Holographic 3D disks

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ABSTRACT

Shift multiplexing is a holographic storage method implemented with spherical wave reference beams. We present the main properties of shift multiplexing, compare it with angle multiplexing, and describe the design of a holographic 3D disk system that is capable of storing 12.4 bits/μm^2 using this method.

Keywords: shift multiplexing, holographic 3D disks, surface storage density.

1 Introduction

Holographic storage was suggested[1] as a method to store data in 3-D. Each hologram contains a data page (usually binary pixels), imprinted on a plane wave signal beam by a spatial light modulator (SLM) and recorded as the result of interference between the signal beam and a reference beam. When the hologram is illuminated by the reference, the stored data page is reconstructed, and is captured by a CCD camera (Fig. 1-a). In a volume holographic memory, multiple holograms are superimposed on the same location of the recording medium. The holograms can be retrieved separately by utilizing the Bragg selectivity.[2] For example, if the reference is a plane wave, then changing the angle of incidence by an amount $\Delta\theta$ (determined by the geometry and the thickness L of the holographic medium) causes the reconstruction to become Bragg mismatched. A new hologram can be stored with the rotated reference and retrieved with minimal crosstalk.[3] If M is the number of holograms that are superimposed at different reference incidence angles at the same location of the 3-dimensional medium, then the surface storage density increases according to

$$\mathcal{D}_{3D} = M \times \mathcal{D}_{2D}, \qquad (1)$$

where $\mathcal{D}_{2D}$ is the surface storage density obtained when a single hologram is recorded. In a recent experiment,[4] $\mathcal{D}_{3D} = 10.6$ bits/μm^2 was demonstrated with a combination of angle[2,5] and peristrophic[6] multiplexing using $M = 32$ and $\mathcal{D}_{2D} = 0.33$ bits/μm^2. The material used was DuPont's HRF-150 100 μm thick photopolymer. Surface densities in excess of 100 bits/μm^2 are possible[7] if thicker materials are used.

In this paper we will describe how to achieve high capacity storage using a different method, shift multiplexing.[8] This method is very convenient in the holographic 3D disk architecture.[7]

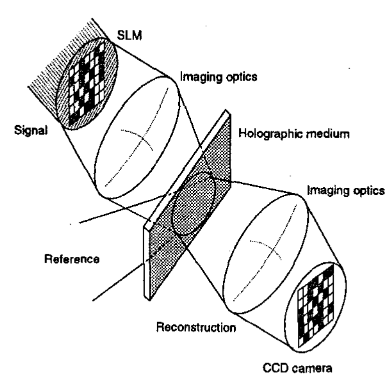

Figure 1: Concept of a holographic memory.

2 Theory of shift multiplexing

Holograms recorded or read-out with spherical reference beams[9–11] have interesting properties. For instance, such a hologram acts as an optically controlled zoom lens when the focus of the reconstructing wave along with its wavelength are changed[9] and yields the correlation without the need for a Fourier transforming lens when read out with a signal beam.[10] A volume hologram recorded with a plane wave reference can be Bragg matched entirely using a spherical wave at wavelength different than the recording wavelength.[11]

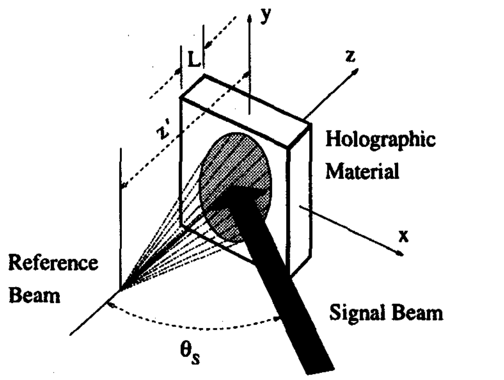

Figure 2: Basic geometry for shift multiplexing using a spherical wave reference.

Recently, it was pointed out that, when the recording reference is a spherical wave, Bragg mismatch occurs when the hologram is translated relative to the spherical reconstructing reference at the same wavelength.[8] The geometry for the demonstration of this effect is shown in Fig. 2. The holographic medium occupies the region $-\infty < x, y < +\infty$, $|z| < L/2$. The angle of incidence (in air) of the signal beam with respect to the optical axis, defined by the spherical reference, is θ' (in radians), and z' is the distance of the focus of the spherical wave from the coordinate origin (also measured in air). Let θ and z_0 denote the angle and focal distance, respectively, measured inside the holographic material. Under the Born and paraxial ($\theta << 1$) approximations, and ignoring variable modulation depth effects, the three-dimensional diffraction problem can be solved analytically.[8] The diffraction efficiency of a plane wave hologram recorded with a spherical wave reference emanating from a point source of infinitesimally small spot size is given by the following expression:

$$\eta(\delta) = \mathrm{sinc}^2\left(\frac{L\theta\delta}{\lambda z_0}\right), \qquad (2)$$

where δ is the translation of the hologram relative to the reference in the x-direction (defined as the normal to the optical axis lying on the plane defined by the optical axis and the signal beam wavevector – see Fig. 2). The reconstruction vanishes at integer multiples of the Bragg shift selectivity

$$\Delta\delta = \frac{\lambda z_0}{L\theta}, \qquad \text{or} \qquad \Delta\delta = \Delta\theta \times z_0, \qquad (3)$$

