Volume Holographic Storage Demonstrator Based on Phase-Coded Multiplexing

Cornelia Denz, Kai-Oliver Müller, Thorsten Heimann, and Theo Tschudi

***Abstract*—We present the design and realization of a compact volume holographic memory based on phase-coded multiplexing. Due to the use of nonmechanical reference beam changes in this multiplexing technique, rapid access of the stored data pages is achieved. Our system can reach a maximum storage capacity up to 480 data pages with a resolution of 640 $\times$ 480 pixels in a single interaction region of a photorefractive $LiNbO_3$ crystal. We present the implementation of the system and first experimental results of both, high-resolution analog image storage and digital data storage. The storage of 180 data pages is demonstrated as well as the application of the system to real-time optical image processing.**

***Index Terms*—$LiNbO_3$, optical storage, phase-coded multiplexing, photorefractive crystal, volume holographic memory.**

I. Introduction

AMONG THE TECHNIQUES that have been envisaged for page-oriented data storage in volume holographic memories, orthogonal phase-coded multiplexing [1], [2] offers several advantages over angular [3], [4] and wavelength multiplexing [5], [6], having the same storage capacity. A holographic data storage system based on phase-coded multiplexing operates with a fixed wavelength and a fixed geometry, avoiding mechanically moving parts. At the same time, it provides short readout times and high energy efficiency. The signal-to-noise ratio (SNR) of phase-coded multiplexing for a given number of holograms is more than two orders of magnitude higher than for angular and wavelength multiplexing [7], [8]. Moreover, it allows to perform arithmetic operations as addition, subtraction or inversion of different data pages directly during readout of the memory [9]–[12]. Therefore, using phase-coded optical memories, high-capacity data storage and high-speed data processing becomes possible simultaneously. Finally, this method can be used for the encryption of the stored data [13]. Experimentally, a storage capacity of 64 pages has been realized using deterministic phase-coded holographic storage [9]. Subsequently several preliminary function demonstrations have been made by other authors [14], [15].

Because these were proof-of-principle experiments with limited capabilities—mainly due to the lack of reliable and high-resolution phase-only modulation devices—it was difficult to show that this technique is as powerful as angular multiplexing in its possibility to replace conventional storage techniques. Therefore, we realized a volume holographic storage demonstrator based on phase-coded multiplexing that allows to assess the practicality of this technology [16], [17]. The requirements we imposed on the system are that it has to combine a reasonable small size with the potential of high storage capacity, fully automated storage and data retrieval, rapid access to arbitrary data pages and the flexibility to process analog as well as digital data. Recently, a first testing of this device gave a storage capacity of 88 data pages easily [18], [19]. Here, we extend these investigations on the storage of high-resolution analog images. Moreover, the storage of digital data is realized. To the best of our knowledge, this is the first succesfull implementation of digital data storage using phase-coded multiplexing.

In this paper, we discuss the architecture and the performance of this demonstrator. In Section II, we give a short review of the principles of phase-coded multiplexing. Section III describes the design and architecture of our memory as well as the characteristics of the key system components. Section IV shows results on binary image storage, high-capacity analog image storage applied to medical (e.g., tomographical) images for archival storage purposes, and the reconstruction of stored digital data. The application of the system to real-time optical image processing, namely addition, subtraction and inversion of analog data pages is also presented. Finally, we discuss the actual constraints of the system and its perspectives for applications in different fields of optical storage.

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The authors are with the Institute of Applied Physics, Darmstadt University of Technology, D-64289 Darmstadt, Germany.

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II. Phase-Coded Multiplexing

In phase-coded multiplexing, each image is stored with a fixed set of N reference beams incident on the crystal with a discrete angular spectrum. As in angular multiplexing, the incident angles of the reference beams obey the Bragg condition. However, in contrast to angular multiplexing, all reference beams interact simultaneously with the signal beam in the storage crystal, each having a relative phase shift of 0 or π. Therefore, it is not the direction of each reference that is varied, but its phase. Each stored data page can be retrieved independently with the appropriate phase address that was used during storage. The maximum number of pages to be stored in a single interaction region is determined by the number of reference beams. During recall, reconstructions of undesired images interfere destructively, thus producing zero intensity. This principle of destructive interference as a means of selective recall is the reason for a significantly higher SNR of this method compared to other multiplexing techniques [8].

For reasons of simplicity in this review, we assume all reference beams and the data beam being plane waves. The extension to more complex beam distributions is straight forward. Assume the jth data page with the complex amplitude $S_j = \hat{S}_j e^{i\vec{k}\vec{r}}$ is stored with N reference beams $R_j = \hat{R}\,\Sigma_{k=1}^{N}\ e^{i\vec{k}_k\vec{r}}\ e^{i\varphi_{jk}}$, which are given by the sum of plane wave components with relative phase shifts φ_{jk}. $e^{i\varphi_{jk}}$ is a definite phase term added to each reference beam component. It is that phase term that gives the set of adjustable phases $(\varphi_{j1},\cdots,\varphi_{jN})$ representing the phase address of the jth data page and allows selective retrieval of stored images during recall. Interference of N data pages with the appropriate references creates a refractive index modulation via the electrooptic effect that is proportional to the intensity distribution of the interference pattern

