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Gray Apertures for Holographic Data Storage System

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In this paper, we propose the idea of gray optical apertures in contrast to the conventional binary apertures for holographic data storage (HDS). A gray aperture can be realized by a liquid crystal display or a binary aperture with a coating near the edge. In our simulation, HDS with a gray aperture shows a better page signal-to-noise ratio and modeling accuracy than HDS using a binary aperture. [DOI: 10.1143/JJAP.47.5957]

KEYWORDS: optical storage, holographic, aperture, filter

Holographic data storage (HDS) is a strong contender for next generation optical data storage. It can achieve terabyte capacity by multiplexing, which enables the recording of multiple holograms in same volume.[1)] The optical aperture, acting as a spatial frequency filter, can lead to increased storage density by limiting the holographic recording to specific regions in the medium. In this paper, we employ the idea of gray optical apertures in contrast to the conventional binary apertures for HDS. A gray aperture can be realized by a liquid crystal display or a binary aperture with a coating near the edge. A similar design was proposed by Karpati *et al.*[2)] for coaxial HDS systems, and an optical apodization filter is suggested to reduce the diffraction noise caused by the reference beam in the object area. In this paper we model the aperture as a Fourier-plane filter in the HDS channel, so as to investigate the effects induced by the aperture design. The analysis is performed from the viewpoints of signal processing and channel design. The simulation results show that HDS with a gray aperture gives a better page signal-to-noise ratio (SNR)[3)] and modeling accuracy than HDS using a binary aperture.

We consider some optical aperture functions (OAF), as shown in Fig. 1. For a 4-f HDS system with a focal length of 20 mm and laser wavelength of 405 nm, corresponding point spread functions (PSFs) are calculated and shown in Fig. 1.

Equation (1) below, connecting $a[p,q]$, the data for spatial-light-modulator (SLM), to $r[k,l]$, the output from the charge-coupled device (CCD), is obtained by modifying the well-known HDS simulation equation.[4)] In eq. (1), $g_1(u,v)$ represents the SLM pixel function, D_1 is the SLM pixel pitch, $g_2(u,v)$ represents the shape function of CCD pixel, D_2 is the size of the CCD pixel, and $h(x,y)$ denotes the PSF. Also, n_o and n_e denote the electronic noise and optical noise, respectively.

$$r[k,l] = \iint_{-\infty}^{\infty} \left\{ \left| \left[\sum_{p}^{N} \sum_{q}^{M} a[p,q] \times g_1(x - pD_1, y - qD_1) \right] * h(x,y) + n_o[x,y] \right|^2 \times g_2(x - kD_2, y - lD_2) \right\} dx\,dy + n_e[k,l] \tag{1}$$

We simulated HDS with several different gray apertures (parameterized by β) and we briefly discuss the numerical results. In our simulation, the pixels of SLM and CCD are rectangular with a 64% fill ratio. The Nyquist aperture (W) is 1013 µm.

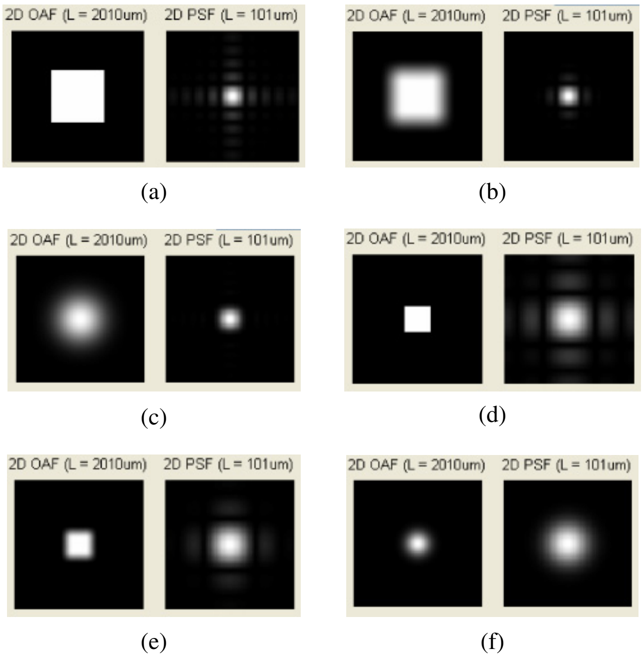

Fig. 1. (Color online) Gray apertures and corresponding PSFs. (a) 800 × 800 µm² binary aperture, (b) 800 × 800 µm² raised-cosine ($\beta = 0.50$) aperture, (c) 800 × 800 µm² Gaussian aperture, (d) 400 × 400 µm² binary aperture, (e) 400 × 400 µm² raised-cosine ($\beta = 0.50$) aperture, and (f) 400 × 400 µm² Gaussian aperture.