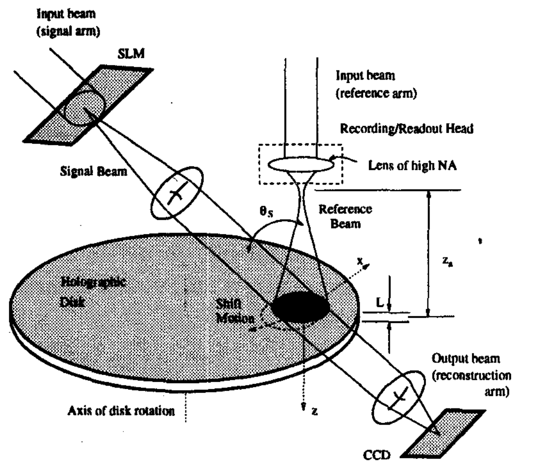

Figure 3: Shift-multiplexed holographic 3D disk.

where $\Delta\theta$ is the angle Bragg selectivity of a system with a plane wave reference propagating along the z-axis in Fig. 2 and the same signal beam. Equation (3) can be corrected for refraction and the finite spot size $\lambda/2(\mathrm{NA})$ of the reference source, yielding the expression:

$$\Delta\delta = \frac{\lambda_0\left[z' - \left(1 - \frac{1}{n_0}\right)\frac{L}{2}\right]}{L\theta} + \frac{\lambda_0}{2\,(\mathrm{NA})}, \qquad (4)$$

where n_0 is the index of refraction of the holographic medium, and λ_0 is the wavelength in vacuum. The distance $\Delta\delta$ can be very small, in the order of a few microns. For example, $\Delta\delta = 3.6\ \mu$m has been demonstrated experimentally[8] using Fe-doped $LiNbO_3$ of $L = 4.5$ mm as recording material, $z' = 1$ cm, $\theta' = 40°$, and (NA)=0.6 .

The shift multiplexing method is particularly applicable to the holographic 3D disk architecture.[8,12] In such a system (Fig. 3), the holographic medium is disk-shaped, and a recording/read-out head produces the spherical reference beam. An SLM modulates the signal beam for recording, and the CCD captures the reconstruction as in any holographic memory (compare, e.g. with Fig. 1). Holograms are recorded after shifting the disk by an amount equal to a multiple of $\Delta\delta$ between successive exposures. To retrieve the data, one simply rotates the disk; each hologram becomes Bragg-matched when the location of the reconstructing reference coincides with the location of the recording reference. Compared to an angle/peristrophic-multiplexed 3D disk,[4,13,7] the architecture of a shift-multiplexed 3D disk is simpler, since the only motion the head needs to perform is in the radial direction, in order to access different tracks on the disk.

Shift selectivity also occurs in the y-direction, i.e. normal to the plane defined by the signal beam and the optical axis of the reference. This is equivalent to the peristrophic[6]/fractal[14] methods when a plane wave reference is used. The effect utilized in this case is that the reconstruction shifts in the Fourier plane as the spherical wave reference is translated in the y direction. The shifted reconstruction can be blocked by a suitable aperture, as shown in Fig. 4, and a new hologram can be recorded with the translated spherical reference. The y-shift selectivity $\Delta\delta_y$ is calculated by requiring that the hologram spectrum shifts completely out of the necessary aperture. The result is:

$$\Delta\delta_y = \begin{cases} N_p b z_0 / n_0 F, & \text{Fourier plane} \\ 2\lambda_0 z_0 / n_0 b, & \text{image plane} \end{cases} . \quad (5)$$

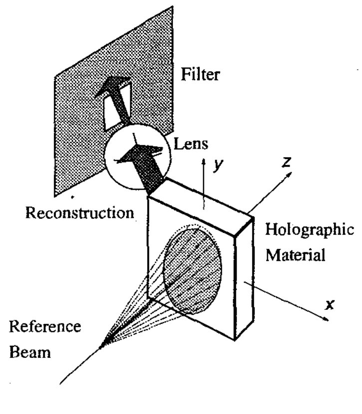

Figure 4: Fractal (y) shift multiplexing.

