Shared-hardware alternating operation of a super-parallel holographic optical correlator and a super-parallel holographic random access memory

M. S. Shahriar
Renu Tripathi, MEMBER SPIE
Northwestern University
Department of Electrical and Computer Engineering
Evanston, Illinois 60208

Mohammad Huq
Digital Optics Technologies, Incorporated
Somerville, Massachusetts 02144

John T. Shen, MEMBER SPIE
Northwestern University
Department of Electrical and Computer Engineering
Evanston, Illinois 60208

Abstract. For practical pattern recognition and tracking systems, it is often useful to have a high-speed random access memory (RAM) that complements a holographic correlator. Recently, we have demonstrated a super-parallel holographic correlator, which uniquely identifies N images from a database using only $O(\sqrt{N})$ number of detector elements. We show how this correlator architecture, operated in reverse, may be used to realize a super-parallel holographic random access memory. We present preliminary results, establishing the feasibility of the superparallel holographic random access memory, and show that essentially the same set of hardware can be operated either as the super-parallel holographic optical correlator or as a super-parallel holographic random access memory, with minor reorientation of some of the elements in real time. This hybrid device thus eliminates the need for a separate random access memory for a holographic correlator-based target recognition and tracking system.
[DOI: 10.1117/1.1767193]

Subject terms: pattern recognition; correlator; random access memory; holography; target tracking.

Paper TPR-009 received Aug. 29, 2003; revised manuscript received Feb. 11, 2004; accepted for publication Mar. 15, 2004.

1 Introduction

Rapid target identification and tracking is essential[1–3] in many military as well as civilian applications. Holographic correlation-based techniques[4–8] play an important part in object recognition. Current image correlation techniques rely on digital signal processing (DSP) elements, which are often too slow for target intercept applications because the data is compared serially. A holographic optical correlator (HOC)[9,10] offers parallel database searches much faster than DSP, but its potential is limited by architectural constraints.

Recently, we demonstrated a super-parallel holographic correlator (SPHOC),[11] which uniquely identifies N images from a database using only $O(\sqrt{N})$ number of detector elements. Briefly, in this system, the spatial location and the reference beam angle for the matched image are identified by using a spatio-angular decoupling architecture, consisting of a combination of a lenslet array, a holographic redirector, a demultiplexer, and two charge-coupled device (CCD) arrays.

We show how this super-correlator architecture, operated in reverse, can be used to realize a super-parallel holographic RAM (SPHRAM). We present preliminary results establishing the feasibility of the SPHRAM. We show that essentially the same set of hardware can be operated either as the super-parallel holographic optical correlator (SPHOC) or the SPHRAM, with minor reorientation of some of the elements in real time. This device thus eliminates the need for a separate RAM for a holographic correlator-based target recognition system.[12]

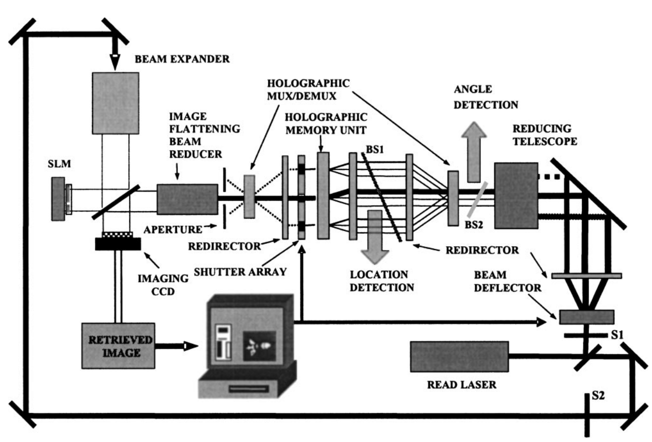

Fig. 1 Schematic illustration of an architecture that can be used as either an SPHOC or as an SPHRAM using potentially the same database. During the operation as an SPHOC, S1 is closed, and S2 is open. All the elements of the shutter array are open. During the operation as an SPHRAM, S1 is open and S2 is closed. An element of the shutter array is opened selectively, according to the address of the data page to be retrieved.