We define the effective aperture size as the aperture width through which 95% of the laser power passes. The effectiveness of gray apertures can be evaluated using SNRpage[3)] vs effective aperture plots, as shown in Fig. 2. $\mathrm{SNR}_{\mathrm{page}}$ is a good measure of the separability between the zeros and ones. HDS with gray apertures ($\beta = 0.25$ and 0.5) has a better $\mathrm{SNR}_{\mathrm{page}}$ than HDS with a binary aperture ($\beta = 0$).

In Fig. 2, Zone 2 is close to the Nyquist aperture; thus, e a threshold detector can be applied and the performance is satisfactory. Our simulations yield the distributions of zeros and ones shown in Fig. 3 and the bit error rate (BER) vs $\mathrm{SNR}_{\mathrm{electronic.}}$ plots in Fig. 4. The BER of the gray aperture ($\beta = 0.5$) is better than that of the binary aperture.

The HDS with an aperture in Zone 1 has significant interpixel interference (IPI); hence, it requires advanced

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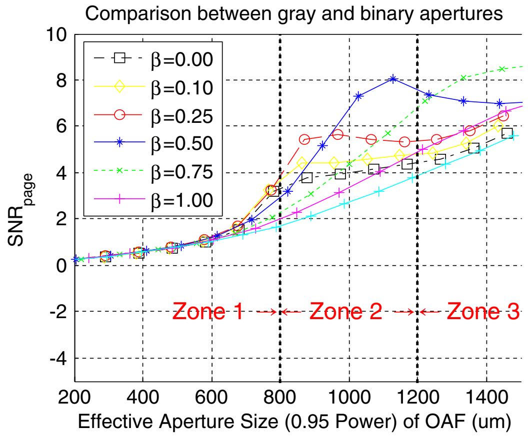

Fig. 2. (Color online) Aperture size vs SNR$_{\mathrm{page}}$.

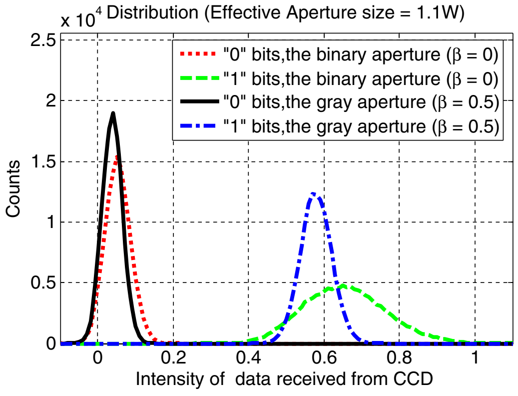

Fig. 3. (Color online) Distributions of "1"s and "0"s.

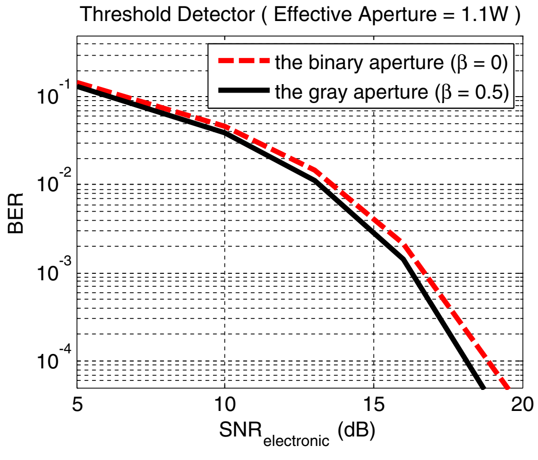

Fig. 4. (Color online) SNR$_{\mathrm{electronic}}$ vs BER.

detectors, such as a decision-feedback equalizer, and a maximum-likelihood detector. In order to utilize these advanced detectors, we need a precise channel model. We can use intensity-modeling and amplitude-modeling schemes[4] to approximate eq. (1), and we then evaluate the modeling accuracy by calculating the normalized mean square error (NMSE)[3] between them.