In addition to the fractal-type selectivity calculated above, Bragg mismatch occurs as the reference is translated in the y-direction. The Bragg selectivity is given by the expression:

$$\Delta\delta_y^{\text{Bragg}} = \sqrt{\frac{2\lambda}{L}} z_0 \quad (6)$$

If the numerical value of $\Delta\delta_y^{\text{Bragg}} << \Delta\delta_y$, then the smaller value of (6) can be used for the shift selectivity in the y-direction. If, however, $\Delta\delta_y^{\text{Bragg}}$ and $\Delta\delta_y$ are comparable, then crosstalk considerations require that (5) be used instead.

In the holographic 3D disk architecture, y-shift multiplexing corresponds to overlapping tracks of holograms in the radial direction. The layout of the 3D disk is shown in Fig. 5. Each hologram

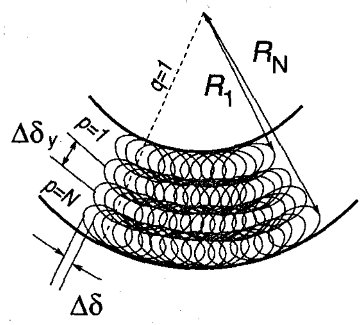

Figure 5: Layout of holograms shift-multiplexed on two dimensions on a holographic 3D disk.

is addressed by two coordinates: its track p and its position q inside the track. Therefore only two motions are required to access any hologram on the disk: radial head motion in order to access different tracks, and disk rotation in order to access different holograms on the same track.

3 Photopolymer-based shift multiplexed holographic 3D disk

The material of choice for the construction of the holographic 3D disk is DuPont's HRF-150 photopolymer. For the design of the shift-multiplexed 3D disk, we will use parameters close to those of the high-capacity experiment[4] with the same material. Thus we have $L = 100\ \mu$m, $\lambda_0 = 0.532\ \mu$m, $n_0 = 1.525$, $\theta = 34.6°$, $z_0 = 2.0$ mm, $N_p = 768$, $b = 45\ \mu$m, $F = 5.46$ cm. The shift selectivities for the Fourier plane storage geometry are:

$$\Delta\delta = 18.0\ \mu\text{m}, \qquad \text{and} \qquad \Delta\delta_y = 0.82\ \text{mm}.$$

The numbers of overlapping holograms in the x and y directions (assuming 3rd-Bragg null storage in the x-direction), respectively, are

$$M_x = 23.9 \qquad \text{and} \qquad M_y = 1.57,$$

yielding a final density of

$$\mathcal{D}_{3D} = M\mathcal{D}_{2D} = (M_x \times M_y)\mathcal{D}_{2D} = 12.4\ \text{bits}/\mu\text{m}^2.$$

Here $\mathcal{D}_{2D} = 0.33\ \text{bits}/\mu\text{m}^2$ for the parameters of this design.[4]

Consider again the 3D disk layout given in Fig. 5. Let R_1 be the radius of the innermost track, and let P denote the total number of tracks. The radii of the remaining tracks are given by $R_p = R_1 + p\Delta\delta_y$. Therefore the number of holograms per track (still assuming 3rd Bragg null storage) is given by

$$Q_p = \frac{2\pi R_p}{3\Delta\delta} = \frac{2\pi R_1}{3\Delta\delta} + p\frac{2\pi\Delta\delta_y}{3\Delta\delta}, \qquad p = 1, \ldots, P. \tag{7}$$

The total number of holograms is

$$N = \sum_{p=1}^{P} Q_p = \frac{2\pi}{3}\frac{PR_1 + \frac{1}{2}P(P+1)\Delta\delta_y}{\Delta\delta} \tag{8}$$

In our design, $R_1 = 1.5$ cm, $R_P = 5.0$ cm $\longrightarrow$ $P = 42$, which yields $N = 1.6 \times 10^5$. The overall raw capacity of the shift-multiplexed 3D disk is, therefore,

$$\mathcal{C} = NN_p^2 = 8.7 \times 10^{10} \text{ bits} \tag{9}$$

One advantage of the photopolymer is high diffraction efficiency. A conservative estimate for the expected diffraction efficiency of holograms in the shift-multiplexed 3D disk we are designing is $\eta = 3 \times 10^{-3}$. Then the required integration time for a standard CCD camera and 10 mW readout power is[15] $t_i = 8$ μsec, corresponding to a continuous data transfer rate of more than 70 Gbits/sec, if the data can be transferred from the detector. The maximum rotation speed allowed for the integration time to be achieved at the outermost track is $\omega = v/R_P$, where $v = 3\Delta\delta/t_i = 6.75$ m/sec is the linear velocity. The result is 8100 rpm, or 7.4 msec per rotation.

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