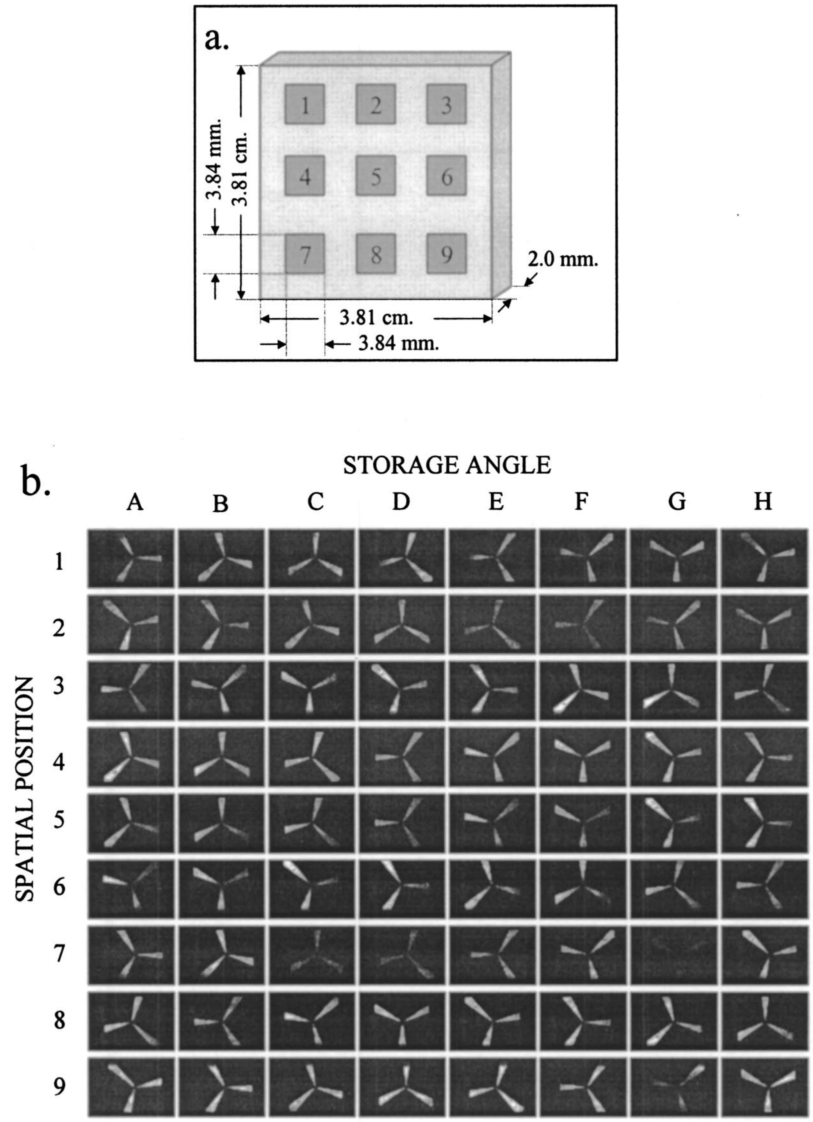

Fig. 2 Images stored in a holographic memory unit (HMU): (a) the layout of the HMU and the spatial location of each memory cell; and (b) holographic images that were read from the HMU where each row of images is stored in a single memory cell.

2 Principle

The architecture of this hybrid device is shown in Fig. 1. Its individual operations as SPHOC and SPHRAM are described next.

2.1 *Super-Parallel Holographic Optical Correlator*

The starting point for target recognition is the super-parallel holographic optical correlator (SPHOC). With shutter S2 open and S1 closed, the architecture works as an SPHOC. $r \times s$ number of images are stored in $n \times m$ locations (where r- and s are the number of horizontal and vertical angle-multiplexed holograms, n is the number of columns, and m is the number of rows) of the holographic memory unit (HMU) via 2-D angular multiplexing. To make the high capacity and high efficiency HMU, we used a photopolymer-based thick holographic material called Memplex®, developed by Laser Photonics Tehnology (Amherst, New York).[13] This material can have a very high M/# (>20), and at room temperature, holograms written in this material may survive many years without noticeable degradation.[14,15]

The process starts by expanding the collimated beam from the laser to match the size of the SLM. The target image is gathered by some image capturing device, such as a CCD camera or a synthetic aperture radar. Note that the CCD camera shown in the figure is not used for this purpose; the role of this camera is described shortly. A copy of the image is sent to the control computer for recording, and another copy is sent directly to the SLM via a high-speed data bus (not shown). The beam reflected from the SLM contains this image information, which is then passed through the image flattening beam reducer (IFBR), which is a combination of two lenses. It reduces the image size by the ratio of the focal lengths of the two lenses, and projects a slowly diverging version of the SLM image to the holographic multiplexer/demultiplexer (HMDX). The HMDX is

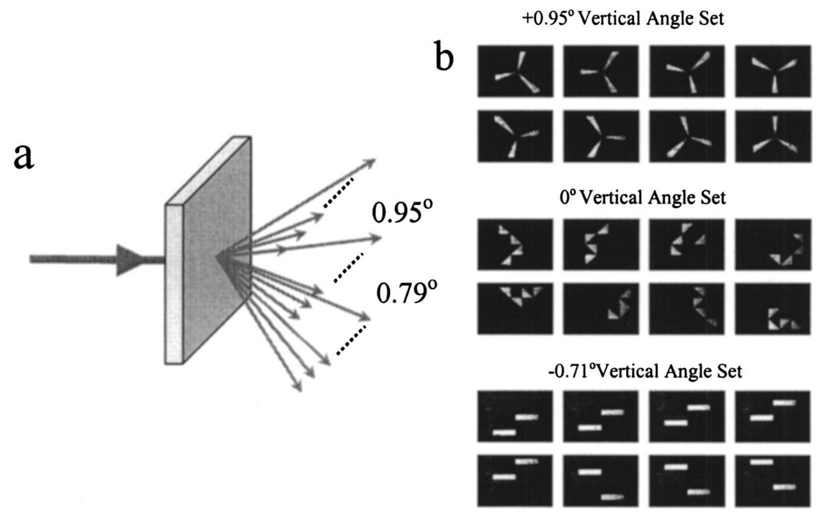

Fig. 3 24 images stored in a single location through angle multiplexing. (a) The schematic of the storage of 24 images in a single location. Eight images are written using the same vertical angle and a set of eight horizontal angles. The vertical angle is then changed gradually to write another set of eight images. A total of 3×8 images were written into a single location. (b) The 24 unique images stored.

a device that produces $r \times s$ copies of the input image, in as many angular directions. Such a device can be constructed by writing $r \times s$ plain wave holograms at each location, over the entire volume.

