Reliability of associative data search in phase encoded volume holographic storage systems

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***Abstract*— We investigate the characteristics of correlation signals obtained during content addressing under different realistic conditions. For two cases, either addressing with defective data or storing similar data sets, we present for the first time a theoretical approach and experimental results when employing phase-code multiplexing.**

I. Introduction

Volume holographic data storage has been thoroughly investigated during the last decade and demonstrated its potential to become one of the next generation storage technologies (e.g. [1]). Its promising features are mainly achieved by exploiting the Bragg condition, which allows superposition of many holograms in one location of the storage media by varying the wavelength or angles of incident of the writing beams. Several superimposing techniques have been proposed, which are combinations or variations of these basic methods and spatial multiplexing (e.g. [2], [3], [4], [5]). Orthogonal phase-code multiplexing is a variant of pure angular multiplexing, in which a discrete number of reference beams are incident on the media from different angles. By means of a spatial light modulator the phase of each of these beams is individually controlled. Between successive recordings, the phases are specifically altered. In order to retrieve a particular data set, the appropriate phases have to be readjusted. Due to the use of orthogonal sets of phase shifts, particular data sets are reconstructed without crosstalk. This technique offers several advantages [6]. Most notably it avoids moving components in the storage setup and provides a signal-to-noise ratio that is two orders of magnitude higher than the case of pure angular multiplexing [7]. Moreover, the special characteristics of orthogonal phase encoding offer the opportunity to perform optical arithmetic operations, i.e. addition, subtraction and inversion, and to implement highly secure address-based data encryption techniques [8], [9].

However, the steadily enormous growing storage demands also require effective database search routines, especially in high capacity systems, in which conventional data search becomes inconveniently slow. Volume holographic storage systems provide an efficient parallel search method by allowing content-addressed readout based on optical correlation. This technique has been demonstrated in systems based on angular or phase-code multiplexing [10], [11].

Here we investigate the impact of real conditions on the received correlation signals. We discuss two cases in which either the stored data possess various degrees of similarity or the storage media is addressed with defective data pages. Finally the results will be compared to the case when angular multiplexing is employed.

II. Content addressing in volume holographic storage systems

During the storage process actually the Fourier transformations of data pages, represented by a 2-D amplitude modulator in the signal arm, are recorded and superimposed in one location of the storage media, Fig. 1a. In order to perform associative recall, the media is addressed with some data page D', Fig. 1b. This page is correlated in the Fourier

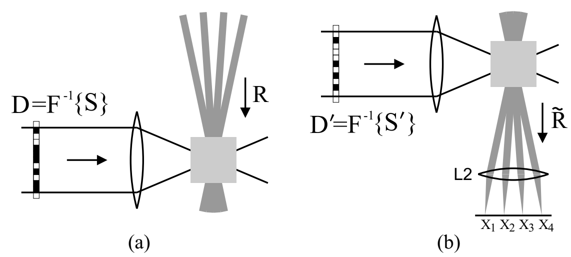


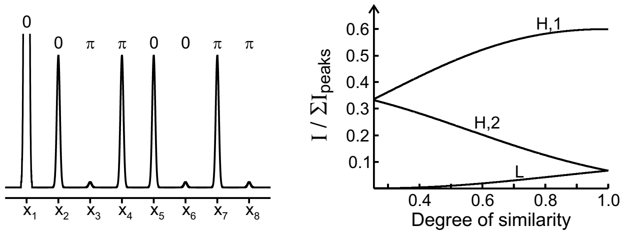
Fig. 1. Volume holographic data storage and retrieval: (a) Recording process; (b) Content addressing yielding correlation signals

domain with all previously recorded pages. If the input page equals a specific stored data page, an exact facsimile of the reference wave, used to store that page, is reconstructed. The pure correlation signal can be accomplished by performing an inverse Fourier transformation, cf. lens L2 in Fig. 1b. The resulting correlation signal, whose actual appearance depends on the used multipllexing technique, can be computed by applying the convolution theorem [11].

