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Effects of cross talk on fidelity in page-oriented volume holographic optical data storage

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Using numerical simulation, we quantitatively examine the effects of cross talk on the recall fidelity of stored binary data in a page-oriented volume holographic memory system. We discuss the trade-off between the signal-to-noise ratio of the reconstructed bits and the optical throughput of the system (i.e., the fraction of the incident beam that is diffracted to the detector plane). We show that significant gains in the signal-to-noise ratio can be achieved with modest decreases in optical throughput in the region where the highest throughput occurs. The magnitude of this trade-off is influenced by both beam degeneracy and coherent recording cross talk. At low optical throughputs an upper limit to the signal-to-noise ratio is set by the cross talk caused by angular sidelobe overlap, which in turn is a function of the angular isolation of the angularly multiplexed data pages.

Volume holographic optical memories provide the potential for high-density, rapid-parallel-access data storage. Recent advances in spatial light modulators (SLM's), storage materials, and detector arrays have increased the possibility of realizing practical volume holographic memory implementations. However, despite these advances in technology, several fundamental issues remain unresolved, including the accuracy with which stored digital data can be read back from volume holograms. The fidelity of recall affects the feasibility and capacity of volume holographic storage and thus is important to determine. In this Letter we quantitatively examine the fidelity achievable in a page-oriented volume holographic memory configuration in which Fourier-transform holograms¹⁻³ are recorded (shown schematically in Fig. 1).

In this type of volume holographic memory system a collimated beam of coherent light is split to illuminate two SLM's. Each pixel in the lower SLM corresponds to an angularly distinct reference beam at the front face of the holographic material. (Alternatively, a beam-deflecting device such as an acousto-optic modulator may be used to generate the reference beams.) The upper SLM represents a refreshable page (hence the term page-oriented memory) of binary data. Each page of data, which may consist of a 100×100 to a 1000×1000 bit array, is recorded in the volume hologram by interference of light from a particular reference beam with light from a corresponding page of information. As shown in Fig. 1 each page of data can be recorded as a Fourier-transform hologram in order to ensure some robustness to media defects. Multiple pages of information, each recorded with an angularly distinct reference beam, are superimposed within the volume hologram. The thickness of the holographic material and the incidence angle of each reference beam are

chosen such that each page of information can be selectively recalled (by use of the Bragg effect^{1,4}).

When multiple holograms are angularly multiplexed within the same volume, several types of cross talk can arise that affect the reconstruction fidelity of each page. The specific types of cross talk that are present in a given volume holographic system as well as their effect depend greatly on the particular architecture of the system.⁵ In a page-oriented volume holographic system in which Fourier-transform holograms are recorded, the existence of cross talk from cross gratings (hereinafter referred to as coherent-recording cross talk),^{1,5} beam degeneracy,⁵ angular sidelobe overlap,^{2,5,6} and grating degeneracy⁷ has been shown previously. Using numerical simulation, we quantitatively examine in this Letter the specific effects of beam degeneracy, coherent-recording cross talk, and sidelobe overlap on the fidelity of recall of stored binary data. The effects of grating-degeneracy cross talk on holographic data storage are not considered in this Letter since they have been examined previously.^{1,2,8}

Fig. 1. Typical page-oriented volume holographic memory system utilizing Fourier-transform holograms⁵: f_1 – f_3 , focal lengths; L_1 – L_3 , lenses.

In general, the numerical simulation of multiple-grating problems in which the above sources of cross talk are all included is computationally intensive for even modest numbers of diffraction gratings.⁵ For this reason we have limited our simulations to a 100-bit memory system, which, although small, is sufficiently large to evaluate the effects of these cross-talk sources.

We used the optical beam propagation method to simulate the readout of ten superimposed pages of one-dimensional binary data (each page consisting of ten binary pixels) in a linear recording material (i.e., one in which the refractive-index modulation is proportional to the local optical intensity) that has no media noise and infinite modulation range.⁵ Such an ideal holographic material was used because we wanted to examine fundamental limitations of the superimposed holographic storage process. The thickness of the recording medium used in our simulations was 4.5 mm, while the angular separation between the center of the reference and data pixel planes was 14.7°. A readout wavelength of 0.514 μm was assumed.

We first considered the case in which no coherent-recording cross-talk gratings were present. Five 100-bit simulations were run with different random bit patterns in each simulation. Using the results of all five simulations (500 bits total with approximately 250 1's and 250 0's), we created histograms of the diffraction efficiencies of the reconstructed bits. (Diffraction efficiency is the fraction of the readout beam that is diffracted into a given output bit.) The histograms of both the reconstructed 1's and the reconstructed 0's exhibited Gaussian shapes. Gaussian distribution functions were therefore fitted to the histograms of the reconstructed diffraction efficiencies. An example is shown in Fig. 2 for the particular case in which the average optical throughput per page was 20% (i.e., the average fraction of the incident light that is diffracted into a reconstructed page of data).