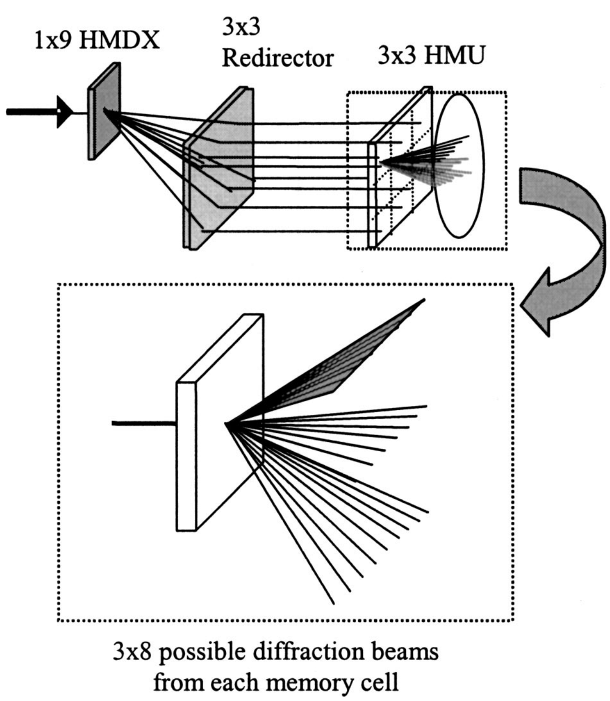

Fig. 4 Schematic illustration of the configuration used for the demonstration of the SPHOC. The input query image is split into 3×3 copies, using the 1×9 HMDX. These images are then redirected by the HR, which contains nine gratings at nine spatial locations. The redirected images are then applied to the HMU, which contains nine corresponding spatial locations. During the query process, simultaneous correlation is performed over 9×3×8 images at nine separate locations.

Output beams from the HMDX are passed through an element termed the holographic redirector (HR). The role of this device is to redirect the output beam from the HMDX into $r \times s$ images propagating parallel to the axis. The $r \times s$ identical copies of flattened images now impinge on the HMU, one at each spatial location. If the image matches a stored image in one of these locations, a diffracted beam (i.e., the correlation beam) will emanate from that location at an angle corresponding to the matched image. The rest of the architecture identifies the spatial position and angular location of the matched image. The output of the HMU is sent through the lenslet array (LLA), which collimates all the beams parallel to the axis. Such a lens array can be made by writing holograms where the object beam is a plane wave, and the reference beam is a converging wave, at each of the $n \times m$ separate spatial locations. Alternatively, one can use a commercial lenslet array for this purpose. The beams are now split into two components by a beamsplitter. One component goes through another LLA and gets focused onto an $n \times m$ array of CCD elements (CCDA). Identifying the detector that sees the highest signal intensity reveals the identity of the spatial location of the matching image. The other part of the beam goes through another HR, redirecting all the beams to a central point. These beams are passed through another HMDX, operating in reverse. A simple aperture can be used to eliminate unwanted spots. A beam expander is used after the filter, to match the size of the second CCD array, which contains $n \times m$ number of elements, corresponding to the number of angles used in the 2-D angular multiplexing during the writing stage. The element of the CCD that sees the brightest signal yields the information about the angle of the matched image. Data gathered from the detector and CCD arrays can be sent through a digital logic circuit to yield the absolute identity of the matched image.

We presented the results for an elementary demonstration of the key components of a 2-D SPHOC in Ref. 11. To increase the dimensionality of the system, it is necessary to record an HMU with multiplexing in increased spatial and angular dimensions. For example, we can have a dataset with nine spatial locations in the HMU, arranged in a 3×3 fashion in two dimensions, as shown schematically in Fig. 2. Figure 2(a) describes the layout of the HMU, and the spatial location of each memory cell. Figure 2(b) shows holographic images that are read from the HMU, where each row of images is stored in a single memory cell. This generates a 3-D HMU. This concept can be further extended to all four dimensions. Figure 3 shows one such example of the 2-D spatial and 2-D angular multiplexing in each of the nine HMU locations. Figure 3(a) illustrates schematically the storage of 24 images in a single location. Eight images are written using the same vertical angle and a set of eight horizontal angles. The vertical angle is then varied by 1 deg to write the next set of eight images. In this way a total of 3×8 images were written into a single location. Figure 3(b) shows recalled versions of the 24 unique images stored.

For correlation, the input query image is split into 3×3 copies, using a 1×9 HMDX, as shown in Fig. 4. These copies of the image are then redirected by the HR, which consists of nine individual gratings in nine spatial locations. The redirected images impinge on the HMU at the nine spatial locations. Each of these locations contains three sets of eight images multiplexed angularly in the vertical plane, with the eight images in each set multiplexed angularly in the horizontal plane. Thus, correlation needs to be performed over 9×3×8 images.

