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ASSOCIATIVE MEMORIES FOR SUPERCOMPUTERS

University of California

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and Ashok Krishnamoorthy

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13. ABSTRACT (Maximum 200 words)

A motionless head 2-D parallel readout system for optical disks is presented. Its unique features are discussed and it is compared to various parallel access optical storage media. The motionless-head parallel read-out system for optical disks is shown to meet current and near-term future requirements for high performance secondary storage. In order to select a memory architecture compatible with the motionless-head disk, inner-product and outer-product associative memory algorithms are compared in terms of their storage requirements, search times, system complexities, and fault tolerance. Based on this comparison, the page serial, bit-parallel inner-product method is shown to be well suited to implementation with parallel readout optical disk, and opto-electronic XNOR gate arrays, using for instance the Si/PLZT technology. Finally, the associative memory system design is presented.

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Table of contents

Optoelectronic Associative Memories

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1. OBJECTIVES

Our objective during the funding period, July 14 1989 to January 13 1991, was to design and study the feasability of the motionless-head parallel readout optical disk system and the optoelectronic associative memory system. The major focus of the work has been on the development and implementation of the parallel readout optical disk prototype and on the simulations of the associative memory architecture and algorithms. Another important research area was in the modification of the disk encoding scheme and on the disk optical readout system to improve the system performance.

2. PARALLEL READOUT OPTICAL DISK SYSTEM

2.1 Disk encoding

A 5.1/4" diameter disk with a 1.5 μm track pitch and a 1 μm pit size is assumed. The disk active surface has a radius of 3 cm and therefore contains 20,000 concentric tracks and has a capacity of 940 Mbytes.

The data encoding method and the readout system are designed to allow reconstructions of 2-D images in the output plane. As illustrated in figure 1, a 2-D image (of size NxN) is first sliced into 1-D elements (lines or columns) and a 1-D Fourier transform computer generated hologram is then calculated for each one of them. These 1-D holograms are shifted one another until their total length equals the radius of the disk active surface and then recorded on the disk. N holograms, representing one image, are then distributed along the disk radius. A disk encoded this way has a capacity of approximately 14,000 128x128 pixel images.

2.2 Optical system

The optical readout system (figure 2) maps the data distribution on the disk to a 2-D image at the output. Lens L2 illuminates an area on the disk whose length is equal to an entire radial line of the disk active surface. Therefore N data blocks are illuminated simultaneously. The cylindrical lens L3 performs a Fourier transform of the illuminated area along the radial direction while lens L4 images and magnifies the data along the tangential direction. N data blocks are read simultaneously, therefore a binary image of NxN pixels is reconstructed on the output plane. Since no mechanical motion of the head is required to access any image stored on the disk, the entire content of the disk can be retrieved in one rotation. Higher performance than any existing optical disk systems can be achieved. For a rotation speed of the disk of 2,400 rpm and an image size of 128x128 pixels, the data rate is then 1.2 Gbytes/sec, the access time 12.5 msec and the retrieval time is 25 msec.

The beam illuminating the disk holograms converges along the tangential direction and is a plane wave along the radial direction. The width of the area containing the data blocks of one image is 22 μm. A relatively large f-number lens (L1) is used to ensure a small illumination solid angle Therefore, the depth of focus is large (> ± 10 μm). This lens is placed out of focus, at a distance calculated to allow the illuminating beam to be slightly smaller than 22 μm at the disk plane. A wobble of 20 μm due to flatness variations of the spinning surface can therefore be tolerated. In addition, due to the hologram information redundancy, even partially illuminated holograms reconstruct the entire data; a loss of 10% of the hologram information inducing a loss of only 3 dB in the reconstruction Signal to Noise Ratio (SNR) [5]. For these reasons, no focusing servo is required. As shown in section 2.1 the data is encoded as 1-D computer generated Fourier holograms. Since Fourier-transform holograms are shift-invariant, the eccentricity (radial motion) of the spinning disk does not affect the reconstruction of the data. Therefore no tracking servo is required.

2.3 Hologram encoding

The data encoding on the disk is a key factor for a good operation of the parallel readout system. The quality of the reconstruction and also the size of the hologram therefore the capacity of the disk will both depend on the holographic encoding. The first criterium is the best compromise between the quality of the reconstruction and the disk capacity. Moreover due to the nature of the data recording on a disk, the holograms must be binary. The reconstructed images have also to be binary. Taking into account all these requirements a CGH encoding method has been developed specifically for the disk holograms. This method based on a grey level encoding scheme has been compared to the existing methods.

Each column of the NxN pixel image to be stored on the disk is used as the 1-D input image (C) for which an hologram of size KxN will be computed. The binary array (C) is then embedded with a specific shift m into a 1-D array (O) of size M of which all elements are zeros. A random phase is then multiplied to this new input array, and its 1-D Fast Fourier Transform (FFT) is computed. The real part is extracted and a bias equal to its minimum is added to it in order to make all the values positive. Each sample value obtained is quantized to n grey levels on a n-1 bit pattern using a density modulation algorithm (see figure 3a). In order to reduce the speckle the resulting binary hologram is replicated once to generate a 2M cells of (n-1) bit data block. An example of such a block is given in figure 3b. For the actual system with images of 128x128 pixel image to be stored, the 128 bits of each column are encoded in a 512 cell holograms with 5 grey levels. Therefore the hologram after replication is a 4x1024 bits data block. Using a larger number of grey levels reduces the disk storage capacity but increases the output SNR. Then depending on the application, SNR can be traded in for capacity.

It is possible to improve greatly the performances of these holograms by calculating them with an iterative algorithm. This algorithm is derived from the Direct Binary Search (DBS) algorithm [8] and adapted for the grey level encoding method described previously. The flow chart of this algorithm is given on figure 4. A random grey level hologram is first generated. The reconstruction of this hologram is then computed by FFT. An error function is calculated by comparing the intensity of the reconstructed image and the original image to be reconstructed. The bits of each cell of the hologram are then inverted one after another and the new reconstruction is computed each time. But it is not neccessary to use an FFT, since changing one bit of the hologram is equivalent of adding (bit changed from 0 to 1) or substracting (bit changed from 0 to 1) a plane wave to the previous reconstruction. The error between the new reconstruction and the original image is calculated. If the new error is smaller than the previous one the change of the bit is maintained and the new error is memorized, if not the change is ignored. A loop is completed when the n grey levels of the M cells of the hologram have been tested.The iterative process continues until a predetermined number of loops is completed (ctr) or until the error is lower than a preset threshold or until all the change are ignored during one complete iteration.

Table 1 shows the comparison of this encoding method with other binary encodings. The reconstructions are simulated on computer and the comparison criteria are: the diffraction efficiency and the contrast ratio. The diffraction efficiency is defined as the ratio between the intensity of the reconstructed image and the total intensity of the reconstruction. Two different cases are defined for the contrast ratio. The average contrast ratio is computed by taking the ratio of the average intensity of the "1" bits over the average intensity of the "0" bits. The worst case contrast ratio is the ratio between the lowest intensity of a "1" bit and the highest intensity of a "0" bit. The values of table 1 are an average for 128 holograms. For all the encoding methods, 4x1024 pixel holograms are used. The cell oriented method is similar to the one proposed by Psaltis [8], only the phase is encoded by variation of the position of "1" bits in a cell. The other methods are the error diffusion as defined by Hauck [9], the grey level method and the iterative method described here. The table 1 shows that the iterative method we proposed gives the best results. However the algorithm must be very carefully implemented on the computer in order to optimize the computing time for the holograms.

2.4 Experimental results

Experiments were conducted to test the hologram encoding method as well as the validity of the disk data layout and the optical system. For these first experiments, the holograms were recorded on glass plate with an electron beam recorder (EBR), using the same feature size as an actual optical disk (1μm spots with 1.5 μm radial pitch, see figure 5). Once the holograms are calculated, they are processed by the UCSD holographic CAD program [10] which generates data files for the EBR. Several holograms were recorded on glass plates of 1.2 mm thickness with a photoresist of 350 nm thickness. The optical system used for reading the disk is described on figure 2. The following lenses are used:

L2	f := 100 mm	aperture: 50 x 60 mm	f/# = 2	illuminating lens
L3	f := 200 mm	aperture: 60 x 50 mm	f/# = 4	Fourier transform lens
L4	f := 25.4 mm	aperture: 22 x 60 mm	f/# = 1.15	imaging lens

The plates were placed in the optical system on a rotation stage at the disk plane, both static and dynamic measurements being conducted. The hologram reconstructions were analysed. Figure 6 shows the intensity of a part of a line in a 128x128 pixel reconstructed image, an average SNR of about 40 is measured. Static measurements revealed that focusing errors of up to 20 μm and tracking errors of over 1 mm could be tolerated without significant degradation of the reconstructed image. Dynamic tests have been conducted and as expected the position of the reconstructed images in the output plane is not moving when the disk is rotating and moving lateraly due to the excentricity. Figure 7 shows the center portion of a 128x128 pixel reconstructed image.

Finally, the performance of the full scale motionless-head parallel readout optical disk system, using a 13 cm disk diameter rotating at 2400 rpm and storing 128x128 pixel images (typical rotation speed of optical disks systems), are expected to be:

Storage capacity:	7.4 Gbits
or	14,000 images
Data rate:	1.2 Gbytes/sec
or	580,000 images/sec
Average access time:	12.5 msec

2.5 Hybrid lens design

The optical system design for the parallel readout optical disk system includes two separate cylindrical lenses with different focal lengths: one for imaging in the X-direction, and one for Fourier transforming in the Y-direction. Besides being bulky and heavy, these cylindrical lenses are extremely difficult to align and suffer from severe aberrations. Code V optical design software is then used to design a single Holographic Optical Element (HOE) to replace the function of the two lenses and to correct for the aberrations (figure 8). Due to the difference in focal lengths in the X and Y directions, it is found advantageous to use orthogonal cylindrical diffractive lenses [11] (OCDL). Two separate designs were studied, both design overcoming the problem associated with refractive cylindrical lenses. The first one is a single element HOE with both focal lengths positive but different. The second design is a hybrid refractive/ diffractive element that combines a HOE with a plano-convex spherical lens. In this case one focal lenth is positive while the other is negative. The respective optical performance of the three systems are shown in the figure 9. The error function is calculated in Code V and corresponds to the distance of all the rays to the chief ray in the output plane. The results show that the best system is the hybrid element for both optical performance and fabrication requirements. Indeed, this combination raises the required f/# of the OCDL, which in turn reduces the minimum feature size of the OCDL. Thus a larger size OCDL with more phase levels and a higher diffraction efficiency can be fabricated. As an illustration of this design a mask of the diffractive element of the hybrid lens can be seen in the figure 10.

3. ASSOCIATIVE MEMORY STUDY

3.1 System overview

The associative memory system (figure 11) presently being developed at UCSD, consists of the parallel readout optical disk, an opto-electronic XNOR gate array, a photo-detector array and a single variable threshold summation circuit. A 2-D query from the host computer, is electronically loaded onto the XNOR gate array. The query image is then compared serially to the binary images from the optical disk (bitwise matching operations). The output of the variable threshold detector is then fed into the decision circuit which controls the data flow between the photo-detector array and the host computer.

This associative memory system using the optical disk is well suited to implement a page serial, bit parallel inner product algorithm system which is shown in figure 12. The search time of this method is higher than those of outer product and parallel inner product methods.[12] However, due to the high data rate achievable with the parallel readout optical disk, the page serial, bit parallel inner product method is still capable of low retrieval times.

The system can support two modes of operation. In the first mode, the threshold value is preselected. Local XNOR operations are performed between the bits of the electronic query and the corresponding bits of the disk image.Therefore only images that are close to the query will be retrieved by the host computer via the photodetector array. The second mode finds the best match to the query image. On the first rotation, the Hamming distance for each image is input to the decision circuit in the manner described above. The best match is identified and retrieved on the subsequent rotation.

The key element of the associative memory system using the motionless head disk is the optoelectronic XNOR integrated circuit which is computing the inner product. Two different approaches have been considered to realize this circuit, one analog approach and a digital approach.

3.2 Analog approach

The XNOR gate array consists of an optically and electronically addressed 2-D PLZT SLM [13] with local Silicon circuitry that performs the Exclusive-nor function. Each unit cell receives three inputs as well as control information. The query bit is electronically loaded from the host computer. The corresponding bit from the stored images arrive from the disk at the detector. The third input is a clock obtained from the disk that signals when a complete image is under observation. The detector circuits of the XNOR gate array are designed to provide large noise margins for the detected input bits. The SNRs achievable with the disk holograms can therefore be tolerated since each detector circuit restores logic levels. The logic circuitry drives the PLZT modulator so as to allow light to pass when a bit match occurs. Therefore, the output light represents a logical Exclusive-nor operation of the query bits and the corresponding bits of the stored image.There are two limitation to this approach. The minimal Hamming distance which can be distinguished is limited by the contrast ratio of the Si/PLZT modulators and by the dynamic range of the variable threshold detector.

3.2 Digital approach

The limitations of the previously described analog approach can be overcome by replacing the Si/PLZT XNOR gate array with an Opto-Electronic Integrated Circuit (OEIC) based on a tree structure [14,15]. This OEIC has light dtectors to receive the light from the images read from the disk. It also has local silicon circuitry perform the XNOR operation between the disk images bits and the query bits and fan-in units to perform the summs of the bits down the tree. A schematic view of such an OEIC, based on a H-tree structure [15] is shown in the figure 13. Using this OEIC system, the Hamming distance between a query and the image stored on the disk can be measured with a precision of one bit. Furthermore, the system maintains high throughputs, since all operations down the tree can be pipelined due to the H-tree structure where all electronic lines have equal length and introduce no signal skew.

A simulation of this system has been implemented. The images are read from the disk using a CCD camera interface to a PC computer. Once an image is read, it is digitized and compared (XNOR operations) to the electronic query. The results of the XNOR operations are then summed and the Hamming distance between the query and the disk images is calculated. The results of the simulation can be seen on the figure 14 where 16x16 images were used.

4. CONCLUSIONS

During this project, we have designed and experimentally tested a motionless-head 2-D parallel readout system for optical disks. Since the optical disk system requires no mechanical motion of the head for access, focusing or tracking, addressing is performed only through the rotation of the disk. A higher data rate than any existing optical disk system can be achieved since the entire memory can be scanned in one rotation. The data is written on the disk as 1-D CGH, and a special CGH encoding method using an iterative algorithm and a grey level representation by density modulation has been developped giving high quality reconstructions. The optical readout system is very simple and consists of only three cylindrical lenses. For easier system alignment and better optical performance, two of these lenses could be replaced by a single hybrid diffractive/refractive optical element. An opto-electronic associative memory system using the parallel readout optical disk has also been designed. This associative memory system consists of the parallel readout optical disk, a host computer, an optoelectronic XNOR gate array and its summation circuit (analog or digital) and a local decision circuit. After simulations, the digital approach based on a serial inner product algorithm has been proven to give the best overall performance.

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10. H. Fahroosh et al., "A knowledge-based system for design of electron-beam fabricated computer generated holograms," submitted to Applied Optics.
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12. P. Marchand, A. Krishnamoorthy, P. Ambs, and S. Esener. "Opto-electronic associative recall using motionless-head parallel readout optical disk", in SPIE Proceedings 1347, San Diego 1990.
13. T. H. Lin, A. Ersen, J. H. Wang, S. Dasgupta, S. C. Esener, S. H. Lee, "Two-dimensional spatial light modulators fabricated in Si/PLZT," *Appl Opt.* **29**, pp1595-1603, April 1990.
14. G. Marsden et al. "Dual-scale topology optoelectronic processor," in OSA annual meeting '90 Boston, paper TUJJ2, November 1990.
15. A. Krishnamoorthy et al., "Optoelectronic associative memory using a parallel readout optical disk," in OSA annual meeting '90 Boston,paper MJ5, November 1990.

6. TABLES AND FIGURES

	Diffraction effiency	Worst case contrast ratio	Average contrast ratio
Cell Oriented	7 %	< 1	10
Error Diffusion	5 %	2	15
FFT Grey level 4x1	5 %	5	25
Iterative Grey level 4x1	12 %	50	350

Table 1: Comparison of encoding methods for disk holograms

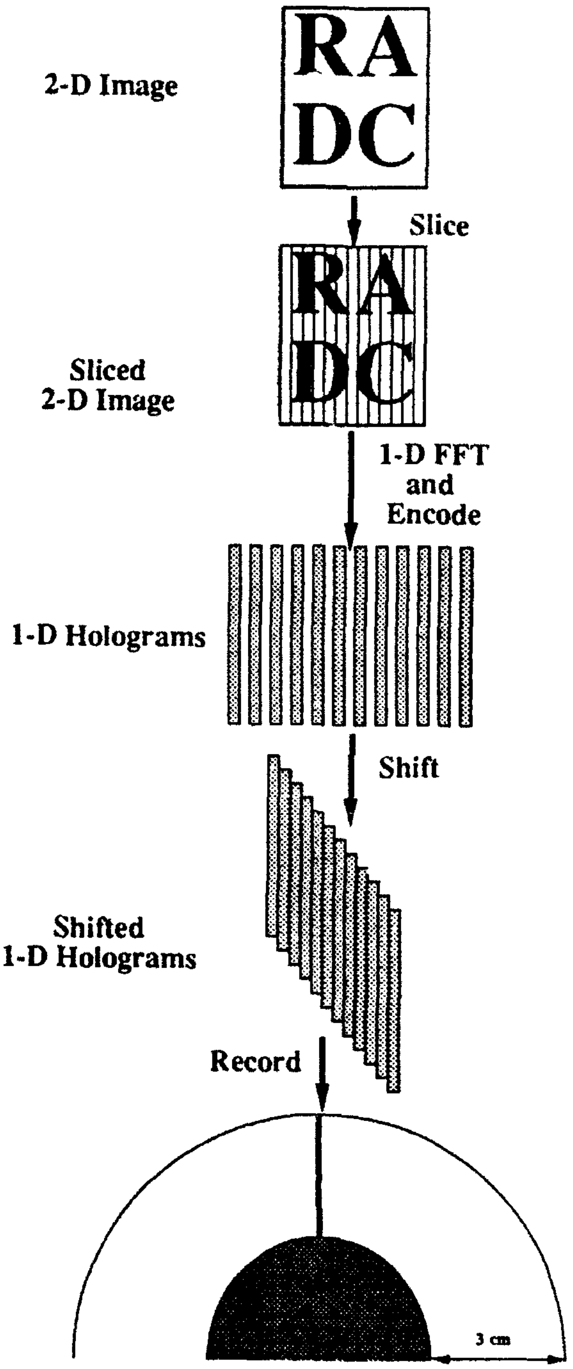


Figure 1: Disk data encoding. A 2-D image is sliced into 1-D columns. These columns are then 1-D Fourier transformed and 1-D CGH are generated. The holograms are then shifted one another and radially recorded.

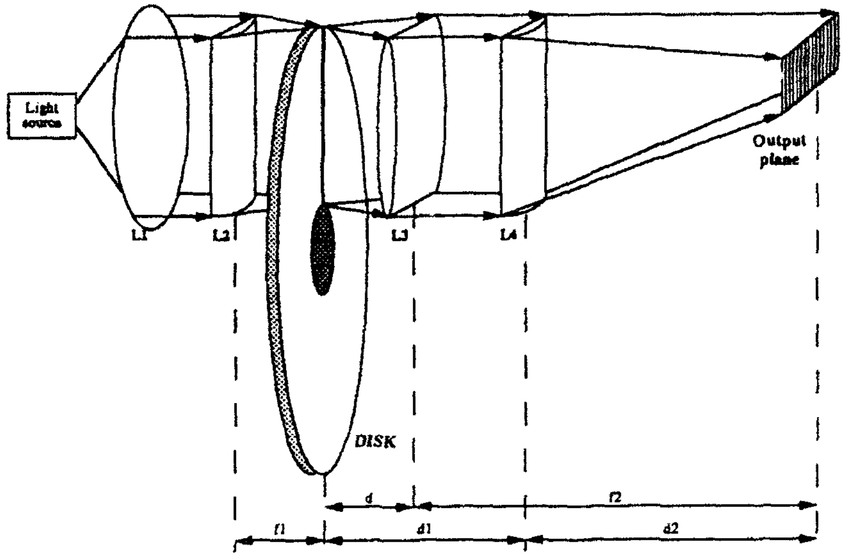


Figure 2 : Optical system. After being collimated by lens L1, the light is focused onto the disk by cylindrical lens L2. Cylindrical lens L3 performs the Fourier transform of the data along the radial direction and cylindrical lens L4 images and magnifies the data(M = d2/d1) along the tangential direction. A binary image of 128 x 128 points is then reconstructed on the ouput plane.

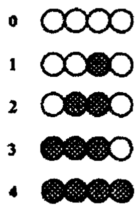


Figure 3a : hologram grey level encoding method

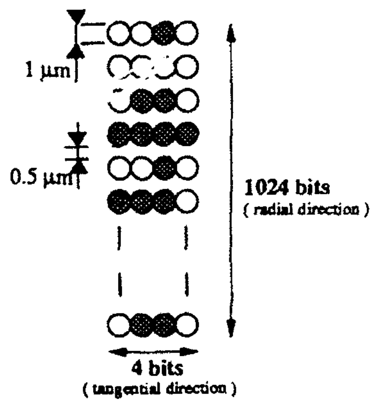


Figure 3b : one data block

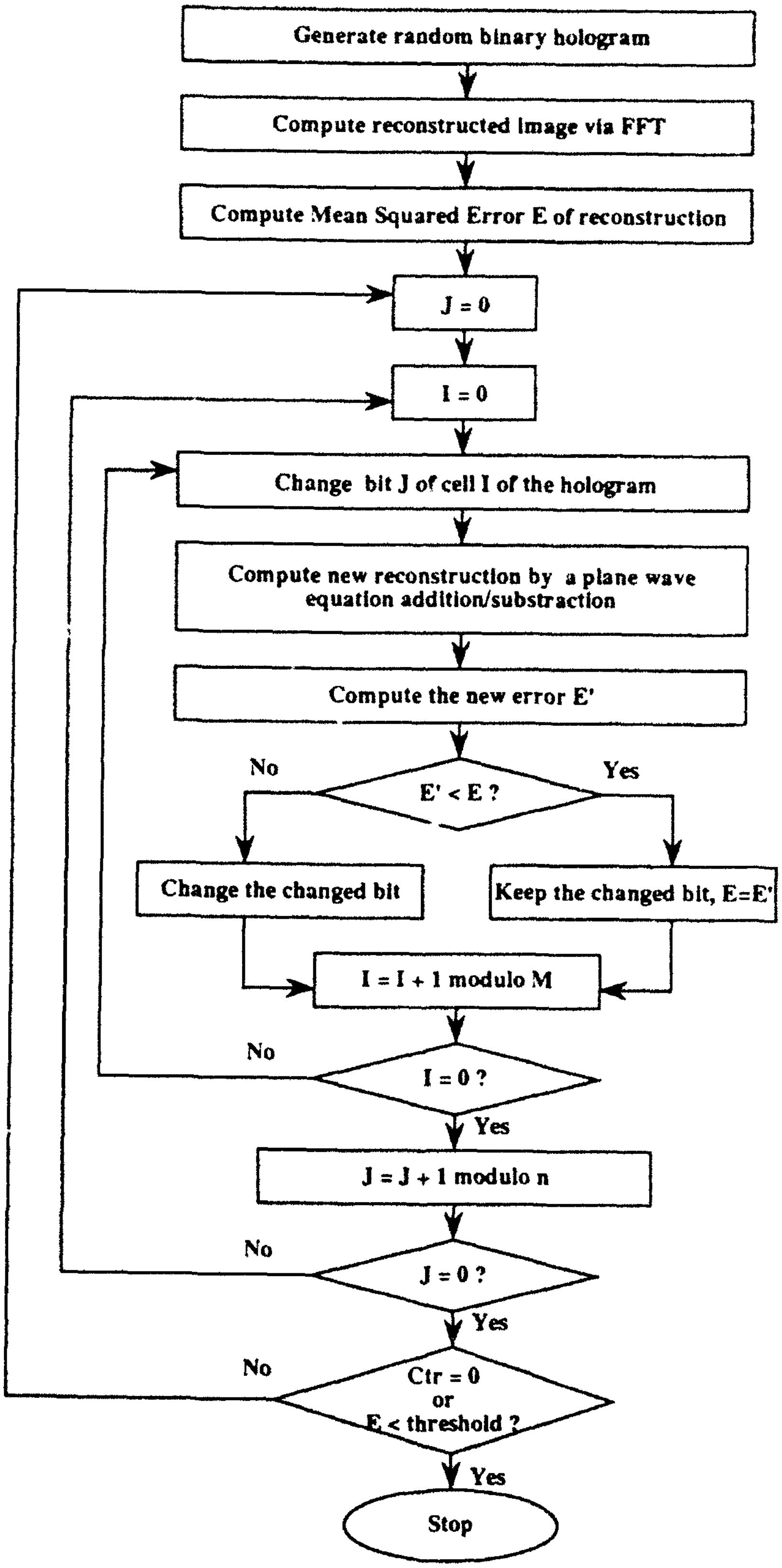


Figure 4: Iterative algorithm flowchart for grey level holograms

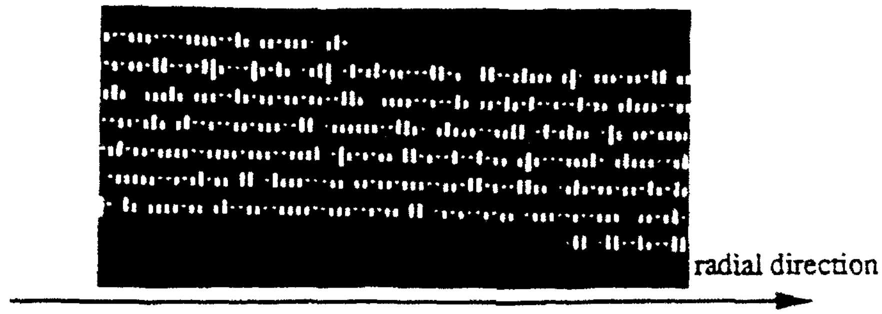
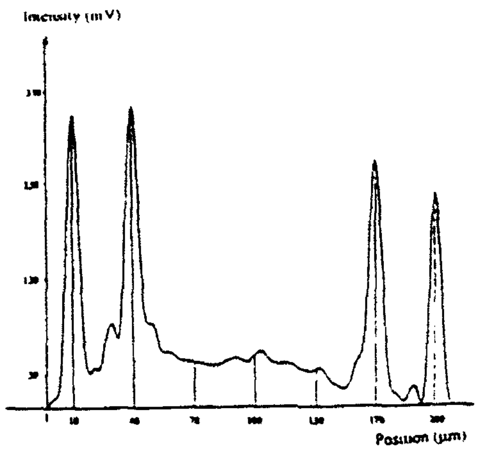


Figure 5 : Experimentally recorded holograms: The holograms are recorded on an E-beam test plate using optical disk pits feature size, i.e 1µm bit size with 1.5 µm pitch according to the format described in figure 1 and 3.



Bit sequence to be detected 1100011 Average SNR= 40

Figure 6: Experimental intensity measurement of an output image

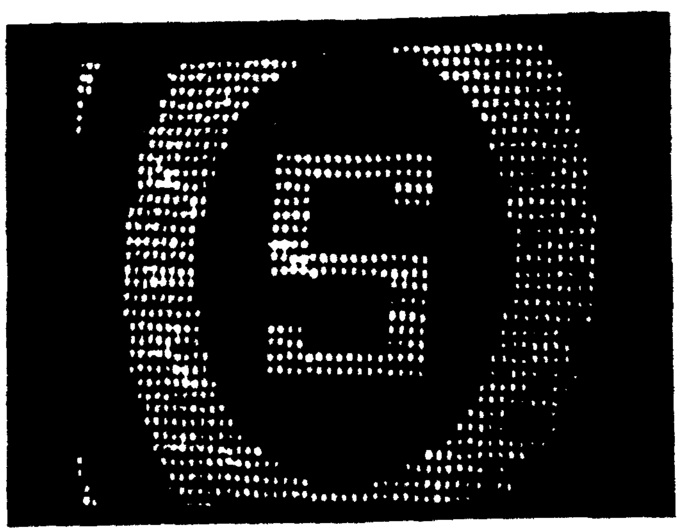


Figure 7: Disk in rotation: center portion of an 128x128 reconstructed image

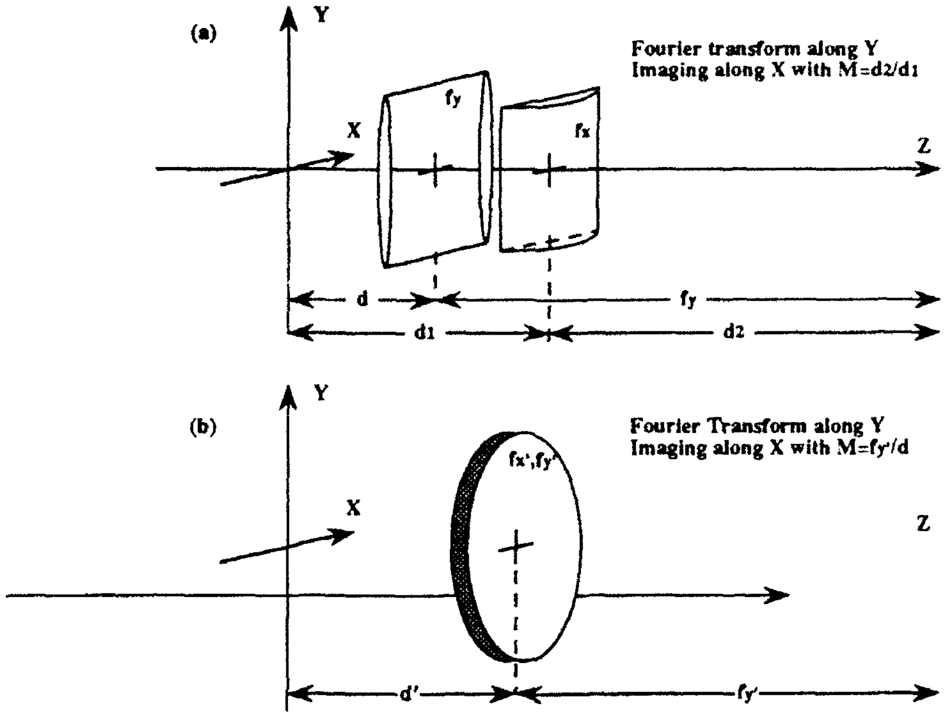


Figure 8: Replacement of the two orthogonal cylindrical lenses with one hybrid refractive/diffractive element

	2 lenses	OCDL	Hybrid lens
Error	15800	950	193
Total length	216 mm	295.4 mm	330.6 mm

Figure 9: Comparison between the three systems studied with Code V

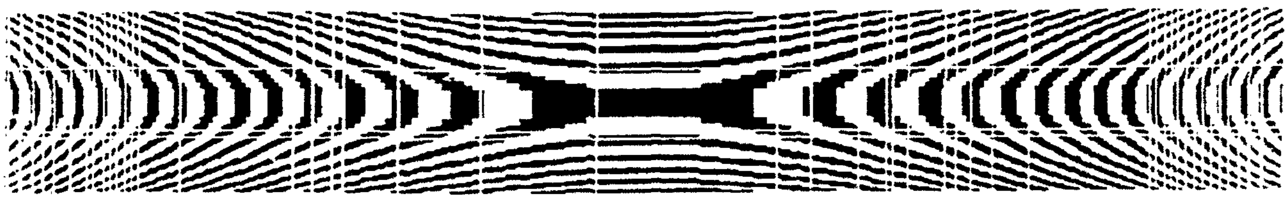


Figure 10: Hybrid lens fabrication, OCDL mask # 1 corresponding to a binary phase

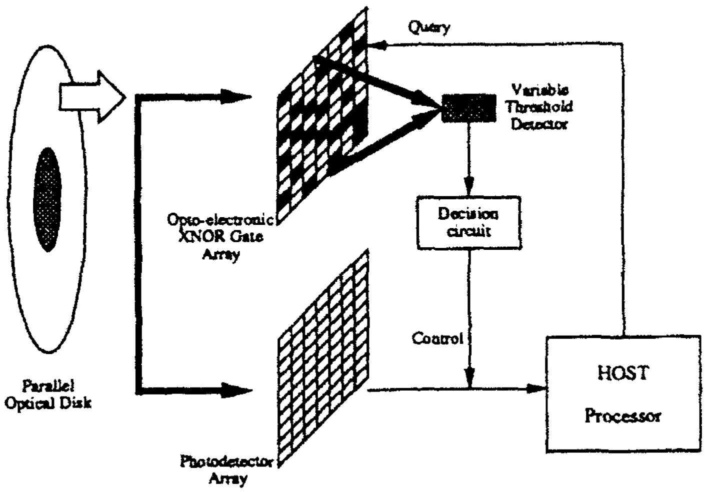
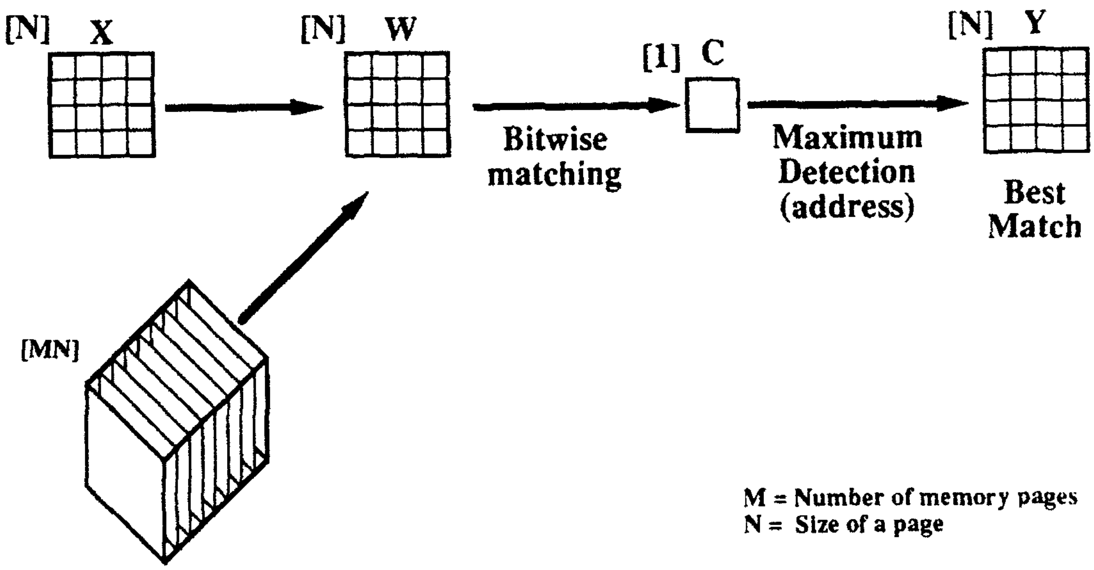


Figure 11: Associative memory design

2 modes of operation :

1. **Preset threshold :** All images that satisfy threshold are retrieved in one rotation
2. **Best match :** detect smallest hamming distance during first rotation and retrieve best matched image during 2nd rotation



$$c_k = \sum W_{ijk} x_{ij}$$

Figure 12: Serial inner-product algorithm

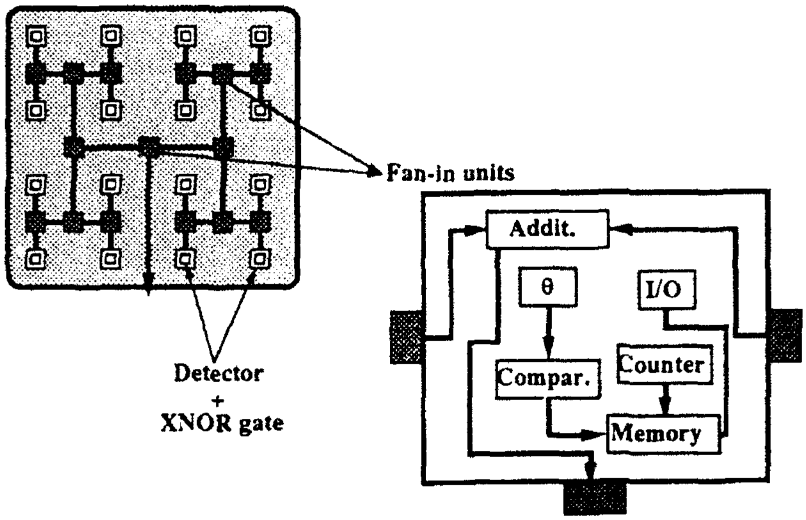


Figure 13: Schematic view of the Opto-Electronic Integrated Circuit (OEIC) based on a H-tree structure, and a fan-in unit detailled view.

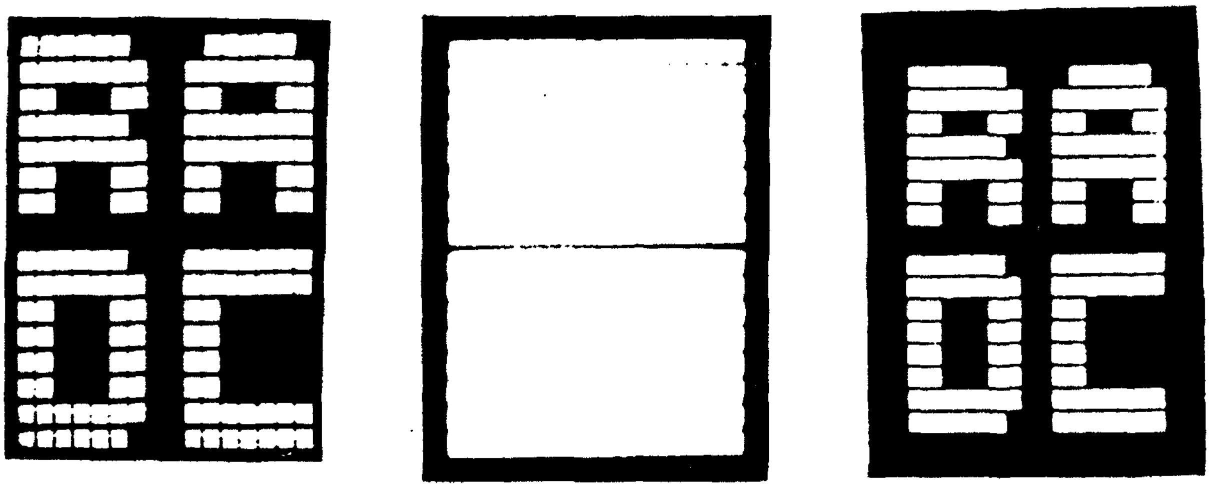


Figure 14: The query (RADC) and the output of the XNOR gate array showing a complete match with one of the image of the memory, the memory is then recovered.

7. LIST OF PUBLICATIONS

Communications and publications

1) "Opto-electronic associative recall using motionless-head parallel readout optical disk"
   P. Marchand, A. Krishnamoorthy, P. Ambs, and S.Esener.
   SPIE's International Symposium on Optical & Opto-Electronic Applied Science and Engineering. July 1990. San Diego. USA.

2) "Motionless parallel readout system for optical disks"
   P. Marchand, A. Krishnamoorthy, P. Ambs, S. Esener and S.H. Lee.
   OSA Annual Meeting. November 1990. Boston. USA.

3) "Opto-electronic associative memory using parallel readout optical disk"
   A. Krishnamoorthy, P. Marchand, G. Yayla and S. Esener.
   OSA Annual Meeting. November 1990. Boston. USA.

4) "Design of a motionless-head for parallel readout optical disk"
   P. Marchand, A. Krishnamoorthy, P. Ambs, J. Gresser , S. Esener and S. H. Lee.
   ECO4 - The International Congress on Optical Science and Engineering.
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5) "Application des hologrammes synthétiques au stockage sur disque optique"
   P. Marchand, A. Krishnamoorthy, P. Ambs, J. Gresser , S. Esener and S. H. Lee.
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Patent applications

1) "Motionless parallel readout head for optical disk"
   P. Marchand, P. Ambs, S. Esener, and S.H. Lee.
   Patent disclosure, UC case # 90-026-1.

2) "Opto-electronic associative memory for parallel access optical storage media"
   A. Krishnamoorthy and S. Esener.
   Patent disclosure, UC case # 90-244-1

8. Appendix: Communications and Publications

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Optoelectronic associative recall using motionless-head parallel readout optical disk

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ABSTRACT

A motionless head 2-D parallel readout system for optical disks is presented. A design for a high performance associative memory system using the parallel readout disk is also described. Such systems offer several advantages: high data rates, low retrieval times and simple implementation.

1. INTRODUCTION

Current secondary storage systems have low transfer rates relative to CPU processing speeds [1]. For memory intensive applications, this creates a performance bottleneck since the I/O subsystem forces the CPU to wait for data. Solid state disk drives, with capacities of 100 Mbytes, can provide bandwidths no better than 10 Mbytes/sec [2]. Although projected developments in main memory technologies such as SRAM and DRAM could provide bandwidths of 100 Mbytes/sec, their capacity will remain severely limited (1-10 Mbytes) [3,4]. However, as depicted in figure 1, the I/O bandwidth limitations to the host CPU can be alleviated by incorporating high parallelism and suitable "intelligence" at the secondary storage. In this paper, we propose a high performance opto-electronic associative memory using a fast, parallel access optical storage medium that can reduce this performance bottleneck.

A motionless-head parallel readout optical disk system is first presented. Its unique features are discussed and it is compared to various parallel access optical storage media. The motionless-head parallel readout system for optical disks is shown to meet current and near-term future requirements for high performance secondary storage. In order to select a memory architecture compatible with the motionless-head disk, inner-product and outer-product associative memory algorithms are compared in terms of their storage requirements, search times, system complexities, and fault tolerance. Based on this comparison, the page serial, bit-parallel inner-product method is shown to be well suited to implementation with the parallel readout optical disk and opto-electronic XNOR gate arrays, using for instance the Si/PLZT technology [5]. Finally, the associative memory system design is presented.

2. MOTIONLESS PARALLEL READOUT SYSTEM FOR OPTICAL DISK

In this section a design for a parallel readout optical disk system is presented. This system is well suited for associative memory implementations because it has the unique advantage that no mechanical motion of the head is required for access, focusing or tracking.

A 5.1/4" diameter disk with a 1.5 µm track pitch and a 1 µm pit size is assumed. The disk active surface has a radius of 3 cm and therefore contains 20,000 concentric tracks. The data encoding method and the readout system are designed to allow reconstructions of 128x128 pixel images at the output. As illustrated in figure 2a, the data blocks are 1-D Fourier transform Computer Generated Holograms (CGH) calculated to reconstruct one column of 128 pixels each. 128 of these blocks, representing one image, are distributed along the radial direction of the disk active surface, shifted radially by 150 tracks from one another (fig 2b).

The optical readout system (figure 3) maps this data distribution on the disk to a 2-D image at the output. Lens L2 illuminates an area on the disk whose length is equal to an entire radial line of the disk active surface. Therefore 128 data blocks are illuminated simultaneously. The cylindrical lens L3 performs a Fourier transform of the illuminated area along the radial direction while lens L4 images and magnifies the data along the tangential direction. 128 data blocks are read simultaneously and a binary image of 128x128 pixels is reconstructed on the output plane. Since no mechanical motion of the head is required to access any image stored on the disk, the entire content of the disk can be retrieved in one rotation. A higher data rate than any existing optical disk system can therefore be achieved.

The beam illuminating the disk holograms converges along the tangential direction and is a plane wave along the radial direction. The width of the area containing the data blocks of one image is 22 μm. A relatively large f-number lens (L1) is used to ensure a small illumination solid angle Therefore, the depth of focus is large ($> \pm 10$ μm). This lens is placed out of focus, at a distance calculated to allow the illuminating beam to be slightly smaller than 22 μm at the disk plane. A wobble of 20 μm due to flatness variations of the spinning surface can therefore be tolerated. In addition, due to the hologram information redundancy, even partially illuminated holograms reconstruct the entire data; a loss of 10% of the hologram information inducing a loss of only 3 dB in the reconstruction Signal to Noise Ratio (SNR) [6]. For these reasons, no focusing servo is required.

The CGH encoding method developed specifically for the disk holograms is based on a grey level encoding scheme. The 128 bits of each image column are embedded in a larger array of 512 elements. This array is then either Fourier transformed or processed by an iterative algorithm. Each sample value obtained is quantized to five grey levels on a four bit pattern (see figure 4a). The resulting hologram (4x512 elements) is replicated once to generate a 4x1024 data block. An example of such a block is given in figure 4b. Since Fourier-transform holograms are shift-invariant, the eccentricity (radial motion) of the spinning disk does not affect the reconstruction of the data. Therefore no tracking servo is required. Using a larger number of grey levels reduces the disk storage capacity but increases the output SNR. Depending on the application, SNR can be traded in for capacity.

The encoding method described above necessitates an accurate recording control system that allows a precise radial alignment of the recorded bits [7]. However, by using a larger number of grey levels, it is possible to suppress the recording alignment requirement without a degradation in the SNR of the reconstructed images. This would enable the disk to be recorded using almost any commercial optical disk drive.

Experiments were conducted to test the hologram encoding method as well as the validity of the disk data layout and the optical system. Several holograms were recorded on glass plates with an electron beam recorder, using the same feature size as an actual optical disk (1μm spots with 1.5 μm radial pitch, see figure 5a). The plates were placed in the optical system at the disk plane and the hologram reconstructions (figure 5b and 5c) were analysed. Average SNRs of over 100 for the smaller images (16x16 pixels) and of about 40 for the larger ones (128x128 pixels) were measured. Static measurements revealed that focusing errors of up to 20 μm and tracking errors of over 1 mm could be tolerated without significant degradation of the reconstructed image.

3. PARALLEL ACCESS OPTICAL MEMORIES

The critical parameters of concern for implementing an opto-electronic associative memory are the capacity, data rate, latency time, and retrieval time of the secondary storage system. The data rate is the maximum rate of information transfer from the memory device. Latency is defined as the delay beween accessing two successive bit-planes. The retrieval time is the time required to read the entire content of the memory. As shown in table 1, several page oriented parallel access optical memories were considered. These include 3-D memories such as photo-refractive crystals and two-photons memories, as well as planar memories such as the Page-Oriented Holographic Memory (POHM) [8], and the motionless-head parallel readout optical disk. Other parallel readout optical disk systems could not be compared since the corresponding numbers were not available.

The POHM approach provides lower data rates. If moving parts are not used, the system is limited by the resolution requirements of the optical system as well as the reduced effective aperture [9]. Volume holography using photorefractive crystals [10] shows promise. By applying a voltage to increase the assymetry between write times and erase times [11], and storing low efficiency holograms, terrabit storage may be possible. However, important questions of fixation, optimal multiplexing methods, and crosstalk must be answered. Other volume media such as the UCSD/UCI 2-photon memory [4] also have excellent performance potentials. However, such memories are not expected to be manufactured before the turn of the century. Based on these figures, the motionless-head parallel readout system for optical disks (section 3) is seen to be well suited to current and near-term future needs for high performance secondary storage.

4. ASSOCIATIVE MEMORY ALGORITHMS

In this section several algorithmic approaches to associative memory using 2-D bit plane storage are investigated. These fall into two broad categories. The first is an outer product algorithm using matrix-tensor multiplications. The second is an inner-product scheme based on bitwise-matching.

In outer-product based associative memory algorithms, the memories are distributively stored via an outer-product construction. If X_m represents one of M two-dimensional images to be stored, and Y_m the desired output, a fourth rank tensor must be stored:

$$W = \sum Y_m X_m^T$$

For autoassociative memories, $Y_m = X_m$. Outputs are obtained by iteratively performing tensor-matrix multiplications on the input followed by thresholding (fig. 6).

In inner-product based algorithms such as the Hamming network [12], the data (X_m's) is stored explicitly. Inner products between the input and all the X_m's are calculated and the output is the corresponding Y_m associated with the largest inner product. The inner products may be calculated in parallel (fig 7), in which case a maximum-selector network is needed, or they may be calculated serially (fig 8).

Outer-product neural network algorithms such as the Hopfield network and its variants suffer several disadvantages when compared to parallel inner-product methods [13,14]. The critical issues for an opto-electronic implementation are the storage requirements, system complexity, search times, and fault tolerance of these methods. In table 2 a comparison of outer-product, parallel inner-product, and serial inner-product methods is presented. Although outer-product based associative memories can provide robust storage and fast convergence when a small number of very large memories are used [15], inner-product methods provide significant hardware savings when a large number of memories must be stored. For the optical disk system with M=14,500 images of N=128x128 bits each, the page-serial, bit-parallel method has the least storage requirements as well as the lowest system complexity because no maximum selector network is needed. For this same reason, the method does not place an upper limit on the number of memories that can be searched. The search time of this method (O[M]) is higher than those of outer product and parallel inner product methods. However, due to the high data rate achievable with the parallel readout optical disk, the page serial, bit parallel inner product method is still capable of low retrieval times. Finally, as discussed in section 3, fault tolerance can be traded in for capacity. For these reasons, the page serial, bit parallel inner product algorithm is well suited to implementation.

5. ASSOCIATIVE MEMORY SYSTEM DESIGN

The associative memory system (figure 9) presently being developed at UCSD, consists of the parallel readout optical disk, a Si/PLZT XNOR gate array, a photo-detector array and a single variable threshold detector with fast local decision circuitry. A 2-D query from the host computer, is electronically loaded onto the Si/PLZT XNOR gate array. The query image is then compared serially to the binary images from the optical disk (bitwise matching operations). The output of the variable threshold detector is fed into the decision circuit which controls the data flow between the photo-detector array and the host computer.

The XNOR gate array consists of an optically and electronically addressed 2-D PLZT SLM [5] with local Silicon circuitry that performs the Exclusive-nor function. Each unit cell receives three inputs as well as control information. The query bit is electronically loaded from the host computer. The corresponding bit from the stored images arrive from the disk at the detector. The third input is a clock obtained from the disk that signals when a complete image is under observation. The detector circuits of the XNOR gate array are designed to provide large noise margins for the detected input bits. The SNRs achievable with the disk holograms can therefore be tolerated since each detector circuit restores logic levels. The logic circuitry drives the PLZT modulator so as to allow light to pass when a bit match occurs. Therefore, the output light represents a logical Exclusive-nor operation of the query bits and the corresponding bits of the stored image.

The system can support two modes of operation. In the first mode, the detector threshold value is preselected. The intensity at the Variable Threshold Detector (VTD) measures the match between the query image and the stored image currently under observation. Therefore only images that are close to the query will be retrieved by the host computer through the photodetector array. The second mode finds the best match to the query image. On the first rotation, the intensity detected for each image is input to the decision circuit. The best match is identified and retrieved on the subsequent rotation.

6. CONCLUSIONS

In this paper, we have presented an opto-electronic associative memory based on a motionless-head 2-D parallel readout system for optical disks. Since the optical disk system requires no mechanical motion of the head for access, focusing or tracking, addressing is performed only through the rotation of the disk. A higher data rate than any existing optical disk system can be achieved since the entire memory can be scanned in one rotation. A design for an opto-electronic associative memory system using the parallel readout optical disk and an optically addressed Si/PLZT SLM with local Exclusive-nor circuitry was presented. The associative memory system can retrieve either the best match or all images that satisfy a preset threshold. Such a system can achieve storage capacities of over 1 Gigabyte (14,500 images per disk) and retrieval times of 25 msec.

ACKNOWLEDGMENT

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	Volume Holograms	UCI / UCSD 3-D Memories	POHM	UCSD Parallel Optical Disk
Capacity	125 GBytes	12.5 GBytes	725 MBytes	940 MBytes
Data rate	12.5 TByte/sec	12.5 TByte/sec	0.1 GByte/sec	1.2 GByte/sec
Latency time	10 µsec	1 µsec	0.1 msec	1.7 µsec
Retrieval time	10 msec	1 msec	0.5 sec	25 msec
Description	$LiNbO_3$, 10x10x1 cm^3 10^3 pages @ 10^9 bits/page	10x10x1 cm^3 10^3 pages @ 10^8 bits/page	6x6 inches card 5800 pages @ 10^6 bits/page	51/4 " disks @ 2400 rpm 14500 pages @ 128x128 bits/page

Table 1 : critical parameters for optical parallel access storage media

	Storage Requirements	Search Time	System Requirements	Fault Tolerance
Outer Product Neural Network Architecture	N^2 and $M<0.15N$ Analog weights	$O\left[\mathrm{Log}\left(\frac{N}{M}\right)\right]$	N^2- element matrix-tensor multiplications	Graceful degradation to : Local memory damage Memory overloading
Parallel Inner Product Neural Network Architecture	MN + LogM binary weights	O[Log M]	M (N-element) matrix-matrix comparisons + maximum selection circuit	- No tolerance to Memory damage - Upper limit on number of stored memories
Serial Inner product Page serial Bit parallel Comparison	MN binary weights	O[M]	N-element matrix-matrix comparisons	Fault tolerance can be traded in for capacity

* N = Number of bits per memory page
M = Number of memory pages

Table 2 : Comparison of associative memory algorithms

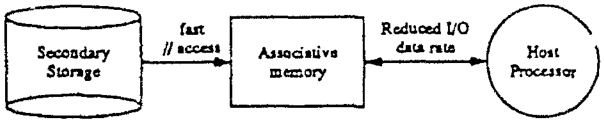


Figure 1 : Schematic of an associative memory system

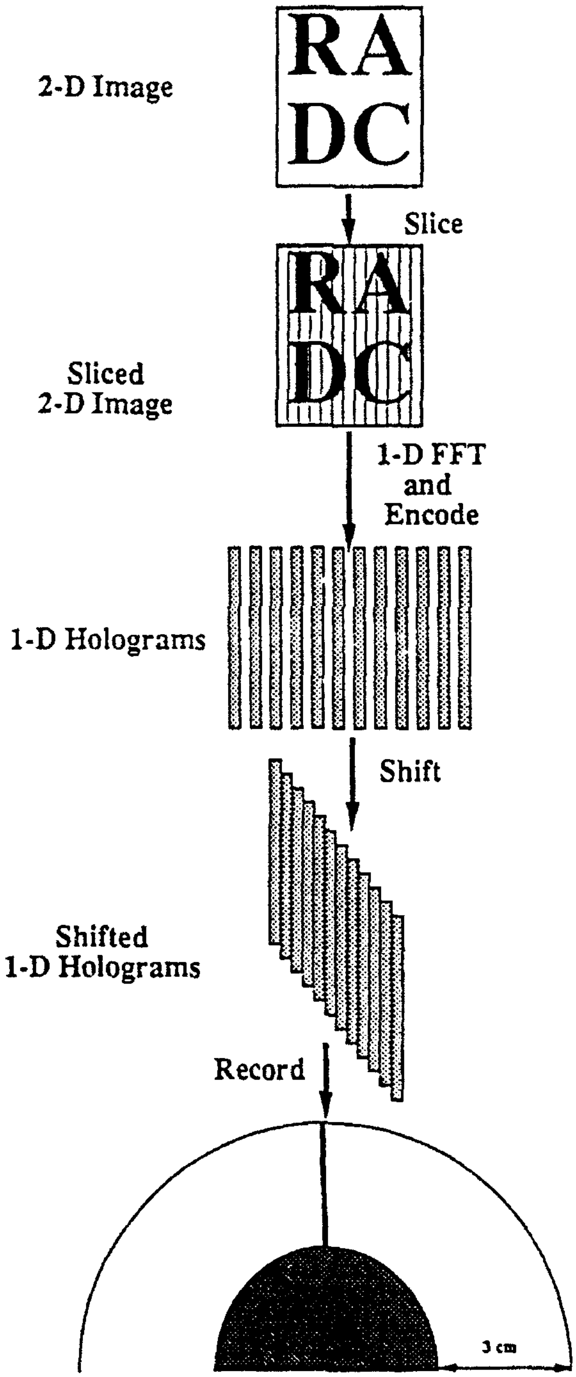


Figure 2a : Disk data encoding. A 2-D image is sliced into 1-D columns. These columns are then 1-D Fourier transformed and 1-D CGH are generated. The holograms are then shifted one another and radially recorded.