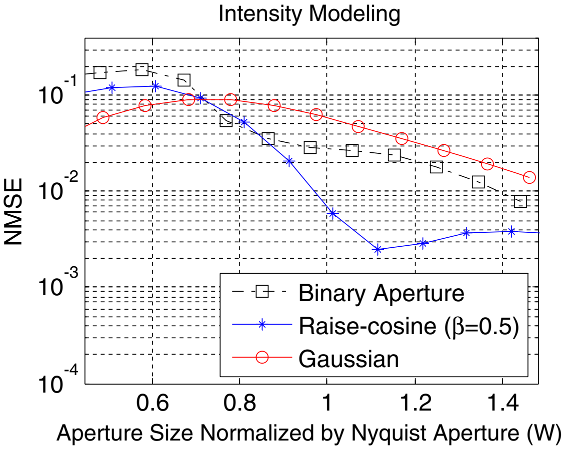

Fig. 5. (Color online) Accuracy of intensity modeling.

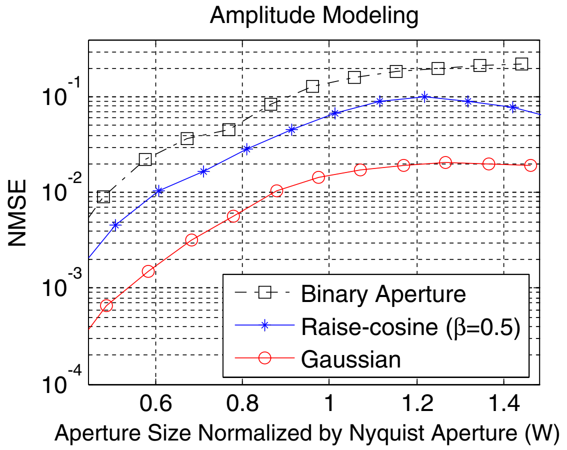

Fig. 6. (Color online) Accuracy of amplitude modeling.

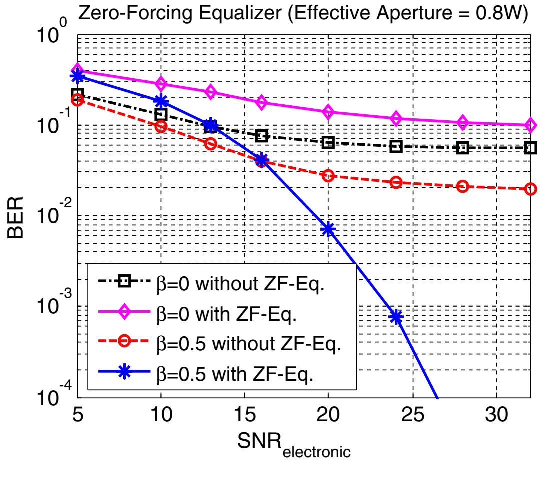

Fig. 7. (Color online) Effectiveness of HDS with gray aperture and ZF equalizer.

The modeling accuracy is compared in Fig. 5 (intensity modeling) and Fig. 6 (amplitude modeling), for three kinds of apertures. The Gaussian aperture has the best accuracy, probably because its PSF has no negative amplitude and there is less phase variation in each CCD pixel. For a Gaussian aperture size of 500 µm, we can achieve accurate modeling (NMSE is only 6.5×10^{-4}).

By applying a gray aperture, we obtain a more accurate channel model to generate detectors. We performed two kinds of application. One was to generate a zero-forcing (ZF) equalizer using the channel model. The ZF equalizer is still effective under a severe IPI, as shown in Fig. 7, because

(a)

0.01763	0.13503	0.26558	0.13503	0.01763
0.13503	1.0341	2.0338	1.0341	0.13503
0.26558	2.0338	4	2.0338	0.26558
0.13503	1.0341	2.0338	1.0341	0.13503
0.01763	0.13503	0.26558	0.13503	0.01763

(b)

Fig. 8. Partial-response channel of HDS with 0.5 W Gaussian aperture: (a) image and (b) value.

the HDS with the gray aperture has more accuracy than HDS with the binary aperture. The other was to generate a partial response channel for a two-dimensional (2D) PRML detector. For the HDS with the 0.5 W Gaussian aperture, the channel model is close to $[1\ 2\ 1]^{T} \times [1\ 2\ 1]$, as illustrated in Fig. 8; thus, the 2D PRML detector can be utilized.[5)]

We presented the idea of gray apertures and showed their effectiveness in terms of $\mathrm{SNR}_{\mathrm{page}}$. When the aperture size is near that of the Nyquist aperture and a threshold detector is adopted, we recommend the use of a raised-cosine aperture ($\beta = 0.5$). Because HDS with this gray aperture exhibits a high $\mathrm{SNR}_{\mathrm{page}}$ and more concentrated distribution of "1" bits, the use of some post processors can be expected to result in superior performance. When a small aperture (<0.7 W) is adopted for achieving high capacity, we suggest the use of a Gaussian aperture. Because they can be used for accurate modeling, we can expect superior performance from advanced detectors.

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