$$\Delta n(\vec{r}) \propto \sum_{j=1}^{N}\sum_{k=1}^{N}\Delta n_{jk}(\vec{r})\cdot e^{i(\vec{k}-\vec{k}_k)\vec{r}}e^{-i\varphi_{jk}} \tag{1}$$

where $\Delta n_{jk}(\vec{r})$ represents the modulation depth of the index grating between the kth reference beam component and the jth signal beam. Reconstruction of the lth image is achieved by illuminating the crystal with the reference beams bearing the lth phase code $(\varphi_{l1},\cdots,\varphi_{lN})$. Under consideration of the Bragg condition, and assuming that $\Delta n_{jk}(\vec{r})$ does not depend on j,k itself, the readout of the storage medium with the reference beams having the complex amplitude R_l yields the diffracted amplitude [1]

$$S^{\text{diff}} \propto \sum_{j=1}^{N}\sum_{k=1}^{N}\hat{S}_j\cdot e^{i\vec{k}\vec{r}}e^{i(\varphi_{lk}-\varphi_{jk})}. \tag{2}$$

To obtain the reconstruction of the desired lth image without crosstalk, the phases of the reference beams have to fulfill the condition [1], [20]

$$\sum_{k=1}^{N}\chi_{lk}\cdot\chi_{jk}^{*} = \sum_{k=1}^{N}e^{i(\varphi_{lk}-\varphi_{jk})} = N\cdot\delta_{lj}$$

where

$$\delta_{lj} = \begin{cases}0, & \text{for } j\neq l,\\ 1, & \text{for } j=l.\end{cases} \tag{3}$$

With such a phase code, the lth image will be reconstructed, giving $S^{\text{diff}} \propto \hat{S}_l\cdot e^{i\vec{k}\vec{r}} = S_l$.

Equation (3) can be solved algebraically by unitary matrices χ fulfilling $\chi\cdot\chi^{*} = 1$, where 1 is the identity matrix. For phase-coded multiplexing, the components χ_{ij} of the matrix χ are pure phase factors, having an absolute value of 1. The phase codes for each data page are given by the N orthogonal columns of the matrix χ. Therefore, N determines the maximum number of data pages that can be stored independently. In the case of binary phase encoding, which can be easily accomplished using phase-only spatial light modulators, the values for the relative phase shifts are 0 or π.

Hadamard matrices $H^{(N)}$ are solutions of (3). They can either be constructed using the Walsh–Hadamard transformation algorithm

$$H^{(1)} = \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix},\quad H^{(n+1)} = \begin{pmatrix}H^{(n)} & H^{(n)}\\ H^{(n)} & -H^{(n)}\end{pmatrix} \tag{4}$$

where the value 1 corresponds to a phase shift of 0 and the value -1 corresponds to a phase shift of π, or by using more complex construction algorithms like the ones of Williamson- or Paley-type [21]. Because H-matrices of order $N = 4m, m = 1,2,\cdots$ can be constructed in general, these construction rules allow to adapt the number of phase-codes to the available number of reference waves or pixels of the phase modulation device.

In addition to high-capacity data storage, phase-coded multiplexing offers the potential of performing coherent arithmetic operations like addition or subtraction of two data pages, linear combinations of different pages as well as inversion of a single page during readout of the memory [10], [12]. Therefore, data processing like the comparison of two stored images or logical operations (OR, XOR, NOT) with digital data pages can be realized using a phase-coded memory.

To obtain addition of several data pages during recall, it is necessary to decrease the selectivity of the phase codes in such a way that the recall of pages with equal phase codes becomes possible. For this purpose, only a subset of reference beams has to be used for the reconstruction, giving the same phase code configuration for certain images. Subtraction of data pages can be achieved in a similar way, using a reference subset that has a phase difference of π between the phase code configurations. Furthermore, image inversion can also be realized during readout of the memory by subtracting a page from a plane wave stored in the photorefractive medium. Of course, linear combinations of images combining addition and subtraction are also possible by chosing the appropriate decrease in selectivity. These operations can be realized experimentally with an additional amplitude modulator by addressing the dynamic memory with only a subset of the original phase-coded beams used for storage of the appropriate images.

III. Design and Key System Components

In order to realize a high-capacity storage system, we initially established several parameters to guide the design of the demonstrator. Information pages would be stored as volume holograms in photorefractive $LiNbO_3$, each containing 640×480 pixels (37.5 kbyte) defined by the liquid crystal display we chose as the spatial light modulation device (SLM). To increase the information content of each hologram, up to 16 gray levels or 4 bits can be assigned to each pixel. This would yield a storage capacity of 150 kbytes per hologram, provided that the bit-error rate (BER) of the system remains the same introducing gray values. Probably a noise reduction technique (e.g., inverse filtering [22]) needs to be applied in order to discriminate these gray levels. The initial requirement of having a fast random data access can be achieved using binary phase encoding with a phase-only liquid crystal device. For that purpose, we used a phase-only liquid crystal spatial light modulator, having a resolution of 480 pixels in a single line. This number limits the number of holograms to be

