Optics Communications 358 (2016) 103–107

Contents lists available at ScienceDirect

Optics Communications

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

Spatial run-length limited code for reduction of hologram size in holographic data storage

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ARTICLE INFO

Article history:
Received 10 June 2015
Received in revised form
20 July 2015
Accepted 30 August 2015
Available online 19 September 2015

Keywords:
Holographic data storage
Run-length limited code
Spatial filtering

ABSTRACT

With holographic data storage (HDS), which is the next generation of optical storage, a Fourier-transformed hologram is usually recorded. As a result, it is characterized by the fact that a smaller high frequency component in the page data corresponds to reductions in the size of the hologram. Therefore, in this study, we have constructed spatial run-length limited (SRLL) codes that have been adapted for HDS, and then evaluated the performance of these codes. By using SRLL codes, it is possible to reduce the high frequency component in the page data with setting run-length bits and narrow the bandwidth with the spatial filtering; therefore, improvements can be expected in the recording density. Utilizing SRLL code, we have shown that it is possible to achieve improvements in the theoretical maximum recording density which are at least double that of instances without SRLL code. Under practical conditions, numerical evaluation results show that there is an increase of least 20%.

1. Introduction

Holographic data storage (HDS) is a next-generation optical storage in which the principle of holography has been applied [1–3]. The HDS allows for the superimposed recording (multiplex recording) of information as a volume hologram on thick media, which makes it possible to achieve a recording capacity that greatly exceeds that of conventional optical discs. The main multiplexing recording methods can be broadly divided into methods that utilize Bragg selectivity and methods that do not use this selectivity. Angular multiplexing [4], wavelength multiplexing [5,6], peristrophic multiplexing [7], and shift multiplexing with spherical reference wave [8–11] are examples of methods that utilize Bragg selectivity; additionally, phase-code multiplexing [12], speckle multiplexing [13], and co-axial shift multiplexing [14] are examples of methods that do not utilize Bragg selectivity. With all of these methods, information that is to be recorded is modulated into two-dimensional page data, and the resulting Fourier-transformed pattern is recoded as a hologram onto a photopolymer medium or other photosensitive recording media. Here, it is important to understand the extent to which the spread of the power spectrum of page data can be suppressed in order to achieve a high recording density. The wavelength of the laser used for recording, the numerical aperture (NA) of the Fourier transform lens, and the pixel size of the spatial light modulator (SLM) can be given as main factors that determine the spread of the power spectrum. Additionally, a Fourier transform optical system is characterized by the fact that the spread of the power spectrum becomes narrow as the high frequency component in the page data is reduced. In this study, we take advantage of this characteristic of a Fourier transform optical system to construct and evaluate highly efficient spatial run-length limited (SRLL) codes for HDS.

The run-length limited (RLL) code is widely used with forms of storage that include hard disk drives (HDDs) as well as optical disks, and setting the minimum values (minimum run-length) and maximum values (maximum run-length) to limit run-length bits allows for the stabilization of sync signals and secures the amplitude of playback signals [15,16]. On the other hand, we apply run-length limited code to HDS in order to set run-length bits for reduction of high spatial frequency components. Run-length bits are set to page data to allow for increases in the apparent pixel size. When the pixel size increases, the power spectrum of page data becomes narrow, and it is therefore possible to expect an increased density by the reduction of the hologram size.

2. SRLL code for HDS

A schematic diagram of the Fourier-transformed hologram recording optical system is shown in Fig. 1. This optical system combines two 4F correlators. Additionally, a spatial filter is installed on the first Fourier transform plane (focal plane) and the recording medium is installed on the second Fourier transform

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http://dx.doi.org/10.1016/j.optcom.2015.08.088
0030-4018/

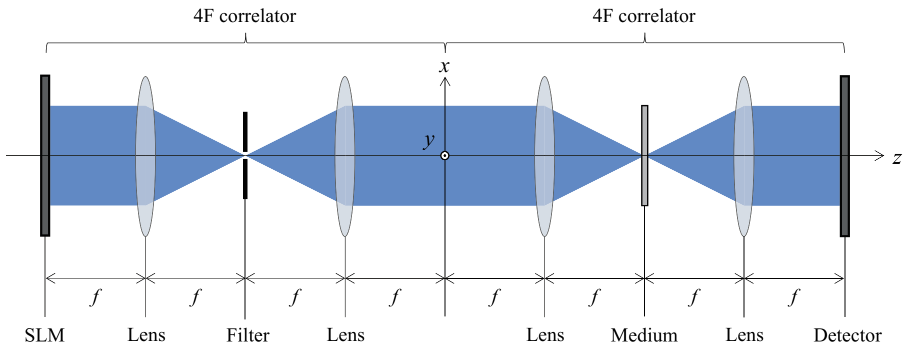

Fig. 1. Fourier-transformed hologram recording optical system.

plane. This filter removes the high frequency component in the page data and is used to limit the size of the Fourier-transformed pattern. SLM pixels are usually square. Therefore, with c as a proportionality constant, the intensity distribution I for the Fourier-transformed pattern can be expressed as [2]

$$I(x, y) = cF^2(x, y)\,\mathrm{sinc}^2\left(\frac{\Delta x}{\lambda f}, \frac{\Delta y}{\lambda f}\right),$$
$$F(x, y) = \sum_{m,n} a_{mn} \exp\left[-j2\pi\left(\frac{mx}{\lambda f} + \frac{ny}{\lambda f}\right)\Delta + j\phi_{mn}\right]. \tag{1}$$

