizes a pinhole detector, the movement of the correlation peak due to laterally shifted input images must be compensated for. As indicated above, the correlation peak will move laterally with a laterally shifted input image. Accordingly, as the correlation peak moves laterally (tracking the movement of the input image), the amount of light received at the detector is diminished. This diminishment of light at the detector due to a shifted input image is generally referred to as translation sensitivity.

Translation sensitivity is a performance parameter which relates to the ability of the correlator to detect a match, given a displacement of the input image. Given the movement of the correlation peak due to a shifted input
image, it would not be convenient to adjust the pinhole position each time to match the input displacement. However, analysis has shown that translation sensitivity for the correlator system of the present invention is strongly dependent on the geometric configuration of the system, namely the relationship of the parameters D2 and D1. Translation sensitivity can be reduced by decreasing the ratio of D2 to D1, resulting in an increase in the overall repeatability of the correlator. Accordingly, the ability to adjust the translation sensitivity of the optical correlator via the adjustment of the ratio between D2 and D1 results in improved image recognition capability of the system.

FIG. 4 shows a diagram of lateral displacement of input image (such as a fingerprint) relative to the intensity of the correlation peak. Ratios of D2 to D1 of less than approximately 1 will yield decreased translation sensitivity. In one embodiment, the ratio is 1 to 4, or .25. The smaller the D2 to D1 ratio, the more tolerant the system is to lateral displacements.

Compensation for Zero Spatial Frequency Term of Images

Another problem effecting the final correlation results is the zero spatial frequency (DC) term of the carrier beam, whose relative value is greater than 0.5 in the practical prism input case. The correlation between D.C. terms of two different images may introduce a significant background peak intensity. A simple approach to eliminate this effect is to overexpose film 265 in the MSF plane during the recording step, so that the DC portion of the center of the spectrum becomes entirely dark and hence has no diffraction function.
Detection of Partially Obscured Images

At the detector the relevant intensity of the light detected from a match or a non-match condition can be described as follows. Assuming that a perfect match provides a relative intensity of 1.0, the system of the present invention typically returns (detracts) approximately 0.35 or 35% of the light in a no-match condition. For the case of no-input image (background test), approximately 18% of the imaging light is defracted through the MSF filter plane. Accordingly, the present invention may be utilized to recognize partially obscured images by setting a threshold for detection to be between the ideal relative intensity of 1.0 and the no-match return level of approximately 35%. In one embodiment, the match threshold is set at approximately between 50% and 90%, with 60% preferred. At these levels, partially obscured objects which otherwise may not have been detectable by other recognition systems may be identified.

Alternative Embodiments

In one embodiment, transform lens 238 and 250 may be multi-channel lens. Electronic shutter associated with MSF plane 260 is used to expose a plurality of locations on film 265. Multi-channel lens create a plurality of focal points at MSF plane 260, each focal point including complex image information associated with the image input at the spatial light modulator. The electronic shutter is used to expose film 265 to only one of the focal points, storing the information at a predetermined position on film 265. Accordingly, a plurality of image interference patterns may be stored on the same film 265. During reconstruction, electronic shutter sequences through the various stored images to detect a match. Alternatively, the electronic
shutter may be opened completely exposing all of the stored interference patterns. A match is detected based on the defracted light received at the detector just as described above.

The present invention has been described in terms of one or more embodiments. The invention, however, is not limited to the embodiments depicted or described. Rather, the scope of the invention is defined by the claims which follow.
What is claimed is:

1. An apparatus for recording images comprising:
   a laser source producing a laser beam;
   a spatial light modulator receiving an image for
   recording and said laser beam, said laser beam acting as a
   carrier for said image, said spatial light modulator
   outputting a carrier beam including image data;
   a first transform lens receiving said carrier beam,
   said first transform lens having a predetermined focal
   length D1 focusing said carrier beam at a first plane;
   an adjustable transform lens for receiving said
   laser beam and outputting a focused reference beam directed
   toward and interfering with said carrier beam at said first
   plane, said focused reference beam having a focal point an
   adjustable distance D2 beyond said first plane; and
   a film located at said first plane for recording an
   interference pattern between said focused reference beam and
   said carrier beam.

2. The apparatus of claim 1 wherein said transform lens
   and said adjustable transform lens are multi channel lens,
   and where said electronic shutter exposes said film to a
   single channel of data at a time.

3. The apparatus of claim 1 where a ratio of D2 to D1
   is approximately 50 to 90 percent.

4. The apparatus of claim 1 where a ratio of D2 to D1
   is approximately 60 percent.

5. The apparatus of claim 1 where said detector is a
   detector array.
6. The apparatus of claim 1 where said detector is a pin hole detector.

7. The apparatus of claim 1 where said spatial light modulator is a 90° prism.

8. The apparatus of claim 1 wherein said laser source is a helium neon laser.

9. An apparatus for reconstructing images comprising:
   a laser source providing as an output a laser beam;
   a spatial light modulator receiving as an input an image for processing and said laser beam, said laser beam acting as a carrier for said image, said spatial light modulator outputting a carrier beam including image data;
   a transform lens receiving said carrier beam, said transform lens having a predetermined focal length focusing said carrier beam at a first plane;
   a film located at said first plane including a recorded interference pattern associated with an image; and
   a detector located a predetermined distance from said first plane for receiving light refracted from said film, such that light is refracted and focused at said detector if said image matches said recorded interference pattern.

10. An apparatus for recording images comprising:
    a laser source providing as an output a laser beam;
    a beam splitter receiving said laser beam and splitting it into an imaging beam and a reference beam;
    a collimating lens for receiving said imaging beam and providing as an output a collimated laser beam;
A spatial light modulator receiving as inputs an image for recording and said collimated laser beam, said collimated laser beam acting as a carrier for said image, said spatial light modulator outputting a carrier beam including image data;
a transform lens receiving said carrier beam, said transform lens having a predetermined focal length D1 focusing said carrier beam at a first plane;
a shutter array between said transform lens and said first plane, said shutter array including an open position, a closed position and means for switching between the two;
an adjustable transform lens for receiving said reference beam and outputting a focused reference beam directed toward and interfering with said carrier beam at said first plane, said focused reference beam having a focal point an adjustable distance D2 beyond said first plane; and
a film located at said first plane and exposed when said shutter array is in said open position for recording an interference pattern between said focused reference beam and said carrier beam.