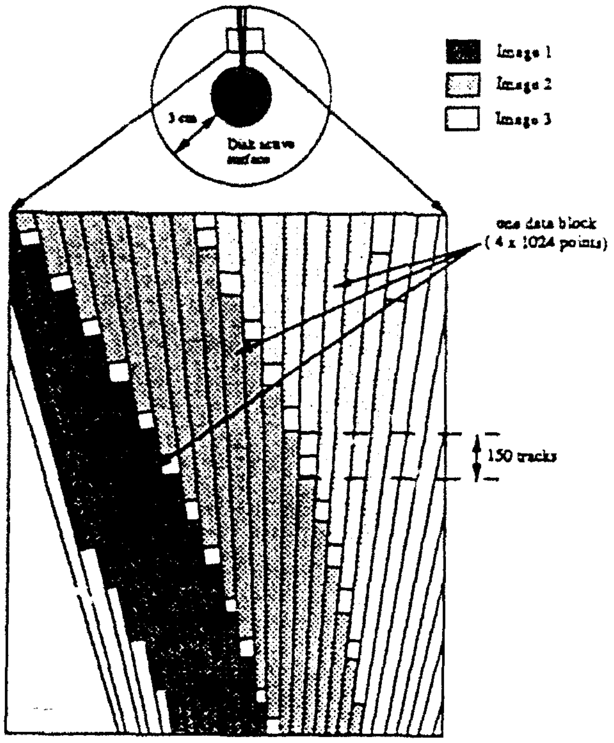


Figure 2b : Disk data layout. Data blocks of one image are radially and laterally shifted

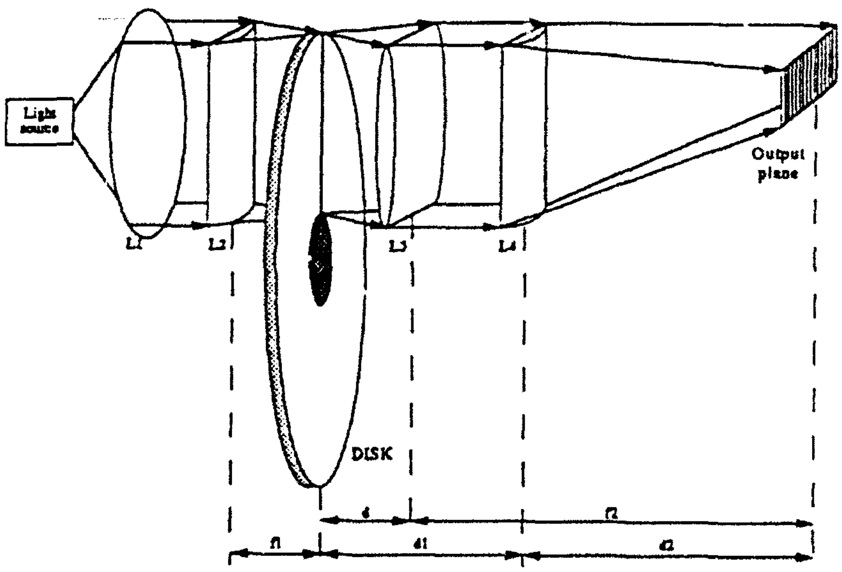


Figure 3 : Optical system. After being collimated by lens L1, the light is focused onto the disk by cylindrical lens L2. Cylindrical lens L3 performs the Fourier transform of the data along the radial direction and cylindrical lens L4 images and magnifies the data(M = d2/d1) along the tangential direction. A binary image of 128 x 128 points is then reconstructed on the ouput plane.

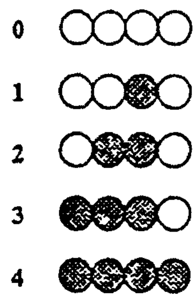


Figure 4a : hologram grey level encoding method

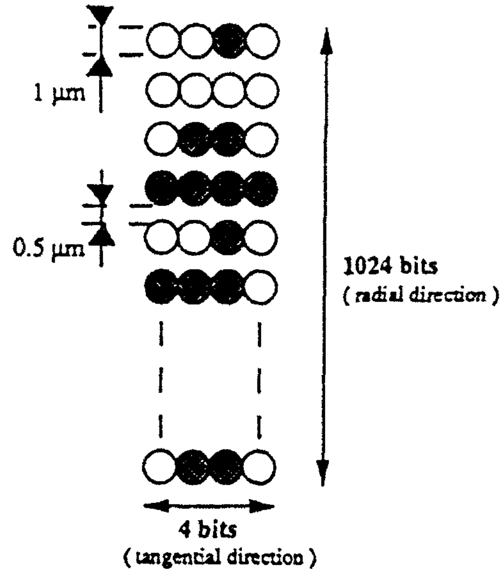


Figure 4b : one data block

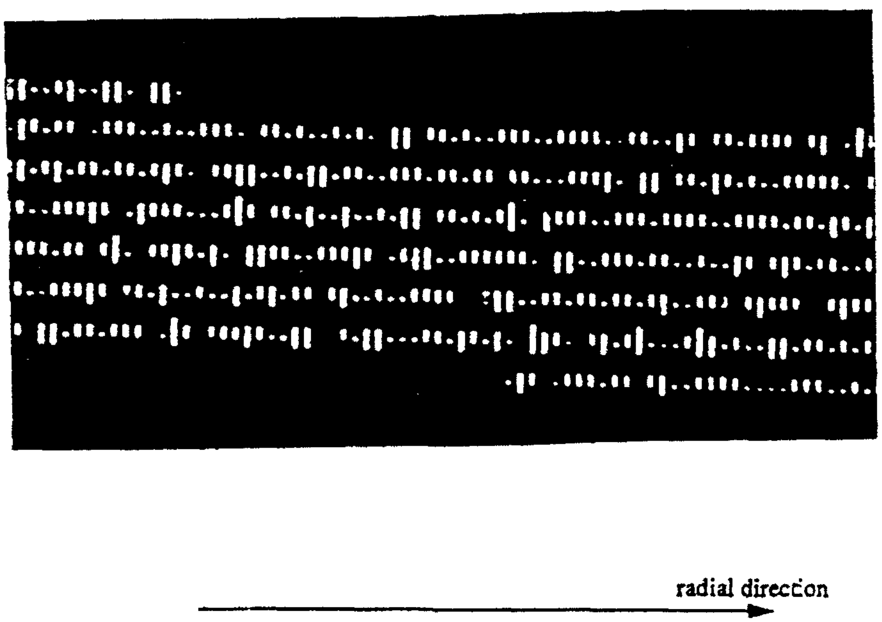


Figure 5a : Experimentally recorded holograms
The holograms are recorded on an E-beam test plate using optical disk pits feature size, i.e 1µm bit size with 1.5 µm pitch according to the format described in figure 2 and 4.

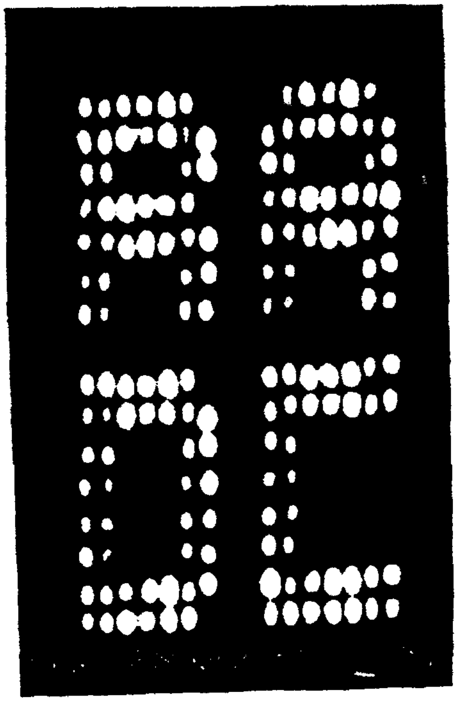


Figure 5b : reconstruction of a 16x16 object

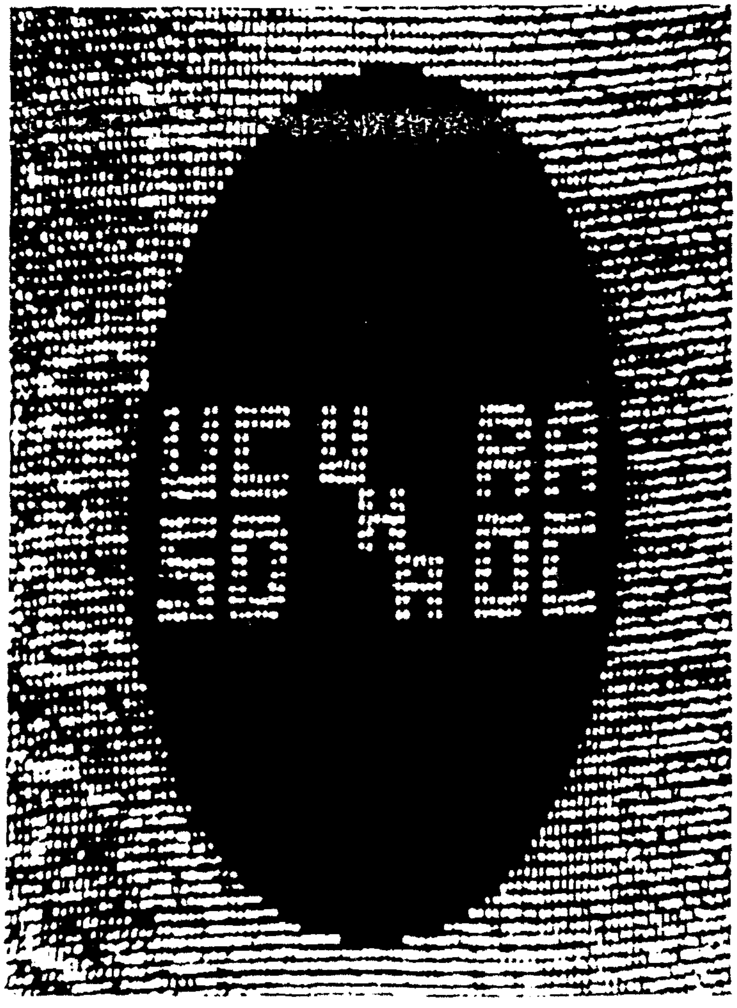
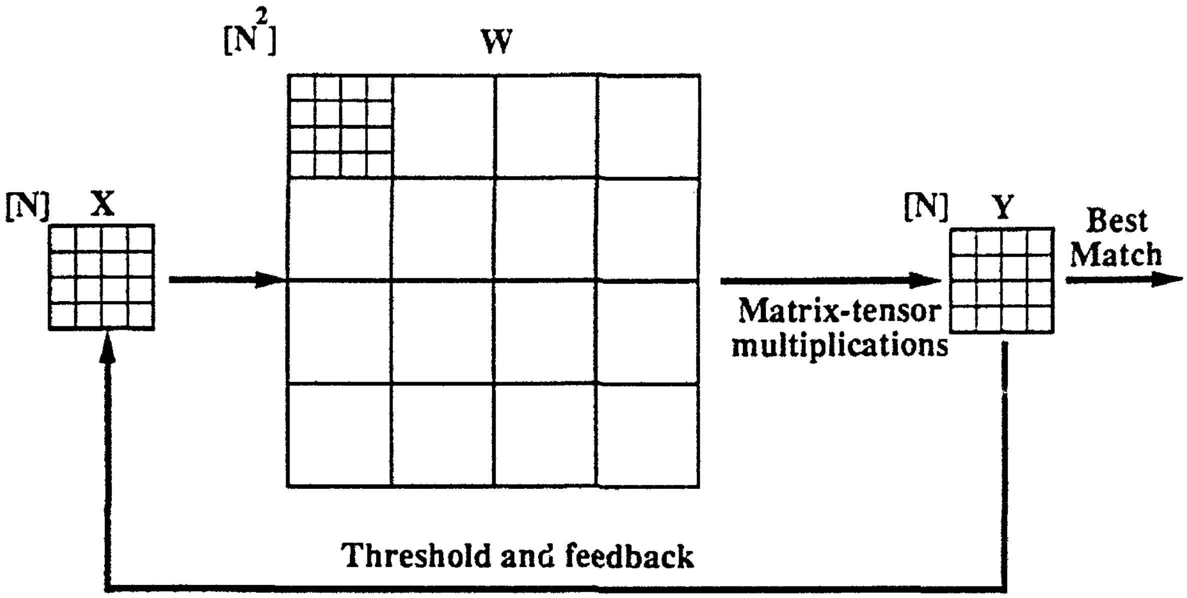


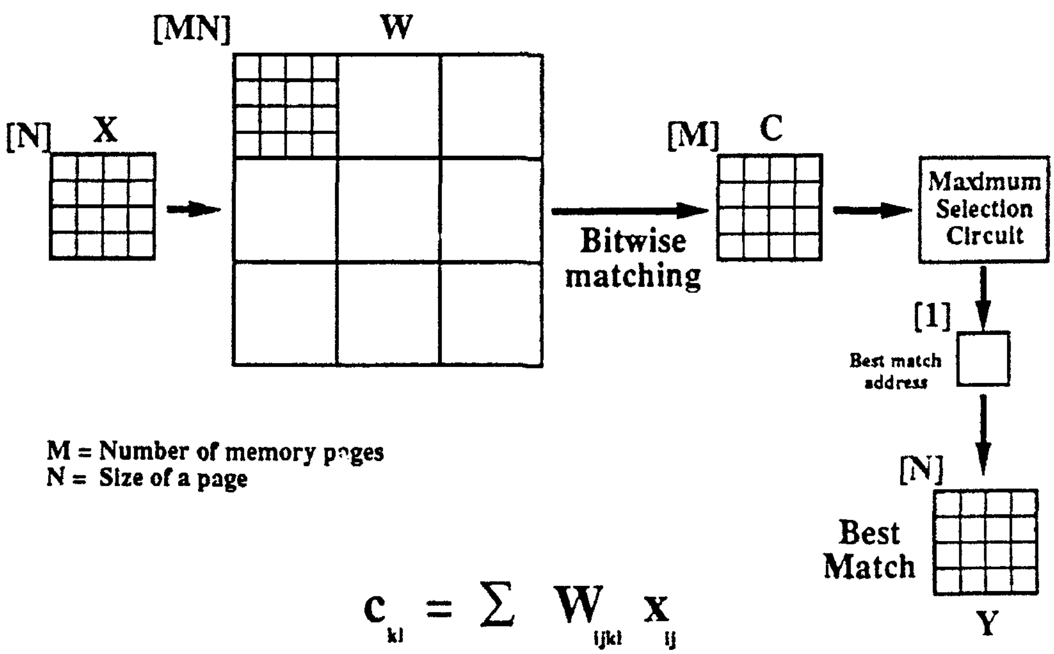
Figure 5c : center portion of the reconstruction of a 128x128 object



$$y_{kl} = \sum W_{ijkl} \; x_{ij}$$

$W_{ijkl} = N^4$ elements of 4^{th}-rank connection tensor W

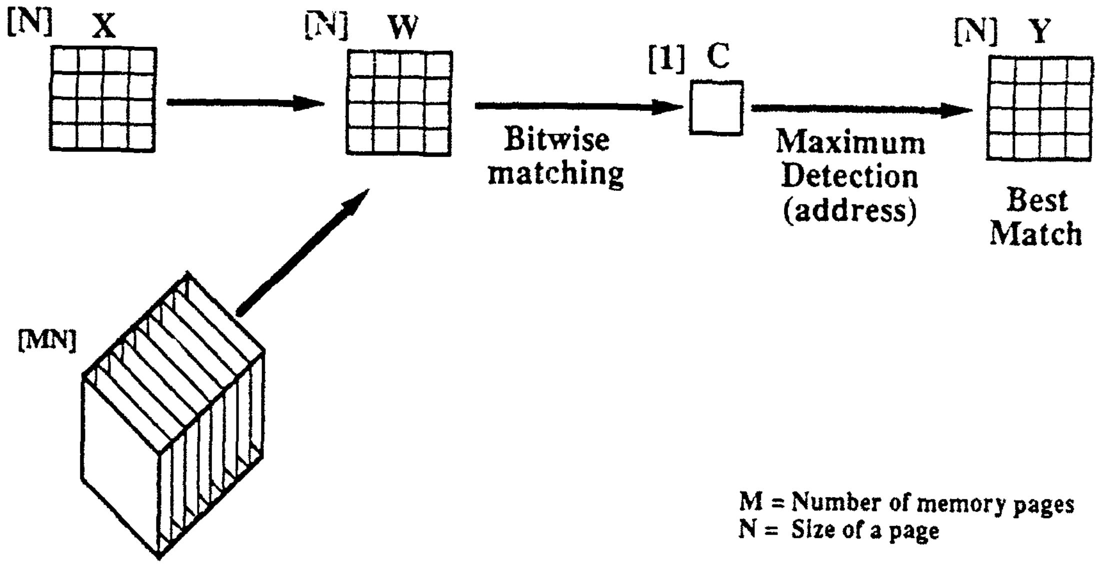
Figure 6 : Outer-product algorithm



M = Number of memory pages
N = Size of a page

$$c_{kl} = \sum W_{ijkl} \; x_{ij}$$

Figure 7 : Parallel inner-product algorithm



$$c_k = \sum W_{ijk} x_{ij}$$

Figure 8 : Serial inner-product algorithm

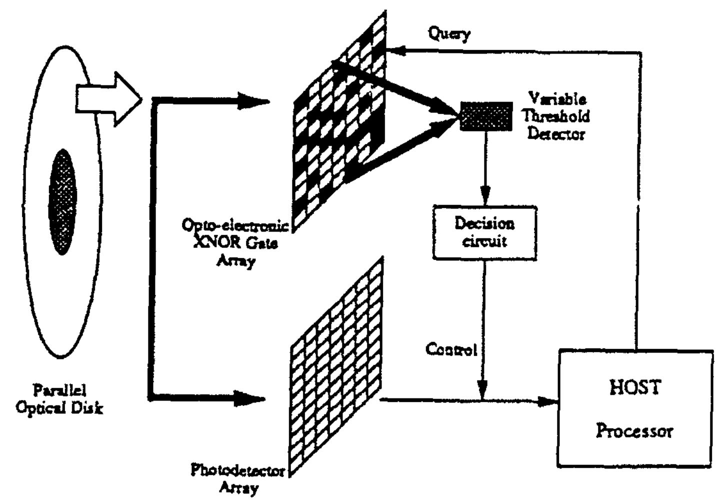


Figure 9 : Associative memory design

2 modes of operation :

1. **Preset threshold :** All images that satisfy threshold are retrieved in one rotation
2. **Best match :** detect smallest hamming distance during first rotation and retrieve best matched image during 2nd rotation

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Motionless parallel readout system for optical disks

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We present a novel motionless parallel readout system for optical disks particularly well suited to high-speed opto-electronic associative memory applications.

