Error-corrective optical recall of digital images by photoburning of persistent spectral holes

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Error-corrective optical recall of digital images by photoburning of persistent spectral holes

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Associative error-corrective recall of spatially- and wavelength (frequency) encoded digital optical signals is carried out by using spectrally highly-selective low-temperature photochromic storage media. It is demonstrated that the technique of photoburning of persistent spectral holes provides, in addition to usual spatial coordinates, new parallel-accessible degrees of freedom which can be used for ultrafast optical processing.

1. Introduction

The phenomena of persistent spectral hole burning (PSHB) [1,2] occurs in a variety of low-temperature impurity solids [3] and makes possible writing and reading of optical data in the form of narrow (10^{-2}–10^{-4} cm^{-1}) "dips" or holes in the inhomogeneously broadened absorption (transmission) spectrum of photochromic impurities. The lifetime of spectral holes is from hours to years [4]. The density of frequency-domain storage reaches, in principle, 10^4–10^6 bits per diffraction-limited size spatial spot which gives an estimate of an overall optical storage density of about 10^{12}–10^{14} bits per cm^2 [3,5].

However, the expected speed of writing a single narrow spectral hole (corresponding to one bit of data) is limited by the lifetime of the excited electronic state of impurity molecules which is, typically (e.g., for organic molecules) on the order of 10^{-7}–10^{-8} s [6] [#1]. Thus, access to a large number of spectral holes in a trivial serial manner [7] will be, inevitably, a rather time consuming procedure.

Alternative approaches to spectrally selective optical memory, which could make better use of po-

tential advantages of PSHB, are the methods designed for parallel and associative storage [8]. As associative (content-addressable) storage usually needs much larger memory space than the conventionally addressed storage, the larger memory space than the conventionally addressed storage, the unique capacity provided by PSHB may turn out to be of remarkable importance. It is also noteworthy that applying PSHB retains the potential for fully parallel optical reading (and writing) of data. The above mentioned properties of PSHB can both be significant factors if we consider optical implementation of efficient error-corrective data processing algorithms such as proposed by Hopfield [9] and studied recently by using conventional optical storage materials [10].

Simultaneous spatial- and frequency domain parallel optical storage has been employed in the method of time- and space domain holography [11–13]. In these experiments PSHB media storages an analog optical signal with an arbitrary wavefront, a polarization state and temporal structure (the last is Fourier-related to the spectrum of the signal). By this method the possibility to reconstruct full holographic image from partial input (associative hologram) has also been demonstrated [14].

In the present paper we apply PSHB media for associative storage and error-corrective recall of digital optical signals following Hopfield's model of an as-

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[#1] Single spectral hole read-out time can be shorter than the impurity electronic excitation lifetime and is limited, in principle, by the reciprocal spectral width of the hole.

sociative memory [14]. We carry out an experimental implementation of an optical memory which is coded as a multidimensional digital auto-associative memory matrix and which has an error-correcting capability with respect to two- or one-dimensional inputs. We show that by using the optical frequency variable PSHB storage media can accomodate a fully parallel-accessable multidimensional optical memory.

2. Mathematical model of associative memory

We assume that the useful data stored in the associative memory comprises S binary images presented by two-dimensional matrices, $v_{ij}^{(s)}$ ($i=1, ..., M$; $j=1, ..., N$; $s=1, ..., S$) of $M \times N$ nonnegative binary elements (0, 1). To calculate the values of the memory matrix elements we use a rule analogous to that described in ref. [15],

$$T_{ijkl} = \frac{T''_{ijkl}}{\sum_{k,l}^{M,N} T''_{ijkl}}, \qquad (1)$$

where

$$T''_{ijkl} = T'_{ijkl}, \quad \text{if } T'_{ijkl} < 0,$$
$$= 0, \quad \text{otherwise} \qquad (2)$$