In the case of phase-code multiplexing, when storing the i-th of N data sets with the reference wave j (bearing the phase shifts Φ_{ij}), the correlation signal is given by [11]

$$\mathcal{R} \quad \propto \quad \sum_{i=1}^{N}\sum_{j=1}^{N}\left(\delta(x_j)\otimes\left[\, e^{i\Phi_{ij}}\cdot(D_i * D')\right]\right) \quad , \qquad (1)$$

where $\otimes$ and $*$ stand for the convolution and correlation respectively. Due to the inverse Fourier transformation the plane



(a) (b)

Fig. 2. Simulated correlation signals. (a) 8 pages are stored and the third page is used for addressing (40% ON pixels per page). (b) Two discrete correlation peak intensities $H_{1,2}$, dependent on the degree of similarity k of two of the stored pages (25% ON pixels per page).

reference beams appear as δ-functions spatially separated at the points x_i on the detector. The number of correlation peaks corresponds to the number of multiplexed pages.

It turns out that the intensity distribution of the correlation signal remains unchanged if the media is illuminated with a signal wave corresponding to any of the stored pages. Considering the same situation in a system based on angular multiplexing, the correlation peaks consist of one auto and $N-1$ cross correlation signals. Hence simple intensity measurements enable associative recall. Nevertheless, characteristic intensity distributions in phase encoded systems achieved if (at least) one of the stored pages is complete black or white [11]. That means when using N reference beams actually N-1 data sets can be recorded at one location. Then the correlation signal consists of high and low peaks (besides the first peak, which contains no useful information), emerging from constructive and destructive interference of auto and cross correlation signals. An example is sketched in Fig. 2a where 7 data pages were recorded, using 8 reference beams, and the media is addressed with the third page. In comparison to angular multiplexing it turns out, that the contrast of the relevant correlation peaks is better for phase code multiplexing, if the fraction of ON pixels in the data pages exceeds 0.33.

III. Defective data pages

Illuminating with not exactly matching data pages is a rather typical case for a real storage application. This may occur for instance due to system noise or due to an incomplete input information by the user. If the storage system is addressed with such a page again (cf. Fig. 2a) only two discrete intensities of the correlation peaks are measured. If k denotes the degree of similarity of the addressing page with some stored data page the intensities of the correlation peaks can be computed to be:

$$P_H = (1+k-2h)^2,\ P_L = (1-k)^2, \qquad (2)$$

where h denotes the fraction of ON pixels in the stored data pages and $P_{H,L}$ corresponds to a high and low peak intensity. It turns out that the contrast remains better than 100:1, if the amount of defective data is less than 14%.

IV. Correlated data pages

In a real storage system it is also quite common that similar data sets occur. This is for instance accomplished by an user who stores several backup copies with marginal changes on the media. Additionally the involved data encoding scheme may give rise to similar effects. In such cases the detected intensities of the correlation peaks have more than two discrete values. Actually the P_H split into several values $P_{H,i}$ as indicated in the simulation in Fig. 2b. In that case 7 data pages and an additional white page have been recorded by means of 8 reference beams. If addressing with an exact match of a particular page, the intensities of the correlation peaks are given by

$$\begin{aligned} P_{H,1} &= (2+k-3h)^2,\ P_{H,2} = (2-k-h)^2, \\ P_L &= (k-h)^2, \end{aligned} \qquad (3)$$

where k now denotes the similarity of stored pages (in this simulation of two pages). While k grows from the pure statistical correlation, in this case $k = 0.25$, to values of $k \approx 0.4$, the contrast still remains better than 100:1. However, if the similarity of stored pages reaches $\approx 80\%$ the contrast becomes insufficient for unambiguously assigning a stored page to the input data. In such a case the correlation signal may be interpreted to yield an hit list of the most matching entries.

V. Conclusion

In our presentation we will discuss the characteristics of associative recall in a volume holographic storage system based on phase code multiplexing under realistic conditions. It turns out that the system is very robust to typical distortions as they would occur in real systems. In order to classify the performance of associative recall when employing phase encoding, we will also present results of angular multiplexing, achieved in the same volume holographic setup.

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