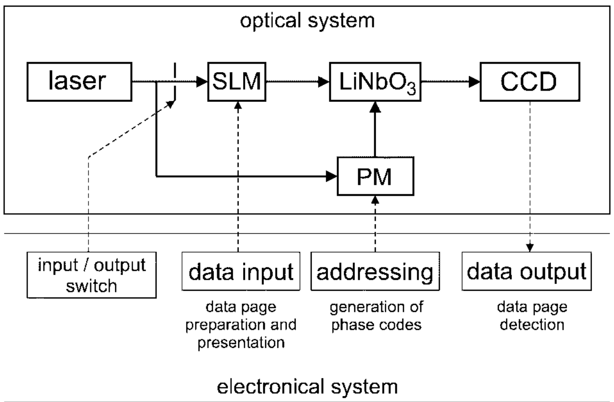

Fig. 1. Schematic architecture of the phase-coded holographic memory. SLM: Amplitude spatial light modulator. CCD: Charge-coupled device. PM: Phase modulator.

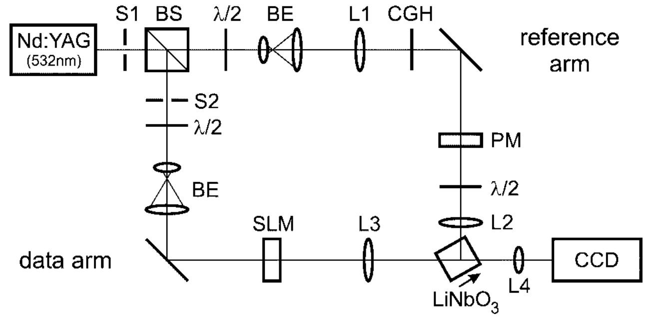

Fig. 2. Setup of the volume holographic memory with phase-coded multiplexing. BE: Beam expansion. CGH: Computer-generated hologram. SLM: Spatial light modulator. PM: Phase modulator. S1, S2: Shutter. L1–L4: Lenses. BS: Beam splitter.

phase-multiplexed at a single interaction region of the storage material, giving a capacity of 17.6 Mbyte for binary data pages (70 Mbyte including gray values). Obviously, the storage capacity is limited by the available number of independent locations that can be realized in the storage material. The storage of around 1-Gbyte data would require 57 independant storage locations or 15 locations for gray-level storage respectively. As a matter of fact, the requirements on the size of the crystal decrease with increasing gray levels. Adjusting of the different storage locations can be achieved using a moveable crystal holder, shifting the crystal to the different positions without changing the imaging system of the memory.

Fig. 1 shows the schematic architecture of the phase-coded memory. Data are introduced into the image arm by computer-driving the amplitude spatial light modulator (SLM). In the reference arm, addressing of data pages is realized by a phase modulating device (PM) in combination with a computer generated hologram serving as a beam separation unit. By means of the driving computer, orthogonal phase codes are generated and transferred to the phase modulator. Subsequently, the beams of both arms are superimposed coherently in the recording medium, a Fe-doped $LiNbO_3$ crystal. During recall of the stored data, the image arm is blocked and the reference arm addresses the storage medium with the appropriate phase codes. The phase-coded set of reference beams thus reconstructs the corresponding page in the storage medium which is imaged onto a charge-coupled device (CCD) camera device.

The recall time of the system is determined by the frame rate of the phase modulating device. Here, we are using a parallel nematic stripe modulation device that is capable of switching a whole data page in 10 ms, allowing a readout rate of 100 Hz. The data retrieval rate is thus given by 30 Mb/s for binary data. However, the data transfer rate is limited by the CCD camera actually used. Its frame rate of 30 Hz for VGA resolution (8 Hz for SVGA) results in a data access rate of 9 Mb/s.

Fig. 2 is a schematic showing the optical elements used in the demonstrator memory. The whole optical setup covers a surface of around 60×50 cm^2. In order to ensure interferometric stability, the setup is isolated against vibrations as well as against air and thermal fluctuations. For the laser, a compact frequency-doubled Nd:YAG laser that has an output power of 200 mW has been selected. Light passing the beam splitter enters the reference arm of the system. The signal beam is reflected off the beam splitter, subsequently expanded and passes through the computer driven amplitude SLM. The SLM presents the data pages to be stored to the memory and modulates the signal beam spatially according to the displayed images. In our experiment, we use a commercially available twisted nematic liquid crystal display (LCD) with active TFT technology. The display has an active area of 56.6×42.5 mm^2 and a pixel pitch of 88.5 μm. Its resolution is 640×480 pixels, corresponding to a capacity of about 37.5 kbyte per data page. Actually, the useable area of the display is determined by the circular aperture of the optical components with a diameter of approximately 50 mm. The frame rate of the SLM is 50 Hz. The contrast ratio of the LCD is $I/I_0 > 1100$ for binary data. Lens L3 performs a two-dimensional (2-D) Fourier transform (FT) of the input data page and projects the Fourier spectrum into the photorefractive crystal. Although image holograms may also be stored with this configuration, adding a suitable image demagnification unit, FT holograms allow to store information over an extended volume range, therefore, being tolerant of media imperfections.