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We present a theoretical and experimental investigation of a novel optical disk memory. The system is designed to read data blocks distributed radially on the disk active surface. These data blocks are 1-D Fourier transform computer generated holograms, each reconstructing one column of a 2-D output image. Due to the properties of Fourier transform holograms (information redundancy, shift invariance), no tracking or focusing servos are required. An area with a length equal to an entire radial line of the disk active surface is retrieved at once. Data is then accessed through disk rotation only, with no mechanical motion of the head. Therefore, the entire disk content can be retrieved in a single rotation (25 msec) making this system very suitable for high-speed opto-electronic associative memory applications. We will discuss the overall system design, compare different encoding methods for the disk holograms and provide static and dynamic experimental results showing the potential of the parallel readout system for optical disks. We will then introduce the design of an opto-electronic associative memory based on this motionless parallel readout system for optical disks.

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Optoelectronic associative memory using parallel readout optical disk
(Title of paper. Capitalize only the first letter of the first word.)

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(Institution)

We present a design for an optoelectronic associative memory using a parallel readout optical disk and a Si/PLZT exclusive-or gate array.

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We evaluate inner-product and outer-product algorithms for associative memory. We show that the page serial, bit parallel, inner-product method has lower storage requirements, lower system complexity, and achieves minimum error recall. Storage capacity can be traded in for fault tolerance. The high capacity (1 GByte) and high throughputs (1.5 GByte/sec) obtained with the motionless parallel readout optical disk make it suitable to implement an associative memory capable of fast retrieval (25 msec). The associative memory system consists of a detector array, a Si/PLZT exclusive-or gate array, and a Variable Threshold Detector (VTD) with fast local decision circuitry. The intensity at the VTD is a measure of the mismatch between the query image and the stored image being read. Two modes of operation are possible. Using a preset threshold at the VTD, all images on the disk close to the query are retrieved in one rotation. Alternatively, all Hamming distances are calculated during the first rotation of the disk and the closest match is retrieved during the next rotation. We examine system noise sources and design a Si/PLZT unit cell compatible with the limited SNR of the disk reconstructed images. We include simulations and experimental results.

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Design of a motionless head for parallel readout optical disk

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ABSTRACT

A motionless head 2-D parallel readout system for optical disks is presented. The system is designed to read data blocks encoded as 1-D Fourier holograms distributed radially on the disk active surface. Such systems offer several advantages: high data rates, low retrieval times and simple implementation. It is used as the secondary storage of a high performance optoelectronic associative memory system.

1. INTRODUCTION

Current secondary storage systems have low transfer rates relative to CPU processing speeds [1]. For memory intensive applications, this creates a performance bottleneck since the I/O subsystem forces the CPU to wait for data. Solid state disk drives, with capacities of 100 Mbytes, can provide bandwidths no better than 10 Mbytes/sec [2]. Although projected developments in main memory technologies such as SRAM and DRAM could provide bandwidths of 100 Mbytes/sec, their capacity will remain severely limited (1-10 Mbytes) [3,4]. Optical disks are good candidates for secondary storage. They combine a high capacity (900 Mbytes for a 5.1/4 " diameter disk), low cost ($ 1 / Mbyte) and robustness (no head crash). There are three limitations for high speed operations of optical disk systems: the tracking, the focusing and the addressing mechanisms. All theses functions require mechanical motions of the head which slow down the disk operation. Moreover the available disk technology is sequential, only allowing data rates of up to 1 Mbyte/sec. It has been shown that optical disks can be read in parallel and several parallel readout systems has been proposed [5,6,7]. Our objective is to implement a parallel system with data rate of 1Gbyte/sec and an average access time of 12.5 msec. In the system we present, data is written radially on the disk as 1-D holograms and data access is achieved solely through the disk rotation. This system has the unique advantage that no mechanical motion of the head is required for access, focusing or tracking. Section 2 introduces the system and the disk data encoding method. The application to associative memory is described in section 3.

2. MOTIONLESS PARALLEL READOUT SYSTEM FOR OPTICAL DISK

2.1 Disk encoding

A 5.1/4" diameter disk with a 1.5 μm track pitch and a 1 μm pit size is assumed. The disk active surface has a radius of 3 cm and therefore contains 20,000 concentric tracks and has a capacity of 940 Mbytes. The data encoding method and the readout system are designed to allow reconstructions of 128x128 pixel images at the output. As illustrated in figure 1, the data blocks are 1-D Fourier transform Computer Generated Holograms (CGH) calculated to reconstruct one column of 128 pixels each. 128 of these blocks, representing one image, are distributed along the radial direction of the disk active surface, shifted radially from one another to fit a complete radius. A disk encoded this way has a capacity of approximately 14,000 128x128 pixel images.

2.2 Optical system

The optical readout system (figure 2) maps the data distribution on the disk to a 2-D image at the output. Lens L2 illuminates an area on the disk whose length is equal to an entire radial line of the disk active surface. Therefore 128 data blocks are illuminated simultaneously. The cylindrical lens L3 performs a Fourier transform of the illuminated area along the radial direction while lens L4 images and magnifies the data along the tangential direction. 128 data blocks are read simultaneously, therefore a binary image of 128x128 pixels is reconstructed on the output plane. Since no mechanical motion of the head is required to access any image stored on the disk, the entire content of the disk can be retrieved in one rotation. Higher performance than any existing optical disk systems can be achieved. For a rotation speed of the disk of 2,400 rpm, the data rate is then 1.1Gbytes/sec, the access time 12.5 msec and the retrieval time is 25 msec.

The beam illuminating the disk holograms converges along the tangential direction and is a plane wave along the radial direction. The width of the area containing the data blocks of one image is 22 µm. A relatively large f-number lens (L1) is used to ensure a small illumination solid angle Therefore, the depth of focus is large (> ± 10 µm). This lens is placed out of focus, at a distance calculated to allow the illuminating beam to be slightly smaller than 22 µm at the disk plane. A wobble of 20 µm due to flatness variations of the spinning surface can therefore be tolerated. In addition, due to the hologram information redundancy, even partially illuminated holograms reconstruct the entire data; a loss of 10% of the hologram information inducing a loss of only 3 dB in the reconstruction Signal to Noise Ratio (SNR) [5]. For these reasons, no focusing servo is required. As shown in section 2.1 the data is encoded as 1-D computer generated Fourier holograms. Since Fourier-transform holograms are shift-invariant, the eccentricity (radial motion) of the spinning disk does not affect the reconstruction of the data. Therefore no tracking servo is required.

2.3 Hologram encoding

The data encoding on the disk is a key factor for a good operation of the parallel readout system. The quality of the reconstruction and also the size of the hologram therefore the capacity of the disk will both depend on the holographic encoding. The first criterium is the best compromise between the quality of the reconstruction and the disk capacity. Moreover due to the nature of the data recording on a disk, the holograms must be binary. The reconstructed images have also to be binary. Taking into account all these requirements a CGH encoding method has been developed specifically for the disk holograms. This method based on a grey level encoding scheme has been compared to the existing methods.

Each column of the NxN pixel image to be stored on the disk is used as the 1-D input image (C) for which an hologram of size KxN will be computed. The binary array (C) is then embedded with a specific shift m into a 1-D array (O) of size M of which all elements are zeros. A random phase is then multiplied to this new input array, and its 1-D Fast Fourier Transform (FFT) is computed. The real part is extracted and a bias equal to its minimum is added to it in order to make all the values positive. Each sample value obtained is quantized to n grey levels on a n-1 bit pattern using a density modulation algorithm (see figure 3a). In order to reduce the speckle the resulting binary hologram is replicated once to generate a 2M cells of (n-1) bit data block. An example of such a block is given in figure 3b. For the actual system with images of 128x128 pixel image to be stored, the 128 bits of each column are encoded in a 512 cell holograms with 5 grey levels. Therefore the hologram after replication is a 4x1024 bits data block. Using a larger number of grey levels reduces the disk storage capacity but increases the output SNR. Then depending on the application, SNR can be traded in for capacity.

It is possible to improve greatly the performances of these holograms by calculating them with an iterative algorithm. This algorithm is derived from the Direct Binary Search (DBS) algorithm [8] and adapted for the grey level encoding method described previously. The flow chart of this algorithm is given on figure 4. A random grey level hologram is first generated. The reconstruction of this hologram is then computed by FFT. An error function is calculated by comparing the intensity of the reconstructed image and the original image to be reconstructed. The bits of each cell of the hologram are then inverted one after another and the new reconstruction is computed each time. But it is not neccessary to use an FFT, since changing one bit of the hologram is equivalent of adding (bit changed from 0 to 1) or substracting (bit changed from 0 to 1) a plane wave to the previous reconstruction. The error between the new reconstruction and the original image is calculated. If the new error is smaller than the previous one the change of the bit is maintained and the new error is memorized, if not the change is ignored. A loop is completed when the n grey levels of the M cells of the hologram have been tested.The iterative process continues until a predetermined number of loops is completed (ctr) or until the error is lower than a preset threshold or until all the change are ignored during one complete iteration.

Table 1 shows the comparison of this encoding method with other binary encodings. The reconstructions are simulated on computer and the comparison criteria are: the diffraction efficiency and the contrast ratio. The diffraction efficiency is defined as the ratio between the intensity of the reconstructed image and the total intensity of the reconstruction. Two different cases are defined for the contrast ratio. The average contrast ratio is computed by taking the ratio of the average intensity of the "1" bits over the average intensity of the "0" bits. The worst case contrast ratio is the ratio between the lowest intensity of a "1" bit and the highest intensity of a "0" bit. The values of table 1 are an average for 128 holograms. For all the encoding methods, 4x1024 pixel holograms are used. The cell oriented method is similar to the one proposed by Psaltis [8], only the phase is encoded by variation of the position of "1" bits in a cell. The other methods are the error diffusion as defined by Hauck [9], the grey level method and the iterative method described here. The

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table 1 shows that the iterative method we proposed gives the best results. However the algorithm must be very carefully implemented on the computer in order to optimize the computing time for the holograms.

2.4 Experimental results

Experiments were conducted to test the hologram encoding method as well as the validity of the disk data layout and the optical system. For these first experiments, the holograms were recorded on glass plate with an electron beam recorder (EBR), using the same feature size as an actual optical disk (1μm spots with 1.5 μm radial pitch, see figure 5). Once the holograms are calculated, they are processed by the UCSD holographic CAD program [10] which generates data files for the EBR. Several holograms were recorded on glass plates of 1.2 mm thickness with a photoresist of 350 nm thickness. The optical system used for reading the disk is described on figure 2. The following lenses are used:

L2	f := 100 mm	aperture: 50 x 60 mm	f/# = 2	illuminating lens
L3	f := 200 mm	aperture: 60 x 50 mm	f/# = 4	Fourier transform lens
L4	f := 25.4 mm	aperture: 22 x 60 mm	f/# = 1.15	imaging lens

The plates were placed in the optical system on a rotation stage at the disk plane, both static and dynamic measurements being conducted. The hologram reconstructions were analysed. Figure 6 shows the intensity of a part of a line in a 128x128 pixel reconstructed image, an average SNR of about 40 is measured. Static measurements revealed that focusing errors of up to 20 μm and tracking errors of over 1 mm could be tolerated without significant degradation of the reconstructed image. Dynamic tests have been conducted and as expected the position of the reconstructed images in the output plane is not moving when the disk is rotating and moving lateraly due to the excentricity. Figure 7 shows the center portion of a 128x128 pixel reconstructed image.

2.5 Hybrid lens design

The optical system design for the parallel readout optical disk system includes two separate cylindrical lenses with different focal lengths: one for imaging in the X-direction, and one for Fourier transforming in the Y-direction. Besides being bulky and heavy, these cylindrical lenses are extremely difficult to align and suffer from severe aberrations. Code V optical design software is then used to design a single Holographic Optical Element (HOE) to replace the function of the two lenses and to correct for the aberrations (figure 8). Due to the difference in focal lengths in the X and Y directions, it is found advantageous to use orthogonal cylindrical diffractive lenses [11] (OCDL). Two separate designs were studied, both design overcoming the problem associated with refractive cylindrical lenses. The first one is a single element HOE with both focal lengths positive but different. The second design is a hybrid refractive/ diffractive element that combines a HOE with a plano-convex spherical lens. In this case one focal lenth is positive while the other is negative. The respective optical performance of the three systems are shown in the figure 9. The error function is calculated in Code V and corresponds to the distance of all the rays to the chief ray in the output plane. The results show that the best system is the hybrid element for both optical performance and fabrication requirements. Indeed, this combination raises the required f/# of the OCDL, which in turn reduces the minimum feature size of the OCDL. Thus a larger size OCDL with more phase levels and a higher diffraction efficiency can be fabricated. As an illustration of this design a mask of the diffractive element of the hybrid lens can be seen in the figure 10.

3. APPLICATION TO ASSOCIATIVE MEMORY

3.1 System overview

The associative memory system (figure 11) presently being developed at UCSD, consists of the parallel readout optical disk, an opto-electronic XNOR gate array, a photo-detector array and a single variable threshold summation circuit. A 2-D query from the host computer, is electronically loaded onto the XNOR gate array. The query image is then compared serially to the binary images from the optical disk (bitwise matching operations). The output of the variable threshold detector is then fed into the decision circuit which controls the data flow between the photo-detector array and the host computer.

This associative memory system using the optical disk is well suited to implement a page serial, bit parallel inner product algorithm system which is shown in figure 12. The search time of this method is higher than those of outer product and parallel inner product methods.[12] However, due to the high data rate achievable with the parallel readout optical disk, the page serial, bit parallel inner product method is still capable of low retrieval times.

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The system can support two modes of operation. In the first mode, the threshold value is preselected. Local XNOR operations are performed between the bits of the electronic query and the corresponding bits of the disk image. Therefore only images that are close to the query will be retrieved by the host computer via the photodetector array. The second mode finds the best match to the query image. On the first rotation, the Hamming distance for each image is input to the decision circuit in the manner described above. The best match is identified and retrieved on the subsequent rotation.

The key element of the associative memory system using the motionless head disk is the optoelectronic XNOR integrated circuit which is computing the inner product. Two different approaches have been considered to realize this circuit, one analog approach and a digital approach.

3.2 Analog approach

The XNOR gate array consists of an optically and electronically addressed 2-D PLZT SLM [13] with local Silicon circuitry that performs the Exclusive-nor function. Each unit cell receives three inputs as well as control information. The query bit is electronically loaded from the host computer. The corresponding bit from the stored images arrive from the disk at the detector. The third input is a clock obtained from the disk that signals when a complete image is under observation. The detector circuits of the XNOR gate array are designed to provide large noise margins for the detected input bits. The SNRs achievable with the disk holograms can therefore be tolerated since each detector circuit restores logic levels. The logic circuitry drives the PLZT modulator so as to allow light to pass when a bit match occurs. Therefore, the output light represents a logical Exclusive-nor operation of the query bits and the corresponding bits of the stored image. There are two limitation to this approach. The minimal Hamming distance which can be distinguished is limited by the contrast ratio of the Si/PLZT modulators and by the dynamic range of the variable threshold detector.

3.2 Digital approach

The limitations of the previously described analog approach can be overcome by replacing the Si/PLZT XNOR gate array with an Opto-Electronic Integrated Circuit (OEIC) based on a tree structure [14,15]. This OEIC has light dtectors to receive the light from the images read from the disk. It also has local silicon circuitry perform the XNOR operation between the disk images bits and the query bits and fan-in units to perform the summs of the bits down the tree. A schematic view of such an OEIC, based on a H-tree structure [15] is shown in the figure 13. Using this OEIC system, the Hamming distance between a query and the image stored on the disk can be measured with a precision of one bit. Furthermore, the system maintains high throughputs, since all operations down the tree can be pipelined due to the H-tree structure where all electronic lines have equal length and introduce no signal skew.

A simulation of this system has been implemented. The images are read from the disk using a CCD camera interface to a PC computer. Once an image is read, it is digitized and compared (XNOR operations) to the electronic query. The results of the XNOR operations are then summed and the Hamming distance between the query and the disk images is calculated. The results of the simulation can be seen on the figure 14 where 16x16 images were used.

4. CONCLUSIONS

In this paper, we have described a motionless-head 2-D parallel readout system for optical disks. Since the optical disk system requires no mechanical motion of the head for access, focusing or tracking, addressing is performed only through the rotation of the disk. A higher data rate than any existing optical disk system can be achieved since the entire memory can be scanned in one rotation. The data is written on the disk as 1-D CGH, and a special CGH encoding method using an iterative algorithm and a grey level representation by density modulation has been developped giving high quality reconstructions. The optical readout system is very simple and consists of only three cylindrical lenses. For easier system alignment and better optical performance, two of these lenses can be replaced by a single hybrid diffractive/refractive optical element. An opto-electronic associative memory system using the parallel readout optical disk was presented. This associative memory system consists of the parallel readout optical disk, a host computer, an optoelectronic XNOR gate array and its summation circuit (analog or digital) and a local decision circuit. The throughputs (1.2 Gbytes/sec) and retrieval times (25ms) of this associative memory system make it well suited to current and near term future needs for high performance associative recall.