and where

$$T'_{ijkl} = \sum_{s=1}^{S} (2v_{ij}^{(s)} - 1)(2v_{kl}^{(s)} - 1), \qquad (3a)$$

$$T'_{ijij} = 0. \qquad (3b)$$

Read-out of a memory by an interrogating image $\tilde{v}_{kl}^{(in)}$ is equivalent to a thresholded scalar product

$$\tilde{v}_{ij}^{(out)} = \text{TRH} \left\{ \sum_{k,l}^{M,N} \tilde{v}_{kl}^{(in)} T_{ijkl} \right\}, \qquad (4)$$

where TRH{ } stands for a threshold function

$$\text{THR}\{x\} = 1, \quad \text{if } x \leqslant 0.5,$$
$$= 0, \quad \text{otherwise}. \qquad (5)$$

Note that here we do not assume effects connected with feedback and multiple pass-through of the processes signals. In our experiment an error-free recollection appears from the memory after the first

pass-through of the interrogating signal.

3. Experimental

In the experiment we use PSHB media prepared from polystyrene doped simultaneously with two types of impurities – molecules of octaethylporphine and protoporphyrine, both contained at a concentration of 10^{-3}–10^{-4} mol/l. The dimensions of the PSHB sample are 3×3 cm^2 across and 4 mm in thickness. During the experiment the PSHB plate is positioned inside an optical cryostate and is immersed in liquid helium.

At low temperatures the PSHB-active absorption bands of the two impurities combine and form in the wavelength interval of 616–622 nm a broad band with an effective width of about 150 cm^{-1}. The spectral transmission of the sample measured before the write-in exposures varies in this spectral range between 1% and 2%. The narrowest possible hole-width (i.e., the ultimate spectral selectivity of the storage) is about 0.05 cm^{-1}.

As a laser source we use a picosecond Rhodamine 6G dye laser synchronously pumped by an Ar ion laser. In order to facilitate easy manual control over the dye laser wavelength we insert into the laser cavity, in addition to the standard birefringent tuning element, also a fixed thin glass etalon. Depending on the thickness of the etalon the longitudinal modes define 10–30 lasing frequencies in the 150 cm^{-1} storage range. The temporal shapes of the picosecond laser pulses and of the recollected signals are measured with a 20 ps time resolution synchroscan streak camera.

4. Experimental procedure and discussion

For model images we take two different 12-bit 3×4-element matrices $v_{ij}^{(1)}$ and $v_{ij}^{(2)}$. Each of the two images is presented on a separate slide and is composed of transparent and opaque squares representing bit values of 1 and 0, respectively (fig. 1a, b). The corresponding calculated values of the memory matrix elements are presented graphically in fig. 1c.

To materialize the four-dimensional memory matrix we use four different physical variables. Two
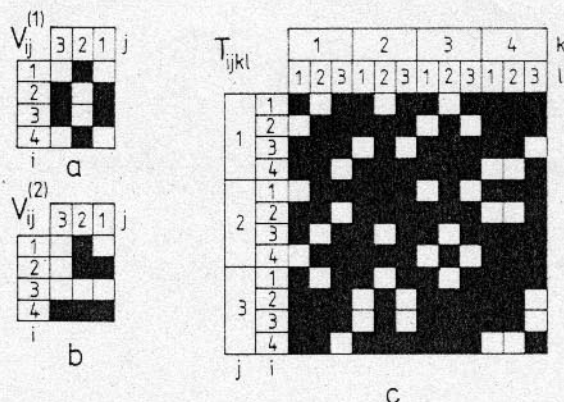
247

Fig. 1. Graphical representation of the two binary images assumed as storaged data (a, b) and of the corresponding calculated memory matrix (c).

variables, corresponding to indexes k and l, are both accomodated by the spectral dimension ν of the PSHB storage media (k corresponds to different holographic signal delays τ_1, τ_2, τ_3 and l corresponds to different spectral range ν_1, ν_2, ν_3, ν_4) while the two remaining variables (indexes i and j) are provided by the two orthogonal spatial coordinates x and y in the plane of the PSHB plate.

The frequency-domain storage is arranged by dividing the working spectral range into four nonoverlapping virtual subintervals (index k), each interval corresponding to a different laser frequency mode of a width of about 2 cm^{-1}. In every of the frequency subintervals we store three picosecond time-domain holograms. Each hologram is stored with a different time delay between the write-in signal and the reference pulse. The value of the time delay τ of the holographically recalled signal serves as the second storage parameter (index l) [*2].

Concerning the spatial coordinates, the PSHB storage plate is divided into 12 square elements arranged in the same way as the storaged images i.e. into a 4×3-element matrix. At every of the 12 spatial locations a virtual two-coordinate storage space is now available: the first coordinate corresponds to

[*2] In the method of time-space holography to get a correct holographic recording the overall duration of the signal and the reference pulse in time-domain should be less than the phase relaxation time T_2 of the PSHB-active impurity molecules (for low-temperature organic systems T_2 is typically about 1 ns) [11,12].

the carrier optical frequency ($\nu = \nu_1$, ν_2, ν_3, ν_4) while the second coordinate corresponds to the temporal delay ($\tau = \tau_1$, τ_2, τ_3) of a holographic time-domain signal. In other words, the 4-D associative memory matrix is physically coded in our experiment in the intensity of a spatial-, frequency- and time-dependent optical response $T(x, y, \nu, \tau)$ of the PSHB plate.

The scheme of the experimental arrangement is presented in fig. 2. The incoming picosecond dye laser beam is expanded and divided into two with a beamsplitter. At the position of the PSHB plate the two beams (signal and reference beam) cross at an angle of 6°. The time delay between the intercrossing beams can have three different values (40, 104, and 180 ps) depending on the thickness of a glass block positioned in the reference beam. The signal beam, which has the shorter pathlength, contains a holder with an interchangable mask slide. The signal laser beam projects the image of a slide upon the PSHB sample so that every spatial element of the slide coincides with a corresponding spatial element of the storage plate. The reference beam posesses a plain wavefront and illuminates uniformly the whole storage area of the PSHB plate.

The memory matrix we write in by tuning the dye laser wavelength sequentially to four fixed storage frequencies. At every frequency we carry out three different write-in exposures, one for every of the three
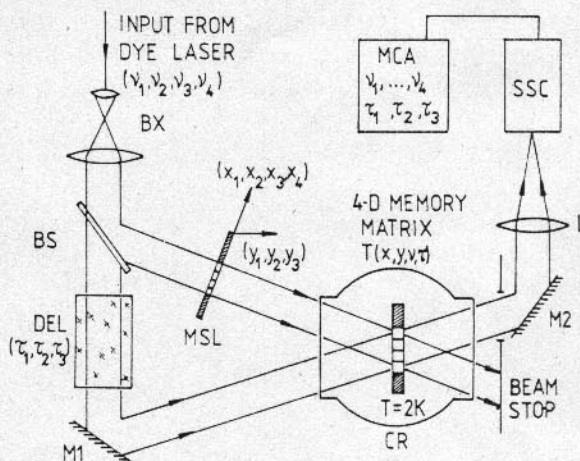

Fig. 2. Scheme of the experimental arrangement used for storage and interrogation of 4-D associative memory matrix. BX, beam expander; BS, 50% beamsplitter; DEL, glass block delay; M1, M2, mirrors; MSL, mask slide; CR, cryostat; L, collecting lens; SSC, synchroscan streak camera; MCA, multichannel analyser.

different delay values. Each exposure (the total number of write-in exposures is 12) is performed by using a special spatial mask slide whose spatial structure corresponds to a specific fragment of the memory matrix. The summary burn-influence applied in the storage process of the memory is about 100 mJ per cm^{-2}.

After completing the storage procedure we attenuate the incoming laser beam by a factor of 100 in order to avoid erasing of the memory by further hole burning during the read-out. The write-in reference beam is blocked and the sample is illuminated only with the signal beam. In the slide holder we fix a mask that resembles one of the two storaged images but differs from it by two error bits. At the output of the memory we have a focussing lens that collects the light diffracted from different spatial elements of the PSHB plate into a single focus spot at the entrance slit of the streak camera. The passed-through read-out beam is blocked and only the diffracted beam reaches the streak camera input. Note that there is only one recorder (the streak camera) in the experimental scheme.

The temporal structure of the spatially integrated hologram response is measured at four different read-out frequencies and is presented in fig. 3. As the exact value of the hologram response corresponding to $x = 0.5$ in eq. (5) is unknown, the half value of the maximum response is taken as the thresholding level. When arranged into a (4×3) matrix the read-out data clearly reproduces one of the true storaged images. The fact that the recollected image is inverted

with respect to the original follows from the used mathematical algorithm and is not connected with our experimental implementation. Read-out of the memory with a different input slide which resembles the other storaged image gives a similar result (correct but inverted output).

It should be noted that in our experiment we perform a full-optical parallel scalar multiplication of two- and four-dimensional matrices. All variables are in our case represented by different physical degrees of freedom and it is very easy to carry out the summation procedure by simply integrating the outcoming signal over one or more of the physical parameters. Also it is noteworthy that at the output the information (actually the image) is completely coded in the spectrum of an optical signal which makes it, in principle, easy to transmit along a optical waveguide.

Also we study a modified case of the experiment in which we do not write time-domain holograms and can thus exclude the reference beam and the streak camera. In this simplified version the same digital information is presented by two 12-bit words ($v_1 = 100101101001$, $v_2 = 101000101110$). The associative memory is now a (12×12) 2-D matrix (instead of 4-D) and depends only on two variables. In the physical materialization one storage variable corresponds to 12 different frequencies where we burn spectral holes while the second variable corresponds to 12 horizontal stripes which are arranged perpendicularly to the vertical x-axis of the PSHB plate. The memory can in the present case be regarded simply as a spatial-spectral transparency or filter $T(x, v)$.

The scheme of the modified experimental set-up is presented in fig. 4. To write in the memory we tune the laser sequentially to 12 different burn-in frequencies and pass the write-in beam through corresponding mask slides with transparent and opaque sections.

For the read-out the incoming light is attenuated and passed through a mask slide with an interrogating 1-D image. The passed-through light is then collected and focused upon the cathode of a photomultiplier. Fig. 5 presents the spatially-integrated intensities (i.e. the average spectral transparency of the sample) which are measured at 12 different frequencies for two different erroneous inputs. Again,
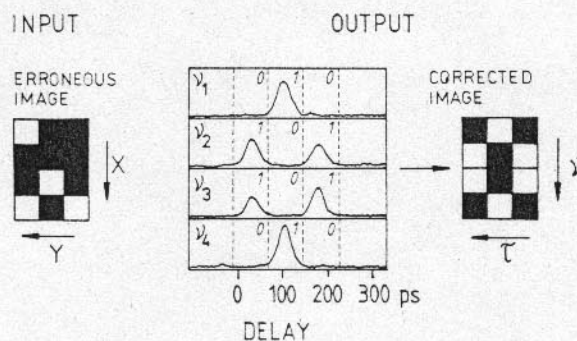
Fig. 3. Read-out of the 4-D memory by interrogation with an erroneous 2-D input image. Output signal measurement is carried out by monitoring the time-domain intensity of the diffracted signal at four different read-out laser frequencies.
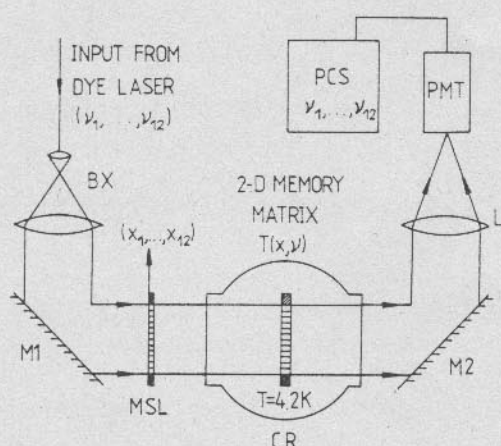
Fig. 4. Scheme of the experimental arrangement with 2-D memory. PMT, photomultiplier; PCS, photon counting system. Other notations referring to optical scheme elements are same as in fig. 2.
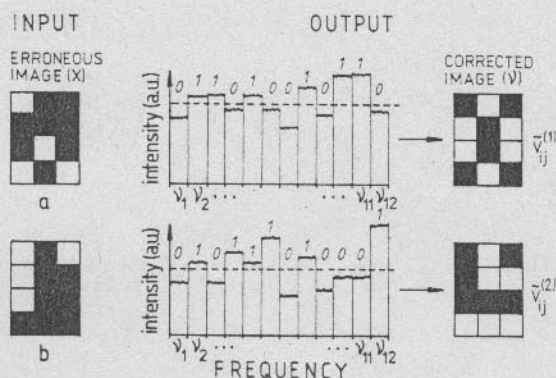

Fig. 5. Read-out of the 2-D memory by interrogating with two different 1-D input images. Thresholding level (horizontal dashed line) is different for different inputs due to the transmitted spectral background signal.

the recollection is contained purely in the frequency-space and it is an inverted replica of the original. However, the information is coded only in one dimension which complicates processing of 2-D images directly. Another drawback of the present arrangement is the occurrence of some background signal due to the spectral background transmission of the sample. The amount of the transmitted background light depends on the input signal and as a result we need to choose for each input signal a suitable thresholding level.

In conclusion, by our model experiments we have demonstrated that photoburning of persistent spectral holes facilitates parallel digital optical processing and storage. We have shown that via PSHB efficient full-optical vector–matrix as well as matrix–matrix multiplication can be completed. In other words, by our experiments we give an example that due to the phenomena of PSHB the optical wavelength regarded up to now prevalently as a purely formal parameter turns out to be a practical extra physical variable which can be applied on equal terms with the spatial coordinates.

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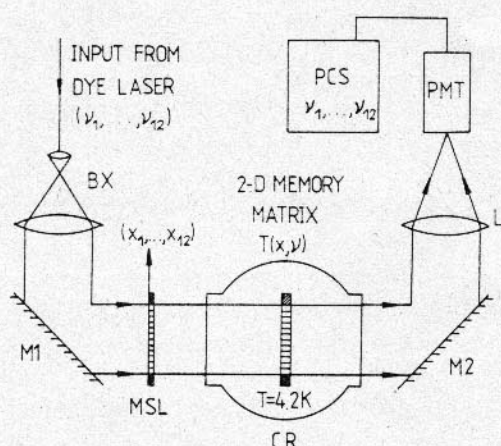[15] I. Shariv and A.A. Friesem, Optics Lett. 14 (1989) 485.

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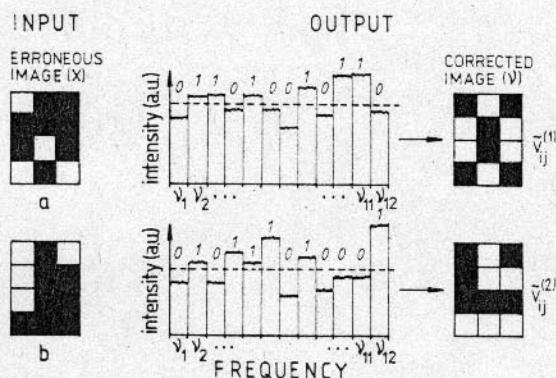

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