11. An apparatus for reconstructing images comprising:
a laser source providing as an output a laser beam;
a beam splitter receiving said laser beam and splitting it into an imaging beam and a reference beam;
a collimating lens for receiving said imaging beam and providing as an output a collimated laser beam;
a spatial light modulator receiving as an input an image for processing and said collimated laser beam, said collimated laser beam acting as a carrier for said image, said spatial light modulator outputting a carrier beam including image data;
12. A method for recording an image comprising the steps of:
   providing a laser beam;
   splitting said laser beam into an imaging beam and a reference beam;
   superimposing an image on said laser beam resulting in a carrier beam;
   focusing said carrier beam by a transform lens at a first plane;
   focusing said reference beam by an adjustable transform lens and outputting a focused reference beam directed toward and interfering with said carrier beam at said first plane, said focused reference beam having a focal point an adjustable distance beyond said first plane; and
   recording an interference pattern between said focused reference beam and said carrier beam at said first plane.
13. A method of verifying an image comprising the steps of:
   providing a laser beam;
   superimposing an image to be verified on said laser beam resulting in a carrier beam;
   focusing said carrier beam through a transform lens at a first plane;
   providing a recorded interference pattern associated with at least one image at said first plane, said recorded interference pattern refracting light from said at least one image to a detecting plane; and
   detecting a match between said image and said recorded interference pattern based upon an amount of light refracted through said recorded interference pattern located at said first plane and received at said detecting plane.

14. A method for recording and reconstructing an image comprising the steps of:
   providing a laser beam;
   splitting said laser beam into an imaging beam and a reference beam;
   collimating said imaging beam resulting in a collimated laser beam;
   superimposing an image on said collimated laser beam resulting in a carrier beam;
   focusing said carrier beam by a transform lens at a first plane;
   focusing said reference beam by an adjustable transform lens and outputting a focused reference beam directed toward and interfering with said carrier beam at said first plane, said focused reference beam having a focal point an adjustable distance beyond said first plane;
recording an interference pattern between said focused reference beam and said carrier beam at said first plane; and
detecting a match between a previously stored interference pattern and a subsequent image by detecting light refracted and focused through said recorded interference pattern at a detection plane a predetermined distance from said first plane.
TRANSLATION SENSITIVE ADJUSTABLE COMPACT OPTICAL CORRELATOR

Abstract of the Disclosure

5 A sensitivity adjustable compact opto-electronic correlator and pattern recognition system for identification of a partially obscured or modified objects includes a laser source, a spatial light modulator, a transform lens, a holographic matched filter, and a detector located at a classification output plane. The laser source outputs a laser beam in an imaging optical path and a reference optical path for use during a recording process. The imaging optical path directs the laser beam output through a spatial light modulator for entering an input image that is to be identified. The laser beam acts as a carrier for the input image which then passes through a transform lens having a focal length D1 at a first (holographic) plane. A complex structure associated with the input image is located within the cross-section of the focal point at the first plane. The reference optical path includes a reference beam which is reflected through an adjustable transform lens whose output is directed toward and interferes with the carrier beam at the first plane. The adjustable transform lens is configured such that the reference beam is focused an adjustable distance D2 beyond the first plane. A film is placed at the holographic plane to record the interference pattern generated by the interference of the imaging optical path and the reference optical path. Thereafter, the film may be developed and acts as a holographic matched filter when replaced back at the holographic plane for use in recognizing an associated object or image.
Relative Intensity of the Correlation Peak

Lateral Displacement of the Input Image

(1/2000 hub = 0.127 mm)
A Large-Capacity Holographic Associative Memory System

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Abstract: The concept of a multi-stage holographic optical random-access memory (HORAM) system is described. The multi-stage HORAM can be used for high-capacity storage and high-speed random retrieval of information. The input to the system may be of the form of pairs of images that are arranged in such a way that joint Fourier transforms can be recorded at the output plane which has a large array of different joint transforms. Associative memory and retrieval can be made based on the principle of inner-product neural net. The spatial multiplexed, instead of angular multiplexed, architecture allows parallel information retrieval without any moving part. A two-stage HORAM, using a Dammann grating and a multi-focus holographic lens, capable of storing 2000 holographic matched filters of input images is used to demonstrate the feasibility of the technique. The multi-stage technique can also be applied to many-to-many free-space interconnections with capability greater than that of a single-stage method. This randomly adaptive and dynamic interconnection technique is useful for a variety of optical neural computing and pattern recognition applications.

1. Introduction

In information management and analysis, parameters such as communication delays, limited resources, and inaccessibility of human manipulation require more intelligent, compact, low-power, and light-weight information management and data storage techniques. Among the various new and innovative techniques being developed, 3-D volume holographic memory has been considered important and promising for data storage. In this letter, we report, for the first time, a multi-stage holographic optical random-access memory (HORAM) system. The multi-stage HORAM can be used for high-capacity storage and high-speed random retrieval of information suitable for a variety of neural computation and pattern recognition applications. The input to the system may be of the form of pairs of images that are arranged in such a way that joint Fourier transforms can be recorded at the output plane which has a large array of different joint transforms. Associative memory and retrieval can be made based on the principle of inner-product neural net. The multi-stage HORAM has much greater storage capacity than that of a single-stage multi-channel optical holographic memory and pattern recognition system.