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ACKNOWLEDGMENT

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	Diffraction effiency	Worst case contrast ratio	Average contrast ratio
Cell Oriented	7 %	< 1	10
Error Diffusion	5 %	2	15
FFT Grey level 4x1	5 %	5	25
Iterative Grey level 4x1	12 %	50	350

Table 1: Comparison of encoding methods for disk holograms

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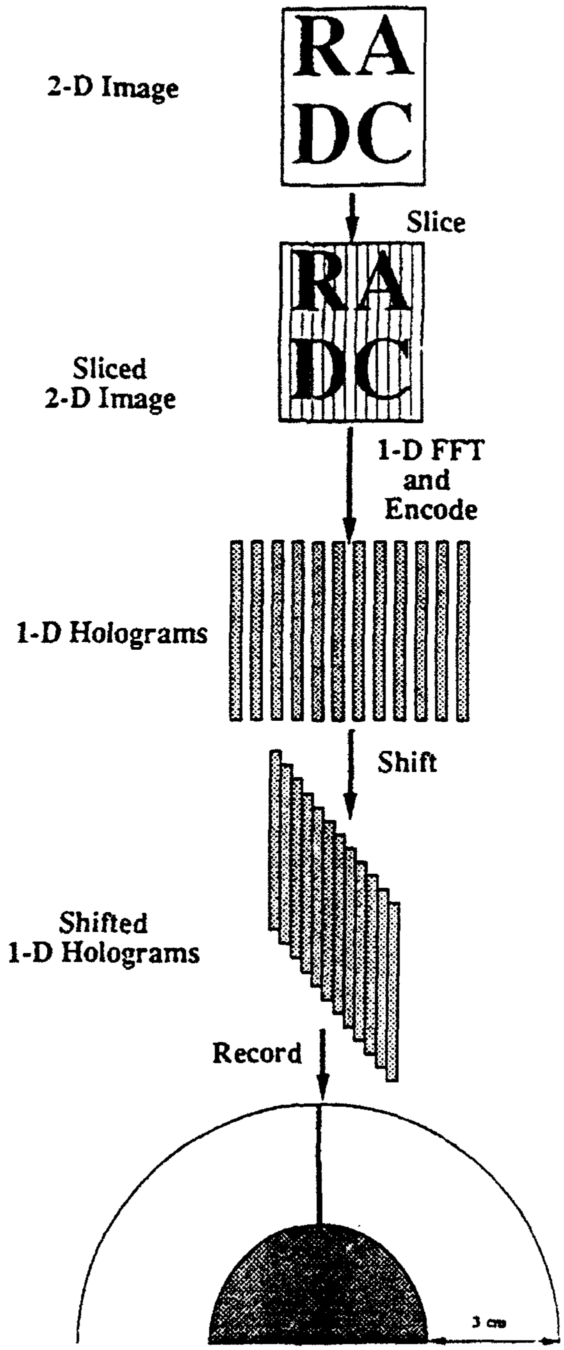

Figure 1: Disk data encoding. A 2-D image is sliced into 1-D columns. These columns are then 1-D Fourier transformed and 1-D CGH are generated. The holograms are then shifted one another and radially recorded.

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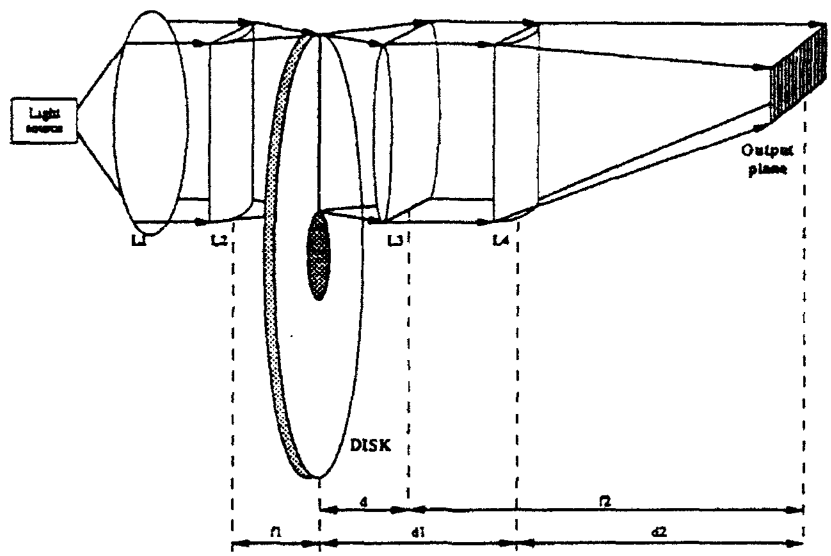

Figure 2 : Optical system. After being collimated by lens L1, the light is focused onto the disk by cylindrical lens L2. Cylindrical lens L3 performs the Fourier transform of the data along the radial direction and cylindrical lens L4 images and magnifies the data($M = d2/d1$) along the tangential direction. A binary image of 128 x 128 points is then reconstructed on the ouput plane.

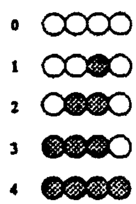

Figure 3a : hologram grey level encoding method

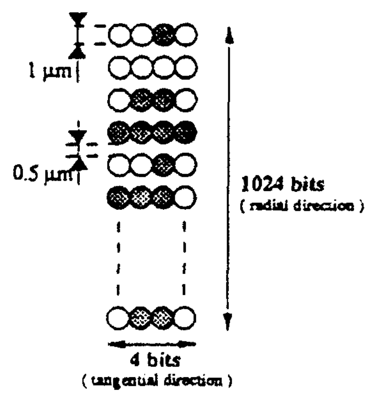

Figure 3b : one data block

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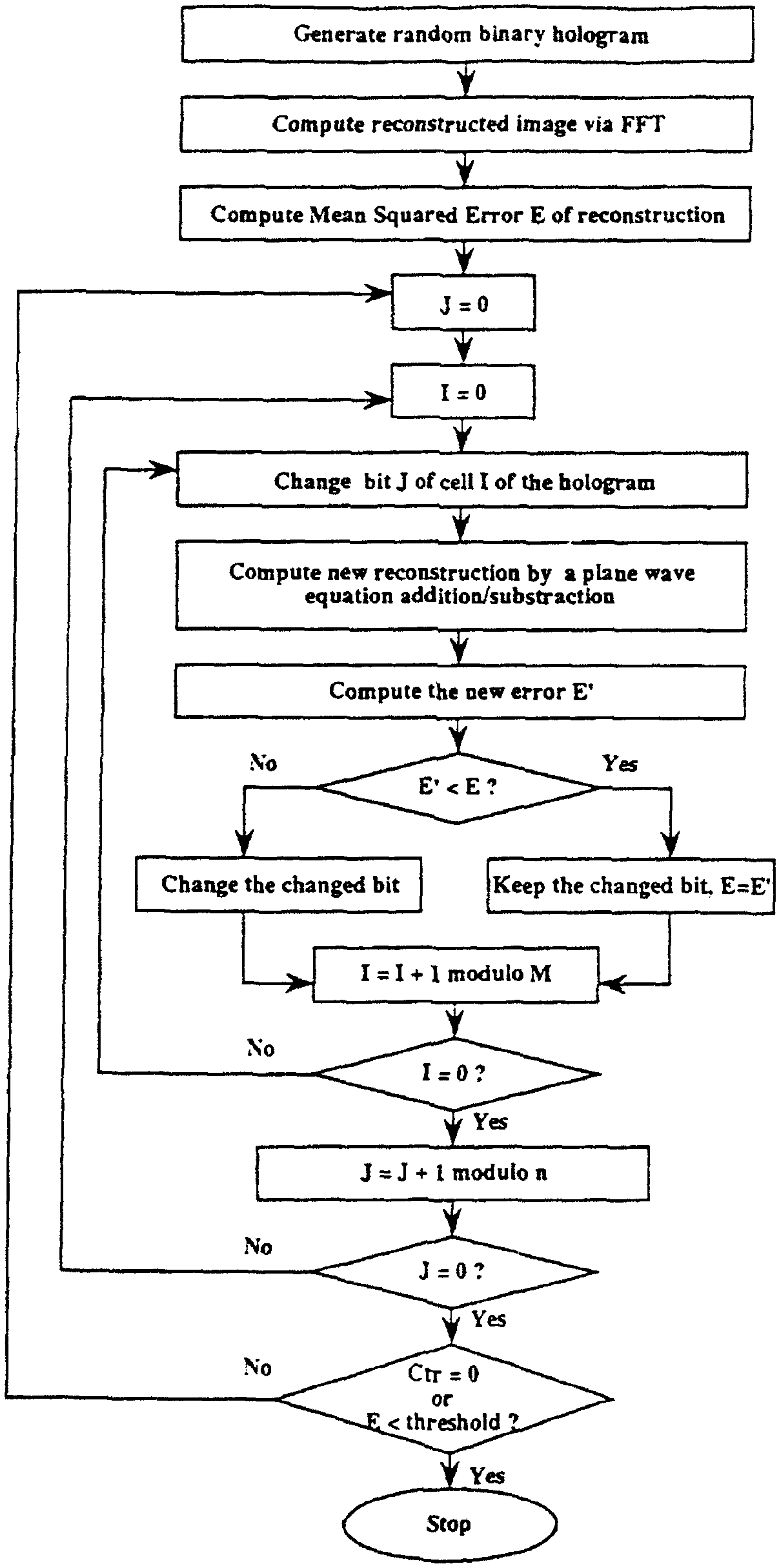

Figure 4: Iterative algorithm flowchart for grey level holograms

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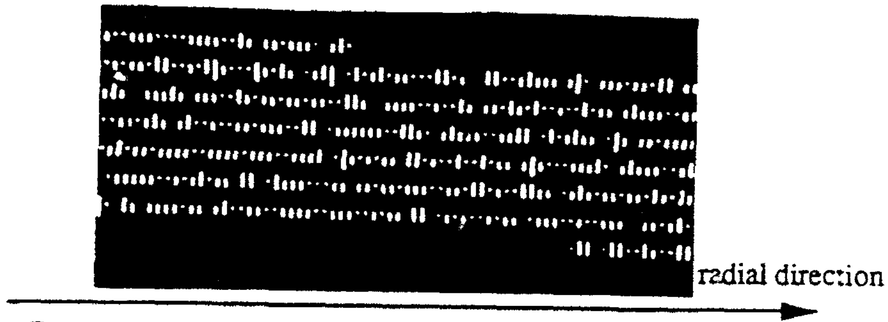
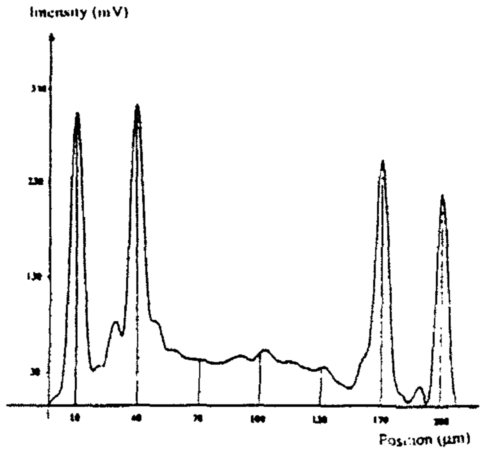


Figure 5 : Experimentally recorded holograms: The holograms are recorded on an E-beam test plate using optical disk pits feature size, i.e 1 μm bit size with 1.5 μm pitch according to the format described in figure 1 and 3.



Bit sequence to be detected 1100011 **Average SNR= 40**

Figure 6: Experimental intensity measurement of an output image

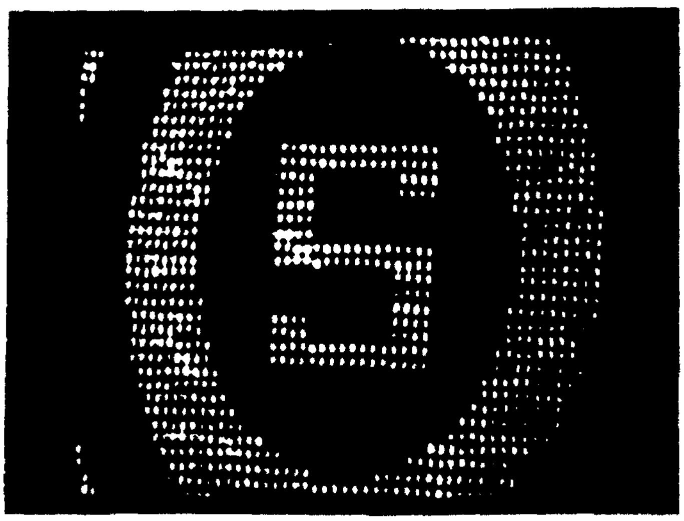


Figure 7: Disk in rotation: center portion of an 128x128 reconstructed image

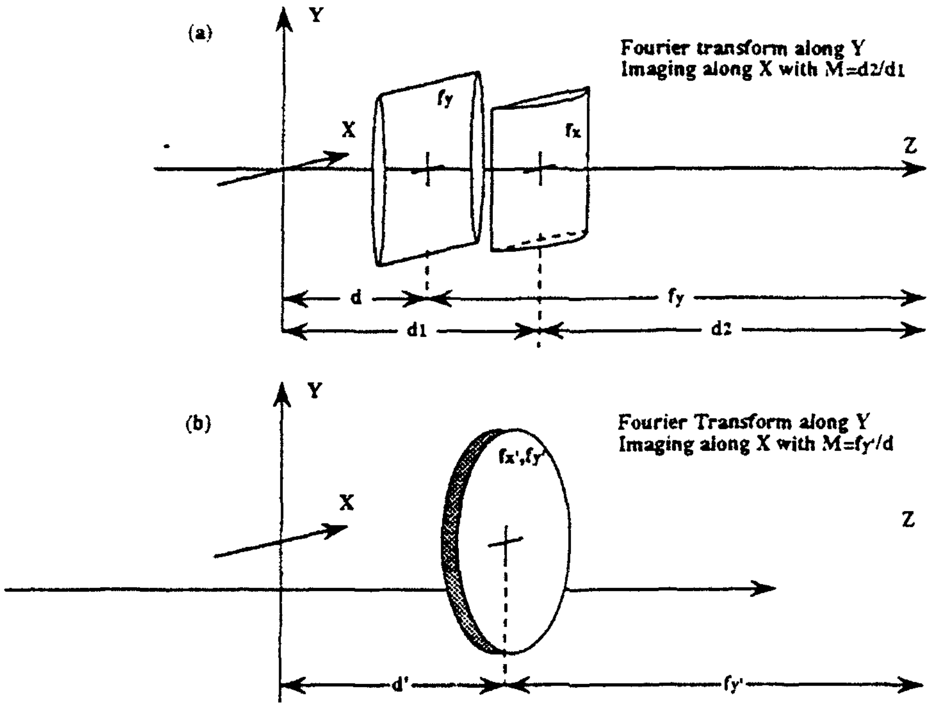


Figure 8: Replacement of the two orthogonal cylindrical lenses with one hybrid refractive/diffractive element

	2 lenses	OCDL	Hybrid lens
Error	15800	950	193
Total length	216 mm	295.4 mm	330.6 mm

Figure 9: Comparison between the three systems studied with Code V

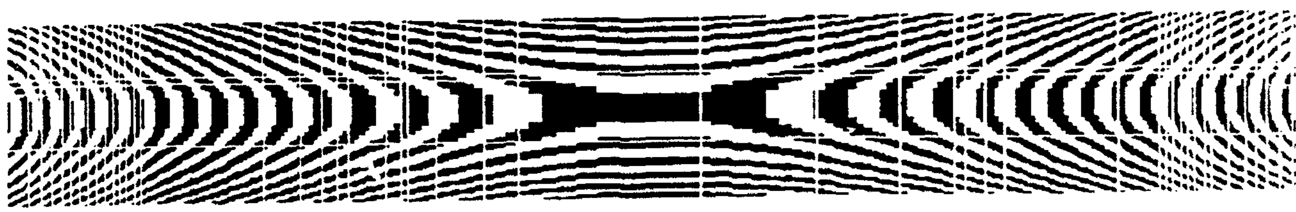


Figure 10: Hybrid lens fabrication, OCDL mask # 1 corresponding to a binary phase

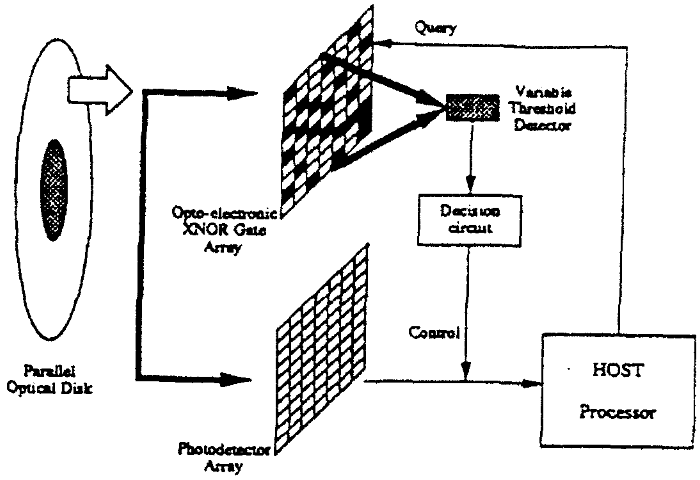
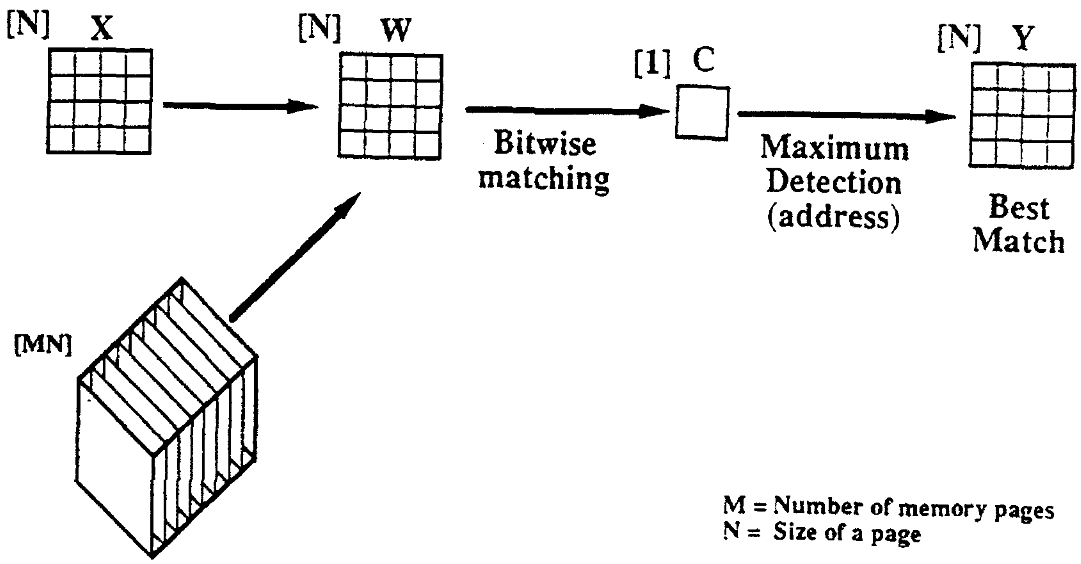


Figure 11: Associative memory design

2 modes of operation :

1. **Preset threshold :** All images that satisfy threshold are retrieved in one rotation
2. **Best match :** detect smallest hamming distance during first rotation and retrieve best matched image during 2nd rotation