Figure 5 illustrates the performance of the whole architecture of Fig. 4, as a demonstration of simultaneous correlation with the images at each of the nine locations of the HMU. Each memory cell was individually aligned to a query beam coming out of the HMDX and then guided by the HR, as shown in Fig. 4. During the query process, the test image was projected onto a memory cell, producing only one correlation spot in each location. Next, a different test image is used, resulting in a diffraction beam in a different direction. In Fig. 5, each of the 24 blocks corresponds to the CCD signal observed at one of the HMU locations for a given input image. There are total of 24 blocks, corresponding to the 24 distinct images stored in each location. Thus, the eight blocks in the left column show correlations from the first row of images. The second block of eight shows the correlations from the second row of images, and the third block of eight shows the correlations from the third row of images.

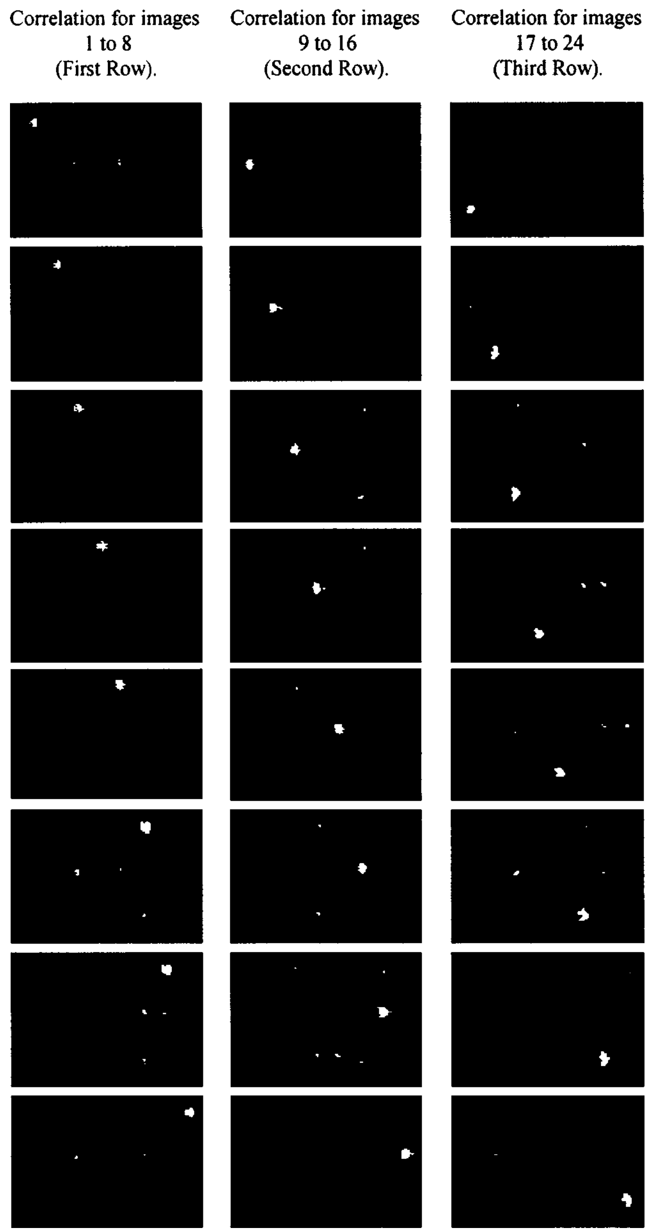

Fig. 5 Correlation result for 24 images stored in one location of the HMU. All 24 stored images were simultaneously queried using one corresponding test image from the stored images. Each image displays all 24 diffraction intensity peaks simultaneously, with one strong match.

2.2 *Super-Parallel Holographic Random Access Memory*

The principle of operation of super-parallel holographic random access memory (SPHRAM) is similar to that of an SPHOC operated in reverse. During the SPHRAM operation, S1 is open and S2 is closed. The holographic memory unit (HMU) is recorded with the database of interest, using multiple spatial locations, each of which contains a set of images that are angularly multiplexed in two dimensions. When operating the RAM, the user enters the coordinates corresponding to the spatial position and the angle of storage for the image of interest. The position coordinate is used to open the corresponding element of a shutter array. The number of elements in the shutter array is the same as the number of spatial locations in the HMU, and the locations are matched. Shutter arrays of this type are available commercially, using individually addressable ferroelectric liquid crystals or MEMS-based microdeflectors that can have fast switching times. Alternatively, one can use a two-photon memory, such as bacteriorhodopsin, as a shutter, in which only the location of interest is illuminated by the activation laser frequency.