2. Theoretical Discussion

A block diagram illustrating the concept of a HORAM is shown in Figure 1. The input object information O(x,y) is presented in a two-dimensional image or data format which is illuminated by a collimated laser beam. The input O(x,y) can either be presented with a photo transparency or in real-time by a spatial light modulator, such as a liquid crystal television spatial light modulator (LCTV SLM). The input is then passed through a number of cascaded stages of holographic optical elements (HOE) and shutter arrays that are represented by the H blocks. For illustration, a two-stage system with blocks H1 and H2 is used as an example. The HOE in H1 replicates O(x,y) into an array of identical O(x,y)'s. The shutter array in H1 may be electronically controlled such that it can let any number of the h1 identical O(x,y)'s pass through and stop the others. A multi-focus holographic lens with two foci may be used for the subsequent H2 block. A second shutter array may be used to select one of the foci of the multi-focus lens. In the recording of the matched filter at plane F, which is the output of the block H2, (h1+h2) Fourier transforms of O(x,y) will be selected one at a time by the opening of one of each of the switches of the two shutter arrays. Meanwhile, a reference beam is applied to interfere with the Fourier transform for the recording of the holographic
matched filter. By using each Fourier transform in the array to record one of the images or 2-D data, a complete array of matched filters can be recorded. For example, if \( h_1 = 9 \) and \( h_2 = 5 \), \((9 \times 5)^2 = 2,025\) Fourier transforms of \( O(x,y) \) can be stored at plane \( F \). If \( h_1 = 33 \) and \( h_2 = 7 \), and a single matched filter at each focus is recorded, a total of 53,361 Fourier transforms of \( O(x,y) \) can be stored at plane \( F \). By randomly switching the shutter in each of the \( H \) block to let only one channel of the reference beam pass, the input images or 2-D data become randomly accessible. More details of the \( H \) blocks are described below.

\[ G(f_x, f_y) = \begin{cases} 1 & |m|,|n| \leq M \\ 0 & |m|,|n| > M \end{cases} \] (3)

With Eq. (3), Eq. (2) can be expressed as

\[ T(f_x, f_y) = \sum_{m=-M}^{M} \sum_{n=-M}^{M} \delta(f_x - \frac{m}{\Delta_d}) \delta(f_y - \frac{n}{\Delta_d}) \cdot G(f_x, f_y). \] (4)

A traditional single-lens Dammann grating Fourier transform system is shown in Figure 2.

Figure 3. The architecture and functionality of the multi-focus hololens.

Figure 4 shows an experimental diagram of a two-stage HORAM as described above. A laser beam from an Argon ion laser is divided into an object beam and a reference beam by a beam splitter. The object beam is collimated by a spatial filter and lens \( L_1 \) combination.
The collimated beam is used to illuminate the Dammann grating and the input image of an object. A lens L2 is used to Fourier transform the grating-multiplied object into a \((2M+1) \times (2M+1)\) Fourier transform pattern array at the focal plane of L2, where the shutter array 1 is placed to selectively let one order pass. The input pattern carried by the single diffraction order is collimated by L3 and passed through the multi-focus lens. It is Fourier-transformed into a \((2N+1) \times (2N+1)\) foci array at the focal plane of the hololens. At the focal plane, the shutter array 2 is placed to selectively let one order to pass for recording. Lenses L4 and L5 are used to re-image the passed Fourier transform where a holographic matched filter can be recorded.

In the recording process, the reference beam is collimated by a spatial filter and lens L combination and is used to interfere with the Fourier transform of the object beam at the matched filter plane. One by one, a total of \((2M+1)^2 \times (2N+1)^2\) array of the input data can be stored at the focal plane of L5, the holographic matched filter plane.

In analysis, as the object in Figure 4 is illuminated by an array of beams diffracted by the Dammann grating, the overall transmittance may be described as \(t(x,y)O(x,y)\), where \(t(x,y)\) and \(O(x,y)\) are the transmittance functions of the Dammann grating and the object respectively. Based on Fourier analysis involving the consideration of all elements in the system, a single Fourier transform of the input selected according to the method described at the holographic matched filter plane may be represented by

\[
U_m(x_m, y_m) = -jA(\lambda f_2)(\lambda f_3)(\lambda f_h) \frac{f_3}{\lambda f_2 f_h} x_m + \frac{f_3}{f_2 f_h} n_2 - \frac{1}{\Delta d} m_1, \\
\frac{f_3}{\lambda f_2 f_h} y_m + \frac{f_3}{f_2 f_h} n_2 - \frac{1}{\Delta d} n_1.
\]

where \(f_2\) represents the focal length of lens L2, \(f_3\) represents the focal length of lens L3, \(f_4\) and \(f_5\) of lenses L4 and L5 are identical and naturally eliminated, \(f_h\) represents the focal length of the hololens, \(1/\lambda_d\) is the period of the Dammann Grating in the frequency domain, \(1/\lambda_h\) is the period of the holographic lens in the frequency domain, \((m_1, n_1)\) is the diffraction order selected from Dammann grating with \(m_1, n_1\) range from \(-M\) to \(M\), \((m_2, n_2)\) is the diffraction order selected from the holographic lens with \(m_2, n_2\) range from \(-N\) to \(N\), \(\lambda\) is the wavelength of the laser, \(A\) is a constant associated with the collimated laser input wave amplitude, and \(\tilde{O}(f_s, f_f)\) is the Fourier transform of the object

\[
\tilde{O}(f_s, f_f) = \mathcal{F}\{O(x,y)\} = \int O(x,y) \exp[-j2\pi(f_s x + f_f y)] dx dy.
\]

### 3. Feasibility Demonstration

To show the feasibility of the HORAM, an experiment using the diagram shown in Figure 4 was performed. In the experiment, we used a Dammann grating with \(M=4\) \((2M+1=9)\) and a 25-foci hololens with \(N=2\) \((2N+1=5)\). A 25-mW Spectra Physics Model 124B He-Ne laser was used as the input laser source. Focal length of the lenses used in the system are \(f_1=10\) cm, \(f_2=20\) cm, \(f_3=f_4=f_5=38\) cm with corresponding apertures of 4 cm, and 5 cm for L1 and L2 respectively. The aperture for the SORL lenses L3, L4, and L5 is 7.6 cm, and the focal length of the hololens \(f_h=25.4\) cm. The effective aperture used for the input image is about 2 mm. The experimental output of the HORAM at plane F of Figure 4 is shown in Figure 5. A total of 2,025 Fourier transforms in a 2-D array of a 45×45 foci array have been obtained in an area of 2 cm by 5 cm at the matched filter plane. Matched filters at a single focus and several randomly selected foci have been conventionally recorded and the correlation signals have been observed.