After expansion, the reference beam illuminates a computer-generated Fourier hologram (CGH). In combination with a Fourier lens (L1), it converts the laser beam into an array of 480 separate beams with equal amplitudes in the Fourier plane of the lens. The purpose of this hologram is to ensure an equal intensity distribution of the reference beam into the 480 references, at the same time minimizing intensity losses. To achieve this aim, the hologram is realized as a kinoform detour phase type, where the concept of the detour-phase is combined with highly efficient carrier gratings. This leads to a high diffraction efficiency of $\eta = 92\%$ for the CGH. The intensity variation between arbitrary spots in the array is less than 2.5% [23]. The spotsize and the spot distance are adjustable by changing the distance of the hologram relative to lens L1.

All 480 beams can be phase-modulated separately by an electronically driven liquid crystal PM that is positioned in the back focal plane of lens L1. It performs binary phase modulation to encode the reference beam array with the orthogonal phase codes. The PM is a twisted nematic liquid crystal stripe array consisting of 480 stripes [24], each switchable to a phase shift of 0 or π for the corresponding beam. It allows to modulate the phase of each beam simultaneously and independently without a modulation of the amplitude. The stripe pitch is 80 μm with a stripe width of 70 μm. Although modulators with ferroelectric as well as parallel aligned liquid crystals have the advantage of phase-only modulation, we chose a twisted nematic device for our phase-coded memory out of two reasons. First, these systems are standard devices that will become available more and more easily for the high resolution required in our configuration. These twisted nematic LC devices can achieve phase-only modulation for a certain driving voltage region and polarizer orientation. The voltage in our device can be switched by the system's driving computer with a "steering byte" in a resolution of 256 steps from minimum to maximum. The phase codes of 0 and π can be adjusted with an accuracy better than 1%. This is an important condition for achieving a minimal BER, because in phase-coded multiplexing it is not random errors that define crosstalk, but systematic deviations of the phase values of π [11]. Second, such a twisted nematic LC cell can be switched from pure phase to amplitude modulation, thus allowing to perform simulaneously the operation of a supplementary intensity modulator that enables to realize arithmetic operations in a single device. Decreasing the selectivity in order to obtain image addition and subtraction is achieved by tuning the voltage of the appropriate modulator stripes to their maximum values, being equivalent to zero transmission. The codes for the phase modulator are generated and provided by a computer using codes of Paley- or Williamson-type (see Section II). Lens L2 is positioned in such a way that the phase-modulated array is focused into the crystal.

The reference and the data beam—both having a power of several milliwatts—are intersecting in an Iron-doped $LiNbO_3$ crystal having a size of $1 \times 1 \times 1$ cm^3, with the c-axis along one of the faces. Alternatively, a crystal of the same size, having a 45°-cut can be used, allowing perpendicular incidence on the storage medium for signal and reference beam ensuring maximum Bragg selectivity in the storage medium [25]. In order to account for the tradeoff between diffraction efficiency and quality of the reconstructions, which decreases severely if the entire dynamic range of the recording material is used, we restricted the recording range to the lower part of the dynamic range of the crystal. A diffraction efficiency of about 10^{-6} for each of the stored images results in a power level sufficiently large to be within the detection range of the CCD camera due to reducing or oversampling the camera pixels as described below. Moreover, the readout intensity can be enhanced using a higher reference beam readout intensity or a longer readout time. In the latter case, however, the readout rate of the system is decreased proportional to the increase in the readout time.

A computer-driven exposure schedule is used to achieve equal diffraction efficiencies for all data pages at the end of the recording procedure. Both, sequential [26] and incremental [2] recording schedules can be used. Although both mechanisms require the same total exposure time for a given diffraction efficiency to be reached for each page [27], technically, the switching delay times between subsequent increments and cycles in incremental recording make this recording procedure slower than sequential recording. Therefore, we use the sequential recording schedule in our experiment, reducing the storage times of subsequent images exponentially. During the data recording process, the exposure times are controlled by a computer which steers the shutter S1 appropriately.

For recall of the stored data pages, shutter S2 will be closed. Only the reference beams illuminate the crystal encoded with the appropriate phase code. The Fourier spectrum is then read out without crosstalk due to destructive interference of the undesired contributions. After an inverse FT by lens system L4, the retrieved data pages are detected on a CCD camera. The CCD camera has 1280×1024 pixels, being slightly oversized in the y direction. Therefore, these supplementary pixels of the CCD camera are not used for our imaging system. By carefully choosing the combination of the Fourier transform optics before and behind the crystal, we are capable of resolving all SLM pixels. For the readout process, this camera size enables two operation modes. It is possible to use only the number of pixels that are necessary for detecting all SLM pixels. Moreover, the demagnification provided by the two FT lenses may also be used to impose one SLM pixel on four CCD camera pixels, two in each direction. This oversampling allows the complete detection of all SLM pixels and enables to lower the requirements of precise pixel-to-pixel adjustment. Both cases reduce the resolution to the one of the SLM device thus allowing a readout rate of 30 fps.