The angular coordinate for the image is sent to a beam deflector (e.g., a pair of acousto-optic deflectors), which orients the read beam at the desired angle, which in turn is translated to a specific position by the redirector. A combination of the reducing telescope, holographic multiplexer,

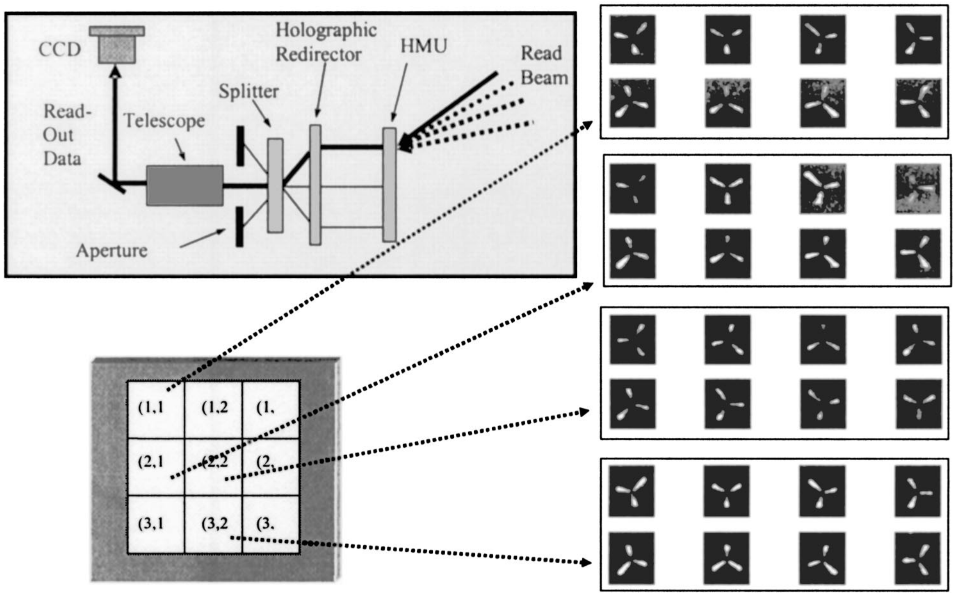

Fig. 6 Data page retrieval using a simplified SPHRAM architecture.

redirector, and the lenslet array produces a copy of the read beam simultaneously at each of the locations[11] on the HMU. The image stored at this angle would be recalled from each spatial location. The shutter array would block all but one of these images, and the redirector and the demultiplexer would send the desired image on to the CCD camera.

To demonstrate the feasibility of an SPHRAM, we used a simplified geometry, as shown in Fig. 6. A pair of galvomounted mirrors was used for deflection. The database comprised of an HMU with images multiplexed at nine locations in a 3×3 arrangement. Each location contained eight images multiplexed in one angular dimension. A holographic redirector and a multiplexer are used in the setup for producing the read beam. The bottom of Fig. 6 shows a typical set of eight image data retrieved from the spatial location (3,2) using this setup. Similar data were also retrieved from other locations.

To avail oneself of the potential advantage of the SPHOC/SPHRAM, it is necessary to have an HMU that can store in many spatial locations, with a large number of images at each location, each image having a high bit density. For example, if the SPHRAM is implemented with the HMU written in a 15-cm$\times$15-cm$\times$5-mm PDA material with 1600 cells, each containing 8000 images, and represented by 1024×1024 bits, the system is potentially capable of searching through approximately one terabyte of storage data. Of course, much work remains to be done before such a capacity is demonstrated.

3 Conclusion

We show how the super-parallel holographic correlator (SPHOC) architecture, operated in reverse, can be used to realize a super-parallel holographic random access memory (SPHRAM). We present preliminary results demonstrating the feasibility of the SPHRAM and show that essentially the same set of hardware can be operated either as the SPHOC or the SPHRAM, with a minor reorientation of some of the elements, in real time. This hybrid device may eliminate the need for a separate RAM for a holographic correlator-based target recognition and tracking system.

Acknowledgments

This research was supported in part by Air Force Office of Scientific Research grant number FA49620-03-1-0408, and Missile Defense Agency grant number DTRA01-02-P-0211.

References

1. R. O. Duda, P. E. Hart, and D. E. Stork, *Pattern Classification*, Wiley-Interscience, New York (2000).
2. S. Theodoridis and K. Koutroumbas, *Pattern Recognition*, 2nd ed., Academic Press, New York (2003).
3. W. W. Goj, *Synthetic-Aperture Radar and Electronic Warfare*, Artech House, Norwood, MA (1993).
4. J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, New York (1996).
5. A. Vanderlugt, *Optical Signal Processing*, Wiley-Interscience, New York (1992).
6. N. Collings, *Optical Pattern Recognition Using Holographic Techniques*, Pearson Addison Wesley, Reading, MA (1988).
7. *Selected Papers on Optical Pattern Recognition Using Joint Transform Correlation*, M. S. Alam, Ed., SPIE Milestone Series MS157/HC, SPIE Press, Bellingham, WA (1999).
8. *Selected Papers on Optical Pattern Recognition*, F. T. S. Yu, Ed., SPIE Milestone Series MS156/HC, SPIE Press, Bellingham, WA (1999).
9. M. J. Murdocca and B. Sugla, ''Design of an optical random access memory,'' *Appl. Opt.* **28**(1), 182 (1989).
10. P. M. Birch, F. Claret-Tournier, D. Budgett, R. Young, and C. Chatwin, ''Optical and electronic design of a hybrid digital-optical correlator system,'' *Opt. Eng.* **41**(1), 32–40 (2002).
11. A. J. B. Hassaun, ''Holographic correlation improves on DSP by six orders of magnitude,'' *Laser Focus World* **38**(7) 44 (2002).
12. M. S. Shahriar, R. Tripathi, M. Kleinschmit, J. Donoghue, W. Weathers, M. Huq, and J. T. Shen, ''Superparallel holographic correlator for ultrafast database searches,'' *Opt. Lett.* **28**(7), 525–527 (2003).
13. R. Burzynski, D. N. Kumar, S. Ghosal, and D. R. Tyczka, ''Holographic recording material,'' U.S. Patent No. 6,344,297 (2002).
14. H. N. Yum, P. R. Hemmer, R. Tripathi, J. T. Shen, and M. S. Shahriar, ''Demonstration of a simple technique for determining the M/# of a holographic substrate using a single exposure,'' Opt. Lett. (in press).
15. M. S. Shahriar, J. Riccobono, M. Kleinschmit, and J. Shen, ''Coherent and incoherent beam combination using thick holographic substrates,'' *Opt. Commun.* **220**, 75–83 (2003).

M. S. Shahriar is an associate professor of electrical engineering at Northwestern University. He is also a visiting scientist at the Massachusetts Institute of Technology. He received his BS (physics), BS (electrical engineering), MS (electrical engineering), and PhD (electrical engineering) all from Massachusetts Institute of Technology. His current research includes quantum information processing, atomic interferometry, and holography.

Renu Tripathi received her PhD in optics from the Indian Institute of Technology, Delhi, India. She is a postdoctoral fellow in the electrical engineering department at Northwestern University. Her research interests include quantum information processing and electromagnetically induced transparency in solids, coherent optical processing, and optical pattern recognition.

Mohammad Huq: Biography and photograph not available.

John T. Shen received his BS in electrical engineering from Northwestern University and is currently working toward a PhD. His research interests include optical data storage and information processing.