![Figure 4](image-url)

**Figure 4.** The experimental setup of a HORAM system utilizing the cascade of a Dammann Grating and a multi-focus hololens.

![Figure 5](image-url)

**Figure 5.** Experimental demonstration: a 2025-channel (45×45) Fourier transform array at the matched filter plane in Figure 4 of a 2-stage optical RAM.
4. Conclusion

In conclusion, we have described a new technique of using multiple stages of free-space interconnection holographic elements to implement a HORAM. We have demonstrated the technique with the memory capacity of over 2000 images. Potentially, tens of thousands of images can be stored. Micro-processors may be used to obtain fast random access to any data set from the memory. An advantage of this technique is that, unlike the angular multiplexed storage method, there is no need of moving any component in the system. High-speed access is therefore achievable. Each of the thousands of Fourier transforms in the array may be used to record a matched filter of an input image of 256×256, 512×512 or any other number of pixels. Therefore, with the HORAM, ultra-high speed special-purpose computing goals can be achieved. For example, simultaneous optical pattern recognition and/or data processing of the super-large array at 1 microsecond means a computing speed on the order of 1.2×10^16 bits/sec assuming that binary images are used. If the finger prints of criminals are stored in the memory, the HORAM can determine whether an arbitrary input finger print belongs to one of the criminals. The recognition can be accomplished remotely and the HORAM can make instantaneous decisions.

The multi-stage architecture can also be applied to many-to-many free-space interconnections with each input pixel reconfigurably connectable to any number of the output foci. The interconnection capability should be much higher than that of any other single-stage free-space optical interconnection method reported. This randomly adaptive and dynamic interconnection technique is useful for a variety of optical neural computing and optical pattern recognition applications.

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References

Advanced ultra-high-capacity optical random access memory and pattern recognition techniques

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Abstract. The architecture and mathematical analysis of a new multichannel multistage holographic optical random access memory (HORAM) architecture and an experimental demonstration of its feasibility are presented. The new HORAM can be used for ultra-high-capacity storage and high-speed random retrieval of information. A two-stage HORAM, using a Dammann grating and a multifocus holographic lens, clearly shows the capability of storing 2000 holographic matched filters. The functional requirements for key optical elements including laser sources, spatial light modulators, and electro-optical shutters for making a desired practical and compact HORAM are described. The potential extension of the HORAM system for multiple-channel optical pattern recognition, classification, and image restoration are described. © 1998 Society of Photo-Optical Instrumentation Engineers [S0091-3286(98)02503-3]

Subject terms: random access memory; optical pattern recognition; holographic lens; Dammann grating; optical pattern classification.

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1 Introduction

Instruments with high speed and large capacity in situ data identification, classification, and storage capabilities are required for information management and analysis. For example, in National Aeronautics and Space Administration (NASA) applications, extremely large volumes of data sets must process in space exploration, space habitation and utilization, and in various missions to planet-earth programs. Parameters such as communication delays, limited resources, and inaccessibility of human manipulation require more intelligent, compact, low-power, and lightweight information management and data storage techniques.1,2 For this reason, new and innovative techniques are being developed by many researchers in the field. Among the various techniques being developed, the 3-D volume holographic memory has been considered as one of the most important and promising for data storage.3–11 For example, Mok9 reported that more than thousands of holograms can be stored in a lithium niobate crystal via angular multiplexing. Hanue et al.12 demonstrated the storage and retrieval of digital data using a volume hologram, and Yu and Yin have used a volume photorefractive crystal to make a reflection type matched filter applicable for pattern recognition.11 The purpose of this paper is to present a new and basic concept of a multichannel multistage spatially parallel holographic optical random access memory (HORAM) system and the theoretical analysis of a two-stage HORAM architecture. The preliminary experimental results demonstrating the storage plane of a 2000-channel system and its potential for optical pattern recognition are presented. We then present various optical computing methods based on the HORAM architecture. The multistage HORAM can be used for the storage and random information retrieval among an extremely large amount of data and a family of pattern recognition applications. Advantages of the HORAM include large data storage capacity and high-speed parallel retrieval without moving parts. For a two-stage HORAM, two orders of magnitude of increment of the storage capacity can be achieved as compared with that of the single-staged spatial multiplexed multichannel optical pattern recognition system previously reported.12–14 The practical limitations of this new architecture, primarily due to the availability of some basic components, are described at the end of the paper to stimulate further technology innovation and advancement required for this important technique.

