PHASE-MODULATED SPARSE-GRAY-LEVEL DATA PAGES FOR HOLOGRAPHIC DATA STORAGE

Bhargab Das*, Joby Joseph, and Kehar Singh
Photonics Group, Physics Department, Indian Institute of Technology Delhi, New Delhi-16
*Email: - bhargab.das@gmail.com

Abstract: A new method is proposed for the implementation of sparse-gray-scale block modulation codes with a spatial light modulator in phase mode, for holographic data storage. Sparse data pages promise higher recording densities with reduced consumption of the dynamic range of the recording material, and reduced inter-pixel crosstalk. A balanced sparse-gray-level phase data page gives a homogenized Fourier spectrum, which is regarded to be necessary for suitable exploitation of the holographic recording medium. Construction rule for sparse three-gray-scale phase data pages, read-out methods, and inter-pixel crosstalk are discussed in detail.

1. INTRODUCTION
Holographic data storage (HDS) [1] is envisioned as one of the promising next generation storage technologies for disk based optical storage systems. It provides high storage densities, fast data transfer rates with extremely short data access times and content-addressable searches [1]. These features are achieved through the page oriented storage principle, and by using different multiplexing schemes.

Over the past few years, rapid progress has been made in the concepts, materials, components, and data detection schemes. However, the storage of 1 Tbytes on a 12 cm disc with data transfer rates near 1 Gbps still remains a challenge. We propose a new method to format binary user data using sparse-gray-scale modulation codes into two-dimensional (2D) optical pages, leading to higher data density on the holographic medium. This new input data page representation meets multiple objectives such as Fourier DC peak suppression, inter-pixel crosstalk reduction, and storage density improvement.

2. HOMOGENIZED FOURIER SPECTRUM FOR PHASE-MODULATED SPARSE-GRAY-LEVEL DATA PAGES
Sparse data pages where the number of ‘ON’ pixels is much smaller than ‘OFF’ pixels are investigated for holographic storage systems [2]. The essence of sparse data pages lies in the fact that storing a smaller number of ON pixels reduces the optical exposure per page during recording. This results in the consumption of less dynamic range of the recording material per page, and leads to an increased number of stored pages. Further, it has the advantage of lower inter-pixel crosstalk because of the reduced probability of occurrence of worst-case pixel patterns (e. g. blocks of ‘ON’ pixels with a center ‘OFF’ pixel).

Apart from binary encoding, non-binary modulation codes are also studied to encode user binary data into blocks of gray-level pixels for 2D holographic data pages [2]. These earlier studies on sparse-gray-scale data pages have been performed with amplitude mode spatial light modulators (SLM). Using the holographic data pages in the amplitude mode has the problem of a high intensity DC peak occurring in the Fourier transform (FT) plane. Several methods have been proposed to circumvent the problem of DC peak occurring in the FT plane [3-5]. However, none of them is suitable for sparse-gray-scale data pages. Hence we propose a new method to format binary user data using sparse-gray-scale modulation codes into 2D optical pages for holographic storage. In our method, the sparse-gray-scale modulation codes create 2D sparse-gray-scale phase data pages represented by a single phase-only SLM, and produce a homogenized Fourier spectrum.

Fig. 1 Fourier plane spectrum distribution along a one-dimensional cross-section for sparse three-gray-level (a) amplitude and (b) phase data pages.
As an illustration of this new method, Figs. 1(a) and 1(b) show the Fourier plane spectrum distribution along a one-dimensional cross section for three-gray-level amplitude, and phase data pages respectively. It can be noticed that the DC component is greatly suppressed in the case of sparse phase data pages, and becomes comparable to the AC components.

3. CONSTRUCTION OF PHASE-MODULATED SPARSE-GRAY-LEVEL DATA PAGES

Modulation codes are used to encode user binary data into blocks of binary or gray-level pixels, which are used to form a 2D data page [2]. Consider the 15:12 (for three-gray-levels) block-modulation code where 15 bits of user binary data is coded to 12 SLM pixels with unequal but fixed pixel probabilities. Let the imposed constraint be that exactly 8 of the 12 pixels are of level-0, 2 are of level-1, and 2 are of level-2 pixels. The sparseness of this code is 1/3 and the code rate is 0.96. The 8 pixels of gray-level 0 are coded with binary phase gratings [6].

The phase grating representation of one data pixel can be realized on \( n \times n \) SLM pixels, where \( n \) can be 2 or higher. Such a phase grating does not give rise to even diffraction orders and light from these pixels can be blocked by using a low-pass spatial filter in the Fourier plane. The pixels corresponding to gray-level 0 thus behave like OFF pixels in the reconstructed data page. The other gray levels are represented by pixels in orthogonal phase states, where each data bit is represented by \( n \times n \) SLM pixels (\( n \) being the same as that for the phase grating), all set to the same gray-scale level according to the required phase shift. The two pixels of gray-level 1 are represented by \( \pi/2 \) and \( 3\pi/2 \) phase-modulated pixels, and the two pixels of gray-level 2 are represented by 0 and \( \pi \) phase-modulated pixels.

(a) \[
\begin{array}{ccc}
0 & 1 & 2 \\
0 & 0 & 0 \\
1 & 0 & 0 \\
\end{array}
\]  
(b) \[
\begin{array}{ccc}
i & 0 & 1 \\
0 & 0 & 0 \\
-i & 0 & -1 \\
\end{array}
\]

(c) \[
\begin{array}{ccc}
\pi/2 & & 0 \\
3\pi/2 & & \pi \\
\end{array}
\]

Fig. 2. (a) Required sparse three-gray-level data pattern. (b) Required simultaneous phase and amplitude modulations. (c) Special pattern applied to the phase-modulating SLM to realize sparse-gray-level modulation codes.

3. CONSTRUCTION OF PHASE-MODULATED SPARSE-GRAY-LEVEL DATA PAGES

An illustration of the above description is presented in Fig. 2 where the binary phase grating is represented by \( 4 \times 4 \) SLM pixels. The data page constructed in such a way gives a homogenized Fourier spectrum in the recording plane as shown in Fig. 3. The FT of the ON data pixels appears around the optical axis with no zero-order (DC) peak, whereas the FT of the OFF data pixels appears around the four first-order spots at higher spatial frequencies. The red square in Fig. 3 represents the low-pass filter aperture used to limit the size of the hologram, as also to block the light coming from the binary phase gratings used to realize amplitude modulation with phase-modulating SLM.

Fig. 3 Beam intensity distribution in the Fourier plane for a sparse three-gray-level random data page implementing the proposed method. The square represents the low-pass aperture.

4. READ-OUT OF SPARSE-GRAY-LEVEL PHASE DATA PAGES

In order to retrieve all the information contained in the reconstructed data pages, the different phase states have to be discriminated. It is assumed that the sparse three-gray-level phase data pages have been multiplexed. In order to retrieve the user information, in the first step, the desired data page is retrieved by addressing the storage medium with an appropriate reference beam. In this step, no phase information is retrieved and one can only discriminate between the OFF (represented by binary phase grating) and ON (with different phase modulations) pixels.

![Intensity distribution](image)
objective focal length, \( \lambda \) is the wavelength of the light used, and \( d \) denotes the data pixel size. A linear characteristic between the sparsity and the light energy is observed. Results (Fig. 5) are also compared with the amplitude-modulated three-gray-scale data page where the pixel values are OFF, 0.5×ON, and ON. We see that the sparse-phase-based data pages together with the low-pass filter perform in line with the sparse-amplitude data pages, and hence can be faithfully used for HDS.

5. PERFORMANCE OF THE SPARSE-GRAY-LEVEL PHASE DATA PAGES

5.1 Sparsity and Fourier Plane Light Energy

One of the major advantages of implementing the gray-scale 'sparse modulation codes' for holographic storage is that the sparse data pages reduce the consumption of the dynamic range of the recording material. In a sparse data page, the number of OFF pixels is much smaller than the ON pixels, so the amount of light energy in the Fourier plane decreases with the decrease in sparsity. Although this is true for amplitude-modulated data pages where OFF pixels do not transmit any light, we want to show that this also happens in the proposed scheme of phase-modulated sparse-gray-level data pages.

Fig. 5 shows the normalized Fourier plane light energy for three-gray-scale data pages (both amplitude and phase) as a function of the sparsity. Since the use of the low-pass filter is essential for the proposed method, we have used an aperture of size 1.8 \( D_N \), where \( D_N \) is the Nyquist aperture diameter of the data pixels specified as \( \lambda f/d \). Here \( f \) is the.

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**Fig. 4(a)** Histograms of OFF and ON pixels of a sparse three-gray-level phase data page in the first step of the reconstruction.

**Fig. 4(b)** Histogram of only the ON pixels (with phase modulations of 0, \( \pi/2 \), \( \pi \), and \( 3\pi/2 \)) when reconstructed using the RTHI method. The positions of the ON pixels have already been ascertained in the first readout step. In the example shown in Fig. 4(b), it is possible to differentiate unambiguously the different phase states and provide high phase-classification reliability.

**5.2 Effect of Low-pass Filter on the Inter-pixel Crosstalk of the Reconstructed Data Pages**

The low-pass filter is a key component that affects the SNR, the BER, and the storage density of HDS systems. A smaller aperture size (\( D \)) is desirable in order to increase the recording density, since the area

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**Fig. 5** Normalized Fourier plane light energy (a. u.) of three-gray-level data pages for both amplitude and phase modulation as a function of the sparsity of the data pages.
occupied by a hologram page is proportional to the square of $D$. However, as the recorded high-frequency components decrease, the SNR of the HDS system decreases. Accordingly, the number ($N$) of possible holograms multiplexed decreases, as $N$ is proportional to the square root of the SNR.

In the proposed method, the low-pass filter is used to obtain amplitude modulation with a phase-modulating SLM, and also to optimize the storage density. Using the $4f$ system model, we have calculated the BER of the reconstructed data pages for different sizes of the low-pass filter and for different sparseness of the recorded data pages. Fig. 6 shows the BER for three-gray-level phase data page as a function of the low-pass filter size expressed in relation to the Nyquist aperture for data pixel sizes of $4 \times 4$ SLM pixels. Three different sparseness of the data pages are considered for the simulation: 67%, 35%, and 12%.

![Figure 6: BER as a function of the low-pass aperture expressed in relation to the Nyquist aperture.](image)

It can be seen that the BER increases for an aperture size below 1.7 $D_N$. Above this, the BER remains at a constant low level up to an aperture size of about 3.2 $D_N$. The BER increases thereafter, since the light coming from the OFF pixels (represented by binary phase grating) becomes unfiltered at higher aperture sizes. The distinction between OFF and ON pixels smears out slowly as the size of the low-pass filter is increased beyond 3.2 $D_N$. From Fig. 6, we can also notice the improvement in the BER for sparsely encoded data pages. Decreasing the sparsity permits recording of gray-scale data pages with lower aperture sizes. For example, at an aperture size of 1 $D_N$, the 67% sparse data page gives a BER of $1.47 \times 10^{-3}$. However, the 12% sparse data page gives a much lower BER, of $4.44 \times 10^{-3}$. In a practical data storage system, the BER should be of the order of $10^{-3}$, which could be handled by error correction codes and the 12% sparse data page result shown above meets this requirement.

Studies have also been carried out for data pixel size of $2 \times 2$ SLM pixels. The BER value for data pixel sizes of $2 \times 2$ and for 12% sparse data page at 1 $D_N$, is $1.07 \times 10^{-3}$, which is within the reach of standard error correction algorithms.

We have also demonstrated [7] the achievable gain in data density with the proposed method. It has been found that the storage density can be 2 times higher with 12% sparse three-gray-level data pages as compared with data pages where the gray value pixel probabilities are equalized.

6. CONCLUSION

We have suggested a new method for realizing the gray-scale sparse modulation codes with a single phase-modulating SLM producing a homogenized Fourier spectrum for efficient exploitation of the recording material’s dynamic range. The influence of the low-pass aperture size on the BER has been discussed. The recording density can be 2 times higher with 12% sparse data pages and at an aperture size of 1.0 $D_N$.

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