The complete experiment—storage as well as recall—is controlled by a single computer which steers the shutters, supplies the input data pages on the SLM, and generates the phase codes for the PM. A photograph of the complete memory is shown in Fig. 3. Light from the doubled Nd:YAG laser (upper left corner) is separated by the beam splitter into the data arm (left and lower portion of the photo) and the reference arm (upper and right portion). The liquid crystal SLM left in front imprints the data onto the data arm. The phase modulation device is visible at the right side of the photo, in the middle part. Both beams are superimposed in the $LiNbO_3$ crystal, which is located in the lower right side and shown also in the inset. The CCD camera is located at the right front corner of the photo, but not visible in the photo.

IV. Experimental Results on Analog and Digital Data Storage

Our demonstrator was used to store and retrieve both analog and digital information. Fig. 4 shows examples of the recall of 180 binary images stored with phase-coded multiplexing. To demonstrate the imaging quality and identify possible crosstalk sources, here simple binary images were used as data pages. Each image had a diffraction efficiency of 10^{-5}. The varying locations of the numbers in the images enabled to detect undesired crosstalk easily. A global uniform contrast enhancement was the only image processing procedure used to enhance all the retrieved images presented in the following for reproduction purposes. However, Fig. 4 shows that the reconstruced images exhibit a very low crosstalk. Results of the storage of high-resolution analog images with several gray

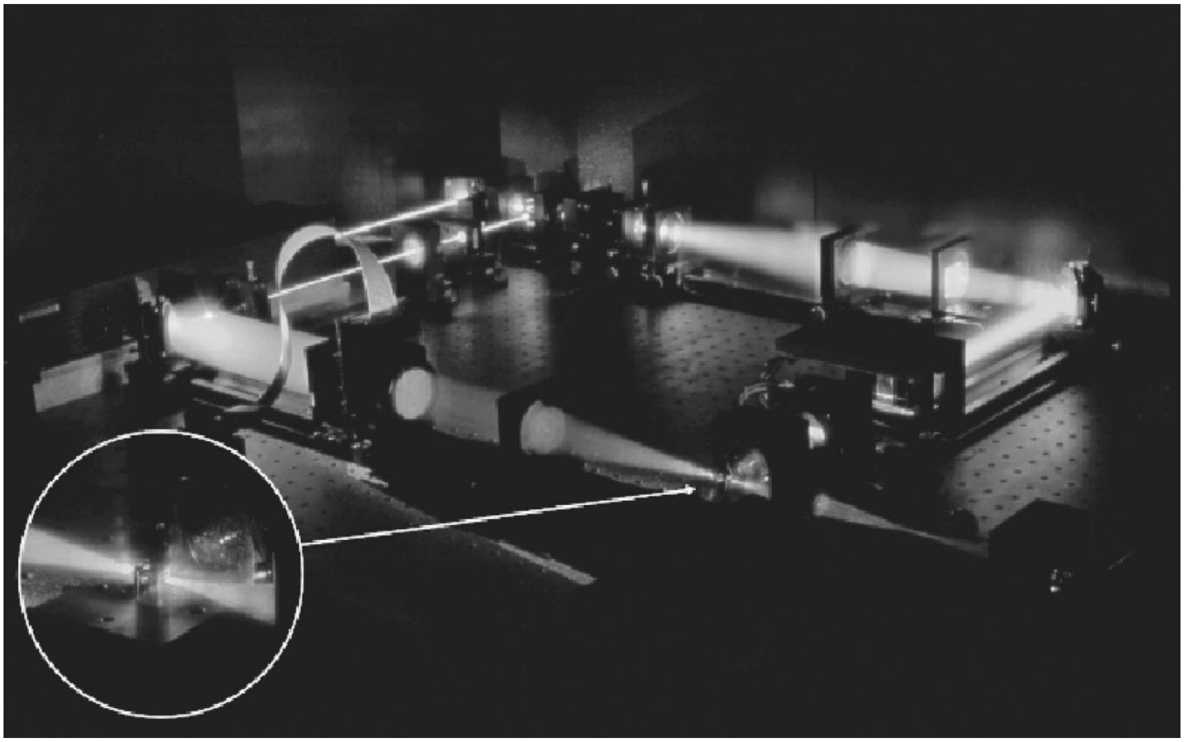

Fig. 3. Photograph of the volume holographic memory system based on phase-coded multiplexing.

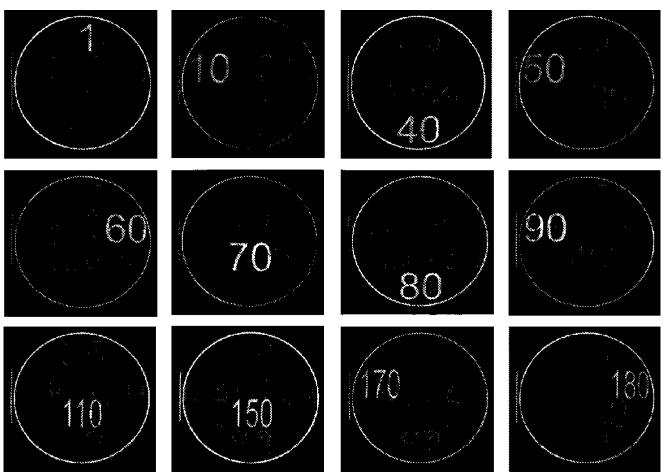

Fig. 4. Examples for the recall of 180 images stored with phase-coded multiplexing.

levels are shown in Figs. 5 and 6. Here, a reduced number of several ten images was recorded in each storage cycle.

Most promising applications of holographic memories up to now are in the area of digital data storage. For the case of angular multiplexing, digital data storage has been performed in several demonstration setups [28], [29]. In order to approach the requirements of digital data storage in our phase-coded memory, we investigated the transfer of binary pixels of a single data page. For this purpose, each pixel of the spatial light modulator or a combination of them represents a digital bit. Examples for the recall of digital data pages with different resolutions are shown in Fig. 7. This method of oversampling SLM data pixels allows to reduce the BER, but at the same time it reduces capacity and transfer rates in proportion to the oversampling rate. In the upper data page, a combination of 3×3 pixels and in the lower data page a combination of 5×5 pixels represents a single digital bit. The pixel-to-bit ratio is limited by the distortions of our imaging system. Using highly corrected, adapted optical systems, it is possible to reduce the number of pixels per bit in order to achieve higher storage capacities.

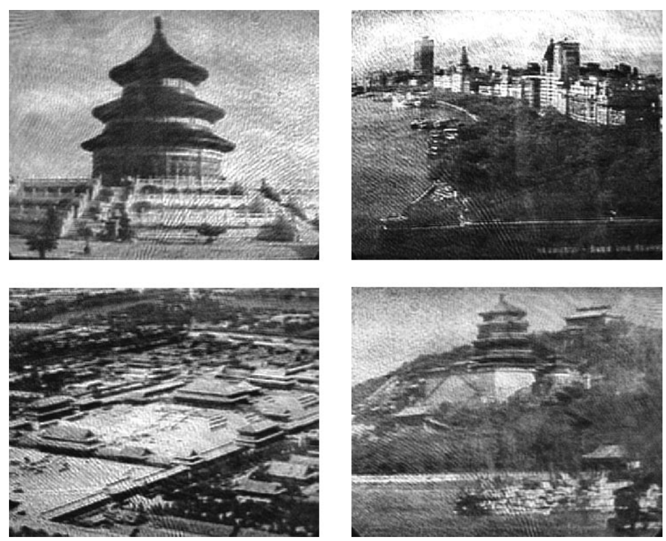

Fig. 5. Simple analog data pages stored in the phase-coded holographic memory.

A complete encoding-reconstruction cycle of a digitally encoded image page was realized for a pixel-to-bit ratio of 5×5 pixels representing one single bit. Using the actual aperture of our system, this results in a page size of 4096 bits. Consequently, several holograms have to be used to store a

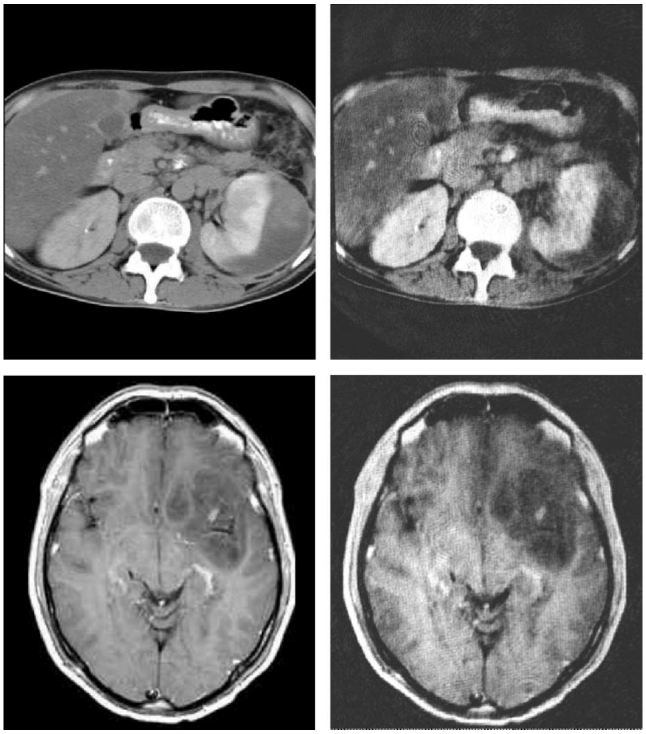

Fig. 6. Original (left) and reconstruction (right) of analog medical (tomographic) images stored in the phase-coded holographic memory.

single digital representation of an image. A simple image was used for an initial testing of the conversion of digital data back into the image, using 23 pages in a single interaction region for storage of the image. In Fig. 8, an example of these digital data pages, its recall by the phase-coded memory as well as the image and its reconstruction are shown. The resulting BER depends on the filling of the binary data page. For the image shown in Fig. 8, we achieved a raw BER of $1.5 \cdot 10^{-4}$. Because we are actually exploiting only one third of the dynamic range of the storage medium (see above), no increase of the BER was observed compared to the single-page storage. Note that actually no modulation or error correction method was yet applied for storing the data. Applying novel techniques of noise reduction [22] as well as modulation coding (see e.g., [28], [30]), a reduction of several orders in BER can be expected.

For the demonstrations of analog and digital data storage shown above, no fixing process is used and, therefore, the holograms are slightly erased during readout. However, due to a strong read–write asymmetry of the response time of the $LiNbO_3$ crystal used, erasure is not a problem for the current single-adressing purposes. However, for long term, multiread device purposes, thermal or electric fixing has to be added in order to circumvent undesired erasure.