2 Theoretical Discussion

The basic concept of the HORAM is shown in Fig. 1, where the input information T is presented in a 2-D image or data format, which is carried by a collimated laser beam. The input can either be presented with a phototransparency or in real time by a spatial light modulator. An example of an inexpensive laboratory type electronically addressed spatial light modulator is the liquid crystal television spatial light modulator (LCTV SLM). The input T is then applied through a multiple number of cascaded stages of holographic optical elements (HOEs) and shutter arrays that are represented by the H blocks. Each H block may contain HOEs and shutter arrays. The functions of these elements are described by using blocks H1 and H2 as examples. The HOE in H1 replicates input T into an array of h1 × h1 identical Ts. The shutter array in H1 can be electronically controlled such that it can let any one of the (h1)2 replicas of T pass through and stop the others. The subsequent H2 block...
has the function of a multifocus holographic lens with \((h_2)^2\) foci. A second shutter array can be used to select one of the foci of the multifocus lens. Hence, at the output of the block \(H_2\), \((h_1 \times h_2)^2\) Fourier transforms of \(T\) will appear one at a time at plane \(F\) since each time one of the Fourier transforms is selected, it is accomplished by the opening of one of each of the switches of the two shutter arrays. If one applies a reference beam to interfere with the Fourier transform, a holographic filter can be recorded at plane \(F\). By using each Fourier transform in the array to record one of the images or 2-D data, a complete array of matched filters can be recorded. For example, if two \(H\) blocks are used with \(h_1 = 9\) and \(h_2 = 5\), a minimum of \((9 \times 5)^2 = 2025\) Fourier transforms of \(T\) can be stored at plane \(F\) if only one Fourier transform is recorded at each point of the array. Since holograms can be superpositioned, if each point is used to record four Fourier transforms by angular multiplexing, over 10,000 matched filters can be recorded at plane \(F\). If \(h_1 = 33\) and \(h_2 = 7\) and a single matched filter at each focus is recorded, a total of 53,361 Fourier transforms of \(T\) can be stored at plane \(F\). In the preceding examples, if the input data are images of human faces, then over 50,000 faces can be memorized in a HORAM. In the pattern recognition process, an input can be used to address all the stored holographic filters and therefore auto- or heterocorrelation signals can be obtained. On the other hand, by switching the shutter in each of the \(H\) blocks to let only one channel of the reference beam pass, one of the input images or 2-D data becomes randomly accessible.

One possible implementation of the HORAM in a two-stage architecture is to use a high-efficiency Dammann phase grating\(^{16,17}\) with a lens and a shutter for \(H_1\), and a multifocus holographic lens\(^{18}\) (hololens) with a shutter for \(H_2\). The transmission of the Dammann grating can be described as\(^{19}\)

\[
t(x, y) = \left[ \text{comb} \left( \frac{x}{L_d}, \frac{y}{L_d} \right) * g(x, y) \right] a(x, y),
\]

where \(*\) indicates the convolution operator; \(L_d\) is the period of grating; \(g(x, y)\) is the shape of the individual groove; and \(a(x, y)\) is the aperture, which in general is the incident Gaussian profile of the laser beam. However, for simplicity, the aperture is assumed to be open and uniform, so that \(a(x, y) = 1\). The Fourier transform of the grating is

\[
T(f_x, f_y) = \frac{1}{L_d^2} \text{comb} \left( \frac{L_d f_x}{L_d}, \frac{L_d f_y}{L_d} \right) G(f_x, f_y),
\]

where \(G(f_x, f_y)\) is the Fourier transform of \(g(x, y)\), and \(G(f_x, f_y)\) acts as a window function to attenuate those peaks of \(\sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \delta(f_x - m/L_d) \delta(f_y - n/L_d)\) that are not wanted. For a \((2M + 1) \times (2M + 1)\) array, we design the grating in such a manner that ideally

\[
G(f_x, f_y) = \begin{cases} 1 & |m|, |n| \leq M \\ 0 & |m|, |n| > M. \end{cases}
\]

With Eq. (3), Eq. (2) can be expressed as

\[
T(f_x, f_y) = \sum_{m=-M}^{M} \sum_{n=-M}^{M} \delta(f_x - m/L_d) \delta(f_y - n/L_d).
\]

A traditional single-lens Dammann grating Fourier transform system is shown in Fig. 2. A multifocus hololens\(^{18}\) with its architecture and functionality as shown in Fig. 3 can be used as the HOE in \(H_2\).
of Fig. 1. The element was designed via a detailed Fourier computation and diffraction analysis such that it will work as a lens with an array of foci. This multifocus hologram is different from an array of microlenses because the multifocus lens has a single aperture where the array of microlenses form foci, each of which has its own aperture. Therefore the multifocus hologram can be used to produce an array of Fourier transforms of the same input image where a microlens array cannot. For example, if the input to the multifocal hologram is a single laser beam, the beam can be directed to the array of foci with energy divided equally among the foci. When the input is an image carried by the collimated laser beam, in an ideal case, the multifocal hologram will produce at its focal plane an array of replicated Fourier transforms of the input. When one of the foci passes through a selection array spatial filter (in the form of small openings), it can be reimaged at the output plane. Special spectral modulation can be performed at the focal plane and image processing can be performed at the image plane. This architecture is therefore highly versatile. Moreover, by properly cascading the two HOEs as described, one can greatly increase the number of channels that can be processed in parallel. For example, the interconnection capacity and computation speed can hardly be matched.

The described HOEs can be invoked in an architecture, as shown in Fig. 4, as one way to implement the concept shown in Fig. 1. The architecture utilizes a cascaded combination of a Dammann phase grating and a multifocal hologram. A laser beam from an argon ion laser is divided into an object beam and a reference beam by a beamsplitter (BS). The object beam is collimated by a spatial filter and lens L₁ combination. The collimated beam is used to illuminate the Dammann grating and the input transparency so that the output carries the input object. Lens L₂ is used to Fourier transform the object-carrying input beam multiplied by the transmittance of the Dammann grating into a (2M + 1) x (2M + 1) equal-intensity Fourier transform pattern array at the focal plane of L₂, where shutter array 1 is placed to selectively let one order pass in the recording process. The input pattern carried by the single diffraction order is imaged by L₃ to pass through the multifocal lens and then Fourier transformed into the (2N + 1) x (2N + 1) foci array at the focal plane of the hologon, where N is the maximum diffraction order of the hologon. At the focal plane, the selection shutter array 2 is placed to selectively let one order pass. Lenses L₄ and L₅ are used to reimage the passed Fourier transform where a holographic matched filter can be recorded. In the recording process, the reference beam is collimated by a spatial filter and lens L₅ combination and is used to interfere with the Fourier transform of the object beam at the matched filter plane. If one let one object pass at each recording and let the reference beam to interfere only with that order, a total of (2M + 1)² x (2N + 1)² array of input data can be stored at the focal plane of L₅, as shown in Fig. 4. The data/image formation property of the HORAM shown in Fig. 4 is described in the following.