Here, λ is the wavelength, f is the focal length of the lens, Δ is the size of SLM pixels, a_{mn} and ϕ_{mn} are the amplitude and the phase value of each pixel, m and n are pixel indices, and $\mathrm{sinc}(x, y) = [\sin(\pi x)/(\pi x)][\sin(\pi y)/(\pi y)]$. The distance between zero points on the intensity distribution is expressed for the x and y directions as

$$D = 2\frac{\lambda f}{\Delta}. \tag{2}$$

From Eq. (2), it is apparent that the spread of the power spectrum is proportional to the focal length as well as the wavelength and is inversely proportional to the pixel size of the SLM. By using the SRLL code to set the run-length bits for the page data, it is possible to increase the apparent pixel size and suppress the spread of the power spectrum.

In this study, we focus on one-dimensional SRLL codes [17] and evaluate their performance. The bits displayed in each pixel for the SLM ("on" or "off"), and when repeated in the x direction for a minimum of $d+1$ times and a maximum of $k+1$ times, it is noted as the SRLL(d, k) code. In this study, SRLL(d, x) codes that do not set a maximum run-length are used. As an example, raw page data, which are page data that have been coded with SRLL(1, x), and their power spectra are shown in Fig. 2. As shown in Fig. 2(d), by using SRLL codes to reduce the hologram size, improvements in recording density can be expected.

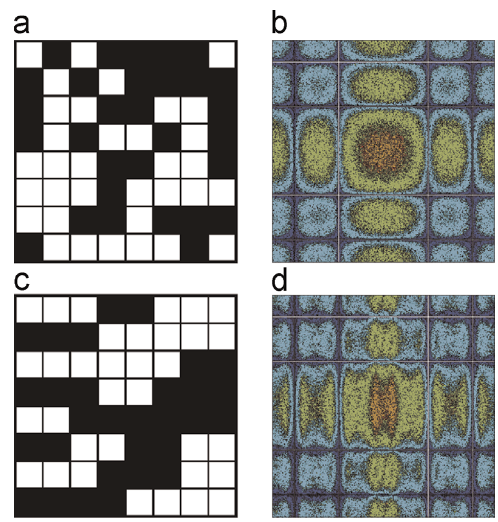

Fig. 2. Examples of page data and their power spectrums: (a) Raw page data. (b) Power spectrum of raw page data. (c) SRLL(1, x) code. (d) Power spectrum of SRLL(1, x) code. It is understood that the spread of the power spectrum was suppressed through the use of the SRLL code.

2.1. Coding efficiency

Next, we will discuss coding efficiency for SRLL codes. Considering an SRLL(1, x) code with a code length of $n \geq 3$, the three-bit ending of the codeword is either (000), (011), (100), or (111). At this time, the number of codewords ending in (000) is expressed as $x_1{}^n$; in the same manner, the number of codes ending in (011), (100), or (111) is expressed as $x_2{}^n$, $x_3{}^n$, or $x_4{}^n$. For example, when n=3, the codewords that are allowed with an SRLL(1, x) code are (000) and (111), so $\boldsymbol{x}^3 = (x_1^3, x_2^3, x_3^3, x_4^3) = (1, 0, 0, 1)$. In a similar manner, when n=4, the allowable codewords are (0000), (0011), (1100), and (1111), so $\boldsymbol{x}^4 = (x_1^4, x_2^4, x_3^4, x_4^4) = (1, 1, 1, 1)$, and when n=5, the allowable codewords are (00000), (11000), (00011), (11100), (00111), and (11111), so $\boldsymbol{x}^5 = (x_1^5, x_2^5, x_3^5, x_4^5) = (2, 1, 1, 2)$. The total number of codewords for SRLL(1, x) codes, which is represented by $M_1{}^n$, is $M_1^n = \sum_i x_i^n$. For $\boldsymbol{x}^n$, the following recursion equation is established

$$\boldsymbol{x}^{n+1} = \boldsymbol{A}\boldsymbol{x}^n \quad (n \geq 3), \quad \boldsymbol{A} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \end{bmatrix}. \tag{3}$$

In Eq. (3), with an initial value of $\boldsymbol{x}^3 = (1, 0, 0, 1)$, $x_1^n = x_4^n$ and $x_2^n = x_3^n$ are established, so Eq. (3) can be simplified as follows:

$$\begin{bmatrix} x_1^{n+1} \\ x_2^{n+1} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} x_1^n \\ x_2^n \end{bmatrix} \quad (n \geq 3). \tag{4}$$

Next, we will consider an instance when an SRLL(2, x) code has a codelength of $n \geq 5$. It is imagined that the last 5 bits of the codeword will be either (00000), (00111), (01111), (10000), (11000), or (11111), and the number of codewords is respectively categorized as $x_1{}^n$, $x_2{}^n$, $x_3{}^n$, $x_4{}^n$, $x_5{}^n$, and $x_6{}^n$. At this time, the initial value is $\boldsymbol{x}^5 = (1, 0, 0, 0, 0, 1)$, so in a similar manner to that of the SRLL(1, x) code, $x_1^n = x_6^n$, $x_2^n = x_5^n$ and $x_3^n = x_4^n$ are established, and it is possible to obtain the following recursion equation: