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Associative recall in a volume holographic storage system based on phase-code multiplexing

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ABSTRACT We present two different techniques on how to realize a content-addressed holographic memory when using phase-code multiplexing, relying on simple intensity measurements rather than phase distributions. Theoretical and experimental results of associative recall in a phase-coded system designed for digital data storage will be presented and compared to the corresponding method when using angular multiplexing.

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1 Introduction

Storage systems based on volume holography provide the potential for large storage capacities of around 1 TByte/cm^3, fast data-transfer rates which exceed 10 GBit/s and short random-access times of less than 100 µs [1–4]. These features are achieved by the page-oriented storage principle and the use of multiplexing techniques such as angular, phase-code or wavelength multiplexing by changing parameters of the Bragg condition (see e.g. [5–10]). Additionally, volume-holographic memories can also be content-addressed in order to perform an associative recall, which allows a simultaneous search in an entire database by performing the correlation of all stored data pages with the data page used for addressing the storage medium (see e.g. [11]). Until now such content-addressed volume-holographic memories have only been demonstrated using angular multiplexing [12–14].

Among the different multiplexing techniques orthogonal phase-code multiplexing offers several advantages over other multiplexing methods. A phase-coded system operates with a fixed wavelength and a fixed geometry, avoiding mechanically moving parts [15, 16, 21]. Moreover, for a given number of holograms the signal-to-noise ratio (SNR) is more than two orders of magnitude higher than for angular or wavelength multiplexing [16, 17]. Additionally, orthogonal phase-code multiplexing (e.g. using Walsh–Hadamard matrices for code generation) allows the performance of arithmetic operations such as addition, subtraction or inversion of different data pages in real time directly during read out [18–20, 22]. It also can be combined with a random-phase key in order to encrypt the data with a great amount of security [23,24]. Despite all these advantages that emphasize the potential of phase encoding, implementation of associative recall in such a system was difficult, since the nature of phase-code multiplexing usually necessitates the measurement of phase distributions. Here we present two approaches on how to perform a content-addressed read out in a phase-encoded storage system by using only intensity measurements.

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2 Phase-code multiplexing and correlation

Figure 1 shows the principle of the phase-encoded system: (a) for storing the data, (b) and (c) for the two different ways of addressing the holographic storage medium during read out, i.e. address-based recall and content-addressed recall, respectively.

For storing a data page the laser beam is divided into a signal beam and a reference beam. In the signal arm the digital information to be stored is impressed onto the expanded beam as a two-dimensional amplitude variation by a spatial light modulator. In the reference arm the beam is transformed into a fixed number N of reference waves whose phases could be adjusted individually by a spatial phase-only modulator. The reference waves are then incident on the storage crystal having a discrete angular spectrum and obeying the Bragg condition. In contrast to angular multiplexing, all reference waves interfere simultaneously with the signal wave in the storage crystal (Fig. 1a). For storing yet another data page, the same reference waves will be used but with a different set of phase shifts. These sets of phases are called the phase codes or the addresses of the data pages in the crystal. For recalling one of the stored data pages one has to readjust the appropriate phase code with the phase modulator. When illuminating the crystal with the reference waves, actually all holograms will be read out at once due to diffraction, since every page has been written by the use of all these reference waves. However, due to the use of orthogonal phase codes holding binary phase shifts of 0 or π for each reference wave, all undesired images interfere destructively (Fig. 1b). Therefore with the appropriate phase codes the stored data pages can be reconstructed independently without low cross talk. This principle of destructive interference gives rise to a significantly higher signal-to-noise ratio of this method compared to other mul-

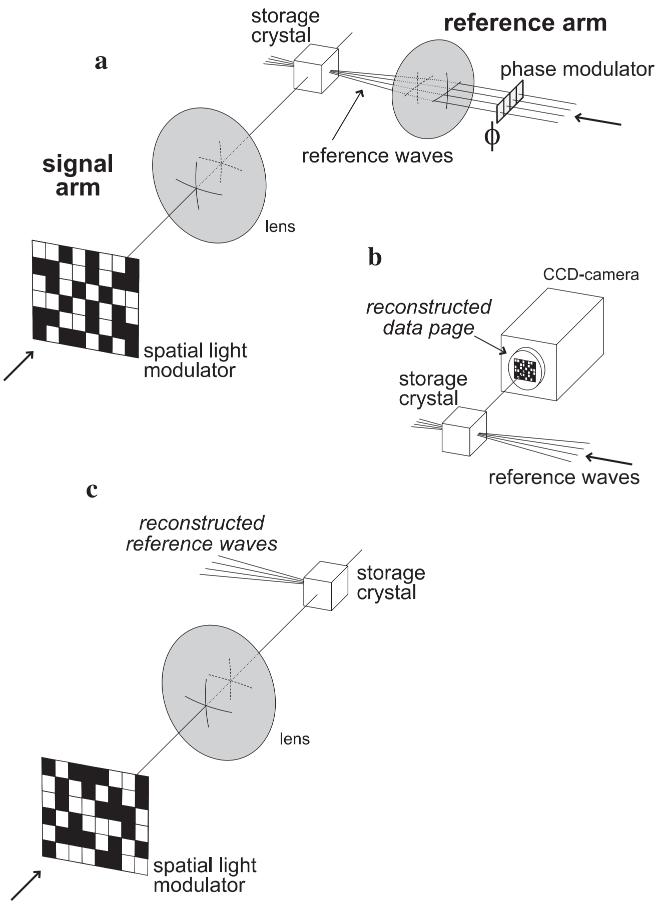

FIGURE 1 **a** Storing a data page by superposition of a signal beam carrying the information and a discrete set of reference waves. **b** Addressing with the appropriate set of reference waves will reconstruct the stored data page (address-based recall). **c** When addressing the storage medium with any data page, the correlation of that page and the stored data pages will be performed in real time (content-addressed recall)

tiplexing techniques [17]. In order to achieve this feature the accuracy of the adjusted phase shifts must be close to the theoretical values within about 1% [21].

In order to perform associative recall, the storage medium is addressed with one of the stored data pages. This results in the reconstruction of the appropriate reference waves, being phase-modulated with the same pattern which has been used for storing that page (Fig. 1c). The phase pattern of the reference beams is not directly visible. Therefore one usually would have to measure the phase distribution, e.g. by interferometric techniques, in order to obtain the reference-beam information.

The process of storing data and associative recall is depicted in Fig. 2 in more detail. During the recording process the Fourier transform S of the data page D is stored in the crystal and the refractive-index modulation is given by [9]

$$\Delta n \propto \hat{S}\hat{S}^{*} + \hat{R}\hat{R}^{*} + \hat{R}\hat{S}^{*}\,\mathrm{e}^{\mathrm{i}\boldsymbol{K}\boldsymbol{r}} + \hat{S}\hat{R}^{*}\,\mathrm{e}^{-\mathrm{i}\boldsymbol{K}\boldsymbol{r}}, \tag{1}$$

where $\boldsymbol{K} = \boldsymbol{k}_r - \boldsymbol{k}_s$, $\hat{R}$ and $\hat{S}$ are the amplitudes and $\boldsymbol{k}_r$ and $\boldsymbol{k}_s$ are the wave vectors of the reference beam R and the signal beam S, respectively. When illuminating the crystal with a signal beam

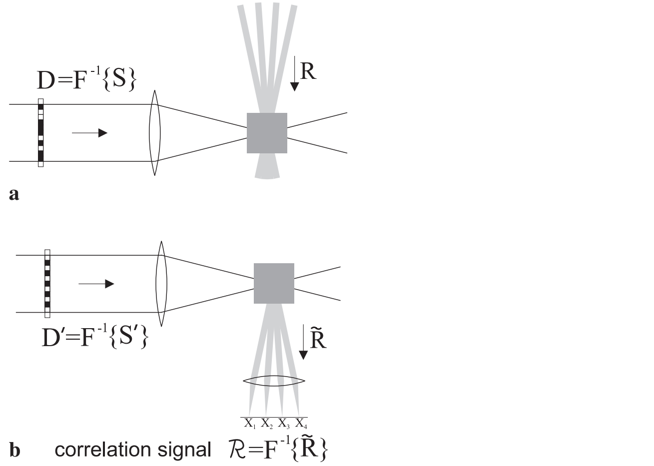

FIGURE 2 **a** Storing the Fourier transform of a data page D by interference with a set of four plane reference waves R in the crystal. **b** Addressing the crystal with a data page D' results in the reconstruction of four reference waves $\tilde{R} \propto R$. With an inverse Fourier transformation the correlation peaks can be detected at the positions x_i

$$S' = \hat{S}'\,\mathrm{e}^{\mathrm{i}\boldsymbol{k}_s\boldsymbol{r}}, \tag{2}$$

the output signal is given by the multiplication of (2) and (1):

$$S'\Delta n \propto S' \cdot \left(\hat{S}\hat{S}^{*} + \hat{R}\hat{R}^{*}\right) + \hat{S}'\hat{R}\hat{S}^{*}\mathrm{e}^{\mathrm{i}(\boldsymbol{k}_s+\boldsymbol{K})\boldsymbol{r}} + \hat{S}'\hat{S}\hat{R}^{*}\,\mathrm{e}^{\mathrm{i}(\boldsymbol{k}_s-\boldsymbol{K})\boldsymbol{r}}. \tag{3}$$

The first term on the right-hand side is the transmitted part of S'. The third term produces a twin image in the direction of $\boldsymbol{k_s} - \boldsymbol{K}$ as it typically appears during holographic read out. Here it will not be detected. The second term means the reconstruction of the reference beam used for storing that particular data page and can be written as

$$\tilde{R} \propto S' S^{*} R = \hat{S}'\hat{S}^{*}\hat{R}\,\mathrm{e}^{\mathrm{i}(\boldsymbol{k}_s+\boldsymbol{K})\boldsymbol{r}} = \hat{S}'\hat{S}^{*}\,\hat{R}\,\mathrm{e}^{\mathrm{i}\boldsymbol{k}_r\boldsymbol{r}}. \tag{4}$$

Since the amplitudes S and S' are equal to the Fourier transforms of the data pages D and D', the reconstructed reference beam in Fourier space is generally given by

$$\tilde{R} \propto R \cdot S^{*} \cdot S' = R \cdot F^{*}\{D\} \cdot F\{D'\}. \tag{5}$$

Applying the convolution theorem, this can be transformed into the spatial domain:

$$\tilde{R} \propto R \otimes F\left\{D * D'\right\}, \tag{6}$$

and the inverse Fourier transform $F^{-1}\left\{\tilde{R}\right\}$ leads to the signal appearing on the detector:

$$\mathcal{R} = F^{-1}\left\{\tilde{R}\right\} \propto \delta(x_0) \otimes (D * D'). \tag{7}$$

This means that the pure correlation signal is detected, since the plane reference waves appear as delta functions due to the inverse Fourier transform operation.

The actual correlation signal is also dependent on the multiplexing method used for storing several data pages at one location in the crystal. In the case of angular multiplexing, i.e. storing each data page by a single reference wave incident from different directions, the refractive-index modulation after storing N holograms is given by:

$$\Delta n \propto \sum_{i=1}^{N} R_i \cdot S_i^*, \tag{8}$$

where only the correlation-relevant term has been taken into account and the index i corresponds to the different angles of incidence of the reference wave. Now the deflected signal, when addressing the crystal with a data page D' (i.e. S' in the Fourier domain), has to be written as

$$\tilde{R} = \left(\sum_{i=1}^{N} R_i \cdot S_i^* \right) \cdot S' \tag{9}$$

$$= \sum_{i=1}^{N} R_i \cdot F \left\{ D_i * D' \right\}. \tag{10}$$

Then the correlation of the input data page D' with all stored data pages D_i can be detected in the focus of the inverse Fourier transform lens:

$$\mathcal{R} = F^{-1} \left\{ \sum_{i=1}^{N} R_i \cdot F \left\{ D_i * D' \right\} \right\} \tag{11}$$

$$= \sum_{i=1}^{N} \left(\delta(x_i) \otimes \left(D_i * D' \right) \right). \tag{12}$$

The correlation peaks will be deflected in the direction of the appropriate reference wave and appear spatially separated at the positions x_i on the detector. The number of correlation signals is equal to the number of stored data pages. The intensities of these peaks are proportional to the strength of the correlation. Therefore the stored page which fits best to the page used for addressing (D') yields the brightest signal and in the case of an exact matching of D' with one stored page one actually detects the auto-correlation signal.

When performing phase-code multiplexing, all data pages will be stored by the use of all reference waves simultaneously (each one having a certain phase shift) and the refractive-index modulation after storing N holograms is given by the sum over the reference waves:

$$\Delta n \propto \sum_{i=1}^{N} \sum_{j=1}^{N} R_j \, \mathrm{e}^{\mathrm{i}\Phi_{ij}} \cdot S_i^*, \tag{13}$$

where again only the correlation-relevant term has been considered and the phase code ($\Phi_{i1}, \ldots, \Phi_{iN}$) corresponds to the address of the data page S_i in the crystal. Hence the correlation of the N stored pages with an input page $S' = F\{D'\}$ is given by

$$\tilde{R} \propto \left(\sum_{i=1}^{N} \sum_{j=1}^{N} R_j \, \mathrm{e}^{\mathrm{i}\Phi_{ij}} \cdot S_i^* \right) \cdot S' \tag{14}$$

$$\propto \sum_{i=1}^{N} \sum_{j=1}^{N} \left(R_j \, \mathrm{e}^{\mathrm{i}\Phi_{ij}} \cdot F\{D_i * D'\} \right), \tag{15}$$

and therefore the signal detected in the focus plane of the Fourier lens will be

$$\mathcal{R} = F^{-1}\{\tilde{R}\} \tag{16}$$

$$\propto \sum_{i=1}^{N} \sum_{j=1}^{N} \left(\delta(x_j) \otimes \left[\mathrm{e}^{\mathrm{i}\Phi_{ij}} \cdot (D_i * D') \right] \right). \tag{17}$$

In comparison to the case of angular multiplexing, here another sum comes into play for the detected correlation signal, which is due to the fact that all data pages have been stored by the use of all reference waves. Additionally there appears a phase factor which corresponds to the phase codes used for storing.

Considering the equations for $\mathcal{R}$ ((11) and (16)), the difference between the expected correlation signals for angular and phase-code multiplexing becomes obvious. Figures 3 and 4 show the correlation signals when assuming a content-addressed read out with the second data page. The bits of the data pages are assumed to be randomly distributed over the pages.

The correlation signal when performing angular multiplexing yields always one peak with a high intensity, which corresponds to the auto-correlation signal, see Fig. 3. The other peaks are produced by the cross correlation of the input data and all other stored pages. In the example, when addressing with the second page, the peak with highest intensity appears at the position of the second reference wave. When

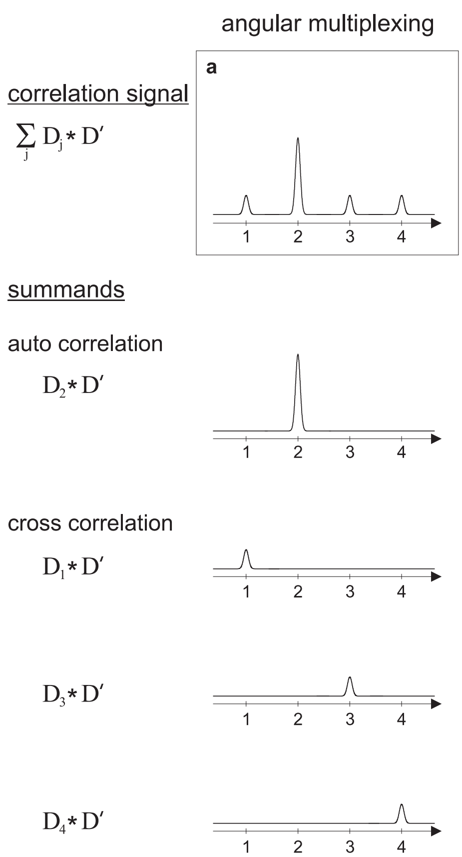

FIGURE 3 Composition of the correlation signal when addressing with the second data page for the case of angular multiplexing

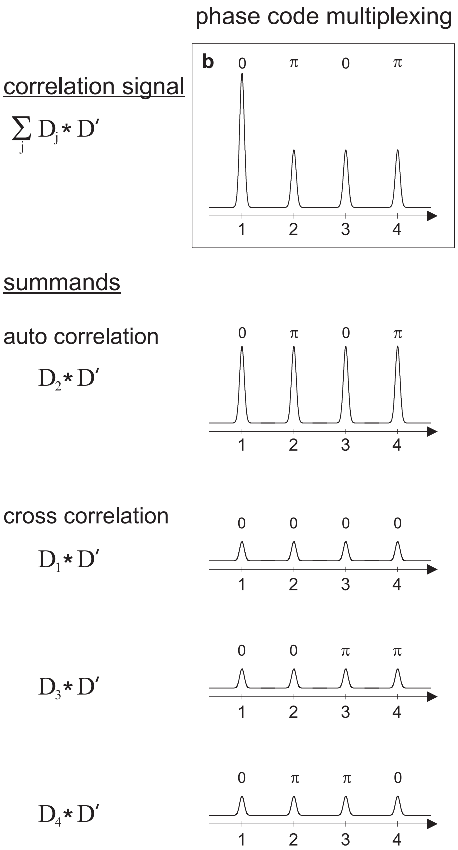

FIGURE 4 Composition of the correlation signal when addressing with the second data page for the case of phase-code multiplexing

addressing with the ith page the peak with highest intensity appears at the position x_i on the detector.

In the case of phase-code multiplexing the intensity distribution of the detected signal will always look the same as shown in Fig. 4 when using orthogonal phase codes. The information regarding which data page was used for addressing the storage medium is only contained in the phase distribution of the peaks.

Therefore, when using angular multiplexing it is straightforward to tell which data page was used for addressing the storage medium simply by looking at intensity measurements. When using phase-code multiplexing the intensity distributions always look the same and it seems not possible to deduce the address of an input data page from such simple intensity measurements. In the following we describe two techniques on how to overcome this problem.

3 Database search in a phase-encoded system

The parallel correlation of any input data and all stored data pages offers a great potential for fast searches in large databases. Such content-addressed memories are of special interest for searching in digital databases, when a bit pattern is the actual search key. That search key can be of the size of a whole data page or just a portion of it. This input data will be compared instantaneously to all stored data pages and the result is contained in the correlation pattern. In order to deduce the proper address of the input data the diffraction efficiency of all stored holograms has to be equal, since otherwise the intensity of a cross-correlation signal could be higher than the one of the auto-correlation signal. In the case of digital data pages this can be achieved by using modulation codes which ensure equal intensities for all pages.

3.1 *Signal-to-noise ratio of the correlation*

The signal-to-noise ratio is a quantitative measure of the quality of associative recall. It is defined as the ratio of the intensities of the auto-correlation signal and the cross-correlation signal and can be statistically calculated.

The whole hologram can be considered to consist of several sub-holograms. During recording each 'On'-bit writes one sub-hologram by interference with the reference beam and during reconstruction each 'On'-bit reads out that appropriate sub-hologram. Hence the correlation signal is given as the coherent addition of the light deflected by all of these sub-holograms. The data pages are assumed to consist of randomly distributed bits and to be modulation-encoded to ensure constant intensity or brightness per page. A measure of the intensity is given by the sparseness h, defined as the ratio of the number of 'On'-bits to the total number N of bits per page, i.e. one page contains $N \cdot h$ 'On'-bits. The transmitted light per 'On'-bit, having the amplitude A_{in}, is deflected by the corresponding sub-hologram with a diffraction efficiency α. Then the amplitude and the intensity of the auto correlation are given by

$$A_{\text{auto}} = \sum_{i=1}^{Nh} (\alpha \cdot A_{\text{in}}) = \alpha \cdot A_{\text{in}} \cdot N \cdot h, \tag{18}$$

$$I_{\text{auto}} = A_{\text{auto}}^2 = (\alpha \cdot A_{\text{in}} \cdot N \cdot h)^2 . \tag{19}$$

The amplitude of the cross correlation is given by the sum over $N \cdot h$ discrete random variables

$$A_{\text{cross}} = \sum_{i=1}^{N \cdot h} x_i , \tag{20}$$

where

$$x_i = \begin{cases} \alpha \cdot A_{\text{in}} & \text{occurs with probability} \quad h \\ 0 & \phantom{\text{occurs with probability}} \quad 1-h . \end{cases} \tag{21}$$

This leads to the cross-correlation intensity

$$I_{\text{cross}} = A_{\text{cross}}^2 = \sum_{i=1}^{N \cdot h} \sum_{j=1}^{N \cdot h} x_i x_j . \tag{22}$$

The signal-to-noise ratio of the correlation is given by the ratio of the auto correlation and the mean value of the cross correlation:

$$\text{SNR} = \frac{I_{\text{auto}}}{\langle I_{\text{cross}} \rangle} . \tag{23}$$

The mean intensity of the cross correlation can be calculated to be

$$\langle I_{\text{cross}}\rangle = \left\langle \sum_{i=1}^{N\cdot h}\sum_{j=1}^{N\cdot h} x_i x_j \right\rangle \tag{24}$$

$$= \sum_{i=1}^{N\cdot h}\left\langle x_i^2\right\rangle + \sum_{i=1}^{N\cdot h}\sum_{\substack{j=1\\ j\neq i}}^{N\cdot h}\left\langle x_i x_j\right\rangle . \tag{25}$$

With the probability functions of the random variables x_i^2 and $x_i x_j$:

$$x_i^2 = \begin{cases} (\alpha A_{\text{in}})^2 & \\ 0 & \end{cases} \quad \text{occurs with probability} \quad \begin{matrix} h \\ 1-h. \end{matrix} \tag{26}$$

$$x_i x_j = \begin{cases} (\alpha A_{\text{in}})^2 & \\ 0 & \end{cases} \quad \text{occurs with probability} \quad \begin{matrix} h^2 \\ 1-h^2. \end{matrix} \tag{27}$$

the mean intensity of the cross correlation becomes

$$\langle I_{\text{cross}}\rangle = Nh\cdot h\alpha^2 A_{\text{in}}^2 + \left[(Nh)^2 - Nh\right]\cdot h^2\alpha^2 A_{\text{in}}^2 \tag{28}$$

$$\approx N^2 h^4 \alpha^2 A_{\text{in}}^2 \;\text{ if }\; N \gg \frac{1-h}{h^2}. \tag{29}$$

The latter approximation is valid if the number of bits per search key N is not too small.

Finally, the signal-to-noise ratio can be written as

$$\text{SNR} = \frac{I_{\text{auto}}}{\langle I_{\text{cross}}\rangle} = \frac{N}{1+Nh^2-h} \approx \frac{1}{h^2}\left(N \gg \frac{1-h}{h^2}\right) \tag{30}$$

and is only dependent on the sparseness of the data pages and hence of the modulation code used.

3.2 *Searching in a digital database*

Figure 4 shows the composition of the correlation signal. When using Walsh–Hadamard codes (for four pages these are (0, 0, 0, 0), (0, π, 0, π), (0, 0, π, π), (0, π, π, 0)) the first correlation spot with the highest intensity is produced by the constructive interference of all reconstructed components for the first reference wave, since these parts all possess the same phase. When making use of the whole code all other correlation spots are created by destructive interference of all cross-correlation signals, resulting in zero intensity, accept one which will actually weaken the auto-correlation signal by destructive interference. Normalizing the auto-correlation intensity to be 1, the intensities of the first peak and of all other peaks are given by $(1+[N-1]\cdot h)^2$ and $(1-h)$ respectively.

The idea of avoiding a complicated phase measurement is not to use the whole code for data storage, but replacing one of the data pages during storing by a page having either a sparseness of $h=1$ (complete bright page) or a sparseness of $h=0$ (complete dark page). In these cases the composition of the correlation signal by destructive and constructive interference is 'disturbed'. Now the intensity distribution of the correlation spots clearly identifies the address of the input data page as explained below.

3.2.1 Storing a data page with sparseness 0. The first option for realizing a database search in a phase-encoded system without measuring phases is to 'store' one data page with zero intensity, i.e. leaving out one of the phase codes. In comparison to the case where all phase codes are used for data storage, now one of the cross-correlation signals is missing and the resulting intensity distribution of the correlation peaks is dependent on the input data. This is sketched in Fig. 5 for the storage of three data pages and leaving out the fourth (Walsh–Hadamard) code. By identifying the peak with the lowest intensity it is now straightforward to tell which data page was used for addressing the storage medium. The first correlation peak has an intensity dependence on the number of stored holograms: $(1+[N-2]\cdot h)^2$. The intensity of all other maxima is equal to the auto-correlation intensity, since the cross-correlation signals interfere destructively. The minimum has the intensity $(1-2h)^2$. Therefore the signal-to-noise ratio of this method is given by

$$\text{SNR} = \frac{1}{(1-2h)^2}, \tag{31}$$

and is independent of the number N of stored holograms. The number of the minima that have to be detected for an unambiguous assignment of the storage address to the input data is given by $N/2-1$. In the example of four stored pages there appears only one minimum.

To judge this method of associative recall in a volume holographic storage system based on phase-code multiplexing, its signal-to-noise ratio is compared to the case when angular multiplexing is used. In Fig. 7 the graphs of the signal-to-noise ratios versus sparseness are plotted. It turns out that for a sparseness larger than 0.33 a content-addressed search

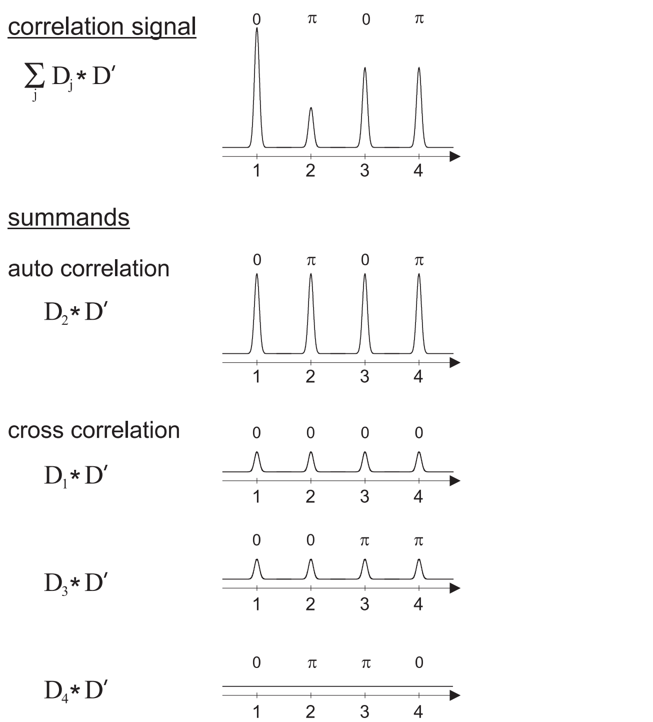

FIGURE 5 Composition of the correlation signal when addressing with the second data page and leaving out the fourth code

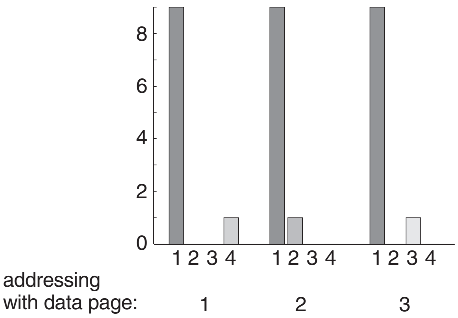

FIGURE 6 Histograms of the expected intensities of the correlation signal when storing a page with sparseness 1 with the fourth code. The sparseness of the data pages was assumed to be 0.50

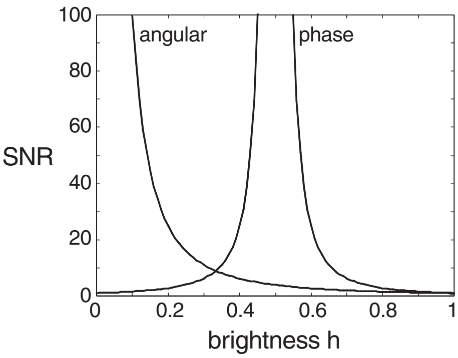

FIGURE 7 SNR versus sparseness of associative recall for angular multiplexing ($\mathrm{SNR} = 1/h^2$) and phase-code multiplexing ($\mathrm{SNR} = 1/(1-2h)^2$)

in a phase-coded memory system results in a higher signal-to-noise ratio. Particularly for a sparseness of 0.5 of the data pages, this technique gives rise to high signal-to-noise ratios.

3.2.2 Storing a data page with sparseness 1. To consider this method, one phase code is used to store a page whose bits are all 'On'-bits, i.e. its sparseness is $h = 1$. All other phase codes are used to store data pages containing digital information assumed to be modulation-encoded in order to guarantee constant sparseness. During associative recall the bright page always gives rise to a correlation signal that corresponds to the auto correlation of the input data. The intensities of the correlation signals can again be calculated by considering the constructive and destructive interference effects. Figure 6 shows the resulting intensity distributions of the correlation peaks when addressing the memory with one of the stored data pages in dependence on the sparseness. It is assumed that three data pages and a fourth page having maximum intensity (i.e. $h = 1$) have been stored by the use of the Walsh–Hadamard code for $N = 4$. It shows that two correlation signals completely disappear due to destructive interference. Again at the position corresponding to the first reference wave always appears the strongest correlation signal, possessing an intensity of $(2 + [N-2] \cdot h)^2$ (normalized to an auto-correlation intensity of 1). The second remaining signal appears at different positions on the detector when addressing with different data pages. Its intensity is given by $(N/2 - 1)$, which is independent of the number N of stored pages. The detection of that signal clearly identifies the address of the input data in the storage medium. Therefore, the theoretical signal-to-noise ratio would be infinity and independent of the sparseness of the data pages. In reality there will be always some noise, so that the quality of the search will actually be dependent on the intensity of these correlation signals. It turns out that the expected signal-to-noise ratio decreases when the sparseness of the data pages is increased. This is mainly due to the fact that the amplitude of the cross correlation is equal to the sparseness of a data page, resulting in a quadratic dependence for the intensity of the cross correlation [25]. The number of maxima to be detected for clearly identifying the storage address of the input data for this method is given by $(N/2 - 1)$.

4 Experimental results

For showing proof of principle we have built a simple setup (see Fig. 8). The laser beam of wavelength 514 nm is divided into a signal beam and a reference beam. In the reference arm the beam is further split in order to realize four plane reference waves incident on the storage medium. The phases of these reference waves can be adjusted with a phase mask corresponding to the Walsh–Hadarmard code for $N = 4$. The data pages presented as photographic slides in the signal arm had a sparseness of 0.25. The storage medium was an iron-doped $LiNbO_3$ crystal.

For experimental demonstration of content-addressed recall in a phase-coded system we stored three data pages and left out the fourth one (see Sect. 3.2.1). After storing the data the crystal was addressed one after another with the three stored data pages. Figure 8 shows the detected correlation signals and the corresponding intensity histograms. The poor signal-to-noise ratio was actually produced by the low quality of the implemented phase mask. The arrows mark the pos-

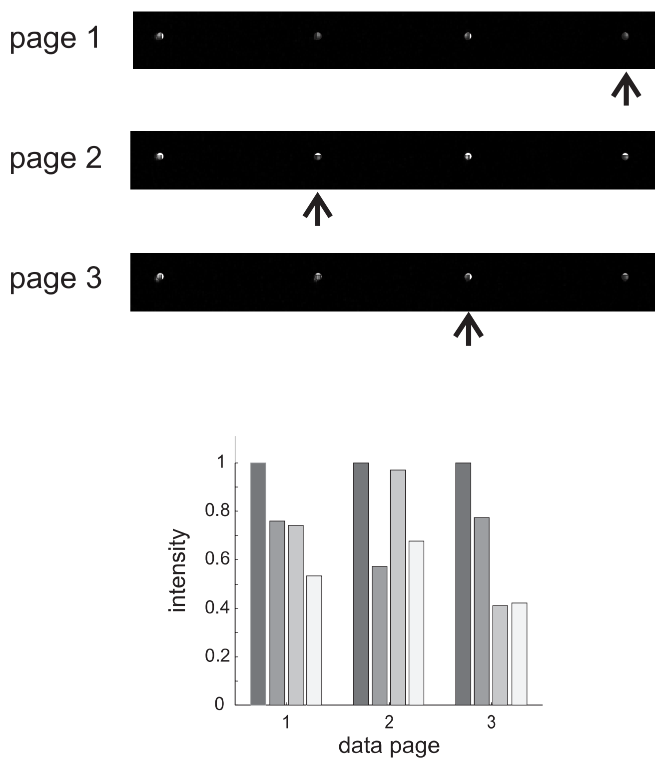

FIGURE 8 Storage and associative recall by leaving out the fourth code (sparseness of the data pages $h = 0.25$)

itions of the correlation peaks with the lowest intensity. Despite the poor signal-to-noise ratio the experiment does yield the correct results, i.e. the storage addresses of the input data could clearly be identified. Numerical simulations based on (16) showed exact agreement with the obtained experimental results when introducing phase errors up to 20%.

5 Conclusion

We have presented two techniques for realizing a content-addressed memory system based on phase-code multiplexing by simple intensity measurements and, therefore, we overcame the problem of phase detection. This is achieved by storing one page with a sparseness of either 1 or 0. Comparing the signal-to-noise ratios for different signal-beam intensities, the phase-code method works best for an intensity of 0.50.

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