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Transmission type twisted nematic liquid crystal display for three gray-level phase-modulated holographic data storage systems

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ABSTRACT

Gray-level data pages enhance the storage capacity of holographic data storage systems. A balanced three gray-scale data page in phase mode produces a homogenized Fourier spectrum which is regarded to be necessary for suitable exploitation of the holographic recording medium. A commercially available transmission type twisted nematic liquid crystal display has been characterized for use as a phase spatial light modulator with phase modulation in the range $0–3\pi/2$ at 532 nm wavelength, such that it may be used for holographic data storage with binary as well as three gray-level phase-modulated data pages. Experimental results of the phase and amplitude modulation characteristics of the SLM, Fourier plane homogeneity, and recording of phase-modulated binary, three gray-level data pages and their reconstruction with a real-time holographic interferometric method are presented.

1. Introduction

Twisted nematic liquid crystal (TNLC) display based spatial light modulators (SLMs) are interesting devices which find applications in holographic data storage [1–6] envisioned as one of the promising approaches [7,8] to increase the recording density of optical storage systems. Holographic data storage, which records two-dimensional (2D) patterns called data pages in a thick recording medium, has the advantages of high storage density, fast data-transfer rate, short random access time, and content-addressable search [7–9]. An SLM is one of the most important system components in page-oriented holographic data storage systems (HDSS). It is used for composing a data page prior to the storage. Both phase- and amplitude-modulated data pages are investigated for HDSS, but the phase-modulated data pages (PMDPs) have an advantage over the amplitude data pages. In the Fourier transform (FT) geometry, when data pages are presented in amplitude modulation, the recording material is illuminated very inhomogeneously because of the strong DC peak that is not suitable for hologram recording. However, a balanced binary (equal numbers of 0 and π phase-modulated pixels) PMDP gives a homogenized Fourier spectrum where the high-intensity DC peak is absent which ensures better recording of the data pages [3,10]. Use of PMDPs has the further advantage that the object beam intensity becomes independent of the actual data pattern, thereby eliminating the variation of the grating strength for different data pages.

Data pages for holographic storage typically use binary encoding: for amplitude encoding, pixels are either 'ON' or 'OFF' while for phase encoding, pixels have either '0' or 'π' phase modulation. The maximum code rate that can be achieved with binary encoding is unity when the block size goes to infinity, which limits the data capacity of each page. However, for many storage systems (even for CDs, DVDs, and BDs), the code rate is the best compromise between the storage capacity and error correction. The code rate is usually kept significantly below 1.0 since larger block sizes suffer a sharp bit-error-rate (BER) performance loss due to the phenomenon of error propagation. Thus any further increase in the data page capacity can only be achieved by utilizing more channel states and hence non-binary modulation codes. The use of non-binary or gray-scale data pages for holographic data storage has been investigated by several authors [11–13]. Gray-scale encoding increases the code rate beyond unity, thereby enhancing the capacity of each page and also improving the transfer speed [11,12]. Although known, the use of gray-scale data pages for holographic storage has not been widespread. One possible reason may be the lack of suitable multi-level SLMs. Also these earlier studies on gray-scale encoding are based on amplitude-modulated SLM producing a very sharp DC component at the FT plane which is not desirable. Recently, Berger et al. [13] proposed the use of hybrid multinary modulation codes to increase the data capacity in HDSS, which utilizes combined phase and amplitude modulations to encode the input data pages. However, the degree of homogeneity of the Fourier spectrum resulting from these mixed amplitude and

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phase block modulation codes has not been investigated, and also multiple read-out steps are required to resolve the different phase-modulated pixels. In this paper, we present the implementation of non-binary modulation codes based on phase modulations of the data pixels. The balancing of different phase modulation states in a data page leads to a 'homogenized Fourier spectrum' which is a compulsory requirement for recording highly efficient holograms in the FT plane. At the same time, a single read-out step will be able to resolve the different states without limiting the transfer speed of the system.

In order to compose PMDPs for holographic storage, we need an SLM operating in pure phase mode. SLMs have been characterized previously for holographic data storage with an aim to use them as binary phase modulators [3,4], for hybrid ternary modulation [1,2,4,5], and for phase-code multiplexing [6]. SLMs used for binary PMDPs and phase-code multiplexing require only two levels of phase modulations (0 and π) and can be easily accomplished with reflective type ferroelectric liquid–crystal SLMs [10]. However, SLMs used for hybrid ternary modulation (HTM) require a mixed amplitude and phase modulation characteristics to supply two 'ON' states with equal amplitude and π phase difference, and an 'OFF' state with much lower amplitude. Although three-level modulations are achieved with this method, the recorded and reconstructed data pages are

Table 1
Phase modulation constraints of the 15:12 block modulation code (d = user bits, b = block length, p = no. of phase states, m = no. of amplitude states).