2.1 Amplitude Distribution at Plane P₂ (Fourier Transform Plane of L₂)

The object is illuminated by an array of beams diffracted by the Dammann grating. The overall transmittance may be described as t(x,y)O(x,y), where t(x,y) and O(x,y) are the transmittance functions of the Dammann grating and the object, respectively. Assuming that the combined grating-object is placed at one focal length in front of lens L₂, the result is an optically Fourier transformed array located at the back focal plane P₂ of L₂. The beam amplitude distribution at P₂ can be represented by a (2M + 1) x (2M + 1) array of Fourier transform of the object by lens L₂:

\[ S_2(f_x, f_y) = \frac{A}{j\lambda f_2} F_2[t(x,y)O(x,y)] \]

\[ = \frac{A}{j\lambda f_2} \sum_{m=1}^{M} \sum_{n=1}^{M} \delta\left(f_x - \frac{m\lambda}{L_d}\right) \]

\[ \times \delta\left(f_y - \frac{n\lambda}{L_d}\right) * F_2[O(x,y)] \]

\[ = \frac{A}{j\lambda f_2} \sum_{m=1}^{M} \sum_{n=1}^{M} \delta\left(f_x - \frac{m\lambda}{L_d}\right) \]

\[ \times \delta\left(f_y - \frac{n\lambda}{L_d}\right) * \tilde{O}(f_x, f_y), \] (5)

where \( \lambda \) is the wavelength of the laser, \( A \) is a constant associated with the collimated laser input wave amplitude, \( f_2 \) is the focal length of lens L₂, \( 1/L_d \) is the period of the Dammann Grating in frequency domain, and \( F_n \) denotes the Fourier transform by lens \( L_n(n=1,2,...) \),
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\[ \tilde{O}(f_x, f_y) = F_2[O(x, y)] \]

\[ = \int \int O(x, y) \exp \left[ -j2\pi(f_x x + f_y y) \right] \, dx \, dy, \]

where \( f_x \) and \( f_y \) are the spatial frequencies: \( f_x = x_2/(\lambda f_2) \) and \( f_y = y_2/(\lambda f_2) \); and \((x_3, y_3)\) are points in plane \( P_2 \). The amplitude distribution at \( P_2 \) can also be expressed in terms of the position at plane \( P_2 \):

\[ U_2(x_2, y_2) = S_2(\frac{x_2}{\lambda f_2}, \frac{y_2}{\lambda f_2}) \]

\[ = \frac{A(\lambda f_2)^2}{j(\lambda f_2)} \sum_{m_d=-M}^{M} \sum_{n_d=-M}^{M} \delta \left( x_2 - \frac{\lambda f_2}{L_d} m_d \right) \]

\[ \times \delta \left( y_2 - \frac{\lambda f_2}{L_d} n_d \right) \times \tilde{O} \left( \frac{x_2}{\lambda f_2}, \frac{y_2}{\lambda f_2} \right) \]

\[ = \frac{A}{j(\lambda f_2)} M_d(x_2, y_2) \times \tilde{O} \left( \frac{x_2}{\lambda f_2}, \frac{y_2}{\lambda f_2} \right), \]

where

\[ M_d(x_2, y_2) = \left( \frac{\lambda f_2}{L_d} \right)^2 \sum_{m_d=-M}^{M} \sum_{n_d=-M}^{M} \delta \left( x_2 - \frac{\lambda f_2}{L_d} m_d \right) \]

\[ \times \delta \left( y_2 - \frac{\lambda f_2}{L_d} n_d \right). \]

An aperture can be placed at plane \( P_2 \) with a selection filter, which is set to select one of the \((2M+1)\times(2M+1)\) equal-intensity diffraction orders.

### 2.2 Amplitude Distribution at Fourier Plane of Lens \( L_3 \)

Lens \( L_3 \) is placed at distance \( f_3 \) from plane \( P_2 \). Due to the input at plane \( P_2 \), the amplitude distribution at the Fourier plane of lens \( L_3 \) can be written as

\[ S_3(f_x, f_y) = \frac{1}{j\lambda f_3} F_3[U_2(x_2, y_2)] \]

\[ = -\frac{A}{(\lambda f_2)(\lambda f_3)} F_3[M_d(x_2, y_2) \times F_2[O(x, y)]] \]

\[ = -\frac{A}{(\lambda f_2)(\lambda f_3)} F_3[M_d(x_2, y_2)] \times F_3 F_2[O(x, y)]. \]

The amplitude distribution Eq. (9) can also be expressed in terms of the position at Fourier plane of lens \( L_3 \), that is

\[ \tilde{O}(x_3, y_3) = S_3 \left( \frac{x_3}{\lambda f_3}, \frac{y_3}{\lambda f_3} \right) \]

\[ = -\frac{A(\lambda f_2)^2}{(\lambda f_2)(\lambda f_3)} M_d \left( \frac{x_3}{\lambda f_3}, \frac{y_3}{\lambda f_3} \right) \]

\[ \times O \left( \frac{-f_2}{f_3} x_3, \frac{-f_2}{f_3} y_3 \right). \]

where

\[ \tilde{M}_d(f_3, f_y) = F_3[M_d(x, y)]. \]

