Optics Communications 282 (2009) 2147–2154

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Phase modulated gray-scale data pages for digital holographic data storage

Bhargab Das *, Joby Joseph, Kehar Singh

Photonics Group, Physics Department, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110 016, India

ARTICLE INFO

Article history:
Received 5 November 2008
Received in revised form 23 January 2009
Accepted 19 February 2009

Keywords:
Holographic data storage
Gray-scale data page
Phase modulation
Spatial light-modulator

ABSTRACT

We propose a method for gray level holographic digital data storage by using three gray levels in the phase mode. Gray level data pages are displayed on a SLM operating in the phase mode to obtain a homogenized Fourier spectrum by suppressing the extremely high intensity DC component in the Fourier spectrum of conventional amplitude based binary/gray level data pages. Holographic interferometry has been used to recover the gray level amplitude data page from phase data page. Numerical simulation results are presented for three-gray level data pages. Fourier plane homogeneity, bit-error-rate, storage density, phase modulation error of the SLM, and misalignment tolerances are investigated through computer modeling. A comparison of the present method with the amplitude-modulated gray level case with and without using a phase mask in conjunction with the data page is carried out. An experimental demonstration of the proposed three-gray level phase data page method is also presented.

1. Introduction

Volume holographic digital data storage is an excitingly new topic of wide spread research interests. Page based data storage and the speciality of recording a large number of information carrying data pages in the same location with the help of different multiplexing techniques results in large storage capacity, fast data transfer rates, and short random access times [1,2]. Most of these systems store the hologram at the back focal plane of a Fourier Transforming (FT) lens to achieve optimal storage density. A data page for holographic storage typically uses binary encoding, in which pixels encode two distinct states: ON and OFF corresponding to binary 1 and 0, respectively. The FT of an amplitude-modulated data page gives rise to very high intensity zero-order (DC) spot. Such high intensity peaks are undesirable and require a very large dynamic range from the recording material. If allowed to be present, these high intensity peaks result in the saturation of the recording material. Thus to avoid saturation of the holographic storage material and make effective use of the dynamic range of the material, it is necessary to minimize the DC spot at the Fourier plane.

Apart from binary encoding, gray-scale encoding for holographic digital data storage has been studied theoretically and experimentally [3–5]. Gray-scale encoding, in which each pixel takes one of the ‘g’ brightness levels, affects both the capacity and read-out rate, because each pixel now conveys ($\log_2 g$) bits of data. It has been shown experimentally that the use of three-gray level data pages provides a 30% increase in both the capacity and the read-out rate over the conventional binary data pages [3]. These results have been achieved by using predistortion and inverse filtering technique to suppress the deterministic noise variation among pixels, balanced modulation codes for encoding, and local-thresholding methods for decoding purposes. However with amplitude-modulated gray-scale data pages, the problem of high intensity DC spot still persists. Several methods were proposed to realize the Fourier plane intensity homogenization [6–9] in the case of binary data pages. We propose a gray level phase data page method resulting in intensity homogenization in the FT plane which eliminates the need for cumbersome Fourier plane smoothing devices. The use of phase modulated images has attracted more and more interest among researchers investigating optical Fourier transform based information systems such as page oriented holographic storage. The proposed method is an extension of the binary phase modulated data pixels used for holographic data storage [8]. In case of binary phase modulated data pixels, ON and OFF pixels are represented as 0 and π phase shifts by using a phase Spatial Light Modulator (SLM). A balanced binary data page with equal number of ON and OFF pixels leads to a Fourier spectrum with no DC peak. In the case of gray level data pages, a three-gray level amplitude data page is represented as a 4 level phase information ensuring a smoother Fourier spectrum. Use of phase only input image has the further advantage that all pixels have the same intensity independent of the data they carry. This eliminates the variations of the grating strength for different data pages and provides a better output image homogeneity. An interferometric method [7] can be used to recover the three-gray level amplitude data page from the 4 level phase information.

In Sections 2 and 3 a simple description of the construction of gray level phase data page method is provided with computer

* Corresponding author. Tel.: +91 11 26596547.
E-mail address: bhargab.das@gmail.com (B. Das).

0030-4018/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2009.02.048

simulation results applied to a holographic storage scheme. Results are also compared with the known method of using a random phase mask in conjunction with the data SLM. Theoretical estimation of improvement of the storage density of three gray-scale encoding over that of binary encoding is also provided. In Section 4, the proposed method is investigated for different kinds of errors in the holographic storage system. Finally in Section 5, a first demonstration of the proposed method is presented to show that the method is generally working.