V. Experimental Results on Arithmetic Operations

Examples for analog image addition and subtraction as described in Section II are given in Fig. 9. The second row shows the optical addition (left) and optical subtraction (right) of pairwise operations of the pages in the first row. The addition of two images is detected as constructive interference

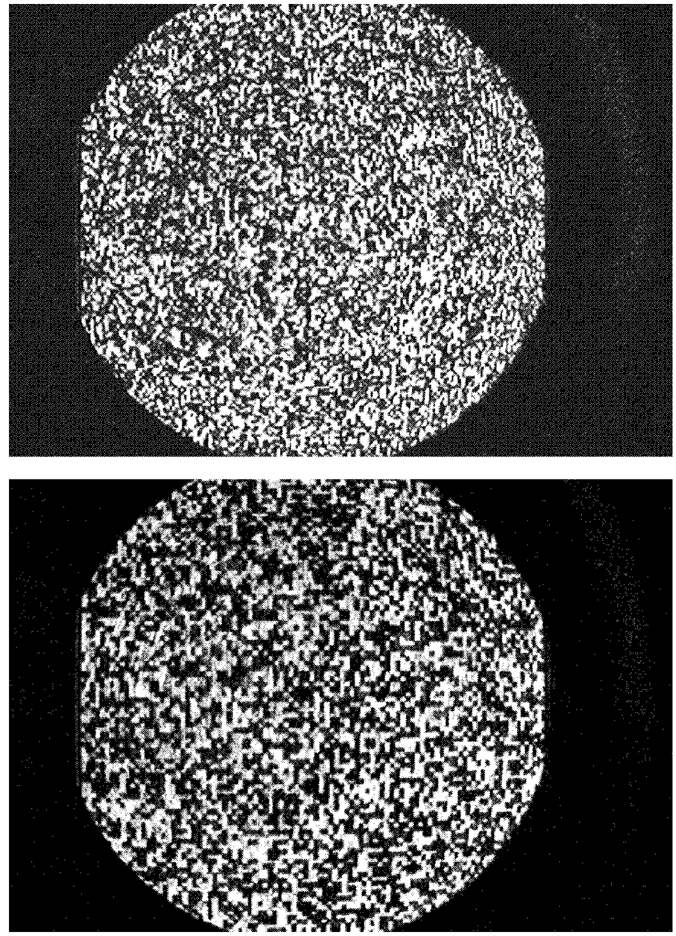

Fig. 7. Recall of digital data pages with different resolutions stored in the phase-coded memory: 3×3 pixels per bit (upper image), 5×5 pixels per bit (lower image).

of them. For analog images, this leads to an appropriate increase of the intensity in regions where both images are bright. The subtraction of two images is detected as destructive interference producing zero intensity in regions where both images have the same intensity. Because the result of this image processing is detected with an intensity-sensitive CCD-camera device, this operation is reduced to give only the absolute value of the subtraction. However, the subtraction process itself conserves the sign of the subtraction due to its coherent nature. Image inversion can be achieved in our memory by storing a supplementary plane wave in the memory and performing subtraction on this page in combination with the page to be inverted. An example on analog image inversion is shown in Fig. 10.

Applying these operations to binary or digital data pages realizes logical operations like XOR (subtraction) and OR (addition). Moreover, the subtraction of a digital data page from a plane wave is a NOT operation. Therefore, signal processing and image operations during readout of a phase-coded holographic memory are possible.

VI. Conclusion

In this paper, we presented a fast and compact volume holographic memory system based on phase-coded multiplexing

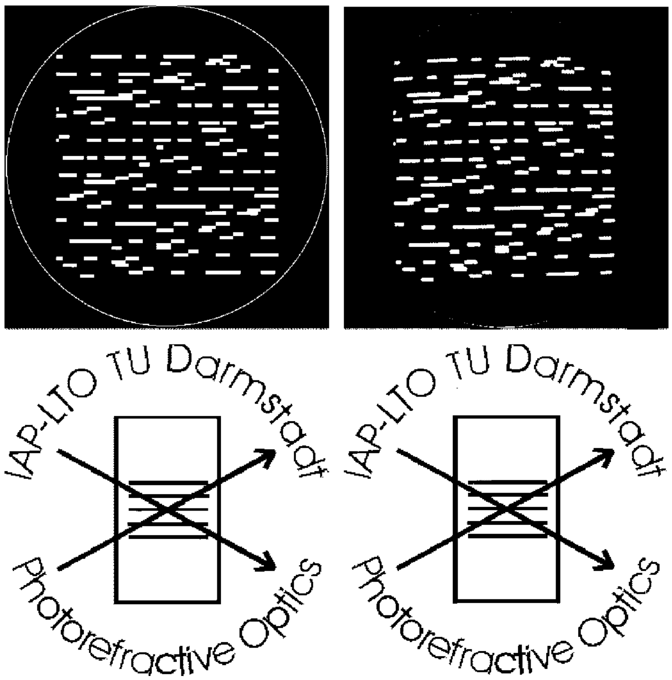

Fig. 8. Original (left) and reconstruction of a digital data page (right) and its decoded image. Data are distributed over several pages. No modulation or error correction was applied to the data.