From the fitted distributions the signal-to-noise ratio (SNR) of the reconstructed binary data can be determined. At the output of a square-law detector the SNR is given by⁹

$$\text{SNR} = 20 \log[(m_1 - \xi)/\sigma_1], \quad (1)$$

in which m_1 is the mean of the distribution of 1's, σ_1 is their standard deviation, and ξ is the calculated optimal decision threshold between the 1's and the 0's. The optimal threshold is expressed as⁹

$$\xi = (\sigma_1 m_0 + \sigma_0 m_1)/(\sigma_1 + \sigma_0), \quad (2)$$

in which m_0 and σ_0 are the mean and the standard deviation of the distribution of 0's. Substituting values for the distributions shown in Fig. 2 into the above equations, we obtain an SNR of 15 dB. To put this number in perspective, we note that magneto-optic disk storage systems typically have SNR's of 17–20 dB (out of the preamplifier).

We consider next the SNR when coherent-recording cross-talk gratings are present. These gratings are recorded by the interference of light from pixels

within any given page. When a page of data is read out, the cross gratings transfer energy unequally among the reconstructed 1's as well as transfer energy from the 1's to the 0's. To reduce this effect, we arbitrarily consider the case in which the reference beam has 100 times the optical intensity of the beam from any given data pixel at the hologram. (For a linear holographic recording material with unlimited modulation range this does not lead directly to a decrease in optical throughput, which would typically be the case in real materials such as photorefractive crystals.¹⁰)

In Fig. 3 we show the fitted distributions for the same case as in Fig. 2 except that cross gratings are included in the simulations. The cross gratings clearly cause a broadening of the distributions relative to those of Fig. 2. This results in a much-reduced SNR of only 7 dB for this case.

Regardless of whether cross gratings are present, our numerical simulations illustrate the trade-off between reconstruction fidelity and optical throughput for the architecture shown in Fig. 1 even when the available modulation range is unbounded. This is shown in Fig. 4, in which the SNR is displayed as a function of the average optical throughput per page for the same random bit patterns (and analysis method) as used above. When no cross gratings are present, the SNR drops precipitously when the average throughput per page is greater than

Fig. 2. Fitted Gaussian distributions for the diffraction efficiencies of reconstructed binary outputs. No cross gratings are present in the holographic recording material.

Fig. 3. Same as Fig. 2 except that cross gratings are present. The beam ratio R is defined as the ratio between the intensity of a reference beam to the intensity of a beam from a single data pixel (at the holographic recording medium).

Fig. 4. SNR of reconstructed binary data as a function of the average optical throughput per page.

approximately 10%. The decrease in the SNR in this region is caused by beam degeneracy, which involves indirect coupling of the diffracted outputs through multiple data gratings (a complete description of this form of cross talk is found in Ref. 5). When cross gratings are added, the SNR is worse at any given optical throughput (for throughputs greater than $\sim 0.5\%$) because of direct coupling of the diffracted outputs through the cross gratings. As the optical throughput drops below 0.5% , the effect of both types of multiple-grating interactions becomes negligible, and the SNR for both cases approaches an asymptote of ~ 25 dB. This upper limit is due to sidelobe overlap of the Bragg angular response peaks (Ref. 5 provides an extensive discussion of angular sidelobe overlap). The effects of angular sidelobe overlap can be reduced by a larger angular separation between the reference beams or by use of a thicker recording material.¹ For example, further simulation shows that if the thickness of the volume holographic material is increased by a factor of 2, the SNR upper limit increases to ~ 30 dB for the above cases.

As illustrated in Fig. 4, significant increases in reconstruction fidelity are achievable at the expense of optical throughput. For example, in the absence of cross gratings the SNR can be increased from 5 to 19 dB with only a factor-of-2 reduction in optical throughput (30% to 16%). Further improvement in the SNR requires a significantly greater reduction in throughput. For example, increasing the SNR from 19 to 25 dB necessitates a drop in the optical throughput by a factor of 5 (16% to 3%). The SNR-throughput trade-off no longer exists in the region for which sidelobe overlap is the dominant cross-talk source (i.e., at throughputs less than $\sim 0.5\%$ for the cases considered herein).

The optimal trade-off between optical throughput and fidelity depends greatly on the total system noise budget, which includes shot noise, media noise, electronic noise, and laser noise. The optical throughput cannot be made arbitrarily small (even if the motivation is achievement of enhanced reconstruction

fidelity) since other system noise sources (such as electronic noise) may overwhelm the signal. The specific resolution of these issues and the resultant consequences for the system's total storage capacity deserve serious attention.

In summary, we have analyzed the reconstruction fidelity of Fourier-transform page-oriented volume holographic memory systems by examining reconstructed diffraction efficiency distributions with beam-propagation-method-based simulations. We have shown the effects of beam-degeneracy cross talk, coherent-recording cross talk, and angular sidelobe overlap on the signal-to-noise ratio for reconstructed random bit patterns stored in an ideal material. Our results indicate the regions in which significant gains in reconstruction fidelity may be made for modest reductions in optical throughput.

Future research directions include incorporation of the effects of real materials in our studies and application of the above analysis methods to other volume holographic memory architectures, including those that employ image-plane holograms¹¹ and double angularly multiplexed holograms.⁵ Such an analysis would enable us to compare the performance of each architecture quantitatively. An additional direction is a detailed examination of how the results presented in this Letter scale with the number of stored bits.

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