2. Construction of phase modulated gray-scale data pages and their recovery

In case of gray level data pages in the phase mode, one needs an SLM that can perform linear phase-only modulation at least in the $0–2\pi$ region. Such kinds of SLMs have been reported in the literature [10–12]. Previous studies on holographic digital data storage with gray-scale data pages suggest that three gray levels produce the highest capacity in the presence of signal-dependent noise and constant noise floor [3]. However these earlier studies have been performed with amplitude-modulated gray-scale data pages, and hence produce high intensity DC spot in the FT plane. To counter this effect, the experiments were performed with the hologram being recorded away from the Fourier plane [6]. Keeping in mind these earlier studies and knowing the advantages of phase data pages for holographic storage [7], we illustrate here the possibility of obtaining three-gray level data pages using the SLM in the phase mode, and simultaneous intensity homogenization in the FT plane. We limit ourselves to the study of three-gray level data pages only. The proposed scheme requires that each gray level occurs with equal probability, but the separation between the gray level pixels can be accessed as a parameter to optimize the performance. Several multilevel block-based modulation codes were developed for gray level data pages. Consider the 15:12 block code (for $g = 3$) where 15 bits of user data will be coded to 12 SLM pixels and vice-versa [3]. The imposed constraint is that exactly 4 of the 12 pixels be of 0 level, 4 be of level 1, and 4 be level 2 pixels. Now for the gray level phase modulation, the SLM is operated in the phase mode such that the pixels with 0 gray levels give 0 phase shift, pixels with 2 gray level give π phase modulation, and half of the total number of pixels of gray level 1 give $\pi/2$ phase shift and other half give $3\pi/2$ phase shift (Fig. 1). Hence the three-gray level data is displayed as a 4 level phase information. This ensures the phase balance required to remove the DC component.

A data page constructed in such a way has equal number of 0 and π phase modulation pixels, and equal number of $\pi/2$ and $3\pi/2$ phase modulation pixels. Fig. 2a shows the Fourier spectrum of a MATLAB simulated three-gray level phase modulated data page. The corresponding Fourier spectrum of a conventional amplitude based three-gray level data page is shown in Fig. 2b. Since only the DC spot is visible in the Fourier plane intensity distribution in Fig. 2b, we make a plot in the logarithmic scale (Fig. 2c) to visualize the other higher spatial frequencies, wherein the presence of high intensity DC spot at the Fourier plane is clearly exhibited. However, the high intensity DC spot is absent in the phase modulation case due to the destructive interference between the light from all the pixels of the SLM. It is to be noted that the given intensity distributions in Fig. 2 depend on many system parameters such as the data page size, modulation code used, and spatial filtering etc.

After homogenizing the intensity distribution in the Fourier plane for three-gray level data page, the next step is to convert the phase information into amplitude information during the retrieval stage. For this purpose, one can use the real-time-, or the double-exposure holographic interferometric method proposed by Joseph and Waldman [7]. Another method such as the interference between the data page and its copy shifted by integer number of pixels proposed by Koppa [13] is also possible. In the real-time holographic interferometric method, a blank object beam and the reference beam simultaneously illuminate the hologram. The reconstructed object beam, due to the illumination by the reference beam contains fields corresponding to the different phase modulations of the recorded data page. At the same time, a uniform data page (all the pixels in the 0 phase mode or π phase mode) is displayed on the SLM. In this way, the blank object beam from the SLM interferes with the holographically reconstructed object beam at the common image plane on the CCD or CMOS. Fig. 3 depicts schematically the resultant interference which converts the 4-level phase information into three-gray level amplitude information, with the SLM used in uniform 0 phase mode. Thus although a 4-level phase information is recorded, one read-out step is sufficient to access the whole data content of a page. Due to the homogeneous intensity distribution in the Fourier plane, a better recording of all the spatial frequency components is possible in the present case, which may lead to better Signal-to-Noise Ratio (SNR) of the reconstructed page.

Using a 4 level phase SLM, one could use all the four gray states for constructing or encoding the holographic data pages, thereby increasing the data capacity of each page. A similar case has been analyzed by Berger *et al.* [14] with hybrid multinary modulation coded data pages for holographic memories. However such kind of data pages would require multiple read-out steps in order to access the whole data content of a page by classifying the different phase modulated pixels thereby increasing the experimental complexity. Furthermore, any imbalance between the numbers of different phase modulated pixels in a data page would lead to the reappearance of the DC spot with non-uniform intensity profile in the Fourier plane. In the proposed scheme, four phase levels have been used to represent a three-gray level data page with homogenized Fourier plane spectrum, and only one read-out step is sufficient to recover the whole data content of a page. One can go up to any desired gray levels with the proposed method. The constraint is that for each level of gray scale greater than 2, two levels of phase modulation are needed to cancel the DC term, e.g. for 8-level gray scale, $6 \times 2 + 2 = 14$ levels of phase modulations are required. At the same time the holographic data storage system should be able to differentiate these 8 gray scales during the read-out stage for acceptable BER, which might limit the performance of the system in actual applications.

2	0	0	1	0	2	2	0	1	1	2	1

a

π	0	0	$\pi/2$	0	π	π	0	$\pi/2$	$3\pi/2$	π	$3\pi/2$

b

Fig. 1. Principle of three gray level data page generation: (a) 12 pixel block of three gray level data. Each gray level occurs with equal probability and the pixel levels are equally spaced, (b) Corresponding phase modulations in the Spatial Light Modulator (SLM).

3. Simulation results

We have investigated the proposed method by computer simulation using 2-D Fast Fourier Transform (FFT) [15]. The data area of the input SLM is chosen to be 128×128 pixels. The three-gray level data page is generated in such a way that each gray level occurs with equal probability and the pixel levels are equally spaced. For taking into account the nonlinear response of the recording material, we adopt the saturation model scheme for the azobenzene polymers described in Ref. [16]. In a holographic data storage