Code	No. of phase states				Code rate	No. of amplitude states after interferometric read-out		
$d:b$	$p_1(0)$	$p_2(\pi/2)$	$p_3(\pi)$	$p_4(3\pi/2)$	$r=(d/b)$	m_1	m_2	m_3
15:12	4	2	4	2	1.25	4	4	4

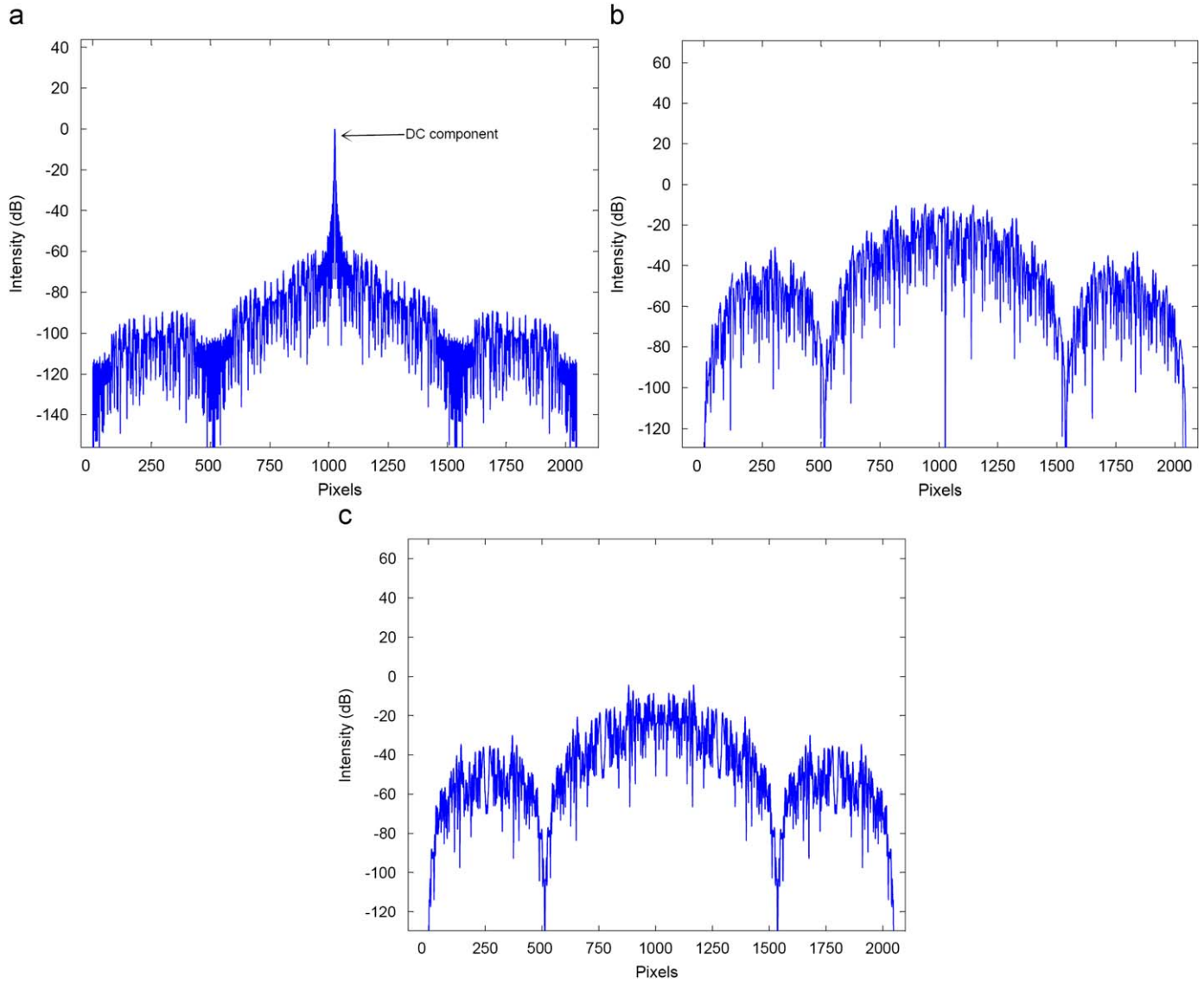

Fig. 1. Simulated results of Fourier plane spectrum distribution: (a) three gray-level amplitude data page, (b) three gray-level phase data page, and (c) three gray-level amplitude data page with pixel matched binary (0 and π) RPM.