M = Number of memory pages
N = Size of a page

$$c_k = \sum W_{ijk} \, x_{ij}$$

Figure 12: Serial inner-product algorithm

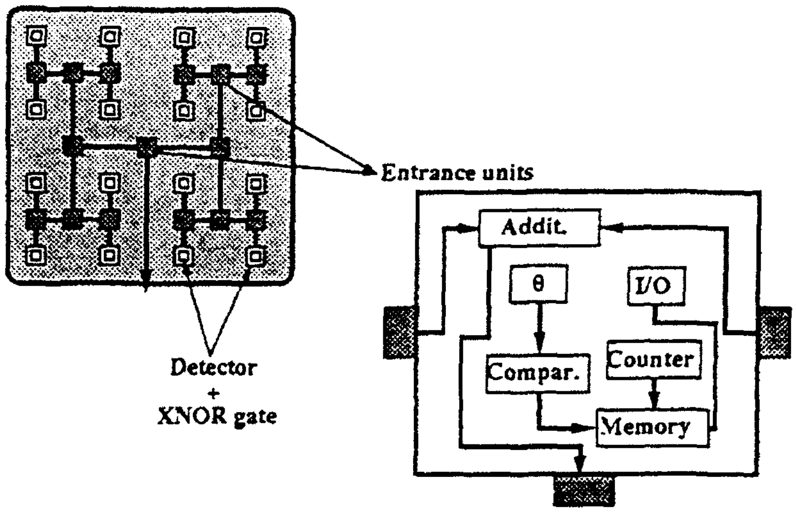


Figure 13: Schematic view of a Opto-Electronic Integrated Circuit (OEIC) based on a H-tree structure, and an entrance unit detailled view

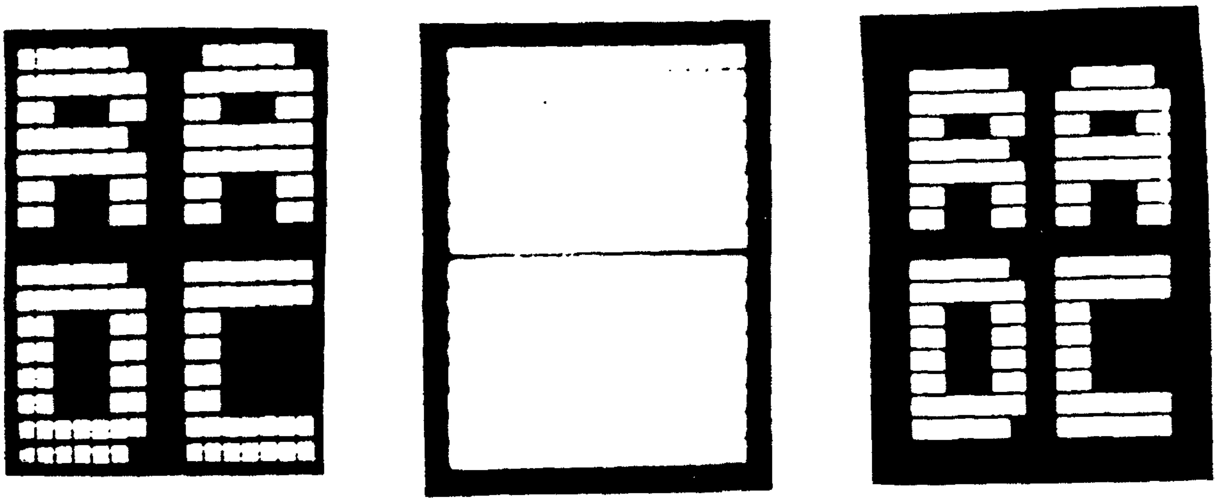


Figure 14: The query (RADC) and the output of the XNOR gate array showing a complete match with one of the image of the memory, the memory is recovered

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APPLICATION DES HOLOGRAMMES SYNTHETIQUES AU STOCKAGE SUR DISQUE OPTIQUE

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Résumé: Un système de lecture parallèle de disque optique utilisant une tête fixe est présenté. Ce système est conçu pour lire des blocs de données codées sous forme d'hologrammes de Fourier à une dimension qui sont distribués radialement sur la surface active du disque. Un tel système a plusieurs avantages: vitesse de transfert élevée, faible temps d'accès et réalisation simple.

1. INTRODUCTION

Depuis quelques années, il existe un besoin de plus en plus important pour des systèmes de bases de données alliant une grande capacité de stockage à une grande vitesse de lecture des données dans des domaines tels que la médecine, l'éducation, l'armée, l'industrie aérospatiale ... Ces systèmes de bases de données sont maintenant considérés comme une ressource indispensable par nombre de ces organisations, mais les tailles de ces systèmes augmentent de plus en plus (maintenant de l'ordre du Teraoctet) et les techniques conventionnelles de stockage et de traitement de l'information ne sont plus suffisantes pour obtenir une manipulation efficace d'une telle quantité de données. En effet les vitesses de transfert des mémoires secondaires sont faibles par rapport à la vitesse de l'unité centrale du calculateur forçant celui-ci à attendre les données. Il existe donc un goulot d'étranglement pour les applications nécessitant des accès mémoire fréquents. Ainsi, de nouveaux moyens de stockage et de nouvelles méthodes de manipulation des données plus performantes, faisant une utilisation extensive du traitement parallèle de l'information, doivent être développés [1,2].

Les mémoires à disque optique peuvent apporter une solution intéressante à ces problèmes. En effet, les systèmes de lecture de disques optiques présentent l'avantage d'une grande capacité de stockage des données (jusqu'à un Goctet pour un disque de 12 cm), un taux d'erreur faible et une importante immunité aux interférences extérieures [3]. De plus, le disque optique est maintenant une technologie de stockage de l'information en plein essor, ayant dépassé le stade de la recherche. Malheureusement, il existe des problèmes importants associés à ces systèmes: vitesse de transfert des données faible (de l'ordre d'un Moctet/sec) puisque la lecture est séquentielle et temps d'accès long (20 à 50 msec pour les systèmes les plus rapides) puisque les mouvements de la tête de lecture sont mécaniques et que la masse de ces têtes atteint plusieurs grammes. Comparativement, les performances des systèmes à disques magnétiques sont bien supérieures: plus de 10 Moctets/sec pour les vitesses de transfert et des temps d'accès inférieurs à 10 msec. Toutefois, la transmission optique des données peut s'effectuer naturellement en parallèle. Ainsi, en profitant de cet avantage de l'optique: en supprimant, les mouvements mécaniques de la tête de lecture, et en adaptant des méthodes d'encodage holographiques aux stockages des données sur disque optique, un système de lecture parallèle de disque optique avec des vitesses de transfert de l'ordre du Goctets par seconde et des temps d'accès de l'ordre de 10 msec a été conçu et réalisé. De cette façon, des pages entières du système de stockage peuvent être lues en parallèle et fournies au calculateur pour traitement.

Le système optique de lecture en parallèle de disques optiques que nous avons réalisé est tout d'abord décrit. Une description détaillée de la nouvelle méthode d'encodage développée pour cette application est ensuite présentée. Une comparaison de différentes méthodes d'encodage des données sous forme holographique pour le stockage sur disque optique est réalisée. Les résultats expérimentaux sont alors présentés suivis de la conception d'une lentille hybride dont l'intégration dans le système permet d'améliorer ses performances.

2. TETE OPTIQUE DE LECTURE PARALLELE

2.1 Présentation du système

Le système de lecture de disque optique que nous avons réalisé utilise un disque de 130 mm de diamètre (5.1/4"), dont la surface utile, c'est à dire celle où les données sont enregistrées, se situe entre un rayon interne de 30 mm et externe de 60 mm. Les pistes sont espacées radialement de 1.5 µm, ce qui donne 20000 pistes sur la surface utile du disque, et les spots ont un diamètre de 1 µm. Ils sont alors enregistrés avec une séparation angulaire constante de 0.001°. Ainsi, la capacité totale de stockage d'un tel disque est 7.5 Gbits ou 940 Moctets par face. En fait, le système de lecture parallèle est prévu pour générer des images de sortie binaires à deux dimensions.

L'approche choisie est de supprimer tous les mouvements mécaniques de la tête de lecture au-dessus de la surface du disque. Ainsi l'adressage des données sur le disque s'effectue uniquement par l'intermédiaire de la rotation du disque car les données correspondant à une image de sortie sont stockées sur une zone dont la longueur est égale à un rayon de la surface utile du disque. En illuminant une telle zone, toutes les images stockées sur le disque seront lues séquentiellement et cela, sans avoir à bouger la tête de lecture. De plus, les données sont stockées sur le disque sous forme d'hologrammes de Fourier ce qui permet de supprimer les asservissements de suivi de piste et de focalisation ainsi que les mouvements mécaniques qui y sont associés.

2.2 Format des données

La façon dont les données sont encodées et enregistrées sur le disque optique est décrite à la figure 1. Une image binaire à deux dimensions (2-D) devant être stockée sur le disque est tout d'abord décomposée en éléments à une dimension (1-D). Chacun de ces éléments 1-D correspond en fait à une colonne (ou une ligne) de l'image originale. Pour une image 2-D de taille NxN points, N colonnes 1-D de N points chacunes sont générées. Un hologramme synthétique de Fourier 1-D de chacune de ces colonnes est alors calculé, soit par une méthode classique de transformée de Fourier rapide, soit en utilisant un algorithme itératif. Les différentes méthodes d'encodage étudiées pour le calcul de ces hologrammes seront détaillées dans la section suivante. Les N hologrammes 1-D alors calculés, sont décalés radialement les un par rapport aux autres jusqu'à ce que leur longueur totale soit égale au rayon de la surface utile du disque (figure 2). Ces N hologrammes 1-D, correspondant à une image 2-D, sont alors enregistrés séquentiellement sur le disque. La capacité pratique d'un disque de 130 mm est compte tenu du codage des hologrammes d'environ 14 000 images de 128x128 points.

2.3 *Système optique*

Le système optique développé pour permettre la lecture en parallèle des images stockées sur le disque en utilisant la méthode d'encodage décrite précédemment est montré à la figure 3. Ce système utilise 4 lentilles. La première lentille L, sphérique, est utilisée pour collimater le faisceau laser et propager une onde plane vers la lentille cylindrique d'illumination L1. Celle-ci illumine une zone du disque correspondant uniquement aux hologrammes d'une seule image, c'est à dire une ligne dont la longueur est égale au rayon de la surface utile du disque. Ensuite, la lentille cylindrique L2 effectue la transformée de Fourier des hologrammes de cette image selon la direction radiale (Y) tandis que la lentille cylindrique L3 image la zone illuminée par L1 sur le plan de sortie selon la direction tangentielle (X). Tous les hologrammes d'une même image sont décalés radialement mais sont reconstruits par la même lentille de Fourier donc toutes les reconstructions seront rapportées au même axe horizontal (X). La lentille d'imagerie, quant à elle, image chacun des hologrammes l'un à côté de l'autre verticalement (Y). Ainsi, une image binaire à deux dimensions est reconstruite sur le plan de sortie.

2.4 *Encodage des hologrammes*

Afin de supprimer les asservissements de suivi de piste et de focalisation, les données sont stockées sur le disque sous forme d'hologrammes de Fourier à une dimension.

L'encodage des données sur le disque est un élément déterminant du bon fonctionnement du système de lecture parallèle décrit précédemment. En effet, selon le codage holographique utilisé, la taille des hologrammes varie, modifiant proportionnellement la capacité de stockage du disque. De plus, la qualité de l'image de sortie dépend également de la méthode d'encodage choisie. Ainsi, le premier critère de choix de la méthode est le meilleur compromis possible entre qualité de reconstruction (dynamique la plus élevée possible) et capacité de stockage du disque. D'autres contraintes viennent alors s'ajouter. Tout d'abord, étant donné que le support d'enregistrement est le disque optique, la méthode d'encodage doit générer des hologrammes binaires. Ensuite, cette méthode doit offrir une bonne qualité de reconstruction d'images qui sont elles aussi binaires. Finalement, cette méthode doit être tolérante à des erreurs d'alignement des bits lors de l'enregistrement des hologrammes. Considérant toutes ces contraintes, une méthode d'encodage 1-D à niveaux de gris a été spécifiquement développée puis comparée à des méthodes existantes, prouvant qu'elle est la plus adéquate pour cette application.

2.4.1. Encodage à niveaux de gris

Chaque colonne de l'image 2-D de taille NxN à stocker sur le disque est donc utilisée comme objet (C) de taille N dont on veut calculer l'hologramme de taille KxN. Chaque colonne est un objet binaire à une dimension. On définit alors un tableau (O) de taille M à une dimension dont tous les éléments sont nuls et on place (C) dans (O) avec un certain décalage m. Le décalage m est choisi pour que la reconstruction de l'objet (C) soit séparée de l'ordre 0 et des autres termes apparaissant lors de la reconstruction. Cet objet (O) est alors multiplié par une phase aléatoire. La transformée de Fourier rapide à une dimension de (O) est effectuée et on en extrait la partie réelle à laquelle on ajoute une constante pour en rendre toutes les valeurs positives. Cette constante est le minimum de cette partie réelle. Chaque point est alors quantifié sur n niveaux de gris, terminant le calcul de l'hologramme. Ces niveaux de gris seront alors enregistrés sur le disque par l'intermédiaire d'un codage binaire sur n-1 bits, en utilisant un algorithme de modulation de densité. L'hologramme est alors répliqué une fois afin de réduire le speckle sur l'image reconstruite. La fonction binaire $H(x,y)$ alors générée, est composée de 2M cellules de (n-1) bits avec $0 \leq y < 2M$ (direction radiale) et $0 \leq x < n-1$ (direction tangentielle). Il est alors possible de déterminer le compromis entre capacité du disque (facteur K) et dynamique des images reconstruites. Comme il sera vu plus loin, la dynamique est en effet proportionnelle à K, c'est à dire au nombre de niveaux de gris des hologrammes. La figure 4 montre comment les 5 niveaux de gris par cellule sont encodés sur 4 bits tandis que la figure 5 représente un hologramme complet utilisant ces cellules. Dans le cas de cette figure, la taille de l'objet 1-D à reconstruire est de 128 bits et l'hologramme généré a 512 cellules, soit 1024 cellules après duplication. (K = 32.)

Il est possible, afin d'améliorer les performances de ces hologrammes, d'utiliser un algorithme de calcul itératif [4,5] au lieu de les calculer par une FFT directe. L'algorithme développé pour le calcul de ces hologrammes est en fait une adaptation de l'algorithme de recherche binaire directe ("Direct Binary Search", DBS [4]) à la méthode d'encodage à niveaux de gris décrite précédemment. L'organigramme de cet algorithme est donné dans la figure 6. Un hologramme aléatoire à niveaux de gris est tout d'abord généré. La reconstruction de cet hologramme est ensuite calculée en effectuant la transformée de Fourier rapide de cet hologramme aléatoire. Une fonction d'erreur est alors calculée en comparant les intensités des bits entre l'image reconstruite et l'image originale que l'on veut reconstruire. Les bits de chaque cellule de l'hologramme sont inversés tour à tour et la nouvelle reconstruction est calculée à chaque fois. Il n'est cependant pas nécessaire d'effectuer une FFT à chaque fois puisque changer un bit de l'hologramme revient à additionner (bit changé de 0 à 1) ou soustraire (bit changé de 1 à 0) l'équation d'une onde plane à la reconstruction précédente. L'erreur entre la nouvelle reconstruction et l'image originale est alors calculée. Si cette nouvelle erreur est inférieure à la précédente, le bit changé est gardé et la nouvelle valeur de l'erreur est mémorisée, sinon le changement est ignoré. Une boucle est complétée lorsque les n niveaux de gris des M cellules de l'hologramme ont été testés. Le procédé itératif continue alors jusqu'à ce que le nombre de changements (contrôlé par Ctr) qui diminuent l'erreur soit nul pendant une boucle complète ou jusqu'à ce que l'erreur calculée soit inférieure à un seuil fixé à l'avance.

2.4.2. Comparaison des méthodes d'encodage

Afin de vérifier que la méthode d'encodage décrite précédemment est effectivement optimale pour les hologrammes 1-D à stocker sur le disque, une comparaison a été effectuée avec d'autres codages binaires holographiques. Les résultats indiqués dans la table 1 sont obtenus par reconstruction simulée par ordinateur et les critères de comparaison sont: l'efficacité de diffraction et la dynamique. L'efficacité de diffraction est définie par le rapport de l'intensité de l'image reconstruite à l'intensité totale de la reconstruction. Deux différents cas sont envisagés pour la dynamique. La dynamique moyenne est calculée en prenant le rapport de la moyenne des bits à 1 à la moyenne des bits à 0 dans l'image reconstruite. La dynamique dans le cas le plus mauvais est le rapport de l'intensité la plus faible d'un bit à 1 à l'intensité la plus élevée d'un bit à 0 dans l'image reconstruite. Les valeurs de la table sont une moyenne des résultats mesurés pour les 128 hologrammes d'une image 128x128 générée aléatoirement.

Quelque soit la méthode utilisée, les hologrammes ont une taille de 4x1024 points. Les différentes méthodes envisagées, outre les deux cas de la méthode à niveaux de gris décrite précédemment, consistent en un codage à diffusion d'erreur [6] et une version binarisée d'un codage à cellules [7] (hologramme à détour de phase) identique à celui proposé par D. Psaltis [8]. Cette méthode utilise uniquement le codage de la phase en variant la position des bits à "un" dans une cellule constituée de quatre points. La figure 7 montre les différentes cellules utilisées pour différentes valeurs de la phase de l'hologramme.

Les résultats montrent que l'algorithme itératif à niveaux de gris donne les meilleurs résultats. Pourtant, il existe un problème majeur lors de l'utilisation d'un tel algorithme: le temps de calcul nécessaire pour générer les hologrammes. Il est toutefois possible d'optimiser ce temps de calcul en utilisant une version rapide de l'algorithme itératif [5]. Si ce temps de calcul est prohibitif, la méthode d'encodage à niveaux de gris par FFT peut être modifiée pour de meilleures performances en sacrifiant la capacité du disque. En effet, la dynamique de l'image reconstruite peut être augmentée en accroissant le nombre de cellules de l'hologramme et/ou en accroissant le nombre de niveaux de gris par cellule (figure 8).

2.4.3. Tolérance d'alignement radial

Ce paragraphe est consacré à l'étude du comportement des performances des hologrammes à niveaux de gris décrits précédemment face aux problèmes d'alignement radial des bits, pouvant intervenir lors de l'enregistrement sur le disque. En effet, les valeurs données jusqu'à présent assument que ces hologrammes seront parfaitement enregistrés sur le disque. Il est effectivement possible d'enregistrer les bits sur le disque avec un alignement radial d'une précision inférieure à 0,1 µm en utilisant par exemple des enregistreurs comme celui fabriqué par Sony [8] ou par Apex [9]. Si un tel enregistreur n'est pas disponible ou si son utilisation s'avère trop coûteuse, il est quand même possible d'enregistrer les hologrammes sur le disque avec une précision moindre tout en conservant des performances identiques à celles données précédemment. Il suffit pour cela d'augmenter le nombre de niveaux de gris par cellule de l'hologramme.

La figure 9 montre comment la dynamique de l'image reconstruite réagit aux problèmes d'alignement des bits sur le disque. On a supposé dans le cas de cette étude que la précision d'alignement radial était d'un micron, c'est à dire un bit sur le disque. Le nombre de bits désalignés est alors indiqué sur l'axe des abscisses par un pourcentage. Ce poucentage indique combien de cellules de l'hologramme ont des bits désalignés, ce qui revient à un décalage vers la droite ou vers la gauche (décidé aléatoirement) des bits de cette cellule. Le nouveau bit contenu dans l'emplacement théorique de la cellule étant également déterminé aléatoirement. Sur ces graphes, 0% correspond au cas d'un alignement parfait et 100% correspond au cas où toutes les cellules sont décalées aléatoirement d'un bit vers la droite ou vers la gauche. On peut voir sur ces courbes que la dynamique baisse lorsque le bruit augmente. Toutefois, un résultat intéressant est que la dynamique moyenne de l'image lorsque les hologrammes sont calculés avec 5 niveaux de gris avec 0% de bits désalignés est identique à la dynamique pour des hologrammes avec 8 niveaux de gris à 100%. Ainsi, en sacrifiant la capacité du disque, il est toujours possible d'envisager l'enregistrement du disque sur un enregistreur de disques optiques n'ayant pas des capacités d'alignement de précision.

2.5 Résultats expérimentaux

Pour prouver la validité et tester les performances de ce système optique, plusieurs séries d'expériences statiques et dynamiques ont été menées en utilisant des plaques holographiques fabriquées avec l'enregistreur à faisceau d'électrons ("Electron Beam Recorder", EBR) pour simuler le plan du disque dans le système de lecture. Le montage expérimental du système de lecture utilisé a été décrit à la figure 3. Les caractéristiques des lentilles utilisées sont les suivantes:

L1: f1 = 100 mm; ouverture : 50 x 60 mm; f/# = 2; lentille d'illumination

L2: f2 = 200 mm; ouverture : 60 x 50 mm; f/# = 4; lentille de Fourier

L3: f3 = 25,4 mm; ouverture : 22 x 60 mm; f/# = 1,15; lentille d'imagerie

Les hologrammes sont enregistrés sur une plaque de verre recouverte d'une résine photo-sensible pour l'enregistrement par EBR. Ils sont calculés en utilisant le programme spécialement développé à cet effet qui permet la génération automatique de tous les hologrammes 1-D à niveaux de gris d'une image 2-D donnée. Ces hologrammes binaires, une fois calculés, sont traités par le programme de CAD holographique développé à UCSD qui génère les fichiers de données pour l'enregistrement avec l'EBR [10]. Les caractéristiques des plaques sont relativement proches de celles d'un disque optique puisque leur épaisseur totale est 1,2 mm avec un film sensible de 350 nm. La taille des ouvertures est de 1 µm avec une séparation verticale (radiale) de 1,5 µm (figure 10). Les hologrammes ont été écrit avec un format spécial sur l'EBR afin de pouvoir simuler le disque. Toutes les mesures sont alors effectuées pour des tailles d'images 2-D de 128x128 points. Dans ce cas, les hologrammes ont une taille de 4x1024 points ce qui correspond à une ouverture de 4x1536 µm. La plaque réalisée à l'EBR a été percée en son milieu et placée sur une table de rotation, des essais statiques et dynamiques ont été réalisés.

L'image de sortie a été analysée avec un photodétecteur. Les courbes de dynamique relevées expérimentalement sont données à la figure 11. La dynamique moyenne, correspondant à une mesure de l'énergie dans chacun des bits observés, est de 40. Cette valeur de la dynamique correspond à l'énergie apportée à un détecteur de la matrice qui sera utilisée dans la mise en œuvre d'un système complet.

L'observation de la plaque holographique en rotation permet de vérifier plusieurs points théoriques. Tout d'abord, même après plusieurs rotations complètes de la plaque, il apparaît que les reconstructions s'effectuent toujours au même endroit et que la légère inclinaison ou les oscillations verticales de la plaque en rotation n'affectent pas les reconstructions. De plus, après avoir légèrement déplacé la plaque et son support le long de la direction radiale, les images 1-D et 2-D sont reconstruites au même endroit avec les mêmes intensités. Ceci prouve qu'il n'y a effectivement pas besoin ni d'asservissement de suivi de piste ni d'asservissement de focalisation dans ce système. Enfin, il apparaît également qu'il est nécessaire de synchroniser soit le laser, soit les détecteurs du plan de sortie avec la rotation du disque pour éviter le régime transitoire correspondant au moment où deux images successives du disque sont partiellement illuminées en même temps. La figure 12 montre la partie centrale de la reconstruction d'une image de 128 par 128 points lue sur le disque en rotation.

2.6 Conception d'une lentille hybride

Le système de lecture parallèle de disque optique comprend deux lentilles cylindriques séparées, ayant des distances focales différentes: l'une pour imager dans la direction X et l'autre pour la transformée de Fourier dans la direction Y. Ces lentilles cylindriques sont très difficiles à aligner et ont des aberrations importantes. Le logiciel de conception de systèmes optiques Code V a été utilisé pour concevoir un élément optique holographique unique (EOH) pour remplacer la fonction des deux lentilles et corriger les aberrations (figure 13). Comme les distances focales sont différentes dans les directions X et Y, il est avantageux d'utiliser une lentille diffractive cylindrique orthogonale (OCDL)[11]. Deux approches ont été étudiées. La première est un EOH unique avec deux distances focales positives différentes. La seconde est un élément hybride réfractif/diffractif qui associe un EOH avec une lentille plan convexe sphérique. Dans ce cas l'une des distances focales est positive tandis que l'autre est négative. La figure 14 montre les performances respectives de chacun des systèmes. La fonction d'erreur est calculée avec Code V, elle correspond à la distance de tous les rayons au rayon principal dans le plan de sortie. Les résultats montrent que la lentille hybride est la meilleure solution tant pour les performances optiques que les contraintes de fabrication. En effet cette combinaison permet d'augmenter le f/# du OCDL, ce qui diminue la résolution nécessaire lors de la fabrication. Ainsi un OCDL plus grand avec plus de niveaux de phase et une meilleure efficacité de diffraction peut être construit . La figure 15 montre l'un des masques utilisés pour la réalisation de cette lentille hybride.

3. CONCLUSION

Nous avons présenté un système original de lecture parallèle de disque optique avec une tête fixe. Aucun mouvement de la tête n'est nécessaire pour la focalisation et le suivi de piste. Les données sont écrites sont forme d'hologrammes de Fourier à une dimension et sont disposées le long de rayons du disque. De ce fait l'addressage se fait par la rotation du disque. Une nouvelle méthode d'encodage holographique a été développée. Ce système permet des temps d'accès de 12,5 ms, un temps de recouvrement des données de 25 ms et une vitesse de transfert des données de 1,2 Goctets/seconde. Vu ses performances, ce système peut avoir de nombreuses applications. En particulier, il est utilisé comme unité de stockage dans un système de mémoire associative opto-électronique actuellement en cours de développement[12,13].

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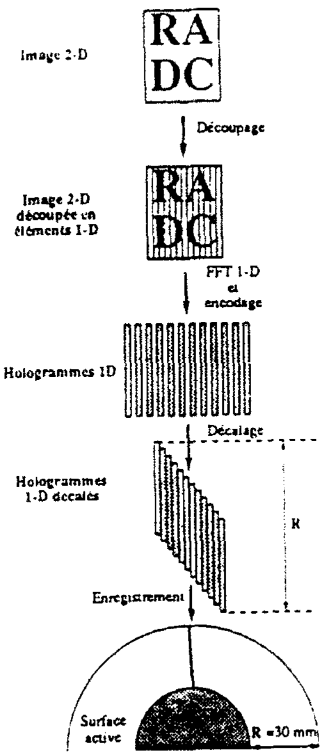


Figure 1: Encodage et enregistrement des données sur le disque optique

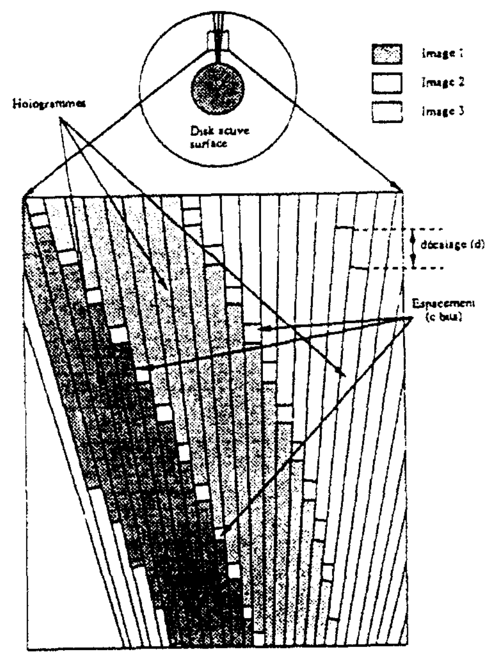


Figure 2: Optimisation de l'organisation des données sur le disque

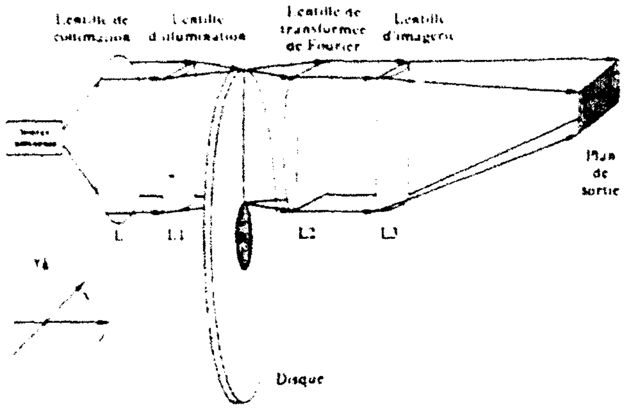


Figure 3 Systeme optique de lecture parallèle de disque optique

	Diffraction efficiency	Worst case contrast ratio	Average contrast ratio
Cell Oriented	7 %	< 1	10
Error Diffusion	3 %	2	13
FFT Gray level 4x1	3 %	3	25
Iterative Gray level 4x1	12 %	50	350

Figure 7 a: Comparaison de methodes d'encodage holographiques pour le disque optique

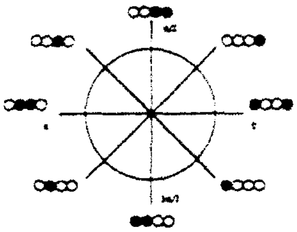


Figure 7 b: Version binaire d'un codage à détour de phase

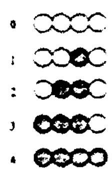


Figure 4: Encodage à niveaux de gris, 5 niveaux encodés sur 4 bits

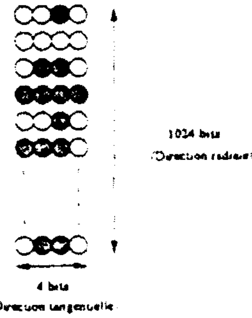


Figure 5: Un hologramme

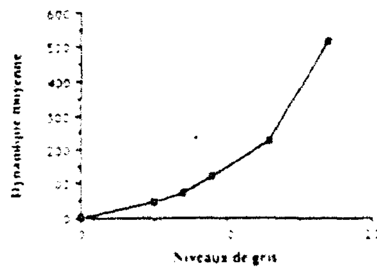


Figure 8: Influence du nombre de niveaux de gris sur la dynamique moyenne de la recontruction

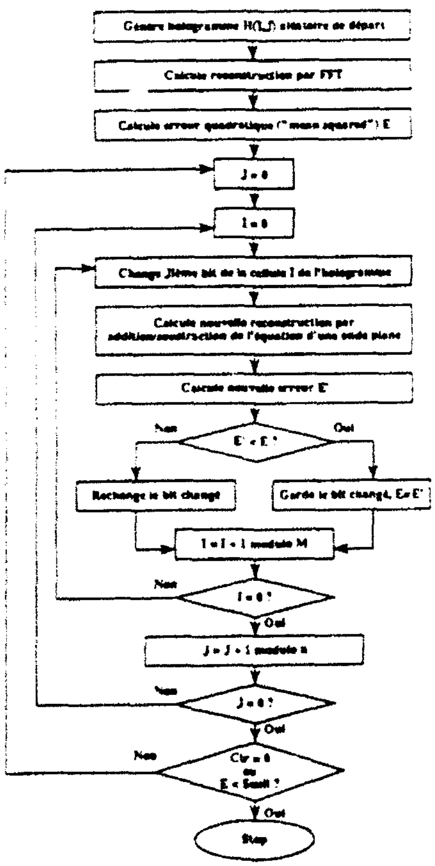


Figure 6: Organigramme du calcul itératif des hologrammes à niveaux de gris

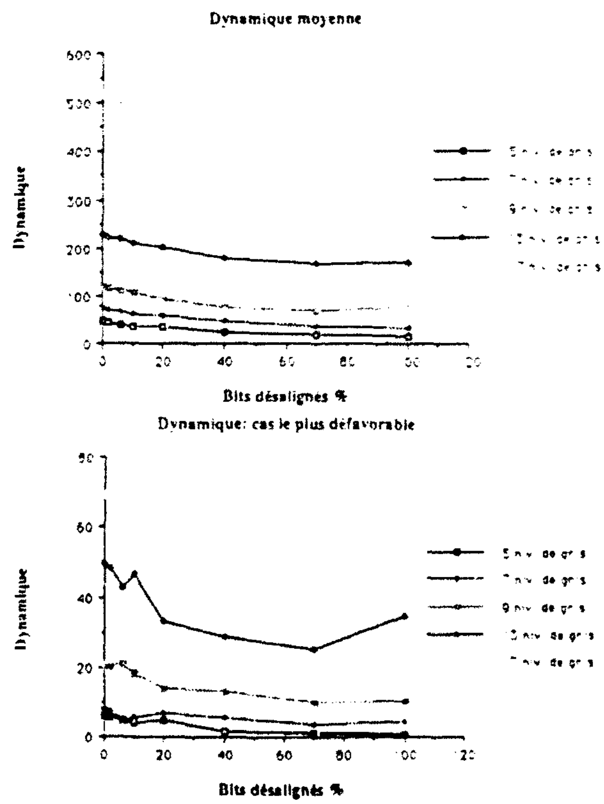


Figure 9: Influence de l'alignement des bits sur la dynamique de l'image reconstruite

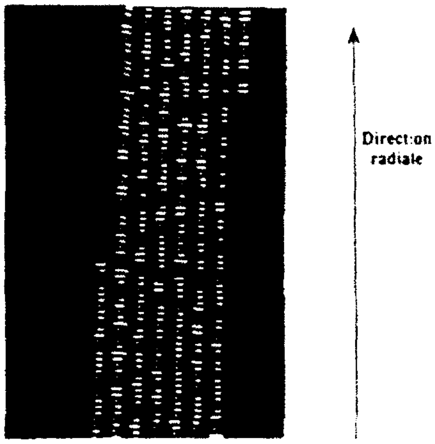
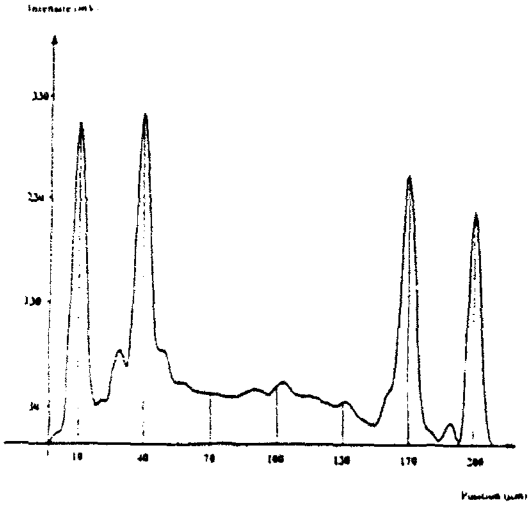


Figure 10: Hologrammes d'une image enregistrés sur une plaque de test



La sequence de bits à detecter est 1100011

La dynamique moyenne est approximativement 40

Figure 11: Relevé expénmental de la dynamique d'une image de sortie

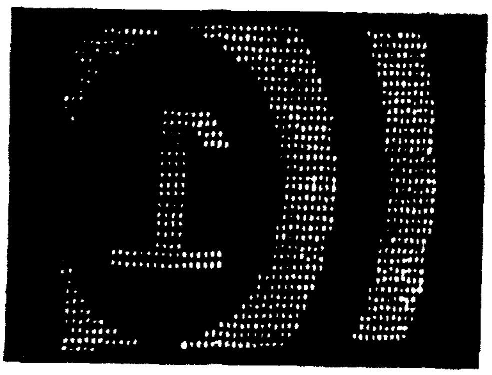


Figure 12: Photographie de la reconstruction obtenue avec la plaque en rotation, montrant le centre d'une image 128x128 points

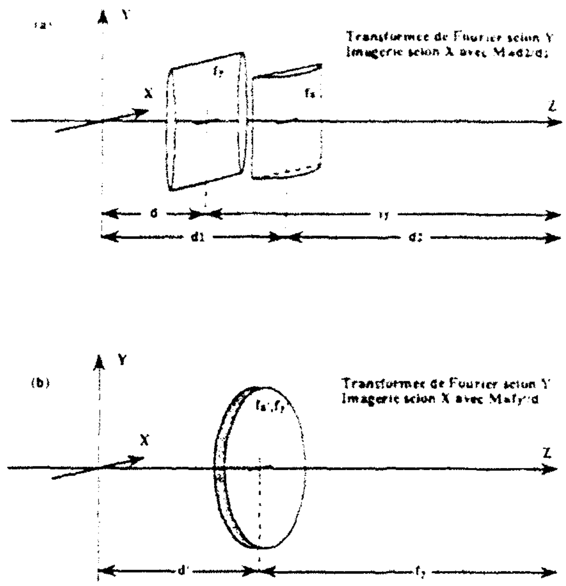


Figure 13: Remplacement de deux lentilles cylindriques orthogonales par un seul élément hybride réfractif/diffractif

	2 lentilles	OCDL	Lentille hybride
Erreur	15800	950	193
Longueur totale	216 mm	295.4 mm	330.6 mm

Comparaison des trois systèmes étudiés avec Code V

	OCDL seule	Lentille hybride
Erreur	950	193
Focale de l'OCDL en X	41.1 mm	57.7 mm
Focale de l'OCDL en Y	250 mm	-946 mm
f/# en X	3.16	4.1
f/# en Y	5.0	18.9
focale de la lent. sph.	N/A	201.7
Epaisseur de la lent. sph.	N/A	26

Figure 14: Comparaison des caractéristiques de l'élement diffractif dans le système à OCDL et dans la lentille hybride

Figure 15: L'un des masques de l'OCDL pour la fabrication de la lentille hybride. Le masque complet est le masque numéro un de l'OCDL correspondant à la phase binaire.

MISSION

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