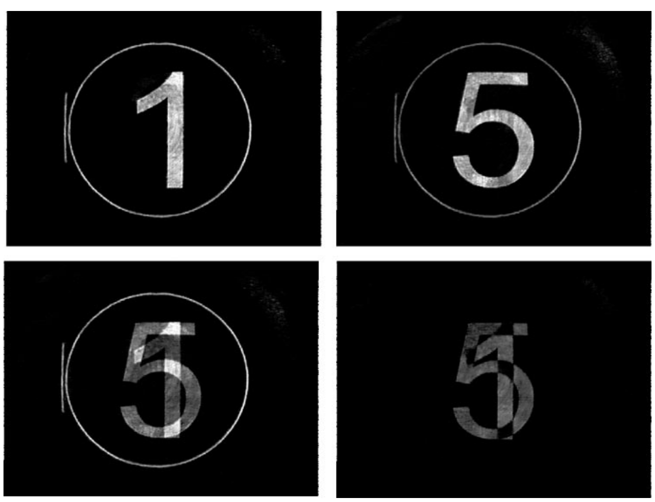

Fig. 9. Examples for optical addition (lower left) and subtraction (lower right) of two image pages.

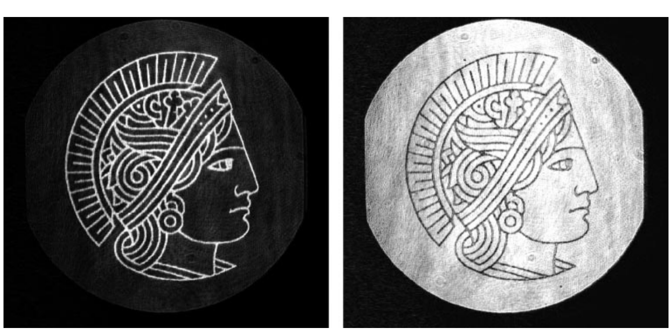

Fig. 10. Example of inversion of an analog data page realized by subtraction of the data page from a plane wave stored in the volume holographic memory.

for high-density analog and digital data storage. Compared to the more commonly used technique of angular multiplexing, this technique allows recording and retrieving of data pages without introducing moving parts or frequency-shifting elements into the setup, being at the same time energy efficient and fast. The device can also be used for image processing, being able to realize arithmetic operations on the stored data pages during readout of the memory. We demonstrated the phase-coded storage and recall of 180 images with low crosstalk. Examples of the storage and almost error-free retrieval of high-resolution analog and digital images have been presented as well as optical addition and subtraction performed on the stored pages during readout of the memory. Testing is now under way to demonstrate the maximum capacity and to realize full, error-corrected digital data retrieval. We expect the fully operating system having a capacity in a single location of up to 18 Mbyte for binary data in a single interaction region or more than 70 Mbyte assuming 16 gray levels to be added. If spatial multiplexing is added, the system capacity can be larger than 1 Gbyte having an access time of about 30 Mb/s. Future challenges remain the extension of the system to add this spatial multiplexing of different locations of the storage crystal, enhancing at the same time the access speed of arbitrary data pages stored at different volume locations.

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Cornelia Denz received the Diploma degree in 1988 from the Institute of Applied Physics, Darmstadt University of Technology and the Ph.D. degree in physics from Darmstadt University in 1992. Her dissertation dealt with implementations of photorefractives for optical neural network realizations.

Previous to her Ph.D. studies, she worked at the Institut d'Optique Théorique et Appliquée in Orsay, France. She is an Assistant Professor at the Darmstadt Institute of Technology. She is currently heading a research group on photorefractive optics, optical memories, information processing and nonlinear optical pattern formation.

In 1993, Dr. Denz was awarded the Lise Meitner price for outstanding work on optical memories.

Kai-Oliver Müller received the Diploma degree in 1996 from the University of Hannover, working on advanced techniques for gravitational wave detectors. Currently, he is working toward the Ph.D. degree at the Institute of Applied Physics, in the realization of a high-capacity analog holographic memory based on phase-coded multiplexing.

Thorsten Heimann is working toward his undergraduate degree.

He joined the Photorefractive Optics Group in 1996. He is currently responsible for the implementation of different phase modulation devices suitable for application in volume holographic memory devices.

Theo Tschudi received the Ph.D. degree in physics from the University of Bern, Switzerland, in 1969.

He then worked in the field of information processing and optical measuring techniques at the University of Bern, the University of Osaka, Japan, and the University of Hamburg, Germany. Since 1981, he is a Professor and Head of the Light and Particle Optics Division at the Institute of Applied Physics at Darmstadt University of Technology. The focus of his current research work is on nonlinear optics, optical information processing and measuring techniques, microoptics, and optical thin film technology. He is the Editor of *Optik, International Journal for Light and Electron and Optics*.

From 1992 to 1996, Dr. Tschudi was President of the German Society of Applied Optics (DGaO). Since 1998, he is the president of the European Optical Society (EOS). Theo Tschudi is a Fellow of the Optical Society of America and member of several Physical Societies.