### 2.3 Amplitude Distribution at the Fourier Plane of the Holographic Lens

The holographic lens Fourier transforms the input \( U_3(x_3, y_3) \) to a \((2N+1)\times(2N+1)\) array of spectrum onto its Fourier transform plane. The amplitude distribution is

\[ S_h(f_x, f_y) \]

\[ = \frac{1}{j\lambda f_h} \sum_{m_h=-N}^{N} \sum_{n_h=-N}^{N} \delta \left( f_x - \frac{m_h}{L_h} \right) \delta \left( f_y - \frac{n_h}{L_h} \right) \]

\[ \times F_h[O(x_3, y_3)] \]

\[ = -\frac{A(\lambda f_2)^2}{j(\lambda f_2)(\lambda f_3)(\lambda f_h)} \]

\[ \times \sum_{m_h=-N}^{N} \sum_{n_h=-N}^{N} \delta \left( f_x - \frac{m_h}{L_h} \right) \delta \left( f_y - \frac{n_h}{L_h} \right) \]

\[ \times F_h \left[ \tilde{M}_d \left( \frac{x_3}{\lambda f_3}, \frac{y_3}{\lambda f_3} \right) \right] F_h \left[ O \left( \frac{-f_2}{f_3} x_3, \frac{-f_2}{f_3} y_3 \right) \right] \]

\[ = \frac{A}{j(\lambda f_2)(\lambda f_3)(\lambda f_h)} \]

\[ \times \sum_{m_h=-N}^{N} \sum_{n_h=-N}^{N} \delta \left( f_x - \frac{m_h}{L_h} \right) \delta \left( f_y - \frac{n_h}{L_h} \right) \]

\[ \times F_h F_3[M_d(x_2, y_2)] \times F_h F_3 \left[ \tilde{O} \left( \frac{x_3}{\lambda f_3}, \frac{y_3}{\lambda f_3} \right) \right]. \]

The amplitude distribution [Eq. (11)] can also be expressed in terms of the position at the Fourier plane of the holographic lens, that is
where \((x_m, y_m)\) is a point at the matched filter plane. It can be seen that the amplitude distribution at the matched filter plane is proportional to a \((N \times N)\) with \((M \times M)\) array of the Fourier transforms of the object

\[
\tilde{O}(f_x, f_y) = F[O(x, y)]
\]

\[
= \int \int O(x, y) \exp \left[ -j2\pi(f_x x + f_y y) \right] \, dx \, dy.
\]

where

\[
f_x = \frac{f_3}{\lambda f_2 f_h} x_m \quad \text{and} \quad f_y = \frac{f_3}{\lambda f_2 f_h} y_m.
\]

### 2.5 Recording of the Holographic Matched Filter

In the recording of the holographic matched filter, two selection shutter arrays are placed at the plane \(P_2\) and at the Fourier plane of the holographic lens, respectively. The shutter arrays are set such that only one order each from the Dammann grating and the holographic lens is selected to pass. Once the order \((m_1, n_1)\) from Dammann grating and the order \((m_2, n_2)\) from holographic lens are selected, the amplitude distribution at the matched filter plane, or Eq. (15), becomes

\[
U_m(x_m, y_m) = -jA(\lambda f_3)(\lambda f_3)^3 \delta \left( x_m - \frac{\lambda f_h}{L_h} m_2 \right)
\]

\[
\times \delta \left( y_m - \frac{\lambda f_h}{L_h} n_2 \right) * \tilde{O} \left( \frac{f_3}{\lambda f_2 f_h} x_m, \frac{f_3}{\lambda f_2 f_h} y_m \right).
\]

or
Um(x_m, y_m) = -jA(λf_2)(λf_3)(λf_h)3/d x_m
+ f_3 / f_2 L_h m_1 / L_d m_2, f_3 / f_2 L_h y_m + f_3 / f_2 L_h n_2
- 1 / L_d n_1),

where m_1 and n_1 range from -M to M, and m_2 and n_2 range from -N to N. Once (m_1, n_1) and (m_2, n_2) are selected by shutter arrays 1 and 2, only one Fourier transform of the input image is recorded at matched filter plane. From this analysis, we can see that the total number of channels of the system is determined by the Dammann grating and the holographic lens used.

4 Optical Pattern Recognition and Computing Methods Based on the HORAM

The HORAM has a broad range of applications. Based on the multistage HORAM architecture, a few optical pattern recognition and special-purpose optical computing methods can be implemented as described next.

4.1 Multichannel Pattern Recognition System

The recording and addressing architecture of a multichannel pattern recognition system are shown, respectively, in Figs. 6(a) and 6(b). In Fig. 6(a), the object is presented to the system via a spatial light modulator illuminated by a collimated laser beam. The image is replicated in a similar manner as that in the HORAM as described. The replicated images form an array of Fourier transform patterns at the holographic matched filter plane where the matched filters can be made by using a single plane reference wave during the image storage process. For each image, a shutter is open to select one of the Fourier transform of the array. In the addressing process, if an input object image is one of the images stored, the output correlation signal will immediately reveal the answer. To give a numerical example, if the same image is rotated five times and stored in the same location of a matched filter, an array of 2000 would enable 10,000 images to be stored. The capacity of storage would allow recognition of images with rotation and scale variations.

4.2 Multichannel Pattern Classification System

The recording and addressing architecture of a multichannel pattern classification system are shown, respectively, in
Fig. 8 Multichannel pattern restoration system addressing architecture.

Figs. 7(a) and 7(b). The recording and addressing processes are similar to those described in Sec. 4.1. The major difference is that in this case, an orientation variable plane wave is used for the image storage process. The images or features belong to the same class as those described in Sec. 4.1 can be classified into 100 classes by using 100 reference waves each of which is oriented at a distinctive angle. For example, the 10,000 images of the example given in Sec. 4.1 can be classified into 100 classes by using 100 reference waves each of which is oriented at a distinctive angle.

4.3 Multichannel Pattern Restoration System

The recording and addressing architecture of a multichannel pattern restoration system are shown in Fig. 8. A single plane wave is used for all the image storage process similar to that of Fig. 6(a). In the image restoration process, the object beam is shut off and the \((i,j)\)th stored object image can be restored by using the same reference beam and electronically controlled selection shutters placed in front of the output imaging lens. The image stored at the \((i,j)\)th matched filter position will be holographically retrieved by the recording reference beam. In this case, only one image at each filter can be stored and recalled. The inverse Fourier transform is performed by the lens placed after the matched filter array. The restored image can be displaced at its focal plane.

5 Discussion

The definition and functional requirements for a traditional RAM have been realized electronically with impressive accomplishments and on-going progress in capacity, speed, and compactness. The optical RAM described in this paper is not intended to compete with the digital electronic RAM. The optical RAM architecture can offer a unique feature in high-speed parallel optical pattern recognition over an extremely large database. However, to achieve the special-purpose computing goals, technological advancement and breakthroughs in some of the key optical components are required. The challenges and opportunities in the research and development of the components are now briefly discussed.

5.1 Laser Sources

It is desired to have a laser source comparable to a laser diode in size with a power level comparable to that of an argon ion laser. However, the laser diodes have very poor coherent length and are not suitable for making holograms. The diode-pumped solid state laser has high power output but also lacks of coherence. Hence at the present time it is necessary to use large-frame lasers as recording sources.

5.2 SLMs for Data Input

The SLM for the input in the optical RAM poses a challenge for device technology development. Many kinds of SLMs have been developed. These include the Hughes liquid crystal light valve, the microchannel plate SLM, the microdeflection mirror SLM, the ferroelectric liquid crystal SLM, and the liquid crystal television SLM. For high-speed optical RAM operation, high-frame-rate SLMs with high dynamic range, small size, and large numbers of pixels are required. The desired functional requirements for the SLM are listed in Table 1.

<table>
<thead>
<tr>
<th>Functional Features</th>
<th>Desired Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space-bandwidth product</td>
<td>1042 x 1042</td>
</tr>
<tr>
<td>Aperture dimensions (mm x mm)</td>
<td>5 x 5</td>
</tr>
<tr>
<td>Speed (frames/s)</td>
<td>1000</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>100:1</td>
</tr>
<tr>
<td>Light efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Cost</td>
<td>$100 or less</td>
</tr>
</tbody>
</table>

No single currently available SLM has all the desired features, and the price of high-quality SLMs is too high to
use to construct a practical optical RAM. The liquid crystal television SLM is the only inexpensive SLM that meets the low-cost requirement, but it has other limitations including speed, contrast, and resolution.

5.3 Optical Lenses and Mirrors
To achieve optimum light utilization efficiency, Fourier optical lenses and mirrors must be specifically designed and fabricated. Ideally, a miniaturized optical system with an input lens of an effective aperture of less than 5 x 5 mm and with other components designed based on this aperture is desired.

5.4 Shutter Arrays
A single-aperture mechanical shutter can be used to write the input data into the memory. Mechanical shutters have an aperture of 100% transmittance. The position of the shutter can be precisely translated under the control of a PC. An alternative method is to use a liquid crystal shutter array. These shutters are available mostly in reflection mode with high distinction ratios. In the addressing mode, the shutters can be completely removed and hence will not affect the performance of the memory retrieval or pattern recognition functions.

5.5 Holographic Recording Materials
Candidates for real-time holographic recording materials include nonlinear photorefractive crystals, photopolymers, and thermoplastic materials. The recording sensitivity of the thermoplastic material is comparable to that of silver halide film. A simple and compact charging system must be developed for the thermoplastic recording device. More sensitive photorefractive and photopolymer materials must be developed for large-capacity memory.

5.6 Output Detectors
Photodiodes can be used for the detection of a single output signal. An array of output signals can be detected by a CCD array. Large-array position determinable smart pixel devices are required for pattern classification applications.

5.7 Light Budget Estimate, Speed, and Applications
Next, we make an estimate of the light budget for a two-stage HORAM based on realizable optical components. Assume a laser power of 5 W is used. The collimating optics reduces its power by a factor of 70%, the input SLM reduces its power by a factor of 90%, the Dammann grating by 80%, the hololens by 50%, and each of the shutter arrays by 50%. Since part of the beam is used by the reference beam, another factor of 90% will be multiplied. Miscellaneous light loss of the components is represented by a factor of 70%. The overall factor is the multiplication of all the factors. The resulting factor is about 4%. By dividing the resulting light power by 2000, a maximum of 100 μW is available for the recording of a single matched filter. The same power level is available for retrieval. If the matched filter has a 50% diffraction efficiency, the correlation signal has an output of at most 50 μW, which is sufficient for the detection devices. Based on this estimate, the power levels will reach its limit if we have a 10,000-channel HORAM.

The retrieval and processing speed is limited by that of the input SLM. For a 10,000-channel HORAM, if all the optimum values of the parameters are used and we assume that the speed the input SLM is 1000 frames/s with 400 x 600 binary pixels, the processing speed is estimated to be 240 Gbits/s. This speed for pattern recognition is valuable for certain specific applications.

With respect to the applications of these specific optical computing methods, one example of these applications is illustrated in Fig. 9. Figure 9(a) shows how memorization is accomplished in the HORAM by placing the objects as represented by the satellite and space shuttle in the view of a video camera. Over tens of thousands of 2-D data can be stored. Microprocessors can be used to control the random access to any data set from the memory. After the HORAM memorizes all the images presented to it, it becomes smart. When an input such as a partial and noisy space shuttle, as shown in Fig. 9(b), is presented to it, the HORAM can recover and display at the output screen the perfectly retrieved image. In addition, the HORAM can be used to recognize an input and tells us whether it belongs to the memory. For example, if the fingerprints of FBI's most wanted criminals are stored in the memory, the HORAM can determine whether an arbitrary input fingerprint belongs to one of the criminals. The recognition can be accomplished remotely and the HORAM can make a decision at the speed of light!

6 Conclusions
We have described a new technique of using multiple stages of free-space interconnection holographic elements
to implement a HORAM. We have demonstrated the technique with a memory capacity of over 2000 images. Potentially, seemingly limited only by the laser power, tens of thousands of images can be stored. Microprocessors can be used to control the random access to any data set from the memory. Each of the thousands of Fourier transforms in the array can be used to record a matched filter of an input image. Simultaneous optical pattern recognition and/or data processing of the superlarge array means a computing speed of the order of at least 10^10 bits/s. This speed is faster than those obtainable by any other methods reported. For example, if the fingerprints of FBI's most wanted criminals are stored in the memory, the HORAM can determine whether an arbitrary input fingerprint belongs to one of the criminals. The recognition can be accomplished remotely and the HORAM can make the decision at the speed of light!

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